MONTREAL PROTOCOL

ON SUBSTANCES THAT DEPLETE

THE OZONE LAYER

UNEP

REPORT OF THE
TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL

MAY 2005

VOLUME 3

REPORT OF THE TASK FORCE ON
FOAM END-OF-LIFE ISSUES

Montreal Protocol On Substances that Deplete the Ozone Layer

UNEP Technology and Economic Assessment Panel

May 2005 Report of the Task Force on Foam End-of-Life Issues

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May 2005 Report of the Technology and Economic Assessment Panel

Volume 3

Report of the Task Force On Foam End-of-Life Issues

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May 2005 Report of the Technology and Economic Assessment Panel

Volume 3

Report of the Task Force On Foam End-of-Life Issues

FOREWORD

The May 2005 TEAP Report consists of three volumes:

Volume 1: May 2005 TEAP Progress Report

Volume 2: May 2005 TEAP Replenishment Task Force Report

Volume 3: May 2005 TEAP Task Force on Foams End-of-Life Issues Report

Volume 1

Volume 1 contains an Executive Summary of all TEAP Progress Report topics, as well as the Executive Summary of Volume 2 and 3. Volume 1 contains the essential use report, progress reports, the MB CUN report, the CTOC report, and TEAP member biographies and membership lists.

Volume 2

Volume 2 is the Assessment Report of the TEAP Replenishment Task Force of the Funding Requirement for the Replenishment of the Multilateral Fund during 2006-2008, in response to Decision XVI/35.

Volume 3

Volume 3 (this volume) is the Task Force on Foams End-of- Life Issues Report according to Decision XV/10.

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REPORT OF THE TASK FORCE ON FOAM END-OF-LIFE ISSUES

EXECUTIVE SUMMARY

This report responds to Decision XV/10 of the Parties of the Montreal Protocol which sought feedback from the TEAP on two issues:

(1) The provision of useful information on the handling and destruction of ODS contained in thermal insulation foams with particular focus on economic and technological aspects of those contained in buildings;
(2) The clarification of the distinction between destruction efficiencies achieved when blowing agents are extracted from foams prior to destruction (re-concentrated sources) and those achieved when foams themselves are destroyed directly (dilute sources).

Although the report touches on the uptake of various destruction technologies in the foam sector, it was not the prime purpose of this report to investigate the success of implementation of end-of-life management strategies (i.e. the efficacy and efficiency of collection). The main focus of the report is to describe the technical and economic aspects of blowing agent recovery and destruction from appliance and building insulation foams.

There have been considerable advances in the understanding and application of end-of-life management strategies for foams over the three years since the TEAP last reported on this issue within the Task Force Report on Collection, Recovery & Storage of ODS. There are two prime categories of destruction option available to the sector. These are:

- Mechanical blowing agent separation techniques followed by the destruction of re-concentrated blowing agent
- Direct destruction of the foam including its blowing agent using techniques such as direct incineration (e.g. co-incineration in power plants or cement kilns)

Efficiency issues

During the finalisation of the report of the TEAP Task Force on Destruction Technologies in 2002, there had been some confusion about how to express efficiencies for these two types of processes. The favoured method for expressing all destruction efficiencies was by use of the term Destruction and Recovery Efficiency (DRE) which focused only on the efficiency of destruction within the incineration 'stack' of the destruction facility. Even the wider scope of the term Destruction Efficiency (DE) was not sufficient to take into account the real situation with foams, since this only dealt with handling efficiencies at the destruction facility itself. It was clear, therefore, that any meaningful statement on the efficiency of destruction of blowing agents within foams needed to consider all steps along the recovery and destruction handling chain including those practised prior to the foam ever reaching a destruction facility.

Three main steps involving potential losses of efficiency have been identified. These are:

(1) Losses on the segregation of the foam from other waste streams

(2) Losses during other pre-incineration steps, particularly where mechanical recovery and re-concentration of blowing agent is practised

(3) Losses during final incineration of the re-concentrated or dilute blowing agent source

The Task Force was able to evaluate these steps for all major end-of-life management options being operated or researched at this time. Table ES-1 summarises these findings based on recent research and evaluations (see Chapter 5):

Product Type	***Recovery Method***	***Losses in segregation***	***Losses in other pre-incineration steps***	***Losses in incineration***	***Recovery & Destruction Efficiency (RDE)***
General Building Foam	Mechanical Recovery	2-8%	0.5%	<0.1%	>90%
General Building Foam	Direct Incineration	2-8%	Not Applicable	<0.1%	>90%
Sandwich Panels	Mechanical Recovery	Not Applicable	<5%	<0.1%	>94%
Sandwich Panels	Direct Incineration	Not Applicable	Not Applicable	<0.1%	>99%
Appliance Foam	Mechanical Recovery	Not Applicable	<5%	<0.1%	>94%
Appliance Foam	Direct Incineration	0.5-4%	Not Applicable	<0.1%	>95%
Appliance Foam	Auto-shredder + managed attenuation	8-40%	<40%	Not Applicable	>20%

Table ES-1 Typical losses experienced in currently considered end-of-life strategies

In seeking to find a means of expressing this combined efficiency, the Task Force decided to introduce a new term entitled Recovery and Destruction Efficiency (RDE) to express the composite efficiency of these three steps. This parameter identifies the proportion of the ‘banked’ blowing agent which is recovered in the overall end-of-life management step. It does not, therefore, cover losses in blowing agent which may have occurred during the production and in-use phases of the product’s lifecycle.

$$RDE\ (\%) = \left\{ \frac{\text{Blowing Agent in foam Immediately prior to Decommissioning} - \text{[Losses in Segregation and/or Mechanical, Recovery and/or Incineration]}}{\text{Blowing Agent in foam immediately prior to decommissioning}} \right\}$$

It can be seen from Table ES-1 that in all but the final end-of-life management option listed (auto shredder + managed attenuation), the potential exists to achieve RDEs of greater than 90%, albeit based on a limited level of information in the buildings sector. The opportunity therefore exists to introduce this, or a slightly lower, minimum value to identify Approved Technologies under the Montreal Protocol in future.

Although not likely to become an Approved Technology, managed attenuation could still prove to be an important technology to minimise emissions from foam already landfilled and building foam that is not segregated. Further work must be done to determine the technology’s capacity and efficacy in mitigating emissions.

Appropriateness of available technologies

Although few genuinely new technological options have emerged for end-of-life management in the period since the last review (TFCRS: 2002), there has been considerable progress in the characterisation and optimisation of existing processes. It would not have been possible to assemble a table similar to Table ES-1 for the earlier report.

There are two key waste streams yielding foams with potential for end-of-life management. These are the appliance sector and the buildings sector.

Appliances

It is estimated that upward of 1 billion domestic refrigerators and freezers are in use globally at this time. Many of these still contain foams blown with CFC-11, although the bank is already in decline. The appliance sector is characterized by the fact that the average global lifetime for such units is around 15 years (range 10-25 years). This distinguishes it from the building sector where, with the exception of a few building services applications, product lifetimes are much longer (50 years plus). These distinctive lifetimes have effects on both the character of waste streams and the processes required to manage them.

There are four key phases in which banks of blowing agent can reside:

- Within products during their normal service life
- Within products during an extended service life (often referred to as re-use)
- Within foams already landfilled without special treatment
- Within landfilled foams which have been segregated, shredded or otherwise treated

Figure ES-1 shows the predicted shift of CFC-11 from the original appliances into the various categories of re-use, normal landfill and shredded landfill, based on the consumption and emissions data used in the IPCC/TEAP Special Report.

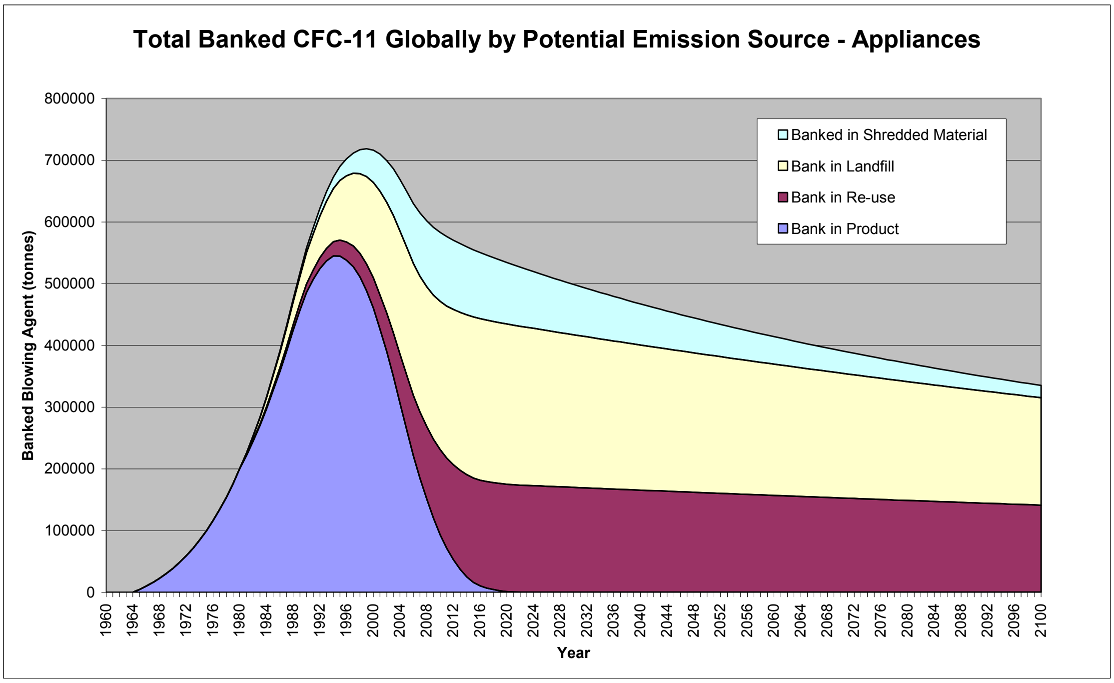

Figure ES-1 Predicted trends in the location of CFC-11 banks from appliances

Several factors emerge from this graph. The first is that total banks of CFC-11 from the appliance sector probably peaked in around 2003 and are now beginning to decline as emissions from banks, coupled with managed recovery and destruction, outstrip any new consumption. The impact of the end-of-life regulation in both Europe and Japan (mostly through mechanical recovery and destruction) can be seen in the period from 2004 -2012 through the overall decline in the bank size.

In contrast, it is also important to note that at least 30% of the world's appliances that contained CFC-11 had been decommissioned by 2003 and much of the resulting foam had found its way into landfill. This is a particularly important factor in the developed countries where the proportion of appliances that had already reached the end of their service lives in 2003 were believed to be greater than 60% (Europe 73%; North America 63%; Japan 73%). This point highlights the need for prompt actions in this area if recovery of CFC-11 is to be further enhanced. It also implies that much of the CFC-11 in these regions had already reached landfill before regulatory provisions for end-of-life recovery were in place.

The situation for HCFC-141b and other more recent CFC-substitutes is different. In most cases HCFC-141b was only introduced in the early 1990s and waste streams are only now beginning to see signs of the first decommissioned units coming through. Accordingly, virtually the whole 'bank' of HCFC-141b contained in appliances (in excess of 200,000 tonnes) is still fully available for end-of-life management.

Buildings

For buildings, the situation is very different. Taking the average lifetime of insulated building products as 50 years, it is not even expected that products containing CFC-11 will reach the waste stream in significant quantities until after 2010. This provides some further time to research appropriate end-of-life management options. However, achieving significant recovery and destruction is still likely to be a daunting task, since the foamed products were often installed with no thought to the fact that the foam might need to be reclaimed at end-of-life. One of the biggest challenges for this sector will be how to segregate foams from other demolition waste. At present, only manual methods exist and these make the economics of recovery and destruction very marginal, particularly in developed countries where labour rates are relatively high and the bulk of building insulation is situated.

Figure ES-2 gives an example of the trends in CFC-11 bank development expected in the building sector. In this instance, the graph addresses the situation for PU Boardstock.

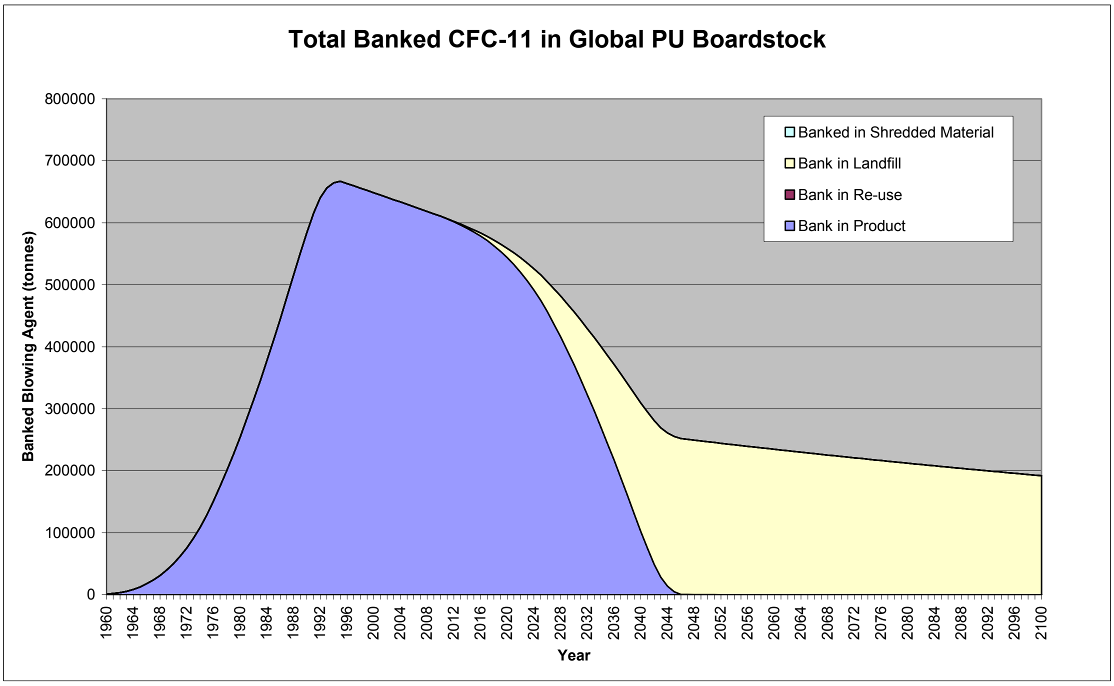

Figure ES-2 Predicted trends in the location of CFC-11 banks from PU Boardstock

For the reasons outlined above, it has been estimated for modelling purposes that 20% or less of the currently installed building insulation will be available for recovery and destruction through technically and economically viable means. The one exception to this is the case of steel faced sandwich panels where deconstruction of the building may be easier and there would be no subsequent requirement for segregation. Trials are already in progress to establish the costs of recovery and destruction of the blowing agent in such panels, and there is expectation that there will be no fundamental technical or economic barriers to either mechanical recovery or direct incineration methods.

Economic and Logistical issues

Although there are significant variations in approach between the various proposed methods of end-of-life management, Table ES-1 illustrates that, when well-practised, most end-of-life methods can be effective in achieving satisfactory recovery levels (i.e. >90%).

However, when it comes to economic viability the range of performance is much greater. The prime reason for this has already been mentioned – namely the potential need for waste segregation. One of the difficulties that the Task Force had in compiling this report was that there is little experience, as yet, in recovery and destruction of blowing agents from buildings on a commercial scale, primarily because most such foams are still in use. One of the challenges for end-of-life management in the building sector will be to provide sufficient incentive for the research and development of segregation methods ahead of the time when significant commercial opportunity exists. The key to optimising recovery and destruction in this sector is likely to be the successful co-ordination of technical feasibility, economic viability and regulatory versatility.

For appliances and steel faced sandwich panels, the situation is far more straight-forward. Infra-structure is already established in key areas of the world and commercial evidence suggests that recovery at $25-40/kg of blowing agent is already an achievable goal. The challenge has been to keep capacity investment (mostly in mechanical recovery) and demand in balance in a fast-moving market environment. Where regulation has been used to encourage the development of such markets, enforcement remains a challenge. Currently, typical efficiencies of collection are believed to be in the 50-65% range although they are generally still improving.

One of the barriers to wider success of such programmes is the quality of infrastructure available for collection and transport. The location of recovery and destruction plants is important, with proximity to large urban populations advantageous. The introduction of mobile recovery units is also likely to assist in reaching less densely populated areas and may have particular advantages in cutting down transport impacts from large building demolition sites.

The issue of logistics is particularly acute for developing countries and the existence of a reliable infra-structure is a pre-requisite for investment in any recovery and destruction facility.

<u>Are there possibilities for dealing with foams already in landfills?</u>

From the previous commentary on both appliances and buildings, it is clear that there has been, and will continue to be, substantial amounts of CFC-11 reaching landfills. Accordingly, methods of containing or otherwise attenuating emissions are of significant interest.

Preliminary laboratory work by the Danish Technical University (and others) has indicated that CFC-11 can breakdown under anaerobic conditions (exclusion of air). The breakdown products include initially HCFC-21 and HCFC-31, but these are then converted on to HFC-41. It appears that the microbes are unable to deal with the carbon-fluorine bond and there is no further breakdown of HFC-41 as currently observed. However, it is not clear why this is.

Another unknown is whether this breakdown mechanism occurs in all landfills to a limited extent or whether it only occurs where conditions are optimised by the 'seeding' of appropriate microbes in a controlled anaerobic setting.

Finally, it should be noted that the breakdown mechanism cited above does not offer a full mass balance and other breakdown products are suspected. It is important that further work be done to identify these breakdown products, not only to establish whether managed attenuation in landfills, if practicable, should be encouraged but to determine whether harmful products are already being generated from CFC-11 breakdown in landfills on a more widespread basis.

With recorded CFC-11 breakdown levels in the range of 60-100% in the laboratory, there is significant emission reduction potential if this technology can be transposed to the landfill environment. However, there is still much to learn about this mechanism and the technologies that could derive from it. Scale-up work would be required to investigate this option further if the breakdown products are seen to be relatively benign.

Emission Reduction Potential and dependence on Economics

Work carried out for the IPCC/TEAP Special Report on HFC & PFC related issues, identified a cumulative emission reduction potential from foam end-of-life measures in excess of 150,000 ODP tonnes based on the assumption that 20% of the blowing agent currently situated in existing buildings can be recovered and destroyed economically.

The sensitivity of this assessment of recovery potential to economic drivers remains a key factor. There are examples in the appliance sector where 'bounty programmes' have made manual segregation possible both technically and economically because the benefit has been associated with another parameter (in this case energy savings and reduced costs). The Task Force believes that much of the opportunity to recover ODSs will depend on the ability to link recovery and destruction to other drivers, such as the POPs treaty or emissions trading schemes, in order to achieve economies of scale on the one hand or full environmental value for the end-of-life management step. In this context, it should be noted that much of the ODS recovery and destruction in the appliance sector has been supported (and sometimes initiated) by parallel recycling targets.

Conclusions

This review of foam end-of-life issues has led to the following key conclusions:

Technical Feasibility

- The increasing focus on the potential for emission reduction through end-of-life measures has led to a greater study of technical options in the past three years and more information is now available.

- A review of the Montreal Protocol technology approval process for blowing agent recovery and destruction suggests that a new parameter, Recovery & Destruction Efficiency (RDE) would be valuable to accommodate the whole recovery and destruction chain and overcome the limitations of both DRE and DE in respect of foams. Parties may wish to consider whether this would make an appropriate basis for re-defining Approved Technologies for foams.

- All currently practiced recovery and destruction processes have the potential to reach an RDE of greater than 90% and a level of this order (e.g. 85%) could be considered as a new minimum standard for determining Approved Technologies in the foams sector.

- Laboratory evidence continues to emerge for anaerobic degradation of ODSs, which could be applicable in the landfill environment. However, it is not clear whether the process occurs to any extent in normal landfills or whether it would require specific landfill management techniques (managed attenuation).

- Optimisation of anaerobic conditions in the laboratory can create high levels of degradation. However, further work would be required on the identification of breakdown products to confirm that no new health or environmental impact are likely to be created inadvertently

- In view of the nature of landfilling processes, there is unlikely to be any circumstance in which the managed attenuation would become an Approved Technology. However, the technology could be highly beneficial in dealing with foamed products already in landfills and those for which no economically viable Approved Technology exists.

Economic Considerations

- The economics of recovery and destruction are greatly affected by the need to manually segregate foams from other components. The most cost-effective options are those mechanical recovery and direct incineration processes which avoid the need to segregate.

- The most demanding requirements for segregation (e.g. traditional building demolition wastes) occur in developed countries where the costs of labour are likely to be at their highest.

- In general, manual segregation can only be avoided where metals or plastics are the other primary component. This is the case for domestic appliances and steel faced panels. Mixed demolition waste will virtually always need to be segregated.

- The most cost-effective of all processes is the incineration of steel faced panels in steel-making furnaces where the steel is immediately recycled and the foam provides energy. Recent work suggests that emissions from this process can be managed without problem, even with the presence of plastisol coatings on the steel. However, the breadth of application of this approach depends on the geographic availability of such furnaces. Steel plants remain very sensitive to high chlorine feed concentrations and these need to be managed.

- Direct incineration using other technologies (e.g. Municipal Solid Waste Incinerators) will normally require segregation of foams unless the feedstock is sufficiently diluted to avoid build-up of incineration residues. Care also needs to be taken to ensure that emissions of halogenated bi-products do not exceed concentration limits.

- Mechanical recovery methods work well with appliances and steel faced panels. Blowing agents can currently be recovered from appliances at a net cost of $25-40/kg. However, work is on-going to establish the full costs of recovery from steel-faced panels.

- The costs of transport can also be a significant factor in the recovery of blowing agents. Indeed, in developing countries, the lack of appropriate supporting infra-structure (e.g. road networks) can negate the value of otherwise viable investments in recovery and destruction facilities. Even in developed countries, cost of transport to recovery and destruction facilities is a factor because of the wide distribution of use and low density of building foams.

- The Montreal Protocol is not alone in seeking to manage the end-of-life recovery and destruction of chemicals. There are similar drivers in both the POPs Treaty and the Kyoto Protocol. An opportunity therefore exists to explore possible cost-sharing mechanisms and other shared drivers.

Environmental Potential

- Existing banks of CFCs and HCFCs are estimated to be in excess of 1.5 million and 0.75 million tonnes respectively. Efforts to corroborate these estimates from bottom-up analysis (e.g. JTCCM and others) have confirmed broad agreement at country-level.

- Emission factors from banks continue to be under review. This is an on-going process requiring the identification of other emissive sources in order to align with observed atmospheric concentrations. In general, foams are among the slowest emitting product groups. This means that opportunities for bank management are maximised, but, if unmanaged, emissions are spread over a very long period.

- Several of the banks are already situated in landfills. In developed countries, over 60% of the domestic refrigerators using CFC-11 were already disposed of by 2003. Accordingly, managed attenuation of blowing agents in landfills would be the only available emission reduction option in many cases.

- Managed attenuation in landfills may also be the only practical option available for many foams currently in buildings unless segregation methods can be improved. Experience with the management of foams in buildings is currently limited, partly because of the longevity of many foam products which have yet to reach end-of-life.

- Published assessments carried out for the IPCC/TEAP Special Report on the inter-relationship between ozone depletion and climate change suggested that cumulative ODS emission reductions in excess of 190,000 ODP tonnes could be achieved by 2100 using appropriate end-of-life management techniques. This does not take into account potential contributions from managed attenuation.

- In the foam sector, there could be incremental environmental benefits accruing from reductions in HFC emissions at end-of-life, through the continued use of equipment originally deployed to manage ODSs at end-of-life.

CHAPTER 1

1.0 SCOPE OF REPORT

1.1 Background

Thermally insulating foams are used to meet two major societal needs. The first is to assist in the maintenance of temperature and the minimisation energy consumption within domestic and commercial appliances (e.g. refrigerators, freezers and water heaters). The second is to minimise heat losses and heat gains in buildings. Other applications also exist (e.g. for temperature-controlled transport), but these are less significant in their overall use of foams.

The manufacturing process involves the use of a chemical agent to blow the foam. Since most of these blowing agents have higher thermal efficiency than air, additional benefit is gained from achieving closed cell foams which can retain the bulk of the blowing agent throughout the operational life of the product in question. However, this technological approach means that the blowing agent will only be substantially released in the period following the decommissioning of the product containing the foam (usually referred to as the 'end-of-life' phase).

In general terms, the contribution of the blowing agent to the overall waste stream is minimal. However, attention has been drawn to this phase of the foam lifecycle because of the fact that ozone depleting substances (ODSs) such as CFCs and, more recently, HCFCs have been used historically to blow foams. The rationale for the selection of these chemicals, as with their use as refrigerants, was based on their excellent thermal properties and stability – properties which, in the end, contributed to their downfall. HCFCs were introduced only as transitional substances to accelerate the phase-out of the more potent CFCs during the early and mid-1990s. However, with annual demand for CFC blowing agents in closed cell foams peaking in 1990 at levels in excess of 200,000 tonnes (see Figure 1), there is clearly a concern about the potential future release of those blowing agents which remain in foams at this time.

With transition out of ODSs favouring the use of hydrofluorocarbons (HFCs) as replacement blowing agents in some instances and the fact that CFCs and HCFCs are also significant greenhouse gases, there has been increasing attention on the issue of foam lifecycles from the Kyoto Protocol community as well as that of the Montreal Protocol. Accordingly, retained foam blowing agents (commonly referred to as 'banks') have featured in a recent IPCC/TEAP Report[1] which addresses the inter-action between efforts to protect the ozone layer and those required to protect climate system. This report often cross-references that work and builds on the foam-specific information contained therein. Readers of this report are therefore encouraged to also read the foam-specific elements of the IPCC/TEAP Special Report as background.

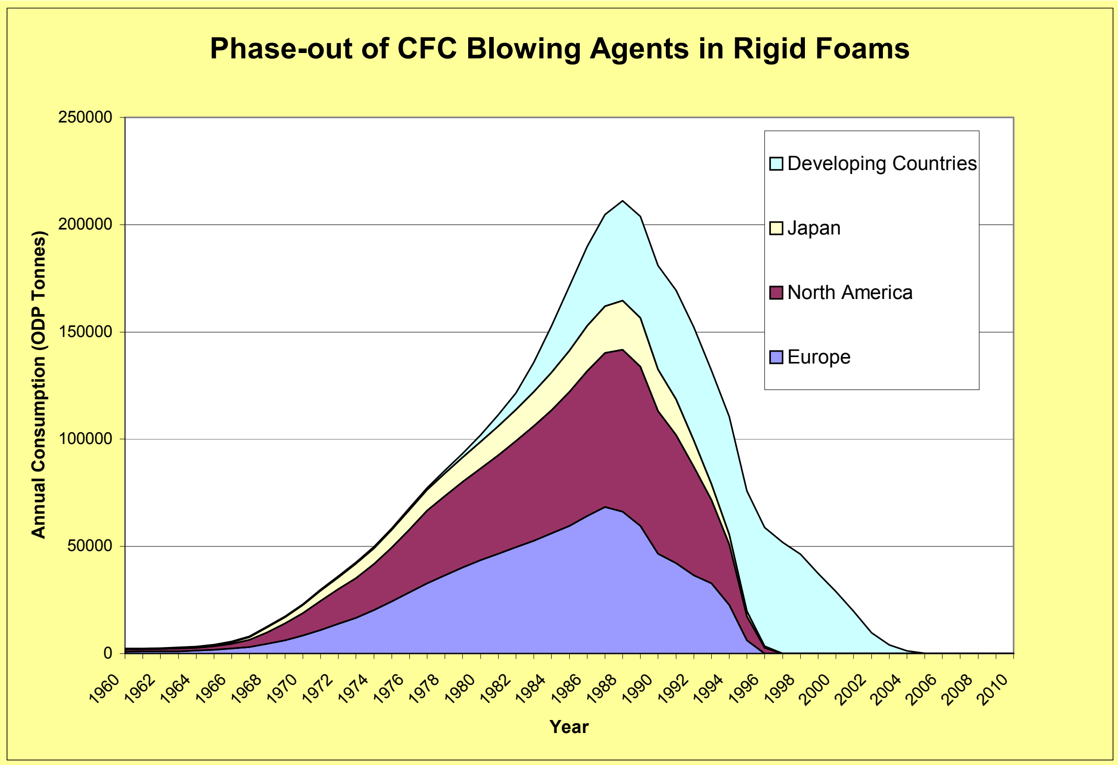

Figure 1 – Patterns in demand for CFCs in closed cell foams by region

[1] IPCC/TEAP Special Report "Safeguarding the ozone layer and the global climate system: issues related to hydrofluorocarbons and perfluorocarbons" - IPCC, April 2005

1.2 Objectives of the Report

Although the Montreal Protocol was established primarily as a mechanism for controlling the production/consumption of ODSs, the Parties have consistently expressed an interest in the minimisation of emissions of CFCs and HCFCs already in use when these can be avoided. Accordingly, initiatives such as refrigerant and halon management plans have been encouraged. Appendix B contains a non-exhaustive list of the Decisions which have dealt with such management and destruction issues.

Of most relevance to the genesis of this report was Decision XII/8 taken at the 2000 Meeting of the Parties which requested the Technical and Economic Assessment Panel (TEAP) to report back to the Parties in 2002 on:

".....the technical and economic feasibility for the long-term management of contaminated and surplus ozone-depleting substances in Article 5 and non-Article 5 countries, including options such as long-term storage, transport, collection, reclamation and disposal of such ozone-depleting substances"

This remit was addressed in what became known as the Task Force on Collection, Recovery and Long-term Storage (TFCRS) in its report to the Parties in April 2002.

In respect of foam, the TFCRS Report addressed, for the most part, the progress being made in Europe and Japan on the recovery of blowing agents from domestic appliances. At that time, there was little, if any, information on the technical and economic potential for recovery of blowing agents from buildings. There was also limited information on the quantities of blowing agent available for recovery. It was therefore recognised that there would be a need for further work on these issues once further experience had been gained.

At the fifteenth meeting of the parties in Nairobi in 2003, Australia and Japan jointly proposed a draft Decision to follow-up on the work of the TFCRS. This focused more specifically on the potential of blowing agent recovery from the buildings sector. The precise working of that Decision (XV/10) was as follows:

Decision XV/10. Handling and destruction of foams containing ozone-depleting substances at the end of their life

To request the Technology and Economic Assessment Panel, in its April 2005 report:

(a) To provide updated useful information on the handling and destruction of ozone-depleting substance-containing thermal insulation foams including thermal foams situated in buildings, with particular attention to the economic and technological implications;

(b) To clarify the distinction between the destruction efficiency achievable for ozone-depleting substances recovered from foams prior to destruction (reconcentrated) and the destruction efficiency achievable for the foams themselves containing ozone-depleting substances (dilute source);

Clause (b) of this Decision picked up on a perceived weakness in the definition of destruction efficiencies as related to foams and recognised the need for more distinction between the various routes available for blowing agent recovery and destruction from within the foam matrix.

This report seeks to address these issues and provide a more in-depth and comprehensive review of the status of blowing agent recovery and destruction from foams. In doing so, the report necessarily takes into account the wider waste management issues being encountered in both the appliance and construction/building waste environments. As noted earlier, the inter-relationship between the Montreal and Kyoto Protocols does have a bearing on policy options, particularly when factors related to energy efficiency are taken into account.

The report has been developed from a Task Force consisting of sixteen members drawn from a variety of foam industry, waste management and regulatory backgrounds. Members came from both developed countries (Belgium, Canada, Denmark, Japan, USA and UK) and developing countries (Brazil, China & Colombia). Full details are provided in Appendix D. The Task Force was headed by three co-chairs, Dr. Koichi Mizuno, Dr. Miguel Quintero and Mr. Paul Ashford. Much of the material was assembled and consolidated through e-mail exchange and remote consultation. However, one critical Task Force meeting was kindly hosted by the United States Environmental Protection Agency in January 2005, for which the co-chairs give thanks.

CHAPTER 2

2.0 OVERVIEW OF FOAM APPLICATIONS

2.1 Introduction and Scope

As noted in Chapter 1, this report is limited to those foam applications which retain their blowing agents during their in-life phases and which have used ODSs historically. Accordingly, the products of several large sectors of the foam industry are not relevant to consider in this report because of their manufacturing process or their physical nature. In particular, these are:

- Expanded polystyrene foams, used in insulation and in packaging, which have always been blown with hydrocarbon blowing agents

- Extruded Polystyrene sheet foams and polyethylene foams, used in packaging, which emit the blowing agent soon after manufacture and have converted to non-fluorocarbon blowing agents

- Flexible polyurethane foams, used for mattresses, upholstered furniture and transport seating, which are open celled and emit the blowing agent during the manufacturing process. (These foams were also the first to stop using fluorocarbon blowing agents)

- Integral skin polyurethane foams, used in transportation and furniture, and the similar microcellular elastomers, used in shoe soles, which emit all the blowing agent well before the end-of-life of the article and usually during the first year after manufacture

- One Component Foams (OCF) rigid polyurethane foams, used as gap fillers and adhesives in the building industry, which are inherently open-celled and also emit all the blowing agent during the first year after manufacture

The foams which do contain a proportion, high or low depending on their age and type, of the initial blowing agent content at the end-of-life are summarised in the table below together with the type of fluorocarbon blowing agent which has been used in their manufacture. All of these are rigid insulating foams characterised by having a high proportion of closed cells with a low diffusion rate of blowing agent through the cell walls designed to retain the low thermal conductivity gas (blowing agent).

Table 2.1 List of Foams with Fluorocarbon Blowing Agent Present at End-of-Life

Type of Foam	Application	CFC use	HCFC use	Comments
Polyurethane – Building	Boardstock	√	√	Nearly all in developed countries
	Panels – continuous	√	√	
	Panel – discontinuous	√	√	
	Spray	√	√	
	Pipe-in-pipe	√	√	Minor HCFC use except developing countries
	Blocks	√	√	
Polyurethane – Appliances and Other	Domestic R&F	√	√	HCFC use mainly outside EU
	Reefers	√	√	Most current manufacture in China but global use
	Commercial refrigeration	√	√	
	Vending	√	√	
	Picnic boxes	√	√	
	Various in-situ – marine	√	√	
Polystyrene – Building	Extruded Boards	√	√	
Phenolic – Building	Boards	√	√	
	Panel - discontinuous	√	√	
	Blocks	√	√	

The foam applications listed in this table are now described in more detail. These thermal insulation foams can be classified into three major categories: polyurethane rigid, extruded polystyrene board and phenolic. All are materials with a fine closed cell structure, consisting almost entirely of polymer and blowing agent.

2.2 Polyurethane (PUR/PIR)

Polyurethane foams are based on the exothermic reaction of isocyanates and polyols, both viscous liquids at room temperature. By itself, the polymerisation reaction produces a solid polyurethane. During a process known as foam blowing, polyurethane foams are made by forming gas bubbles in the polymerising mixture. The "blowing agent" can be either a gas, generally carbon dioxide, chemically formed in-situ by water reacting with the isocyanate, or a physical blowing agent such as low boiling inert organic compounds separately introduced into the reaction (CFCs, HCFCs, HFCs, Hydrocarbons).

The PUR foams used for insulation are highly cross-linked polymers with an essentially closed cell structure and a density range of 28 to 50 kg/m3. The individual cells in the foam are isolated from each other by thin polymer walls, which effectively stop the flow of gas through the foam. The cells usually contain a mixture of "blowing agents" with the insulation efficiency of the foam itself strongly depending on their characteristics and relative proportions.

2.2.1 Construction

2.2.1.1 Boardstock/Flexible-Faced Lamination

Polyurethane (PUR) and polyisocyanurate (PIR) foam can be continuously laminated to various facing materials, such as aluminium 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).

2.2.1.2 Sandwich Panels

Sandwich panels, produced by continuous or discontinuous process, have foam cores between rigid facings. The facings are often profiled to increase rigidity. Facing materials are typically steel, aluminium or glass fibre reinforced plastic sheet. They are 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

- Factories: particularly where hygienic and controlled environments are required such as in electronics, pharmaceuticals, and food processing.

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

2.2.1.3 Spray

Sprayed foams are used for in situ application of rigid thermal insulation. Their major use is in roofing applications, especially in North America and parts of Europe. World-wide, sprayed foams are used for residential and commercial buildings, industrial storage tanks, piping and ductwork, and refrigerated transport trailers and tanks. Sprayed foam is directly applied onto the substrate using a hand-held pressurised spray gun, in which separate polyol and isocyanate liquids are metered under pressure, mixed and then dispensed.

2.2.1.4 Slabstock

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 by either the discontinuous or the continuous manufacturing process.

2.2.1.5 Pipe-in-Pipe/Pre-formed Pipe

Foam-insulated pipe-in-pipe sections typically have an inner steel pipe that 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. 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.

2.2.2 Appliances and Other applications

2.2.2.1 Domestic Refrigerators and Freezers

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 an effective insulation. Today, as CFC-11 substitutes, hydrocarbons, HFCs and HCFCs –in most of the developing countries-, are used. Although the basic requirements for refrigerator/freezer foam insulation are similar for most manufacturers, local market conditions and regulations have resulted in tailored solutions . For example, in the USA, the importance of energy consumption has influenced manufacturers to use, as an intermediate step, formulations based on HCFC-141b to achieve lower foam conductivities.

Liquid chemicals are injected between the outer shell and the interior plastic 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 that are under pressure from the foam. It is estimated that no more than 5 % of the blowing agent escapes from the chemical mixture and is vented during the foaming process directly to the atmosphere.

2.2.2.2 Other Appliances/Applications

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

- Water Heaters.
- Commercial Refrigerators and Freezers.
- Picnic Boxes (Coolers)
- Flasks and Thermoware
- Refrigerated Containers (Reefers)

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 or by fixing sandwich panels onto a frame. In other cases, the panel may be assembled by using slabstock (see above) adhered to facing materials.

2.3 Extruded Polystyrene Insulated Board (XPS)

Polystyrene foam boardstock was invented in Sweden in 1931 and the commercial boardstock extrusion process was subsequently developed in the United States. It is rigid foam with a fine closed-cell structure. CFC-12, introduced as blowing agent in the early 1960s, has been replaced by a HCFC-142b/HCFC-22 blend and, more latterly, in some markets by HFCs or gaseous CO_2.

Globally, approximately 90% of extruded polystyrene rigid foam boards are used for thermal insulation purposes. There are two main types of foam boards available:

- Self-skinned material, used for insulation in 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.

2.4 Phenolic (PF)

Phenolic foams represent well under 5% of the foamed insulants used world-wide. Their excellent generic fire properties (extremely low smoke emissions) have led to the use of phenolic products in many niche applications previously served by other insulation products. They have gained increasing acceptance in public and commercial building application where fire concerns are at their highest. By far the greatest proportion of substitution that has occurred against other foam products is in the flexibly faced laminate sector but their market acceptance varies considerably by region. Japan has undoubtedly seen the highest growth in recent years, albeit based primarily on the use of hydrocarbon blowing agents. In Europe, phenolic laminates are used primarily for wall and roofing applications, particularly within the growing single-ply roofing market where, not surprisingly, designers and builders are seeking the most fire-safe products for this purpose.

Phenolic foams are produced by either discontinuous processes, where the most prevalent forms are blocks and panels, or continuous processes, where lamination with flexible facings has been the major development over the last years. CFCs have been substituted by HCFCs, HFCs and hydrocarbons.

CHAPTER 3

3.0 RELEVANT LIFE-TIMES AND LIFE-CYCLE DRIVERS

3.1 Lifetimes

As is explained in more detail in Chapter 4, banks of accumulated blowing agents can exist throughout the life-cycle of foamed products. Although, they are most typically associated with products in their use phase, significant banks of blowing agent also exist in such places as landfills after disposal of the foams in question. The overall sizes of the ODS banks in closed cell foam insulations in appliances and buildings are roughly equal, however the product lifetimes are quite different. Product lifetimes determine when the ODS banks can be expected to transfer from one bank to another (i.e. when they reach end-of-life). At such times, there can be significant releases of blowing agent dependent on the treatment of the foam at that time. In some cases, blowing agent capture is practiced. Lifetimes can be expected to follow a Gaussian distribution, however, these data are not often available. Estimates of average product lifetime are more widely available. The turnover rate (often referred to in terms of de-commissioning or, in the case of a building, demolition) estimates the rate at which appliances or buildings reach end-of life compared to the total population.

3.1.1 Appliances

Average appliance lifetimes are relatively short compared to the lifetimes of buildings. There is some variation in appliance lifetime among developed regions. The lifetime of home refrigerators in Japan, in general, is considered to be among the shortest, with a range of 8 years to 15 years. Data from an annual survey estimated the average lifetime of home refrigerators in Japan at 13.4 years in 2001 and 13.5 years in 2002. An AHAM study found the average U.S. refrigerator lifetime was 22 years. This agrees well with data from California, where incentives are used to promote refrigerator recycling, which show an average age of 21 years. Europe is understood to have average product lifetimes of around 15 years, but corroborating information on this is relatively scarce.

The distribution of appliance lifetimes is relatively narrow, so it can be assumed that the turnover rate of appliances and the average lifetime match.

3.1.2 Buildings

Average building lifetimes are much longer than for appliances. The joint IPCC/TEAP special report uses an average building lifetime of 50 years. Data from a Japanese research project on the recovery and processing of CFCs from foam insulation materials for buildings has yielded estimates of average building lifetime as well as distribution (see Figure 2 below).

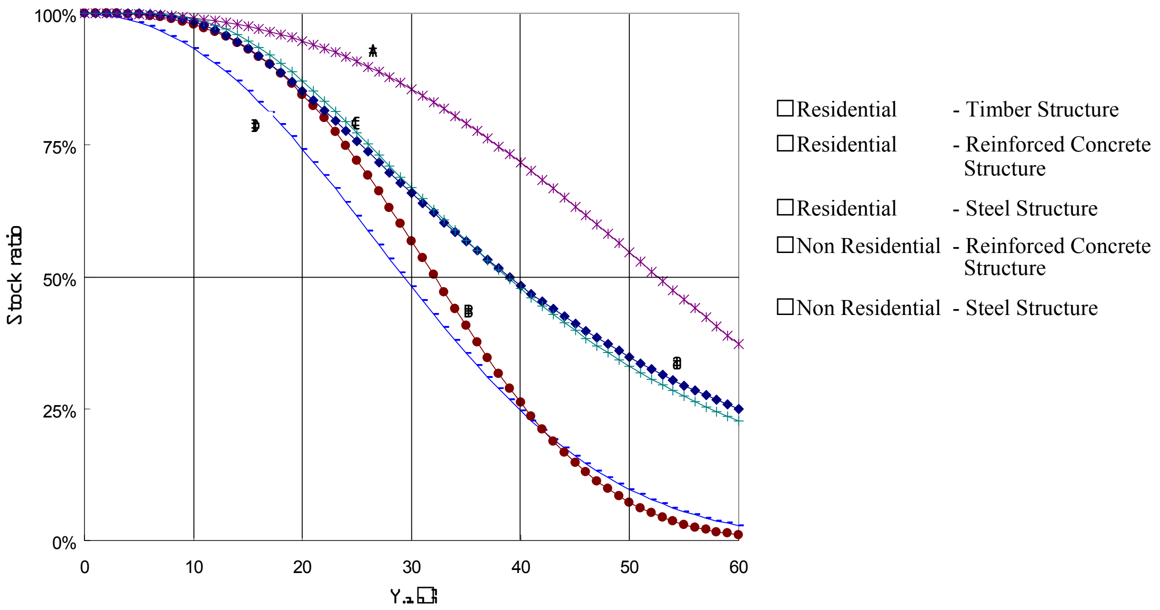

Figure 2 Variation in stock ratios for a variety of Japanese building types

Depending on the type of construction and market, 50% of the buildings have a lifetime between 30 and 50 years, with an average of about 40 years. U.S. Census Bureau data show the median age of U.S. residential housing stock was 32 years in 2001, with the number of homes more than 50 years old in 2000 reported as 26 million out of a total housing stock of 125 million. This median age is rising as both new construction and removal rates are at the lowest in the past decade.

In Europe, the focus has been on new build to accommodate such trends as general population growth, immigration, regional migration, family breakdown and an ageing population (more single occupancy properties). This is reflected in Figure 3 by the downward trend in average occupancy. However, of most importance to this discussion is the fact that demolition rates among dwellings run at roughly 0.25-1% per year. The implication is that stock turnover only takes place fully over a 100-400 year time horizon.

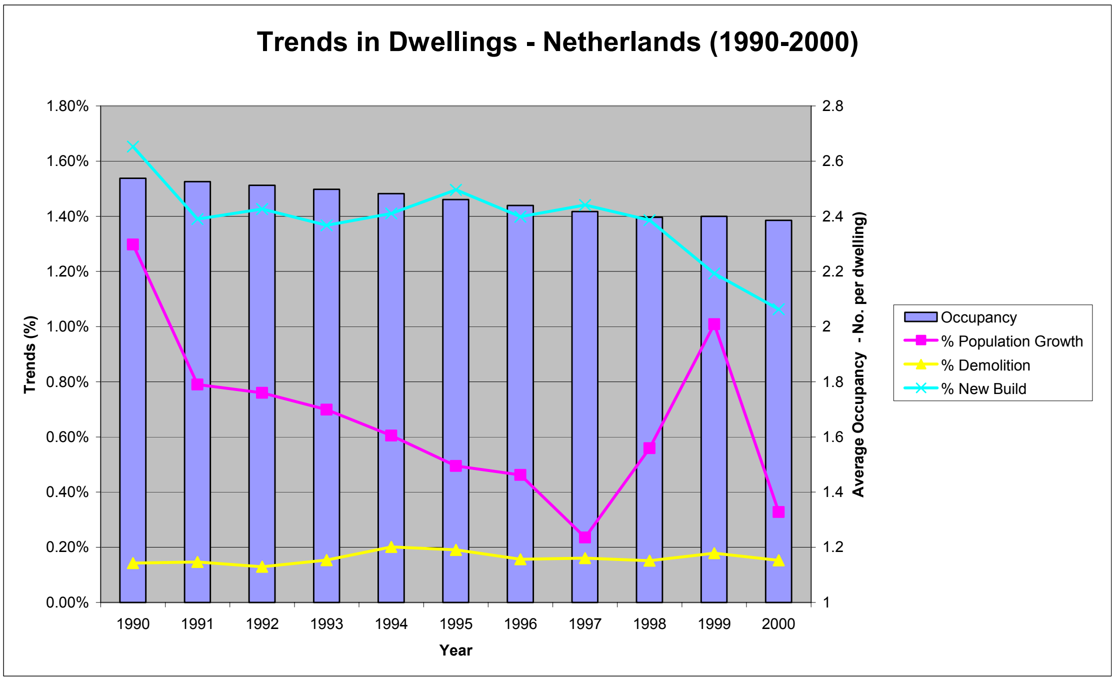

Figure 3: Trends in the construction, occupancy and demolition of dwellings in the Netherlands

The breadth of the distribution of building lifetimes is much larger than for appliances – some buildings may become obsolete and torn down in less than a decade, while others may last for centuries. In North America, as in Europe, it can be difficult to reconcile building turnover rates with the average age of building unit stock. This is, in part because of the availability of less expensive land around rapid growth areas and shifting demographics, turnover rates are today less than 1% per year. A 2004 analysis based on data from the 2000 U.S. Census Bureau estimated the net removal (including demolition and removals due to natural disasters) of existing residential buildings at 360,000/year. With an existing housing stock of 120 million units, this represented a net turnover rate of 0.3%/year. Approximately 1.5 million new homes were built in the U.S. in 1999. The U.S. commercial buildings sector had 4.9 million buildings in 2003 with an average demolition rate of 44,000 buildings per year, giving a net turnover rate of 0.9%/yr. Approx. 170,000 new commercial buildings are built in the U.S. each year. This low turnover rate implies that the majority of housing stock would be expected to last another 200 years.

3.2 Life-cycle Drivers

Although, this report addresses end-of-life issues and options for ODS used as blowing agents in appliance and building insulating foams, it needs to be recognized that management of blowing agent issues is often not the principal driver. Other drivers, many of them regional, influence current practices. The key ones are briefly discussed below.

3.2.1 Appliances

3.2.1.1 Energy Efficiency Improvement

Older appliances are much less energy efficient than new ones and keeping them operating may force power generators to add additional, costly capacity or to purchase extra power at a premium. In these instances, there is a very strong incentive to decommission older appliances. This can help relieve shortages in the electrical supply grid and, at the same time, reduce greenhouse gas emissions from fossil fuels used to generate the extra power. Programmes to retire older appliances are operating very successfully in the western United States.

3.2.1.2 Material Recycling/Waste Stream Minimisation

In regions with a shortage of landfill sites, there are strong incentives to minimize or divert waste streams. Existing legislation in the European Union and Japan is resulting in diversion of significant quantities of appliances at end-of-life. It isn't known whether the legislation shortens the appliance lifecycle.

3.2.1.3 Product Design/Ergonomics/Aesthetics

The lifetime of appliances (particularly refrigerators) can be affected by consumer preferences. The desire to adopt new technology advances or features or update the appliance "look" can result in shorter appliance lifecycles.

3.2.1.4 Other

Environmental programs (desire to retire appliances in order to minimize ODS & GHG emissions) can shorten appliance lifecycles. Because appliances are accessible and portable, export to developing countries for reuse can prolong the product lifecycle.

3.2.2 Buildings

3.2.2.1 Energy Efficiency Improvement

The energy efficiency of a building depends on many factors in addition to the building envelope insulation. Such factors include building design and operation, heating/air conditioning systems, windows, lighting, etc. A desire to improve building energy efficiency can affect insulation lifecycle. The effect will depend on whether the improvements can be achieved through other measures (longer lifecycle); whether the insulation can be upgraded and at what cost (longer lifecycle if reused or left in place; shorter if removed); and how retrofit costs compare to building demolition and rebuilding (shorter lifecycle).

3.2.2.2 Sustainable Construction

There is a growing trend to more environmentally-sustainable buildings, including all aspects from design and construction through building operation and end-of-life considerations. An example is the Leadership in Energy and Environmental Design (LEED) program in North America. While the trend does not necessarily drive changes in building insulation lifecycles, adoption of more modular design techniques (e.g. panelization) and building component design for re-use or deconstruction at end-of-life could improve the accessibility of future building insulation at end-of-life.

3.2.2.3 Material Recycling/Waste Stream Minimisation

The situation is very similar to that for appliances above. Short-term market situations can also act to shorten product lifecycles. For example, the current shortage of steel has driven up prices and, rather than re-using an insulated steel-faced building panel at the building end-of-life, it may be more attractive to recycle the panel and recover the steel.

3.2.2.4 Product Design

From a building insulation perspective, this means being able to reuse or convert an existing product at its end-of-life into another product that has value (and a new end-of-life). For example, reusing PU foam insulation as a thermally-efficient, light-weight filler in concrete blocks. Changes to the original insulation (e.g. particle size reduction) will determine emissions and the new end-of life. This is not typically practised in developed countries, but often can be a lifecycle driver for developing countries.

3.2.2.5 Economics

Where land is available and reasonably-priced, it may be less expensive to build a new building rather than demolish and rebuild an existing one. In this case, existing building lifecycles will tend to increase. In urban areas, the economics and attractiveness of retrofit or demolition and rebuilding on prime land close to the city core may be preferred to new construction in the suburbs. This can shorten a building lifecycle. The cost of waste disposal (restrictions on construction and demolition waste, disposal fees, etc.) must also be considered.

3.3 Legislative Drivers

Blowing agent related drivers usually exist as a result of commitments made under the Montreal Protocol to phase out of ODS or as a result of concern with future Kyoto emissions. Additional regulations addressing recycling and waste minimization are beginning to appear in many regions, and it is here that we see wide differences affecting foam insulation.

3.3.1 Japan

Because of the global environmental problems and shortage of landfill sites, coupled with awareness of conservation of resources, the government of Japan has been enacting seven laws and regulations related to waste management. Those which apply to foams include (1) the basic policy for waste reduction and management (May 2001), and (2) effective utilization of resources, which follows recycling laws covering home appliances (effective in April 2001) and construction materials (enacted in May 2000).

In June 2001, the law concerning the recovery and destruction of fluorocarbons ("Fluorocarbon Recovery and Destruction Law") was promulgated to promote the recovery and destruction of CFCs, HCFCs and HFCs from commercial refrigeration and car-air conditioning

Laws Related to Waste Management		
Basic Policy for Comprehensive and Systematic Promotion of Measures on Waste Reduction and Other Proper Waste Management		Announced on 7th May 2001
Law for the Promotion of Effective Utilization of Resources		Effective from April 2001
Law for the Promotion of Sorted Collection and Recycling of Containers and Packaging	Container and Packaging Recycling Law	Effective from April 1997
Law for the Recycling of Specified Kinds of Home Appliances	Home Appliance Recycling Law	Effective from April 2001; Amended April 2004
Construction Material Recycling Law		Enacted in May 2000
Law for Promotion of Recycling and Related Activities for the Treatment of Cyclical Food Resources	Food Waste Recycling Law	Effective from 1st May 2001
Law for the Recycling of End-of-Life Vehicles	End-of-life Vehicle Recycling Law	Effective 1st Jan 2005

Table 3.1. Laws Related to Waste Management

3.3.1.1 Appliances

The Law for Recycling of Specific Kinds of Home Appliances, so called "home appliance recycling law", promotes recycling of home refrigerators, TVs, washing machines, and room air-conditioners. Regarding the used home refrigerators, refrigerants, metals such as steel and copper, and other valuable materials are recovered, dismantled and recycled to use. The law was amended to add the recovery of FC in foams on April 2004.

3.3.1.2 Buildings

The Construction Material Recycling Law was enacted in May 2000, targeting the recycling rate of waste of the specified construction materials to be 95% by 2010. The specified materials are concrete including pre-cast plate, asphalt/concrete, and wood building materials. Presently, the law does not include insulation foams.

3.3.2 Europe

3.3.2.1 Appliances

In the EU, the use of ODS ended by 1996 in new domestic refrigerators and freezers. EC2037/2000, Article 16, requires ODS in refrigerators and freezers to be recovered for recycling or destruction (by technology approved by Parties) after end 2001. This requirement applied to the enlarged EU 25 after May 1st 2004.

Directive 2002/96/EC (commonly known as the WEEE Directive) deals with the recycling of refrigerators and freezers and sets material recycling targets. The Directive calls for national legislation to be in place by 2006 for the recovery of 80% of materials and substances together with a target of 75% of recycling and reuse of the materials and substances.

3.3.2.2 Buildings

In the EU, the use of ODS ended by end 2003 in all foam applications. CFC use ended by end 1994 in the then EU (15 countries) but later in Eastern countries. EC2037/2000, Article 16, requires ODS in foam applications other than refrigeration to be recovered for destruction or recycling where practicable. This requirement applied to the enlarged EU 25 from May 1st 2004.

3.3.3 North America

3.3.3.1 Appliances

In the U.S., Section 608 of the Clean Air Act does not allow any refrigerant to be vented into the atmosphere during installation, service, or retirement of equipment (e.g., appliances). Therefore, when an appliance is disposed of or repaired, all of the refrigerant must be recovered and recycled (for reuse in the same system), reclaimed (reprocessed to the same purity levels as new), or destroyed. There are no regulations about the recovery of blowing agent from foam.

In Canada, some assessment of the landfill implications of end-of-life foam management of appliances has been carried out at provincial level, but no formal country-wide action has yet been taken to deal with this issue.

3.3.3.2 Buildings

In the U.S., the production of HCFC-141b was phased out on January 1, 2003. As a result, polyisocyanurate (PIR) boardstock foams ended their use of HCFC-141b in 2003. Additionally, a ban on the use of HCFC-141b in all foams was effective January 1, 2005. The production of HCFC-142b and HCFC-22 will be phased out on January 1, 2010. It is expected that XPS boardstock foams and PU foams will end their use of HCFC-142b and HCFC-22 by 2010.

In Canada, the new use of ODS in insulating foams will be banned on January 1, 2010.

CHAPTER 4

4.0 DEVELOPMENT OF BANKS AND EMISSIONS

4.1 Appliances

4.1.1 Market Volumes

The annual market for domestic refrigerators and freezers is currently estimated to be in excess of 80 million units. With typical lifetimes as indicated in Chapter 3, this implies that upwards of 1 billion units are in use globally at any given time. Blowing agent requirements to manufacture a refrigerator are typically within the range of 400g to 600g per unit, making the total 'banked' blowing agent contained in these products during the use-phase around 500,000 tonnes.

As indicated in Chapter 2, within the appliance sector there are other smaller sectors which also consume blowing agents. These include the 'other appliances' category which is made up of commercial units (e.g. supermarket display cabinets) and items such as water heaters and picnic coolers. Additionally, there is use in the refrigerated transport sector (primarily in reefers) which is also accounted for under this section. Figure x indicates the overall growth in blowing agent use in the appliances sector since the introduction of foam in the mid-1960s. The graph also projects the likely annual demand for blowing agent in this sector through to 2015.

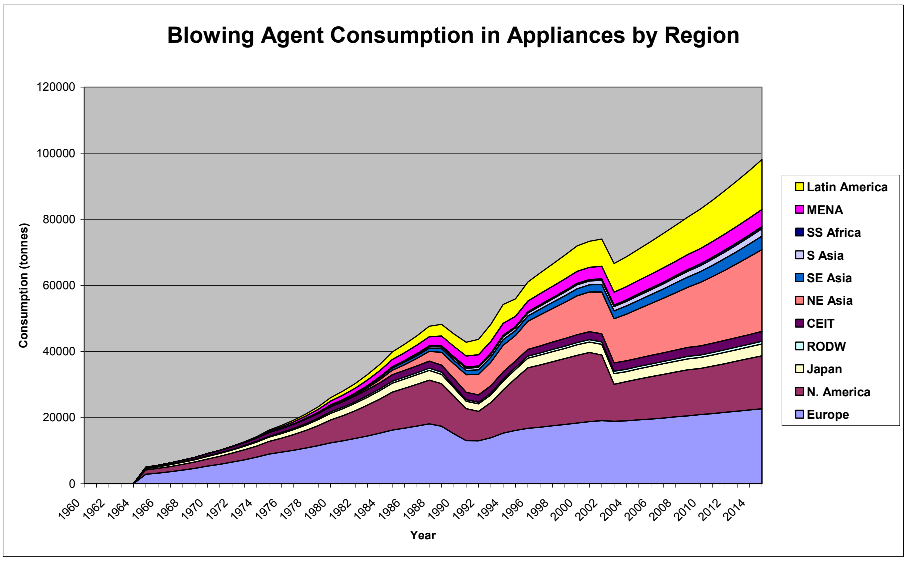

Figure 4.1: Growth in global blowing agent demand by region in the Appliance sector

It can be seen that, in the period through to 2015, a substantial contribution to growth is anticipated from North East Asia (most notably China). This will take annual demand close to 100,000 tonnes per year by 2015.

The 'steps' observed in consumption growth are related to changes in blowing agent technology which influenced the blowing efficiency of systems and therefore demand. In the early 1990s, what became known as 'reduced CFC' formulations were introduced to limit the consumption and emission of CFCs for self-evident environmental reasons. These formulations relied on the fact that CO_2 could be generated in-situ by the reaction of isocyanate with water to co-blow the foams. A similar approach has been adopted more recently to minimise the use of HFCs as replacements for HCFCs. This transition is well documented in the IPCC/TEAP Special Report on HFCs and PFCs. However, while there is a genuine environmental case for reducing reliance on HFCs, the more pressing reason for many appliance manufacturers has been the desire to minimise the cost of formulations (HFCs being considerable more expensive).

4.1.2 History of Blowing Agent Selection

Figure 4.2 illustrates the blowing agent transitions which have occurred in the domestic appliance sector since 1960. The proliferation of blowing agent options is self-evident over the period.

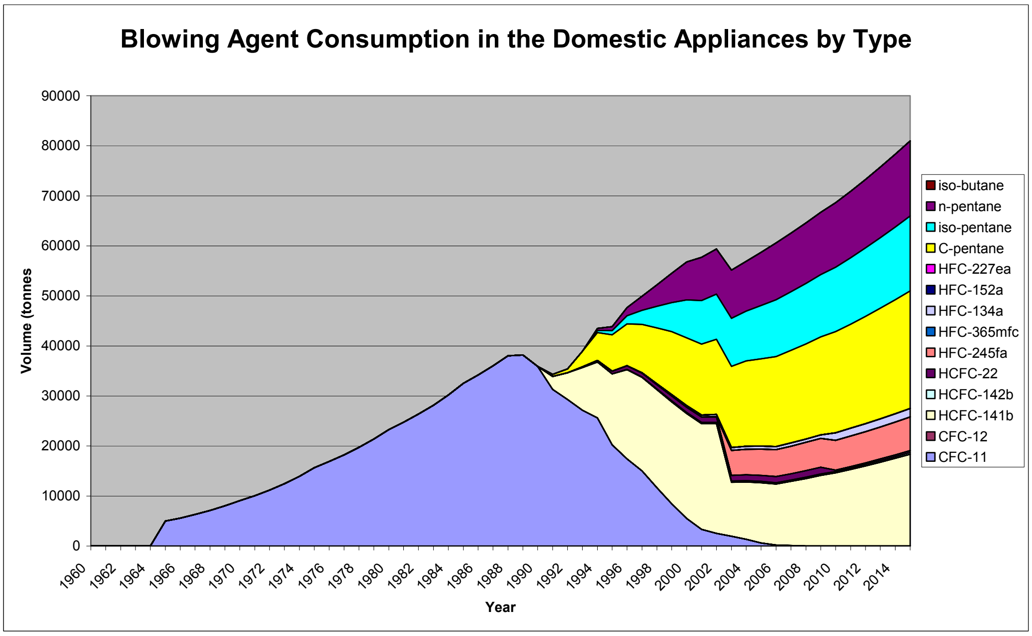

Figure 4.2: Consumption of Blowing Agent by Type for Domestic Refrigerators

The growing dominance of hydrocarbon technologies at the expense of fluorocarbon blowing agents is a significant characteristic of the graph. This is not only driven by trends in Europe and Japan, but also in North East Asia where hydrocarbon technologies are already in widespread use. Notwithstanding this, on-going use of HCFC-141b in other developing countries will be a significant contributor to blowing agent banks over the next decade.

4.1.3 Emission Factors

Emissions from appliances over their lifecycles are heavily focused at end-of-life. This arises from the fact that the vast majority of such units are manufactured in controlled factory environments which minimise emissions during production and emissions in use are broadly prevented by the encapsulation of the foam between the steel shell and the plastic liner. The situation with commercial refrigeration units (e.g. supermarket display cabinets) is slightly more variable, but the same basic points apply.

At end-of-life, it has been traditional (worst case) to assume that remaining blowing agent losses are instantaneous. However, recent research commissioned by the Alliance of Home Appliance Manufactures (AHAM) and sponsored by the US EPA has indicated that this is far from the case [Baumgartner & Kjeldsen, 2005]. Even when an appliance passes through an auto-shredder without any recovery facility, losses are only in the range of 8-40% (25% average). On the basis of such observations, Table 4.1 below sets out the assumptions used for the baseline case:

Product Type	***Losses in manufacture***	***Annual losses in use***	***End of Life Option (Initial loss/Annual thereafter)***			
			Re-use	***Landfill***	***Shredding without recovery***	***Shredding with recovery***
Domestic Appliances	4.0%	0.25%	0.0%/0.25%	10.0%/0.5%	25.0%/2.0%	5.0%/0.0%
Other Appliances	4.0%	0.25%	0.0%/0.25%	10.0%/0.5%	25.0%/2.0%	5.0%/0.0%
Reefers	4.0%	0.5%	0.0%/0.5%	10.0%/0.5%	25.0%/2.0%	5.0%/0.0%

Table 4.1 Emission factor assumptions used for establishing emissions in the appliance sector

As an additional point the Baumgartner & Kjeldsen work confirmed that losses during manufacture and use were indeed low with 25 year-old cabinets showing little or no loss.

4.1.4 Bank Dynamics

Figure 4.3 illustrates the four specific areas where banks can develop. These are:

- In the products themselves
- In products which are assigned to re-use at the end of their normal service life
- In appliances which are landfilled
- In appliances which are shredded prior to landfill

It is assumed that appliances which are shredded <u>with recovery</u> have 5% losses during the process and that these losses are instantaneous. Accordingly, with the balance being captured, there is no accumulation of banks from this stream. In reality, there may be marginal retention of blowing agent in the matrix (usually less than 0.5%) but this is discounted for the sake of simplicity.

The total CFC-11 bank in appliances appears to have peaked in around 2003 at just over 700,000 tonnes and is now believed to be showing the first signs of decline as the emission losses from banks exceed the new consumption for the first time.

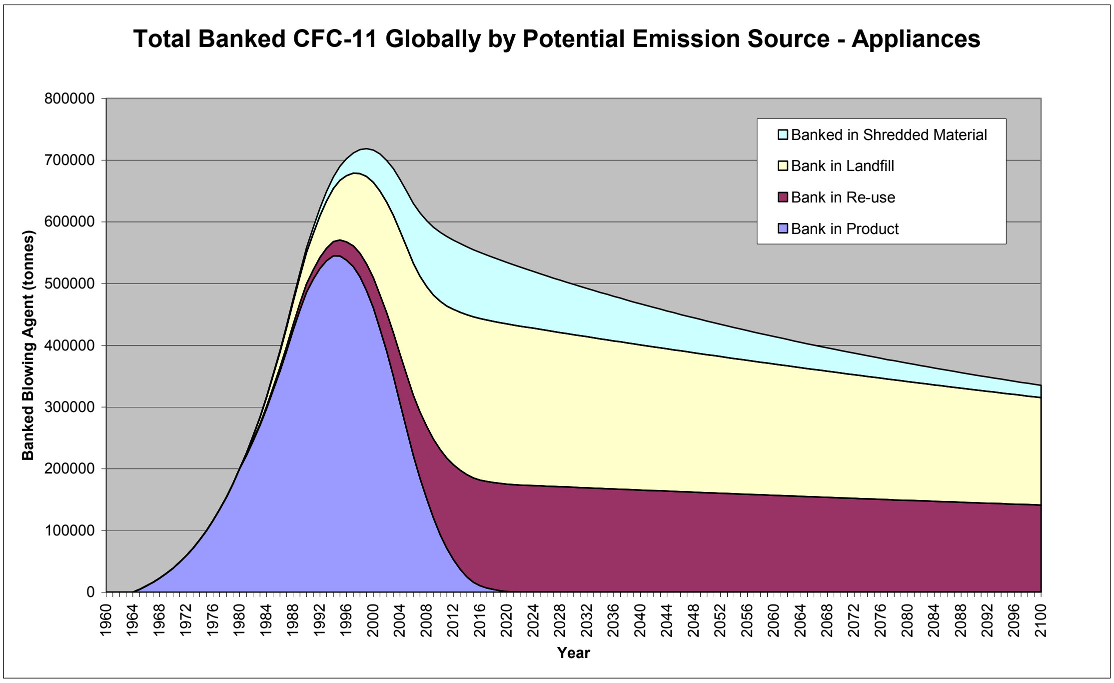

Figure 4.3: Anticipated trends in CFC-11 banks for appliances

One of the particularly interesting aspects of Figure 4.3 is that over 30% of appliances containing CFC-11 had already been decommissioned by 2003. This proportion is even higher in developed countries (Europe 73%, North America 63%, Japan 73%). The rate of decommissioning is expected to continue to be rapid in the period to 2010 based on a global average lifetime of 15 years. Accordingly, measures to capture CFC-11 at end-of-life need to be implemented promptly in the appliance sector if significant contributions to emission reduction are to be achieved. The period of opportunity is extended to a degree by the number of appliances entering the re-use phase (i.e. being granted extended life-times). Estimates suggest that upwards of 150,000 tonnes of additional CFC-11 could be available for capture in the post 2015 period.

Notwithstanding this, the majority of CFC-11 emanating from the appliance sector will be in landfill in the post-2015 period and there is now increasing focus on the fate of upwards of 250,000 tonnes of this blowing agent. The modeling work supporting this report assumes that gradual release from the bank will occur. However, this does not account for the potential of anaerobic degradation (see Chapter 5.5). The extent to which this needs to be stimulated in the landfill environment is still under review, but there is a possibility of some degradation occurring under non-optimised conditions. This makes it particularly important to understand the breakdown products.

4.1.5 Uncertainties

One of the important aspects of any banking and emissions model is the need to understand the prevailing uncertainties. These can arise from at least three key sources:

(1) Uncertainties in the emissions factors applied
(2) Uncertainties in the consumption patterns
(3) Uncertainties in the timing of events

As noted earlier, evidence continues to be amassed supporting low emission patterns in manufacture and use phases. In addition, consumption patterns are fairly well understood – particularly for domestic refrigerators and freezers where good statistics are available both on numbers and sizes. Accordingly, blowing agent consumption can be calculated with a reasonable degree of confidence.

In fact, the main area of uncertainty for annual CFC-11 emissions arises from the inability to determine precisely when appliance decommissioning will occur. Although it is statistically reasonable to consider a Gaussian distribution around the mean life-time of 15 years, there is a finite probability that any given year will have significant fluctuations around a mean value. Accordingly, estimates of appliances decommissioned will be much more accurate (as a percentage) over a ten year period than they will be in any single year. Since CFC-11 containing appliances are in a period of substantial decommissioning, the year-to-year uncertainties may become quite significant.

4.2 Buildings

4.2.1 Market Volumes

Global blowing agent consumption in the construction sector is about two and a half times larger than that in the appliance sector and has grown in similar fashion. However, because the number of products and processes is considerably greater in the construction sector, the impact of individual transition steps and technology choices (e.g. reduced CFC-11 formulations) is less pronounced. The lower gradient of the growth curve in the period since 1988 (as shown in Figure 4.4) does however illustrate the general impact of better blowing efficiencies obtained from hydrocarbon-based PU foam formulations over that period.

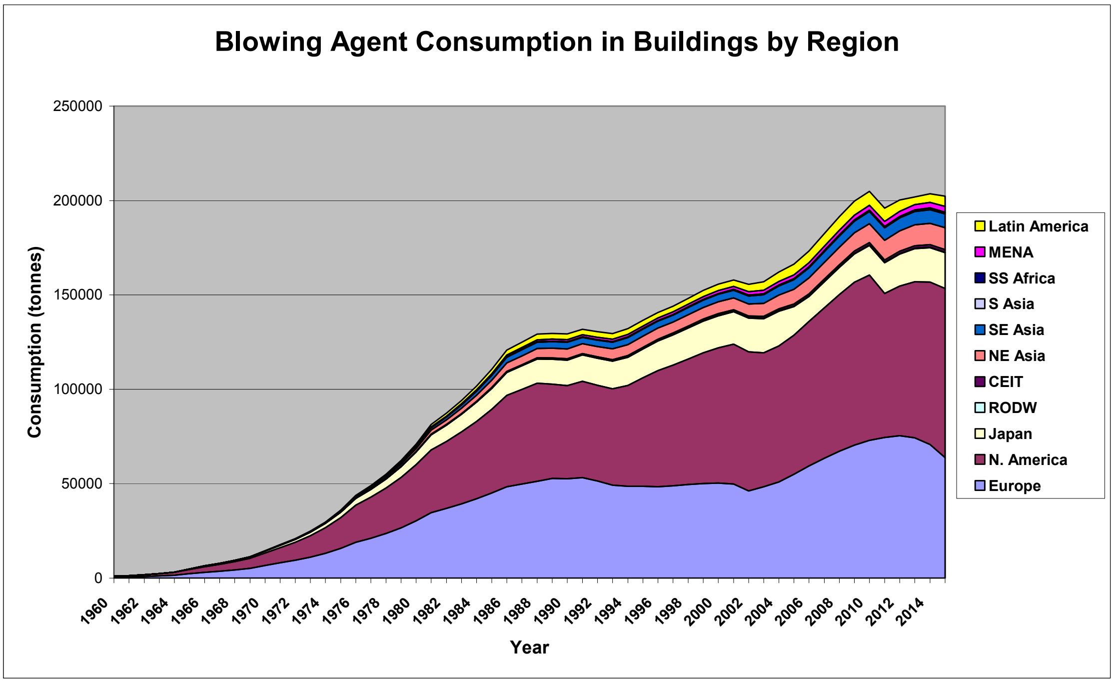

Figure 4.4: Growth in global blowing agent demand by region in the Buildings sector

Of particular relevance to this Report is the fact that the vast majority (in excess of 80%) of the consumption for building applications has taken place in three regions: Europe, North America and Japan. Since buildings are generally not traded items, this means that the bulk of the blowing agent banks in buildings are also in these three regions. This trend is likely to continue in future, although the growth of concerns over energy generating capacity in some developing countries (e.g. those in North East Asia) has heightened the future need for improved building energy efficiency.

4.2.2 History of Blowing Agent Selection

Blowing agent selection in the buildings sector has been considerably more varied than in the appliance sector, because of the number of processes practised and because of significant regional variations in construction methods and resulting building codes. By way of example, Figure 4.5 illustrates the situation for PU discontinuous panels.

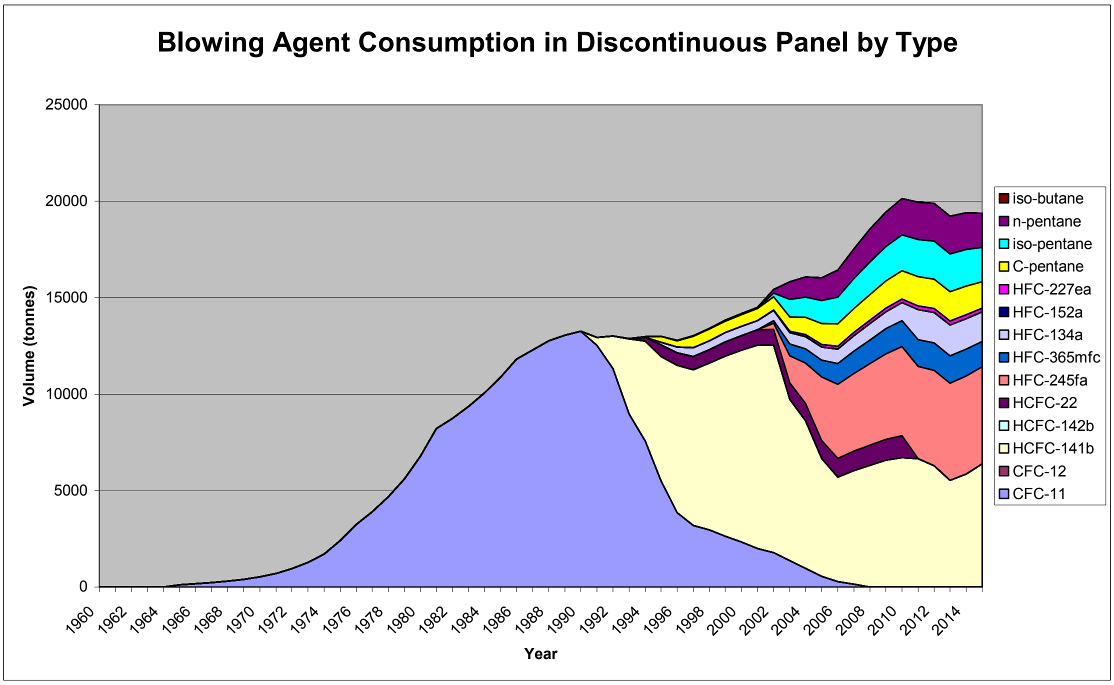

Figure 4.5: Consumption of Blowing Agent by Type for Discontinuous Panels

In general, the selection of blowing agents is more varied for discontinuous processes than for continuous ones, primarily because of the wide range of discontinuous plants in existence and the variety of products manufactured. The uptake of hydrocarbons within discontinuous processes has been less pronounced than for their continuous counter-parts as a result of process safety concerns. Concerns have also extended to product fire performance in some parts of the construction sector where either building codes or insurance premiums have countenanced against hydrocarbon options.

In this more complex decision-making environment, the use of blends has become increasingly common-place as foam manufacturers have sought to optimise process and product performance while minimising cost. This has involved blends within blowing agent groups (e.g. cyclo- with iso- pentane; HFC-365mfc with HFC-227ea) but is now even extending to blends between groups.

Although there are moves to improve product labelling as it relates to blowing agent selection, the proliferation of blowing agent options and the potential to use blends will make it increasingly difficult for the recognition of precise blowing agent compositions when current and future products reach their own decommissioning stage. This will make it increasingly important for any future foam end-of-life facilities to be designed to cope with a variety of blowing agent options, including highly flammable mixtures. Even now, this has the potential to slow up the extension of end-of-life activities for building foams, since there is also a prospect that production and installation waste (e.g. hydrocarbon blown steel-faced panels) could reach existing foam end-of-life installations. The only way to counter this would be to mandate the determination of blowing agent content of foams entering such facilities. However, this would almost certainly add unacceptable costs to the process.

4.2.3 Emission Factors

As with appliances (section 4.1.3), there has been considerable study and development of emission factors both among foam industry experts and out in the field. Among the field evaluations, the work of the Japanese Technical Centre for Construction Materials (JTCCM) has been probably the most comprehensive, with over 500 buildings sampled. However, the length of the in-life phase, and uncertainties about original formulations have still contributed to significant debate about the precise value of emission factors, particularly in the case of XPS. Current thinking acknowledges the fact that there could be extenuating local practices in the Japanese market (e.g. the machining of the faces of finished boards) which would lead to higher initial and annualised losses. With these local factors in view, it is possible to envisage that both the foam industry experts and the field evaluators could both be right at the same time, thereby making the bank estimates similar for both bottom-up and top-down evaluations. Table 4.2 provides averaged data which reflects these regional variations.

Product/Process Type	*Losses in first year*	*Annual losses in use*	*End of Life Option (Initial loss/Annual thereafter)*			
			Re-use	*Landfill*	*Shredding without recovery*	*Shredding with recovery*
PU Boardstock	6.0%	0.5%	0.0%/0.5%	20.0%/1.0%	25.0%/2.0%	5.0%/0.0%
PU Cont. Panel	5.0%	<0.5%	0.0%/0.5%	20.0%/0.5%	25.0%/2.0%	5.0%/0.0%
PU Disc. Panel	6.0%	<0.5%	0.0%/0.5%	20.0%/0.5%	25.0%/2.0%	5.0%/0.0%
PU Cont. Block	35.0%	0.75%	0.0%/0.75%	20.0%/1.0%	25.0%/2.0%	5.0%/0.0%
PU Disc. Block	40.0%	0.75%	0.0%/0.75%	20.0%/1.0%	25.0%/2.0%	5.0%/0.0%
PU Spray	15.0%	0.75%	0.0%/0.75%	20.0%/1.0%	25.0%/2.0%	5.0%/0.0%
PU Pipe-in-Pipe	6.0%	0.25%	0.0%/0.25%	5.0%/0.25%	25.0%/2.0%	5.0%/0.0%
XPS Board	25.0%	0.75%	0.0%/0.75%	20.0%/1.0%	25.0%/2.0%	5.0%/0.0%
Phenolic Board	6.0%	0.5%	0.0%/0.5%	20.0%/1.0%	25.0%/2.0%	5.0%/0.0%
Phen. Disc Panel	6.0%	<0.5%	0.0%/0.5%	20.0%/0.5%	25.0%/2.0%	5.0%/0.0%
Phen. Disc Block	40.0%	0.75%	0.0%/0.75%	20.0%/1.0%	25.0%/2.0%	5.0%/0.0%
PE Board	90.0%	5.0%	N/A	N/A	N/A	N/A
PE Pipe	100.0%	N/A	N/A	N/A	N/A	N/A

Table 4.2 Emission factor assumptions used for establishing emissions in the buildings sector

4.2.4 Bank Dynamics (including comparison with refrigerants)

It can be seen that, in general, emission rates are low over the long use-phases of the foams in question, although there are some fairly emissive product/process combinations (e.g. PU Spray and XPS board) in the first-year (manufacturing and installation) phase. One of the relevant implications of slow emissions from the stock of installed foams is that there are substantial banks of blowing agent available at end-of-life. However, since product life-times can be in excess of 50 years, even the earliest products manufactured using CFC-11 may be yet to reach the waste stream. Figure 4.6 illustrates the likely situation for one of the largest sectors, PU Boardstock. Similar profiles can also be generated for the other product types listed in Table 4.2.

In the absence of the application of positive end-of-life recovery and destruction techniques, it can be seen that banks (and therefore emissions) are likely to continue at significant levels over the remainder of this century. One of the other key messages from this assessment is that there is still considerable time to develop and perfect appropriate end-of-life technologies for the building sector.

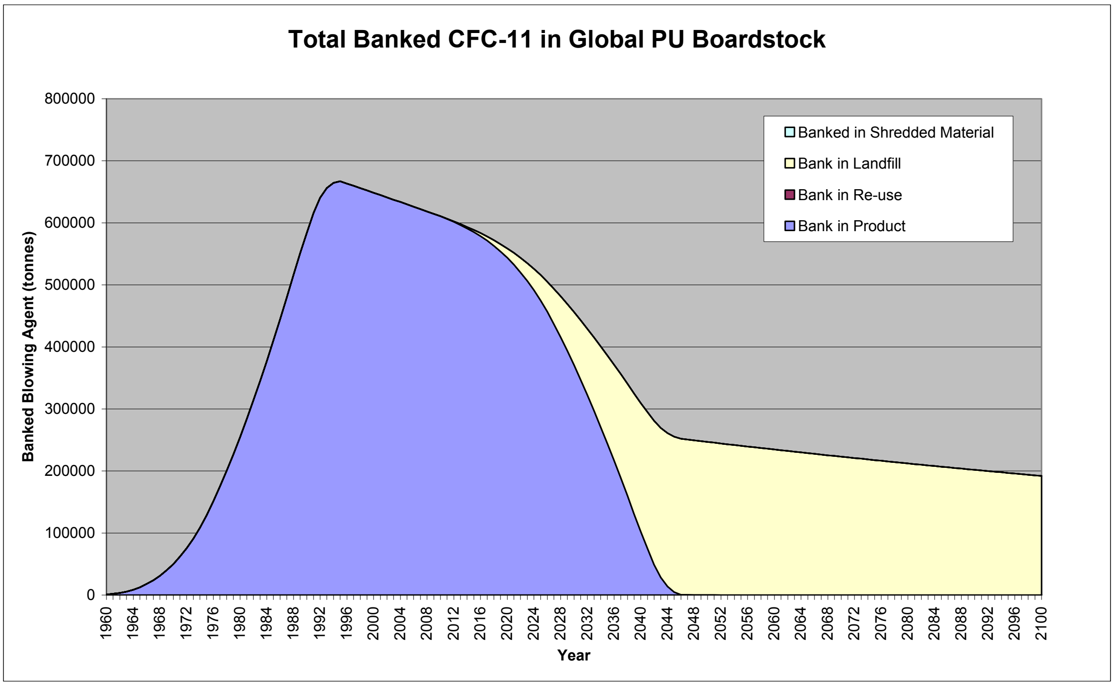

Figure 4.6: Anticipated trends in CFC-11 banks for PU Boardstock

There are two contributors to the drop in bank size between 2015 and 2045. The first is the recovery of blowing agent from some of the boardstock decommissioned during the period. The second is from blowing agent released during the land-filling process. In combination, these two factors reduce the size of the bank by approximately 50% over the period.

4.2.5 Uncertainties

With large bank sizes and relatively small emission rates there are significant sensitivities to emission factor assumptions. However, in the period from 1995 to 2015, the situation is relatively stable year-on-year for CFC-11 in PU Boardstock because of the lack of contribution from first-year losses or end-of-life emissions. The same situation extends to most building fabric insulation materials.

The IPCC/TEAP Special Report on issues related to HFCs and PFCs was particularly helpful in highlighting that, although the banks of ODSs contained in refrigeration equipment as refrigerant and contained as blowing agents in foams were broadly similar in size, their emissions were fundamentally different, with refrigerant banks reducing at rates up to ten times faster than from foams. Put another way, the ‘turnover’ of banked ODS is much greater for the refrigerant sector than for the blowing agent sector. This becomes important when considering the wider impact of uncertainties. Nonetheless, with little use of CFC-11 as a refrigerant except in large chillers, the contributions from refrigerant and foam sources are much more similar as Figure 4.7 illustrates.

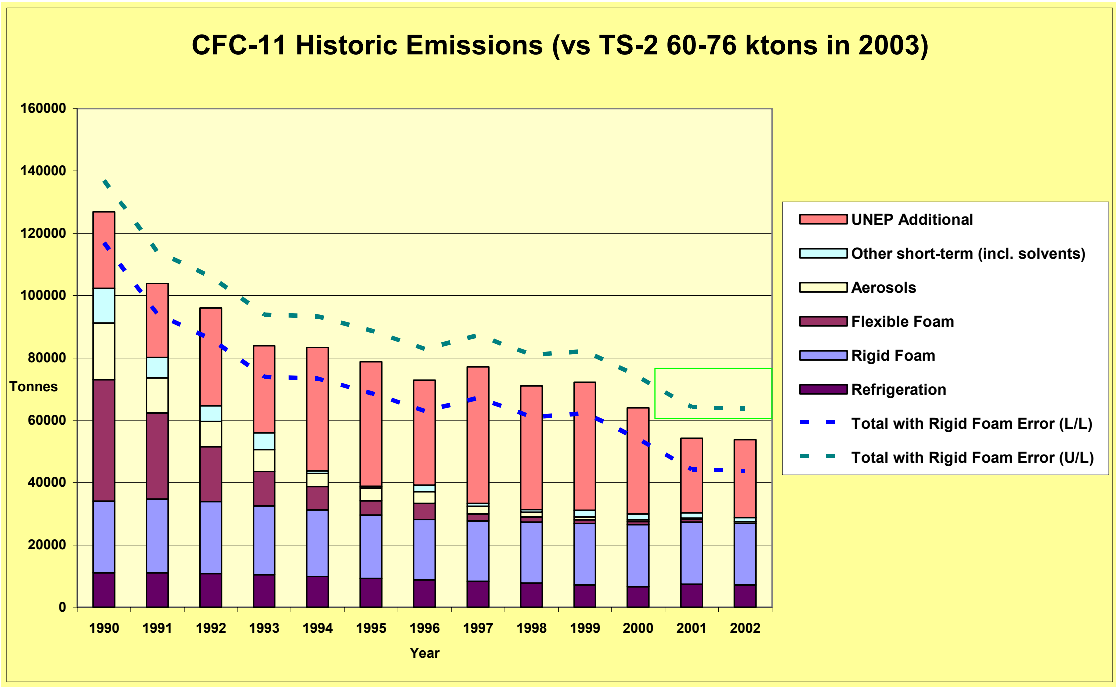

Figure 4.7: Sources of CFC-11 emission compared with atmospheric observation

The graph illustrates the decline in CFC-11 emission since 1990 on the basis of reduction in use of CFC-11 in directly emissive applications such as open-celled (flexible) foam, aerosols and solvents. The relative stability of emissions from refrigeration and foam banks is also clear over the period. However, for rigid foams, the average annual loss across all foam applications was estimated at no more than 20,000 tonnes in 2002, which was around 1.2% of the total bank at that time. If the emission factors are, however, 0.5% higher or lower than those assumed (i.e. 0.7% or 1.9%) the overall effect would be an error on foam emissions alone of close to +/- 10,000 tonnes for foams alone. This range of uncertainty is expressed by the broken lines on the graph.

However, even this level of uncertainty cannot explain the fact that atmospheric concentration changes indicate emissions in the order of 60,000-76,000 tonnes of CFC-11 annually (as represented by the 'shaded green box'). This situation is only reconciled once it is realised that there is substantial consumption taking place in Developing

Countries (labelled in the graph as UNEP additional) for which no use-pattern information exists. Although these uses may not all be in emissive applications, there is a likelihood that a significant proportion will be. Accordingly, adding the 'UNEP additional' data as potential emissions in Figure 4.7 gives an upper bound to the bottom-up emission assessment of approximately 65,000 tonnes. Therefore, it is possible to postulate a reasonable element of agreement between bottom-up emission assessment and the atmospheric (top-down) mass balance. Further work is undoubtedly required to better understand the historic and current use-patterns of ODS in developing countries and Parties may wish to consider whether this is something which should be taken up at Montreal Protocol level.

4.3 Banks in the context of historic consumption and emissions

In considering the apparently large banks of blowing agent stored in foams globally, it is always important to bring these back into the context of total historic consumption and emission. At its peak in 1989, CFC-11 consumption was believed to have reached 142,000 tonnes in rigid foams. This means that the bank of CFC-11 in 2002 (1.64 million tonnes) represents approximately 11.5 years of peak consumption. This is certainly plausible in a growing market and with the long average product lifetimes pertaining. However, when compared to the cumulative CFC-11 produced for all applications, the banked CFC-11 in foams represents less than 20% of the total. Accordingly, one of the joint challenges for the bottom-up modellers and the atmospheric scientists is to assess the potential environmental impact, both in terms of ozone depletion and climate change, of the release of this remaining CFC-11 over a prolonged period which potentially extends up to and beyond 2100. Depending on approaches taken to end-of-life management, the timing and extent of CFC-11 emissions could vary significantly. This will hopefully be the subject of further co-operation between the Science Assessment Panel (SAP) and the TEAP in the period leading up to the 2006 Assessment.

CHAPTER 5

5.0 OPTIONS FOR END-OF-LIFE MANAGEMENT

5.1 Overview

As hinted at in Chapter 4, there are many options for handling building and appliance foam at their end of life (EOL). These include leaving the foam in place; reusing the intact foam or unit (refrigerator or freezer); landfilling the foam with and without managed attenuation; mechanical recovery of blowing agent with and without polymer recycling; and direct incineration of the foam. In general, those methods which are most efficient at preventing the emission of Ozone Depleting Substances (ODS) to the atmosphere involve more expensive and complex processes that require special infrastructure. Additionally, and with the exception of leaving the foam in place and reuse, pre-disposal emissions beyond normal diffusion must be examined to determine the comprehensive efficiency of these methods to minimize overall ODS emissions. The application of some of these methods differs for building and appliances.

5.2 Leave in place

For buildings, leave-in-place means not replacing the foam insulation during refurbishment. It may be left in place if it still retains sufficient thermal performance to mean that the additional energy savings resulting from replacement with more efficient insulation do not outweigh the financial and/or environmental cost of replacing the old insulation. Even where additional insulation can be afforded, it is common for the old insulation to be left in place. A typical example would be in the case of re-spraying a roof with PU foam. This method would apply to both developed and developing nations.

For appliances, leave-in-place can have different definitions. Abandonment is one. This practice is believed to occur most often in low-income and rural areas where mandatory disposal practices such as refrigerant recovery can prove expensive and logistically difficult[2]. As a result, it is easier for the owner to dump the unit in the wilderness. This practice is especially harmful to the environment as it removes the option of recovering the ODS refrigerant and blowing agent, ODS-contaminated compressor oil, and other harmful substances that may be released into the atmosphere or the ground.

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[2] UNEP: *Report of the Task Force on Collection, Recovery, and Storage*; April 2002

Leave-in-place for appliances can also describe the practice of moving an older, inefficient unit to the basement or garage to serve as extra food and beverage storage. This is distinguished from other forms of re-use by the fact that no change of ownership normally takes place. Because older units can consume two to three times the electricity as more modern units, they are often the target of utility "bounty programmes". In these programmes the utility's customer is paid a bounty, or cash reward, to get rid of the secondary unit and not replace it, or get rid of their primary inefficient unit and replace it with a modern, efficient unit. Over an extended period both the utility and the private citizen can realize net financial savings arising from decreased energy demand and usage. These programmes are particularly successful when they target low-income areas where citizens are more likely to have older units and not possess the financial means to overcome the upfront cost of replacing their older units. The units recovered in these programmes can then be disposed of through landfilling, mechanical recovery, or direct incineration, described below. Refurbishment and resale is normally discouraged owing to the high energy usage of these units.

In rare cases, leave-in-place may also refer to the practice of using the cabinet of a non-working unit as furniture, such as a cupboard or table. However, as this would most likely only occur with a non-operational unit, no energy savings are realized. Additionally, there is typically no recovery of the ODS refrigerant and blowing agent, ODS-contaminated compressor oil, or other harmful substances.

5.3 Other product re-use (change in ownership)

For buildings, product reuse is similar to leave-in-place. If the insulation boards, such as polyurethane boardstock (flexible-faced laminate) retain a low k-factor at the time of replacement it is feasible that they may be reinstalled in another structure. In reality, because the process of removal and subsequent handling requirements may damage the foam and reduce the foams insulation value while releasing some of the ODS blowing agent, it may be better to process any removed insulation instead so as to recover and destroy the blowing agent. However, for buildings constructed using polyurethane foam-cored sandwich panels, which are inherently more durable, the option exists to disassemble the building structure and to reuse the panels for the construction of a new building at another location. The initial low k-factor of the panels is likely to be retained for many years because of the encapsulating properties of the steel facings. Another example where disassembly may be an appropriate option is for XPS roof boards used in "upside-down" roof constructions. In these cases, the removal of the boards should be possible without them being damaged.

In addition to the ‘leave-in-place’ options discussed above, reuse also refers to the practice of refurbishment and resale of older units. Unfortunately, individuals on low-income and the populations of developing nations are typically the consumers of these units which may be inexpensive to purchase at first, but carry additional financial cost over their period of operation owing to their inefficient use of energy.

5.4 Foam recycling

As noted in Section 5.3, it can be difficult to extract foam for recycling without damaging it. Accordingly, the foam is usually ‘down-cycled’ to applications where it can still be of use. As an example, used appliance foam has been experimentally encapsulated for use as encased thermal insulation in structural concrete. While concrete is too porous to prevent ODS emissions from the foam, sealing the foam in airtight plastic, which would then be covered by the concrete, may significantly delay emissions. If effective, this option would also work for building foam. However, eventual emissions might still occur once the reuse product is finally disposed.

5.5 Landfill

5.5.1 Traditional approaches

Landfill has traditionally been the final destination for most of the world’s insulation foam disposals to date. In the case of building foam, the demolition process may prevent the foam from being easily separated from the rest of the waste, although some countries (e.g. Denmark) have been successful in separating over 90% of demolition waste. Where foam is not among the recoverable materials salvaged, the mixed waste of unrecoverable materials is trucked to landfills.

Disposed appliances are often recycled by being shredded in automobile shredders for metals recovery before the balance of the waste is landfilled. Units are fed by conveyer into a shredding mill chamber where large spinning hammers disaggregate the appliances against a metal grate. Pieces smaller than the selected grate openings pass through onto a conveyer belt for further separation. For appliances the shredding process can be accomplished in only a few seconds.

The shredded material is first passed under magnets where ferrous metals are separated. Following removal of the ferrous fraction, an additional down-stream operation process, such as an eddy current unit or water separation unit (using differential density heavy media baths), is used to separate non-ferrous metals. The resultant automobile shredder residue (ASR) is a mix of plastics, rubber, dirt, broken glass, wire, paper and other materials. The ASR is then most often loaded onto trucks for landfill disposal. In some countries, such as in the United States, ASR can only be incinerated at permitted facilities because of the potential PCB concerns. There is significant research underway to attempt to remove, sort, and reuse the plastic fraction in ASR for the manufacture of new plastic products. However, the PCB issue has slowed the progress of the practical reuse of plastic in ASR.

5.5.2 Managed attenuation

Managed attenuation is among the most promising technologies for mitigating ODS emissions from foam. Its primary advantage is that it has the potential to deal with previously landfilled foams and that the basic infrastructure already exists in most developed and developing countries. However the technology has not yet been proven in a real landfill environment. Two preliminary studies done in Denmark[3] and Colombia[4] (described in detail in Chapter 6) suggest that naturally occurring microbes in landfills are able to degrade CFCs and HCFCs into potentially less environmentally harmful chemicals. It is not yet clear, however, whether the microbes will appear over time in any landfill and thereby induce degradation or whether they have to be introduced and cultured to thrive.

The specific microbes capable of digesting particular ODSs are in the process of being identified. From the Colombian and Danish studies, they are known to be anaerobic and methanogenic. These characteristics of the bacteria may pose a challenge for this method as it can take months to reach anaerobic conditions under normal operating procedures in a landfill[5]. During this time, ODS released in the post-shredding, short term, accelerated release period will have escaped to the atmosphere, as well as any additional ODS released during compaction of the landfill (Baumgartner, Kjeldsen 2005).

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[3] Scheutz, Kjeldsen: *Attenuation of Alternative Blowing Agents in Landfills.* Technical University of Denmark, 2003

[4] Altamar, Quintero, Arango, Guerra: *Study of the Biodegradation of CFC-11 and HCFC-141b by a Pool of Bacteria Extracted From a Colombian Sanitary Landfill.* Universidad de los Andes, 2004

[5] Baumgartner, Kjeldsen: *Disposal of Refrigerators-Freezers In the U.S.: State of the Practice,* 2005

If it can be demonstrated effectively, this technology would build on existing appliance and building deconstruction waste disposal infrastructures, primarily landfills, and in the case of appliances, the outputs of automobile shredders. However, the issue of formation of potentially harmful degradation products (i.e. HCFC-21 and HCFC-31) must first be addressed (Scheutz, Kjeldsen 2003). If the degradation products are not ultimately harmful or can be mitigated in some other way, the opportunities are significant.

While the Danish and Colombian studies have shown rapid degradation of CFC-11, HCFC-141b takes much longer to degrade. Therefore it may be necessary to devise ways to keep even the ODS released through normal diffusion contained in the landfill until the bacteria can break it down. It must also be determined whether sufficiently sized colonies of the necessary microbes develop naturally. If this is not the case the viability of "seeding" landfills with the desired microbes will have to be studied.

5.6 Mechanical recovery

In its most widespread use, this technology is used for appliances. The foam is brought to the recovery plant in the walls of refrigerator or freezer cabinets. After having the refrigerant and oil drained, batches of cabinets are fed by conveyor into the recovery plant where the cabinets are shredded. During this first stage, nitrogen is often fed into the shredding chamber to act as a carrier agent for the released blowing agent and to prevent the risk of explosion (particularly for processing hydrocarbon-blown foams).

As some plants are custom made, the order of materials separation may differ. Typically, however, all separate ferrous metals and non-ferrous metals. As with the auto-shredders described in Section 5.5, foam can be separated from other non-metal materials using sieves or water technologies that utilize the different buoyancies of materials. Once the shredded foam is separated it is heated to high temperature, liberating almost all of the remaining ODS. This ODS vapor can then be condensed and liquefied at extremely low temperatures. Carbon filters have also been utilized to collect released ODS. Once collected, the ODS and processed polymer can be handled in various ways described below. Ferrous and non-ferrous metals are easily recycled, and the remaining mixed residue, including rubber, glass, and other plastics require further separation for recycling or disposal.

This technology is an option for building foam as well. Since the separation of the foam from demolished concrete and other building materials within such a unit will normally prove impractical, the most likely option is that foam will have to be scraped manually from walls either before or after building demolition. While this will require a great deal of manual labour, it should be possible to cut costs significantly for larger sites by utilizing mobile recovery plants as opposed to shipping the foam to fixed installations. This will also eliminate the emissions of ODS during transit to recovery plants.

Some recovery plants also have incineration capability for destruction of the concentrated ODS and/or processed polymer. These options for dealing with the outputs of this method are discussed in more detail below.

5.6.1 Blowing agent

5.6.1.1 Destruction

The 2002 TEAP Report on Destruction Technologies examined a number of methods for destruction of concentrated sources of ODS. The report screened the technologies based on four criteria (pgs. 29-34):

1. A Destruction and Removal Efficiency (DRE) of 99.99%.

2. Emissions of dioxins (PCDDs: polychlorinated dibenzo-p-dioxins and PCDFs: polychlorinated dibenzofurans) in a maximum concentration of 0.2 ng-TEQ/Nm^3.

3. Emissions of other atmospheric pollutants (acid gasses, carbon monoxide, particulates) in a maximum concentration in stack gases of:

   - < 100 mg/Nm^3 HCl/Cl_2;
   - < 5 mg/Nm^3 HF;
   - < 5 mg/Nm^3 HBr/Br_2;
   - < 100 mg/Nm^3 carbon monoxide;
   - < 50 mg/Nm^3. total suspended particulate (TSP)

4. Technical capability: The technology must have demonstrated at least once its ability to achieve the above DRE with an ODS or suitable surrogate while maintaining the above emissions controls at a capacity of at least 1 kg/hour.

The TEAP determined that incineration at over 850°C satisfied the first three criteria. It recommended eleven technologies for destruction of concentrated sources of CFCs or HCFCs (pgs. 65-67). They were cement kilns, liquid injection incineration, gaseous/fume oxidation, reactor cracking, rotary kiln incineration, argon plasma arc, inductively-coupled radio-frequency plasma, nitrogen plasma arc, microwave plasma, gas phase catalytic de-halogenation, and super-heated steam reactor. Of these, cement kilns and rotary kilns were also specifically highlighted for dealing with the direct incineration of foams. If no new installations are built to manage re-concentrated ODSs , these technologies will hold the most promise for widespread ODS destruction within foams. Additionally, municipal solid waste incinerators (MSWI) are included as approved technologies for direct incineration of foams provided that foams represent less than 5% w/w of the feed. Since most waste-to-energy plants typically operate above 850°C, these may also be suitable for concentrated ODS destruction.

5.6.1.2 Recycling as an alternative chemical

There is also the option of processing recovered blowing agent into another chemical for reuse. There are many possible transformations of the different ODS blowing agents available, although their economic feasibility has not been determined.

CFC-11 can be converted to CFC-12, which in turn can be transformed into HCFC-22. HCFC-22 is a raw material for the production of poly(tetrafluoroethylene) or PTFE. CFC-12 can also be converted into HFC-32, a refrigerant component. HCFC-141b can be converted into HCFC-142b, which is a raw material for production of poly(vinylidene fluoride) or PVDF.

It should be noted that in 2002 the U.S. EPA interpreted the Clean Air Act as prohibiting transformation of an ODS to another chemical if the resultant chemical was also an ODS, as this would represent new production prohibited by the CAA and the Montreal Protocol[6]. As mentioned before, EU regulations mandate the destruction of recovered ODS from appliances, so even if economically viable, this option is still limited by region.

5.6.1.3 Recycling as a recovered chemical

Recovered ODS blowing agent can be processed and reclaimed for reuse. The market for reclaimed CFC-11 will vary by region but much of it would be used in aging, centrifugal chillers. However it must be reclaimed to a high purity before use and its current low price may make reclamation economically unviable. CFC-12 can also be recycled for use as a refrigerant, possibly to service the aging CFC-12 motor vehicle air conditioning (MVAC) fleet. HCFC-141b can be reclaimed for reuse as a blowing agent or as a solvent. HCFC-22 and HCFC-142b can be cleaned for use as refrigerants and, in the case of

[6] See letters to Honeywell and Coolgas, available at http://www.epa.gov/ozone/title6/convert.html

HCFC-142b, foam blowing agent. However, it should be noted that, in the United States, new and reclaimed HCFC-141b cannot be used as a blowing agent at all. Additionally, in EU countries, ODS recovered from foam must be destroyed.

5.6.2 Polymer

5.6.2.1 Re-use and recycling

Once the ODS has been recovered from the foam, there remain options for reuse of the processed polymer. Because the polymer has been separated from other materials, like rubber and other plastics, it is easier to recycle. However, the fact that polyurethane is a thermosetting matrix makes it more difficult to re-process than some thermoplastics. It is also sometimes the case that small metal fragments are found lodged in the shredded polymer which can either make it unsuitable for recycling or increases the cost. Additionally, processed polymer that is free from impurities may be too fine to be suitable for recycling. One common use for the shredded foam which cannot more beneficially be re-used is as daily landfill cover, since it serves to lessen landfill odors and helps with pest control, such as birds and rodents. This is also a common use for ASR.

5.6.2.2 Destruction

Depending on the capability of a recovery plant to liberate the ODS from the foam, there is a chance that there will be a significant amount of ODS remaining in the shredded foam. In some regions, this could even be classified as hazardous waste. Moreover, because of an accelerated release rate over the 200 hours immediately after shredding[7] this polymer is likely to need incineration as soon as is possible and to be kept encapsulated until that point.

5.7 Direct incineration

5.7.1 Segregation

Segregation and direct incineration involves separating relatively intact foam pieces from other materials and incinerating them, destroying the ODS with the foam. This method

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[7] Kjeldsen, P. & Scheutz, C. (2003): Short and Long Term Releases of Fluorocarbons from Disposal of Polyurethane Waste. *Environmental Science and Technology*, 37, 5071-5079

does not require the equipment investment associated with mechanical recovery but does require substantial manual labour. Therefore, costs will vary substantially by region. Foam must be cut from refrigerator and freezer cabinets or pulled from building walls and shipped to an incinerator (typically a cement kiln, rotary kiln, MSWI, or a waste-to-energy incinerator). Attempts to feed non-separated foamed products into such equipment have tended to cause problems (see Section 5.7.2).

According to parallel foam hand shredding studies performed at the Technical University of Denmark in 2002 (Scheutz, Kjeldsen 2003) and the Japanese Technical Centre for Construction Materials (JTCCM, 2004), resultant foam particles that are cut or broken by hand and are larger than 32 mm^3 release only a relatively small percentage of their contained blowing agent to the atmosphere when compared with mechanical shredding in automobile shredders. Accordingly, manual segregation techniques have a distinct advantage over uncontrolled shredding, even if they are more emissive than closed mechanical recovery options. These larger foam pieces will also have a lower release rate during the 200 hours immediately following cutting and breaking. Because separating the foam from the metal and plastic casings will damage large areas of foam surface causing additional emissions, best practice is to remove foam in the largest pieces that are practical. For both appliance and building foam, another good practice is to seal the foam in bags, immediately after removal, where practical, to minimize any emissions beyond the immediate emissions from cutting and breaking the foam.

While the 2002 TEAP Report on Destruction Technologies recommends eleven technologies for destruction of concentrated sources of CFCs and HCFCs, it only formally recommended two technologies for destruction of diluted sources, or foam sources, of CFCs and HCFCs foams (pg 67). They were municipal solid waste incinerators and rotary kiln incinerators. These two technologies meet the required criteria mainly due to their ability to handle solids. Cement kilns were also recognised as having high potential, but there was insufficient evidence available at the time to validate the inclusion of the technology. Since then, a study done at the University of Massachusetts, Lowell on CFC-11 appliance foam[8] suggests that harmful byproduct emissions like dioxins and polychlorinated aromatics from incineration of the plastic component of the foam can be avoided if the CFC-11 containing foam is incinerated above 900°C. Similarly, studies performed at the TAMARA waste-to-energy facility in

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[8] Golomb: *Complete and Safe Incineration of CFC-11 Containing Polyurethane Foam*; University of Massachusetts Lowell, 1994

Germany[9] indicate above 99% destruction of CFC-11 and CFC-12 and HCFC-22 and HCFC-142b with controllable emissions of harmful byproducts. Additionally, the Spokane Regional Waste-to-Energy facility in Washington State has been conducting research on these emissions for the past 2 years using various quantities of foam and intervals between burns[10]. The results suggest that the stack controls in their facility are adequate to prevent the release of any detectable amounts of harmful byproducts.

While labour intensive, this method lends itself to complete separation of nearly all appliance materials, including different plastics. Cabinet shells can then be sent to an automobile shredder for metals recovery.

Similar methods can also be used for building foam if the foam can be segregated from other building materials before incineration. It is unlikely that the foam will be separable from other building materials once a building is demolished and some materials, like concrete and glass, are probably not suitable for incineration. Therefore, as is the case for mechanical recovery, foam will likely have to be removed prior to demolition, with all the implications for manual labour that this entails.

5.7.2 Complete product incineration

Attempts to feed non-separated foamed products into such equipment has tended to cause problems with accumulation of debris in the past, even when the other primary material was metallic (e.g. in the case of appliances). An exception is in the case of basic oxygen steelmaking (BOS) furnaces and Electric Ark Furnaces (EAFs) where steel faced panels can be processed directly. However, even in these cases, care needs to be taken over the possible incremental generation of dioxins from the organic plastisol used as an adhesion promoter and protective coating for the steel.[11]

5.8 Schematic flowcharts summarising the options for appliances and buildings

The following flow charts summarise the options available for the end-of-life management of foams contained in appliances and buildings. They are not

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[9] Vehlow, Mark: *Co-Combustion of Building Insulation Foams with Municipal Solid Waste*; 1992-1998

[10] Stationary Source Sampling Report, Ref. Nos. 03-2024, 04-2102 can be viewed at http://www.solidwaste.org/wte.htm

[11] The Steel Construction Institute: Recycling organically-coated steel sandwich panels: Identification and removal of the barriers – Phase 2 Report, Sansom M; 2005

comprehensive but provide a sense of the breadth of options available and the key areas where recovery (green) and unintentional emissions (red) can take place.

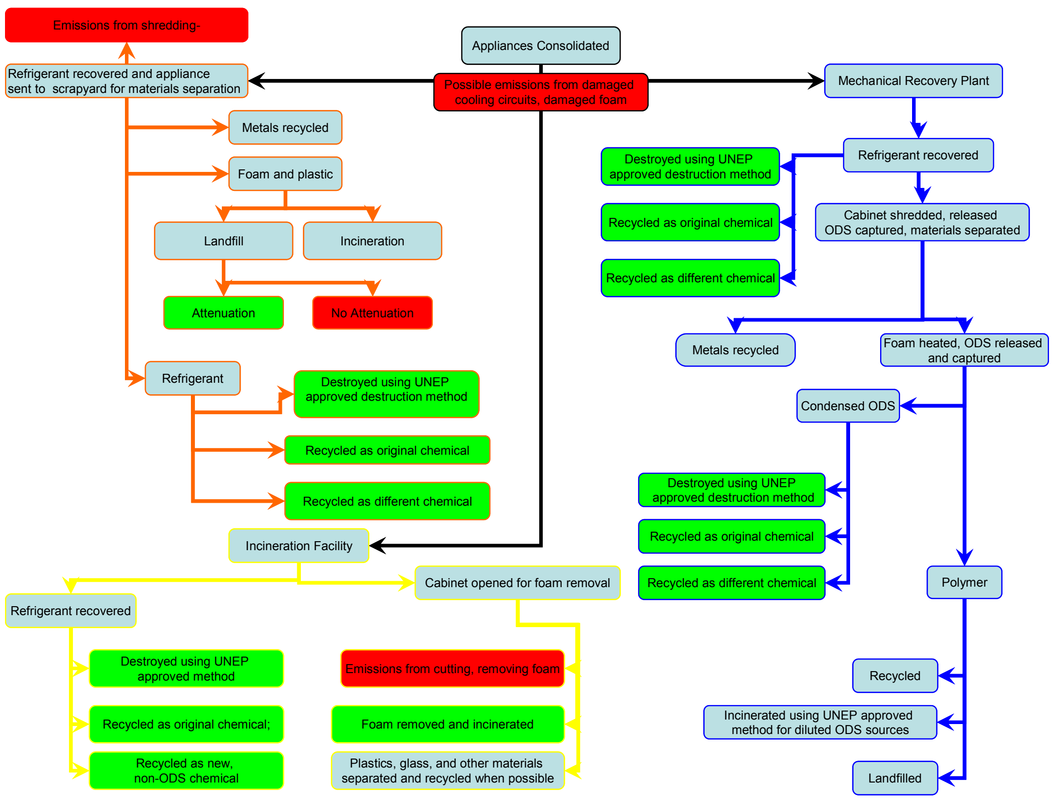

Figure 5.1 End-of-life options available for appliances

Options available for appliances are more advanced than for foams contained in buildings and this is easily seen when comparing Figures 5.1 and 5.2. It is expected that the options available for building products will increase over coming years as the sustainable construction agenda becomes more established and more ODS-containing foams enter the waste stream.

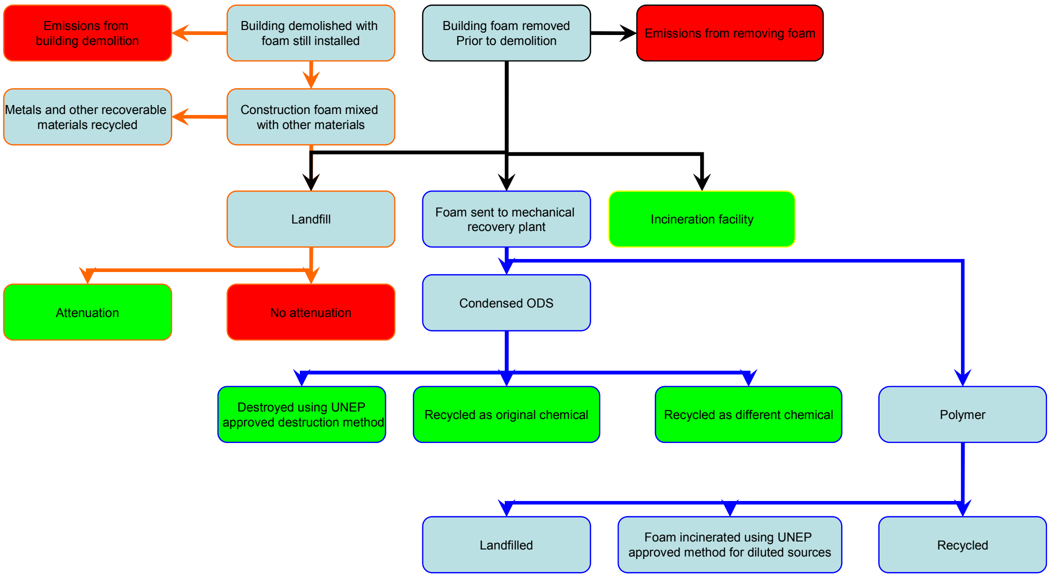

Figure 5.2 End-of-life options available for building foams

CHAPTER 6

6.0 UNINTENDED CONSEQUENCES OF END-OF-LIFE MANAGEMENT

6.1 Recovery efficiencies and releases

6.1.1 Mechanical recovery and subsequent destruction

Mechanical recovery with appliances will likely have the lowest predisposal emissions of the three methods examined in this section. If the cabinet is left intact prior to processing by a recovery plant, nearly all emissions beyond normal diffusion should be prevented. However, for better utilization of truck space, units bound for disposal may be cut into panels for easy stacking. This may result in ODS emissions of about 3g (7g/m^2 of cut surface area).[12] Additionally there may be post-processing emissions due to residual foam adhered to metal and plastic fragments.

To mechanically recover foam from buildings it will be necessary to remove the foam prior to demolition. Studies have shown that emissions from manual removal of foam can range from 1.5%-5%[13] however this will be labor intensive. Emissions appear to be least when the foam is removed with a mechanical scraper. Further emissions may result from the handling of the foam from the building to the recovery plant, but, if practical, these emissions can be minimized by sealing the foam in airtight bags.

Mobile recovery plants may hold the greatest potential for maximizing efficiency in the disposal of building foam. Because of the large volume of foam likely to be generated from a single building, transport to a disposal facility may prove a problem both in the expense of separate trucks to haul it and time and money spent sealing pieces in bags. Furthermore, there is a risk of further emissions from foam in transit to a stationary facility, albeit they will probably be insignificant compared other emission sources. A mobile recovery plant can travel from site to site and recover the ODS from the foam almost as soon as it is removed mitigating the short-term release that follows damage to foam cells.

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[12] *Cutting of fridges: Estimating CFC releases & recommended best practice.* DEFRA, 2002

[13] *Research on the Recovery and Processing of CFCs/HCFCs Contained in Thermal Insulator*, JTCCM 2004

The efficiency of mechanical recovery and subsequent destruction can be high. Tests done by a quality assurance organization on three different Norwegian recovery plants (of at least two different models) indicate residual CFC concentrations of 1.5%, 0.7%, and 0.2%[14]. This indicates that these plants are capable of recovering close to 99% of the ODS in the unit when it arrives for recycling. As mentioned before, the efficiency of recovery plants may be reduced by ODS in foam that remains adhered to metal and plastic; residual ODS contained in the polyurethane matrix; losses to air and water; and fugitive losses from the plant[15]. This was confirmed by a recent survey conducted by the U.K.'s Department for Environment, Food, and Rural Affairs (DEFRA). The survey covered eights U.K. plants and indicated that less than 65% of the estimated amount of recoverable ODS in appliances disposed of across the U.K. is actually captured. It should be noted that this percentage includes both refrigerant and blowing agent, and the survey did not indicate where the losses occurred. This is important because, qualitatively, a damaged refrigerant circuit that releases all of its contents will have a larger impact on the perceived recovery efficiency of a plant than a dented door that causes some release of blowing agent from the foam. This serves to underscore the importance of vigilant maintenance, proper operation, and regular testing to assure the potential of this method is realized.

6.1.2 Direct incineration

For refrigerators and freezers, emissions initially result from the cutting of cabinets, possibly for transport, and later to access the foam. Studies done in the early 1990s indicated that emissions from cutting open cabinets and removing the foam can range from 10-15%[16]. However, these emissions are most likely extreme and can surely be reduced below 10% through careful foam removal practices, such as limiting the amount of cuts. Also, further out-gassing can be prevented by sealing foam pieces in airtight bags. Care must be taken not to puncture the bags or otherwise compromise the airtight seal. Once the bags are fed into the incinerator, maintaining the incineration chamber at a negative atmosphere will ensure all ODS released during the burning does not escape as

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[14] *Audit Report on an investigation of the infrastructure (collection sites, transport arrangements, recycling plants) for the demanufacture of refrigeration equipment containing CFCs in Norway based on the RAL GZ 28 quality standard* RAL 2004

[15] Guidance on the Recovery and Disposal of Controlled Substances Contained in Refrigerators and *Freezers.* SEPA, 2003

[16] Bericht uber die Abnahme und Kontrolle der Entsorgungsstellel fur Kuhlgerate fur das Jahr 1992

backflow. As in the case of mechanical recovery, some ODS will be unrecoverable, since some foam will remain adhered to the metal or plastic liner.

There have been several trials to obtain the burn data associated with the destruction of foams containing CFC-11 using a municipal solid waste incinerator ("FY1998 Research Report of CFC Destruction Business Model," prepared for the Agency of Environment of Japan, Mitsubishi Research Institute). The results indicated that CFC-11 in insulation foams of refrigerators was destroyed at a destruction efficiency of more than 99.92% and below the emission standards of acid gases and PCDDs/PCDFs when incinerated in the range of 870 and 948 ^{o}C.

6.1.3 Auto-shredding followed by managed attenuation

For appliances the most likely source of predisposal emissions from managed attenuation will come from the shredding of cabinets for metals recovery. Work done at the Technical University of Denmark on post-shredding foam samples from four U.S. automobile shredders showed an average instantaneous release of 24.2%, ranging from 8.5% to 38.9%, of the ODS blowing agent (Baumgartner, Kjeldsen 2005). This is followed by a slower release of about 8% of the pre-shredding ODS content over approximately 200 hours (Kjeldsen, Scheutz 2003, Hand-shredding). After that time the release rate drops again to a much lower annual diffusion rate. The wide range of immediate emissions from shredding foam suggests that hammer configuration, grate size, and temperature in the hammer mill may play a large role in the quantity of ODS released. It may be possible to reduce immediate emissions by adjusting these components.

One of the goals of managed attenuation would be to minimize the amount of time it takes for microbial degradation to commence. This may require special practices for landfilling ASR including concentrating ODS containing foam in certain parts of the landfill and taking steps to create anaerobic conditions quicker. Long-term emissions are probably currently being prevented somewhat by microbial degradation, although to what extent is unknown. Still the shredding of appliances for the practice of managed attenuation will most likely result in higher predisposal emissions than mechanical recovery or segregation and direct incineration.

In many cases an appliance may be crushed and buried in the landfill intact. While small emissions would be expected from the compression of the foam, this practice does not allow for metals or other materials recovery and takes up a great deal of space. Once in the landfill, the microbes should be capable of digesting some portion of the gradually released ODS.

Current building deconstruction methods favour building demolition with the foam inside as opposed to removing the foam first. Therefore predisposal emissions will likely result from the breaking and crushing of foam when a building is demolished. As the resultant pieces of foam from building deconstruction will likely be large the emissions will likely be small. Also, due to the larger size foam pieces, there is unlikely to be a pronounced period of accelerated emissions as in the case of shredded appliance foam (Scheutz, Kjeldsen 2003, Hand-shredding). However this has not been verified.

Two studies have been done thus far investigating the potential for microbial attenuation of ODS blowing agents in landfills. The first was done at the Technical University of Denmark (DTU) in 2003 using soil from an American landfill (Scheutz, Kjeldsen 2003, Attenuation). The blowing agents studied were CFC-11, HCFC-141b, HFC-134a, and HFC-245fa. The second, done at the Universidad de los Andes in Colombia, used soil from a Colombian landfill and studied CFC-11 and HCFC-141b (Altamar, Quintero, Arango, Guerra 2004). Both showed the potential for microbial breakdown of CFC-11 and HCFC-141b, but the DTU study did not reveal any breakdown of the two HFCs.

In the DTU study, rapid and almost complete degradation of CFC-11 was observed. Nearly 100% of the CFC-11 was broken down in 10-14 days, with a half life of 2 days. Its breakdown products were HCFC-21 and HCFC-31, which were broken down further, and HFC-41, which did not break down further. HCFC-141b was degraded much more slowly with an approximate half-life of 50 days. The study mimicked the relatively fast release rate of blowing agent from the foam that occurs for approximately 200 hours after shredding. While the microbes appeared to be able to digest CFC-11 at a rate high enough to prevent its release to the atmosphere, the breakdown of HCFC-141b was insignificant compared to the release rate.

The lack of observed breakdown of HFC-134a, HFC-245fa, or HFC-41 suggests a correlation between the presence of chlorine and the potential for attenuation. However, the research notes that landfill bacteria have had over 50 years to adapt to the presence of CFC-11, and hence attenuation of HFCs may develop in the future (this ‘effect’ requires further study)

In the Colombian study, a 60% reduction in the concentration of CFC-11 was observed with an unknown byproduct substance. It confirmed the DTU study's results that CFC-11 and HCFC-141b can be degraded microbially in landfills and that it must occur under anaerobic conditions. While not identifying the specific microbes responsible for the degradation, it did observe four likely candidates. Additionally, the formation of methane agreed with previous studies, including the DTU study, that dechlorination can be performed by methanogenic bacteria.

Managed attenuation may have the potential for over 90% destruction efficiency of the ODS that arrives at the landfill. But the average immediate loss of almost 25% of the ODS from shredding must be taken into account when determining the overall efficiency of this technology. It may be the case that to achieve efficiency rates comparable to that of mechanical recovery and direct incineration, the foam may still have to be removed prior to cabinet shredding. Also, further research is required to determine if current landfill designs are conducive to managed attenuation or if new technologies or methods must be developed to realize the potential of the technology, as detailed in Chapter 5.

6.1.4 Destruction efficiencies

In the 2002 TEAP assessment of Destruction Technologies, distinction was drawn between Destruction Efficiency (DE) and Destruction & Removal Efficiency (DRE). The significance of this distinction related to whether only stack inefficiencies were considered (DRE) or whether the whole plant was taken into account (DE). In the treatment of dilute sources (e.g. foams), the authors of that report decided to set a minimum DRE of 95% for foams.

In the analysis that followed the publication of that assessment, it has become clear that the stack inefficiencies represented by DRE for directly incinerated foams are in excess of 99.9% typically (see Section 6.1.2). In fact, the 95% minimum established in the 2002 assessment could not even claim to represent a DE because it was intended to address factors even beyond the plant boundary. In reality, a better term for the overall performance of the end-of-life treatment of a foam would be simply Recovery & Destruction Efficiency (RDE), where the RDE represents the proportion of banked blowing agent actually recovered and destroyed and is represented by the following equation:

$$RDE\ (\%) = \left\{ \frac{\begin{array}{c}\textit{Blowing Agent in foam} \\ \textit{Immediately prior to} \\ \textit{Decommissioning}\end{array} - \begin{array}{c}\textit{[Losses in Segregation and/or Mechanical ,} \\ \textit{Recovery and/or Incineration]}\end{array}}{\begin{array}{c}\textit{Blowing Agent in foam} \\ \textit{immediately prior to} \\ \textit{decommissioning}\end{array}} \right\}$$

From the analyses contained in Sections 6.1.1 and 6.1.2, the following outline summary can be drawn as shown in Table 6.1

Product Type	***Recovery Method***	***Losses in segregation***	***Losses in other pre-incineration steps***	***Losses in incineration***	***Recovery & Destruction Efficiency (RDE)***
General Building Foam	Mechanical Recovery	2-8%	0.5%	<0.1%	>90%
General Building Foam	Direct Incineration	2-8%	Not Applicable	<0.1%	>90%
Sandwich Panels	Mechanical Recovery	Not Applicable	<5%	<0.1%	>94%
Sandwich Panels	Direct Incineration	Not Applicable	Not Applicable	<0.1%	>99%
Appliance Foam	Mechanical Recovery	Not Applicable	<5%	<0.1%	>94%
Appliance Foam	Direct Incineration	0.5-4%	Not Applicable	<0.1%	>95%
Appliance Foam	Auto-shredder + managed attenuation	8-40%	<40%	Not Applicable	>20%

Table 6.1 Assessment of Recovery & Destruction Efficiencies (RDE)

Although the economics of several of these methods may ultimately determine their uptake, this Report would propose to redefine the Approved Technologies for foams on the basis of Recovery & Destruction Efficiency and set the minimum level at perhaps 85% or 90%.

The situation with respect to managed attenuation is somewhat exceptional in that it is targeted at blowing agents which may already be in landfills. Under these circumstances, it would be reasonable to assume that any significant emission prevention through attenuation would be welcome. However, in order to set an appropriate target and to provide a justification for the investment in landfill management, it is proposed that a minimum of 35% attenuation is achieved. Since the breakdown of ODS blowing agents other than CFC-11 is less fully researched, this might also set a performance target for HCFCs and, ultimately, HFCs.

It should be stressed, however, that landfilling and managed attenuation will not become an approved destruction technology for foamed products yet to be disposed of. Equally, where attenuation products are either not characterised or demonstrated to present other health and/or environmental risks, there can be no basis for approved status under any circumstances.

6.2 Attenuation breakdown products

The work carried out by the Danish Technical University on attenuation processes relative to CFC-11, HCFC-141b, HFC-245fa and HFC-134a has already demonstrated some important lessons. These can be summarized as:

- Breakdown of CFCs is more efficient than other blowing agents
- Microbes seem capable of dealing with the Carbon-Chlorine bond but not the Carbon-Fluorine bond. This may be the result of “insufficient practice”, but may also reflect the higher bond strength of the latter.
- The transitional breakdown products of CFC-11 include HCFC-21 and HCFC-31, both of which are toxic. The fact that these are transient may make their toxicity less relevant in the wider landfill environment. However, the toxicity of the final breakdown product HFC-41 is also the subject of further confirmation.
- The quantities of HFC-41 observed do not provide an adequate mass balance against the quantities of CFC-11 converted.

There is therefore an urgent need for further work to assess these breakdown products further and to look at the practicalities of landfill management in this context.

CHAPTER 7

7.0 ECONOMIC CONSIDERATIONS

7.1 Over view of options

7.1.1 Mechanical recovery and subsequent destruction

At the current state of technological development, it is understood that blowing agents within foams contained in building products, [with the important exception of steel faced sandwich panels], cannot be mechanically recovered without first being segregated. Although experience is very limited today, it is self-evident from Chapter 4 that the bulk of blowing agents in buildings are situated in developed countries where labour is at a premium. While mobile mechanical recovery units could save on transportation costs (and losses), it seems unlikely that widespread segregation and recovery will be possible, even though it is understood to be already practiced in some countries (e.g. Denmark).

For appliances and sandwich panels the situation is much more optimistic and experience is already well established. For domestic refrigerators, costs in the order of $10/unit or less are emerging from Europe, although this figure may be distorted to a degree by over-capacity. Although direct incineration of sandwich panels in a BOS Furnace or EAF would still be considerably cheaper at this point, a cost of £5-6 per m^2 of panel for mechanical recovery would still suggest slightly better economics than for appliances. The reason for this is that these panels tend to be thicker and provide more blowing agent per processed item. A potential drawback of this observation is that there may need to be additional investment costs to safely manage higher atmospheric concentrations of hydrocarbons as and when such products are processed.

7.1.2 Managed attenuation

The costs for managed attenuation are still far from being established. Much will depend on how much baseline microbial activity exists and how much 'management' is therefore required. Further work is required to manage this aspect. However, for the reasons outlined above, the future value of landfill management could be very important for dealing with foams currently contained in buildings.

7.1.3 Direct incineration

Where segregation is not required (e.g. for sandwich panels), direct incineration with energy recovery represents by far the most efficient means of destroying ODS. However, in that case, there needs to be a local co-combustion facilities (e.g BOS Furnace or EAF) to avoid inordinate transport costs. Work on the logistics of building disassembly is on-going to establish both the efficacy and costs of panel reclamation.

Costs of direct incineration vary significantly between waste-to-energy, co-combustion and dedicated hazardous waste plants. Table 7.1 summarises the situation in Europe:

Incineration Type	***Cost Range (€/tonne)***
Waste-to-Energy*	50 – 400
Co-combustion (e.g. steel or cement kiln)*	50 – 100
Dedicated Hazardous Waste facility	500 – 700

* based on low CFC containing PU foam

Table 7.1. Cost comparisons for various incineration options in the EU

The main drawback of direct incineration for other product types is the fact that segregation is required. Unless such activities can be funded by alternative financial mechanisms such as ‘bounty programmes’ driven by energy efficiency benefits, or by tradable emissions under a suitable greenhouse gas emission prevention scheme, there seems little likelihood that segregation will occur on a widespread scale.

7.2 Specific issues for appliances

7.2.1 Experience of existing recycling facilities with blowing agent recovery

As briefly indicated in Chapters 3 and 5, and further elaborated in Chapter 8, blowing agent recovery and destruction programmes are well established in both Europe and Japan. Costs have been estimated to be in the range of $10-45/unit processed depending on a number of factors, including the supply/demand balance and the value of other recyclable components (e.g. steel prices). Since this range of costs equates to between $25 and $150 per kg of blowing agent recovered and is considerably greater than the cost of preventing consumption in the first place, most end-of-life programmes are justified on a wider spread of environmental indicators. In the case of appliances, the other relevant indicators are typically minimum recycled content or improved energy efficiency. These various issues are dealt with in the following sections.

7.2.2 Logistics of collection and transportation of appliances

In some cases consumers may deliver appliances directly to the recycling facility, but generally they will be accumulated at a waste disposal facility, or by the retailer, and then transported to the recycling facility and can contribute significantly to the total costs incurred in recovery or destruction of the blowing agent in appliance foam. Estimates for collection of waste appliances under the WEEE directive are in the range of 150 to 340 Euros per tonne of collected waste. But, costs could be significantly higher in sparsely populated regions or where existing infrastructure makes transportation expensive. Distances to the recycling facility may vary substantially, have a significant impact on cost, and result in added energy consumption and associated GHG emissions.

7.2.3 Impact of financing methods

One element to consider is the potential effect of any charges, or incentives, on consumer behavior and subsequently on the effectiveness of any program to recover and destroy ODS from appliances. If the program includes an up-front cost, there is a possibility that consumers will delay purchase of new appliances, thus delaying any possible savings in energy consumption (and related CO2 emissions from power plants). If the program includes a charge for decommissioning the appliance, there is the possibility that consumers will bypass the system by keeping the old appliance, or disposing of it in a manner that bypasses the recycling system. On the other hand, programs that include an incentive to the consumer to surrender products for recycling are believed to increase the number of products that are recycled and may reduce emissions related to energy consumption. (New units are generally much more efficient than the products that they replace.) There have been several programs conducted by utilities, in cooperation with environmental advocacy groups and recycling companies where utilities have offered a financial incentive for consumers to surrender old inefficient products for recycling and have subsidized the recycling costs of these products. The benefit to the utilities is avoided investment and energy costs that otherwise would be needed to power the old inefficient products if they were to continue to operate in the consumer's homes, either as the primary refrigerator in the household or as a second refrigerator.

7.2.4 Value of recycled materials from appliances

The key value drivers for appliance recyclers are those related to metals – most notably steel, copper and aluminium. Table 7.2 illustrates the proportion of each of these metals recovered from appliances at end-of-life in Japan for the years 2001-2004. Significantly, the table does not provide financial values for the recovered components, since these will vary considerably depending on the market conditions pertaining at the time.

		April 2001 – March 2002	*April 2002 – March 2003*	*April 2003 – March 2004*
Steel	tonnes	58,423	65,832	68,417
Copper	tonnes	406	998	1,113
Aluminium	tonnes	117	404	293
Mixed Metals	tonnes	15,500	18,880	18,179
Other Valuables	tonnes	1,909	4,890	9,115
Refrigerant	kg	135,779	233,946	286,646

Table 7.2 Materials from Recycling of Used Home Refrigerators in Japan

7.3 Specific issues for buildings

There is little or no experience in the recovery of foams from building insulation or of the ODS contained within the foams. Hence, economic information based on direct evidence is not available.

There are several reasons why this is the case:

- Few buildings being demolished, deconstructed or renovated contain foam insulation. Buildings are long-lived and the turnover in building stock is very low. Estimates of the average overall lifecycle of buildings in Europe, North America and Japan ranges from 30 to 50 years (with many buildings already several hundred years old in Europe) and is rising as commercial building and housing stock ages. The estimated turnover or renewal rate is also very low – less than 1%/year in North America and less than 2%/year in most European countries. Only a few European countries (Ireland, Portugal, Spain) have renewal rates as high as 2 - 4%/year. The use of foam insulation in buildings only really began in earnest 30 years ago, driven by increased insulation requirements resulting from the energy crisis of the 1970s. This suggests that we would not expect to see significant amounts of foam insulation in C&D waste for at least another decade.

- Foam insulation containing ODS is a minute proportion of all C&D waste. Data from a 1998 report prepared for the U.S. EPA estimated that plastics C&D waste made up less than 1% of total C&D waste. Most of this is from vinyl siding, doors, windows, pipe and flooring - foam insulation is only a very small fraction of this total. In many countries and regions C&D waste is predominantly glass, concrete, bricks and stones, which can be reused as foundations for buildings or as fill for other works such as roads. The size of the waste stream of foams based on ODS would be very small and the feasibility and cost of separation would, therefore, be difficult and expensive

- In many building applications (such as walls, conventional roofs, or foundations), foam insulation is adhered or mechanically attached to the building structure. This will make it very difficult and economically unattractive to separate the foam insulation from the structural substrates after demolition. Foamed plastic insulation is also very low density, which makes collection of quantities significant enough to enable recovery very challenging.

- So far, most C&D waste which is not reused is landfilled without any pre-treatment. It is estimated (1998 EPA report) that building demolitions and renovations only result in the recycling of 20 – 30% of the building-related C&D waste in the U.S. Valuable materials like wood, asphalt, concrete and metal are recycled or sold. The recycle rate for scrap steel from buildings in the U.S. is about 85% because of its high value. Much of the structural rubble (concrete, brick, etc.) is reused as fill on this or other projects. While building deconstruction can result in much higher material recovery rates, the U.S. National Demolition Association estimates that deconstruction can take two to ten times longer than demolition alone, and cost at least five times as much. Low landfill tipping fees in North America ($15 - $50/ton) provide little incentive to do anything other than landfill the bulk of C&D waste.

- Even in the EU (EC2037/2000) there is no regulatory necessity to recover ODS in foams other than appliances. In terms of waste stream legislation in the EU there have been no directives resulting from the discussions on Construction and Demolition (C&D) waste. In Europe there a general phase-out of the landfilling of waste with and organic content. There are landfill acceptance criteria with very precise controls on leachates. The industry will have to address ODS leachates. In Japan, the Construction Material Recycling Law enacted in May 2000 establishes a target recycling rate of 95% by 2010 for specific waste construction materials (including pre-cast plate, asphalt/concrete, and wood), but the law does not include insulation foams. There are no regulations governing recovery of foam building insulations or the ODS contained within them in North America.

- More than 50% of building insulation is based on mineral fibres which do not raise ODS issues. A significant proportion of foams for building insulation are now made with non-ODS and non-fluorocarbon blowing agents which will reduce future pressure on their treatment. Because of the long lifecycle and slow turnover rates of building stock, records of the origin and type of foams used may not exist at the time of demolition.

However, some building products could be subject to economic considerations similar to other products, such as refrigerators. An example could be metal sandwich panels. In this case, the value derives from the steel content, the high price and current shortage of steel, and the panel accessibility. These panels can be recovered because of their steel content and the fact that many of the panel manufacturers are owned by steel makers. The steel can be recovered by putting panels, cut in sections or not, into steel blast furnaces. They could also be shredded but the higher foam density and heavier gauge steel, compared to refrigerators, would have to be taken into account. This assumes, of course, that the metal panels do not have further value as insulating panels and cannot be reused.

As discussed above, many building foam applications are mechanically fastened to the building structure and not easily accessible. The following table summarises typical foam building applications according to the viability of recovering the foam. ODS recovery is an additional step which is very dependant on the facilities available.

PUR/PIR					XPS				
	Panels	Roofs	Walls	Spray walls & roofs	Conventional roofs	Protected membrane roofs	Walls	Floors	Panels
Accessible	Good	Moderate	Moderate	Moderate	Moderate	Good	Moderate	Moderate	Good
Ability to separate	Moderate	Difficult	Difficult	Difficult	Difficult	Moderate	Difficult	Difficult	Moderate

Table 7.3 Summary of accessibility of various foam types

CHAPTER 8

8.0 REGIONAL VARIATION AND LOCAL EXPERIENCES

End of life management of foam products varies regionally throughout the world, with Europe, Japan, the United States and developing countries taking different approaches to such management. This section explores regional variation and local practices related to foam end of life management, including the legislation, drivers, cost, practice and infrastructure present in each region.

8.1 Europe

As discussed in Chapter 3, existing legislation (EU Regulation 2037/2000) in Europe mandates the recovery of ODS from both the compressor (refrigerant) and the foam (blowing agent) in refrigerators and commercial refrigeration units and has been supported by relevant standards (RAL GZ728, 2001; Draft DIN-8975-12, 2002). At this time, the legislation does not require recovery of blowing agent from foam insulation in buildings and will not do so until such recovery is determined to be "practicable". However, increasing use of prefabricated building elements (e.g., steel faced panels) in Europe could necessitate recovery of blowing agent from both a technical and economic standpoint. Current work in the UK, expected to be complete in 2005, will determine the economic feasibility of recovery of blowing agent from steel faced panels. Additionally, work done by the Japan Technical Centre for Construction Materials (JTCCM), also expected to be complete in 2006 and explained later in this section, will further inform the discussion on the technical and economic feasibility of recovery of blowing agent from building foam.

The strongest driver to recover blowing agent and recycle appliances is likely material recycling and waste stream management. This is demonstrated by WEEE Directive 2002/96/EC (as also described in Chapter 3) which is related to the recycling of refrigerators and freezers and sets material recycling targets. The Directive calls for national legislation to be in place by 2006 for the recovery of 80% of materials and substances together with a target of 75% of recycling and reuse of the materials and substances. That said, EU Regulation 2037/2000 (mandating the recovery of blowing agents from foam) is an ozone protection based regulation. In the future, the global warming potential (GWP) of blowing agents could also become an important driver for recovery and recycling of blowing agents from foams, particularly if the cost of recovery is considered in Kyoto Protocol terms.

The implementation of Article 16 of the European Regulation 2037/2000 is understood to be resulting in the controlled disposal of well in excess of 5 million refrigerator cabinets per year. This equates to the recovery of at least 1,250 tonnes of ODS blowing agent annually at a cost of approximately $40/kg of ODS or about $10-15/unit. The vast majority of these units have been disposed of through the mechanical recovery and recycling plants with the blowing agent itself incinerated either during the process or immediately afterwards. Direct incineration of complete refrigerators has also been practiced, however, there continues to be problems with the incineration residue thus limiting the commercialisation of this approach (2002 TEAP Task Force Report on Destruction Technologies).

The infrastructure to manage these refrigerators and freezers has been built up since the implementation of the EU regulation with most countries hosting a number of recycling plants. The following table illustrates the current status by Member State, where Step I refers to refrigerant recovery and Step II refers to blowing agent recover from foams.

	Actual activity (as of: 7 Febr 2005)		National law with quality specifications	Other regulations governing recycling quality
	Step I	Step II		
Austria	Yes	Yes	Yes	UFH specifications
Belgium	Yes	Yes	No	No
Cyprus	No	No	No	No
Czech Republic	Some	Some	Yes	No
Denmark	Yes	Some	No	Regional specifications
Estonia	No	No	No	No
Finland	Yes	Some	No	No
France	Some	No	No	No
Germany	Yes	Yes	No	UBA guidelines / LAGA
Great Britain	Yes	Yes	No	EA / SEPA Fridge Guidance
Greece	No	No	No	No
Hungary	Yes	Yes	No	No
Ireland	Some	Some	No	No
Italy	Yes	Yes	No	No
Latvia	No	No	No	No
Lituania	No	No	No	No
Luxembourg	Yes	Yes	No	Regulations from nat. env. agengy
Malta	No	No	No	No
Netherlands	Yes	Yes	No	No
Norway	Yes	Yes	No	Specifications from *Hvitevareretur*
Poland	Some	Some	No	No
Portugal	No	No	No	No
Slovakia	No	No	No	No
Slovenia	No	No	No	No
Spain	Some	Some	No	No
Sweden	Yes	Yes	No	Recommendations from env. agency
Switzerland	Yes	Yes	No	Specifications from *SENS*

Table 8.1 Current status of implementation of ODS recovery in appliances (RAL)

As mentioned earlier, steel faced panels could potentially be recycled and the blowing agent recovered using the same plants that are currently processing refrigerators. One of the largest panel manufacturers in Europe, is currently doing a study on the feasibility of such an approach and results are expected by the end of 2005. Assuming the panels can be processed in the refrigerator plants, new infrastructure would not have to be developed. However, it is not known at this time whether recovery of blowing agents from other types of building insulation would require the development of additional technology and infrastructure and/or if managed attenuation would play a role in Europe.

Compliance with this regulation across the EU is varied, with some Member States disposing and recovering the blowing agent in over 75% of their units. Compliance with the disposal and recovery regulation in some of the other states is less clear. Overall, it is expected that by 2007 >50% of units will be disposed of and the blowing agent recovered across the EU. Furthermore, as mentioned earlier, recovery of blowing agent from some types of building insulation (e.g. steel-faced panels) could also commence by 2007 in the EU.

8.2 Japan

As discussed in Chapter 3, existing recycling legislation in Japan mandates the component recovery and recycling from domestic appliances; this includes the refrigerant from the compressor (started April 2001) and the blowing agent from foam (started April 2004). At this time, the legislation does not require the recovery of blowing agent from foam insulation in buildings. The Construction Material Recycling Law was enacted in May 2000, targeting the recycling rate of waste of the specified construction materials to be 95% by 2010. The specified materials are concrete including pre-cast plate, asphalt/concrete, and wood building materials. Although the law does not currently include insulation foams, there is a commitment to formulate a policy on the recycling of blowing agent from construction materials by 2009.

		April 2001 – March 2002	*April 2002 – March 2003*	*April 2003 – March 2004*	*April 2004 – December '04*
Recovery of used refrigerators	'000 units	2,191	2,565	2,664	2,321
	tonnes	127,596	148,662	153,531	
Recycling to use	tonnes	76,359	91,006	97,119	
Percent recycled	%	60	61	63	

Table 8.2 Recycling of Used Home Refrigerators

Related to the recycling and blowing agent recovery legislation is an extensive multi-year National Project conducted by JTCCM and sponsored by the Ministry of Economy, Trade and Industry (METI), entitled, "Research on the Recovery and Processing of CFCs/HCFCs Contained in Thermal Insulator." The objectives are to assess, among other things, the stock of insulation foam manufactured with ODS and the current practice of recovery and destruction of ODS in foams, including the technical and economic feasibility of recovery of blowing agent from foam, specifically in buildings.

This project has also led to a standardisation of the method for measuring the quantity of blowing agent in foams. It has been incorporated as a draft Japanese standard on the subject that has been submitted to the International Standards Organization (ISO/TC146/SC6). Complete results from this project are expected to be reported internationally in March 2006.

Similar to the legislation in Europe, one of the main drivers for the recovery and recycling of blowing agent in appliances in Japan is material recycling and waste stream management due to a shortage of landfill sites. Additionally, under Japan's National Plan to meet its Kyoto Protocol targets, there is a new focus on reducing the emissions and use of HFCs in foam insulation, indicating the importance of GWP as a driver.

The implementation of the Japanese legislation on recovery and recycling of household appliances has resulted in the recycling of millions of refrigerators per year. The annual recovery of used refrigerators was approximately 2,191,000 units in 2001, gradually increasing to 2,664,000 units in 2004[17]. The recovery of that many units in 2004 equates to the recovery of approximately 1,332 tonnes of CFCs from both the refrigerant and foam insulation[18]. It should be noted that although the refrigerator recovery rates are fairly high, the number of used refrigerator waste may still be greater. The statistics indicate that the sale of domestic home refrigerators equaled 4,234,000 units in 2003. The cost of the disposal and recycling of the refrigerator is borne by the owner of the appliance. Currently, the recycling fee is 4,830 yen (approximately USD $46). Japan, notably, is one of the few countries where an end-of-life fee to recycle appliances succeeds.

Beginning in 1995, the blowing agent in refrigerators has been gradually switched to non-fluorocarbons, i.e. cyclopentane. By 2003, 95% of refrigerator insulation foams were manufactured with cyclopentane and in January 2004, the use of HCFC-141b as a blowing agent was phased out. Presently, most home refrigerators use cyclopentane as a blowing agent and isobutane as a refrigerant.

year	1995	1996	1997	1998	1999	2000	2001	2002	2003
percent of non-fluorocarbon blowing agent (wt%)	13	23	28	32	45	58	72	82	95

Table 8.3 Percent of foams blown by non-fluorocarbon agents

In Japan, there are two different blowing agent recovery and destruction methods practiced in recycling plants. The first is direct incineration of foams which contain CFCs and the second is mechanical recovery of CFCs by shredding, followed by

[17] The lifetime of refrigerators in Japan ranges from 8-14 years.

[18] This assumes 100 grams of CFC refrigerant per unit and 400 grams of CFC or HCFC blowing agent in the foam. For refrigerators made today (with hydrocarbons), there is approximately 150 grams of refrigerant and 550-600 grams of blowing agent in the foam insulation.

condensation of CFCs and destruction. There are 41 Japanese recycling plants that can be categorized into two groups; 26 plants in A-group (direct incineration) and 15 plants in B-group (mechanical recovery).

Additionally, there are 74 facilities for destruction of CFCs approved by the fluorocarbon recovery and destruction law in July 2003. The facilities include the co-incineration furnaces such as rotary kiln, cement kiln, and lime calcinations furnace, as well as the fluid injection-type reactors such as submerged combustion furnace, catalytic reactor, plasma reactor, superheated steam reactor, and so forth. A-group recycling plants use the co-incineration furnaces such as industrial waste incinerators, cement kiln, and lime calcinations plants, whereas B-group recycling plants use the fluid injection-type reactors as well as the co-incineration furnaces.

As mentioned above, manufacturers started to use cyclopentane as a blowing agent in refrigerator foam in 1995. Today, approximately 10% of the appliances recycled have hydrocarbons in them. Within ten years, industrial waste officials expect that 100% of refrigerators recycled will contain hydrocarbons because presently the production refrigerators use almost c-pentane as foams and isobutene as refrigerants. Therefore, the safety at recycling plants is becoming more important as processing of flammable substances such as cyclopentane and isobutane gradually increases. Many of the recycling plants are already equipped with monitoring instruments. The addition of hydrocarbons to the waste stream has lead to a cost increase of 2-3 greater than recycling plant construction was in the past.

The detectors suitable for the flammable substance detection in the plants were investigated by NEDO (the New Energy and Industrial Technology Development Organization) and explosion limits were tested in a practical plant. Based on the explosion and detector performance studies, the plant management was set at a level of 1400 ppm cyclopentane, which is 1/5 of the lower limit of the explosion, for plant safety system. In addition, experiments were successfully carried out to separate CFC-11 from cyclopentane in recovered mixtures by distillation for reuse of cyclopentane. Also, the performance of foams blown by recycled cyclopentane was obtained.

8.3 United States

As presented in Chapter 3, existing legislation in the U.S. requires the recovery of only the ODS refrigerant from the compressor prior to disposal of the appliance. At this time, there are no regulations requiring the recovery of ODS blowing agent from foam insulation in appliances. However, there is language in Section 608 of the Clean Air Act suggesting it could be possible for EPA to initiate a rulemaking to require the recovery of ODS blowing agent from foam in appliances.

Unlike recycling legislation in Europe and Japan, the main driver in the U.S. for recycling of appliances is energy efficiency. There are ongoing efforts across the country to encourage the retirement of older appliances due to the considerable energy savings associated with newer energy efficient models. These efforts are generally local and/or regional and usually include participation of a local government or utility sponsor, an appliance manufacturer, a retailer and a recycler. Under this type of program (i.e., a bounty program), an owner of a refrigerator can have their refrigerator or freezer picked up and disposed of through a rebate from the sponsor and/or receive a discount on the purchase of a new energy efficient unit.   Successful programs in some states or regions have retired approximately 120,000 units per year, with each unit consuming an average of 1000 kilowatt hours of electricity per unit. Retiring that many units translates to a savings of 81,800 tonnes of CO_2 per year. In some of these cases, the entity running the recycling program requires the blowing agent to be recovered as well. The capacity for blowing agent recovery in the U.S. is discussed in more detail below[19].

As opposed to Europe and Japan, there is little existing infrastructure that can recycle and recover blowing agents from foam in the U.S. today. Upwards of 90% of appliances are sent to an auto-shredder at the end of life for metals recovery and the leftover ASR is landfilled[20]. The size and construction of these shredders, as they are today, makes them unsuitable for encapsulation and subsequent blowing agent capture. There are approximately 177 shredders throughout the U.S. which handle over 90% of the appliances disposed of today.

In fact, based on results from a survey done by AHAM and the current AHAM/EPA project, appliance disposal practices in the U.S. could roughly be described as:

- 90% appliances shredded without blowing agent recovery and landfilled
- 7.5% appliances crushed whole and landfilled[21]

[19] The California Public Utility Commission (CPUC) mandates that any refrigerator recycling program paid for with citizens' System Benefit Charge (SBC- a small charge added to the monthly electric bill) must include ODS blowing agent recovery.

[20] Current TSCA regulations prohibit the incineration of shredder fluff due to PCB.

[21] According to the Appliance Recycling Information Center, at least 19 states prohibit the practice of crushing whole and landfilling appliances (http://www.aham.org/aric/3aric.pdf)

- 1.5% appliances shredded with blowing agent recovery or destruction
- 1% appliances abandoned

As mentioned earlier, under the energy efficiency/early retirement programs, sometimes the blowing agent from appliance foam is recovered. Currently, there are only two companies in the U.S. handling appliance foam; both operate predominantly in the western states. One company operates a pulverization and recovery facility that is similar to those in Europe and Japan, the major difference being that it is an older, hand-fed machine that requires the foam to be manually removed from the refrigerator. The blowing agent is recovered, recycled and destroyed or re-sold. The other company manually removes the foam and incinerates it with the blowing agent.

The facilities of the two companies that recover the blowing agent typically process approximately 120,000 refrigerator and freezer cabinets per year. The processing of that number of units equates to preventing the emission of up to of 55 ODP-weighted tonnes of CFC-11 blowing agent to the atmosphere. The cost of recovery per ODS tonne varies greatly, depending on the type of operation. Currently, neither method is self-sustaining in the U.S. and requires sponsorship. Further work needs to be done to determine the infrastructure capacity for recovery of blowing agent from appliances in the U.S. as well as the related economics.

Despite the apparent lack of existing infrastructure for blowing agent recovery, there are a number of facilities in the U.S. that can incinerate and destroy both the foam itself and the concentrated blowing agent. The capabilities of each type of facility are discussed in Chapter 5 while the numbers for each type of facility in the U.S. are as follows:

(1) In the category of Municipal Solid Waste (MSW) incinerators, there are many different subclasses of incinerators, designated mainly by capacity size. For example, there are approximately 167 large MSW units, 117 smaller units and 14 very small units.

(2) Another category of incinerator is Commercial and Industrial Solid Waste Incinerators (CISWI). There are approximately 120 CISWI units today, but that number could grow to as much as 280 units, if regulations regarding this type of incinerator change.

(3) A third category of incinerator is cement kilns. There are approximately 106 non-hazardous waste cement kiln incinerators.

(4) Finally, there are two types of Hazardous Waste Combustion (HWC) incinerators that accept commercial waste (waste from off-site). There are 14 HWC cement kilns and 17 HWC incinerators.

8.4 Developing Country perspectives

Most developing countries present similar opportunities in relation to end-of-life foam management as their developed counterparts. However, there are also some important differences in perspective:

Similarities

- The fact that most of the insulating rigid foam is polyurethane based. The usage of extruded polystyrene for building insulation is not significant and phenolic foams are not used.

- The fact that appliances represent a significant part of the market and can be targeted with end-of-life technologies similar to those used elsewhere in the world.

Differences

- Up until the early 1990s, a large proportion of refrigerators produced in developing countries were still insulated with mineral fibre. Considering the long lifetime of refrigerators in these countries, the presence of a large number of mineral fibre refrigerators impacts the development of end of life strategies.

- The usage of polyurethane rigid foam in buildings is very small compared to that in appliances, where domestic refrigerators, freezers, reefers and commercial equipment represent the largest foam sectors. Continuous and discontinuous panels are mainly manufactured for industrial refrigeration: cold rooms, large displays, etc.

- One of the preferred options actually is the secondary use of foam based products, particularly refrigerators and freezers. Within the country geography there commonly is a significant trade where second-hand units are sold at affordable prices to poorer sectors of the population, providing access to better standards of living. However, this practice often extends the use period of a less energy efficient equipment. In many cases, even when the unit has lost its capacity to work as a refrigerator, the product is used as cabinet.

- The deficient infrastructure in terms of recycling facilities and transportation roads is a critical factor to consider for feasibility assessment of ODS recovery.

There is no existing legislation on recovery of ODS blowing agent from either appliances or buildings in developing countries. However, the current and future use of ODS as blowing agents (HCFC-141b likely until 2040) presents a relatively significant opportunity to reduce emissions of ODS from appliances (and potentially buildings) at end of life.

Examples of initiatives in developing countries are given below:

- *Refrigerator recycling for energy efficiency (Colombia)*: The local Colombian association of appliance manufactures along with local universities and the national ozone unit carried out a study to assess the technical and economical feasibility of installing a refrigerator recycling facility to replace annually 100,000 units based on CFC-11 and CFC-12, currently in operation, for new products based on HCFC-141b and HFC-134a. The Japanese and United Kingdom experiences were taking into account for ODS recovery (characteristics of the destruction plant, investment cost, etc.). The result was very promising: when an additional consumer charge of 5 dollars to the new equipment price was considered, the ODS recovery option gave a positive net present value representing energy consumption savings for the country of 60 GWh per year.

- *ODS-based PU foam containment (Brazil)*: A pilot project is in place to reduce amount of waste that is landfilled from scrapped refrigerators. After dismantling, foam is separated from refrigerator cabinet and cut into slabs fitted into plastic bags, formatted to a suitable, regular size. Resulting packages are incorporated into concrete slabs, substituting expanded polystyrene, and thereby ensuring long term ODS containment.

CHAPTER 9

9.0 DISCUSSIONS ON THE SIGNIFICANCE OF FINDINGS

9.1 Technical feasibility

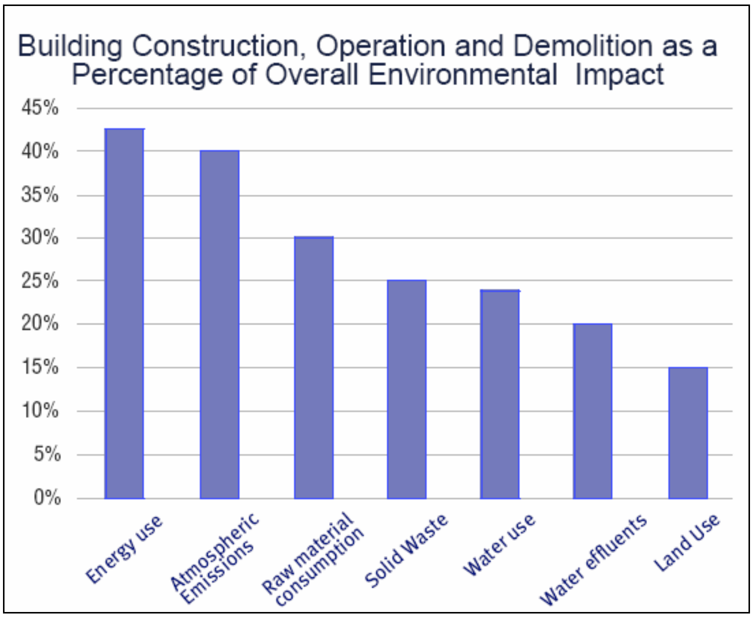
There is little doubt that the recovery and destruction of blowing agent from foams is a technically feasible proposition for most foam types, either through direct incineration of the foam or through mechanical recovery and subsequent incineration of the blowing agent itself. Limitations do, however, emerge when considering aspects such as the practicality of waste segregation and the logistics of recovery and destruction. Other important factors are the availability of co-combustion MSWI capacity and the need to limit the throughput of foams in these and other co-combustion units (e.g. steel furnaces and cement kilns) in order to avoid unwanted product, process or emission impacts. This also requires some knowledge of the composition of the foams being processed, which is unlikely to available without product testing. As with many other types of recovery/incineration process, this means that large sources of single product types are much more practical to manage than a multitude of disparate small sources.

9.2 Economic criteria

It is self-evident that all of these practicality and logistical aspects have a strong economic component and it is seldom possible to completely dissociate one component from the other. This explains why Article 16 of the current European Regulation (EC 2037/2000) uses the word 'practicable' to express the minimum requirement to trigger mandatory recovery and destruction of blowing agent from products other than domestic refrigerators and freezers. In legal terms, the word 'practicable' carries with it both a technical and economic component which fits the reality of the situation well.

As has been noted elsewhere in this report, the economics of recovery and destruction of blowing agents is greatly assisted by linkage with other programmes. This is particularly the case where minimum recycling targets have been established for the products in question. Such is the case in Europe and elsewhere for automotive applications (End-of-Life Vehicle Directive) and for most 'white goods' (WEEE Directive). Under these circumstances, the extension of existing recovery processes to deal with blowing agents has been relatively painless.

In contrast, one of the major challenges associated with the buildings sector to date is the lack of mandated recycling targets. With the notable exception of Japan (Construction Material Recycling Law), efforts to establish such targets have been fraught with difficulty, particularly when these are traditionally defined in other sectors in terms of percentage by weight. Nonetheless, the growth in awareness of the environmental impact of the buildings sector is encouraging many Governments to look at the sector more closely and to promote significant sustainable construction initiatives. Figure 9.1 illustrates the proportion of global environmental impacts associated with the sector.



Source: Metropolis

Figure 9.1 Proportion of global environmental impact caused by buildings

9.3 Environmental benefits and impacts

Although the evaluation of the full environmental benefits of end-of-life management extend well beyond the scope of this report, the scenarios established in the IPCC/TEAP Special Report on issues related to HFCs and PFCs allow the evaluation of the impact of emission abatement in respect of both greenhouse gases and ODSs. Of most interest to the focus of this report is the impact on ODS emissions and this is shown in Figure 9.2. The assumptions behind the end-of-life mitigation scenario are as follows:

- *The extension of existing end-of-life measures to all appliances and steel-faced panels by 2010 together with a 20% recovery rate from other building-based foams from 2010.*

The outcome of these additional measures would be a cumulative emission reduction of between 190,000 and 195,000 ODP tonnes by 2100 or in excess of 10% of the total bank.

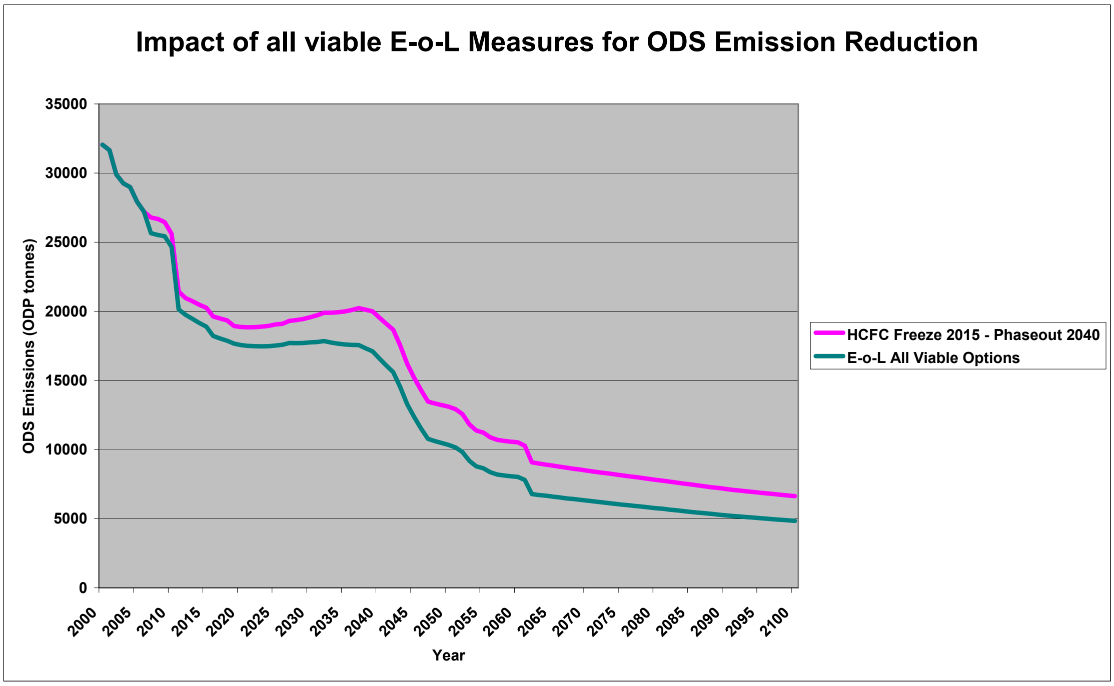


Figure 9.2 Potential reduction in ODS emissions resulting from E-o-L measures

This saving would be over an above those steps already being taken to recover blowing agent at end-of-life in the domestic refrigeration sector, which are included in the business-as-usual scenario. In the context of greenhouse gas emissions, the cumulative saving would be in the order of 1200 Million tonnes of CO_2 equivalent, as shown in Table 9.1 below, which is a reproduction of Table TS-18 in the IPCC/TEAP Special Report.

Measure	*Year*	*CFCs*	*HCFCs*	*HFCs*	*CO_2 equiv*
		(tonnes)	(tonnes)	(tonnes)	($MtCO_2$-eq.)
HFC consumption reduction (2010-2015)	2015	0	0	31,775	36
	2050	0	0	225,950	259
	2100	0	0	352,350	411
Production/Installation improvements	2015	78	14,450	16,700	36
	2050	58	31,700	32,700	68
	2100	47	24,350	26,500	55
End-of-life management options	2015	8,545	16,375	105	52
	2050	64,150	144,650	88,540	540
	2100	137,700	358,300	194,800	1200

Table 9.1 – Comparison of Cumulative Emission Reduction Scenarios by IPCC/TEAP

The saving identified in Table 9.1 also includes the incremental component of greenhouse gas emission savings that would accrue from the future mitigation HFC emissions. This highlights once more the importance of linkages between programmes. In this instance, actions taken to mitigate the emissions of ODSs will also have a favourable impact on those related solely to greenhouse gases. Such effects should be factored in to any overall environmental assessment and may also influence any related cost-effectiveness considerations.

Environmental impacts and other unintended consequences are covered in Chapter 6. It is clear that poorly implemented end-of-life management programmes can do more short-term damage than 'leave alone' options and therefore management strategies need to be thought through carefully. Impacts related to Recovery and Destruction Efficiency (RDE) need particularly careful consideration, as does the potential for unintended emission of halogenated by-products when emission reduction units on incinerators are unknowingly overloaded.

9.4 Societal consequences

Again, the societal consequences of wider environmental impacts are beyond the scope of this report. However, for the specific matter of ozone depletion, the impact of future ODS emission (in excess of 900,000 tonnes for CFC-11 alone) on ozone recovery and human health needs to be considered. As mentioned at the end of Chapter 4, the timing of blowing agent releases may influence both the recovery of the ozone layer and its influence on human health, requiring the Effects Assessment Panel to also be involved in any evaluation of potential consequences. Whether emission savings in excess of 150,000 tonnes would have significant impacts on ozone layer recovery and hence on human health would be a further facet of such an evaluation.

Juxtaposed against the potential environmental and human health benefits of bank management are the costs. Even at the lowest level of cost for the recovery of blowing agent at the end of life ($25/kg), the cost of recovery of 150,000 tonnes of blowing agent would be $3.75 billion. Although, if spread equally across a period of perhaps 90 years, the annualised investment figure would drop below $50 million globally. This figure would need to be offset against any healthcare savings that could result from emission abatement measures at end-of-life.

9.5 Specific industry consequences

Although the primary contribution of industry groups was (and is) in the early elimination of ODS dependency for newly produced products, these same groups are now recognising that they can assist Governments in identifying the technical and economic potential of recovery and destruction of ODS. This involvement is spreading across the whole range of products and recovery/destruction technologies. It is sometimes associated with wider recovery and recycling programmes, but the involvement of ODS in potential waste streams has tended to engender specific focus.

In the context that both the Montreal and Kyoto Protocols have been largely ‘no regrets’ agreements, the voluntary contribution of industry to assist in technology development and implementation has been matched by Governments’ willingness to fund specific technology transitions and ‘clean-up’. A clear example of this has been the Multilateral Fund established to support transitions in developing countries. As attention has moved to the end-of-life phase, Governments have, so far, largely followed the same approach. The cost of management of domestic refrigeration has either been met from general Government tax revenue or, in some cases (e.g. Japan) through specific consumer levies. If similar approaches can be assured for the buildings sector, it would seem that there would be no barrier to the proactive involvement of the building products manufacturers, in conjunction with the waste management industry, to develop and demonstrate the methods required to maximise recovery of blowing agents from products manufactured historically.

Parties may wish to consider how co-operative activity in this area between all relevant stakeholders could be encouraged.

CHAPTER 10

10.0 CONCLUSIONS

This review of foam end-of-life issues has led to the following key conclusions:

Technical Feasibility

- The increasing focus on the potential for emission reduction through end-of-life measures has led to a greater study of technical options in the past three years and more information is now available.

- A review of the Montreal Protocol technology approval process for blowing agent recovery and destruction suggests that a new parameter, Recovery & Destruction Efficiency (RDE) would be valuable to accommodate the whole recovery and destruction chain and overcome the limitations of both DRE and DE in respect of foams. Parties may wish to consider whether this would make an appropriate basis for re-defining Approved Technologies for foams.

- All currently practiced recovery and destruction processes have the potential to reach an RDE of greater than 90% and a level of this order (e.g. 85%) could be considered as a new minimum standard for determining Approved Technologies in the foams sector.

- Laboratory evidence continues to emerge for anaerobic degradation of ODSs, which could be applicable in the landfill environment. However, it is not clear whether the process occurs to any extent in normal landfills or whether it would require specific landfill management techniques (managed attenuation).

- Optimisation of anaerobic conditions in the laboratory can create high levels of degradation. However, further work would be required on the identification of breakdown products to confirm that no new health or environmental impact are likely to be created inadvertently

- In view of the nature of landfilling processes, there is unlikely to be any circumstance in which the managed attenuation would become an Approved Technology. However, the technology could be highly beneficial in dealing with foamed products already in landfills and those for which no economically viable Approved Technology exists.

Economic Considerations

- The economics of recovery and destruction are greatly affected by the need to manually segregate foams from other components. The most cost-effective options are those mechanical recovery and direct incineration processes which avoid the need to segregate.

- The most demanding requirements for segregation (e.g. traditional building demolition wastes) occur in developed countries where the costs of labour are likely to be at their highest.

- In general, manual segregation can only be avoided where metals or plastics are the other primary component. This is the case for domestic appliances and steel faced panels. Mixed demolition waste will virtually always need to be segregated.

- The most cost-effective of all processes is the incineration of steel faced panels in steel-making furnaces where the steel is immediately recycled and the foam provides energy. Recent work suggests that emissions from this process can be managed without problem, even with the presence of plastisol coatings on the steel. However, the breadth of application of this approach depends on the geographic availability of such furnaces. . Steel plants remain very sensitive to high chlorine feed concentrations and these need to be managed.

- Direct incineration using other technologies (e.g. Municipal Solid Waste Incinerators) will normally require segregation of foams unless the feedstock is sufficiently diluted to avoid build-up of incineration residues. Care also needs to be taken to ensure that emissions of halogenated bi-products do not exceed concentration limits.

- Mechanical recovery methods work well with appliances and steel faced panels. Blowing agents can currently be recovered from appliances at a net cost of $25-40/kg. However, work is on-going to establish the full costs of recovery from steel-faced panels.

- The costs of transport can also be a significant factor in the recovery of blowing agents. Indeed, in developing countries, the lack of appropriate supporting infrastructure (e.g. road networks) can negate the value of otherwise viable investments in recovery and destruction facilities. Even in developed countries, cost of transport to recovery and destruction facilities is a factor because of the wide distribution of use and low density of building foams.

- The Montreal Protocol is not alone in seeking to manage the end-of-life recovery and destruction of chemicals. There are similar drivers in both the POPs Treaty and the Kyoto Protocol. An opportunity therefore exists to explore possible cost-sharing mechanisms and other shared drivers.

Environmental Potential

- Existing banks of CFCs and HCFCs are estimated to be in excess of 1.5 million and 0.75 million tonnes respectively. Efforts to corroborate these estimates from bottom-up analysis (e.g. JTCCM and others) have confirmed broad agreement at country-level.

- Emission factors from banks continue to be under review. This is an on-going process requiring the identification of other emissive sources in order to align with observed atmospheric concentrations. In general, foams are among the slowest emitting product groups. This means that opportunities for bank management are maximised, but, if unmanaged, emissions are spread over a very long period.

- Several of the banks are already situated in landfills. In developed countries, over 60% of the domestic refrigerators using CFC-11 were already disposed of by 2003. Accordingly, managed attenuation of blowing agents in landfills would be the only available emission reduction option in many cases.

- Managed attenuation in landfills may also be the only practical option available for many foams currently in buildings unless segregation methods can be improved. Experience with the management of foams in buildings is currently limited, partly because of the longevity of many foam products which have yet to reach end-of-life.

- Published assessments carried out for the IPCC/TEAP Special Report on the inter-relationship between ozone depletion and climate change suggested that cumulative ODS emission reductions in excess of 190,000 ODP tonnes could be achieved by 2100 using appropriate end-of-life management techniques. This does not take into account potential contributions from managed attenuation.

- In the foam sector, there could be incremental environmental benefits accruing from reductions in HFC emissions at end-of-life, through the continued use of equipment originally deployed to manage ODSs at end-of-life.

APPENDIX A - DECISION OF PARTIES (RELEVANT TO ODS RECOVERY & DESTRUCTION)

The Parties of the Protocol have taken a number of decisions that need to be mentioned here. Decision I/12F gave a clarification of the definition of a destruction process. Decision IV/11 approved a number of destruction technologies, which were listed in an Annex (Annex VII to the Meeting Report of the 4th Meeting of the Parties). Decision V/26 and VII/35 added "municipal solid waste incinerators" and "radio frequency plasma destruction" to the list of approved technologies. Decision XII/8, taken in 2000, contains the request of the Parties to establish a Task Force on Destruction Technologies and to report on all new developments in the field of destruction technologies for ODS.

The text of the Decisions and the Annex to the Meeting Report of the Fourth Meeting in 1992 are given below.

Decision I/12F: Clarification of terms and definitions: Destruction

The *First Meeting of the Parties* decided in *Dec.I/12F* with regard to destruction:

(a) to agree to the following clarification of the definition of Article 1, paragraph 5 of the Protocol: "a destruction process is one which, when applied to controlled substances, results in the permanent transformation, or decomposition of all or a significant portion of such substances";

(b) to request the Panel for Technical Assessment to address this subject for the Parties to return to it at its second and subsequent meetings with a view to determining whether it would be necessary to have a Standing Technical Committee to review and recommend for approval by the Parties methods for transformation or decomposition and to determine the amount of controlled substances that are transformed or decomposed by each method.

Decision II/11: Destruction technologies

The *Second Meeting of the Parties* decided in *Dec.II/11* with regard to destruction technologies to establish an *Ad Hoc* Technical Advisory Committee on Destruction Technologies and to appoint its Chairman, who shall appoint in consultation with the Secretariat up to nine other members on the basis of nomination by Parties. The members shall be experts on destruction technologies and selected with due reference to equitable geographical distribution. The Committee shall analyse destruction technologies and assess their efficiency and environmental acceptability and develop approval criteria and measurements. The Committee shall report regularly to meetings of the Parties.

Decision III/10: Destruction technologies

The *Third Meeting of the Parties* decided in *Dec.III/10* to note the constitution of the *Ad Hoc* Technical Advisory Committee on Destruction Technologies, established by the Second Meeting of the Parties, and to request the Committee to submit a report to the Secretariat for presentation to the Fourth Meeting of the Parties, in 1992 at least four months before the date set for that meeting;

Decision IV/11: Destruction technologies

The *Fourth Meeting of the Parties* decided in *Dec.IV/11:*

1. to note the report of the *Ad Hoc* Technical Advisory Committee on Destruction Technologies and, in particular, the recommendations contained therein;
2. to approve, for the purposes of paragraph 5 of Article 1 of the Protocol, those destruction technologies that are listed in Annex VI to the report on the work of the Fourth Meeting of the Parties which are operated in accordance with the suggested minimum standards identified in Annex VII to the report of the Fourth Meeting of the Parties unless similar standards currently exist domestically; *[see Section 2.4 in this Handbook]*
3. to call on each Party that operates, or plans to operate, facilities for the destruction of ozone-depleting substances:
   (a) to ensure that its destruction facilities are operated in accordance with the Code of Good Housekeeping Procedures set out in section 5.5 of the report of the *Ad Hoc* Technical Advisory Committee on Destruction Technologies, unless similar procedures currently exist domestically; and
   (b) for the purposes of paragraph 5 of Article 1 of the Protocol, to provide each year, in its report under Article 7 of the Protocol, statistical data on the actual quantities of ozone-depleting substances it has destroyed, calculated on the basis of the destruction efficiency of the facility employed;
4. to clarify that the definition of destruction efficiency relates to the input and output of the destruction process itself, not to the destruction facility as a whole;
5. to request the Technology and Economic Assessment Panel, drawing on expertise as necessary:
   (a) to reassess ozone-depleting substances destruction capacities;
   (b) to evaluate emerging technology submissions;
   (c) to prepare recommendations for consideration by the Parties to the Montreal Protocol at their annual Meeting;
   (d) to examine means to increase the number of such destruction facilities and making available the utilization to developing countries which do not own or are unable to operate such facilities;
6. to list in Annex VI to the report on the work of the Fourth Meeting of the Parties approved destruction technologies; *[see Section Destruction Procedures]*
7. to facilitate access and transfer of approved destruction technologies in accordance with Article 10 of the Protocol, together with provision for financial support under Article 10 of the Protocol for Parties operating under paragraph 1 of Article 5.

Decision V/26: Destruction Technologies

The *Fifth Meeting of the Parties* decided in *Dec.V/26,* further to decision IV/11 on destruction technologies*:*

(a) That there shall be added to the list of approved destruction technologies, which was set out in Annex VI to the report of the work of the Fourth Meeting of the Parties *[see Section 2.4 in this Handbook]*, the following technology:
    Municipal solid waste incinerators (for foams containing ozone-depleting substances);

(b) To specify that pilot-scale as well as demonstration-scale destruction technologies should be operated in accordance with the suggested minimum standards identified in Annex VII to the report of the Fourth Meeting of the Parties *[see Section 2.4 in this Handbook]* unless similar standards currently exist domestically.

Decision VII/35: Destruction technology

The *Seventh Meeting of the Parties* decided in *Dec.VII/35:*

1. To note that the Technology and Economic Assessment Panel examined the results of testing and verified that the "radio frequency plasma destruction" technology of Japan meets the suggested minimum emission standards that were approved by the Parties at their Fourth Meeting for destruction technologies;
2. To approve, for the purposes of paragraph 5 of Article 1 of the Protocol, the radio frequency plasma destruction technology and to add it to the list of destruction technologies already approved by the Parties.

Decision XII/8: Disposal of controlled substances

The *Twelfth Meeting of the Parties* decided in *Dec. XII/8:*

Noting decisions II/11, III/10, IV/11, V/26 and VII/35 on destruction technologies and the previous work of the Ad Hoc Technical Advisory Committee on Destruction Technologies;

Also noting the innovations that have taken place in the field of destruction technologies since the last report of Advisory Committee;

Recognizing that the management of contaminated and surplus ozone-depleting substances would benefit from further information on destruction technologies and an evaluation of disposal options;

1. To request the Technology and Economic Assessment Panel to establish a task force on destruction technologies;
2. That the task force on destruction technologies shall:
   (a) Report to the Parties at their Fourteenth Meeting in 2002 on the status of destruction technologies of ozone-depleting substances, including an assessment of their environmental and economic performance, as well as their commercial viability;
   (b) When presenting its first report, include a recommendation on when additional reports would be appropriate;
   (c) Review existing criteria for the approval of destruction facilities, as provided for in section 2.4 of the Handbook for the International Treaties for the Protection of the Ozone Layer;
3. To request the Technology and Economic Assessment Panel:
   (a) To evaluate the technical and economic feasibility for the long-term management of contaminated and surplus ozone-depleting substances in Article 5 and non-Article 5 countries, including options such as long-term storage, transport, collection, reclamation and disposal of such ozone-depleting substances;
   (b) To consider possible linkages to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal and other international treaties as appropriate regarding the issue of disposal;
   (c) To report to the Parties on these issues at their Fourteenth Meeting in 2002.

Decision XIV/6: Status of destruction technologies of ozone-depleting substances, including an assessment of their environmental and economic performance, as well as their commercial viability

The *Fourteenth Meeting of the Parties* decided in *Dec. XIV/6:*

1. To note with appreciation the Report of the Task Force on Destruction Technologies presented to the twenty-second meeting of the Open-ended Working Group;

2. To note that the Task Force has determined that the destruction technologies listed in paragraph 3 of this decision meet the suggested minimum emission standards that were approved by the Parties at their Fourth Meeting;

3. To approve the following destruction technologies for the purposes of paragraph 5 of Article 1 of the Protocol, in addition to the technologies listed in annex VI to the report of the Fourth Meeting and modified by decisions V/26 and VII/35:

(a) For CFC, HCFC and halons: argon plasma arc;

(b) For CFC and HCFC: nitrogen plasma arc, microwave plasma, gas phase catalytic dehalogenation and super-heated steam reactor;

(c) For foam containing ODS: rotary kiln incinerator;

4. To request the Technology and Economic Assessment Panel to update, in time for consideration by the twenty-third Open-ended Working Group, the Code of Good Housekeeping to provide guidance on practices and measures that could be used to ensure that during the operation of the approved destruction technologies, environmental release of ODS through all media and environmental impact of those technologies is minimized;

5. To consider, at the twenty-fourth meeting of the Open-ended Working Group, the need to review the status of destruction technologies in 2005, including an assessment of their environmental and economic performance, as well as their commercial viability.

APPENDIX B - DEFINITIONS AND ABBREVATION

Definitions

Attenuation – A decrease in the intensity or magnitude of a process. In this instance, a decrease in the process of emission (particularly from landfill)

Approved Technology - Any destruction technology approved by the Parties to the Montreal Protocol for destruction of ODS.

Blowing Agent - A liquefied gas, a volatile liquid, or a chemical that during the foaming process generates gas. The gas creates bubbles or cells in the plastic structure of a foam.

By-product - A chemical substance produces without specific commercial intent during the manufacturing or processing of another chemical substance or mixture.

Chlorofluorocarbon (CFC) – A family of organic chemicals composed of chlorine, fluorine and carbon atoms, usually characterized by high stability contributing to a high ODP. These fully halogenated substances were commonly used in refrigeration, foam blowing, aerosols, sterilants, solvent cleaning and a variety of other applications. CFCs have the potential to destroy ozone in the stratosphere.

Commercially Available – A technology that is viable, available on an industrial scale, and not significantly limited in capacity by any factor or combination of factors.

Destruction Process - Any combination of equipment, including piping and instrumentation, that is used to destroy ODS. Included in the process are any add-on or supplementary pollution control equipment required to minimize product and environmental releases.

Destruction Facility - The total activity of process and supplementary operational requirements connected with the receiving of ODS material together with their sampling, storage, handling, preparation, and their destruction via the process(es) itself. The term generally refers to the location on which these activities are sited.

Destruction Technologies - Processes that transform ODS to a non-ODS.

Disposal – The method used to eliminate a substance that will no longer be used for the original purpose for which it was made. The method may include transformation, destruction, or disposal as a hazardous waste if mixed with other substances.

Emerging Technology - Any technology demonstrated in the laboratory, bench, or pilot scale, or any commercial technology developed to destroy other compounds, but not yet proven to be effective at destroying ODS.

Environmental Release - Any release into the environment (multi-media; via air, water, and land). These release streams are commonly referred to as air emissions, wastewater discharges and solid residues.

Existing Technology - Any technology commercially demonstrated to destroy ODS.

Feedstock - ODS used in a chemical process. Any ODS not transformed in the chemical process must go to an approved destruction process in order to be exempt from production. (Feedstock can come directly from an ODS production unit, from a unit in which the ODS is a by-product, or from ODS that is first used in other ways and recovered).

Fugitive Losses - Releases to the environment from miscellaneous sources such as flanges, valve packing, seals, safety devices, etc. Quantities are to be estimated through the use of good engineering practices.

Global Warming Potential (GWP)- The relative contribution of certain substances (greenhouse gases), e.g. carbon dioxide, methane, CFCs, HCFCs and halons, to the global warming effect when the substances are released to the atmosphere by combustion of oil, gas and coal (CO_2), direct emission, leakage from refrigerating plants etc. The standard measure of GWP is relative to carbon dioxide (GWP=1.0), which is consistent with the Intergovernmental Panel on Climate Change (IPCC) indexing approach. The GWP can be given with 20, 100, or 500 years integration time horizon. There is not a complete agreement within the scientific community on what is the proper time horizon, but 100 years is most commonly used.

Greenhouse Gas (GHG) - A gas, such as water vapour, carbon dioxide, methane, CFCs and HCFCs, that absorbs and re-emits infrared radiation, warming the earth's surface and contributing to climate change.

Halocarbon– A compound derived from methane (CH_4) and ethane (C_2H_6), where one or several of the hydrogen atoms are substituted with chlorine (Cl), fluorine (F), and/or bromine (Br). These compounds are so called "partly halogenated halocarbons". When all the hydrogen atoms are substituted the compound is said to be fully halogenated. The ability of halocarbons depleting ozone in the stratosphere is due to their content of chlorine and/or bromine and their chemical stability. Fully halogenated halocarbons have much higher chemical stability (atmospheric lifetime typically 100-500 years) than partly halogenated halocarbons (atmospheric lifetime typically 1-20 years). CFCs, HCFCs and HFCs are examples of halocarbons.

Hydrocarbon (HC) - A chemical compound consisting of one or more carbon atoms surrounded only by hydrogen atoms. Examples of hydrocarbons are propane (C_3H_8, HC-290), propylene (C_3H_6, HC-1270) and butane (C_4H_{10}, HC-600). HCs are commonly used as a substitute for CFCs in aerosol propellants and refrigerant blends. The hydrocarbons have an ODP of zero. Hydrocarbons are volatile organic compounds and their use may be restricted or prohibited in some areas. Although they are used as refrigerants, their highly flammable properties normally restrict their use as low concentration components in refrigerant blends.

Hydrochlorofluorocarbon (HCFC) – A family of chemicals contains hydrogen, chlorine, fluorine and carbon atoms. HCFCs are partly halogenated and have much lower ODP than the CFCs. Examples of HCFC blowing agents are HCFC-141b (CH_3CCl_2F) and HCFC-142b (CH_3CClF_2).

Hydrofluorocarbon (HFC) – A family of chemicals contains one or more carbon atoms surrounded by fluorine and hydrogen atoms. Since no chlorine or bromine is present, HFCs do not deplete the ozone layer. HFCs are widely used as refrigerants and foam blowing agents. Examples of HFC blowing agents are HFC-134a (CF_3CH_2F), HFC-245fa ($CF_3CH_2CHF_2$) and HFC-365mfc ($CF_3CH_2CHF_2CH_3$).

Incineration–See Thermal Oxidation, below.

Incinerator - An engineered device using controlled flame combustion to thermally destroy ODS. Examples of incinerators include rotary kilns, liquid injection incinerators, and high temperature furnaces.

Managed Attenuation – The management of an emission source in such a way as to reduce (attenuate) emissions. In this instance, the design and management of a landfill to minimise, or otherwise restrict emissions from foams already landfilled.

Montreal Protocol – An international agreement limiting the production and consumption of chemicals that deplete the stratospheric ozone layer, including CFCs, Halons, HCFCs, HBFCs, methyl bromide and others. Signed in 1987, the Protocol commits Parties to take measure to protect the ozone layer by freezing, reducing or ending production and consumption of controlled substances. This agreement is the protocol to the Vienna convention. It was developed under the auspices of the United Nations Environment Programme (UNEP) to provide a coordinated response to the global problem of ozone depletion. More than 160 countries have signed the Protocol.

Non-incineration Technologies – Those technologies that destroy ODS without using thermal oxidation (e.g., chemical reaction, UV photolysis) or use processes that break down the chemical bonds of the ODS in an oxygen-free atmosphere.

Ozone-depleting Substance (ODS) – Any substance with an ODP greater than 0 that can deplete the stratospheric ozone layer. Most of ODS are controlled under the Montreal Protocol and its amendments and they include CFCs, HCFCs, halons and methyl bromide.

ODS Production - The amount of controlled substances produced, minus the amount destroyed by technologies to be approved by the Parties and minus the amount entirely used as feedstock in the manufacture of other chemicals. The amount recycled and reused is not to be considered as "production".

ODS Consumption - Production plus imports minus exports of ODS.

Ozone Depletion Potential (ODP) – A relative index indicating the extent to which a chemical product may cause ozone depletion. The reference level of 1 is the potential of CFC-11 and CFC-12 to cause ozone depletion. If a product has an ozone depletion potential of 0.5, a given weight of the product in the atmosphere would, in time, deplete half the ozone that the same weight of CFC-11 would deplete. The ozone depletion potentials are calculated from mathematical models which take into account factors such as the stability of the product, the rate of diffusion, the quantity of depleting atoms per molecule and the effect of ultraviolet light and other radiation on the molecules. The substances implicated generally contain chlorine and bromine.

Particulates - Includes solids and condensable organics (aerosols). Measurable sub-micron particles are included.

Perfluorocarbon (PFC) – A non-ozone depleting chlorinated solvent commonly used in a variety of metal, electronic and precision cleaning applications. There are potential health problems associated with its use, which makes it important to enact strict health and safety measures to prohibit excessive exposure to the chemical.

Plasma Technologies–Those technologies in which the thermal energy to break the chemical bonds of the ODS is provided by a plasma. The plasmas used in the recommended ODS destruction technologies are thermal plasmas, and are at temperatures between 5000 and 30000 Kelvin. The plasma is a mixture of electrons, ions and neutral particles, created by the ionization and heating of a gas through its interaction with a DC or AC electric field, or a radio-frequency or microwave-frequency electromagnetic field. The energy source in plasma technologies is thus electricity rather than combustion as in Thermal Oxidation technologies.

Product Release - Any ODS in the products leaving a destruction facility (e.g. carbon tetrachloride in hydrochloric acid produced by a destruction facility).

QA/QC - Program of quality assurance and quality control to ensure compliance with national regulations on environmental and product releases.

Reclamation – Processing and upgrading of a recovered controlled substance through such mechanisms as filtering, drying, distillation and chemical treatment in order to restore the substance to a specified standard of performance. Chemical analysis is required to determine that appropriate product specifications are met. It often involves processing off-site at a central facility.

Recommended Technology - Any destruction technology recommended by the TFDF for approval by the Parties to the Montreal Protocol for the purpose of destroying ODS.

Recovery – The collection and storage of controlled substances from machinery, equipment, containment vessels, etc., during servicing or prior to disposal without necessarily testing or processing it in any way.

Recycling – Reuse of a recovered controlled substance following a basic cleaning process such as filtering and drying. For refrigerants, recycling normally involves recharge back into equipment and it often occurs "on-site".

Thermal Oxidation–Thermal oxidation (incineration) is a process that ideally converts organic compounds, whether hydrocarbon or oxygenated, to CO_2 and H_2O. Incineration is widely used for the destruction of a wide variety of compounds. There are two main types of incinerators: thermal and catalytic. In thermal incineration, the organic compounds are heated to very high temperatures to oxidize the organic compounds in the gas phase. In catalytic incineration, a catalyst promotes the oxidation reaction on its surface (i.e., solid-gas interface) at lower temperatures by providing alternative reaction pathways that have faster rates than the corresponding gas-phase reactions. A thermal incinerator burns the compounds at very high temperatures, usually in the 750º to 1,000ºC range; catalytic incinerators typically operate between 350º and 500ºC.

Abbreviations

A/C	Air conditioning
CFC	Chlorofluorocarbon
CFC-11	Trichlorofluoromethane
CFC-12	Dichlorodifluoromethane
CFC-115	Chloropentafluoroethane
GHG	Greenhouse gas
GWP	Global Warming Potential
Halon 1211	Bromochlorodifluoromethane
Halon 1301	Bromotrifluoromethane
HBFC	Hydrobromofluorocarbon
HCFC	Hydrochlorofluorocarbon
HCFC-22	Chlorodifluoromethane
HFC	Hydrofluorocarbon
HRAI	Heating, Refrigerating and Air Conditioning Institute
ICFB	Internally Circulated Fluidized Bed
ICRF	Inductively Coupled Radio Frequency
MeBr	Methyl bromide (bromomethane)
MSWI	Municipal solid waste incinerator
NO_x	Nitrogen oxides
ODP	Ozone Depletion Potential

ODS	Ozone-depleting Substance
PCDD	Polychlorinated dibenzo-*para*dioxins
PCDF	Polychlorinated dibenzofurans
PIC	Products of incomplete combustion
PF	Phenolic foam
PFC	Perfluorocarbon
PU	Polyurethane foam
R/R	Recovery and Recycling
R/R/R	Recovery, Recycling, and Reclamation
R-134a	1,1,1,2-tetrafluoroethane
R-502	An azeotropic refrigerant blend of HCFC-22 and CFC-115
ITEQ	International Toxic Equivalence Factor
TDGR	Transportation of Dangerous Goods Regulations
TEAP	The Technology and Economic Assessment Panel of the UNEP
TFCRS	The Task Force on Collection, Recovery and Storage of the UNEP Technology and Economic Assessment Panel
TFDT	The Task Force on Destruction Technologies of the UNEP Technology and Economic Assessment Panel
UNEP	United Nations Environment Programme
XPS	Extruded polystyrene

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