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Incineration of HFC-23 Waste Streams for Abatement of Emissions from HCFC-22 Production: A Review of Scientific, Technical and Economic Aspects

**Prepared for
United Nations Framework Convention on Climate Change**

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List of Contents

Executive Summary	iii
1. Introduction	1
1.1 <i>Basis of this Report</i>	1
1.2 <i>The Chemical Compounds</i>	2
1.3 <i>The Chemical Compounds - Sources and Uses</i>	2
2. The Market for HCFC-22	3
2.1 <i>Historic Demand</i>	3
2.2 <i>Predicted Production and Consumption</i>	3
Table 1. Historical and Projected HCFC-22 Production	4
2.3 <i>Price</i>	5
Table 2. HCFC-22 Projected Demand and Production (from UNEP, 2003c) compared with the Demand derived in this Review.	6
2.4 <i>Value</i>	6
3. Technical Aspects of HCFC-22 Production	7
3.1 <i>Process</i>	7
Figure 1. Simplified line diagram of a typical process to produce HCFC-22 and HCl from chloroform and HF	8
3.2 <i>"Swing" Plant</i>	10
3.3 <i>Alternative processes for HCFC-22 production</i>	10
3.4 <i>Release or Treatment of HFC-23</i>	10
3.4.1 <i>Fugitive emissions</i>	10
3.4.2 <i>Removal with the HCFC-22 product</i>	11
3.4.3 <i>Vents from product storage</i>	11
3.4.4 <i>Aqueous phases losses</i>	11
3.5 <i>Emission Reduction</i>	11
3.6 <i>Capture and destruction</i>	12
3.7 <i>Cost of Destruction</i>	12
4. Default Emission Factors	13
5. Estimating Historical Emissions	14
5.1 <i>Overlap and Surrogate Methods</i>	14
5.2 <i>Trend Extrapolation</i>	15
6. Measurement and estimation at the plant level	15
6.1 <i>Guidelines and Guidance revised methodology</i>	15
6.2 <i>Simple methodology, use of the default factor or a factor derived from process efficiencies</i>	15
6.3 <i>Direct measurement of HFC-23 releases</i>	16
6.4 <i>Continuous estimate of HFC-23 production using a proxy</i>	17
7. Projected emissions of HFC-23	18
7.1 <i>The Business as Usual Case</i>	18
7.2 <i>Projected Reduction in Emissions using Current Best Practice</i>	19
Table 3. Calculated Emissions of HFC-23 under the Business as Usual Case, representing a maximum, and a Reduced Emissions Case, representing application of current best practices.	20
8. Economic Considerations	20
8.1 <i>Value of HCFC-22 and added value</i>	20
8.2 <i>Global Economic Effects of the Clean Development Mechanism</i>	21
8.2.1 <i>Value of HCFC-22 Production</i>	21
8.2.2 <i>Total Value of HFC-23 Abated under CDM (with no constraints)</i>	21
8.2.3 <i>Value of HFC-23 Abated under CDM (with constraints on eligibility)</i>	22
8.3 <i>Local Value of Abatement and Downstream Economic Effects</i>	22
9. Conclusions	23
References	25

Appendix 1. Approved Baseline Methodology - AM0001

Appendix 2. List of Supplementary Questions from the Methodology Panel

Appendix 3. Responses from Public Consultation

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Incineration of HFC-23 Waste Streams for Abatement of Emissions from HCFC-22 Production: A Review of Scientific, Technical and Economic Aspects

Executive Summary

This paper addresses concerns about the first Approved Method (AM0001) for the Clean Development Mechanism which covered the abatement by thermal oxidation of HFC-23 produced during the manufacture of HCFC-22. At issue are the quantities of baseline emissions, the way in which they were estimated and the possibility that the value from this and other similar CDM projects might distort the economics of HCFC-22 production. The particular concerns of the Methodology Panel are elaborated in the series of questions shown in Appendix 2 and the responses to the Public Consultation Process are given, in full, in Appendix 3. Many of these are concerned with the procedural issues around changing an agreed methodology after it has been implemented and only the technical questions raised in the consultation have been addressed in this paper. The apparent disconnection between cost and benefit and the high gearing of the HFC-23 CDM projects underlies many of the comments and objections.

HFC-23 has few uses, all of which could lead to its eventual emission. It has a GWP of 11700, which accounts for the high gearing. Almost all HFC-23 is generated as a by-product during the manufacture of HCFC-22 and the process can be adjusted to minimise, but not eliminate, HFC-23 production; and so its total abatement is possible only by installing the capability to destroy potential emissions.

HCFC-22 is used as a refrigerant in several different applications and as a blend component in foam blowing. In developed countries, the Montreal Protocol scheduled phase out of HCFC consumption in these uses will occur by 2040. Consumption in developing countries will be phased out over a longer time period, using consumption (and production) in the year 2015 as a baseline. HCFC-22 is also used as a chemical feedstock for manufacturing fluoropolymers such as polytetrafluoroethylene (PTFE) but this use is permitted to continue indefinitely in any area of the world. Production in the U.S.A., Europe and Japan is falling while that in other Asian countries (notably China and India) has increased dramatically in recent years.

HCFC-22 is traded internationally. Europe is the major source but production in China and India also significantly exceeds consumption in those countries.

Consumption for potentially emissive commercial end uses in developed countries is expected to continue to decrease as a consequence of increasingly stringent national and regional regulations and is expected to fall by at least a factor of 10 from the level in 2000-2003. However, in the same region, growth in demand for fluoropolymer feedstock is increasing and the feedstock demand for HCFC-22 may double in developed countries by 2015. The net result is that, by 2015, the total demand for HCFC-22 in the developed world will be significantly reduced

In the remaining countries of the world, production of HCFC-22 for both the potentially emissive commercial uses and feedstock uses has grown rapidly in recent years. Production forecasts to the year 2015 are developed for HCFC-22.

Prices in the developed world now are \$2100 to \$2400/tonne in U.S.A. and Western Europe and export prices (mainly into South East Asia) are somewhat lower, in the region of \$1100 to \$1500/tonne. These prices are dictated by conventional market forces, even in centrally planned economies. However, the cost of HCFC22 constitutes an insignificant part of the value of the equipment in which it is used; less than 1% of the selling price of a

typical air conditioner. So that, even if the HCFC were given away, the effect on the selling price of the air conditioner would be insignificant. Consequently, the quantity of HCFC 22 produced depends on the demand for the final products rather than its production cost and subsidising the latter, while it may change the economic situation of a particular facility, will have little effect on total demand.

HFC-23 production is an inevitable consequence of the manufacture of HCFC-22. Even in the largest facility in the world, after extensive process optimisation, HFC-23 is still made at a rate of some 1.4% of the total production. While it is possible to eliminate this HFC-23 by, for example, a thermal oxidation system, all abatement procedures require intervention and carry capital and operating costs.

The default emission factor set by IPCC for older plants is 4%, with 3% for newer facilities, but use of a default is no substitute for actual measurement (which is required by AM0001). The measurements and estimates may be conducted in a number of ways, using tried and tested protocols. The default emission factor limits the maximum abatement that can be claimed for a CDM project. However, the presumption that this value may be set, for plants that already exist, to the best that the largest plant in the world can accomplish (1.37%) is illogical. It would mean that the technology to meet this rate would have to be available to all and presupposes that no costs are involved.

Further reduction in emissions beyond what is technically achievable through process optimisation requires additional equipment. Thermal oxidation is an effective treatment in which the hydrofluorocarbon is incinerated in a furnace fuelled by, for example, natural gas. The consequent high temperature oxidation yields carbon dioxide and hydrogen fluoride. After neutralisation the products are harmless salts (such as sodium or calcium fluoride and chloride) that may be safely disposed of using conventional procedures and, while the costs are not trivial they are small compared to the value of the HCFC product. Furthermore, it is possible to dispose of calcium fluoride by recycling it into the hydrogen fluoride production process.

Global emissions of HFC-23 increased by an estimated 12% between 1990 and 1995, however this trend has not continued and since 1995 has become smaller than the increase in production. The emission factor averaged over all plants is now equal to 2% of HCFC-22 production and, for a *Business as Usual* scenario to represent the maximum level of emissions to 2015, it has been assumed that emissions from existing capacity will continue at this factor. For the same scenario it is assumed that new capacity will emit HFC-23 at a rate of 4%, again giving a maximum. Consequently, emissions of HFC-23 would grow between now and 2015, from 14,000 tonnes/year in 2003 to 24,000 tonnes/year.

It is apparent from historical trends that approximately half of the HFC-23 co-produced with HCFC-22 in the developed world is abated. For the reduced emissions case, it is assumed that destruction technology is progressively introduced for all new and non-abated existing capacity from 2005 onwards. This has the effect of reducing emissions to 2,400 tonnes/year by 2014.

Against this background, CDM projects for HFC-23 abatement have the potential to alter economics radically and have the effect of becoming subsidies perhaps equal to the value of the HCFC-22 the facility produces. The reasons for this large impact are the high gearing that is a consequence of the high GWP of HFC-23 and the value of a carbon dioxide equivalent unit (the CER or Certified Emission Reduction credit), that is set by the cost of ameliorating CO₂ from fossil fuel combustion.

The market for HCFC-22 is into refrigeration (and air conditioning) and fluoropolymers (PTFE). In both cases, volume is driven by the economics of selling the finished products; HCFC-22 costs are a tiny fraction of finished product costs and so do not materially affect the size of those markets. Consequently leakage, in terms of increased use of HCFC-22 due to lower costs, is not significant. Nor would there be any economic incentive for HCFC-22 plants to be constructed speculatively since, even if the product were given away, the effect on the size of the final market and hence the demand for HCFC-22 would be insignificant. The fossil fuel use in thermal oxidation will increase carbon dioxide emissions, but the effect is small compared with the abatement of HFC-23 and its magnitude can be calculated easily.

On the other hand distortion of market economics from a CDM project can have a profound effect on individual facilities, allowing the subsidised facility to capture greater market share by consistently undercutting the competition (particularly the competition in developed countries). Further CDM projects will assist the pre-existing trend towards production in developing countries at the expense of the developed world.

It would be perverse to reward the future construction of an HCFC-22 plant that had been built without the capability to destroy its HFC-23 simply in order to provide a CDM opportunity when the capability was installed. Possible remedies include the restriction of CDM projects for future plants to the cost of installing the destruction capability, or setting the maximum value claimable to the 1.37% suggested by DuPont, provided that the technology to do this were made freely available. Restricting the availability of future CDM money in these sorts of ways could halve the value of CDM projects by 2015.

In any event, CDM projects for HFC-23 abatement are likely to have a value of several hundred million dollars a year if all the existing potential is realised. The resulting saving in greenhouse gas emissions could amount to, on average, 160 MTe CO₂ equivalent/year. For comparison, if all HFC-23 were abated in the same way, the global total (including abatement not eligible for CDM) would average 290 MTe CO₂ equivalent/year.

1. Introduction

1.1 Basis of this Report

In the spring of 2004, the first Approved Method (AM0001) for the Clean Development Mechanism (CDM) was placed on hold by the Executive Board for the CDM, in response to concerns expressed by interested parties. The text of AM0001 is attached as Appendix 1 and describes the methodology to be used for a CDM project in Korea: the *HFC Decomposition Project* in Ulsan, Republic of Korea whose Baseline study, Monitoring and Verification Plan and Project Design Document were prepared by INEOS Fluor Japan Limited (Japan), Foosung Tech Corporation Co., Ltd. (Korea) and UPC Corporation Ltd. (Korea).

In this project, the HFC-23 (CHF_3 , trifluoromethane) that was produced during the manufacture of HCFC-22 (CHF_2Cl , chlorodifluoromethane) and normally released into the atmosphere was to be destroyed by thermal oxidation. Concerns arose about the quantities of baseline emissions, the way in which they were estimated and the possibility that the value from this and other similar CDM projects might distort the economics of HCFC-22 production.

This paper addresses the general concerns expressed by the Methodology Panel (Meth Panel) embodied in three issues:

- i) Possible alternative approaches to assessing the baseline scenario for destruction of HFC 23 in the HCFC 22 industry,
- ii) Common practices in this industry, complementing previously available information, and
- iii) Possible impacts of such project activities on the supply and demand of HCFC22.

The particular concerns of the Meth Panel were further elaborated into the series of questions shown in Appendix 2. This report does not respond to these questions, point by point, in the order posed but the series of questions has illuminated the writing. Similarly, the Public Consultation Process has provided a number of responses that have been appended in full (and unedited) to this report. Many of these are concerned with the procedural issues around changing an agreed methodology after it has been implemented and only the technical questions raised in the consultation have been addressed in this paper.

The fundamental aim of the CDM is to reduce greenhouse gas emissions, hence it is abatement that is rewarded. The value of that abatement is dictated by the value of the carbon dioxide equivalent, which is governed by the value of fossil fuel reduction. The cost of abatement depends on the mechanism to accomplish it and all mechanisms are equally valid, even the cheapest. The apparent disconnection between cost and benefit and the high gearing of the HFC-23 CDM projects underlies many of the comments and objections.

1.2 The Chemical Compounds

HFC-23 is also known as trifluoromethane (or fluoroform) and has the chemical formula CHF_3 . It is among the most stable of the fluorocarbons and decomposes only slowly in the atmosphere, with an atmospheric lifetime of 206 years (Ramaswamy *et al.*, 2001). It absorbs infrared radiation efficiently and so has a high "Global Warming Potential" (GWP). One kilogram of HFC-23 released into the atmosphere now would have the same effect as 11700 kg of CO_2 within the next 100 years: its GWP is therefore 11700 (Albritton *et al.*, 1996). HFC-23 is included in the basket of gases with emissions controlled under the Kyoto Protocol (UNFCCC, 1997).

On the other hand, HCFC-22 (the chemical chlorodifluoromethane - CHClF_2) has a much shorter atmospheric lifetime of 12 years (Ramaswamy *et al.*, 2001), is somewhat less efficient in absorbing infrared radiation and hence has a GWP of 1700 (Ramaswamy *et al.*, 2001). HCFC-22 is excluded from the provisions of the Kyoto Protocol because it is an ozone depleting substance and its production and consumption will be phased out under the Montreal Protocol (UNEP, 2003a). Neither compound is flammable and neither is appreciably toxic so that, under the framework of environmental legislation common during the last century, it was permissible to vent both of them into the atmosphere.

1.3 The Chemical Compounds - Sources and Uses

Almost all HFC-23 is generated as a by-product during the manufacture of HCFC-22. Historically, some of this HFC-23 was recovered and used as a feedstock to produce Halon-1301 (bromotrifluoromethane). However, when production of Halon-1301 ceased in the developed world in 1994 in accordance with the Montreal Protocol, this requirement for HFC-23 also ceased. The remaining uses (as a low temperature refrigerant and as a specialised fire extinguishant) are small relative to the total quantity produced as by-product and are also potentially emissive, meaning that, unless care is taken to recover and reuse or destroy it, the HFC-23 used will be released into the atmosphere when equipment is serviced or when it is scrapped. Thus capture of HFC-23 for use in such equipment does not eliminate, but does delay, its emission.

HCFC-22 is used as a refrigerant in several different applications; as a blend component in foam blowing and as a chemical feedstock for manufacturing fluoropolymers such as polytetrafluoroethylene (PTFE). Almost all of the HCFC-22 is bought by industrial consumers to be used in the systems that they manufacture or service; effectively, no HCFC-22 is sold to domestic consumers. Potentially, the fluid used in refrigeration and foam blowing may be emitted: during servicing, particularly of large scale refrigeration systems, at the end of the system life and as small continuous leakage, for example from within the plastic matrix of an insulating foam. With the exception of the last, emissions such as these can be ameliorated by efficient recovery of the fluid and its re-use or destruction.

In developed countries, the Montreal Protocol scheduled phase out of HCFC-22 consumption will occur by 2040. Consumption in developing countries will be phased out over a longer time period, using consumption (and production) in the year 2015 as a baseline. Because substantial amounts will continue to be present in existing equipment, these controls on consumption will not cause emissions of HCFC-22 to cease immediately but will effect reductions in the longer term. Feedstock production, however, is permitted to continue indefinitely in any area of the world because it does not involve the release of HCFC-22 to atmosphere in the same way as the dispersive uses.

2. The Market for HCFC-22

2.1 Historic Demand

HCFC-22 is produced in several developed and developing countries and global statistics on production and consumption are available. For the developed countries, a database of production and use in emissive applications going back to 1943 has been maintained by industry (AFEAS, 2004). In addition, all parties to the Montreal Protocol, including China, India, Korea and Russia (which do not report into the AFEAS database), report their production and consumption to the United Nations Environment Programme (UNEP, 2002; 2003b). It has been shown that, like-for-like, the two data sets for HCFCs agree to within a few percent (McCulloch *et al.*, 2003) and so can be combined.

The U.S.A. is a major world producer of HCFC-22, with three plants and approximately one-half of all developed country production. There are 10 manufacturing plants for HCFC-22 in the EU, with a total capacity estimated to be 184,000 metric tonnes/year; the reported European levels of production are very close to this capacity and are falling slowly (Irving and Branscombe, 2000; EFCTC, 2001; UNEP, 2002). Japan is another large producer of HCFC-22, with a reported production of 88,000 metric tonnes in 2001, shared between four companies, and production in other Asian countries (notably China and India) has increased dramatically in recent years. There are now 19 HCFC-22 producers in China with a total capacity of 200,000 metric tonnes, which produced 177,000 metric tonnes in 2003 (CCR, 2002; CAOFSMI, 2003). Production in India, based on the data in UNEP (2002 and 2003b) rose from 4,000 tonnes in 1992 to 17,000 in 2002; there are four significant producers. However, over the same period, the same data source suggests that there has been much less growth in Korea and Russia. Korean production has remained between 3000 and 5000 tonnes/year and Russian production fell from over 4000 tonnes/year to under 1000 in 1996 to 1998, before recovering to almost 6000 tonnes/year in 2002 (UNEP, 2003b).

The historic time series of global HCFC-22 production is given in Table 1.

HCFC-22 is traded internationally. For example slightly over one third of the HCFC-22 manufactured within the EU is exported out of the single European market (Cefic, 2003). It is also offered for sale by all of the producing countries but exports from Europe were historically an order of magnitude greater than the net export from U.S.A. and Japan, combined (SRI, 1998). Production in China and India also significantly exceeds consumption in those countries (UNEP, 2003b). Importing nations include Australia, Canada, Indonesia, Korea, Malaysia and the countries of south and central America.

2.2 Predicted Production and Consumption

Consumption for potentially emissive commercial end uses in developed countries is expected to continue to decrease as a consequence of increasingly stringent national and regional regulations. Thus, within the European Union, use in foam blowing and in many refrigeration applications is now prohibited and the total consumption quota has been reduced to one quarter of the 1999 levels. Total phase out of consumption is scheduled for 2010 (EU, 2000).

Other regions have less draconian regulations; for example, in Japan use of HCFC-22 for new equipment will cease in 2010 and for servicing existing equipment in 2020. Similar regulations apply in U.S.A. (Arap, 2004). However, in order to provide a "maximum envelope" for predicting the change in demand for HCFC-22 in these countries, a scenario that followed the requirements of the Montreal Protocol exactly was adopted as the best estimate in the most recent Scientific Assessment of Ozone Depletion (Montzka, Fraser *et*

al., 2003). This envisages that, by 2015, consumption of HCFC-22 for potentially emissive uses in the developed world should have fallen by a factor of 10 from the level in 2000-2003.

Table 1 Historical and Projected HCFC-22 Production

Year	Production in the Developed World ktonnes for		Production in the Developing World ktonnes for		Total ktonnes
	Commercial use	Feedstock	Commercial use	Feedstock	
1990	214	107	18		339
1991	237	118	17		373
1992	246	123	17		385
1993	241	120	21		382
1994	239	120	27		387
1995	243	122	19		385
1996	271	136	20		427
1997	251	126	26	4	407
1998	261	131	48	8	448
1999	252	126	70	12	460
2000	244	122	92	16	473
2001	217	128	114	20	479
2002	198	134	135	24	491
2003	198	139	157	28	523
2004	168	145	179	32	524
2005	168	151	201	36	556
2006	168	157	223	40	587
2007	168	163	244	44	619
2008	168	168	266	49	651
2009	168	174	288	53	682
2010	90	180	310	57	637
2011	90	186	331	61	668
2012	90	192	353	65	700
2013	90	198	375	69	732
2014	90	203	397	73	764
2015	26	209	419	77	731

By contrast, in the same region of the developed world, growth in demand for fluoropolymer feedstock increased linearly at a rate of 5800 tonnes/year, with a coefficient of variance (R^2) of 0.84, over the 1990s (Cefic, 2003; SRI, 1998). In the absence of other influences, this rate of increase could continue, leading to the feedstock demand for HCFC-22 doubling in developed countries by 2015. The net result is that, by 2015, the total demand for HCFC-22 in the developed world will be significantly reduced. Historically, this type of situation has resulted in closure of the less economic (generally smaller) facilities so that market forces are likely to reduce the future productive capacity for HCFC-22 in the developed world.

In the remaining countries of the world, production of HCFC-22 for both the potentially emissive commercial uses and feedstock uses has grown rapidly in recent years. Over the period 1997 to 2001, production for commercial uses grew linearly at 20,000 tonnes/year, with a coefficient of variance (R^2) of 0.95, and feedstock use grew at 4100 tonnes/year (R^2 equal to 0.99) (Bingfeng *et al.*, 2000; CCR, 2002; UNEP, 2002; 2003b). The sharp increases in production are driven by rapid growth in demand, particularly in China where HCFC-22 is used in one third of commercial and industrial refrigeration and in most commercial and domestic air conditioning. These sectors are growing in China at rates between 8 and 37%/year (IIR, 2003; 2004) and the HCFC-22 is being provided mainly by new plants constructed in China which also provide significant quantities for export (UNEP, 2003b). Clearly the growth in demand for equipment is unsustainable at this rate in the long term; the domestic refrigeration market in China is already saturated having started from essentially nothing 15 years ago (IIR, 2004). Nevertheless, such growth puts pressure on both production and price.

Because the installation of new HCFC-22 capacity is now prohibited in India (see Appendix 3. 19) and growth appears to be slow or non-existent in Korea and Russia, most of the future expansion has been predicted to take place in China. Projected at these rates until 2015, the total global requirement for HCFC-22 could become about 730,000 tonnes/year, about 40% of which would be for feedstock, compared with a total of 470,000 tonnes/year in the year 2000. These values are also shown in Table 1 and reflect the situation where demand depends solely on commercial considerations without distortion due to any form of subsidy.

This analysis is broadly consistent (for historic and future demand) with that carried out by the UNEP Technology and Economic Assessment Panel (UNEP, 2003c). Where the analyses differ most is in the estimated expansion in production, particularly in non-Article 5(1) (i.e. developing) countries. The TEAP estimates are shown in Table 2 and predict a significant shortfall in capacity towards the end of the current decade. Such a shortfall would now be considered very unlikely because the capacity in countries such as China has already been increased to match current demand at least (UNEP, 2003b).

2.3 Price

HCFC-22 is a globally traded commodity, sold by the manufacturers either directly to the end users or through distributors, and the major part of this trade is covered by long term fixed price contracts. The prices in these contracts are significantly different from the "spot" prices quoted for individual lots bought on the open market. The latter are heavily influenced by the immediate balance of supply and demand. Some of that is apparent in the widely differing prices in Japan, USA and Europe quoted in SRI (1998), where it is not clear that the quotations are all on identical bases. For example, in the U.S.A. from 1985 to 1995, the quoted price was in the region of \$2400/tonne, rising to \$3000/tonne in 1996 to 1998; in Western Europe the price from 1986 to 1995 was \$2700/tonne yet the quoted price in Japan started at \$4000/tonne in 1980 and peaked at \$8600/tonne in 1988 before falling to \$5000/tonne in 1996.

Prices in the developed world now are apparently very similar to those of the 1980s, at \$2100 to \$2400/tonne in U.S.A. and Western Europe. The export prices (mainly into South East Asia) are somewhat lower, in the region of \$1100 to \$1500/tonne.

The price charged by manufacturers is controlled by a number of factors that vary in importance during time. The "flat" market and idle plant capacity that featured during the early to mid 1990s caused prices to remain stable then or to fall. At that time the cost and

availability of raw materials (chloroform and hydrogen fluoride) were not causing a discernible pressure on the price of HCFC-22 and any such cost pressure seems to have been absorbed by the producers, among whom there is intense competition (SRI, 1998). Since then, production in China has increased dramatically (see above) to meet burgeoning

Table 2. HCFC-22 Projected Demand and Production (from UNEP, 2003c) compared with the Demand derived in this Review.

HCFC-22	Demand and Production (ktonnes/year)			
	2002	2005	2010	2015
Commercial demand non A5(1)	189	180	99	37
Commercial demand A5(1)	104	132	212	305
Total commercial demand	293	312	311	342
Feedstock requirement	212	239	290	337
Total Demand	505	551	601	679
<i>For comparison, demand shown in Table 1</i>	491	556	637	731
Production capacity non A5(1)	440	410	353	335
Production capacity A5(1)	166	181	205	230
Total production capacity	606	591	558	565
Unused Capacity (insufficient is negative)	101	40	-43	-114
Capacity Utilisation	83%	93%	100%	100%

demand within China itself (IIR, 2003; 2004). The reduction in HCFC-22 demand for potentially emissive end uses (particularly in Europe) is roughly balanced by increases in the demand for feedstock and the growing Chinese demand. This has maintained the pressure on world supplies of chloroform, much of the Chinese requirement apparently being imported. Furthermore, the demand for hydrogen fluoride, made from fluorspar is beginning to absorb spare Chinese fluorspar capacity previously exported (Miller, 2003). Consequently, the price of Chinese fluorspar imported into the U.S.A. increased from \$130/tonne in 2002 to \$170/tonne in 2003, making it among the most expensive of the internationally traded fluorspars. The increases in raw materials costs are now working through into hardening of the price of HCFC-22, particularly in South East Asia (although there is considerable scope there to catch up with Western prices).

By and large, the view that emerges from these considerations is that price is dictated by conventional market forces, even in centrally planned economies. Furthermore, the shortfall predicted by UNEP (2003c) shows no sign of materialising and capacity has already been put in place to meet demand.

2.4 Value

Of the 60 to 70% of HCFC-22 that is not used as a feedstock for fluoropolymer manufacture, nine tenths are used in refrigeration and the sector with the largest growth rate, particularly in developing countries is unitary air conditioning (UNEP, 2003c). The current growth in demand for HCFC-22 therefore largely depends on original equipment

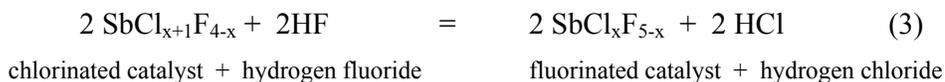
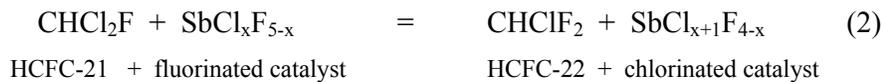
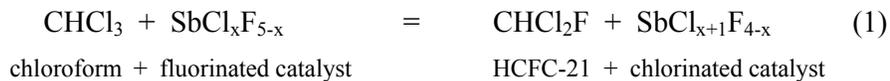
manufacture. In the future, this may translate into replacement use for refrigeration and air conditioning (RAC) equipment. The cost of the HCFC22, however, constitutes an insignificant part of the RAC equipment cost (<1%). This may be illustrated with a real example: to charge a typical air conditioner adequately, some 700-800 grams of HCFC-22 is required, at a selling price of between \$1 and \$2 from the fluorocarbon manufacturer but the value of the air conditioner is of the order of \$500 to \$1000. So that, in this case, even if the HCFC were given away, the effect on the selling price of the air conditioner would be insignificant. Consequently, the quantity of HCFC 22 produced depends on the demand for the final products rather than its production cost and subsidising the latter, while it may change the economic situation of a particular facility, will have little effect on total demand. These economic considerations are discussed in Section 8 and in Appendices 3.9 and 3.11.

3. Technical Aspects of HCFC-22 Production

3.1 Process

In the most commonly used process, accounting for well over 90% of global capacity, chlorodifluoromethane (HCFC-22) is produced by the reaction of chloroform (CHCl_3) and anhydrous hydrogen fluoride (HF) in the presence of antimony pentachloride (SbCl_5) catalyst (Hamilton, 1963). The plants established in the developed world have had a service lifetime of many decades but may have been extended and expanded during the course of that life. Newly constructed plants could be expected to have a similar lifetime (of at least 20 years).

The process chemistry is represented by Equations 1 to 3.



Overall, two molecules of HF react with one molecule of chloroform to yield one molecule of chlorodifluoromethane and two molecules of hydrogen chloride. Raw materials are internationally traded commodity chemicals. Production of HCFC-22 is the largest single use for chloroform which is made in a number of developed countries using chlorine and natural gas. Hydrogen fluoride is made by reacting highly concentrated sulphuric acid (100% H_2SO_4) with calcium fluoride (mined as the mineral - fluorspar, CaF_2).

The products are more volatile than the reactants, leading to an elegant engineering solution to the requirement to remove the reaction products: the reaction is carried out in a continuous-flow reactor full of boiling liquid, products being removed from the reaction system as vapours. The process engineering components of a typical process are shown in Figure 1. The reactor operating temperature is generally in the range 50 to 100 °C at a pressure between 5 and 20 Bars. Reflux to the reactor column is provided by a condenser

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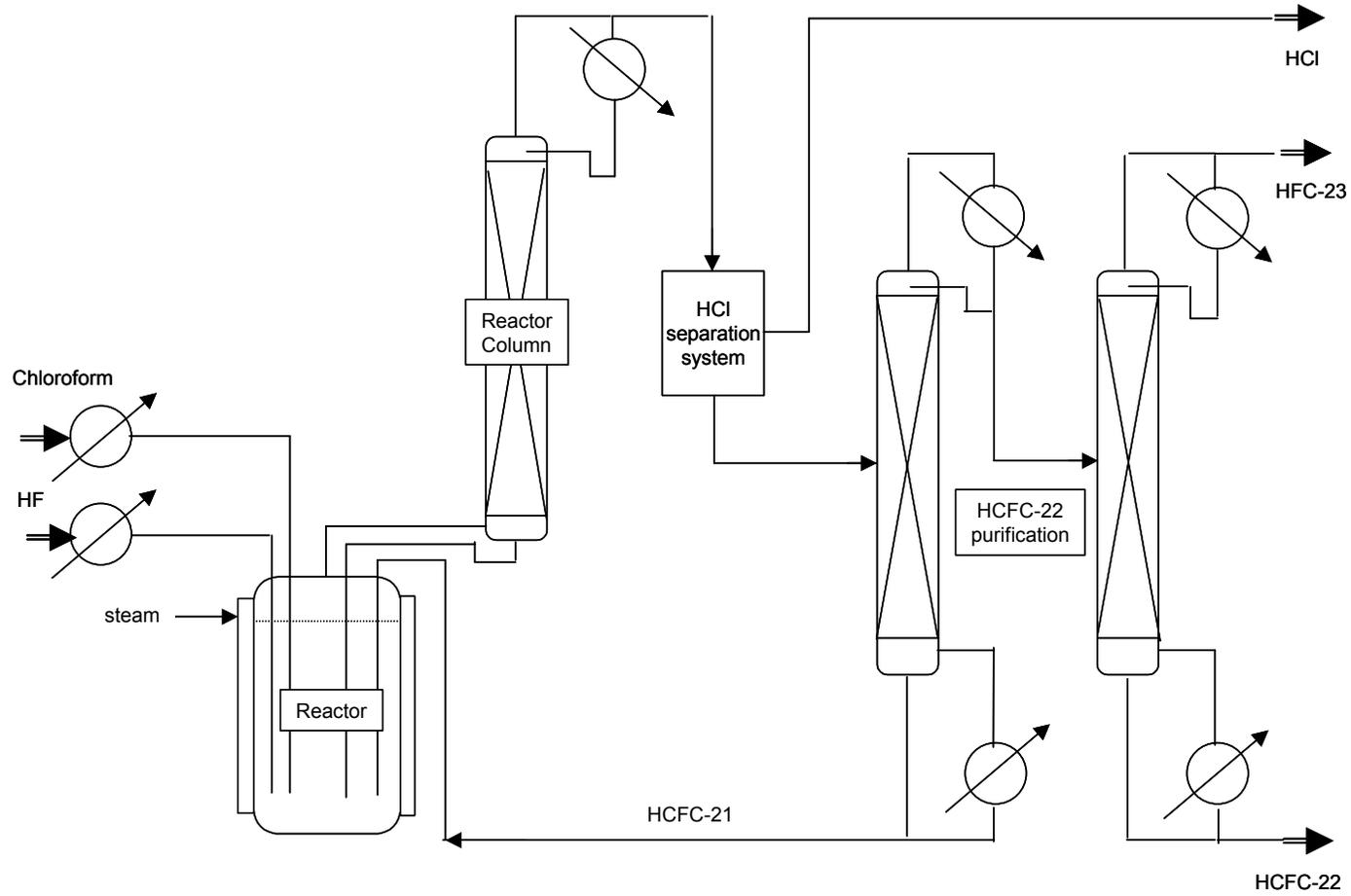


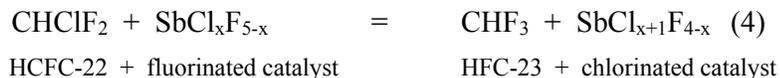
Figure 1. Simplified line diagram of a typical plant to produce HCFC-22 (chlorodifluoromethane) and HCl (hydrogen chloride) from chloroform (CHCl_3) and HF (hydrogen fluoride)

operating at -30 to 0°C, with the condenser and column system returning unreacted materials to the reactor for reprocessing. The catalyst itself is volatile and is a component of the reflux into the reactor.

These reaction conditions are maintained to optimise HCFC-22 production and to obviate corrosion by the halogen acid/catalyst mixture which is potentially extremely aggressive. At some compositions, when the catalyst contains high levels of fluorine, fluoroantimonic acid (H^+SbF_6^-) can be formed. This is a free protonic acid (Sommer *et al.*, 1978.) that can rapidly dissolve metals (even those that are commonly regarded as corrosion resistant), leading to catastrophic loss of containment and risk to human life. The conditions leading to this situation are unpredictable and so the process is operated within parameters that are known to maintain the catalyst in a chemical condition far removed from the most aggressive state. This is particularly important in the reactor column where the returning catalyst in the reflux may become mixed with significant amounts of unreacted hydrogen fluoride. In view of the engineering and materials problems that influence scale-up, one favoured means of increasing capacity is to install an additional reactor system that can be operated in exactly the same way as the existing systems.

The operating conditions are a balance between maximising the space time yield for production of HCFC-22, maintenance of safe operating conditions and minimising process inefficiencies. All of these have economic implications: the highest space time yield represents the most efficient use of the capital asset (the plant), competent containment affects the licence to operate the plant at all and process inefficiencies are waste and have a direct cost.

The most important inefficiency in the HCFC-22 process is overfluorination (further reaction of HCFC-22) which yields HFC-23 (CHF_3) (Equation 4).



Essentially, this overfluorination depends more on concentrations of the carbon containing materials in the liquid reaction medium than on catalyst conditions (although the catalyst conditions influence the composition of the reaction mixture, so that there is an indirect link to the catalyst composition). It is therefore heavily influenced by the design of the reactor column and the reactor operating conditions of temperature and pressure.

The vapour stream leaving the reactor contains, in addition to HCFC-22 (CHClF_2); HCFC-21 (CHCl_2F), CHCl_3 , HF and some entrained catalyst (which are recycled to the reactor) and also HFC-23 (CHF_3) and HCl. Separation of the hydrocarbon compounds is facilitated by the differences in volatility, which make it possible to condense the chloroform and HCFC-21 for recycle and conversion to HCFC-22. A significant design and operating problem arises because the mixtures in the reactor column are far from ideal. In particular, hydrogen fluoride associates chemically with both itself and hydrohalocarbons to form weak compounds that complicate the distillation process and tend to carry more hydrogen fluoride out of the reaction system than would be expected solely from volatility considerations (Hamilton, 1963).

It is not possible to convert HFC-23, once formed, back into HCFC-22. Most of the HFC-23 produced is released from the reaction system along with the HCl and HCFC-22 products and, unless separated for collection or treatment, is emitted to the atmosphere subsequently.

This production process is relatively old (over 50 years) and has been extensively researched. However, the optimum operating conditions dictated by business economics are not necessarily the same conditions that minimise HFC-23 production. The upper bound for HFC-23 emissions is of the order of 3 to 4 percent of HCFC-22 production and a default value of 4 percent (to be used only when no measurements of HFC-23 production and release are available) is set in the IPCC Guidance and Guidelines (IPCC, 1996; 2001). However, as described above, the actual quantity of HFC-23 produced depends in part on how the process is operated and the degree of process optimisation that has been performed. In processes that have been fully optimised to reduce formation of HFC-23, the likely range of emissions is between 1.5 to 3 percent of production with 2 percent being a reasonable average estimate. Actual achievements vary depending on the age and design of the facility as well as the process management techniques applied. However, it is not possible to completely eliminate HFC-23 production by this means.

3.2 "Swing" Plant

One variation on the liquid phase process is the so-called "swing" plant, designed to be capable of manufacturing either CFC-12 or -11 from carbon tetrachloride feedstock or HCFC-22 from chloroform. Reactor designs for the two products are basically very similar, with differences only in operating pressure and temperature and heat load. However, the chemical engineering design of the whole plant is, of necessity, a compromise between the ideals for the two products and consequently optimisation of the process to minimise HFC-23 when producing HCFC-22 is intrinsically more difficult than in a plant designed for HCFC-22 specifically. It is to be expected that swing plants will operate at the higher end of the HFC-23 production range (say 3 to 4% of HCFC-22 by mass). Furthermore, the nature of swing plants is that they can produce either CFC-12 and -11 or HCFC-22 but not both at the same time and this need to operate the plant in campaigns will also tend towards larger production factors for HFC-23 because of the difficulties of optimising conditions when restarting after changeover.

3.3 Alternative processes for HCFC-22 production

Although it is technically feasible to manufacture HCFC-22 by reaction of chloroform and HF in the vapour phase over a solid catalyst (Hoechst, 1962) most, if not all, modern processes operate by the liquid phase route described above. Furthermore, control of a vapour phase process to minimise formation of HFC-23 is intrinsically more difficult than in the liquid phase. In the latter, conditions can be adjusted so that the boiling liquid in the reactor contains little HCFC-22, so minimising the possibilities to fluorinate it to HFC-23. In the vapour phase, on the other hand, all HCFC-22 that is produced co-exists towards the exit of the catalyst with the excess of HF (Hamilton, 1963). In a vapour phase process it is not impossible to adjust conditions to minimise HFC-23, only more difficult than in the liquid phase.

3.4 Release or Treatment of HFC-23

The major exit point for HFC-23 from the reaction system in the HCFC-22 production process is the condenser vent, whence it can be collected for use and sent to a disposal system (or discharged into the atmosphere) after the useful products (HCFC-22 and HCl) have been recovered. There are four additional sources of HFC-23 emissions, three of which are inconsequential:

3.4.1 Fugitive emissions from leaking compressors, valves and flanges: Because the process is maintained under relatively high pressures, there is a potential for fugitive emissions from leaking equipment. However, there is a strong incentive to prevent leaks

because of the noxious nature of the reactor contents and the potential for loss of valuable product (HCFC-22). Any leaks can usually be identified and repaired quickly and effectively. Fugitive emissions are a minor source; in two plants where they were measured, the HCFC-22 lost in this way amounted to less than 0.1% of plant production (Irving and Branscombe, 2000), and the loss of HFC-23 is likely to be much less.

3.4.2 Removal with the HCFC-22 product and subsequent emission is insignificant. Industry standard specifications limit the concentration of HFC-23 allowed in the product to a small fraction of a percent. Consequently, removal with the product also accounts for only a very small portion of the HFC-23 that is generated.

3.4.3 Vents from product storage are not significant sources, even when plants capture HFC-23 (by condensation at high pressures and low temperatures) and subsequently store it as pure material. The storage tanks are enclosed vessels, not normally venting to atmosphere, and only a very small fraction of the plants producing HCFC-22 practice recovery of HFC-23. This is clear from the small quantity of HFC-23 that is sold.

3.4.4 The most important of the additional loss routes is in the aqueous phases from caustic and water scrubbers used in the process. These may yield useful product, such as hydrochloric acid (aqueous HCl), or be destined for waste treatment but in any case volatile materials (such as HFC-23) in such aqueous streams are readily emitted when the streams are subsequently managed in open systems, such as wastewater treatment processes. HFC-23 concentrations in the aqueous effluent streams are only a few parts per million (ppm) at the most but the concentration in aqueous HCl can be several hundred ppm and this can represent an important release vector if the acid is used untreated. However, compared to the condenser vent, the aqueous HCl source is minor. Furthermore, the HFC-23 can be removed from the aqueous HCl by air-stripping for subsequent treatment in the thermal oxidiser.

3.5 Emission Reduction

It is clear from the process description that the actual quantity of HFC-23 produced, and potentially available to be released into the atmosphere, depends on the process design, how it is operated and the degree of process optimisation (within the scope dictated by economic constraints) that has been performed. In fully optimised processes, the likely range of emissions is about 1.5 to 3 percent of production with 2 percent being a reasonable average estimate. By definition, the default parameter (4% of HCFC-22 production) cannot be applied to an optimised process because the mere fact of optimisation requires production to be measured, hence a default parameter is redundant.

A value of 1.37% has been submitted by DuPont to the Emission Function Database maintained by IPCC and suggested to represent an appropriate baseline for all currently existing processes after they have been optimised (Appendices 3. 4 to 3. 7). Leaving aside the tautology of applying default to an optimised situation, the process described does not appear to be representative:

It is claimed to be the largest HCFC-22 facility in the world; this would mean that, with shrinking demand, the operators may be better placed than most to cope with the productive capacity implications of operating at lower HFC-23 make.

Apparently there was pre-existing equipment on the plant to recover HFC-23 for sale (SRI, 1998). Not only does this mean that the capital assets to remove and store HFC-23 were already emplaced, but the considerable expenditure of technical manpower resource needed to characterise the process operating parameters controlling HFC-23 would have been spent already.

The Dupont experience is interesting in that it is likely to represent the minimum level of HFC-23 achievable by process changes. Nevertheless, the potential reductions are not necessarily achievable by another HCFC-22 manufacturer because of differences in plant design and, even so, the technology to effect the changes would have to be made available. In addition, the cost implications for other manufacturers are likely to be significant and destruction facilities are still necessary to completely eliminate releases of HFC-23 to atmosphere.

3.6 Capture and destruction

Further reduction in emissions beyond what is technically achievable through process optimisation requires additional equipment and, given that there is one main outlet for HFC-23 from the process, the most favourable option to eliminate emissions is to collect and treat the vent gases. Thermal oxidation is an effective treatment in which the hydrofluorocarbon is incinerated in a furnace fuelled by, for example, natural gas. The consequent high temperature oxidation yields carbon dioxide and hydrogen fluoride. This is a special treatment process where the system must be designed to cope with, and render harmless, the halogen acids (HF and possibly HCl, depending on the waste mixture) produced as a result of combustion. This is accomplished by constructing the facility with appropriate acid resistant materials and by neutralising the acids as they are formed. See Figure 1 in Appendix 1. Neutralisation can be accomplished using any alkaline material and gives rise to harmless salts (such as sodium or calcium fluoride and chloride) that may be safely disposed of using conventional procedures. A potential advantage of using calcium hydroxide is that one of the products formed, calcium fluoride, is an insoluble solid, which may make disposal easier in some situations. In the context of global demand for acid neutralisation and for cement production, the resource requirements for neutralising the gases from a thermal oxidiser are trivial. Because the calcium or sodium salts formed are relatively cheap minerals, recovery from the thermal oxidiser effluent is unlikely to be viable and they will probably have to be disposed of as waste. One route for disposal is recycle into the HF production process (to partially replace mined calcium fluoride).

Depending on cost and availability, thermal oxidation treatment can be on- or off-site. On-site treatment has the advantage that the HFC-23 need not be captured and stored, minimising capital and operating costs. Treatment off-site will require the HFC-23 to be collected and stored, which may be less of an imposition if equipment and expertise to accomplish this exists already, and the costs might be offset by economies of scale and the ability to continue operating the HCFC-22 facility during periods when the destruction facility is being maintained. Emission tests at one plant showed that over 99.996 percent of the HFC-23 was destroyed (Irving and Branscombe, 2000) making this a highly effective treatment option but the impact of 'down-time' for maintenance of on-site thermal oxidation units on the emissions of HFC-23 needs to be considered (EFCTC, 2001).

3.7 Cost of Destruction

As of mid-2000 within the EU, thermal destruction was available, either on- or off-site, to six of the ten HCFC-22 manufacturing facilities. These facilities made up approximately 80% of EU HCFC-22 production but manufacturing plants in Spain (2), UK (1) and Greece (1) remained without such facilities then. The capital cost of a typical unit is Euro 3 million (about USD 4m) to destroy 200 metric tonnes of HFC-23 per year plus Euro 200,000 yr⁻¹ (250,000 USD) operating costs (EFCTC, 2001; Harnisch and Hendriks, 2000). There is little or no information on how the capital cost would change with scale but a facility to destroy a small amount of HFC-23 is likely to be very similar to one

capable of destroying a much larger amount. This is because the size of the equipment is dictated by the size of the thermal incinerator which depends on the fuel-gas throughput that, in turn, depends on the maximum instantaneous rate of non-flammable HFC-23 or other halocarbon fed into it.

4. Default Emission Factors

A default parameter is a number that is used in a calculation when the actual value is not known. The fact that the value is a default does not influence its magnitude, which could be an average value, a minimum or a maximum, depending on the logical reason for using a default. The only necessary condition for the use of a default value is that the real value is unknown (in this case probably because it has not been measured) and, conversely, if a value has been measured then the condition for using a default value fails.

For HCFC-22 plants in operation during the general baseline year of the Kyoto Protocol (1990), the default emission factor to be used in national greenhouse gas inventories is 0.04 kg HFC-23 per kg of HCFC-22 produced (4%) (IPCC, 1996). This value was based on broad experience of the operation of HCFC-22 plants up to the year 1990 and is representative of the emission when no abatement measures are implemented.

The extent to which this default matches with the overall operation of HCFC-22 facilities, world-wide, can be gauged using atmospheric measurements. Up to 1995, records of atmospheric concentrations of HFC-23 (Oram *et al.*, 1998) and global HCFC-22 production (McCulloch *et al.*, 2003) indicated a globally averaged emission intensity for HFC-23 of 20 Kg per tonne of HCFC-22 or 2%. The recorded atmospheric concentration was a consequence of total emissions of HFC-23 up to then and suggests that there was substantial abatement, either by capture for use as a raw material or process optimisation or destruction; unabated emissions would be expected to be of the order of 4% (Irving and Branscome, 2000).

An historical average emission of 2% is consistent with a default emission of 4%. Before 1995, HFC-23 was required for the manufacture of Halon-1301 and capture and use in this raw material application would have been a substantial part of the abatement then. Subsequently the requirement shrank dramatically after the phase out of Halon consumption in developed countries and process optimisation and destruction became the more important abatement options.

For plants constructed since 2000, a default emission factor of 0.03 kg HFC-23 per kg HCFC-22 (3%) will be recommended in the revision of the IPCC Guidelines, reflecting the improvements in technology and operating procedures that should have occurred during the 1990s. For the purpose of calculating national inventories, default values for intermediate dates are assigned using expert judgement based on the plant design and standard of operation. Uncertainty of the default value is in the region of 50%.

Approved Method AM0001 requires that, for an existing plant, the baseline is set from the lowest value of the HFC-23 emission factor measured during the three previous years. The IPCC default value then defines the upper boundary. Thus the baseline for CDM projects is the measured value of actual HFC-23 emissions (that include pre-existing process abatement measures). The IPCC default comes into play in AM0001 only if the measured values are "too high".

If abatement were in the form of vent gas treatment, significant emission should only occur when this was not in operation. The IPCC methodology allows for calculation of the emission when vent gas treatment is intermittent (IPCC, 2001).

For new plants, the revised default value (3%) should be used. In all cases, the cap implied by the default value is intended to obviate excessively rewarding abatement at plants which had been operated particularly inefficiently or to avoid over-rewarding abatement where the HFC-23 emissions had been over-estimated. The cap is therefore set at the IPCC default value.

If the cap were set at the level that can be achieved in an "optimised process" the abatement implied by optimisation would be have been effectively ignored. The optimisation will have required significant expenditure of technical resources, will likely require modifications to the existing equipment and capital expenditure. Depending on the actual design of the process, the optimisation may give rise to additional operating costs or to significant reduction in the quantity of HCFC-22 that the plant can make. Furthermore, in order to avoid inequities, the optimised value would have to be set for the "average plant", which does not exist. There is no logical reason for choosing the largest (or the smallest) plant in the world as the benchmark *when the requirement in AM0001 is for estimation of the actual baseline emissions*.

5. Estimating Historical Emissions

A default emission factor is of limited use in the CDM process because "emission of HFC-23 from HCFC-22 production should be estimated using the same method for the entire time series", as required for national inventories in the IPCC Guidelines (IPCC, 1996). Hence the only circumstance under which the default value *alone* may be applied to abatement of HFC-23 is where the abatement has been accomplished by stopping emissions of HFC-23 completely; either by total destruction of the HFC-23 or by shutting down HCFC-22 facilities. Unless the HCFC-22 facility and its HFC-23 destruction capability are only operated together (that is, the HCFC-22 plant is always shut down immediately the capability to destroy HFC-23 is not available), the condition of total destruction of HFC-23 will not be met. Thus, estimation of HFC-23 releases will be required and the default condition does not apply.

According to the IPCC Guidelines, in all cases the post-abatement form of calculation should also be applied to the situation pertaining before abatement commenced. The calculation may not be possible with the same degree of rigour throughout and allowance is made for this in the Guidance (IPCC, 2001). Four methods are suggested to enable comparisons over a time series, three of which can be applied to HFC-23 emissions: Overlapping Estimation, Surrogate Methods and Trend Extrapolation (the fourth, Interpolation, is unlikely to be useful since it implies that data are available at the start and finish of the time series).

5.1 Overlap and Surrogate Methods

In the case of HFC-23 from HCFC-22, there is no practical difference between the overlap and surrogate methods. Both methods require that the estimates prepared using both the previously used and the new method are compared in terms of the level and the trend. The surrogate method relates emissions estimates to underlying activity or other indicative data. For HFC-23 production from HCFC-22 this could mean that the HFC-23 production factor, relative to the HCFC-22 made (and measured *after* destruction facilities have been installed), could be applied throughout the time period. The quantity of HCFC-22

produced would then provide the surrogate to calculate the quantity of HFC-23 produced and either released or destroyed.

5.2 Trend Extrapolation

This is used when the historical data are incomplete and it may be necessary to extrapolate from the closest detailed estimate. Trend extrapolation simply assumes that the observed trend in data during the period when detailed estimates are available remains constant over the period of extrapolation. Given this assumption, it is clear that the method cannot be used for the trend in estimated emission but could be used to estimate the surrogate parameter. Extrapolation should not be used over long periods of time without detailed checks at intervals to confirm the continued validity of the trend.

6. Measurement and estimation at the plant level

6.1 Guidelines and Guidance revised methodology

The IPCC Guidance for development of greenhouse gas inventories recognises that two broad approaches to estimating HFC-23 emissions from HCFC-22 plants exist. Both approaches were valid within the framework of the IPCC Guidelines for National Emissions Inventories (IPCC, 1996) and have been used in the development of some national inventories (Defra, 2002a and 2002b).

6.2 Simple methodology, use of the default factor or a factor derived from process efficiencies

In the simpler methodology, a default factor, or a more appropriate number derived for the particular facility's circumstances, can be used to estimate emissions of HFC-23 from the total HCFC-22 production (for both potentially dispersive and feedstock end-uses) from each facility.

$$\text{By-product HFC-23 Emissions (kg)} = \frac{\text{HFC-23 Factor (kg/kg)} \times \text{Total HCFC-22 Production (kg)}}{\quad} \quad (5)$$

The "HFC-23 factor" may be the default emission factor if no other information is available but it should be possible in any plant to derive an actual HFC-23 emission factor from records of process efficiencies. The factor can be calculated from both the carbon efficiency (Equation 6) and the fluorine efficiency (Equation 7) and the value used in Equation (5) should normally be the average of these two values unless there are overriding considerations (such as a much lower uncertainty of one of the efficiency measures) that can be adequately documented.

The carbon balance efficiency is the ratio of the carbon in the HCFC-22 product sold to the carbon in the total quantity of chloroform fed into the plant. Thus losses of chloroform itself, HCFC-22 and byproducts such as HFC-23, are all included in the loss in efficiency. Similarly, the fluorine balance efficiency is the ratio of fluorine in the HCFC-22 product sold to that in the hydrogen fluoride fed into the plant. The most accurate means of measuring these quantities is by weight but the design and situation of the facility will dictate whether or not that is possible. It is likely that all of the HCFC-22 product will be weighed but, if the raw materials are delivered by pipeline from other plants in the same complex (as is often the case for hydrogen fluoride), measurements may be made by flowmeter(s) that are inherently less accurate than weighing.

$$\text{HFC-23 factor (kg/kg)} = (100 - \text{Carbon Balance efficiency})(\%) \times \text{Factor to assign efficiency loss to HFC-23} \times$$

$$\text{Factor for the Carbon content of HFC-23 compared to HCFC-22} \quad (6)$$

or

$$\begin{aligned} \text{HFC-23 factor (kg/kg)} &= (100 - \text{Fluorine Balance efficiency})(\%) \times \\ &\text{Factor to assign efficiency loss to HFC-23} \times \\ &\text{Factor for the fluorine content of HFC-23 compared to HCFC-22} \end{aligned} \quad (7)$$

The factor to assign the efficiency loss to HFC-23 is specific to each plant and, if this method of calculation is used, the factor should have been established by the operator of the facility. By default, the value is 1; that is all of the loss in efficiency is due to co-production of HFC-23. Other inefficiencies can arise from losses of raw material or loss of product but these would be expected to be random, uncontrolled and relatively small while the release of HFC-23 into the atmosphere, if carried out, is systematic and is generally the largest single factor affecting efficiency.

The factors for carbon and fluorine contents are calculated from the molecular compositions of HFC-23 and HCFC-22 and so are common to all HCFC-22 plants at 0.81 for carbon and 0.54 for fluorine.

This can give an adequate value for the HFC-23 emission factor that has a much smaller uncertainty than the default; typically better than 20%, compared to 50%. The limits are posed by the accuracy of measurement of the quantities of HCFC-22 produced and the raw materials used. Typically, for a plant producing about 4% HFC-23, the carbon efficiency is in the region of 95% and the fluorine efficiency 92%. If these efficiencies can be measured to within 1%, then the error in the HFC-23 estimate would be less than 20%. Estimating efficiencies to this degree of accuracy will require rigorous accounting procedures and that all raw materials and product for sale should be weighed in or out of the facility.

6.3 Direct measurement of HFC-23 releases

A potentially more accurate estimate is given by factory specific emissions determined using standard methods to estimate the composition and flowrate of gas streams vented to atmosphere. In this case:

$$\text{HFC-23 Emissions} = \sum_i \int_t f_i C_i \quad (8)$$

where:

the sum over all i streams of the emitted mass flows f and concentrations C is integrated over time t .

or, where proxy methodology is used (as described in Equation 11 below):

$$\text{HFC-23 Emissions} = \sum_i \int_t E_i \quad (9)$$

Where E_i are the emissions from stream determined by the proxy methods.

The method is based on measurement of the concentration and flow-rate from the vent at an individual plant. So that the quantity emitted to atmosphere is the mathematical product of the mass concentration of the component in the stream, the flowrate of the total stream (in units compatible with the mass concentration) and the length of time that this flow occurred:

$$\text{HFC-23 Emissions (kg)} = \text{Concentration of HFC-23 in vent stream} \times \text{mass flow of vent stream} \times \text{duration(s) of release(s) from vent} \quad (10)$$

6.4 Continuous estimate of HFC-23 production using a proxy

In many cases, measurements are not continuous but were gained during an intensive process survey or plant trial, and the results of the trial may be used to provide a proxy for calculating emissions during normal plant operation. In this case, the emission rate of the byproduct is normalised to a more easily (or accurately) measurable parameter, such as feedstock flow rate. The trial(s) must meet the following conditions:

There should have been no major process design, construction or operating changes that affect the plant upstream of the measurement point and so could render relationships between emissions and production invalid.

The relationship between emissions and plant operating rate must be established during the trial(s), together with its uncertainty.

For almost all cases the rate of plant operation is a suitable proxy and the quantity of HFC-23 emitted depends on the ratio of current plant operating rate to that at which the trial was conducted, a proportionality constant relating operating rate to the rate of production of HFC-23 and the length of time that the vent flow was released:

$$\text{HFC-23 Emissions (kg)} = \text{Standard Emission of Component during trial} \times \text{Factor relating Emission to Plant Operating Rate} \times \text{Plant Operating Rate} \times \text{On-line time} \quad (11)$$

$$E_{j,k} = S_{j,k} \cdot F_{j,k} \cdot P_c \cdot t \quad (12)$$

Where:

$E_{j,k}$ is the mass emission of component k in vent stream j ,

$S_{j,k}$ is the standard mass emission of component k in vent stream j (described in Equation 13, below),

$F_{j,k}$ is a factor relating the emission rate during the trial to plant operating rate. This is the proportionality constant for emissions that are linearly related to operating rate and in many cases will be unity. For situations where the emissions are a more complex function of operating rate the proxy method is not considered appropriate and continuous measurement is desirable. The units of the factor are mass per unit process operating rate and must be compatible with the standard mass emission calculated in Equation 11.

P_c is the current process operating rate, averaged over t and

t is the actual total duration of venting for the year, or the period if the process is not operated continuously, and annual emissions become the sum of all the periods during the year.

$$\text{Standard Emission of Component} = \text{average mass concentration of HFC-23 in the vent during trial} \times \text{average Mass Flowrate in vent during trial} / \text{Plant Operating Rate during trial} \quad (13)$$

$$S_{j,k} = C_{j,k} \cdot R_j / P_T \quad (14)$$

Where:

$S_{j,k}$ is the standard mass emission of component k in vent stream j , in units compatible with the factors in Equation 12,

$C_{j,k}$ is the average mass fractional concentration of component k in vent stream j during the trial,

R_j is the average mass flowrate of vent stream j during the trial and

P_T is the process operating rate during the trial.

The accuracy and precision of the estimates of annual HFC-23 emissions depend on the number of samples (the frequency of sample collection) together with the accuracy of measurement of flowrates and the extent to which discrete flow measurements can represent the total quantity vented. For example, a study of HCFC-22 producers has indicated that sampling once per day is sufficient to achieve an extremely accurate annual estimate of the composition of the vent stream in those plants where the HFC-23 release is estimated directly (RTI, Cadmus, 1998). Such regular sampling of the vent stream can achieve an accuracy of 1-2% at a 95% confidence level in the composition of HFC-23 emissions, measured continuously. The uncertainty of the flowrate of the vent stream may be considerably higher, depending on the design and installation of the flow measuring equipment.

The proxy methodology is potentially the most accurate, if only because the difficult parameters, such as the composition and flowrate of the vent stream, should be measured during an intensive campaign with significant technical resources. Subsequent measurements are then based on parameters that are routinely measured as part of process operation and can be checked independently.

In both cases, the uncertainty may be calculated statistically from the uncertainties of the input parameters. Production processes are not completely static, however each HCFC-22 process described here has relatively small process variability so that production of HFC-23 should generally scale to plant throughput (or some similar measure). The exception arises where the plant has been substantially altered, for example by putting in new equipment or by operating the reaction system under different physical conditions. These will introduce systematic changes that would need a revised procedure for HFC-23 measurement but may not affect the uncertainty (random error) of the measurement.

7. Projected emissions of HFC-23

7.1 *The Business as Usual Case*

Global emissions of HFC-23 increased by an estimated 12% between 1990 and 1995, due to a similar increase in global production of HCFC-22 (Oram *et al.*, 1998). However, apparently due to widespread implementation of process optimisation and thermal destruction, this trend in HFC-23 emissions has not continued and since 1995 has become smaller than the increase in production (USEPA, 2003). The average emission factor is now equal to 2% of HCFC-22 production and, for a *Business as Usual* scenario to represent the maximum level of emissions to 2015, it has been assumed that emissions from existing capacity will continue at this factor. For the same scenario it is assumed that new capacity will emit HFC-23 at a rate of 4%, again giving a maximum. Consequently, emissions of HFC-23 would grow by 60% between now and 2015, from about 14,000 tonnes/year in 2003 to 24,000 tonnes/year.

In view of the uncertainties of scenario generation, the Business as Usual scenario uses consumption forecasts based on adherence to the Montreal Protocol, with no further controls. This is a fixed scenario (for the developed world) and amounts to a 90% reduction in production and consumption of HCFCs for non-feedstock uses there by 2015, although many countries already have or plan more stringent regulations. In 2010 in the US, producing and importing HCFC-22 is banned, except for use in equipment manufactured before 2010, under the U.S. Clean Air Act (USEPA, 1993). Within the EU, it is estimated that levels of HCFC-22 production for non-feedstock uses will decrease by 30% by the year 2010 under the EU Regulation 2037/2000 on Substances that Deplete the Ozone Layer (EFCTC, 2001; EU, 2000). Such legislation is well documented and the current effect on production of HCFC-22 is recorded in the data reported by AFEAS (2004), which shows a fall of 73,000 te yr⁻¹ by the year 2002 from the peak production of 271,000 te yr⁻¹ that occurred in 1996. Thus the potentially dispersive consumption in the developed world is already substantially below that in the Business as Usual Scenario and could fall faster, skewing the probability of HFC-23 emissions towards the reduced emissions case.

Under the Montreal Protocol, the baseline year for developing countries is 2015, so that the regulatory maximum has yet to be established and production of HCFC-22 was extrapolated from prior trends. In China, production of HCFC-22 for commercial (dispersive) use grew over the four years from 1998 to 2001 at a linear rate of 18,100 te yr⁻¹ ($R^2 = 0.95$), or 26% in the year 2000 (CCR, 2002). When the other developing and CEIT country producers are added in, the growth rate is calculated to reach 20,000 tonnes yr⁻¹ and this rate has been assumed for both business as usual and reduced emissions cases. Changes in production rates will scale directly to change in the forecast HFC-23 emissions, assuming that abatement policy does not vary.

Historically, the demand for HCFC-22 in fluoropolymers has been growing linearly in the developed world at a rate that approximated to 3% in the year 2000, or absolute growth rates of 2200 te yr⁻¹ in U.S.A., 1600 te yr⁻¹ in Japan and 2000 te yr⁻¹ in the EU (Cefic, 2003; SRI, 1998). For China in the year 2001, the demand for HCFC-22 in production of fluoropolymers was 20300 metric tonnes and the linear growth rate was 4100 te yr⁻¹, with an R^2 value of 0.99, over four years (CCR, 2002). There is every reason to expect that this demand will continue to grow and there is no evidence to predict a change in the growth rate. Hence, for both cases, demand for HCFC-22 in fluoropolymers was extrapolated using linear growth at these rates.

7.2 Projected Reduction in Emissions using Current Best Practice

It is apparent from historical trends, as described above, that approximately half of the HFC-23 co-produced with HCFC-22 in the developed world is abated. For the reduced emissions case, it is assumed that destruction technology is progressively introduced for all new and non-abated existing capacity 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. Introduction of the destruction technology is assumed to take 10 years, with no difference in the timescale between developed and developing countries.

Reduced emissions were calculated from 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 deployment of destruction technology. Values for the forecasts and the HCFC-22 production on which they are based are shown in Table 3. These forecasts are illustrative and are designed to represent

potential extreme cases, so that future changes in activity will tend to increase the probability of one possible outcome over the other.

Table 3. Calculated Emissions of HFC-23 under the Business as Usual Case, representing a maximum, and a Reduced Emissions Case, representing application of current best practices.

Year	Business as Usual (Maximum) Case					Reduced Emissions Case		
	HCFC-22 production (Developed Countries)	HFC-23 releases (Developed Countries)	HCFC-22 production (Developing Countries)	HFC-23 releases (Developing Countries)	Total HFC-23 releases	HFC-23 releases (Developed Countries)	HFC-23 releases (Developing Countries)	Total HFC-23 releases
1990	321	6.1	18	0.7	6.8	6.1	0.7	6.8
1991	355	6.7	17	0.7	7.4	6.7	0.7	7.4
1992	369	7.0	17	0.7	7.7	7.0	0.7	7.7
1993	361	6.8	21	0.9	7.7	6.8	0.9	7.7
1994	359	6.8	27	1.1	7.9	6.8	1.1	7.9
1995	365	6.9	19	0.8	7.7	6.9	0.8	7.7
1996	407	7.7	20	0.8	8.5	7.7	0.8	8.5
1997	377	7.1	30	1.2	8.3	7.1	1.2	8.3
1998	392	7.4	56	2.2	9.7	7.4	2.2	9.7
1999	379	7.2	82	3.3	10.5	7.2	3.3	10.5
2000	366	6.9	108	4.3	11.2	6.9	4.3	11.2
2001	345	6.6	134	5.3	11.9	6.6	5.3	11.9
2002	332	6.3	159	6.4	12.7	6.3	6.4	12.7
2003	338	6.4	185	7.4	13.8	6.4	7.4	13.8
2004	313	5.9	211	8.4	14.4	5.9	8.4	14.4
2005	319	6.0	237	9.5	15.5	5.5	8.6	14.1
2006	325	6.2	263	10.5	16.7	5.1	8.6	13.7
2007	330	6.3	289	11.6	17.8	4.6	8.4	13.0
2008	336	6.4	315	12.6	19.0	4.1	8.1	12.1
2009	342	6.5	341	13.6	20.1	3.6	7.5	11.1
2010	270	5.1	366	14.7	19.8	2.4	6.7	9.1
2011	276	5.2	392	15.7	20.9	1.9	5.8	7.7
2012	282	5.4	418	16.7	22.1	1.5	4.7	6.2
2013	288	5.5	444	17.8	23.2	1.0	3.4	4.4
2014	294	5.6	470	18.8	24.4	0.6	1.9	2.4
2015	235	4.5	496	19.8	24.3	0.4	2.0	2.4

8. Economic Considerations

8.1 Value of HCFC-22 and added value

As was demonstrated in Section 2 above, the price of HCFC-22 charged by manufacturers lies between \$1100 and \$2400 per tonne, depending on where in the world the material is sold and on the terms and conditions of supply; contracts for long-term, secure supplies having a different value from material bought immediately on the open market as "spot" lots. Such a differential, by a factor greater than two, is consistent with a market dominated in the developed world by long term contracts and short supply chains. This has the effect that, although the market for HCFC-22 is highly competitive, changes in price do not immediately translate into a change for the user industries.

The systems manufactured and serviced by the user industries have values in the region of 100 times that of the HCFC-22 that they contain. Thus changes in price of HCFC-22 have little effect on the economics of the operations of user industries. Consequently, a major price reduction would have little or no effect on the demand for the systems provided by user industries and a similarly small effect on the demand for HCFC-22.

8.2 Global Economic Effects of the Clean Development Mechanism

8.2.1 Value of HCFC-22 Production

Tables 1 and 3 show the shift of production of HCFC-22 from developed countries to the developing world that has already started and is expected to continue throughout the next decade. Only the HFC-23 produced as by-product in the developing countries could be considered for abatement under the Clean Development Mechanism (CDM); releases in the developed world are expected to be abated without subsidy. Nevertheless, all of the HCFC-22 produced can be traded throughout the world, potentially.

Between now and the year 2015, the average quantity of HFC-22 produced in the developing world (in the forecast scenario outlined in this review) is expected to be about 380,000 tonnes/year. The range of this forecast is 240,000 to 500,000 tonnes/year. The average production would have a value of between \$420 million and \$910 million per year, at the range of current manufacturers' selling prices (at \$2000/tonne, the value would be \$760 million per year). The values at the extremes of the range of forecast production are considerably larger at \$260 million to \$1.2 billion per year but, for the purposes of this illustration, the average will be used.

8.2.2 Total Value of HFC-23 Abated under CDM (with no constraints)

This calculation is highly dependent on the values assumed for the parameters and so can only be illustrative. Table 3 shows the range of HFC-23 emissions that would be eligible for consideration in the CDM in an unconstrained system that sanctioned CDM projects at plants built in the future without HFC-23 abatement. Assuming that the forecast Business as Usual Scenario could actually happen, the average quantity of HFC-23 that is potentially available in the unrestrained scenario is just over 15,000 tonnes/year. Also assuming that abatement is performed by thermal oxidation that operates for 90% of the time that the HCFC-22 plant is running and is totally effective while it is operating, the actual abatement that could be accomplished averages 13,700 tonnes/year.

For the purposes of this illustration, it is assumed that the value in the CDM of one tonne of CO₂ equivalent abated is \$5. So that, with a GWP of 11,700, the value of the abated HFC-23 becomes 13,700 x 11,700 x 5 or \$800 million per year on average. The effects of emissions from the thermal oxidiser associated with fossil fuel combustion are trivial in this context.

The cost of abating 13,700 tonnes/year of HFC-23 from an assumed 30 individual facilities would total some \$31 million per year. This assumes that each facility costs \$4 million to build and that operating costs are \$250,000/year/facility. A 20% return on the capital cost to amortise and reward the outlay is assumed. Despite these generous terms, the cost of abatement is only a small fraction of the value of the HFC-23 as its CO₂ equivalent.

Since the GWP of HFC-23 is fixed, the potential for different values depends on only the value of the CO₂ equivalents, which is fixed by the value of actual CO₂ reductions (from fossil fuel combustion) and on the quantity adopted for CDM projects. The latter has the

larger potential variability and may be effectively influenced by constraints on the eligibility of projects or of the extent of abatement claimed within the project.

8.2.3 Value of HFC-23 Abated under CDM (with constraints on eligibility)

The current plants that are eligible for CDM projects already exist and may have been constructed at a time when the value of abating HFC-23 was not as readily apparent as it is now. However, it is questionable that CDM money should be claimed for abating HFC-23 emissions in future plants (not yet constructed) when the technology to perform that abatement exists now and could be incorporated at the design stage for new facilities. In this case, the emission factor of 1.37% suggested by DuPont for a process without thermal oxidation would have merit; provided that such technology were made available. In any event, the prospect of facilities being constructed in the future without abatement technology just in order to take advantage of the CDM when that technology is installed would, indeed, be perverse.

Restricting CDM projects to facilities that exist now would act to approximately halve the total value of HCFC-23 abatement in the CDM between now and 2015, based on the expected demand for HCFC-22 shown in Table 3. Given that the aim of the CDM is to reduce greenhouse gas emissions, the future value when a new plant is built could be restricted to, for example, the cost of constructing and operating the HFC-23 disposal facility.

8.3 Local Value of Abatement and Downstream Economic Effects

If the global values are scaled down to an individual facility, it is possible that the value of the HFC-23 abated under a CDM project could become equivalent to the value obtained from selling the HCFC-22 produced in the facility. If the value of the CDM project were acquired by the facility's operators, this would radically alter the economics of their HCFC-22 production and could mean that a substantial part of its price is subsidised. This is likely to have several effects.

The operator would have a massive competitive advantage in the HCFC-22 market. This could enable significant price reductions. However, as has been demonstrated earlier in this review, such price reductions would not have a significant effect on the quantity of HCFC-22 sold. This is dictated by the demand for systems containing HCFC-22 and, since the value of each system is in the region of 100 times the value of the HCFC-22 it contains, the price of the system is hardly influenced at all by the HCFC-22 price. For the one third of HCFC-22 that is used as a feedstock for the manufacture of fluoropolymers, such as polytetrafluoroethylene (PTFE), the economic outcome is similar. Although a reduced price for HCFC-22 translates directly into reduced costs for PTFE manufacturers, the value added to PTFE is even greater than that added to HCFC-22. As a simple example, the PTFE content of non-stick kitchenware costs a fraction of a cent compared to a selling price of dollars.

Where price reduction would severely affect the market is in the competition between HCFC-22 and fluoropolymer manufacturers. The availability of subsidised HCFC-22 would depress prices generally. This could result in producers with higher costs becoming non-viable and closing their facilities. The effect of this on greenhouse gas emissions would be neutral at worst and could be beneficial. Given that the market size is (at least in the short term) governed by the demand for systems containing HCFC-22, production would simply switch to the subsidised facility which, by definition, has abatement technology installed and operating. A switch from a facility that, itself, is abated would be

environmentally neutral. If the abatement were any less effective than that in the facility having the CDM project, there would be an environmental benefit.

The migration of HCFC-22 production from the developed world to developing countries is already happening (see Table 1) and one effect of subsidy of facilities by CDM projects would be to hasten this trend.

9. Conclusions

HFC-23 production is an inevitable consequence of the manufacture of HCFC-22. Even in the largest facility in the world, after extensive process optimisation, HFC-23 is still made at a rate of some 1.4% of the total production. While it is possible to eliminate this HFC-23 by, for example, a thermal oxidation system, all abatement procedures require intervention and carry capital and operating costs.

The default emission factor for older plants is 4%, with 3% for newer facilities, but use of a default is no substitute for actual measurement (which is required by AM0001). The measurements and estimates may be conducted in a number of ways, using tried and tested protocols, and so ability to make the measurements should not be a barrier. The default emission factor limits the maximum abatement that can be claimed for a CDM project. However, the presumption that this value may be set, for plants that already exist, to the best that the largest plant in the world can accomplish (1.37%) is illogical. It would mean that the technology to meet this rate would have to be available to all and presupposes that no costs are involved.

CDM projects for HFC-23 abatement have the potential to alter economics radically and have the effect of becoming subsidies on the production of HCFC-22. As an illustration, using global costs and values it is clear that a CDM project would have a significant impact on the economics of the facility receiving it and could be equal to the value of the HCFC-22 the facility produces. The reasons for this large impact are the high gearing that is a consequence of the high GWP of HFC-23 and the value of a carbon dioxide equivalent unit, that is set by the cost of ameliorating CO₂ from fossil fuel combustion.

The market for HCFC-22 is into refrigeration (and air conditioning) and fluoropolymers (PTFE). In both cases, volume is driven by the economics of selling the finished products; HCFC-22 costs are a tiny fraction of finished product costs and so do not materially affect the size of those markets. Consequently, leakage (defined as increased use of HCFC-22 due to lower costs) is not significant. Nor would there be any economic incentive for HCFC-22 plants to be constructed speculatively since, even if the product were given away, the effect on the size of the final market and hence the demand for HCFC-22 would be insignificant.

On the other hand distortion of market economics from a CDM project can have a profound effect on individual facilities, allowing the subsidised facility to capture greater market share by consistently undercutting the competition (particularly the competition in developed countries). This may actually benefit the environment if the consequence is that facilities lacking abatement are shut down. Further CDM projects will assist the pre-existing trend towards production in developing countries at the expense of the developed world.

It would be perverse to reward the future construction of an HCFC-22 plant that had been built without the capability to destroy its HFC-23 simply in order to claim CDM money when the capability was installed. Possible remedies include the restriction of CDM projects for future plants to the cost of installing the destruction capability, or setting the

maximum value claimable to the 1.37% suggested by DuPont, provided that the technology to do this were freely available. Restricting the availability of future CDM money in these sorts of ways could halve the cost by 2015.

In any event, CDM projects for HFC-23 abatement are likely to have a value of several hundred million dollars a year if all the existing potential is realised. The resulting saving in greenhouse gas emissions could amount to, on average, 160 MTe CO₂ equivalent/year. For comparison, if all HFC-23 were abated in the same way, the global total (including abatement not eligible for CDM) would average 290 MTe CO₂ equivalent/year.

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Appendix 1. Approved Baseline Methodology - AM0001

Paragraph 12 from the report of the fifteenth meeting of the CDM Executive Board (for full report please see <http://cdm.unfccc.int/EB/Meetings/>):

12. Taking into consideration information that has emerged since the approval of AM0001, the Board agreed to request the Meth Panel to review this methodology and make a recommendation on the possible revision in order to address, inter alia, the potential leakage, for consideration of the Board. The Board further agreed that such revision shall be completed no later than four months. The Board agreed that this revision is significant and the methodology should therefore be put on hold.

Approved baseline methodology AM0001

“Incineration of HFC 23 waste streams”

Source

This methodology is based on a proposal from the HFC Decomposition Project in Ulsan, Republic of Korea whose Baseline study, Monitoring and Verification Plan and Project Design Document were prepared by INEOS Fluor Japan Limited (Japan), Foosung Tech Corporation Co., Ltd. (Korea) and UPC Corporation Ltd. (Korea) (version 2.4, July 8, 2003). For more information regarding the proposal and its consideration by the Executive Board please refer to case NM007: “HFC Decomposition Project in Ulsan” on <http://cdm.unfccc.int/methodologies/approved>.

Selected approach from paragraph 48 of the CDM modalities and procedures

“Existing actual or historical emissions, as applicable”

Applicability

This methodology is applicable to HFC 23 (CHF₃) waste streams from a HCFC production facility where the project activity occurs and where regulations do not restrict HFC 23 emissions.

Project Activity

Production of HCFC 22 generates the HFC 23. Some of the HFC 23 may be captured and sold, but the HFC 23 may also be released to the atmosphere. The project activity captures and decomposes the HFC 23 that would otherwise be released to the atmosphere (and any HCFC 22 present in this waste stream)¹.

Emission Reduction

Waste HFC 23 is typically released into the atmosphere. Thus, absent regulations to restrict HFC 23 emissions, any HFC 23 not recovered for sale is assumed to be released to the atmosphere.

¹ In the example of the Ulsan project activity proposal the destruction process will decompose the HFC 23 by heating it to more than 1,200°C in a thermal oxidation chamber with air and steam using LNG as a supplemental fuel. This yields CO₂, HCl and HF as by-products in a hot stream of offgas that also contains nitrogen, oxygen, carbon dioxide and moisture. This gas stream is cooled, the acids and moisture are absorbed in an aqueous solution and the acids in the solution are then neutralized with slaked lime to yield calcium chloride (CaCl₂) and calcium fluoride (CaF₂). The CaCl₂ and CaF₂ are disposed in a landfill. The remaining cooled and neutralised gas (now nitrogen/oxygen/carbon dioxide with low levels of moisture) is vented to atmosphere.

The greenhouse gas emission reduction achieved by the project activity is the quantity of waste HFC 23 actually destroyed less the greenhouse gas emissions generated by the destruction process less leakage due to the destruction process. Specifically, the greenhouse gas emission reduction (ER_y) achieved by the project activity during a given year (y) is equal to the quantity of HFC 23 waste from HCFC production facility (Q_HFC23_y) destroyed by the project activity less the baseline HFC 23 destruction (B_HFC23_y) during that year multiplied by the approved Global Warming Potential² value for HFC23 (GWP_HFC23) less the greenhouse gas emissions generated by the destruction process (E_DP_y) less greenhouse gas leakage (L_y) due to the destruction process.

$$ER_y = (Q_HFC23_y - B_HFC23_y) * GWP_HFC23 - E_DP_y - L_y$$

Where ER_y is the greenhouse gas emission reduction measured in tonnes of CO₂ equivalents (tonnes CO₂e), Q_HFC23_y is the quantity of waste HFC 23 destroyed during the year measured in metric tonnes, and B_HFC23_y is the baseline quantity of HFC 23 destroyed during the year measured in metric tonnes. The Global Warming Potential converts 1 tonne of HFC 23 to tonnes of CO₂ equivalents (tonnes CO₂e/tonnes HFC 23). The approved Global Warming Potential value for HFC 23 is 11,700 tonnes CO₂e/tonne HFC 23. The emissions due to the destruction process (E_DP_y) and leakage (L_y) are both measured in tonnes of CO₂ equivalent. The quantity of waste HFC 23 destroyed (Q_HFC23_y) is calculated as the product of the quantity of waste HFC 23 supplied to the destruction process (q_HFC23_y) measured in metric tonnes and the purity of the waste HFC 23 (P_HFC23_y) supplied to the destruction process expressed as the fraction of HFC 23 in the waste [$Q_HFC23_y = q_HFC23_y * P_HFC23_y$].

The destruction process uses fuel (e.g., natural gas), steam and/or electricity. The steam and electricity are assumed to be purchased, so the emissions associated with these energy sources are included in the leakage calculation.³ The emissions due to the destruction process (E_DP_y) are the emissions due to the natural gas use, the emissions of HFC 23 not destroyed and the greenhouse gas emissions of the destruction process. Thus:

$$E_DP_y = ND_HFC23_y * GWP_HFC23 + Q_NG_y * E_NG_y + Q_HFC23_y * EF$$

Where ND_HFC23_y is the quantity of HFC 23 not destroyed during the year, Q_NG_y is the quantity of natural gas used by the destruction process during the year measured in cubic-metres (m³), and E_NG_y is the emissions coefficient for natural gas combustion measured in tonnes CO₂ equivalent per cubic metre of natural gas (t CO₂e/m³). The value of E_NG_y will vary by region and over time⁴, but is of the order of 0.00188 tCO₂e/m³. If a different fuel, such as liquid petroleum gas (LPG), is used for the incineration process, the variables Q_NG_y and E_NG_y are replaced with variables for the quantity of fuel used and emissions coefficient for that fuel.

The quantity of HFC 23 not destroyed (ND_HFC23_y) is typically small⁵; the monitoring plan provides for its periodic on site measurement. Theoretically HFC 23 can also leak to the water effluent and then escape to the atmosphere. This possibility is ignored because it is infinitesimally small; the solubility of HFC 23 is 0.1% wt at 25°C water.

² Global Warming Potential values used shall be those provided by the Intergovernmental Panel on Climate Change in its Second Assessment Report (“1995 IPCC GWP values”).

³ If the steam and/or electricity was generated within the project boundary, the associated emissions would be included in the equation for the emissions due to the destruction process.

⁴ In the example of the proposed Ulsan project activity it is of the order of 0.00188 tCO₂e/m³.

⁵ In the example of the proposed Ulsan project activity the quantity of HFC 23 not destroyed is estimated at 0.001% of the quantity of HFC 23 supplied to the destruction process.

The thermal destruction process converts the carbon in the HFC 23 into CO₂, which is released to the atmosphere. The quantity of CO₂ produced by the destruction process is the product of the quantity of waste HFC 23 (Q_HFC23_y) destroyed and the emission factor (EF). The emission factor is calculated as follows:

$$EF = 44 / [(\text{molecular weight of HFC 23}) / (\text{number of C in a molecule of HFC 23})] = 44 / [70 / 1] = 0.62857$$

The thermal destruction process also produces a small quantity of N₂O emissions. The N₂O emissions, on a CO₂ equivalent basis, are a small fraction of the CO₂e emissions and so are ignored.

Baseline

The baseline quantity of HFC 23 destroyed is the quantity of the HFC 23 waste stream required to be destroyed by the applicable regulations. If the entire waste stream is destroyed, Q_HFC23_y is the total amount of HFC 23 waste generated and the quantity required to be destroyed by the applicable regulations is:

$$B_{\text{HFC23}_y} = Q_{\text{HFC23}_y} * r_y$$

Where r_y is the fraction of the waste stream required to be destroyed by the regulations that apply during year y. In the absence of regulations requiring the destruction of HFC 23 waste, the typical situation in non-Annex B Parties, r_y = 0. Absent regulations on HFC 23 emissions, the HFC 23 waste is typically released to the atmosphere so the baseline is zero destruction.

To exclude the possibility of manipulating the production process to increase the quantity of waste, the quantity of HFC 23 waste (Q_HFC23_y) is limited to a fraction (w) of the actual HCFC production during the year at the originating plant (Q_HCFC_y).

$$Q_{\text{HFC23}_y} \leq Q_{\text{HCFC}_y} * w$$

Where Q_HCFC_y is the actual production of HCFCs during the year at the plant where the HFC 23 waste originates measured in metric tonnes. The coefficient w is the waste generation rate (HFC 23⁶)/(HCFC 22) for the originating plant. The value of w is set at the lowest actual value during the three years prior to the start of HFC 23 destruction to a maximum of the IPCC default value of 4% (0.04 tonnes of HFC 23 produced per tonne of HCFC 22 manufactured). If the waste originates at a new plant or no historical data are available, the lowest IPCC default value of HFC 23 produced per tonne of HCFC 22 manufactured shall be used.

Additionality

In the absence of regulations requiring HFC 23 destruction it is typically released to the atmosphere because a destruction facility entails significant capital and operating costs and the host entity has no direct economic incentive to incur these costs. If the quantity of HFC 23 destroyed is greater than the baseline quantity destroyed, the project activity is additional. The baseline quantity of HFC 23 destroyed is the quantity, if any, required to be destroyed by the host country's regulations governing the plant.

Leakage

⁶ The quantity of HFC 23 used to calculate this coefficient is the sum of HFC 23 recovered for sale plus the waste HFC 23.

Leakage is emissions of greenhouse gases due to the project activity that occur outside the project boundary. The sources of leakage due to the destruction process are:

- Greenhouse gas (CO₂ and N₂O) emissions associated with the production of purchased energy (steam and/or electricity)
- CO₂ emissions due to transport of sludge to the landfill

$$L_y = \sum_i (Q_{F_{i,y}} * E_{F_{i,y}}) + ET_y$$

Where $Q_{F_{i,y}}$ is the quantity of energy type F_i purchased for the destruction process during year y , $E_{F_{i,y}}$ is the greenhouse gas emissions factor for energy type F_i during year y , and ET_y and the greenhouse gas emissions associated with sludge transport during year y .

Approved monitoring methodology AM0001

“Incineration of HFC 23 waste streams”

Source

This methodology is based on the HFC Decomposition Project in Ulsan, Republic of Korea whose Baseline study, Monitoring and Verification Plan and Project Design Document were prepared by INEOS Fluor Japan Limited (Japan), Foosung Tech Corporation Co., Ltd. (Korea) and UPC Corporation Ltd. (Korea) (version 2.4, July 8, 2003). For more information regarding the proposal and its consideration by the Executive Board please refer to case “NM007: HFC Decomposition Project in Ulsan” on <http://cdm.unfccc.int/methodologies/approved>.

Applicability

This monitoring methodology can be used for project activities that incinerate HFC 23 wastes in excess of any regulatory requirements from sources of a HCFC production facility in a non-Annex I Party.

Monitoring Methodology

Monitoring methodology is based on direct measurement of the amount of HFC 23 waste destroyed and of the energy used by the destruction process as shown in Figure 1.

This monitoring methodology provides for direct and continuous measurement of the actual quantity HFC 23 destroyed, as well as the quantities of electricity, steam and fossil fuel used by the destruction process.

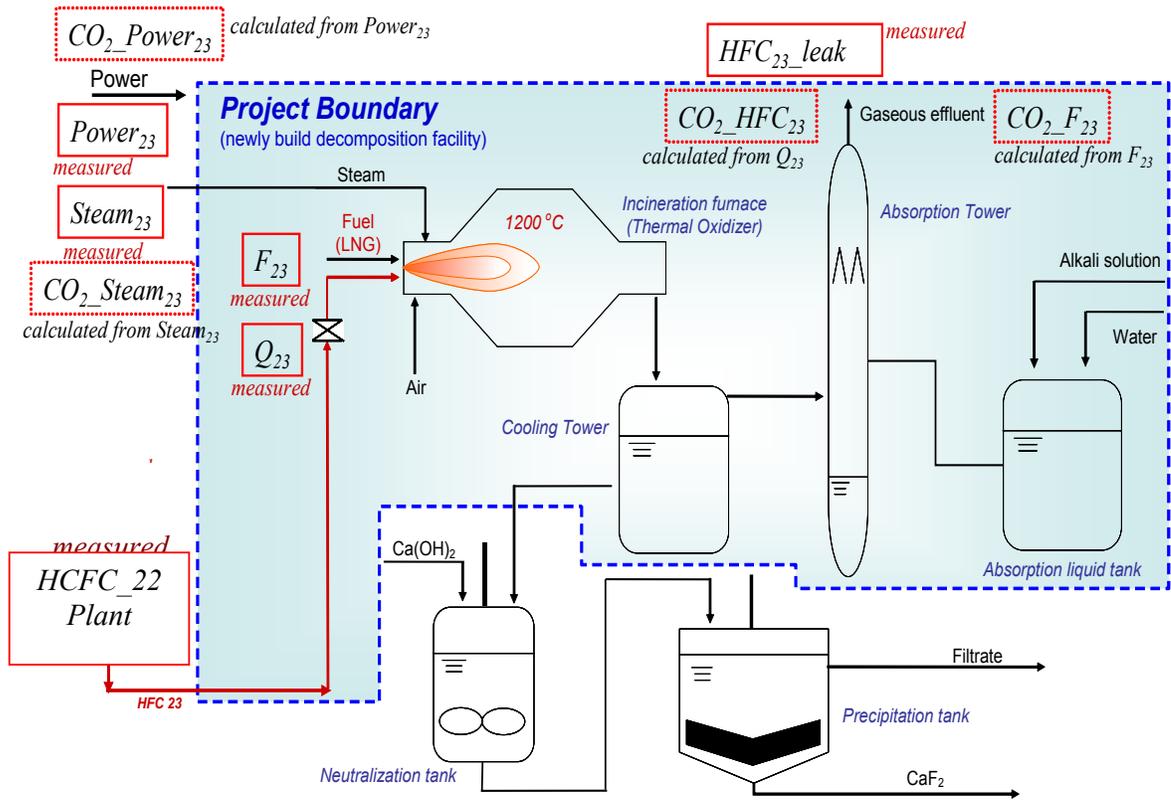
The emission reductions are dominated by the quantity of HFC 23 destroyed. To measure this quantity accurately two flow meters, each of which is recalibrated weekly, are used.

Other factors in the monitoring process for quality control are:

- Purity of HFC 23 is checked monthly by sampling using gas chromatography. Combinations of continuous flow measurement and calculation will be used to estimate quantities of other materials, e.g., air that may be in the HFCs if this is appropriate.
- Amount of HFC 23 waste generated. The output of HFC 23 from the HCFC 22 plant will be checked yearly by comparing the amount of HCFC 22 produced to the sum of the HFC 23 recovered for sale and HFC 23 decomposed.

The quantities of gaseous effluents (CO, HCl, HF, Cl₂, dioxin and NO_x) and liquid effluents (PH, COD, BOD, n-H (normal hexane extracts), SS (suspended solid), phenol, and metals (Cu, Zn, Mn and Cr) are measured every six months to ensure compliance with environmental regulations.

Figure 1
Monitoring Plan



$$\begin{aligned}
 CO_2_Power_{23} &= E_F_{1,y} \\
 Power_{23} &= Q_F_{1,y} \\
 Steam_{23} &= Q_F_{2,y} \\
 CO_2_Steam_{23} &= E_F_{2,y} \\
 HCFC_22\ Plant &= Q_HCFC_y \\
 F_{23} &= Q_NG_y \\
 CO_2_F_{23} &= Q_NG_y * E_NG_y \\
 Q_{23} &= Q_HFC23_y \\
 HFC_{23_leak} &= ND_HFC23_y \\
 CO_2_HFC_{23} &= Q_HFC23_y * EF
 \end{aligned}$$

FINAL

Data to be collected or used to monitor emissions from the project activity, and how this data will be archived

Monitored data for project emissions in the boundary (GHG)

ID number <i>(Please use numbers to ease cross-referencing to table D.6)</i>	Data type	Data variable	Data unit	Measured (m), calculated (c) or estimated (e)	Recording frequency	Proportion of data to be monitored	How will the data be archived? (electronic/paper)	For how long is archived data kept?	Comment
1. <i>q_HFC23y</i>	<i>mass</i>	<i>Quantity of HFC 23 supplied to the destruction process</i>	<i>kg-HFC</i>	<i>(m) measured by flow meters in parallel that are calibrated weekly</i>	<i>monthly</i>	<i>100%</i>	<i>electronic</i>	<i>Project lifetime</i>	
2. <i>HFC23y</i>	<i>%</i>	<i>Purity of the HFC 23 supplied to the destruction process</i>	<i>%</i>	<i>(m) measured monthly by sampling</i>	<i>monthly</i>		<i>electronic</i>	<i>Project lifetime</i>	<i>Measured using gas chromatography</i>
3. <i>Q_NGy</i>	<i>mass</i>	<i>Quantity of natural gas used by the destruction process</i>	<i>m³</i>	<i>(m) measured</i>	<i>monthly</i>	<i>100%</i>	<i>electronic</i>	<i>Project lifetime</i>	<i>Measured using a fuel meter</i>

In addition the quantities of gaseous effluents (CO, HCl, HF, Cl₂, dioxin and NOX) and liquid effluents (PH, COD, BOD, n-H (normal hexane extracts), SS (suspended solid), phenol, and metals (Cu, Zn, Mn and Cr) are measured in a manner and with a frequency that complies with local environmental regulations.

D.4. Potential sources of emissions which are significant and reasonably attributable to the project activity, but which are not included in the project boundary, and identification if and how data will be collected and archived on these emission sources.

Monitored data for project emissions outside of the boundary (GHG)

ID number <i>(Please use numbers to ease cross-referencing to table D.6)</i>	Data type	Data variable	Data unit	Measured (m), calculated (c) or estimated (e)	Recording frequency	Proportion of data to be monitored	How will the data be archived? (electronic/paper)	For how long is archived data kept?	Comment
4. ND_HFC23y	mass	Quantity of HFC 23 in gaseous effluent	kg-HFC	(m) measured	monthly	100%	electronic	Project lifetime	When the thermal oxidizer stops, analysis of the effluent gas is done to check leaked HFC 23 by sampling.
5. Q_F1,y,y	energy	Electricity consumption by the destruction process	kWh	(m) measured	monthly	100%	electronic	Project lifetime	Metered
6. Q_F2,y,y	energy	Steam consumption by the destruction process	kg-steam	(m) measured	monthly	100%	electronic	Project lifetime	Metered

D.5. Relevant data necessary for determining the baseline of anthropogenic emissions by sources of GHG and identification if and how such data will be collected and archived.

Monitored data for baseline emissions (GHG)

ID number <i>(Please use numbers to ease cross-referencing to table D.6)</i>	Data type	Data variable	Data unit	Measured (m), calculated (c) or estimated (e)	Recording frequency	Proportion of data to be monitored	How will the data be archived? (electronic/paper)	For how long is archived data kept?	Comment
7. Q_{HCFC_y}	mass	<i>The quantity of HCFC 22 produced in the plant generating the HFC 23 waste</i>	tonnes - HCF C22	<i>(m) measured</i>	<i>monthly</i>	<i>100%</i>	<i>electronic</i>	<i>Project lifetime</i>	<i>Reference data to check cut off condition and rough estimation of Q_{HFC23_y}</i>
8. $HFC23_{sold}$	mass	<i>HFC 23 sold by the facility generating the HFC 23 waste</i>	tonnes -HFC 23	<i>(m) measured</i>	<i>annually</i>	<i>100%</i>	<i>electronic</i>	<i>Project lifetime</i>	<i>Reference data to check cut off condition and rough estimation of Q_{HFC23_y}</i>

D.6. Quality control (QC) and quality assurance (QA) procedures are being undertaken for data monitored. **(data items in tables contained in section D.3., D.4. and D.5 above, as applicable)**

Data (Indicate table and ID number e.g. 3.-1; 3.-2.)	Uncertainty level of data (High/Medium/Low)	Are QA/QC procedures planned for these data?	Outline explanation why QA/QC procedures are or are not being planned.
1. <i>q_HFC23y</i>	Low	<i>Yes. A QA & QC organization will be formed and QA & QC procedures that are equivalent to JIS (Japanese Industrial Standard) in terms of equipment and analytical method will be set. Will be measured using two flowmeters in parallel with weekly calibration</i>	<i>QA & QC procedures are set and implemented in order to, 1. Secure a good consistency through planning to implementation of this CDM project and, 2. Stipulate who has responsibility for what and, 3. Avoid any misunderstanding between people and organization involved.</i>
2. <i>P_HFC23y</i>	Low	<i>Will be measured using gas chromatography</i>	<i>Ditto</i>
3. <i>Q_NGy</i>	Low	<i>Will be metered using natural gas meter</i>	<i>Ditto</i>
4. <i>ND_HFC23y</i>	Low	<i>Will be measured from the gas effluent of the destruction process</i>	<i>Ditto</i>
5. <i>Q_F_{1y}</i>	Low	<i>Will be metered using electricity meter</i>	<i>Ditto</i>
6. <i>Q_F_{2y}</i>	Low	<i>Will be metered using steam meter</i>	<i>Ditto</i>
7. <i>Q_HCFC_y</i>		<i>Will be obtained from production records of the facility where the HFC 23 waste originates</i>	<i>Ditto</i>
8. <i>HFC23_sold</i>		<i>Will be obtained from production records of the facility where the HFC 23 waste originates</i>	<i>Ditto</i>

All of the measurement instruments are to be recalibrated monthly per internationally accepted procedures except for the HFC 23 flowmeters whose recalibration frequency is weekly to reduce the error level.

Miscellaneous parameters

Calculation of the emission reductions also requires data for:

E_{NG_y} - The emissions coefficient for the natural gas used by the destruction process in tonnes of CO₂ equivalent per cubic metre of natural gas (t CO₂e/m³). The value of E_{NG_y} will vary by region and over time.

$E_{F_{i,y}}$ - The emissions coefficient for the electricity used by the destruction process in tonnes of CO₂ equivalent per kWh. The value of $E_{F_{i,y}}$ for electricity depends on the source of the electricity and may vary over time.

$E_{F_{i,y}}$ - The emissions coefficient for the steam used by the destruction process in tonnes of CO₂ equivalent per tonne steam. The value of $E_{F_{i,y}}$ for steam depends on the source of the steam and may vary over time.

GWP_HFC23 - The 100 year Global Warming Potential of HFC 23. The Global Warming Potential converts 1 tonne of HFC 23 to tonnes of CO₂ equivalents (tonnes CO₂e/tonnes HFC 23). The approved Global Warming Potential value for HFC 23 for the first commitment period is 11,700 tonnes CO₂e/tonne HFC 23.

Appendix 2. List of Supplementary Questions from the Methodology Panel

(1) Sectoral overview:

- What is current production of HCFC22? Where does it take place (which countries)? What is the growth in the market in different countries/regions (recent historical and projected future growth)? Where is this growth concentrated? Is HCFC22 traded internationally? Where are the markets for HCFC22 concentrated?
- What is the current production (emissions) of HFC23? Where does it take place (which countries)? What is the size of the HFC23 market? Is HFC23 traded internationally? What are the relative locations of the HFC23 market and demand?
- Are there markets for products of HFC23 destruction (de-icing salts)? If so, where are these markets and what is the size of these markets compared to production of HFC23?
- Does HCFC22 production occur in dedicated plants, or always in plants that produce other HFCs or HCFCs? If so, what are the other outputs of plants producing HCFC22?
- What determines the relative production levels of HCFC22 and these other products?
- Is production and/or consumption of any of the "other products" produced in HCFC22 plants controlled by national legislation or international agreements?
- What is the expected technical life of a plant producing HCFC22?
- Are there plans to build any new HCFC22-producing plants?
- What is the current production capacity of HCFC22 plants (i.e. if all plants currently capable of producing HCFC22 were to produce just that product, how much could be produced)?

(2) Price/cost information:

- What is the approximate price (and price trends) for HCFC22, HFC23 and products from HFC23 decomposition?
- What is the cost of different HCFC22 production processes (or equipment)?
- What is the approximate price (and price trends) for other products produced in HCFC22 plants?

(3) Technical questions - general:

- What technical or other factors affect the emissions of HFC23 from HCFC22 production? (Information already available from IPCC??)
- How can emissions of HFC23 be reduced from HCFC22 manufacture?
- Is the technology used to produce HCFC22 in dedicated plants the same as that used to produce HCFC22 in "swing plants"? If not, what is the difference?
- What are typical levels of HFC23/HCFC22 production ratios? What causes the variation in such production levels between different plants? Would this ratio be expected to be different in dedicated HCFC22 plants from swing plants?
- Is HFC23 produced/emitted in any other manufacturing process? If so, which ones?

(4) Common practice:

- How many HCFC22-production plants are there in countries that produce this?
- How many companies produce HCFC22 and/or HFC23?

- Can "common practice" be determined at a company level and/or at a national level? If so, how? What is an appropriate sample size in order to determine common practice?
- Do HCFC22-producing companies operate both in Annex I and non-Annex I countries?
- For companies that produce HCFC22 in more than one country, does the HFC23 emission factor vary widely between sites? If so, is this to satisfy domestic regulation? Does a particular company operate HFC23 decomposition facilities in one of its HCFC22-producing plants but not in another? (Yes, Ineos Fluor reduces HFC23 emissions in Japan and UK. What about elsewhere? What about other companies?)

(5) CDM-related questions:

- What would be the volume of CERs generated if all existing plants actually producing HFC23 apply to CDM for HFC 23 destruction activities ?
- Would the market be able to absorb a strong increase of HCFC22 offer resulting from the perverse incentive created (e.g. HCHC22 offered at a far lower prices than current ones)?
- Would it be possible to determine a baseline scenario for HCHC22 demand in the absence of CDM ?
- What is the likely impact of HFC23-related CERs on production from "swing" plants?
- What other refrigerants compete with HCFC22? Are these higher or lower in terms of ozone depletion properties? In other words, how would increased supply and/or lower cost HCFC22 be likely to affect the net emissions of ODSs? Please comment on the shorter and longer-term impacts in light of the Montreal Protocol.

Appendix 3. Responses from Public Consultation

These are appended as full copies without annotation or abridgement.