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HFCs and PFCs: Current and Future Supply, Demand and Emissions, plus Emissions of CFCs, HCFCs and Halons

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EXECUTIVE SUMMARY

- Current production capacity for HFCs and PFCs exceeds current demand. There are a number of plants in developed countries and one plant in a developing country. The estimated production capacity for HFC-134a in 2002 was 185,000 tonnes. No published data are available to forecast future production capacity. However, as there are no technical or legal limits to production, it can be assumed that production will continue at a rate necessary to satisfy demand over time, although short-term fluctuations are possible. Future production has therefore been estimated by aggregating sectoral demand.
- Major drivers of demand for HFCs and PFCs include the Montreal Protocol and the expected worldwide increase in disposable income. HCFCs, HFCs and PFCs, together with not-in-kind alternatives, have contributed to the phase-out of CFCs and halons. The Multilateral Fund of the Montreal Protocol has been instrumental in introducing CFC replacements in the markets of the developing countries. Nearly US\$ 130 million has been disbursed to the developing countries for the conversion to HFCs, with another US\$ 250 million being disbursed for the conversion to HCFCs.
- Emissions of CFCs have fallen significantly over the period 1990–2000. HCFC emissions have grown significantly during this period. HFC emissions are also increasing. Demand for HCFCs, and hence emissions, are expected to continue to rise significantly between 2000 and 2015, especially in developing countries. The fall in CFC emissions will not necessarily be accompanied by a directly proportional increase in emissions of HCFCs and HFCs because of the switch to alternatives, improvements in design, containment, and improved recovery and disposal practices.
- Despite the fall in the production of CFCs, the existing bank of CFCs is over 1.1 million tonnes and is therefore a significant source of potential future emissions. Banks of HCFCs and HFCs are being established as use increases. The management of CFC and HCFC banks is not controlled by the Montreal Protocol or taken into account under the United Nations Framework Convention on Climate Change (UNFCCC).
- Byproduct emissions of HFC-23 are expected to rise globally by 60% during this period – especially in developing countries – but these emissions can be significantly reduced with best-practice capture and the destruction of vent gases.
- The estimates of aggregate emissions for the business-as-usual scenario differ from other emission estimates (the IPCC (2000) SRES scenarios, for example), largely as a result of the more detailed analyses of the current applications that have been carried out for the purposes of this report. The SRES scenarios relied mainly on the application of regional economic growth factors to the baseline consumption of individual compounds; furthermore, little distinction was made between annual consumption and annual emission.
- Total direct emissions amount to about 2.5 GtCO₂-eq yr⁻¹ (2.0 GtCO₂-eq yr⁻¹ using SAR/TAR values), which is similar to the estimate derived in Chapter 2 from atmospheric measurements. However, as shown in Table 11.6 and in Figure 2.4, there are significant differences between calculated and observed emissions of individual substances. For CFC-11, HCFC-141b and HCFC-142b in particular, the observations indicate significantly higher emissions but the resolution of these systematic errors, while important and urgent, is outside the scope of this report. The errors affect the results quantitatively, but qualitative conclusions are sound.
- There are opportunities to reduce direct emissions significantly through the global application of best practices and recovery methods, with a reduction potential of about 1.2 GtCO₂-eq yr⁻¹ of direct emissions by 2015, as compared to the business-as-usual scenario. The potential emission reductions involve a broad range of costs: from net zero to US\$300 per tonne of CO₂ equivalent. These estimates are based on a mitigation scenario which assumes the global application of best practices for the use, recovery and destruction of these substances. About 60% of this potential is HFC emission reduction; HCFCs and CFCs contribute about 30% and 10% respectively.
- Recovery, recycling and reclamation, and the destruction of refrigerant not suitable for reprocessing, may reduce emissions by as much as 20%. Licensing and compliance programmes may have a significant impact, with average leakage rates being achievable of less than 5% for stationary equipment and 12% for mobile systems. The costs for units used for recovery and recovery/recycling start at approximately US\$500. Recovery, recycling and reuse costs may be offset by the savings in new refrigerant purchases. The destruction of contaminated and unwanted refrigerant can be achieved for less than US\$3.
- In some sectors, action to reduce indirect emissions (for example, through the improved energy efficiency of appliances) will have a significantly higher impact than focusing exclusively on the chemicals used.

11.1 Introduction

11.1.1 Objectives

This chapter has three major objectives. The first is to produce global estimates for current and future demand by aggregating “bottom-up” sectoral information, and to compare this with information about supply from known chemical production facilities. The second is to compare the associated “bottom-up” sectoral estimates of emissions with the “top-down” estimates derived from observations of atmospheric concentrations of the selected chemical species presented in Chapter 2. The third objective is the identification of the global extent of the opportunity for additional emission reductions through the implementation of additional sectoral measures beyond business as usual. Data have been presented in both metric tonnes and also in CO₂-equivalent-weighted tonnes. These data have been calculated using the global warming potentials that appear in Section 2.5 of this report and also the global warming potentials in the IPCC 2nd and 3rd Assessment Reports (IPCC, 1996, 2001). These SAR and TAR values are those used by parties to the UNFCCC for reporting inventory data and also adopted (Decision 1CP/5) in the Kyoto Protocol¹. Use of these values facilitates a comparison against the regulatory commitments adopted within these agreements.

11.1.2 Structure

Following a brief explanation of the methodology used, the chapter identifies current and planned production facilities for the supply of HFCs, and compares this capacity with estimates of aggregate current demand and emissions (based on the sectoral information provided in Chapters 4 to 10). A comparison is then made between these “bottom-up” emission estimates and the “top-down” observed atmospheric concentrations presented

in Chapter 2. The chapter then discusses the drivers of future demand and supply, and provides estimates of demand and emissions in 2015 under both a business-as-usual and a mitigation scenario. It concludes with a comparison of these estimates with those derived under previous scenarios, and the identification of the aggregate extent of the additional emission reduction opportunities that may be available through the implementation of additional measures.

11.2 Methodology for estimations

In estimating the supply of HFCs and PFCs, the basic assumption is that supply will match demand. In addition, for current production, the aggregate supply of some individual substances can be verified using published capacity and production data. For projections, a check of this kind is not possible. Demand can exceed supply in some circumstances because chemical producers may be unwilling to invest in new plants due to uncertainties resulting from the threat of government regulation. This, in turn, may result in tight supply, which will increase prices and may increase the use of alternatives. If this happens, actual use and emissions of HFCs and PFCs will be lower than projected in this chapter.

Two scenarios have been developed for demand (see Section 11.5), the first one based on business-as-usual assumptions (i.e. that all existing measures, including the Montreal Protocol, will continue and that no new measures will be introduced), and another mitigation scenario based on an increased effort to achieve emission reductions through the global application of current best-practice emission reduction techniques (e.g. containment, recovery, recycling and destruction). The precise assumptions included in the mitigation scenario vary between chapters – and therefore these assumptions are discussed in detail in each of the chapters. Because the Kyoto Protocol does not impose specific emission limitations on a substance-by-substance basis, the entry into force of the Kyoto Protocol does not directly alter either of the scenarios. However, national measures related to fluorocarbons have been included where they have been introduced or announced.

Wherever possible, the “bottom-up” methodology has been used to develop demand and emission estimates; the “top-down” approach often has to rely on a limited number of data points since the substances concerned are often in their early stage of market introduction (see also section 11.4).

11.3 Current supply, demand and emissions situation for HFCs and PFCs, plus emissions for CFCs, HCFCs and halons

11.3.1 Current and planned global supply of HFCs and PFCs – production and number of facilities

From a number of data sources, including UNFCCC, AFEAS and the World Bank, it is possible to make estimates of the global capacities for the production of HFC-134a in different

¹ These GWPs for HFCs, PFCs and SF₆ are the values adopted for the Kyoto Protocol pursuant to paragraph 3 of Article 5 of Decision 1/CP.3 (FCCC/CP/1997/7/Add.1). “3. The global warming potentials used to calculate the carbon dioxide equivalence of anthropogenic emissions by sources and removals by sinks of greenhouse gases listed in Annex A shall be those accepted by the Intergovernmental Panel on Climate Change and agreed upon by the Conference of the Parties at its third session. Based on the work of, inter alia, the Intergovernmental Panel on Climate Change and advice provided by the Subsidiary Body on Scientific and Technological Advice, the Conference of the Parties serving as the meeting of the Parties to this Protocol shall regularly review and, as appropriate, revise the global warming potential of each such greenhouse gas, taking fully into account any relevant decisions by the Conference of the Parties. Any revision to a global warming potential shall apply only to commitments under Article 3 in respect of any commitment period adopted subsequent to that revision.” and Paragraph 3 of Decision 2/CP.3 (FCCC/CP/1997/7/Add.1): “3. Reaffirms that global warming potentials used by Parties should be those provided by the Intergovernmental Panel on Climate Change in its Second Assessment Report (“1995 IPCC GWP values”) based on the effects of the greenhouse gases over a 100-year time horizon, taking into account the inherent and complicated uncertainties involved in global warming potential estimates. In addition, for information purposes only Parties may also use another time horizon, as provided in the Second Assessment Report.”

Table 11.1. Estimated HFC production capacity for HFC-134a (in ktonnes) in 2003 and number of production facilities (in brackets).

| | HFC-134a | HFC-125 | HFC-143a | HFC-23 | HFC-32 | HFC-152a | HFC-227ea | HFC-245fa | HFC-365mfc |
|--------------------|----------|---------|----------|--------|--------|----------|-----------|-----------|------------|
| European Union | 40 (4) | (2) | (2) | | (1) | | | | (1) |
| USA | 100 (4) | (1) | (2) | | (1) | (1) | (1) | (1) | - |
| Japan | 40 (3) | (2) | (1) | | (1) | - | - | - | - |
| Russian Federation | | (1) | (1) | (1) | - | (1) | (2) | - | - |
| China | 5 (1) | | (1) | | (1) | (1) | | | |
| Korea | | | | | (1) | | | | |

regions, and the companies and the number of production facilities that produce the other main HFCs (see Table 11.1 and Figure 11.1). A complicating factor is that, apart from HFC-134a, -125 and -143a, the other individual HFCs are produced by three producers or less. Consequently, the actual production volumes are not publicly available for those substances under anti-trust rules. Moreover, AFEAS data do not cover all producing companies, but only those established in Japan, the EU and the USA. Facilities in China, Korea and the Russian Federation, for example, are not covered under AFEAS.

At present, global capacity just exceeds aggregate demand, since fluorocarbon producers have made investments in anticipation of the likely future needs for, among other substances,

HFCs and PFCs triggered by phase-out under the Montreal Protocol.

There is no available information about supply that enables a forecast of future production capacities for different HFCs or PFCs. However, as there are no technical or legal limits to the production of these chemicals, it has been assumed that production will continue to occur at the rate necessary to satisfy demand, and it has been assumed that construction lead time on the year-to-year availability of product and the perception of potential legislative controls on investors' confidence have no effects. Future production has been estimated by the simple aggregation of sectoral demand projections.

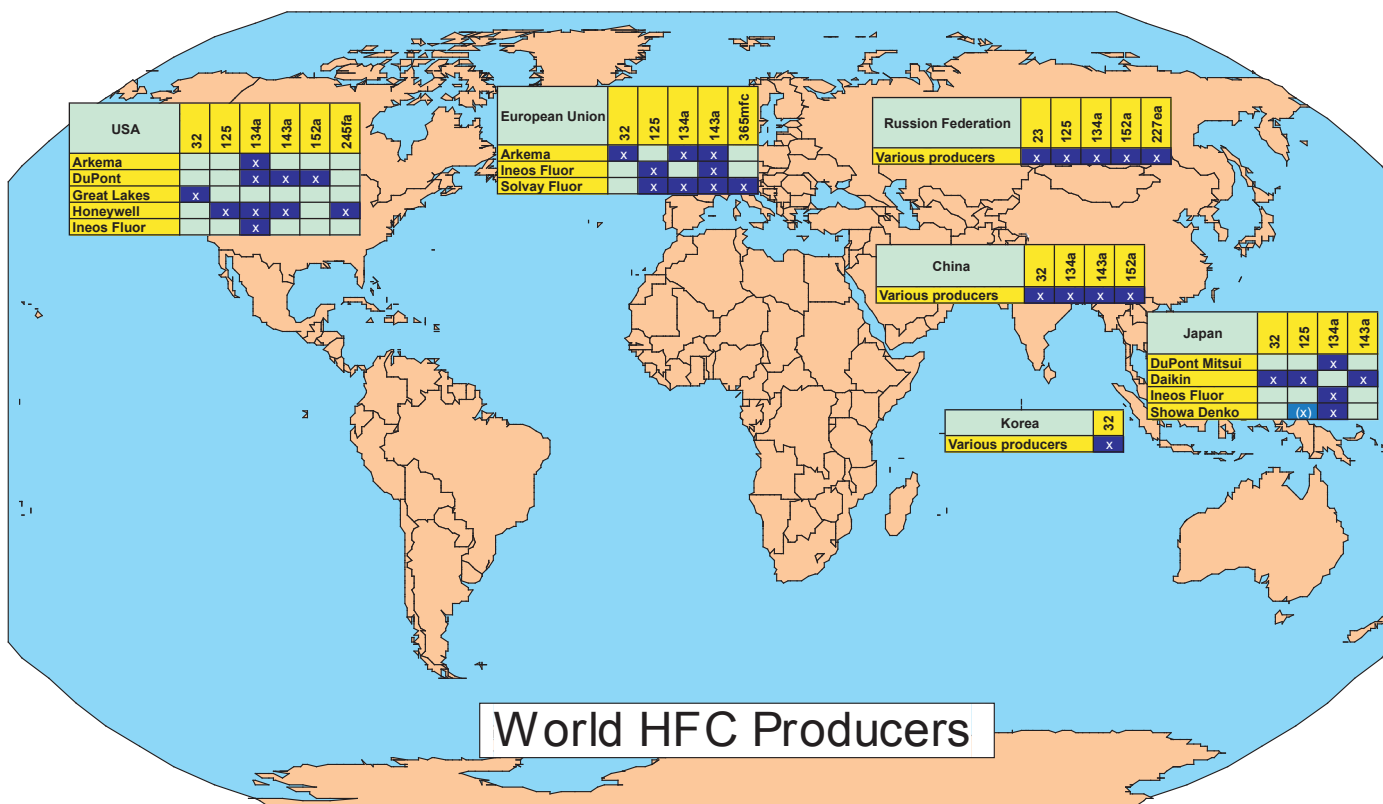
**Figure 11.1.** Global HFC production.

Table 11.2. Demand for CFCs, halons, HCFC

| | 2002 demand | | | | 2015 business-as-usual (BAU) demand | | | | 2015 mitigation scenario (MIT) demand | | | | | | |
|------------------|---|---------------------------------|---|---|-------------------------------------|---|---------------------------------|---|---|---------------------------------|---|---------------------------------|---|---|---------------------------------|
| | Refrige- ration, SAC, MAC ¹ (kt yr ⁻¹) | Foams (kt yr ⁻¹) | Medical aerosols (kt yr ⁻¹) | Fire protec- tion & other ² (kt yr ⁻¹) | Total (kt yr ⁻¹) | Refrige- ration, SAC, MAC ¹ (kt yr ⁻¹) | Foams (kt yr ⁻¹) | Medical aerosols (kt yr ⁻¹) | Fire protec- tion & other ² (kt yr ⁻¹) | Total (kt yr ⁻¹) | Refrige- ration, SAC, MAC ¹ (kt yr ⁻¹) | Foams (kt yr ⁻¹) | Medical aerosols (kt yr ⁻¹) | Fire protec- tion & other ² (kt yr ⁻¹) | Total (kt yr ⁻¹) |
| CFC-11 | 6 | 11 | 3 | 3 | 19 | 2 | 1 | 1 | 1 | 2 | 1 | | | 1 | 1 |
| CFC-12 | 132 | 1 | 5 | 1 | 137 | 8 | 1 | 1 | 1 | 9 | 6 | | | 6 | 6 |
| CFC-113 | | | | | n.a. | | | | | n.a. | | | | | n.a. |
| CFC-114 | | | 0.4 | | 0.4 | | | 0.1 | | 0.1 | | | 0 | | |
| CFC-115 | 12 | | | | 12 | 2 | | | | 2 | 1 | | | 1 | 1 |
| Halon-1211 | | | | 3 | 3 | | | | | | | | | | |
| Halon-1301 | | | | 1 | 1 | | | | | | | | | | |
| HCFC-22 | 346 | 7 | | 0.3 | 353 | 482 | 0.4 | | 0.1 | 482 | | | | 0 | 324 |
| HCFC-123 | 8 | | | 0.2 | 8 | * | * | * | * | 3 | * | * | * | * | 1 |
| HCFC-124 | 3 | | | 0.04 | 3 | * | * | * | * | 1 | * | * | * | * | 1 |
| HCFC-141b | | 97 | | 5 | 102 | 49 | 49 | 10 | 10 | 59 | 49 | | | 10 | 59 |
| HCFC-142b | | 25 | | 6 | 25 | 1 | 1 | 6 | 6 | 1 | 1 | | | 6 | 1 |
| HCFC-225 | | | | 0.1 | 0.1 | * | * | * | * | 0 | * | * | * | * | 0.1 |
| HFC-32 | 3 | | | | 3 | 25 | | | | 25 | | | | | 28 |
| HFC-125 | 23 | | | | 23 | 86 | | | | 86 | | | | | 58 |
| HFC-134a | 133 | 6 | 3 | | 142 | 408 | 27 | 10 | | 446 | 7 | 12 | | 337 | |
| HFC-143a | 28 | | | | 28 | 72 | | | | 72 | | | | 35 | |
| HFC-152a | 1 | 3 | | | 4 | 0.4 | 3 | | | 4 | 2 | | | 2 | |
| HFC-227ea | | 0.1 | 1 | 3 | 4 | * | * | * | * | 7 | * | * | * | 7 | |
| HFC-245fa | | 2 | | | 2 | 32 | 32 | | | 32 | 15 | | | 15 | |
| HFC-236fa | | | | 0.1 | 0.1 | * | * | * | * | 0 | * | * | * | 0.1 | |
| HFC-365mfc | | 0 | | | 0 | 9 | 9 | | | 9 | 5 | | | 5 | |
| HFC-43-10mee | | | | 1 | 1 | | | | 1 | 1 | | | | 1 | |
| Other HFCs | | | | p.m. | p.m. | | | | p.m. | p.m. | | | | p.m. | p.m. |
| PFC-14 | | | | 0 | 0 | * | * | * | * | 0.005 | * | * | * | * | 0 |
| PFC-3-1-10 | | | | 0 | 0 | * | * | * | * | 0.01 | * | * | * | * | 0 |
| PFC-5-1-14 | | | | 0 | 0 | | | | 0.01 | 0.01 | | | | 0 | 0 |
| Per group | | | | | | | | | | | | | | | |
| Halons | | | | 4 | 4 | | | | | 0 | | | | 0 | 0 |
| CFCs | 149 | 11 | 8 | | 169 | 12 | | 2 | | 14 | 8 | | | 8 | 8 |
| HCFCs | 357 | 128 | | 12 | 496 | 485 | 50 | 16 | 16 | 551 | 325 | 50 | 16 | 391 | 391 |
| HFCs | 190 | 11 | 4 | 4 | 209 | 591 | 73 | 13 | 5 | 681 | 440 | 30 | 15 | 5 | 490 |
| PFCs | | | | 0.1 | 0.1 | | | | 0.02 | 0.02 | | | | 0.02 | 0.02 |
| Total | 696 | 150 | 12 | 20 | 877 | 1,087 | 123 | 15 | 21 | 1,246 | 773 | 80 | 15 | 21 | 889 |

* Data not available due to commercial confidentiality of data.

¹ "Refrigeration" comprises "conditioning" (SAC) comprises residential and commercial air conditioning and heating; MAC stands for mobile air-conditioning.² "Other" includes solvents, but excludes non-medical aerosols. Estimates expressed in MtCO₂-eq are available for non-medical aerosols only.

11.3.2 Current demand for HFCs and PFCs

Sectoral demand: past trends and current situation in developed and developing countries

When the Montreal Protocol was signed in 1987, alternatives to CFCs and halons were not commercially available for most applications. By 1989, the first reports of the UNEP Technology Assessment Panels of the Montreal Protocol (UNEP-TEAP, 1989, Chapter 3.10) concluded that, while non-fluorocarbon alternatives including not-in-kind alternatives would be important, HCFCs and HFCs would be necessary in order to make substantial and timely reductions in CFC and halon consumption. In 1990 the Montreal Protocol was amended to require a phase-out of CFCs, halons, carbon tetrachloride and 1,1,1-trichloroethane.

Technical advances subsequently accelerated the commercial availability and use of the new alternatives, including not-in-kind technologies. Consistent with these advances, the Montreal Protocol was further amended in 1992 to require a phase-out of HCFCs. By 1998, the TEAP reports were noting a rapid development of technologies that were no longer reliant on fluorocarbons (UNEP-TEAP, 1998).

Table 11.2 shows the aggregated demand for CFCs, HCFCs and halons, as well as HFCs and PFCs. The data are derived primarily from Ashford *et al.* (2004) and supplemented by data from Chapters 4 – 10 in this report, UNEP (2004b) and AFEAS (2004). These data serve as the baseline for the projections of 2015 demand and emissions in both the business-as-usual and mitigation scenarios.

In the absence of the Montreal Protocol, the use of CFCs would have increased significantly (Prather *et al.*, 1996). However, as a result of its adoption, the use and production of CFCs and halons have almost completely ceased in developed countries (UNEP, 2004b), and are rapidly falling in developing countries, as demanded by the schedule in the protocol. The use of HFCs has facilitated this rapid phase-out in developed countries, particularly (but not solely) in applications where

other alternatives were not available. In many cases, HFCs are still important for the safe and cost-effective phase-out of CFCs and halons in countries with economies in transition and in developing countries (UNEP-TEAP, 2004). Developed countries have replaced about 8% of projected CFC use with HFCs and 12% with HCFCs. They have eliminated the remaining 80% by controlling emissions, making specific use reductions, or by using alternative technologies and non-HCFC and HFC fluids, including ammonia, carbon dioxide, water and not-in-kind options. Approximately 20% of halon use has been replaced by HFCs, less than 1% by PFCs and 50% by non-gaseous agents (UNEP-TEAP, 1999b). Some of the options are shown in Table 11.3.

11.3.3 Current emissions of CFCs, halons, HCFCs, HFCs, and PFCs

Emissions occur during both the production and use of these substances. During production, the emissions are largely inadvertent, whereas emissions arising from use of the substances can be either intentional or inadvertent.

11.3.3.1 Production emissions

Emissions of HFCs and PFCs occur during the production of fluorocarbons, either as undesired byproducts or as losses of useful material, for example during the filling of containers or when production equipment is opened for maintenance. In general, the emissions during production are much smaller than the emissions during the use of the products. Nevertheless, techniques and procedures to minimize emissions have been developed, including the thermal oxidation of gas streams before they are released into the atmosphere. Calculating emissions from such sources requires data about not only the quantities of materials produced (the activity) and the rate of emission (which is influenced by the process design and operating culture) but also about the extent to which emissions are abated. This is particularly important in determining the uncertainty of

Table 11.3. Replacement of CFCs and halons in developed countries (derived from UNEP-TEAP, 2000).

| Application | Replacement rate of CFCs and halons by HCFCs and HFCs | Dominant alternative fluid or technology |
|------------------------------------|---|---|
| Refrigeration and air-conditioning | 30% | Emission reductions (containment, recycle, recovery), hydrocarbons and ammonia, reduced charge size, design improvements (e.g. heat exchangers) |
| Closed-cell foam | <45-50% | hydrocarbons and carbon dioxide |
| Open-cell foam | 15% | water and hydrocarbons |
| Aerosol propellant (not MDIs) | 3% | hydrocarbons and alternative dispensing technologies |
| Fire extinguishants | 20-25% | conservation, water mist, sprinklers, foam, carbon dioxide, inert gases |
| Other (primarily solvents) | 3% | “no-clean technologies”, water-based systems and chlorocarbons |
| All applications | HCFCs 12% HFCs 8% | |

estimates of future emissions. The majority of these estimates are made using standardized tables for emissions that cover valves, joints, pumps and other processing parts.

Byproduct emissions of HFC-23

The most significant of the byproducts is HFC-23 (fluoroform). It is produced during the manufacture of HCFC-22. Global emissions of HFC-23 increased by an estimated 12% between 1990 and 1995, due to a similar increase in the global production of HCFC-22 (see Table 10.10 in Chapter 10, and the description of chemical routes of manufacture in Appendix 11A).

The quantity of HFC-23 that is produced (and that, potentially, may be emitted) is directly related to the production of HCFC-22 and so emission forecasts require a scenario for future HCFC-22 production volumes. These will depend on the consumption of HCFC-22 in developed countries, which is declining, and the consumption in developing countries and global demand for fluoropolymers feedstock, both of which are increasing (see Section 10.4). After thorough investigation, the US EPA concluded that process optimization reduces, but does not eliminate, HFC-23 emissions. To reduce the emissions below the 1% level, thermal oxidation is required (Irving and Branscombe, 2002).

On the basis of a business-as-usual scenario that assumes that consumption of ozone-depleting substances will match the maximum levels permitted under the Montreal Protocol, the consumption and production of non-feedstock HCFC-22 will fall by a factor of almost 10 by 2015 from the average level in 2000-2003 in developed countries (including the 15% production allowance to meet the basic domestic needs of developing countries). In developed countries, demand for fluoropolymer feedstock is projected to continue increasing linearly, leading to a doubling in feedstock demand for HCFC-22 in those countries by 2015 (see Section 10.4). In developing countries, production of HCFC-22 for both feedstock and non-feedstock uses has grown rapidly in recent years; over the period 1997 to 2001, production for potentially emissive (or non-feedstock) uses grew linearly at 20,000 tonnes yr⁻¹ and feedstock use grew at 4,100 tonnes yr⁻¹ (see Chapter 10). Assuming that these rates continue until 2015, the total global requirement for HCFC-22 will be about 707,000 tonnes yr⁻¹, about 40% of which would be for feedstock, compared to a total of 490,000 tonnes yr⁻¹ in the year 2000 (Table 10.10).

In the business-as-usual case prior to 2015, it has been assumed that emissions from existing capacity will continue at 2% of HCFC-22 production (reflecting the average of plants

in developed and developing countries, including current levels of abatement) and that new capacity (mainly in developing countries) will emit HFC-23 at a rate of 4% (see Chapter 10). Consequently, emissions of HFC-23 could grow by 60% between now and 2015, from about 15,000 tonnes yr⁻¹ in 2003 to 23,000 tonnes yr⁻¹ (Table 10.10).

In the variant for this scenario, the current best-practice technology, which includes the capture and thermal oxidation of the “vent gases”, is introduced into all facilities progressively from 2005 onwards. Destruction technology is assumed to be 100% efficient and to operate for 90% of the on-line time of HCFC-22 plants. Reduced emissions were calculated for the same activity (in the form of assumed future HCFC-22 production) as the business-as-usual case. The difference between the two HFC-23 forecasts is therefore solely due to the extent of the deployment of destruction technology. The forecasts represent potential extreme cases, and future changes in activity will tend to increase the probability of one or the other.

The reduction of HCFC-22 production due to market forces or national policies, or improvements in facility design and construction to reduce HFC-23 output, could further influence these scenarios. An additional factor is the possible implementation of Clean Development Mechanism projects to install destruction facilities in non-annex I countries. This could result in a more rapid reduction of HFC-23 emissions than would otherwise have occurred.

11.3.3.2 Emissions arising from use

As noted under 11.3.2, the production and use of CFCs and halons have almost completely ceased in developed countries, and are rapidly falling in developing countries (Ashford *et al.*, 2004). HFCs and HCFCs have replaced about 8% and 12% of projected CFC use respectively in developed countries (UNEP-TEAP, 1999b). Similarly, about 20 % of halon use has been replaced by HFCs and less than 1% by PFCs (UNEP-TEAP, 1999b). The resulting changes in historic emissions of CFCs and HCFCs are shown in Table 11.4 (Ashford *et al.*, 2004).

Despite an equivalent fall in production of CFCs, the bank of material that remains in equipment and has not yet been emitted remains significant. For example, in the year 2002, the CFC bank amounted to over 2.4 million tonnes, consisting mainly of CFC-11 in foams (UNEP-TEAP, 2002ab). In addition to the emissions of CFCs and HCFCs from future consumption in developing countries, it is expected that a substantial proportion of these banks will eventually be released into the atmosphere under a business-as-usual scenario. There are opportunities

Table 11.4. Estimated historic emissions of ozone-depleting substances (tonnes yr⁻¹).

| Year | CFC-11 | CFC-12 | CFC-113 | HCFC-123 | HCFC-124 | HCFC-141b | HCFC-142b | HCFC-22 |
|------|---------|---------|---------|----------|----------|-----------|-----------|---------|
| 1990 | 258,000 | 367,000 | 215,000 | 0 | 0 | 0 | 2,100 | 217,000 |
| 1995 | 106,000 | 256,000 | 28,000 | 2,100 | 1,600 | 25,400 | 9,500 | 252,000 |
| 2000 | 75,000 | 134,000 | 2,700 | 4,200 | 2,900 | 25,600 | 11,100 | 286,000 |

to make significant reductions in these emissions through the global application of best-practice handling and eventual destruction of these gases (UNEP-TEAP, 2002ab).

Tables 11.5a and 11.5b show the development of banks of some fluorocarbons.

Refrigeration, air conditioning (particularly air conditioning in vehicles) and heat pumps are the largest source of emissions of HFCs. In the future, improved design, tighter components, and recovery and recycling during servicing and disposal could reduce HFC emissions at moderate to low costs (see Chapter 6). The impact of improved practices will vary between regions and countries.

Insulating foams are expected to become the second-largest source of HFC emissions, and HFC use is expected to grow rapidly as CFCs and HCFCs are replaced with HFC-134a, HFC-

227ea, HFC-245fa and HFC-365mfc (see Chapter 7). In replacing CFC-11 use in insulating foams in the refrigeration sector, around 66% of the ozone-depleting substances (ODSs) were replaced by hydrocarbons in investment projects approved by the Multilateral Fund of the Montreal Protocol. In non-refrigeration uses, 30% of the ODSs were replaced by hydrocarbons, 25% by HCFCs and 45% by zero-ODP/zero-GWP alternatives (UNEP-TEAP, 1999b, Chapter 24).

Other sources of HFC emissions are industrial-solvent applications, medical aerosol products, other aerosol products, fire protection and non-insulating foams. Increased containment, recovery, destruction and substitution can reduce emissions. In some applications in all these sectors, there are zero- or low-GWP options.

Limited data are available about PFC emissions and use.

Table 11.5a. Evolution of banks (in metric ktonnes).

| 2002 | Banks (ktonnes of substance) | | | | | | | Total |
|--------------|------------------------------|--|-------------------------|--------------|-------------------------------|-----------------|----------------------|--------------|
| | Refrigeration ¹ | Stationary air-conditioning ² | Mobile air-conditioning | Foams | Medical aerosols ⁴ | Fire protection | Other ^{3,4} | |
| Halons | - | - | - | - | - | 167 | - | 167 |
| CFCs | 330 | 84 | 149 | 1,858 | - | - | - | 2,430 |
| HCFCs | 461 | 1,028 | 20 | 1,126 | 8 | 4 | 11 | 2,651 |
| HFCs | 180 | 81 | 249 | 12 | - | 19 | p.m. | 543 |
| PFCs | - | - | - | - | 3.5 | 0.5 | 0.1 | 1 |
| Total | 971 | 1,192 | 418 | 2,996 | | 191 | 11 | 5,791 |

| 2015 Business-as-usual scenario | Banks (ktonnes of substance) | | | | | | | Total |
|---------------------------------|------------------------------|--|-------------------------|--------------|-------------------------------|-----------------|-----------|--------------|
| | Refrigeration | Stationary air-conditioning ² | Mobile air-conditioning | Foams | Medical aerosols ⁴ | Fire protection | Other | |
| Halons | - | - | - | - | - | 43 | - | 43 |
| CFCs | 64 | 27 | 13 | 1,305 | 2 | - | - | 1,411 |
| HCFCs | 891 | 878 | 23 | 1,502 | - | 6 | 16 | 3,317 |
| HFCs | 720 | 951 | 635 | 566 | 13 | 64 | p.m. | 2,949 |
| PFCs | - | - | - | - | - | 1 | 0.01 | 1 |
| Total | 1,675 | 1,856 | 671 | 3,374 | 15 | 114 | 16 | 7,722 |

| 2015 Mitigation scenario | Banks (ktonnes of substance) | | | | | | | Total |
|--------------------------|------------------------------|--|-------------------------|--------------|------------------|-----------------|-----------|--------------|
| | Refrigeration | Stationary air-conditioning ² | Mobile air-conditioning | Foams | Medical aerosols | Fire protection | Other | |
| Halons | - | - | - | - | - | 43 | - | 43 |
| CFCs | 62 | 27 | 13 | 1,305 | 0 | - | - | 1,407 |
| HCFCs | 825 | 644 | 23 | 1,502 | - | 6 | 16 | 3,017 |
| HFCs | 568 | 1,018 | 505 | 443 | 15 | 64 | p.m. | 2,612 |
| PFCs | - | - | - | - | - | 1 | 0.01 | 1 |
| Total | 1,455 | 1,689 | 541 | 3,250 | 15 | 114 | 16 | 7,080 |

¹ "Refrigeration" comprises domestic, commercial, industrial (including food processing and cold storage) and transportation refrigeration.

² "Stationary air-conditioning" comprises residential and commercial air conditioning and heating.

³ "Other" includes solvents, but excludes non-medical aerosols. Estimates expressed in MtCO₂-eq are available for non-medical aerosols only.

⁴ Emissive use applications are assumed to have banks that are equal to annual emissions.

Table 11.5b. Evolution of banks (in MtCO₂-eq).

| 20002 | Banks (MtCO ₂ -eq) | | | | | | | |
|------------------------------------|-------------------------------|--|-------------------------|-----------------------|-------------------------------|------------------|----------------------|------------------------|
| | Refrigeration | Stationary air-conditioning ² | Mobile air-conditioning | Foams | Medical aerosols ⁵ | Fire protection | Other ^{3,5} | Total |
| Halons | | | | | | [531 (391)] | | [531 (391)] |
| CFCs | 3,423 (2,641) | 631 (489) | 1,600 (1,209) | 10,026 (8,008) | 69 (53) | 0 | | 15,749 (12,400) |
| HCFCs | 810 (682) | 1,755 (1,480) | 36 (31) | 1,229 (1,009) | | 5 (5) | 6 (6) | 3,841 (3,212) |
| HFCs | 518 (446) | 123 (111) | 350 (323) | 16 (14) | 6 (6) | 65 (59) | 25 (25) | 1,103 (984) |
| PFCs | | | | | | 4 (3) | 1 (1) | 5 (4) |
| Total⁴ | 4,751 (3,769) | 2,509 (2,079) | 1,987 (1,563) | 11,270 (9,031) | 75 (59) | 74 (67) | 32 (31) | 20,698 (16,600) |
| 2015 Business-as-usual scenario | Banks (MtCO ₂ -eq) | | | | | | | |
| | Refrigeration | Stationary air-conditioning ² | Mobile air-conditioning | Foams | Medical aerosols ⁴ | Fire protection | Other | Total |
| Halons | - | - | - | - | - | [206 (156)] | | [206 (156)] |
| CFCs | 653 (510) | 208 (161) | 138 (104) | 7,286 (5,798) | 17 (13) | 0 | | 8,302 (6,587) |
| HCFCs | 1,582 (1,333) | 1,536 (1,295) | 42 (35) | 1,696 (1,391) | | 6 (5) | 9 (9) | 4,871 (4,068) |
| HFCs | 1,922 (1,661) | 1,488 (1,333) | 896 (826) | 644 (612) | 23 (21) | 226 (204) | 27 (27) | 5,227 (4,683) |
| PFCs | | | | | | 4 (4) | 0.1 (0.1) | 4 (4) |
| Total⁴ | 4,157 (3,504) | 3,232 (2,788) | 1,076 (965) | 9,626 (7,801) | 40 (34) | 236 (212) | 37 (36) | 18,404 (15,341) |
| 2015 Mitigation scenario | Banks (MtCO ₂ -eq) | | | | | | | |
| | Refrigeration | Stationary air-conditioning ² | Mobile air-conditioning | Foams | Medical aerosols ⁴ | Fire protection | Other | Total |
| Halons | - | - | - | - | - | [206 (156)] | | [206 (156)] |
| CFCs | 627 (491) | 208 (160) | 138 (104) | 7,286 (5,798) | 0 | 0 | | 8,258 (6,553) |
| HCFCs | 1,466 (1,235) | 1,134 (956) | 41 (34) | 1,696 (1,391) | | 6 (5) | 9 (9) | 4,352 (3,630) |
| HFCs | 1,455 (1,255) | 1,586 (1,422) | 712 (656) | 494 (471) | 26 (24) | 226 (204) | 27 (27) | 4,527 (4,059) |
| PFCs | | | | | | 4 (4) | 0.1 (0.1) | 4 (4) |
| Total⁴ | 3,548 (2,980) | 2,928 (2,539) | 891 (795) | 9,475 (7,659) | 26 (24) | 236 (212) | 37 (37) | 17,141 (14,247) |

Note: Direct GWPs for a 100-year time horizon were used from IPCC 2001 and WMO 2003 (as listed in Table 2-6). Data in brackets use the direct GWPs for a 100-year time horizon from IPCC 1996 (SAR) and IPCC 2001 (TAR).

¹ "Refrigeration" comprises domestic, commercial, industrial (including food processing and cold storage) and transportation refrigeration.

² "Stationary air-conditioning" comprises residential and commercial air conditioning and heating.

³ "Other" includes non-medical aerosols and solvents.

⁴ Halons cause much larger negative indirect than positive direct radiative forcing and, in the interests of clarity, their positive direct effects are not included in the totals.

⁵ Emissive use applications are assumed to have banks that are equal to annual emissions.

These substances are predominantly used in fire protection and in solvent applications. In the case of fire protection, use is emissive but products remain in the equipment until use once it has been installed and the options for reducing these emissions are therefore limited (see Chapter 9). PFC solvents are no longer considered technically necessary for most applications and use has decreased since the mid-1990s due to replacement with lower-GWP solvents (see Chapter 10).

11.3.4 Comparison of emissions estimated via a bottom-up approach with those calculated from observed atmospheric concentrations of CFCs, HCFCs and HFCs

As noted in Chapter 2, one approach to evaluating the total global emissions of long-lived greenhouse gases uses observations of their atmospheric concentrations. By contrast, Table 11.6 presents the breakdown of direct emissions of each halocarbon for the year 2002, as derived via the bottom-up approach described in Chapters 4 to 10. Total direct emissions amount to

Table 11.6. Emissions for CF

| | 2002 emissions | | | | | | 2015 business-as-usual (BAU) emissions | | | | | | 2015 mitigation scenario (MIT) emissions | | | | | | | | | | |
|---------------------------|-------------------------|---------------------------------|-------------------------|----------------|---|-------------------------|--|---------------|---|-----------|-------------------------|--------------|---|---------------------------------|------------|-------------------------|---|---------------|---------------------------------|-------|------|-----------|------------|
| | Total | | Global Estimate (Ch. 2) | | Total (direct GWP-weighted) (MtCO ₂ -eq yr ⁻¹) | | Total | | Total (direct GWP-weighted) (MtCO ₂ -eq yr ⁻¹) | | Total | | Total (direct GWP-weighted) (MtCO ₂ -eq yr ⁻¹) | | Total | | Total (direct GWP-weighted) (MtCO ₂ -eq yr ⁻¹) | | | | | | |
| | Refr. Etc. ³ | Fire Prot. & Other ⁴ | Aerosols | Foams | Med. Aerosols | Refr. Etc. ³ | Foams | Med. Aerosols | Fire Prot. & Other ⁴ | Total | Refr. Etc. ³ | Foams | Med. Aerosols | Fire Prot. & Other ⁴ | Total | Refr. Etc. ³ | Foams | Med. Aerosols | Fire Prot. & Other ⁴ | Total | | | |
| CFC-11 | 7 | 20 | 3 | 70-90 | 140 | 113 | 3 | 14 | 1 | 19 | 87 | 71 | 2 | 14 | 15 | 71 | 58 | | | | 15 | 71 | 58 |
| CFC-12 | 127 | 2 | 5 | 110-130 | 1,433 | 1,083 | 19 | 2 | 1 | 22 | 235 | 177 | 11 | 2 | 13 | 140 | 105 | | | | 13 | 140 | 105 |
| CFC-113 | | | | 5-12 | 4 | 4 | | | | 0.1 | 1 | 1 | | | | | | | | | | | |
| CFC-114 | | | 0.4 | - | 75 | 74 | 2 | | | 2 | 15 | 15 | | | | | | | | | | | |
| CFC-115 | 10 | | | - | 32 | 23 | | | | 2 | 3 | 2 | | | | | | | | | | | |
| Halon-1211 | | 17 | | 7-8 | 14 | 11 | | | | 2 | 3 | 2 | | | | | | | | | | | |
| Halon-1301 | | 2 | | 1-2 | 411 | 346 | 448 | 1 | | 1 | 9 | 7 | | | | | | | | | | | |
| HCFC-22 | 229 | 2 | 0.1 | 240-260 | 0 | 0 | 6 | 1 | | 0.1 | 449 | 674 | 257 | 1 | 258 | 459 | 387 | | | | 0.1 | 258 | 459 |
| HCFC-123 | 4 | | 0.04 | - | 2 | 1 | 1 | | | 0.1 | 6 | 0.4 | 2 | | 2 | 0.1 | 0.2 | | | | 0.1 | 2 | 0.1 |
| HCFC-124 | 3 | | 0.01 | - | 14 | 11 | 1 | | | 0.01 | 1 | 0.5 | 0.4 | | 0.01 | 0.3 | 0.2 | | | | 0.01 | 0.4 | 0.3 |
| HCFC-141b | | 14 | 5 | 55-58 | 19 | 15 | | 17 | 10 | 10 | 27 | 16 | 14 | 14 | 24 | 17 | 14 | | | | 10 | 24 | 17 |
| HCFC-142b | | 8 | | 25 | 19 | 15 | | 3 | | 3 | 6 | 5 | | 3 | 3 | 6 | 5 | | | | | 3 | 6 |
| HCFC-225 | | 6 | | - | 2 | 3 | | | | 6 | 2 | 3 | | | 6 | 2 | 3 | | | | | 6 | 2 |
| HFC-23 | | 14 | | 13 | 195 | 159 | | | | 23 | 332 | 272 | | | 2 | 33 | 27 | | | | | 2 | 33 |
| HFC-32 | 1 | | | - | 0 | 0 | 10 | | | 10 | 7 | 6 | 8 | | 8 | 5 | 5 | | | | | 8 | 5 |
| HFC-125 | 10 | | | 9-10 | 34 | 28 | 51 | | | 51 | 175 | 142 | 23 | | 23 | 81 | 66 | | | | | 23 | 81 |
| HFC-134a | 74 | 2 | 3 | 96-98 | 111 | 102 | 249 | 8 | | 8 | 376 | 347 | 105 | 3 | 120 | 169 | 156 | | | | | 120 | 169 |
| HFC-143a | 15 | | | - | 65 | 56 | 49 | 3 | | 49 | 215 | 186 | 19 | | 19 | 82 | 71 | | | | | 19 | 82 |
| HFC-152a | 1 | | | 21-22 | 1 | 1 | 0.4 | | | 4 | 0.5 | 1 | 0.2 | | 2 | 0.3 | 0.3 | | | | | 2 | 0.3 |
| HFC-227ea | | 0.01 | 1 | - | 3 | 3 | | 0.2 | 3 | 1 | 4 | 12 | 11 | 0.2 | 4 | 13 | 12 | | | | | 4 | 13 |
| HFC-245fa | | 0.2 | | - | 0.2 | 0.1 | | 5 | | 5 | 5 | 5 | 3 | | 3 | 3 | 3 | | | | | 3 | 3 |
| HFC-236fa | | | 0.02 | - | 0.2 | 0.1 | | | | 0.05 | 0.5 | 0.3 | | | 0.05 | 0.5 | 0.3 | | | | | 0.05 | 0.5 |
| HFC-365mfc | | 0.1 | | - | 0.1 | 0.1 | | 2 | | 2 | 1 | 2 | | 1 | 1 | 1 | 1 | | | | | 1 | 1 |
| HFC-43-10mee | | | | - | 2 | 1 | | | | 1 | 2 | 1 | | 1 | 1 | 2 | 1 | | | | | 1 | 2 |
| Other HFCs | | | | - | 23 | 23 | | | | p.m. | 26 | 26 | | | p.m. | 26 | 26 | | | | | p.m. | 26 |
| PFC-14 | | | 0.001 | - | 0.005 | 0.005 | | | | 0 | 0.002 | 0.01 | | | 0 | 0.002 | 0.01 | | | | | 0 | 0.002 |
| PFC-3-1-10 | | | 0.01 | - | 0.1 | 0.1 | | | | 0 | 0.01 | 0.1 | | | 0 | 0.01 | 0.1 | | | | | 0 | 0.01 |
| PFC-5-1-14 | | | 0.10 | - | 1 | 1 | | | | 0 | 0.01 | 0.1 | | | 0 | 0.01 | 0.1 | | | | | 0 | 0.01 |
| Per group | | | | | | | | | | | | | | | | | | | | | | | |
| Halons⁵ | | | | 8-10 | [47] | [34] | | | | 3 | 3 | [12] | | | 3 | 3 | [12] | | | | | 3 | 3 |
| CFCs | 144 | 22 | 8 | 185-232 | 1,651 | 1,274 | 25 | 16 | 2 | 43 | 338 | 264 | 14 | 15 | 30 | 221 | 173 | | | | | 30 | 221 |
| HCFCs | 236 | 24 | | 310-333 | 447 | 377 | 455 | 21 | | 16 | 492 | 699 | 259 | 17 | 292 | 484 | 408 | | | | | 16 | 292 |
| HFCs | 100 | 5 | 4 | 133-137 | 434 | 374 | 359 | 18 | 13 | 25 | 415 | 999 | 155 | 9 | 184 | 416 | 369 | | | | | 4 | 184 |
| PFCs | | | 0.1 | - | 1 | 1 | | | | 0.02 | 0.02 | 0.2 | | | 0.02 | 0.2 | 0.2 | | | | | 0.02 | 0.2 |
| Total¹ | 481 | 51 | 12 | 652-728 | 2,534 | 2,026 | 838 | 55 | 15 | 44 | 953 | 1,961 | 429 | 42 | 509 | 1,121 | 951 | | | | | 24 | 509 |

¹ A: Direct GWPs for a 100-year time horizon were used from IPCC 2001 and WMO 2003 (as listed in Table 2-6)

² B: Direct GWPs for this column were taken from the Intergovernmental Panel on Climate Change Second Assessment Report (SAR) (Climate Change 1995: The Science of Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.), Cambridge University Press, Cambridge, UK, 1996). Where no value was published in the SAR, the value was taken from Scientific Assessment of Ozone Depletion: 1998, World Meteorological Organisation Global Ozone research and Monitoring Project report No. 44, Geneva, 1999).

³ "Refr. Etc." comprises refrigeration, stationary air-conditioning (SAC) and mobile air-conditioning (MAC) (see Table 11.2)

⁴ "Other": i. These are included in the columns "Total (direct GWP-weighted)".

⁵ Halons cause much larger negative indirect than positive direct radiative forcing and, in the interests of clarity, their positive direct effects are not included in the totals in the columns A and B.

Table 11.7. Estimated historic emissions of HFCs (tonnes yr⁻¹).

| Year | HFC-125 | HFC-134a | HFC-143a | HFC-152a | HFC-227ea | HFC-245fa | HFC-32 | HFC-365mfc |
|------|---------|----------|----------|----------|-----------|-----------|--------|------------|
| 1990 | 0 | 180 | 0 | 12 | 0 | 0 | 0 | 0 |
| 1995 | 200 | 17,500 | 1,110 | 7,340 | 100 | 0 | 0 | 0 |
| 2000 | 5,150 | 73,700 | 9,180 | 15,200 | 1,950 | 0 | 230 | 0 |

about 2.5 GtCO₂-eq yr⁻¹ (2.0 GtCO₂-eq yr⁻¹ using SAR/TAR values), which is similar to the estimate derived in Chapter 2 from atmospheric measurements. However, as shown in Table 11.6 and in Figure 2.4, there are significant differences for individual substances between calculated and observed emissions, notably for CFC-11, HCFC-141b and HCFC-142b. The possible reasons for such differences are examined in Appendix 11B, together with suggestions for further work in this area that could clarify the sources. The lack of information on use patterns for these substances makes it difficult to assess the contribution to observed emissions from current production and use.

The differences between emissions estimates constitute a long-standing problem that has yet to be resolved by the research community. Nevertheless, qualitative conclusions can be drawn for all gases and for some gases, notably the HFCs, atmospheric concentrations match emissions estimates and quantitative conclusions are justified. Current CFC emissions are dominated by delayed releases from banks (such as material contained in existing foams, air conditioning, refrigeration, and other applications). Calculating the magnitude of these emissions is therefore a complicated process requiring massive amounts of data and there is significant scope for systematic error. Observations of the changes in concentrations of CFCs can

provide direct insights into their emissions. The observed rates of change differ among CFCs, depending mainly upon the gas lifetimes and emissions (see Chapter 2). The concentrations of some CFCs have peaked and a slow decline is now being observed, while others are expected to decline in the future. CFC-11 concentrations are decreasing about 60% slower than they would in the absence of emissions, while CFC-12 has only now stabilized. These changes show that CFC-12 emissions, largely from the banks, remain similar in magnitude to the quantities of these gases that are naturally destroyed in the atmosphere.

Table 11.7 shows the historical emissions arising from the use of HFCs, as derived from production and sales data, and sector-specific emission factors. For HFC-134a, these concur well with measured atmospheric concentrations where known. For example, Figure 11.2 compares concentrations of HFC-134a measured at Mace Head, Ireland with northern hemispherical concentrations calculated from the emission data.

The good historic match for HFC-134a is found for emissions calculated using both top-down methodology (as in Table 11.7) and bottom-up methods (that rely on sector-specific activities and emission functions).

The EDGAR database contains other historical data for 1990 and 1995 (<http://arch.rivm.nl/env/int/coredata/edgar/>). This database relies on calculations described in Olivier (2002) and Olivier and Berdowski (2001). Although the values quoted for emissions of HFC-134a and HFC-23 agree with the data used in this chapter, those for HFC-125, -143a, -152a and -227ea are markedly different. The lack of exact information about production volumes (see 11.3.1) introduces major uncertainties with regard to top-down estimates of the future emissions based on those data.

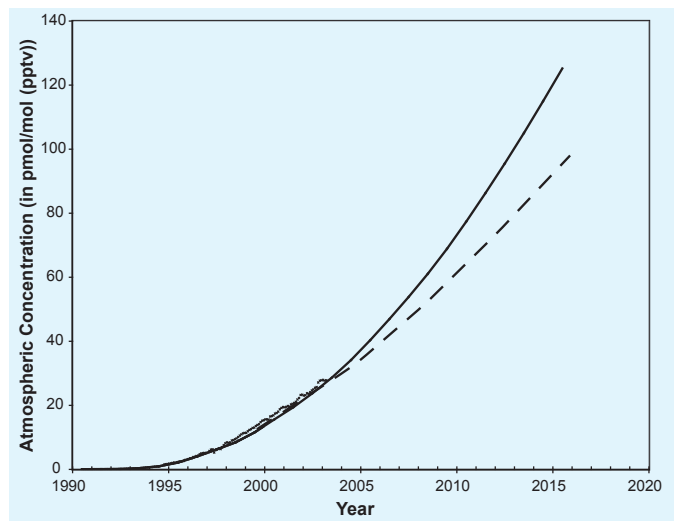


Figure 11.2. Comparison of measured HFC-134a concentrations at Mace Head, Ireland (crosses) with concentrations calculated from emissions (solid line: historic data and BAU scenario for the future; dashed line: reduced emissions). The future trends are simply illustrative. (The scenarios are described in Ashford *et al.* (2004)).

11.4 Discussion of demand drivers, including differentiation between developed and developing countries

11.4.1 Demand drivers for HFCs and PFCs

By far the most important factor in the demand for HFCs and to a lesser extent PFCs has been the adoption of the Montreal Protocol and the subsequent amendments to it. Moreover, a number of developed countries have accelerated the phase-out of ozone-depleting substances under the Montreal Protocol, thus providing extra impetus for demand. These substitution effects have been discussed extensively in the previous chapters.

Perhaps the single most important demand factor after the

implementation of the Montreal Protocol is the expected increase in disposable income in the developing world and the acquisition by families of more than one appliance of the same kind, as noted in various chapters above. In the next decade, hundreds of millions of families can be expected to pass the wealth threshold enabling them to purchase products that may contain or be manufactured with HFCs or PFCs. As noted in SRES, world population growth and GDP growth are also major factors in future global demand for HFCs and PFCs.

Other factors that are expected to have a positive impact on demand for HFCs and PFCs are:

- energy efficiency requirements which may in some cases encourage the use of fluids with superior thermodynamic properties or insulation values;
- safety requirements (including standards) which exclude the use of flammable or toxic substances or fluids with very high operating pressures;
- other environmental legislation, e.g. VOC rules that set a ceiling on emissions, or that prohibit their use in particular applications;
- especially in the USA, product liability concerns encourage the use of HFCs rather than flammable or toxic substances;
- in the mobile air-conditioning sector, the primary replacement for CFC-12 is HFC-134a. There has been a steep rise in the use of these systems in Europe and developing countries in recent years and this is predicted to continue;
- financial mechanisms that enable the compliance of developing countries and of countries with economies in transi-

tion under the Multilateral Fund of the Montreal Protocol and the Global Environment Facility respectively have had a positive impact on demand for HFCs, but this impact may decline in the future. A number of the projects that were supported by these mechanisms converted CFCs to HCFCs and HFCs.

Other developments may reduce demand:

- in the context of their commitments under the Kyoto Protocol, some countries have adopted legislation restricting the use of fluorinated greenhouse gases in some applications;
- the establishment of a recovery, recycling, reclamation and destruction infrastructure for ozone-depleting substances will prove useful for HFCs and PFCs as well, thus reducing demand for virgin material;
- because of their complex chemistry, HFCs and PFCs tend to be an order of magnitude more expensive than ozone-depleting substances, thus further encouraging recovery/reuse and the switch to not-in-kind technology;
- intellectual property rights for particular uses may equally encourage the switch to not-in-kind technology;
- other countries tax these gases according to their global warming potential and/or require their recovery when equipment is serviced or disposed;
- awareness among the governments and public in general of the linkages between ozone layer protection and climate change and impacts of HFCs/PFCs on the climate system

Box 11.1 The Multilateral Fund of the Montreal Protocol

The Multilateral Fund of the Montreal Protocol funded projects totalling approximately US\$ 130 million that have contributed to the replacement of nearly 13,000 tonnes per year of CFCs by HFC-134a in developing countries (10,000 tonnes of conversion under these projects has already been completed). This represents approximately 30% of the CFCs phased out in the refrigeration sector under the Multilateral Fund. Most (99%) of the replacement by HFCs is in the refrigeration sector, in other words chillers, commercial refrigeration, compressors, domestic refrigeration and mobile air-conditioning. The remaining introduction of HFCs was in the solvents, aerosols and foam sectors. The introduction of HFC-152a and R-404A as replacements for CFCs in developing countries has been minimal.

The Multilateral Fund has also supported projects in developing countries totalling nearly US\$ 250 million for the replacement of approximately 32,000 tonnes per year of CFCs by HCFCs (20,000 tonnes of conversion under these projects has already been completed). Eighty-five percent of this replacement has involved HCFC-141b (majority of which in the foam sector) and the remainder HCFC-22 in the refrigeration sector.

The Multilateral Fund has provided incremental costs for the shut-down of CFC production facilities in developing countries. The flexibility provided has enabled China, for example, to use part of the funds to establish the small-scale production of HFC-134a.

There is no inventory system for GEF-funded projects in CEITs that enables a clear determination of the overall share of ODS replacement by HCFCs and HFCs.

(Calculations based on information in UNEP (2004a).)

as a result of the decisions in the Conference of the Parties (Climate Convention)/ Meeting of the Parties.

The impact of technology is more uncertain. During the phase-out of ozone-depleting substances, many industries had significant technical hurdles to overcome, as described in previous chapters. This has led, in many cases, to the introduction of new technology and has significantly reduced equipment leakage rates through improved containment. Furthermore, energy efficiency has improved in many cases. Consequently, energy use and associated indirect emissions have grown less than they would have otherwise.

11.4.2 Discussion of drivers of supply for HFCs and PFCs

Drivers that will influence the business-as-usual scenario for the supply of HFCs and PFCs include the impact of current and anticipated policies and measures (including impact on demand), mitigation options, the economics of manufacturing HFCs and PFCs (both direct and indirect), technological change, supply capacity, and the timing and nature of the transition from ozone-depleting substances.

As indicated above, the basic assumption is that supply will follow demand. Individual manufacturers will make their own assessment of the market potential (=demand) and take investment decisions accordingly. In doing so, several considerations will be taken into account:

- the manufacture of HFCs and PFCs is increasingly complex and often surrounded by measures for protecting intellectual property;
- using existing infrastructures (HCFC plants, for example) will reduce the required capital expenditure and construction time;
- economies of scale are more important for HFCs because of the large capital investment required for these plants due to their complexity (see appendix 1A);
- the reluctance of downstream users to be dependent on a single source of supply;
- access to, and the availability of, key raw materials are gaining importance;
- new recovery and reclamation requirements will result to some extent (albeit an uncertain extent) in a switch away from newly produced substances;
- uncertainties relating to future policies and measures for greenhouse gases will add a risk premium to the minimum acceptable rate of return;
- the disposal of carbon tetrachloride co-generated from chloromethane plants may drive some producers in developing countries to use this product to start the manufacture of HFC-245fa and HFC-365mfc;
- producers of HFCs/PFCs may not make investment decisions due to uncertainties about the future of HFCs/PFCs arising out of the assessments and also due to impending regulations at the national, regional and global levels.

As a result, investments are likely to be made in existing sites and the number of production sites can be expected to remain limited. Greenfield investment will most likely occur in regions with substantial market potential, particularly China. Equally, supply can be expected to follow demand more closely than has been the case for CFCs and HCFCs. The perceived regulatory risks, and the existence of valid process patents, may discourage the conversion of current production facilities for ozone-depleting substances in developing countries to HFC and PFC production (with the latter being less likely). Furthermore, due to the complexity of the processes, most production facilities for ozone-depleting substances are not easily convertible to HFC production.

With CFCs phased out in developed countries, the production of HFCs and PFCs for supply is now focused upon maintaining the existing market, satisfying market growth, exports to other markets and developing capacity to cater for the demand for replacing HCFCs. Rapidly expanding markets in developing countries, in particular for CFC replacements, are resulting in new capacity for fluorinated gases, currently through the expansion of HCFC-22 and -141b capacity. Much of this is being achieved through local production in developing countries and joint ventures.

11.4.3 Impact of recovery, recycling and reclamation of CFCs, HCFCs, halons and HFCs

11.4.3.1 Current situation

Emissions may be reduced by cutting back on demand and destroying refrigerant at end of life. Demand may be reduced by the reuse of refrigerant affected by recovery programmes, and the prevention of leakage and losses through improved work practices and higher standards. These measures may be voluntary or mandatory and experience indicates that a co-regulatory approach, and cooperation between industry and governments resulting in mutually agreed regulation, provide a genuine and sustainable reduction in emissions.

Recovery, recycling and reclamation take place on a number of levels in developed countries. In many developed countries and regions – Australia, the European Union, United States and Japan for example – there are regulatory requirements that mandate the removal of “used” fluorinated gases from equipment during dismantling and destruction, and/or regulations that prohibit the venting of fluorinated gases. These requirements have been extended, or are in the process of being extended, to include HFCs and PFCs (Snelson and Bouma, 2003). In certain regions, the regulatory requirements are supported by industry voluntary schemes. In developing countries, UNEP has launched initiatives to encourage the recovery and recycling of CFCs and HCFCs although, at present, these have not been extended to HFCs and PFCs (UNEP, 2003).

Product stewardship schemes have been established by industry and governments in numerous countries to take back, and either reclaim or destroy, recovered refrigerant. These schemes may provide incentives for technicians to recover and return

refrigerant, although the potential to charge for the service exists.

Current recovery and reuse practices include: service companies and technicians recovering and reinstalling used fluorinated refrigerants; major users (supermarkets, buildings etc.) recovering and reinstalling fluorinated gases in their own plant; large distributors of fluorinated gases collecting and either recycling or reclaiming fluorinated gases for resale; and producers of the fluorinated gases recovering and reusing refrigerants, sometimes as feedstock. In the EU, where used refrigerants are classed as “hazardous waste”, transportation is a costly bureaucratic process that acts as a disincentive, particularly when the used refrigerants must be moved across national borders. In the EU, it is mandatory to destroy recovered CFCs under Regulation 2037/2000.

Similar recovery, recycling and reclamation processes take place in the fire-fighting industry. For the foam industry, the recovery of the foam products during the dismantling of foam-containing equipment and buildings is possible and, in some developed countries, mandatory. Fluorinated gases that are recovered will primarily be sent for destruction, as the presence of contaminants makes recycling and reuse non-economic. In the case of solvent use, recycling is an integral part of the process in which they are used: the solvents are boiled constantly in the equipment in which they are used and the vapour is condensed and reused. Solvents are also recovered from equipment and recycled externally from that equipment; this work is mainly done by the user of the solvent. Once the solvent reaches a level of contamination where recycling is not possible, it is destroyed. During the manufacture of metered dose inhalers, fluorinated gases are captured during the filling process and recycled in the filling equipment, thereby reducing emissions. Recycling of fluorinated gases externally is not often seen as an option because of contamination with pharmaceutical residues.

As a result of the majority of recovery, recycling and reclamation being carried out either on the premises of the user of the fluorinated gases or by independent distributors of the gases, there is only limited information on which to base estimates of the quantities of gases recovered, recycled or reclaimed. The cost of the gases is a major driver for recovery, recycling and reclamation, and some countries – notably Australia, the Netherlands and Norway – have a system that encourages the return of gases through a payment (or equivalent compensation) based upon quantity and quality.

11.4.3.2 Future opportunities

Recovery and reuse or destruction are important components of emission reduction. Whilst it is difficult to assess the volume of refrigerant that may be recovered, there has been some quantification work. A survey undertaken by Refrigerant Reclaim Australia (RRA) (Bennett, 2001) suggests that the equivalent of 25% of refrigerant sales may be recovered in any given year. The amount of recovered refrigerant recycled, reclaimed or destroyed translates directly to an equivalent reduction in demand and emissions. The survey indicated that the equivalent of 20%

of sales may be recovered from service and maintenance applications, and that the equivalent of 5% of sales may be recovered from decommissioned plants.

The RRA study, which included two hundred direct interviews with service companies, sought to establish a picture of the applications for new refrigerant first in order to ascertain the potential for recovery. Figure 11.3 shows the uses for new refrigerant.

The quantification project used the methodology outlined in Figure 11.3. Essentially, this process tracks imported product through the sales and application chain to determine the amount of product that may be returned. A number of the data points in the graphic were determined through research and survey work. The balance of required information was collected through surveys of contractors.

Figure 11.4 displays the applications using purchased new refrigerants. These results refer only to refrigerant sold to contractors and not refrigerant purchased by original equipment manufacturers (OEMs).

The results from the survey indicate that only about 20% of new refrigerant applications, retrofitting and contaminations lead to the controlled recovery of existing refrigerant.

The other application from which installed refrigerant is recovered is the decommissioning of existing aged plants. Industry experience indicates that approximately 5% of sales of new refrigerant are recovered annually from decommissioned plants. This figure does not include domestic refrigeration and air conditioning, as coordinated recovery and recycling programmes for electrical goods have not commenced in Australia as yet.

The second section of the survey looked at the processes contractors and technicians applied to the refrigerant they recovered. The responses can be found in Figure 11.5.

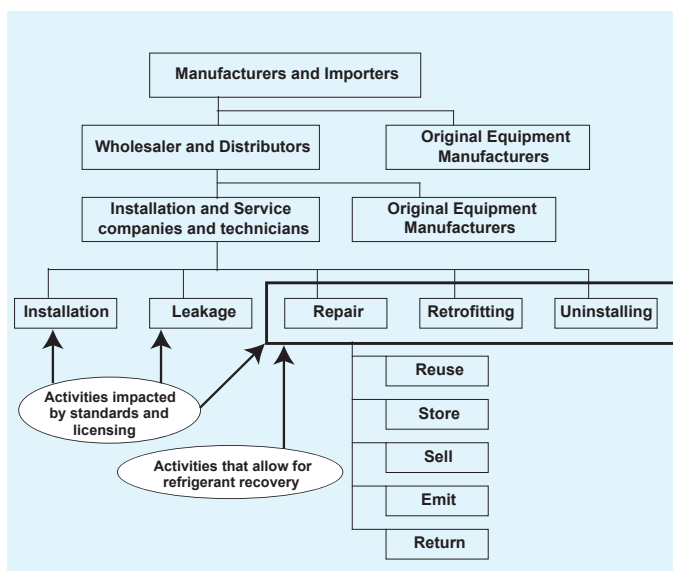


Figure 11.3. Estimating refrigerant recovery and reuse potentials: methodology of a survey in Australia (Bennett, 2001).

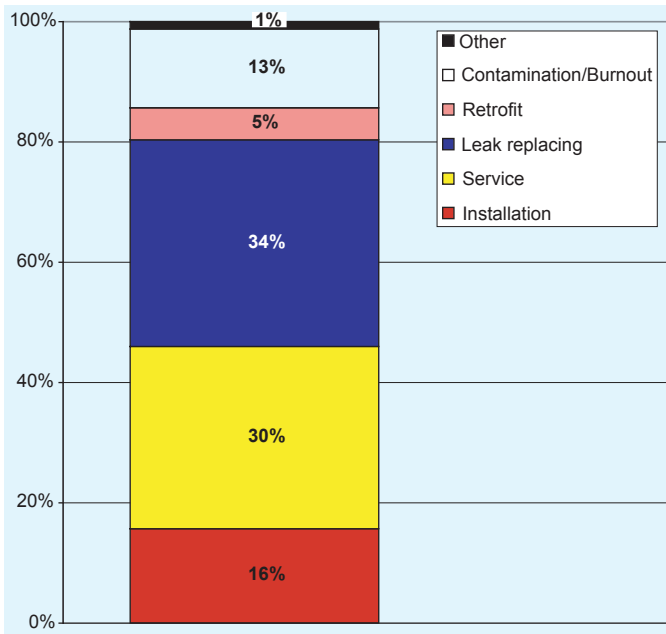


Figure 11.4. Applications to which purchased new refrigerants are applied: results of a survey by Refrigerant Reclaim Australia (Bennett, 2001).

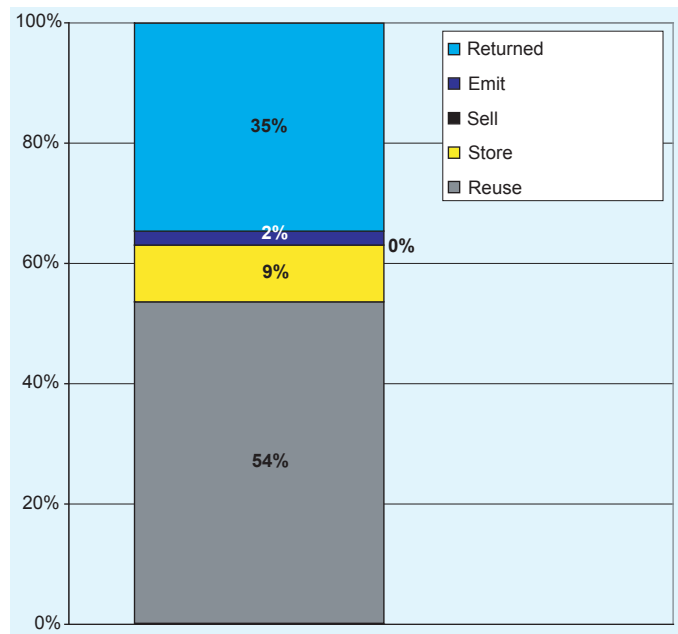


Figure 11.5. Destiny of recovered refrigerants: results of a survey by Refrigerant Reclaim Australia (Bennett, 2001).

The results are as follows:

- **Reuse/Store:** Approximately 63% of all refrigerant recovered was recycled and reused or stored by contractors for later use. This is an encouraging result, as recycling was not an activity undertaken by the industry in Australia only some years before. This activity impacts directly on emission levels by reducing the volume of refrigerant being imported.
- **Emit/Sell:** A very small percentage of contractors admitted to contravening the law by emitting refrigerant or selling impure recovered refrigerant.
- **Returned:** Contractors indicated that approximately 35% of all refrigerant recovered was returned to RRA for safe disposal.

The key results are firstly that a volume equivalent to 25% of sales of new refrigerant may be recovered in any year, and secondly that approximately 35% of the amount recovered – about 9% – may be expected to be returned for destruction.

Impact of financial incentives on recovered volumes

The impact of financial incentives on the volume of refrigerant recovered and returned may be significant. In early 2003, RRA doubled the financial incentive paid to service companies for returned refrigerant. This measure, in conjunction with promotional and information programmes highlighting the environmental and financial benefits of recovery, produced an increase of more than 50% of refrigerant returned to RRA (RRA Annual Report, 2004), see Figure 11.6.

Other financial incentives

Some countries tax imports and/or sales of HFC and PFCs, thereby increasing their price and encouraging reuse. Norway and Denmark use taxation based on the global warming potential of the refrigerant (Chapter 4), and then provide a rebate for

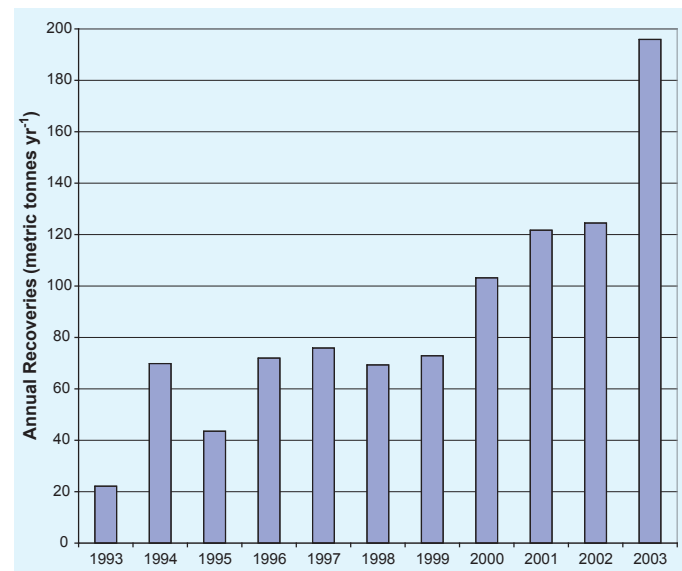


Figure 11.6. Impact of financial incentives on recovered volumes of refrigerants: doubling the financial incentive paid to service companies for returned refrigerant in 2003 in Australia resulted in an increase of more than 50% of refrigerant returned (RRA, 2004).

the return of recovered refrigerant. In the Netherlands, a subsidy of 50% on the cost of collection and destruction of halons and CFCs was provided to discourage venting.

Whilst there are no comparative studies of programmes available, logic and general behaviour would suggest that programmes that provide financial incentives, such as payments for return, will perform better compared to those that charge for the return of recovered refrigerant.

Funding of recovery programmes

There are numerous methods for funding refrigerant recovery programmes (Snelson and Bouma, 2003). In general, the ultimate user of the refrigerant, the equipment owner, will bear the cost in accordance with the polluter-pays principle. Where there is government funding (USA) and joint government and industry funding (Japan), the most common method of funding is the application of an industry-wide levy on sales of new refrigerant.

A good example is Australia, where a levy of Australian \$1.00 (0.78 US\$) per kilogramme was applied in 1993 (Bennett, 2001). The collected funds are held in a special purpose trust. Initially, the levy applied only to ozone-depleting refrigerants but it was extended in 2004 to “synthetic greenhouse gas” refrigerants to fund the expansion of the recovery programme to take back those products. Anti-trust issues were managed through application to, and approval from, the Australian Competition Commission. An industry-wide levy has numerous advantages, including cost sharing as a result of the contribution from all of industry, guaranteed revenue over the long term, and the flexibility to allow for increased recovery and subsequent costs.

Licensing, accreditation and standards

Improvements in technical standards and their conscientious application will result in significant reductions in direct and indirect emissions. The application of technical standards can be effectively achieved within a licensing or accreditation programme. The benefits of such programmes are: improved standards of workmanship; more efficient installations; lower leakage rates; improved and more regular maintenance practices; and increased rates of recovery, recycling, reuse and safe disposal. It should be noted that a common element of successful licensing schemes is a robust compliance programme.

The two best-known programmes of this type are the KMO programme in Denmark, and the STEK programme in the Netherlands. In the Netherlands, emissions have been significantly reduced through national mandatory regulations established in 1992 for CFCs, HCFCs, and HFCs, assisted by an industry-supported certification model. STEK is the abbreviation for the institution that certifies practices for installation companies in the refrigeration business. Elements of the regulation are detailed by Van Gerwen and Verwoerd (1998). They include, among other requirements, technical requirements to improve tightness, system commissioning to include pressure and leakage tests, refrigerant record keeping, periodic system inspections for leak tightness, maintenance and installation work by

certified companies and servicing personnel.

The success of the Dutch regulations and the STEK organization in reducing refrigerant emissions was demonstrated with results from a detailed study in 1999 of emission data from the refrigeration and air-conditioning sectors. For commercial refrigeration, annual refrigerant emissions (emissions during leakage plus disposal) were 3.2% of the total bank of refrigerant contained in this sector (Hoogen *et al.*, 2002). The overall loss rate from stationary equipment has been reduced to less than 5%, whilst the loss rate for automotive air conditioning has been reduced to less than 12%.

Influence of associated product-stewardship programmes

Product-stewardship programmes, sometimes known as producer responsibility, have been established in numerous countries for a range of products that contain refrigerants and foam agents. The best examples are the WEEE and EOL Vehicle Directives in Europe, and the Japanese Appliance and Recycling Act. The recovery and recycling of refrigerators, air-conditioning units and motor vehicles provides for the extraction of refrigerant from systems, and also for the recovery of the blowing agent from foam. In Japan, where 1,800 tonnes of fluorocarbons were recovered in 2003, electrical goods and automotive recycling programmes contributed 1,000 tonnes (RRC, 2003).

Foam

It is uncertain whether recovery, recycling or reclamation of the actual fluorinated gases from foam products will increase in the future and thereby have a substantial impact on emissions. For CFC-11, recovery from foams is discouraged by the chemical's low market value and by laws requiring the destruction of CFCs. For HFCs, recovery may be more attractive due to the higher market values of the chemicals. Even if the chemicals are not recovered, however, a major abatement option will be the recovery of used foam products and their subsequent destruction. Either destruction or chemical recovery could substantially reduce emissions of CFCs, HCFCs and HFCs from the banks in foams (see Table 7.10).

11.4.4 Destruction technologies and capacities

11.4.4.1 Current situation

The decomposition or destruction of ozone-depleting substances, HFCs and PFCs can be achieved using various technologies. The commercially available and successfully demonstrated technologies are listed by region in Table 11.8. A more detailed overview of destruction technologies and capabilities can be found in Appendix 11C.

The costs for recovery and recovery/recycling units start at approximately US\$ 500 per unit. Recovery, recycling and reuse costs may be offset by the savings in new refrigerant purchases. Contaminated and unwanted refrigerant can be destroyed for less than US\$ 3 per kilogramme.

At the present time, the quantities of fluorinated gases destroyed by the techniques described above are extremely low;

Table 11.8. Commercially available destruction technologies by region.

| Region | Country | Technology | Capacity |
|---------------|--------------------|------------------------------|--|
| Australasia | Australia | Argon plasma | 60 kg/hr fluorocarbons 120 kg/hr halons |
| Europe | France | Reactor cracking | 200 kg/hr fluorocarbons |
| | Germany | Reactor cracking | 200 kg/hr fluorocarbons |
| | Denmark | Incineration | |
| | Norway | Cement kiln | |
| | Switzerland | Rotary kiln | |
| | Russian Federation | Plasma chemical incineration | |
| North America | Canada | Rotary kiln | |
| | United States | Reactor cracking | |
| | | Gas/fume oxidation | |
| | | Rotary kiln | |
| | | Cement kiln | |
| | | ICRF plasma | |
| Asia | Japan | Gas/fume oxidation | 165 kg/hr fluorocarbons |
| | | ICRF plasma | |
| | | Rotary kiln | |
| | | Cement kiln | |
| | | Liquid injection | |

potentially, they do not exceed a few thousand tonnes. In the European Union, the EU Regulation mandates the destruction of CFCs following their recovery; this also applies to foam insulation when recovered from dismantled equipment. Similarly, CFCs recovered from refrigeration and air-conditioning equipment must also be destroyed.

The different technologies involve varying costs, effluents and emissions, energy usage, and destruction efficiencies.

11.4.4.2 Future opportunities

Considerable scope exists to increase the quantities of CFCs, HCFCs, HFCs and PFCs recovered and then destroyed at the end of their useful life. This particularly applies to the quantities that are “banked” in foam insulation products. Recovery and destruction could have a substantial impact on emissions of the fluorinated gases. Further work is required to estimate whether the current number of destruction facilities globally could cope with the quantities of fluorinated gases recovered and destroyed. Another concern would apply to regions and countries where destruction facilities do not exist and where transport regulations for hazardous wastes prevent their transfer to such facilities in other countries.

11.5 Scenarios for 2015

11.5.1 Business-as-usual projections

The previous chapters have developed business-as-usual (BAU) projections for the use and emissions of CFCs, HCFCs, HFCs

and some PFCs (where these are used as replacements for ozone-depleting substances). These projections have assumed that all existing measures will remain in place, including the Montreal Protocol (phase-out) and relevant national regulations. It is also assumed that the usual practices and emission rates will remain unchanged up to 2015 and that recovery efficiency will not increase. In order to facilitate the calculations of emissions, estimates have been made of the size of the bank of ozone-depleting substance and fluorinated gases in equipment and applications in 2002. Table 11.9 summarizes the key assumptions of the business-as-usual projections.

The activities underlying emissions of fluorocarbons are expected to expand significantly between now and 2015. These activities (such as the requirements for refrigeration, air conditioning and insulation) will involve a number of technologies, including CFCs and HCFCs. In industrialized countries, the use and emissions of CFCs and HCFCs will decline as obsolete equipment is retired. In developing countries, ozone-depleting substances (particularly HCFCs) may be used for most of the first half of this century and significant growth is expected. These changes, and their impacts as developed by previous chapters, are reflected in the data in Table 11.2 (demand), 11.5 (banks), and 11.6 (emissions).

The fall in CFC emissions is not accompanied by a similar increase in emissions of HFCs because of continuing trends towards non-HFC technology and substitutes with lower GWPs. Additional factors not included in the BAU scenario are the capture and safe disposal of materials that would historically have been emitted. The business-as-usual case assumes the

Table 11.9. Key assumptions in the business-as-usual (BAU) and mitigation (MIT) scenarios.

| Sector | Annual market growth 2002-2015 (both in BAU and MIT) ¹ (% yr ⁻¹) | | | | Best-practice assumptions | | | | | | | | |
|------------------------------|--|---------------------------|-----------------------------|--|---------------------------|---|---|---|---|--|--|----------------------|--|
| | EU % yr ⁻¹ | USA % yr ⁻¹ | Japan % yr ⁻¹ | DCs ¹ % yr ⁻¹ | Type of reduction | EU MIT | | USA MIT | | Japan MIT | | BAU | DCs ¹ MIT |
| Refrigeration SAC and MAC | | | | | | | | | | | | | |
| Domestic refrigeration | 1 | 2.2 | 1.6 | 2-4.8 | Substance | HFC-134a / HC-600a | HFC-134a / HC-600a (50%) | HFC-134a / HC-600a (50%) | HFC-134a / HC-600a (50%) | HFC-134a | HC-600a | CFC-12 / HFC-134a | Plus HC- 600a (50% in 2010) |
| Commercial refrigeration | 1.8 | 2.7 | 1.8 | 2.6-5.2 | Recovery | 0% | 80% | 80% | 80% | 0% | 80% | 0% | 50% |
| | | | | | Substance | R-404A / R-410A | R-404A / R-410A (50%) | R-404A / R-410A (50%) | R-404A / R-410A (50%) | HCFC / R-404A | R-404A / R-410A (50%) | CFC / HCFC | R-404A / R-410A (50%) |
| Industrial refrigeration | 1 | 1 | 1 | 3.6-4 | Recovery | 50% | 90% | 90% | 90% | 50% | 90% | 25% | 30% |
| | | | | | Charge | -30% | -30% | -30% | -30% | | | | -10% |
| | | | | | Substance | HFC-NH ₃ (35%) | HFC-NH ₃ (70%) | HFC / HFC-NH ₃ (80%) | HCFC / HFC-NH ₃ (70%) | HCFC / HFC-NH ₃ (35%) | HCFC / HFC-NH ₃ (70%) | CFC / HCFC-22 | NH ₃ (40-70%) |
| Transport refrigeration | 2 | 3 | 1 | 3.3-5.2 | Recovery | 50% | 90% | 90% | 90% | 50% | 90% | 15-25% | 50% |
| | | | | | Charge | -40% | -40% | -40% | -40% | | | | -10% |
| | | | | | Substance | HFCs | HFCs | HCFCs / HFCs | HCFCs / HFCs | HCFCs / HFCs | HCFCs / HFCs | CFC / HCFC-22 | Plus HFCs, up to 30% |
| Stationary AC | 3.8 | 3 | 1 | 5.4-6 | Recovery | 50% | 80% | 80% | 70% | 50% | 70% | 0% | 20-30% |
| | | | | | Substance | HFCs | HFCs | HCFCs / HFCs | HCFCs / HFCs | HCFCs / HFCs | HCFCs / HFCs | CFC / HCFC-22 | CFC / HCFC-22 (HFCs 30% in some DCs) |
| | | | | | Recovery | 50% | 80% | 80% | 80% | 30% | 80% | 0% | 50% |
| | | | | | Charge | -20% | -20% | -20% | -20% | | | | |
| Mobile AC | 4 | 4 | 1 | 6-8 | Substance | HFC-134a / CO ₂ (10%) as of 2008 | HFC-134a / CO ₂ (50%) as of 2008 | HFC-134a / CO ₂ (30%) as of 2008 | HFC-134a / CO ₂ (30%) as of 2008 | HFC-134a | CO ₂ (30%) as of 2008 | CFC / HCFC-134a | CFC / HFC-134a |
| | | | | | Recovery | 50% | 80% | 70% | 70% | 0% | 70% | 0% | 50% |
| | | | | | Charge | 700 g | 500 g | 700 g | 700 g | 750 g | 500 g | 750-900 g | 750-900 g |

Table 11-9 (continued)

| Sector | Annual market growth 2002-2015 (both in BAU and MIT) ¹ (% yr ⁻¹) | Best-practice assumptions |
|-----------------------------|---|--|
| Foams | About 2% yr ⁻¹ | <p>Assumptions on substance use (see Chapter 7)</p> <p>HFC consumption reduction: A linear decrease in use of HCFCs between 2010 and 2015 leading to 50% reduction by 2015.</p> <p>Production / installation improvements: The adoption of production emission reduction strategies from 2005 for all block foams and from 2008 in other foam sub-sectors.</p> <p>End-of-life management options: 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.</p> |
| Medical aerosols | 1.5–3% yr ⁻¹ | <p>BAU MIT</p> <p>Partial phase-out of CFCs Complete phase-out of CFCs</p> |
| Fire protection | –4.5% yr ⁻¹ (all substances) +0.4% yr ⁻¹ (HCFCs/HFCs/PFCs) | <p>BAU MIT</p> <p>Phase-out of halons Not quantifiable</p> |
| HFC-23 byproduct | 2.5% yr ⁻¹ | <p>BAU MIT</p> <p>HFC-23 emissions of existing production capacity: 2% of HCFC-22 production (in kt) HFC-23 emissions of new production capacity: 4% of HCFC-22 production (in kt) 100% implementation of reduction options (90% emission reduction)</p> |
| Non-medical aerosols | 16% increase period in total CO-weighted emissions over 2002–2015 | <p>BAU MIT</p> <p>See Chapter 10 Not quantifiable</p> |

¹ BAU: Business-As-Usual Scenario; MIT: Mitigation Scenario; DCs: developing countries

continuing application of all existing measures and the alternative scenario(s) embody improvements that could be implemented assuming global application of current best-practice emission reduction techniques.

Future emissions from use

Table 11.6 above shows, for the business-as-usual case, the expected future emissions arising from the use of HFCs in all sectors, predominantly refrigeration, foam blowing, solvents and aerosols. Sectoral emission functions that reflect the current levels of containment were applied to the activities projected for these uses so that growth in emissions reflects growth in use. These emissions will be accompanied by significant changes in the banks of fluorocarbons remaining in equipment and not yet released. In the case of HFC-134a, the quantity retained in equipment is expected to increase in this scenario to 2.2 million metric tonnes by 2015 from the 2002 level of 517,000 metric tonnes (Ashford *et al.*, 2004).

Growth was calculated as a projection of current demand patterns and has no connection to the global capability to produce HFCs. The most important of these materials continues to be HFC-134a. However, current production capacity for this material is about 180,000 tonnes yr⁻¹, so that the increase in demand (and therefore emissions) after 2008 cannot be sustained and would require the construction of new plants.

Future atmospheric concentrations of HFC-134a that would result from these emissions (solid line) are indicated in Figure 11.2. In the second scenario (dashed line), the current best practices for containment are implemented in all new equipment, recovery efficiency and the extent of recovery are improved, and the quantities in systems are reduced. This has the effect of reducing the atmospheric concentration (and also the climate impact) in 2015 by some 23% but still requires additional capacity. The projected emissions are given in Table 11.6 as well. In this case, no expansion of current capacity would be needed.

Byproduct emissions of HFC-23

Emissions of HFC-23 from the production of HCFC-22 have significant climate impact. As discussed above, these emissions may be reduced by changes to process procedures or eliminated by thermal oxidation without compromising the ability to produce HCFC-22, which will continue to be required as a fluoropolymer feedstock after its commercial uses have been phased out. The emissions of HFC-23 expected under the business-as-usual case to 2015 are shown in Table 10.10. It has been assumed that emissions from existing capacity (in both developed and developing countries) will continue at 2% of HCFC-22 production and that new capacity (mainly in developing countries) will emit HFC-23 at a rate of 4%. Consequently, emissions of HFC-23 could increase by 60% between now and 2015 from about 15,000 tonnes yr⁻¹ in 2003 to 23,000 tonnes yr⁻¹.

The US EPA (2004) has developed a business-as-usual scenario for HFC-23, projecting emissions of 100 MtCO₂-eq in 2000, 115 MtCO₂-eq in 2010 and 130 MtCO₂-eq in 2020. The

difference between the EPA projections and those in this report is primarily due to EPA's use of a lower emission factor for developing countries (3% instead of 4%).

11.5.2 Mitigation scenario for supply and demand through to 2015

As shown above, previous chapters have identified the potential impact on demand (and supply) under BAU assumptions (i.e. all existing measures continue to be applied). These chapters have also considered the potential impact of the global application of current best-practice emission reduction techniques. The key assumptions of the mitigation scenario are summarized again in Table 11.9, and Tables 11.2, 11.5, and 11.6 present the implications for demand, banks, and emissions.

Byproduct emissions of HFC-23

The alternative scenario for byproduct emissions of HFC-23 assumes that the current best-practice technology, comprising the capture and thermal oxidation of "vent gases", is introduced into all facilities progressively from 2005 onwards. Destruction technology is assumed to be 100% efficient and to operate for 90% of the on-line time of the HCFC-22 plant. Reduced emissions were calculated on the basis of the same level of activity (in the form of assumed future HCFC-22 production) as the business-as-usual case. The difference between the two HFC-23 forecasts is therefore solely due to the extent of deployment of destruction technology. The forecasts represent potential extreme cases and future changes in activity will tend to increase the probability of one forecast or the other.

11.5.3 Comparison with other scenarios

Future global HFC and PFC use and/or emissions as substitutes for ozone-depleting substances have been separately estimated by IPCC (2000), Midgley and McCulloch (1999), McCulloch (2000) and Madronich *et al.* (1999). Midgley and McCulloch (1999) projected carbon-equivalent emissions of HFCs and PFCs (excluding unintended chemical byproduct emissions) at 60 MtC-eq in 2000, 150 MtC-eq in 2010 and 280 MtC-eq in 2020 (220, 550 and 1030 MtCO₂-eq, respectively). Considering that emissions lag behind consumption by many years, the Midgley and McCulloch figures are much larger than the values in Madronich *et al.* This discrepancy is consistent with the Midgley and McCulloch scenario which was constructed to represent plausible upper limits to future emissions (McFarland, 1999).

The Intergovernmental Panel on Climate Change published in its Special Report on Emissions Scenarios (IPCC, 2000), scenarios for emissions of HFCs through to 2100 (Figure 2.9 and Table 11.10). Scenarios are alternative images of how the future might unfold and are used to analyze the effects of different driving forces on emissions outcomes and to allow contingency planning; they are not predictions or projections of future emissions. The emission values contained within the SRES report

Table 11.10. Global anthropogenic emissions (kt) projections for the years 2000, 2010 and 2020 for ODS, HFC and PFC emissions in the four marker scenarios (from SRES, 2000, Table 5-8, and <http://sres.ciesin.org>), and comparison with the 2002 and 2015-BAU results from this report.

| Emissions (kt) | | SRES Marker Scenario | | | | SROC-BAU (This report) |
|--|-------------------------|-------------------------|------------------------|-------------------------|--------------------------|---------------------------|
| | | A1 | A2 | B1 | B2 | |
| 2000 (SRES) / 2002 (SROC) | ODSs | | | 842 | | 569 |
| | HFC-23 | 12.6 | | | | |
| | HFC-134a | 80.0 | | | | |
| | HFCs – Total | 93 | 124 | | | |
| | PFCs – Total | 14 | 0.1 | | | |
| 2010 | ODSs | | | 786 | | |
| | HFC-23 | 14.8 | 14.8 | 14.8 | 14.8 | |
| | HFC-32 | 3.7 | 3.5 | 3.2 | 3.3 | |
| | HFC-43-10 | 7.2 | 6.8 | 6.2 | 6.3 | |
| | HFC-125 | 12.1 | 11.4 | 10.9 | 11.1 | |
| | HFC-134a | 175.7 | 165.8 | 162.9 | 166.4 | |
| | HFC-143a | 9.3 | 8.8 | 8.0 | 8.1 | |
| | HFC-227ea | 13.1 | 11.8 | 13.2 | 13.6 | |
| | HFC-245ca | 62.1 | 58.6 | 59.7 | 61.4 | |
| | HFCs – Total | 298 | 282 | 279 | 285 | |
| | PFCs – Total | 17 | 22 | 16 | 23 | |
| 2015 (interpolation for SRES) | ODSs | | | 519 | | 538 |
| | 2000/2-2015 growth rate | | | (-3% yr ⁻¹) | | (1% yr ⁻¹) |
| | HFCs – Total | 408 | 342 | 340 | 354 | 415 |
| | 2000/2-2015 growth rate | (10% yr ⁻¹) | (9% yr ⁻¹) | (9% yr ⁻¹) | (9% yr ⁻¹) | (10% yr ⁻¹) |
| | PFCs – Total | 20 | 25 | 17 | 26 | 0.02 |
| 2000/2-2015 growth rate | (2% yr ⁻¹) | (4% yr ⁻¹) | (1% yr ⁻¹) | (4% yr ⁻¹) | (-12% yr ⁻¹) | |
| 2020 | ODSs | 253 | | | | |
| | HFC-23 | 4.9 | 4.9 | 4.9 | 4.9 | |
| | HFC-32 | 8.3 | 6.4 | 6.0 | 6.2 | |
| | HFC-43-10 | 8.8 | 7.6 | 6.9 | 7.2 | |
| | HFC-125 | 27.1 | 20.7 | 20.6 | 21.5 | |
| | HFC-134a | 325.5 | 252.2 | 248.8 | 261.9 | |
| | HFC-143a | 20.6 | 16.0 | 15.0 | 15.6 | |
| | HFC-227ea | 22.2 | 16.6 | 18.5 | 19.7 | |
| | HFC-245ca | 100.5 | 78.7 | 80.3 | 85.4 | |
| | HFCs – Total | 518 | 403 | 401 | 422 | |
| | PFCs – Total | 23 | 28 | 17 | 30 | |

are scenarios of potential emissions to the year 2100 assuming that no action is taken to limit emissions based on concerns over climate change. The scenarios are based upon historical market information and expected developments in use and emissions. Projected emissions in SRES are lower than the reported 2015 emissions in the BAU scenario of this report, although annual growth rates are more or less the same (Table 11.11). These differences are the consequence of differences in scenario methodologies and assumptions.

The Mitigation Scenario demonstrates that emission levels can be significantly reduced below those of business as usual leading to reductions of over 200,000 metric tonnes of HFCs (Table 11.11). This clearly demonstrates that potential benefits

could be gained by implementing measures such as improved containment, recovery and recycling and end of life treatment of HFCs. Such measures would reduce the environmental impact of HFCs and PFCs and allow the benefits of their use in many applications (such as energy efficiency, non-flammability etc.) to be maintained.

A paper by Harnisch and Höhne (2002) contains estimates of historic emissions based on atmospheric concentrations. These are consistent with the data in this chapter and in AFEAS (2004) and Madronich *et al.*, 1999. A similar paper on halogenated compounds and climate change (Harnisch *et al.*, 2002) contains graphical estimates of future emissions in which HFC-23 levels are expected to fall markedly (potentially a factor of 5

Table 11.11. Summary of direct emission projections for 2015 for CFCs, halons, HCFCs, HFCs and PFCs.

| | 2015 business-as-usual | | 2015 mitigation scenario | | 2015 reduction potential | |
|---------------------------|-----------------------------|-------------------------------------|-----------------------------|-------------------------------------|-----------------------------|-------------------------------------|
| | ktonnes yr ^{-1 a)} | MtCO ₂ -eq ^{b)} | ktonnes yr ^{-1 a)} | MtCO ₂ -eq ^{b)} | ktonnes yr ^{-1 a)} | MtCO ₂ -eq ^{b)} |
| Halons ^{c)} | 3 | [12 (9)] | 3 | [12 (9)] | - | - |
| CFCs | 43 | 338 (264) | 30 | 221 (173) | 13 | 117 (91) |
| HCFCs | 492 | 828 (699) | 292 | 484 (408) | 200 | 344 (290) |
| HFCs | 415 | 1,153 (999) | 184 | 416 (369) | 231 | 737 (630) |
| PFCs | 0.02 | 0.2 (0.2) | 0.02 | 0.2 (0.2) | - | - |
| Total^{o)} | 953 | 2,319 (1,961) | 509 | 1,121 (951) | 444 | 1,198 (1,011) |

Note: Direct GWPs for a 100-year time horizon were used from IPCC 2001 and WMO 2003 (as listed in Table 2-6). Bracketed data use direct GWPs for a 100-year time horizon from SAR/TAR.

^{a)} Excluding non-medical aerosols.

^{b)} Including non-medical aerosols and solvents.

^{c)} Halons cause much larger negative indirect than positive direct radiative forcing and, in the interests of clarity, their positive direct effects are not included in the totals showing total CO₂-equivalents.

to 10 between 1996 and 2020). This is consistent with the HFC-23 mitigation scenario rather than the business-as-usual scenario. The same seems to apply to future emissions of HFCs:

- The total HFC emissions in the graph in Harnisch *et al.* (2002) are approximately 200, 450 and 700 MtCO₂-eq yr⁻¹ for the years 1996, 2010 and 2020 (IPCC (1996) SAR values for GWPs).
- In this report (using 1996 SAR/ 2001 TAR GWP values for consistency), the values for the business-as-usual scenario are 375 MtCO₂-eq yr⁻¹ in 2002 (159 MtCO₂-eq of which are from HFC-23), increasing to 1001 MtCO₂-eq in 2015 (272 MtCO₂-eq of which are from HFC-23).
- In the mitigation scenario, these emissions are reduced to 368 MtCO₂-eq yr⁻¹ in 2015 (27 MtCO₂-eq of which are from HFC-23).

The Harnisch *et al.* (2002) numbers are, therefore, consistent with this report up to 2010; from then on they continue to increase, whereas the mitigation scenario envisages emissions under better control. Similarly, the values calculated for developed countries by the US EPA (2001) are also consistent with those considered here (as the sub-set of the same countries in the global databases).

11.5.4 Aggregate additional emission reduction opportunities

Tables 11.11 and 11.12 summarize the projections of the business-as-usual and mitigation scenario emissions for 2015. In the business-as-usual scenario, total direct emissions are projected to represent approximately 2.3 GtCO₂-eq yr⁻¹ in 2015 (2.0 GtCO₂-eq yr⁻¹ using SAR/TAR values), as compared to about 2.5 GtCO₂-eq yr⁻¹ in 2002 (2.0 GtCO₂-eq yr⁻¹ using SAR/TAR values).

Refrigeration applications, and stationary and mobile air-conditioning (MAC) contribute most to global direct greenhouse-gas emissions. A significant reduction in CFC emissions,

notably from refrigeration banks, can be expected during the next decade (CFC emissions fall to approximately 0.3 GtCO₂-eq yr⁻¹ in 2015). Most greenhouse-gas emissions from foams are expected to occur after 2015. HCFC emissions are projected to increase by a factor of two between 2002 and 2015, owing to a steep increase in the use in refrigeration and air-conditioning (AC) applications, in particular in commercial refrigeration and stationary air-conditioning (commercial refrigeration represents about 25% of the total of all refrigeration, AC and MAC systems). HFC emissions are projected to increase by about a factor of three, particularly in refrigeration, the stationary AC and MAC sectors, and due to byproduct emissions of HFC-23 during HCFC-22 production. It is expected that these projected increases will be accompanied by a build-up of banks and a corresponding added potential for future radiative forcing, depending on bank management and, notably, end-of-life measures. Action in these sub-sectors could therefore have a substantial influence on future emissions of HCFCs and HFCs.

There are opportunities to reduce direct emissions significantly through the global application of best practices and recovery methods, with a reduction potential of about 1.2 GtCO₂-eq yr⁻¹ (1.0 GtCO₂-eq yr⁻¹ using SAR/TAR values) of direct emissions by 2015, as compared to the BAU scenario. About 60% of this potential is HFC emission reduction; HCFCs and CFCs contribute about 30% and 10% respectively. A key factor determining whether this potential will be realized are the costs associated with the implementation of the measures to achieve the emission reduction. These vary considerably from a net benefit to 300 US\$/tCO₂-eq (Chapters 4–10 of this report, US- EPA, 2004). Chapters 4–10 of this report have identified various reduction opportunities. The major opportunities for reducing greenhouse-gas emissions in the period prior to 2015 include:

Refrigeration: In refrigeration applications, direct greenhouse-gas emissions can be reduced by 10% to 30%. For the refrigeration sector as a whole, the mitigation scenario indicates an overall direct-emission reduction of about 490 MtCO₂-eq

yr⁻¹ by 2015 (411 MtCO₂-eq yr⁻¹ using SAR/TAR values), with most being predicted for commercial refrigeration. Specific costs are in the range of 10 to 300 US\$/tCO₂-eq². Improved system energy efficiencies can also significantly reduce indirect greenhouse-gas emissions. In full supermarket systems, reductions of values for life cycle climate performance (LCCP) of up to 60% can be obtained by using direct expansion systems with alternative refrigerants, improved containment, distributed systems, indirect systems or cascade systems.

The emission reduction potential in domestic refrigeration is relatively small. Indirect emissions of systems using either HFC-134a or isobutane (HC-600a) dominate total emissions, practically regardless of the carbon intensity of electric power generation. The difference between the LCCP of HFC-134a and isobutane systems is small and end-of-life recovery can further reduce the magnitude of the difference.

Residential and commercial air conditioning and heating: Direct greenhouse-gas (GHG) emissions of residential and commercial air conditioning and heating equipment can be reduced by about 200 MtCO₂-eq yr⁻¹ (169 MtCO₂-eq yr⁻¹ using SAR/TAR values) relative to the BAU scenario (2015). Specific costs range from -3 to 170 US\$/tCO₂-eq². Improved system energy efficiencies can significantly reduce indirect GHG emissions, leading in some cases to overall savings of 75 US\$/tCO₂-eq. Opportunities to reduce direct GHG (i.e. refrigerant) emissions can be found in (i) more efficient recovery of refrigerant at end-of-life (in the mitigation scenario, this is assumed to be up to 50% and 80% for developing and developed countries, respectively); (ii) charge reduction (up to 20%); (iii) better containment and (iv) the use of non-fluorocarbon refrigerants in suitable applications.

Mobile air-conditioning: In mobile air-conditioning, a reduction potential of 179 MtCO₂-eq yr⁻¹ (162 MtCO₂-eq yr⁻¹ using SAR/TAR values) could be achieved by 2015 at a cost of 20 to 250 US\$/tCO₂-eq². Specific costs differ per region and per solution. Improved containment, and end-of-life recovery (both of CFC-12 and HFC-134a) and recycling (of HFC-134a), could reduce direct GHG emissions by up to 50%, and total (direct and indirect) GHG emissions of MAC units by 30 to 40%. New systems with either CO₂ or HFC-152a are likely to penetrate the market in the coming decade, leading to total GHG system emission reductions estimated at 50 to 70% in 2015. Hydrocarbons are in use as service refrigerants in several countries, despite manufacturer recommendations.

Foams: Because of the long life span of most foam applications, only a limited emission reduction of about 17 MtCO₂-eq yr⁻¹ (about 15 MtCO₂-eq yr⁻¹ using SAR/TAR values) by 2015 is projected, with costs ranging from 10 to 100 US\$/tCO₂-eq². There are two key areas of potential emission reduction in the foams sector. The first is a potential reduction in halocarbon

use in newly manufactured foams. However, the enhanced use of blends and the further phase-out of fluorocarbon use both depend on further technology development and market acceptance. Action to reduce HFC use by 50% between 2010 and 2015 would result in an emission reduction of about 10 MtCO₂-eq yr⁻¹ (about 9 MtCO₂-eq yr⁻¹ using SAR/TAR values), with further reductions thereafter, at a cost of 15 to 100 US\$/tCO₂-eq².

The second opportunity can be found in the worldwide banks of halocarbons contained in insulating foams in existing buildings and appliances (about 9 and 1 GtCO₂-eq for CFC and HCFC respectively in 2002 (about 7 and 1 GtCO₂-eq using SAR/TAR values)). Although recovery effectiveness is yet to be proven, particularly in the buildings sector, commercial operations are already recovering halocarbons at 10 to 50 US\$/tCO₂-eq² for appliances. Emission reductions may be about 7 MtCO₂-eq yr⁻¹ (about 6 MtCO₂-eq yr⁻¹ using SAR/TAR values) in 2015. However, this potential could increase significantly in the period between 2030 and 2050, when large quantities of building insulation foams will be decommissioned.

Medical Aerosols: The reduction potential for medical aerosols is limited due to medical constraints, the low emission level and the higher costs of alternatives. The major contribution (14 MtCO₂-eq yr⁻¹ by 2015 compared to a BAU emission of 40 MtCO₂-eq yr⁻¹ (using SAR/TAR values, this is 10 as compared to 34 MtCO₂-eq yr⁻¹) to a reduction of GHG emissions for metered dose inhalers (MDIs) would be achieved by the completion of the transition from CFC to HFC MDIs beyond what is already assumed to be BAU. The health and safety of the patient is of paramount importance in treatment decisions, and there are significant medical constraints on the use of HFC MDIs. If salbutamol MDIs (approximately 50% of total MDIs) were to be replaced by dry powder inhalers (this is not an assumption in the mitigation scenario) this would only result in an annual emission reduction of about 10 MtCO₂-eq yr⁻¹ by 2015, at a project cost in the range of 150 to 300 US\$/tCO₂-eq.

Fire protection: In fire protection, the potential reduction by 2015 is small due to the relatively low emission level, the significant shifts to not-in-kind alternatives in the past and the lengthy procedures for introducing new equipment. Direct GHG emissions for the sector are estimated at about 5 MtCO₂-eq yr⁻¹ (about 4 MtCO₂-eq yr⁻¹ using SAR/TAR values) in 2015 (BAU). Agents with no climate impact have replaced 75% of original halon use. Four percent of the original halon applications continue to employ halons. The remaining 21% has been replaced by HFCs, with a small number of applications switching to HCFCs and to PFCs. PFCs are no longer needed for new fixed systems and are limited to use as propellants in one manufacturer's portable-extinguisher agent blend. Due to the lengthy process of testing, approval and market acceptance for new types of equipment and agents for fire protection, no additional options are likely to have an appreciable impact by 2015. With the introduction of a fluoroketone (FK) in 2002, additional reductions at increased cost will be possible in this sector through 2015. Currently, those reductions are estimated to

² The presented cost data relate to direct emission reductions only. Taking into account energy efficiency, improvements may even result in net negative specific costs (savings).

be small compared to other sectors.

For *non-medical aerosols and solvents*, the reduction potentials are likely to be rather small because most remaining uses are critical to performance or safety. The projected BAU emissions by 2015 for solvents and aerosols are about 14 and 23 MtCO₂-eq yr⁻¹ respectively (the figures are about the same with SAR/TAR values). The replacement of HFC-134a by HFC-152a in technical aerosol dusters is a leading option for reducing GHG emissions. For contact cleaners and mould release agents for plastic casting, the substitution of HCFCs by HFEs and HFCs with lower GWPs offers an opportunity. Some countries have banned HFC use in novelty aerosol products, although HFC-134a continues to be used in many countries for safety reasons.

A variety of organic solvents can replace HFCs, PFCs and ozone-depleting substances in many applications. These alternative fluids include lower-GWP compounds such as traditional chlorinated solvents, HFEs, and n-propyl bromide. Many not-in-kind technologies, including hydrocarbon and oxygenated solvents, are also viable alternatives in some applications.

The destruction of byproduct emissions of HFC-23 from HCFC-22 production has a reduction potential of up to 300 MtCO₂-eq yr⁻¹ by 2015 (245 MtCO₂-eq yr⁻¹ using SAR/TAR values) and specific costs below 0.2 US\$/tCO₂-eq according to two European studies in 2000. Reduction of HCFC-22 production due to market forces or national policies, or improvements in facility design and construction also could reduce HFC-23 emissions.

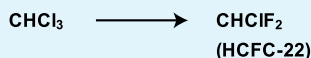
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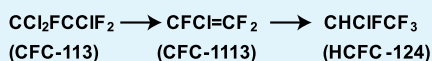
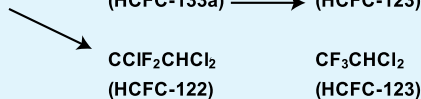
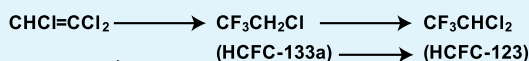
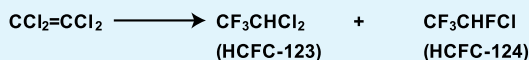
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Production pathways of HCFCs

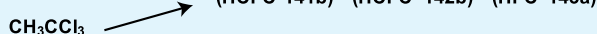
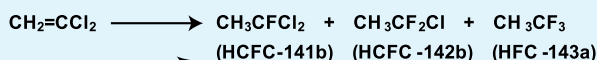
HCFC-22



HCFC-123/124



HCFC-141b/142b



Production pathways of PFCs

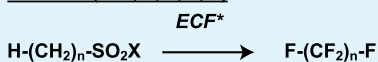
CF₄



C₂F₆



C_nF_{2n+2} (n=3, 4, 6, 7, 8)



c-C₄F₈



*ECF: Electrochemical Fluorination

Appendix 11B Analysis of the potential reasons for discrepancies in calculated emissions and the means of reconciling data sets

The origins of discrepancy

The average residence time of a fluorocarbon in equipment or other products varies from less than a year to many decades, depending on the application. At the time of the publication of the ozone-depletion hypothesis by Molina and Rowland (1974), fluorocarbons were mainly used as propellants in aerosols, resulting in rapid emissions of these gases to the atmosphere within a year of sale. Use as propellants, and other applications with rapid emissions, have largely disappeared in developed countries (AFEAS, 2004; Montzka and Fraser, 2002) and are gradually being minimized in developing countries. Current fluorocarbon consumption is dominated by their continuing use in applications with relatively slow emissions to the atmosphere such as refrigerant and closed-cell foam applications. The slow emission of refrigerants and blowing agents establish banks, which can emit fluorocarbons for prolonged periods and long after consumption of the chemical has ceased.

When calculating banks of fluorocarbon and other chemicals in refrigeration and in foams, it is necessary to study sales of equipment and/or products, lifetime aspects, leakage during use, and end-of-life issues. This bottom-up approach is based on data from surveys, which must be well designed to ensure complete coverage. However, there are usually cross-checks to ensure completeness. Emission factors for refrigeration equipment and foams have been assessed over several years. These vary significantly according to the application and good market analysis is required to ensure the use of appropriately weighted emission factors. The differences between consumption and forecast emissions using these functions are assigned to banks, which accrue and diminish with time. Verification of the physical existence of these banks (e.g. Mizuno, 2003) has largely served to confirm the appropriateness of the emission functions adopted, although year-to-year emission projections can have significant error bars for banks that release slowly (e.g. foams), particularly where emission projections are largely based on end-of-life practices. These year-to-year errors tend to be offset with time, making the level of confidence greater over a multi-year period³.

Observations of concentrations of long-lived species in the atmosphere can be used to estimate past emissions. If the lifetime of the chemical is long enough and the rate of mixing is sufficient to ensure a more or less homogeneous concentration in the whole lower troposphere, then past emissions can be derived by simple inverse modelling using

Figure 11A. Manufacturing routes for HFCs, HCFCs and PFCs.

³ For instance, it is difficult to assess with any accuracy the number of domestic refrigerators that will be decommissioned in a given year, but it is much easier to assess the number that will be decommissioned in a ten-year period based on the knowledge of the age profile of the global stock.

the change in observed concentration and the lifetime of the species (see Table TS-2 in the Technical Summary).

Measurements of long-lived species are performed frequently and with high accuracy in several measurement networks. The uncertainty in derived emissions depends on the uncertainty in the trend in observed concentration and on the uncertainty in the lifetime. Both are relatively small for most species. Using different measurement networks may also yield different emissions and therefore information about the uncertainty. On this basis, the uncertainty in derived emissions is about 10% for CFC-11 and between 1% and 6% for other long-lived halocarbons.

The determination of emissions via the bottom-up method has revealed substantial discrepancies with the emissions calculated from atmospheric measurements of the same chemicals. However, closer analysis of these discrepancies has found that even relatively small levels of consumption of fluorocarbons in rapidly emitting uses in developing countries can dominate emissions for specific chemicals (e.g. CFC-11) in specific years. This implies that there is a need to investigate production data, both from producers as reported to AFEAS and from countries as submitted to UNEP under the Montreal Protocol (Article 7 on data reporting), in order to determine where such emissions might appear. However, the key weakness in the UNEP data set is that it makes no provision for the recording of use patterns. Nonetheless, the quantification of the gap between UNEP production/consumption data and AFEAS data is essential.

Production and consumption issues

Since 1987, countries have reported production and consumption data as well as exports and imports for each of the relevant

CFC and HCFC chemicals to UNEP. UNEP publishes aggregated data for production and consumption on an annual basis (in ODP tonnes) for developed (i.e., non-Article 5(1)) and developing (i.e., Article 5(1)) countries. Annual production data for certain groups of countries can also be obtained, although data at the country level are confidential.

Since 1976, the chemical industry has voluntarily reported the production and sales of fluorocarbons through a survey compiled by an independent accountant. The purpose is to provide the scientific community with data estimating the atmospheric release of CFCs and the alternative fluorocarbons. Data are currently available up until 2002 for all relevant CFCs, HCFCs and HFCs. The sum of all CFC production reported as above to AFEAS in 2002 was only 3% of the total in the peak year, 1988 (AFEAS, 2004). The alternatives initially grew rapidly after their introduction to replace CFCs but currently have varied growth rates, with most levelling off as they become more mature products (Table 11B).

The companies surveyed by AFEAS include subsidiaries and joint ventures in all developed and many developing countries. Some production in developing countries, for example in China, India and Korea, is not included in the survey. The data collected by AFEAS for 2002 are thought (by comparison with the UNEP totals for production) to cover about 30-35% of global CFC production. Global coverage is much greater in the AFEAS survey for the HCFCs and HFCs. The AFEAS data currently cover 73% of all non-feedstock HCFC production, and are thought to represent at least 97% of global HFC production (AFEAS, 2004). Table 11B shows the decreasing trend in the coverage of the production reported to AFEAS in the total.

With respect to the accuracy of reporting, the numbers re-

Table 11B. AFEAS and UNEP production data (for the same group of countries/ manufacturers reporting to AFEAS and those not reporting, for CFC-11, HCFC-22 and -141b)

| Year/Chemical | 1989 | 1995 | 1997 | 1999 | 2000 | 2001 | 2002 |
|-------------------|---------|---------|---------|---------|---------|---------|---------|
| CFC-11 – AFEAS | 302,489 | 32,683 | 18,577 | 12,871 | 9,900 | 8,311 | 6,795 |
| CFC-11 – UNEP* | 314,749 | 36,098 | 27,798 | 20,616 | 15,064 | 11,831 | 10,336 |
| CFC-11 – UNEP° | 39,251 | 36,495 | 34,675 | 33,370 | 28,960 | 20,353 | 21,487 |
| CFC-12 – AFEAS | 379,778 | 82,822 | 32,900 | 27,132 | 24,564 | 20,873 | 20,181 |
| CFC-12 – UNEP* | 378,992 | 70,419 | 30,906 | 32,814 | 22,016 | 22,556 | 22,666 |
| CFC-12 – UNEP° | 98,350 | 86,186 | 59,069 | 54,707 | 61,389 | 43,049 | 36,505 |
| HCFC-22 – AFEAS | 219,537 | 243,468 | 251,108 | 252,375 | 243,847 | 217,465 | 198,208 |
| HCFC-22 – UNEP* | 204,460 | 297,981 | 214,717 | 235,416 | 220,260 | 196,467 | 181,483 |
| HCFC-22 – UNEP° | 36,602 | 30,075 | 41,044 | 86,016 | 118,533 | 140,589 | 144,757 |
| HCFC-141b – AFEAS | - | 113,154 | 122,356 | 132,355 | 134,393 | 123,565 | 118,406 |
| HCFC-141b – UNEP* | 287 | 111,319 | 109,120 | 132,667 | 128,385 | 117,531 | 123,931 |
| HCFC-141b – UNEP° | 445 | 0 | 5,112 | 11,605 | 11,975 | 13,360 | 24,697 |

Notes:

* non-Article 5(1) and Article 5(1) countries reporting to AFEAS

° countries not reporting to AFEAS

ported to AFEAS and the ones reported by the same countries to UNEP concur quite well in the early 1990s for CFC-11 and CFC-12. The differences increase after 1995, particularly for CFC-11, where there seems to be a systematic over-reporting to UNEP, or under-reporting to AFEAS, whilst the differences for CFC-12 remain more or less the same, also because quantities are larger. Reporting for HCFC-22 generally shows significant under-reporting by UNEP compared to AFEAS, with differences in the order of 10% or more. In the case of HCFC-22 it can be clearly seen that the quantity produced in 2002 by countries not reporting to AFEAS is more than 40% of the total. In the case of HCFC-141b, the agreement between AFEAS and UNEP reporting is remarkably good, with annual differences smaller than about 5%.

Determining use patterns and emissions

Annual production and sales data are reported to AFEAS for each of the 12 fluorocarbons surveyed. Sales are divided into use categories – refrigeration, foam blowing distinguishing between open-and closed-cell foams, aerosols, and all other uses – to the best knowledge of the fluorocarbon producers. Some degree of geographical breakdown is also provided but the AFEAS survey does not distinguish between developing and developed countries. Emissions of the individual fluorocarbons to the atmosphere are estimated by applying emission factors to the sales reported in each use category. These factors are derived from a consideration of the respective emission patterns and release delays for each application but are not always as sophisticated as those used in the bottom-up assessments. By way of an example, the allocation of all HCFC-141b foam sales to “closed-cell foams” may be inappropriate in view of uses in integral skin and other more rapid-release foam applications.

This said, estimates of atmospheric concentrations based on production statistics provided by manufacturers and national governments coupled with historical emission factors were, until recently, a good match with observations (McCulloch *et al.*, 2001, 2003), largely because of the dominance of rapid-release applications in developed countries. However, as the detailed assessment of delayed-release applications has become more important in developed countries and the gap between UNEP data and AFEAS data has increased, reflecting higher levels of activity in developing countries, the lack of use pattern data via the UNEP reporting structure is now a key impediment, particularly where usage might be occurring in rapid-release applications.

The improvement of knowledge about the use of the individual chemicals, both in the developed and in the developing countries, as well as uncertainties in emissions factors from banks following the bottom-up method, is unlikely to bear fruit within the time scale of this report. This has implications for the calculation of emission scenarios for the period 2002-2015, in particular the contributions from developing countries. It may therefore be the case that the emissions are significantly larger than calculated via the bottom-up method for refrigeration and

foams only because of additional contributions from rapid-release applications.

In addition, the emission factors applied to HCFCs and HFCs were derived from those developed earlier for CFCs and HCFC-22. However, there have been considerable changes in use practices in the wake of the Montreal Protocol and emission factors are subject to continual review. Revised emission factors, as described in McCulloch *et al.* (2001 and 2003), have helped improve the situation and have been used in the most recent calculation of emissions (AFEAS, 2004). Nonetheless, the view is that variation and uncertainties in emission factors per se are less significant overall than uncertainties in overall use pattern distributions between rapid-release applications and the delayed-release applications represented by refrigeration and foams.

This implies that, in the near future, further study is needed of the use patterns for the total production forecast for the period 2002-2015 in both the developed and the developing countries. Further study will also be needed to make more precise estimates of future emissions from banks in refrigeration and foams, given the accuracy of calculations of the size of the banks and the emissions derived from them, as well as servicing practices, and issues relating to recovery and recycling and end-of-life..

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Appendix 11C Destruction technologies and capacities

The decomposition or destruction of ozone-depleting substances, HFCs and PFCs/SGG can be achieved using various technologies. The commercially developed and successfully demonstrated technologies are described briefly in this section. Commercially available operations are also listed by region. The main source documents upon which this section is based are as follows:

- Proceedings of the International Workshop on the Disposal of Ozone-depleting Substances (UNEP, 2000).
- Guidance Document on Disposal Technologies for Ozone-depleting Substances (ODS) in Canada (Environment Canada, 2001)
- Refrigerant Recovery, Recycling, Reclamation and Disposal – an International Assessment, (Snelson and Bouma, 2003, Part 2)

The Canadian study reported, in their Guidance Document, 16 available and potentially efficacious technologies for the effective destruction of ODSs. The selected technologies all had stack emissions of less than 0.1 ng/m³ toxic equivalence for dioxins and furans, destruction or conversion efficiency not less than 99.7%, and the potential to be commercially available in 2003.

Plasma technologies (non-incineration)

- Argon Plasma Arc (Plascon)
- Inductively Coupled Radio Frequency Plasma (ICRF)
- Alternating Current Plasma (ACP)

Other non-incineration technologies

- Solvated Electron
- Gas Phase Chemical Reduction
- Catalytic Dehalogenation
- Liquid Phase Chemical Conversion
- Vitrification

UV photolysis incineration technologies

- Liquid Injection
- Rotary Kiln
- Gaseous/Fume Oxidation
- Internally Circulated Fluidized Bed (ICFB)
- Cement Kiln
- Reactor Cracking
- High Performance Incineration

Table 11C shows technical data for the evaluation of ODS-destruction technologies.

Commercially available technologies

Argon Plasma Arc

The “in-flight” argon plasma process, which has the waste mixing directly with the argon plasma, was developed in Australia and has been operating commercially since 1996. The technology and plant is owned and operated by BCD Technologies. Approximately 1000 tonnes of halons and 800 tonnes of fluorocarbons have been destroyed since commissioning. Destruction efficiencies of 99.9999% have been achieved. Destruction rates

Table 11C. Technical data for the evaluation of ODS-destruction technologies.

| Technology | Destruction efficiency (%) | Dioxins & furans (ng/m ³) | Other effluents | Energy consumption (kWh/kg CFC) | Estimated costs US\$/kg | Availability |
|----------------------------------|----------------------------|---------------------------------------|-----------------|---------------------------------|-------------------------|--------------|
| Incineration | | | | | | |
| High Performance | 99.99990 | 0.100 | salt/GHG | 1.71 | 6.00 | commercial |
| Liquid Injection | 99.99000 | 0.100 | salt/GHG | 1.30 | 5.00 | commercial |
| Rotary Kiln | 99.99000 | 0.100 | salt/GHG | 1.54 | 5.00 | commercial |
| Gas/Fume | 99.99000 | 0.100 | salt/GHG | 1.30 | 5.00 | commercial |
| ICFB | 99.99900 | 0.100 | salt/GHG | 1.30 | 5.00 | demo |
| Cement Kiln | 99.99000 | 0.100 | GHG | 1.86 | 4.00 | commercial |
| Reactor Cracking | 99.99900 | 0.100 | wastewater | 1.55 | 3.75 | commercial |
| Plasma | | | | | | |
| IC RF | 99.99000 | 0.025 | salt | 3.70 | 3.00 | Demo |
| Argon | 99.99990 | 0.025 | salt | 2.30 | 2.75 | Commercial |
| AC | 99.99000 | 0.025 | salt | 2.10 | 2.75 | Condition |
| Other | | | | | | |
| Solvated Electron | 99.99000 | 0.010 | salt | 10.00 | 8.00 | Demo |
| UV Photolysis | 99.99990 | 0.010 | spent liners | 10.00 | 11.00 | Commercial |
| Gas Phase Chemical Reduction | 99.99000 | 0.060 | salt | 1.38 | 6.00 | Condition |
| Catalytic Dehalogenation | 99.99000 | 0.010 | salt | 0.79 | 3.60 | Demo |
| Liquid Phase Chemical Conversion | 99.99990 | 0.010 | salt | 3.00 | 5.00 | Commercial |
| Vitrification | 99.99000 | 0.100 | glass frit | 4.88 | 3.80 | Condition |

vary from 60 kg/hr for fluorocarbons to 120 kg/hr for halons. Waste refrigerants are rapidly heated to 3000°C where pyrolysis occurs. This process is followed by rapid alkaline quenching that prevents the formation of dioxins and furans. Neutralization occurs with alkaline liquor. The waste gases, CO₂ and argon are vented, whilst the resulting halide salt solution consisting of NaCl and NaF is discharged to wastewater treatment.

Inductively Coupled Radio Frequency Plasma (ICRF)

This process does not require the electrodes needed for the DC process as the energy coupling to the plasma is achieved through the electromagnetic field of the induction coil. A demonstration plant operated from 1993 to 1996, during which time 2443 tonnes of CFC-12 was destroyed. Gaseous CFCs and steam are fed through the plasma torch where they are heated and enter directly into the destruction reactor maintained at approximately 2000°C. The subsequent gases are cooled and scrubbed with a caustic solution to remove acid gases. This process has been commercialized in Japan by Ichikawa Kankyo Engineering. Neutralization occurs with the use of Ca(OH)₂, resulting in solid waste CaF₂ and CaCl₂. An average of 50 tonnes per annum was destroyed during the second half of the 1990s.

Reactor Cracking

The reactor cracking process uses a cylindrical water-cooled reactor made of graphite, and an oxygen-hydrogen burner system. The reactor is flanged directly to an absorber. Waste refrigerants are fed into the reaction chamber where the temperature is maintained at between 2000°C and 2600°C. The waste is broken down into HF, HCl, Cl₂, CO₂, and H₂O. The cracked products are cooled in the absorber and the acid gases purified and recovered at technical grade quality. This is the most widely used commercial process for the destruction of fluorocarbons in Europe. The plant and technology are owned and operated by Solvay. In mid-2000, approximately 7000 Mt of fluorocarbons had been decomposed with a reactor capacity of 200 kg/hr.

Gaseous/Fume Oxidation

The gaseous/fume process uses refractory-lined combustion chambers for the thermal destruction of waste vapour streams. Waste fluorocarbons may be destroyed by feeding directly from their pressurized storage into the incinerator. Fume incinerators are typically found installed with manufacturing plants and are seldom used for commercial hazardous waste incineration. A version of this process known as High Temperature Steam Decomposition is operated by Ineos Fluor at Mihara in Japan. The rated throughput for CFCs is up to 165 kg/hr. Neutralization occurs with the use of Ca(OH)₂, resulting in solid waste CaF₂ and CaCl₂.

Liquid Injection

Liquid injection incinerators are usually single chamber units with one or more waste burners into which liquid waste is injected, atomized into fine droplets, and burned in suspension. Problems of flame stability may result with high concentrations

of fluorocarbons. This process has not been applied commercially to waste refrigerants. In Japan, Asahi Glass operates a liquid injection incinerator. The process involves two-stage neutralization using NaOH and Ca(OH)₂.

Cement Kiln

Existing cement kilns can destroy organic compounds as the temperature in the burning zone is over 1500°C with a relatively long residence time. The disadvantage is that fluorine and chlorine input rates need to be carefully monitored. Fluorine can be beneficial to the cement process whereas chlorine is generally regarded as an unwanted constituent.

Rotary Kiln

Rotary kiln incinerators are refractory-lined rotating cylindrical steel shells mounted on a slight incline from the horizontal. Most rotary kilns are equipped with an after-burner which ensures complete destruction of exhaust gases. Waste gases can be fed into the rotary kiln or directly into the after-burner. Rotary kilns are most frequently incorporated into the design of commercial incinerator facilities. Because of the production of acid byproducts, there are generally severe restrictions on the amount of halocarbons in the raw material feed.

Demonstrated and pilot processes

Alternating Current Plasma (ACP)

AC plasma is produced directly with 60 Hz high-voltage power but in other respects is similar to ICRF. CFCs have been effectively destroyed in a demonstration plant but the process is not commercially available for this application.

Solvated Electron

The solvated electron process is a batch process operated at atmospheric pressure using two vessels: one heated reaction vessel, and the other a refrigerated ammonia recycle vessel. Refrigerants are decomposed in the reaction vessel with liquid ammonia and metallic sodium. The resulting wastes are chiefly halide salts and biodegradable organic compounds. On a pilot scale, the process has been shown to destroy various fluorocarbons at an efficiency of 99.99% but a commercial facility for this application has not been established.

Gas Phase Chemical Reduction

This process involves the preheating of liquid or gas with boiler steam before injection into the reactor. The atomized gas mixture is heated by vertical radiant tubes with internal electric heating elements to approximately 850°C. Organic compounds are ultimately reduced to methane, hydrochloric acids and low-molecular-weight hydrocarbons. The formation of some dioxins and furans is possible. Hydrochloric acid is neutralized by caustic soda, and a scrubbing system removes inorganics. Hydrogen and methane are recovered for energy use. This process has successfully destroyed other wastes on a commercial basis but not fluorocarbons.

Catalytic Dehalogenation

In this process, CFCs are destroyed over a proprietary metal oxide catalyst at 400°C at atmospheric pressure. The resulting HF and HCL are absorbed in a lime solution. This process has been commercialized for other chlorinated compounds but not fluorocarbons.

Liquid Phase Chemical Conversion

This technology uses a liquid-phase chemical conversion process operating between 80°C and 120°C, where waste is reacted with a blend of potassium hydroxide and polyethylene glycol. Pilot-scale tests have proven a capability for fluorocarbons and the process is used commercially for other chlorinated substances.

Vitrification

This process fixes the products of chlorinated chemical dissociation and hydrolysis into chemically durable glass frit, which can be processed into glass products. The process has not been applied to fluorocarbons but has been proven effective for other chlorinated substances.

Internally Circulating Fluidized Bed (ICFB)

This process involves the waste refrigerant and air being blown through the incinerator fluidized bed, where the refrigerant is broken down by the presence of methane and hydrogen in the reducing atmosphere. The process has been proven to be successful but has not been commercialized.

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