

Cost Curves for the Abatement of Heavy Metal, PAH and Dioxin Emissions

A report produced for the Department for
Environment, Food & Rural Affairs, the National
Assembly for Wales, the Scottish Executive and the
Department of the Environment in Northern Ireland

Martin Peirce
Haydn Jones
Neil R. Passant
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AEA Technology Environment
 E6 Culham
 Abingdon
 Oxfordshire
 OX14 3ED
 Telephone 01235 463024
 Facsimile 01235 463005

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	Name	Signature	Date
Author	Neil R Passant		
Reviewed by	G Hayman		
Approved by	M Woodfield		

Executive Summary

The Department for Environment, Food & Rural Affairs, the National Assembly for Wales, the Scottish Executive and the Department of the Environment in Northern Ireland have let a contract to AEA Technology on Emission Factors and Cost Curves for Air Pollutants (EPG 1/3/134). The objective of the project is to obtain new and more reliable information on emission factors and the cost of implementing different abatement technologies. The information will be used to improve the emission estimates produced as part of the National Atmospheric Emission Inventory programme and to construct cost curves for different pollutants. The work has comprised a combination of literature surveys, contact with industry and trade associations, and commissioned measurement programmes.

This report presents cost curves for the abatement of emissions to air of heavy metals, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated dibenzo-p-dioxins and -furans (PCDD/F or dioxins for short) in the UK.

A cost curve is a ranking of abatement measures in terms of increasing marginal cost by size of emission reduction. Cost curves can be presented graphically or as tables or rankings. Cost curves are useful for policy analysis because they identify cost effective measures to achieve various emission reductions, or conversely how much it would cost to achieve a given reduction.

This report contains a compilation of data on costs and efficiencies of measures to reduce emissions. A wide range of sectors - industrial, commercial, domestic and other - were considered and a variety of possible abatement measures were assessed in terms of the abatement efficiency and the costs involved.

As part of this work, a software tool has been developed which takes the information on emissions and control measures compiled in this report, and uses it to produce cost-effectiveness rankings and graphical cost curves. The software tool is simple to update with new information to keep the cost curves up to date.

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1 Introduction

1.1 BACKGROUND

The Department for Environment, Food & Rural Affairs, the National Assembly for Wales, the Scottish Executive and the Department of the Environment in Northern Ireland have let a contract to AEA Technology on Emission Factors and Cost Curves for Air Pollutants (EPG 1/3/134). The objective of the project is to obtain new and more reliable information on emission factors and the cost of implementing different abatement technologies. The information will be used to improve the emission estimates produced as part of the National Atmospheric Emission Inventory programme and to construct cost curves for different pollutants. The work has comprised a combination of literature surveys, contact with industry and trade associations, and commissioned measurement programmes.

This report presents cost curves for the abatement of emissions to air of heavy metals, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated dibenzo-p-dioxins and -furans (PCDD/Fs, abbreviated to dioxins in this report) in the UK. A cost curve is a ranking of abatement measures in terms of increasing marginal cost by size of emission reduction. Cost curves can be presented graphically or as tables or rankings. Cost curves are useful for policy analysis because they identify cost effective measures to achieve various emission reductions, or conversely how much it would cost to achieve a given reduction.

This report contains a compilation of data on costs and efficiencies of measures to reduce emissions. In addition, a software tool has been developed which takes information on emissions and control measures and produces cost-effectiveness rankings and graphical cost curves (Section 6 and Appendix A). The software tool is simple to update with new information to keep the cost curves up to date.

AEA Technology has also conducted a parallel study to develop cost curves for PM₁₀ (AEA Technology, 2001). The pollutants assessed in the present study often behave similarly to, are associated with, or are abated using the same techniques as, particulate matter. Consequently there are areas of overlap between the two studies, which should be seen as complementary.

1.2 STRUCTURE OF THIS REPORT

Section 2 gives an overview of the construction of a cost curve. One of the key inputs to a quantitative cost curve is data on emissions of the different pollutants, broken down by sector and based on the year chosen as the baseline for the cost curves. This emission information is taken from the NAEI, as described in Section 3. A brief overview of the general types of measure available to control emissions is given in Section 4. Each cost curve embodies, abstracts and illustrates a great deal of information. This underlying information is presented in full in Section 5. This section documents in detail the methodology used for calculating the costs and emission reductions; the data sources and references; and any assumptions made.

The information compiled in Section 5 can be summarised in graphical form as a set of cost curves. Cost curves are explained in Section 6. A short discussion of the uncertainties associated

with the cost curves is given in Section 7. The cost curve graphs developed for this project are presented as a set of figures in Appendix D.

Square brackets are used for references or to indicate information sources or justifications for assertions.

2 Construction of Cost Curves

2.1 APPROACH

A cost curve is a ranking of abatement measures in terms of increasing marginal cost by size of emission reduction. Cost curves can be presented graphically or as tables or rankings. Cost curves are useful for policy analysis because they identify cost effective measures to achieve various emission reductions. The steps involved in the derivation of a cost curve for emission reduction are:

1. *Identify sources of the relevant air pollutants, and quantify emissions of air pollutants from each source.*
2. *Establish what level of abatement is currently used in the UK, and identify where current or emerging technologies or techniques are available which could give further improvements in the level of abatement.*
3. *Quantify costs for implementing these further abatement measures.*
4. *Estimate the effectiveness of these further abatement measures at reducing emissions.*
5. *Combine cost and effectiveness data to provide a list of options ranked by marginal cost per unit abated.*

In practice, some measures are often ignored. Coverage of technical abatement technologies is generally good although future developments improving efficiency in evolving technologies are not usually included. Coverage of non-technical options, such as management or housekeeping measures, is generally more difficult to incorporate.

2.2 THE INFORMATION GATHERING PROCESS

Emissions data are taken from the National Atmospheric Emissions Inventory (NAEI). This inventory uses approximately 250 categories of emission source and includes forecast emissions for future years as well as estimates for past years.

Information on technology in place (process technology and abatement measures) was available from a number of sources including the published literature and from industrial contacts. The most important published sources were the series of BAT notes produced for HMIP and the BREF notes being produced by the European IPPC Bureau at Seville (<http://eippcb.jrc.es/exe/FActivities.htm>). The BAT notes were produced during the early 1990s and, although it is likely that some information given in them is out of date, they represent the most comprehensive recent survey of the UK processes that are of interest here. Some of the BREF notes are still only available as drafts; however they are more recent than the BAT notes and contain detailed reviews of industrial sectors (EU-wide rather than specifically UK). Other sources included information gleaned from industry, which has been reported in the AEAT publication 'UK Fine Particulate Emissions from Industrial Processes' (Passant *et al*, 2000). Finally, the US EPA's Compilation of Air Pollutant Emission Factors (AP-42) contains information for many industries.

Information on abatement options and their costs and efficiencies is available from the BAT and BREF notes. As well as published sources, representatives of industry and other experts were considered to have an important contribution to make to this work. For many sectors, a trade association was contacted; although some individual companies were also contacted. Appendix B contains a full list of organisation contacted. Although some additional information has been collected through these contacts, the overall response has been disappointing. Finally, some limited information was derived from the EPA's AP-42 report. However, much of the information in this is specific to the US and is often seriously dated, so its use has been very limited.

The information gathering for this project took place iteratively. Published sources were consulted, and initial contacts were made with representatives of industry and other experts. Information so gathered is written up in such a way as to contain all the information required to make a cost curve (Section 5 of this report). At this stage, there are likely to be important assumptions or uncertain information, and these are documented as explicitly as possible. A second pass was then made, contacting industry sources again and inviting them to comment on the first draft, its figures and assumptions. Their comments were fed back into refined cost curves.

In the case of a number of industrial sectors, it has not been possible to determine costs for any abatement options which go beyond that which is currently in place or which will be implemented under existing legislation. This may be because the abatement systems in place are BAT (best available techniques), or it may simply be that cost data for further options do not exist.

2.3 COMPILATION OF DATA FOR THE COST CURVES

It has been the intention to include all possible abatement techniques in the cost curves. In reality, we have been severely limited by lack of data and so the cost curves presented here give an incomplete picture of the reductions that can be achieved and their associated costs. Where incomplete information has been obtained, it has been included in this report in the hope that it may be possible to build on it in future. In some cases where information is lacking, it has been possible to make reasonable enough assumptions or deductions to include the measure in the cost curve.

The measures identified have generally been end-of-pipe abatement systems rather than process management or process changes. This reflects both the fact that these pollutants are most usually dealt with using end-of-pipe solutions, and also that most of the cost data found refers to end-of-pipe abatement.

There are a number of measures which might be considered to be "good housekeeping" or "good practice", and these may be omitted because they are difficult to quantify or because they are considered to be mandatory under BAT. For example, many controls on materials handling and storage come under this category, such as storing dusty materials indoors or applying sealing agents to them, and use of enclosed conveyors with suitable extraction and filtration equipment. Other examples include the careful control of process conditions and operating parameters, control of feedstocks for VOC and dioxin precursors, and general plant maintenance. These measures often apply to a wide range of sectors and for brevity are not individually included in

this document. This is not to say they are not important. Indeed, because they are generally low-cost and often act to reduce fugitive emissions, they can be extremely cost-effective.

Generally, more information is available on particulate matter than on individual heavy metals, PAHs or dioxins. Where no better information is available, therefore, we have made a general assumption that all the individual pollutants act like particulate matter in terms of how much they are abated. An exception is mercury, which is associated with both the vapour and particulate phases. Unless otherwise stated, we have assumed that the removal efficiency for mercury is half that of the other substances. Cases where information on individual pollutants is available (for example, the Stahlwerke Bremen sinter plant, Section 1.1.1) suggest that this is a reasonable approximation.

2.4 COSTS

In this report, all costs are reported in their original currency and year, as given in the source material. Where the costs are in Euros, the report also gives costs in pounds sterling, converted at the rate of £1 = 1.6 Euro.

For the cost curves themselves, further cost conversions are necessary. These are calculated in the software tool and are not documented for individual abatement measures in this report. The calculations are as follows.

Costs in Euros have been converted to pounds at a rate of £1 = 1.6 Euros. Costs have been converted to year 2000 values using a factor of 3% per year (for comparison UK RPI inflation excluding mortgage costs averaged 2.7% between 1993 and 2000). Costs have been annualised using a discounted cash flow technique [EEA, 1999]. The present value of the capital cost is multiplied by the capital recovery factor, which is given by the formula:

$$r \frac{(1+r)^T}{(1+r)^T - 1}$$

where r is the discount rate and T is the lifetime in years. For $r = 0.06$ and $T = 20$ years, the capital recovery factor is 0.087. Annual operating costs (which are assumed to be constant for the lifetime of the equipment) are added to the annualised capital cost to obtain the total annual cost. This methodology is consistent with the approach recommended by the Treasury Green Book and is derived by simply equating the capital cost of the equipment with the present value of T equal annual payments made in successive years, the first payment being made at the end of year 1. This annual payment is the annualised capital cost.

The discount rate used is 6% by default. Plant and equipment lifetimes are generally assumed to be 15 or 20 years. Add-on equipment used in harsh conditions may have a shorter useful lifetime, while new plant built from scratch may be expected to have a longer lifetime.

3 Sources and Emissions

3.1 INTRODUCTION

The emission inventory used for the cost curves is based on the 1999 version of the NAEI, the most recent available at the time of writing. The NAEI includes estimated emissions for all of the pollutants of interest and may be considered to be complete in the sense that it includes all the major sources. The NAEI classifies emissions into about 250 source categories, including a fuel breakdown where appropriate. In order to keep this work manageable, many of these NAEI source categories have been grouped together. The guidelines for grouping sources are:

- sources which are grouped together should be similar in terms of process technology and mechanism for the emission (fuel combustion, oxidation of molten metal, re-suspension etc.)
- sources which are grouped together should be similar in terms of the abatement options which are applicable to them

The only exceptions to these rules are a few groupings of miscellaneous sources that do not fit well with any of the other sources. In general, no cost data has been found for any of these sources and so they will not feature in the cost curve in any case.

The final list of sources used in the cost curve work is shown in Box 1. Details of how the NAEI categories are grouped are given in Appendix C.

Box 1. Source categories used in the cost curves

• Accidental fires	• MSW incineration
• Alkyl lead production	• Natural fires
• Anode baking	• Non-industrial combustion
• Basic oxygen furnaces	• Other NFM
• Blast furnaces	• Other sources
• Cement	• Other transport
• Chloralkali process	• Power stations
• Chrome chemicals	• Primary aluminium
• Clinical waste incineration	• Primary lead/zinc
• Coke production	• Refineries
• Cremation	• Road transport
• Domestic combustion	• Secondary copper
• Electric arc furnaces	• Secondary lead
• Foundries	• Sinter plant
• Glass	• Tyre wear
• Industrial combustion	

3.2 1999 EMISSIONS

The NAEI estimates of the emissions of heavy metals from each sector in 1999 are given as the absolute emissions in Table 1 as a percentage of the total emission of each pollutant in Table 2.

Similarly, the NAEI estimates of the emissions of dioxins and PAHs from each sector in 1999 are given as the absolute emissions and as a percentage of the total emission of each pollutant in Table 3. The NAEI maintains data on some sixteen different PAHs. For conciseness, present only the sum of the emissions from all of the sixteen PAHs. In the cost curve software tool, the PAHs are handled individually.

Table 1 UK Heavy Metal Emissions in 1999 (tonnes).

Source	As	Cd	Cr	Cu	Hg	Ni	Pb	Se	V	Zn
Accidental fires	-	-	-	-	-	-	-	-	-	-
Alkyl lead production	-	-	-	-	-	-	25.61	-	-	-
Anode baking	-	-	-	-	-	-	-	-	-	-
Basic oxygen furnaces	0.19	0.38	1.26	1.26	0.04	0.63	11.20	0.04	0.32	50.53
Blast furnaces	0.97	0.19	0.97	4.86	0.08	1.46	0.85	0.16	4.86	48.56
Cement	0.82	0.08	0.60	1.43	0.24	0.48	4.49	0.15	0.90	3.38
Chloralkali process	-	-	-	-	1.41	-	-	-	-	-
Chrome chemicals	-	-	17.92	-	-	-	-	-	-	-
Clinical waste incineration	0.00	0.37	0.02	0.33	0.37	0.01	3.28	-	-	2.61
Coke production	0.06	0.08	2.31	0.40	0.05	1.35	4.11	-	-	4.11
Cremation	-	-	-	-	1.34	-	-	-	-	-
Domestic combustion (coal)	5.08	0.15	3.06	2.27	0.43	16.01	11.03	3.41	5.73	5.53
Domestic combustion (gas)	-	-	-	-	-	-	-	-	-	-
Domestic combustion (oil)	0.00	0.03	0.03	0.09	0.00	0.19	0.21	0.00	0.42	0.03
Domestic combustion (other)	-	-	-	-	-	-	-	-	-	-
Domestic combustion (SSF)	2.93	0.07	1.02	1.31	0.17	3.98	4.19	0.85	3.81	0.85
Domestic combustion (wood)	-	0.07	-	0.09	0.03	-	0.82	-	-	1.09
Electric arc furnaces	0.26	0.20	12.65	2.35	0.21	7.67	22.00	0.04	0.47	107.3
Foundries	0.03	0.08	0.10	0.69	0.21	0.05	0.66	0.07	0.07	0.45
Glass	4.22	0.53	3.10	0.69	0.06	2.16	51.95	20.41	9.48	12.37
Industrial combustion (coal)	14.13	0.32	3.37	6.33	0.85	19.18	20.19	4.14	18.35	59.08
Industrial combustion (coke)	1.16	0.03	0.40	0.52	0.06	1.57	1.66	0.33	1.51	4.75
Industrial combustion (gas)	-	-	-	-	-	-	-	-	-	-
Industrial combustion (oil)	0.02	0.03	0.26	0.40	0.01	20.14	0.89	0.29	78.56	0.46
Industrial combustion (other)	9.00	0.13	0.00	0.13	0.13	0.01	0.13	0.00	0.02	2.51
MSW incineration	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural fires	-	-	-	-	-	-	-	-	-	-
Non-industrial combustion (coal)	0.50	0.01	0.09	1.65	0.14	0.46	1.56	0.17	0.31	2.15
Non-industrial combustion (coke)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Non-industrial combustion (gas)	-	-	-	-	-	-	-	-	-	-
Non-industrial combustion (oil)	0.01	0.02	0.18	0.27	0.01	14.37	0.65	0.21	56.11	0.33
Non-industrial combustion (other)	-	-	-	-	-	-	-	-	-	-
Other NFM	0.05	0.08	0.04	4.13	0.00	1.81	2.79	0.05	0.05	23.07
Other sources	0.13	0.64	0.03	4.44	0.56	0.95	3.19	0.03	0.06	16.95
Other transport	0.04	0.15	0.55	0.83	0.02	43.91	7.65	0.63	171.3	1.00
Power stations (coal/coke)	5.07	0.39	17.15	12.48	1.56	8.97	16.37	11.31	9.75	8.97
Power stations (gas)	-	-	-	-	-	-	-	-	-	-
Power stations (oil)	0.01	0.05	0.04	0.05	0.01	1.82	0.08	0.21	5.12	0.00
Power stations (other)	0.67	0.06	0.19	0.51	0.11	0.50	0.54	0.03	0.05	12.45
Primary aluminium	-	0.03	-	-	-	2.72	-	-	-	2.72
Primary lead/zinc	0.61	1.25	0.03	0.30	0.29	0.02	10.87	-	-	23.15
Refineries	0.56	0.17	0.36	0.72	0.07	34.85	0.64	1.05	13.15	12.10
Road transport (diesel exhaust)	-	0.15	0.15	0.15	0.00	0.56	0.76	0.15	0.76	0.15
Road transport (other)	-	-	-	-	-	-	-	-	-	-
Road transport (petrol exhaust)	-	0.21	0.21	0.43	-	0.75	326.5	0.21	-	0.59
Secondary copper	0.18	0.08	-	6.24	-	0.35	4.74	-	-	13.06
Secondary lead	0.01	0.29	-	0.07	0.02	-	5.87	0.66	-	1.45
Sinter plant	0.11	0.27	1.09	4.37	0.09	1.70	8.92	0.23	5.46	10.93
Tyre wear	-	0.00	-	-	-	-	-	-	-	10.21
Total	46.83	6.58	67.21	59.77	8.55	188.6	554.4	44.81	386.6	442.9

Table 2 UK Heavy Metal Emissions in 1999 (percentage of total emissions).

Source	As	Cd	Cr	Cu	Hg	Ni	Pb	Se	V	Zn
Accidental fires										
Alkyl lead production							4.6			
Anode baking										
Basic oxygen furnaces	0.4	5.8	1.9	2.1	0.4	0.3	2.0	0.1	0.1	11.4
Blast furnaces	2.1	2.9	1.4	8.1	1.0	0.8	0.2	0.4	1.3	11.0
Cement	1.8	1.2	0.9	2.4	2.8	0.3	0.8	0.3	0.2	0.8
Chloralkali process					16.5					
Chrome chemicals			26.7							
Clinical waste incineration	0.0	5.6	0.0	0.5	4.3	0.0	0.6			0.6
Coke production	0.1	1.2	3.4	0.7	0.5	0.7	0.7			0.9
Cremation					15.7					
Domestic combustion (coal)	10.8	2.3	4.6	3.8	5.1	8.5	2.0	7.6	1.5	1.2
Domestic combustion (gas)										
Domestic combustion (oil)	0.0	0.4	0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.0
Domestic combustion (other)										
Domestic combustion (SSF)	6.3	1.0	1.5	2.2	2.0	2.1	0.8	1.9	1.0	0.2
Domestic combustion (wood)		1.1		0.2	0.3		0.1			0.2
Electric arc furnaces	0.6	3.0	18.8	3.9	2.5	4.1	4.0	0.1	0.1	24.2
Foundries	0.1	1.2	0.1	1.2	2.4	0.0	0.1	0.2	0.0	0.1
Glass	9.0	8.1	4.6	1.2	0.7	1.1	9.4	45.5	2.5	2.8
Industrial combustion (coal)	30.2	4.9	5.0	10.6	9.9	10.2	3.6	9.2	4.7	13.3
Industrial combustion (coke)	2.5	0.4	0.6	0.9	0.7	0.8	0.3	0.7	0.4	1.1
Industrial combustion (gas)										
Industrial combustion (oil)	0.0	0.5	0.4	0.7	0.1	10.7	0.2	0.6	20.3	0.1
Industrial combustion (other)	19.2	2.0	0.0	0.2	1.5	0.0	0.0	0.0	0.0	0.6
MSW incineration	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Natural fires										
Non-industrial combustion (coal)	1.1	0.2	0.1	2.8	1.6	0.2	0.3	0.4	0.1	0.5
Non-industrial combustion (coke)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Non-industrial combustion (gas)										
Non-industrial combustion (oil)	0.0	0.3	0.3	0.4	0.1	7.6	0.1	0.5	14.5	0.1
Non-industrial combustion (other)										
Other NFM	0.1	1.2	0.1	6.9	0.0	1.0	0.5	0.1	0.0	5.2
Other sources	0.3	9.7	0.0	7.4	6.6	0.5	0.6	0.1	0.0	3.8
Other transport	0.1	2.3	0.8	1.4	0.2	23.3	1.4	1.4	44.3	0.2
Power stations (coal/coke)	10.8	5.9	25.5	20.9	18.2	4.8	3.0	25.2	2.5	2.0
Power stations (gas)										
Power stations (oil)	0.0	0.7	0.1	0.1	0.1	1.0	0.0	0.5	1.3	0.0
Power stations (other)	1.4	1.0	0.3	0.8	1.3	0.3	0.1	0.1	0.0	2.8
Primary aluminium		0.4				1.4				0.6
Primary lead/zinc	1.3	19.0	0.0	0.5	3.4	0.0	2.0			5.2
Refineries	1.2	2.5	0.5	1.2	0.8	18.5	0.1	2.3	3.4	2.7
Road transport (diesel exhaust)		2.3	0.2	0.3	0.0	0.3	0.1	0.3	0.2	0.0
Road transport (other)										
Road transport (petrol exhaust)		3.2	0.3	0.7		0.4	58.9	0.5		0.1
Secondary copper	0.4	1.2		10.4		0.2	0.9			2.9
Secondary lead	0.0	4.4		0.1	0.3		1.1	1.5		0.3
Sinter plant	0.2	4.1	1.6	7.3	1.0	0.9	1.6	0.5	1.4	2.5
Tyre wear		0.1								2.3

Table 3 UK Dioxin and PAH Emissions in 1999.

Source	Dioxin Emissions		PAH Emissions	
	(g)	% of total	(kg)	% of total
Accidental fires	57.8	16.7	-	-
Alkyl lead production	-	-	-	-
Anode baking	-	-	17114	19.4
Basic oxygen furnaces	-	-	-	-
Blast furnaces	-	-	-	-
Cement	8.5	2.5	-	-
Chloralkali process	-	-	-	-
Chrome chemicals	-	-	-	-
Clinical waste incineration	24.1	7.0	-	-
Coke production	1.3	0.4	4927	5.6
Cremation	18.4	5.3	-	-
Domestic combustion (coal)	7.3	2.1	19035	21.6
Domestic combustion (gas)	-	-	-	-
Domestic combustion (oil)	-	-	-	-
Domestic combustion (other)	-	-	-	-
Domestic combustion (SSF)	1.8	0.5	1316	1.5
Domestic combustion (wood)	0.2	0.1	13407	15.2
Electric arc furnaces	17.3	5.0	-	-
Foundries	2.9	0.8	-	-
Glass	0.0	0.0	-	-
Industrial combustion (coal)	4.8	1.4	10248	11.6
Industrial combustion (coke)	0.9	0.3	174	0.2
Industrial combustion (gas)	0.0	0.0	-	-
Industrial combustion (oil)	15.4	4.4	-	-
Industrial combustion (other)	31.3	9.1	10	0.0
MSW incineration	0.0	0.0	-	-
Natural fires	5.8	1.7	5933	6.7
Non-industrial combustion (coal)	14.9	4.3	167	0.2
Non-industrial combustion (coke)	0.0	0.0	0	0.0
Non-industrial combustion (gas)	-	-	-	-
Non-industrial combustion (oil)	1.0	0.3	-	-
Non-industrial combustion (other)	6.7	1.9	-	-
Other NFM	7.3	2.1	-	-
Other sources	22.4	6.5	6579	7.5
Other transport	0.5	0.1	259	0.3
Power stations (coal/coke)	15.6	4.5	116	0.1
Power stations (gas)	0.0	0.0	-	-
Power stations (oil)	0.4	0.1	-	-
Power stations (other)	2.7	0.8	-	-
Primary aluminium	5.0	1.4	221	0.3
Primary lead/zinc	4.8	1.4	-	-
Refineries	12.3	3.6	287	0.3
Road transport (diesel exhaust)	0.4	0.1	1266	1.4
Road transport (other)	-	-	-	-
Road transport (petrol exhaust)	5.1	1.5	5889	6.7
Secondary copper	2.4	0.7	-	-
Secondary lead	6.3	1.8	-	-
Sinter plant	40.1	11.6	1331	1.5
Tyre wear	-	-	3	0.0
Total	345.7		88282	

4 Abatement of Air Pollutants: General Aspects

Emissions of heavy metals, dioxins and PAHs – representing around 30 different pollutants – all tend to be emitted in association with particulate matter. Metals may be emitted as physically-produced dust or as aerosols condensed from vapour. Dioxins and PAHs tend to become adsorbed onto the surface of particulate matter. Consequently, measures to abate particulate matter tend to abate heavy metals, dioxins and PAHs as well.

The extent of the association with particulate matter will depend on the pollutant, operating conditions such as temperature, the amount of other particulate present, and the nature of the particulate. At high temperatures, volatile substances such as mercury may be partly present in the vapour phase. Different types of particulate are better or worse at adsorbing dioxins and PAHs. (Activated carbon is a particularly good adsorbent, so where dioxins or PAHs are a problem, a common measure is to add carbon to the air-stream before filtering it.)

Particulate size is also an important issue. In general larger particles are easier to capture than smaller ones. Abatement equipment may be optimised for the size range found at a given process.

Measures to control and abate air pollutants broadly fall into two categories:

- Primary measures, also called process-integrated measures, seek to prevent the pollutant being emitted from the main process.
- Secondary measures, or end-of-pipe measures, try to destroy or recapture emissions after they have been emitted from the main process, but before they are emitted to the atmosphere.

4.1 PRIMARY MEASURES

For heavy metals, primary measures include preventing metals being present as contaminants in the feedstocks. Where the metal is a key element of the process, this is obviously not possible. Another primary measure might be to prevent volatilisation of the substance through careful temperature and process control.

In general, end-of-pipe measures are preferred for controlling heavy metals. Heavy metals are normally present in the particulate phase, as aerosols or dust, and so particulate abatement equipment will also capture metals. Such equipment includes electrostatic precipitators (ESPs), fabric (bag) filters, and cyclones. Cyclones generally have lower removal efficiencies than ESPs or fabric filters, and are generally only suitable for larger particulate matter. They are sometimes used as pre-cleaners, upstream of an ESP or fabric filter.

ESP performance depends largely on the resistivity of the dust; if this is too high or too low performance is impaired. Collection can sometimes be improved by conditioning the dust, for example with ammonia or sulphur trioxide. A well-designed ESP in suitable conditions can achieve dust emissions down to 5–10 mg/Nm³.

Fabric filters potentially can potentially achieve the lowest emission levels, 1 mg/Nm³ or below in good modern installations. However, they are not suitable for all conditions because of their sensitivity to fire and their tendency to blind. Modern fabrics are capable of operating at higher temperatures than older ones.

For dioxins, primary measures either:

- prevent precursors from being present in the first place
- destroy or remove precursors before they become available for dioxin formation
- prevent conditions being suitable for dioxin formation

The extent to which it is possible to prevent precursors from being present in a process is limited. The basic building blocks of dioxins are chlorinated organic compounds. In some instances, for example the melting of scrap metal, reducing the input of organic material is a valid approach but in most cases organic matter is an important feed material. Chlorine is usually present only as a trace impurity but it would generally be impractical to remove this prior to the process.

The organic precursors which form dioxins can be oxidised, ultimately to carbon dioxide and water. All of the processes which emit dioxins involve combustion or heating and so an important approach for minimising emissions of these compounds is to ensure that combustion is very efficient and that all organic compounds are fully oxidised.

Measures to ensure good combustion conditions including careful feed preparation (e.g. shredding etc.), good control of fuel and air input, and good secondary combustion. In particular, secondary combustion should be carried out with regard to ensuring that the following three criteria are met: high combustion gas temperature, good gas turbulence, and sufficient gas residence time.

If precursors survive the combustion process, then dioxins can be formed and this occurs most significantly between the temperatures of 200 and 450 °C. To prevent their formation, gases can be cooled rapidly after secondary combustion. Dioxin formation is also promoted by the presence of deposited particulate matter on surfaces and so a further control measure is to prevent the build up of material on surfaces. Various systems have been developed which use mechanical means to remove deposited dust. Metals such as copper catalyse the reactions and so the addition of chemicals which poison the metals is another control measure. Injection of ammonia, urea or amines have been proposed.

4.2 SECONDARY MEASURES

A number of secondary measures exist which have been shown to reduce emissions of particulate matter, heavy metals, polycyclic aromatic hydrocarbons and dioxins. Arrestment plant such as electrostatic precipitators and fabric filters can reduce emissions, as can acid gas cleaning plant. Wet systems (using water), semi-dry (using calcium hydroxide or similar alkaline material as a slurry), or dry (calcium hydroxide injected as a powder) have all been claimed to remove dioxins. Activated carbon or activated lignite coke adsorbents used in conjunction with ESPs or fabric filters have also been used to reduce dioxins. Carbon can be used with existing dry or semi

dry scrubbing systems with little modification. Fixed bed adsorbers can also be used. (Note that carbon also removes mercury.)

Selective catalytic reduction (SCR) can, in addition to reducing NO_x emissions, reduce dioxin emission since the catalyst also catalyses oxidation of the dioxins. SCR is used in conjunction with either an adsorption system or additional catalyst treatment.

Some new electrical techniques show promise; these involve bombardment of pollutant molecules by electrons with sufficient energy to break chemical bonds.

5 Cost and Efficiency of Abatement Measures

In this section, the abatement measures which can be used to reduce emissions of heavy metals, PAHs and dioxins are summarised for the emission sources considered. For the source sectors considered, information was obtained on the abatement technology, its cost and effectiveness at reducing pollutant emissions. On expert review of the information obtained for many of the sectors, the technology was considered to represent *Best Available Technology* (BAT). These control measures have been discounted and the cost information not included.

The sectors considered have been grouped under the headings of sectors with measures beyond BAT and those which represent BAT. For the former, information is provided on costs and effectiveness. For the latter, only a short remark has been included.

5.1 MEASURES BEYOND BAT

5.1.1 Accidental fires

Remarks

Accidental domestic and car fires are sources of dioxins. See also the natural fires group.

Broadly speaking, three possible measures to reduce the frequency, extent and duration of domestic fires have been identified:

- Improved education and awareness of the public regarding fire prevention and control
- Tightening regulations to reduce the fire risk of houses and furnishings
- Installation of fire alarms and extinguishers.

The Home Office (1998) and local authority fire services already run education campaigns. Although these could be stepped up further, it has not been possible to obtain a reasonable estimate of the cost-effectiveness of such measures.

Improving the Building Regulations, for example, to reduce fire loads and improve fire retardancy of materials would potentially be effective for new houses, but would be prohibitively expensive to retrofit to the existing housing stock. This measure would therefore only have a significant effect over very long timescales. Improving the fire characteristics of furnishings would be valuable over a shorter timescale, but unfortunately it has not been possible to assess the cost-effectiveness of this.

Estimates of the cost-effectiveness of the installation of fire alarms and extinguishers are presented below.

1. Abatement Measure: Installation of Fire Alarms

Description

For this measure, it is assumed that one fire alarm is provided for each household. Where households already have the equipment, they are considered additional.

Cost

Smoke alarms cost about £5 each. There are about 24M households in the UK. The total cost is therefore £120M.

Effectiveness

The effect of fire alarms is to provide early warning of a fire. Assuming someone is present, this may result in the fire being extinguished before it takes hold, or in fire services attending sooner and having a better chance of controlling the fire quickly. (For our purposes, dioxin emissions are assumed to be proportional to the number, extent and duration of fires.) Although hard to quantify accurately, we assume here that the effect is to reduce emissions from this source by 20%.

2. Abatement Measure: Installation of Fire Extinguishers

Description

For this measure, it is assumed that one fire extinguisher is provided for each household. Where households already have the equipment, they are considered additional.

Cost

Domestic-sized fire extinguishers cost about £20 each. There are about 24M households in the UK. The total cost is therefore £500M.

Effectiveness

Domestic fire extinguishers permit the early extinguishing of a fire, as long as it is detected at an early stage. Although hard to quantify accurately, we assume here that the effect is to reduce emissions from this source by 5%.

5.1.2 Chloralkali Process

The chloralkali process is a source of mercury. The process involves electrolysis of brine, which flows co-currently over a bed of mercury, which acts as the cathode. Chlorine is liberated at anodes suspended in the brine, while sodium amalgamates with the mercury. The mercury-sodium amalgam is reacted with water to strip the sodium from the mercury. Hydrogen gas and sodium hydroxide are formed as saleable by-products. The mercury is re-circulated back to the electrolysis cell. Potential releases of mercury include vapours from the brine system, process air and cell room ventilation system. Downstream releases can also occur due to the presence of mercury in by-products.

There are three mercury cell units in the UK with a total capacity of 856,000 t Cl₂ (Table 5.1).

Table 5.1 Mercury Cell Plants in the UK

Company	Site	Capacity (t Cl ₂)	Hg emission to air (1999 PI)
ICI	Runcorn	738,000	1,277 kg
Hays	Sandbach	89,000	118 kg
Rhodia	Staveley	29,000	14 kg
Total		856,000	1,409 kg

[Sources: EIPPCB (2000d) (columns 1–3); Pollution Inventory (column 4)]

1. Abatement Measure: Miscellaneous Improvements to mercury cell plants

Description

As part of negotiations under the OSPAR convention, the European chlor-alkali industry has proposed targets for the total release to air, to water, and in products of no more than 1 g Hg/t Cl₂ by 2007 and 0.7 g Hg/t Cl₂ by 2010. It is estimated that the component to air is likely to be about 80% of the total.

In general UK plants have fitted abatement to the major mercury release points. Further improvements are likely to be achieved through refinements and incremental improvements to cellroom infrastructure, mercury-containing components, and housekeeping and good practice — that is, through packages of small measures rather than individual large measures [Curry, CIA, personal communication, 2000]. Examples of such measures are likely to include:

- Improving performance and reliability of treatment units
- Minor modifications to equipment to avoid potential release routes
- Improved surface finishes to facilitate mercury clean-up
- Changes to materials of construction to avoid mercury absorption.

Cost

The cost of achieving the targets is estimated to be about £20M [Curry, CIA, personal communication, 2000].

Effectiveness

The current overall emission level to air, based on the figures in Table 5.1, is 1.65 g Hg/t Cl₂. The target is 0.7 g Hg/t Cl₂ overall, of which 80% is to air, which is 0.56 g Hg/t Cl₂. This would be a reduction in mercury emissions of 66%. The other pollutants in the present study would not be affected.

2. Abatement Measure: Conversion of Mercury Cell Plants to Membrane Technology

Description

This abatement measure would see the three UK mercury cell units converted to membrane technology, which does not use mercury and is generally much less polluting. It also uses significantly less energy and offers operational savings.

Cost

BREF [EIPPCB 2000d] quotes a range of costs for the conversion. For the present purpose, it is not appropriate to include costs of waste disposal or clean-up, since these would have to be borne at the end of plant life in any case. This implies a cost of around 300 Euro per tonne of Cl₂

capacity, or about £200/t Cl₂ (assuming £1 = 1.6 Euro approx.). However, these are likely to be lower than the costs to UK industry, partly because they are based on smaller plant which is easier to fit into existing buildings and infrastructure. The UK capital cost of conversion has therefore been assumed to be £500/t Cl₂. To convert all the UK mercury plant would therefore cost £500 × 856,000 = £428M.

There are savings in the operation of the converted plant. BREF quotes a 30% saving in electricity and a 25% saving in personnel for one converted plant. This plant achieved a return on investment of 5 years, partly because of market conditions giving a better price for sodium hydroxide. Entec (1996) (quoting Hays) suggest a payback time of 50 to 70 years. Industry sources [Curry, CIA, personal communication, 2000] suggest a saving in operational costs of about £20/t Cl₂ annually. It is assumed here, therefore, that the operating costs for this abatement measure are increased by -£20M/y (negative increase, i.e. a cost saving). This corresponds to a payback time of roughly 20 years.

Effectiveness

Mercury emissions are eliminated. (Note, however, that there may be short-term emissions from existing mercury contamination within the buildings as they are demolished. These emissions would occur anyway at the end of the plants' lives, so are not relevant for this study.) No other pollutants in the present study are affected.

5.1.3 Cremation

Remarks

Crematoria are sources of mercury (from dental amalgam in cadavers being cremated), and dioxins. They are also minor sources of PAHs.

1. Abatement Measure: Selenium Ampoules

Description

This measure, taken from Entec (1996) involves placing an ampoule of selenium on top of the coffin before it enters the cremator; during combustion the selenium reacts with mercury to form the stable compound mercury selenide.

Cost

The cost of an ampoule is £29. The number of cremations is assumed by Entec to be 430,000/y, giving an annual cost of £12.5M/y.

Effectiveness

Tests carried out during 22 cremations in Sweden achieved reductions in mercury emissions of 80 to 85% while other pollutants were not abated. However, more recent measurements of the efficiency of the ampoules at a UK crematorium found no evidence that the ampoules had any significant impact on mercury emissions. In the light of these findings, the measure is excluded from the cost curves.

2. Abatement Measure: Fabric Filter with Activated Carbon Injection

Description

This measure, taken from Entec 1(996) is the installation of fabric filters with activated carbon injection at crematoria.

Cost

Entec suggest a capital cost of £600,000, while a more recent estimate from the Federation of Crematoria Operators suggests a capital cost of circa £200,000 per cremator for a complete system. Small crematoria typically have two cremators, while large operations usually have four or six. Assuming an average of 3 cremators per crematorium would give a cost of £600,000 which agrees with Entec's earlier estimate. Taking this cost for each of the UK's 228 crematoria, gives a UK total of £136.8M. Entec also assume an annual labour cost for each crematorium of £50,000/y, equivalent to about two full-time maintenance staff, but this seems excessive for such small units; here we will assume £10,000/y per crematorium or £2.3M total. Entec also assume running costs of £60,000/y per crematorium (based on 10% of the capital cost), or £14M/y total.

Effectiveness

Entec do not propose any level of effectiveness for this measure. Fabric filters can achieve removal efficiencies of over 99%, but it is judged that 90% is more likely in practice for this sort of smaller unit. With carbon injection, the same removal efficiency is assumed for mercury as for other substances.

5.1.4 Domestic Combustion**Remarks**

Domestic combustion is a source of heavy metals, dioxins, and PAH. Solid smokeless fuel and coal are the most significant sources of emissions, although PAH emissions result mainly from the use of wood as a fuel.

Other than switching from a solid or liquid fuel to an alternative source of energy such as gas or electricity, or reducing the use of fuels through energy efficiency measures, there are no control techniques for abatement of heavy metal and particulate matter emissions. Emissions of dioxins and PAH could be reduced by changes in fuel or changes in the combustion system.

1. Abatement Measure: Switch to Gas**Description**

This measure involves households that have access to mains gas but are currently using solid fuel, oil or wood as their main fuel, to switch to using gas. Current and potential use of bottled gas is ignored.

It is assumed that extension of the gas main to further households is not cost-effective. No quantitative data has been obtained which would justify or refute this assumption; the main factor would be the remoteness of the households from the gas network. It should be noted, however, that natural gas has only recently become available in Northern Ireland.

The total number of households in Great Britain is 23.482M; there are a further 2.5% in Northern Ireland [Domestic Energy Fact File 1998]. The number of households in Great Britain

using different fuels as their main source is given in Table 5.2, from data in the Domestic Energy Fact File 1998. Numbers in the UK have been calculated by adding 2.5% in each case. (In fact, there are proportionately fewer gas-burning households in Northern Ireland, and more coal- and oil-burning households; this effect is however ignored in the absence of hard quantitative data.)

Table 5.2 Use of fuels in Great Britain and the United Kingdom (thousands of households)

	Gas	Solid fuel	Oil	Electric	Other	Total
Number in GB (thousands)	17,587	1,359	918	2,965	653	23,482
Number in UK (thousands)	18,027	1,393	941	3,039	669	24,069
Percentage	74.9	5.8	3.9	12.6	2.8	100

There are 19.9M households in the UK with gas supply regulated by Ofgem [Robert Jones, Ofgem]. Given these totals, and assuming that the ratio of solid fuel, oil and electric-using households is the same for households with and without access to gas, it is possible to calculate the number of households which have access to gas but which actually use each of the other fuels (Table 5.3).

Table 5.3 Breakdown of fuel usage between households with and without access to gas (thousands of households)

	Have access to gas	Don't have access to gas	Total
Use CH ¹ gas	15,992	0	15,992
Use CH solid fuel	267	594	861
Use CH oil	290	646	937
Use CH electricity	795	1,769	2,565
Use CH other fuel	182	405	586
Use non-CH gas	2,035	0	2,035
Use non-CH solid fuel	165	367	532
Use non-CH oil	1	3	4
Use non-CH electricity	147	327	475
Use non-CH other fuel	26	57	83
Total	19,900	4,169	24,069

It may be deduced that:

- 267,000 + 165,000 = 432,000 households could convert from solid fuel to gas
- 290,000 + 1,000 = 291,000 households could convert from oil to gas
- 182,000 + 26,000 = 208,000 households could convert from other fuel to gas

Of these, 165,000 + 1,000 + 26,000 = 192,000 would need a central heating system installed.

¹ Central heating

Cost

The cost of boilers ranges from around £400 to more than £1000, with more energy-efficient condensing boilers at the top of this range. For the purposes of this work, we need to assume a reasonably high level of energy efficiency, so an average cost of £900 will be assumed. Where a full central heating system needs to be installed, the additional cost would be approximately £1200 [based on a selection of quotes obtained from suppliers and installers]. Multiplying these costs by the number of households identified above, gives a national cost of $£900 \times (432,000 + 292,000 + 208,000) + £1200 \times 192,000 = £1,070\text{M}$.

DUKES 1999, Table 9.3, gives the UK average expenditure on fuel per consuming household in 1997/98, reproduced in Table 5.4. Given the number of households converting from each fuel calculated above, the annual national expenditure on fuels can be calculated (Table 5.4). The expenditure before conversion is $£248\text{M} + £238\text{M} = £486\text{M}$ per year. The expenditure after conversion is £370M. Therefore there is an increase in annual costs of $£370\text{M} - £486\text{M} = -£116\text{M}$ (a negative increase, i.e. a saving).

Table 5.4 Cost of fuels before and after conversion to gas

Fuel	Weekly expenditure per household	Number of households	Annual national cost of fuel
Before conversion:			
Solid fuel	£11.05 per week	432,000	£248M
Heating oils and other fuels	£9.16 per week	292,000 + 208,000	£238M
After conversion:			
Gas (households with gas central heating)	£7.62 per week	932,000	£370M

Effectiveness

Using the previous assumptions and data, the fraction of solid-fuel, oil or wood burning households converting to gas will be $432,000 / 1,393,000 + 292,000 / 941,000 + 208,000 / 669,000 = 31\%$. All emissions associated with these sources will therefore be reduced by 31%.

There will be emissions from burning gas, but the NAEI assumes that these are zero for heavy metals and persistent organic pollutants.

2. Abatement Measure: Improved insulation

Description

Assume that households could improve their insulation by measures such as loft and wall insulation and draught-proofing. This would produce emission reductions for households which burn coal, wood, oil etc.

The Domestic Energy Fact File 1998 gives the following figures for the percentage of households with poor insulation (1996 basis):

- 7,557,000 households have loft insulation of three inches or less
- 12,725,000 households do not have cavity wall insulation
- 11,720,000 have double glazing in less than 60% of rooms

Numbers of households given above only relate to those which have the potential for the insulation to be fitted (i.e. those with accessible lofts, cavity walls etc.). For loft insulation and double glazing, the numbers include a proportion for those where the insulation depth or room coverage is “not stated” in the Fact File.

The Fact File gives figures for draught-proofing but includes double glazing within these. It is therefore not practical to include draught-proofing measures (e.g. on external doors) in this analysis.

Percentages of households using different fuels are given in Table 5.2 above. Assuming that these proportions are independent of the level of insulation, we can calculate the number of households using each fuel that can improve their insulation — see Table 5.5.

Table 5.5 Number of households with potential for improvements in insulation, by fuel used

	Solid fuel	Oil
Loft insulation	437,000	295,000
Cavity wall insulation	736,000	497,000
Double glazing	678,000	458,000

Cost

The following figures are from the Energy Saving Trust (www.est.org.uk).

- The average household fuel bill is around £500 per year (based on a three bedroom semi-detached house), of which space heating and hot water cost about £350 per year.
- Loft insulation saves about 20% of heating costs (and hence fuel), or £60–70 per year. It costs £200–300 (say £250) for professional installation.
- Cavity wall insulation saves about £60–70 per year, which implies 20% of fuel is saved; cost £350–500 (say £425).
- Double glazing saves about £15–35 per year, which implies about 7% of fuel is saved; cost £150–400 (say £300) for each single-glazed window replaced. Assuming that an average house has ten windows gives a total cost of £3000.

Multiplying the cost of installation, and the cost saving from using less fuel, by the number of households from Table 5.5 gives the total national costs in Table 5.6. Note that the annual costs are negative, that is, there is an annual cost saving from this measures. The annualised costs are presented in and are given for 3 different annualisation periods. The values based on an annualisation period of ten years have been used in the example cost curves presented in this report but values calculated using two years and five years are also shown, since a ten year period might be considered unattractively long to drive peoples purchasing decisions.

Table 5.6 Installation and annual costs for improved insulation, by fuel used

	Installation costs		Annual costs	
	Solid fuel	Oil	Solid fuel	Oil
Loft insulation	£110M	£75M	-£28M	-£19M
Cavity wall insulation	£310M	£210M	-£48M	-£32M
Double glazing	£2030M	£1370M	-£17M	-£11M

Table 5.7 Annualised costs for improved insulation, by fuel used

	Annualised costs	
	Solid fuel	Oil
	Annualisation = 2 years	
Loft insulation	+£32M	+£22M
Cavity wall insulation	+£121M	+£82M
Double glazing	+£1090M	+£736M
	Annualisation = 5 years	
Loft insulation	-£2M	-£1M
Cavity wall insulation	+£26M	+£18M
Double glazing	+£465M	+£314M
	Annualisation = 10 years	
Loft insulation	-£13M	-£9M
Cavity wall insulation	-£6M	-£4M
Double glazing	+£259M	+£175M

Effectiveness

The effectiveness of these measures, in terms of the reduction in emissions, is calculated by multiplying the fraction of the fuel-using houses having the insulation improved, by the percentage fuel saving for each measure. For example, the overall saving from improving loft insulation in suitable oil-burning households is $295,000 / 941,000 \times 20\% = 6.3\%$. The results of the calculations are given in Table 5.8

Table 5.8 Number of households with potential for improvements in insulation, by fuel used

SOLID FUEL	Total households	Households improved	Percentage reduction per household	Total percentage reduction
Loft insulation	1,393,000	437,000	20	6.3
Cavity wall insulation	1,393,000	736,000	20	10.6
Double glazing	1,393,000	678,000	7	3.4
Total				20.3
OIL	Total households	Households improved	Percentage reduction per household	Total percentage reduction
Loft insulation	941,000	295,000	20	6.3
Cavity wall insulation	941,000	497,000	20	10.6
Double glazing	941,000	458,000	7	3.4
Total				20.3

It can be seen that emissions from domestic burning of solid fuel and oil are each reduced by 20% (for all pollutants).

5.1.5 Electric Arc Furnaces

Remarks

Electric arc furnaces are sources of heavy metals and dioxins. PAHs are also emitted, albeit in small quantities. Mercury can be emitted from raw material storage. The major source of emissions of all pollutants is the furnace itself with less significant emissions from secondary processes. BAT for abatement of particulate matter from electric arc furnaces is recognised as being fabric filtration, however, this should be in the baseline (Powlesland, 2001). Fugitive emissions could be reduced through greater enclosure of furnaces (only one UK plant has a 'dog-house', unfortunately no cost data have been found. The use of either a post-combustion chamber or post-combustion in the off-gas duct system to minimise the production of dioxins is considered BAT. Fast cooling of the fumes from the combustion chamber is essential to prevent *de-novo* synthesis of dioxins; this may be achieved by dilution or by a water quenching tower.

1. Abatement Measure: Injection of Lignite Coke Powder for Off-gas Treatment**Description**

This measure involves the injection of lignite coke powder into the off-gas stream before the fabric filters, in order to increase removal of dioxins [EIPPCB 2000a].

Cost

BREF gives investment costs as about 300,000 ECU (1997) = £200,000 for an EAF plant of 1 Mt (steel)/y capacity. Total UK capacity is some 4 Mt/y, so the total UK cost would be £800,000. Running costs are stated to be not considerable.

Effectiveness

BREF reports that emission concentrations of dioxins lower than 0.1 ng ITEQ/Nm³ are achievable. Given current levels of around 0.25 ng/Nm³, this corresponds to a reduction of $(0.25 - 0.1) / 0.25 = 60\%$.

5.1.6 Glass**Remarks**

Glass production is a source of heavy metals and a minor source of dioxins. Emissions can occur due to suspension of dusty raw materials or due to volatilisation of materials from the glass batch.

1. Abatement Measure: Primary Measures in Melting Activities**Description**

The European IPPC Bureau (2000e) describe a package of measures that can be taken to reduce emissions of particulate matter from melting activities in their BREF note on glass production. Because of the wide variety of glass-making installations, it is very difficult to draw precise conclusions about the cost and effectiveness of the package, or even the applicability of individual measures.

Cost

The BREF note suggests that very little data is available, but costs are considered to be low and may even produce savings (through reduction in energy consumption). It is therefore assumed here that the costs of this abatement measure are zero.

Effectiveness

Again, the BREF note states that emission levels achievable using these primary techniques are difficult to quantify, because of the wide range of factors that can affect the results and the wide variation in furnace types and glass formulations.

However, it does suggest that reductions in particulate material (and presumably associated pollutants) could be reduced by 20% by optimisation of primary measures.

2. Abatement Measure: Electrostatic Precipitators and/or Fabric Filters**Description**

All information is from European IPPC Bureau (2000e) unless otherwise stated.

This measure involves installation of electrostatic precipitators or fabric filters to plant. Fabric filters can achieve a somewhat higher collection efficiency than ESPs. Fabric filters have somewhat lower investment costs but higher running costs than ESPs; overall costs are comparable. Smaller plants often prefer fabric filters.

For the purposes of this study, the differences between ESPs and fabric filters are considered to be unimportant compared with other uncertainties, and recommendations are made on this basis. In practice, the decision about which to install would be made plant by plant, depending on local circumstances.

Following BREF, the assessment of this abatement measure is based on emissions from the melting activities. Emissions from other processes are assumed to be either negligible, or reduced at the same rate for the same cost.

Note that this abatement measure can be implemented in parallel with primary measures (q.v.).

Cost

Capital costs are not directly proportional to plant size, and the cost per tonne of glass produced is higher for smaller furnaces. BREF gives ranges of prices, for small container plants to large float plants, of 0.5 to 2.75 Meuro capital cost and 37,000 to 186,000 Euro per year operating cost. It is assumed that this is the cost per plant, not per furnace. There are 14 installations in the UK and 32 furnaces. The size range of installations seems to be fairly symmetrically distributed, so the central value of the cost ranges can be used as a mean.

Therefore, the total capital cost of implementing this abatement measure in the UK is $14 \times (0.5 + 2.75) / 2 = 20$ Meuro = £13 M (assuming £1 = 1.6 Euro approx.).

The operating cost is $14 \times (37,000 + 186,000) / 2 = 1.5$ Meuro/y = ~£1M/y.

Effectiveness

Emissions can be reduced by 95%. This is based on emission concentrations without secondary abatement (but with primary abatement) of 100 – 200 mg/Nm³ being reduced to 5 – 10 mg/Nm³ by secondary abatement [BREF].

3. Abatement Measure: Control of Feedstocks

Description

One of the most important heavy metals emitted from glass manufacture is chromium, which largely arises from the use of cullet. Reduction in the use of cullet is considered undesirable on other environmental grounds, but if techniques for reducing chromium emission, for example by removing it from the cullet prior to processing, are available, they should be investigated. No information on any such techniques has been found.

5.1.7 Industrial Combustion

Remarks

Industrial combustion plant are sources of heavy metals, dioxins and PAH. Combustion of coal is the most significant source of emissions, although other fuels are significant sources of particular pollutants, for example large emissions of arsenic and PAH result from the use of wood as a fuel while the bulk of nickel emissions occur as a result of oil combustion.

1. Abatement Measure: Switch to Gas

Description

Conversion of industrial combustion plant from coal, wood or oil-fired to gas-fired significantly reduces emissions of heavy metals, PAHs and dioxins. It also offers commercial benefits due to the relatively low cost of gas and easier fuel handling and storage. Consequently, there is a steady shift towards the use of gas, especially as plants reach the end of their lives. In particular, new coal-fired boilers are no longer made and replacements will be either gas-fired or dual fuel (gas and oil) fired. According to DUKES, the Digest of UK Energy Statistics [DTI 1999], coal consumption in this sector fell by 45% from 1994 to 1998.

Coal and wood-fired boilers cannot be converted to another fuel and would need to be replaced. Oil-fired boilers can be converted to gas simply by replacing the burner, and this is relatively cheap. The major constraint on conversion to gas is the provision of a gas supply where it does not already exist. This can be very expensive, but this factor is of course very site-specific.

Cost

Approximate costs for installing dual-fuel burners are given in Table 5.9 [manufacturers' estimates]. Costs for installing gas-only burners are about £3,000 cheaper.

Table 5.9 Costs of Converting Oil burners to Natural Gas

Size of burner	Approximate cost
0.5 MW or less	£5k
0.5 to 1 MW	£6-7k
2 MW	£10k
3 MW	£12k
5 MW	£15k
10 MW	£20k

The cost of installing a gas pipeline, where necessary, is roughly in the range £20–50,000 [manufacturers' estimates]. Not all plants will need this, so it is assumed that the cost per plant averaged over all plants is £20,000.

The total industrial combustion consumption of fuels is given in DUKES [DTI 1999] in tonnes of oil equivalent (1998 figures). In Table 5.10, these are converted to GWh assuming that 1 tonne of oil is equivalent to 11,630 kWh. The equivalent number of 5 MW installations is then calculated assuming that the average plant has an operating time of 6000 hours per year. Given the cost of conversion for a 5 MW plant of £15,000, the total cost of converting all the installations to gas can then be calculated.

This method of calculating the total cost of conversion assumes that the cost for a given plant varies linearly with capacity. This is not strictly the case (larger plants are cheaper per unit power than smaller ones), but choosing a specimen size close to the average will minimise the error involved and provide an acceptable estimate.

Table 5.10 Costs of converting to gas (excluding gas connection)

Fuel	Consumption (1000 toe)	Consumption (GWh)	Equivalent number of installations	Conversion cost
Coal	1,839	21,400	713	£10.7M
Manufactured solid fuels	979	11,400	380	£5.7M
Petroleum	6,154	71,600	2,390	£35.9M

The total conversion cost is £52M excluding gas connection. Including gas connection the total cost is £52M + 3,483 × £20,000 = £122M.

Effectiveness

The costs above relate to conversion of the whole industrial combustion sector burning fossil fuels to gas. Emissions of heavy metals and PAHs will be eliminated since these are not present in significant quantities in the waste gas from natural gas combustion. Some particulate matter is emitted and so the efficiency of the measure for PM₁₀ will be less than 100%. The following efficiency calculations are based on NAEI emission factors for 1999.

Coal → Gas	97% reduction
Coke → Gas	79% reduction
Fuel oil → Gas	96% reduction (approx. 40% of petroleum use)
Gas oil → Gas	84% reduction (approx. 60% of petroleum use)

An overall efficiency of 89% can be calculated.

Although it is also possible to switch to other fuels *e.g.* coal to smokeless fuel, this was not considered.

2. Abatement Measure: End-of-pipe Filters

Description

Fabric filters, ESPs and ceramic filters can be applied to coal or oil-fired boilers. For smaller boilers (less than 1 MW approximately), ceramic filters might be preferred as they are more compact and, because they can operate at higher temperatures, do not always require extra ducting. However, the filters/candles tend to wear/fail very quickly if the gas flow entering them is not laminar and aligned with them and this is a significant cause of failures with this technology.

This measure is an alternative to (exclusive of) the above measure, conversion to gas.

Cost

Entec (1996) present a range of costs for different systems and capacities (Table 5.11). The original sources are a Euro BAT note dating from 1991 (in the table, costs are converted to 1996 values) and the age of these data is a cause for some doubt that they are still valid. In general, one might expect that the costs of fabric filters would have decreased since 1991, as the technology has become greatly more common and the number of manufacturers has grown.

Table 5.11 Summary of cost data for industrial combustion plant (1996 basis)

Plant size	Fuel	Control	Capital cost	Operating cost
100–300 MWth	All	Bag/fabric filter	£18.5/kWth	£0.00043/kWth
100–300 MWth	All	ESP	£25.3/kWth	£0.00026/kWth
50–100 MWth	All	Bag/fabric filter	£21.0/kWth	£0.00043/kWth
50–100 MWth	All	ESP	£33.7/kWth	£0.00026/kWth
50 MWth	Coal	ESP	£5.7/kWth	Not available
50 MWth	Coal	Fabric filter	£8.5/kWth	Not available
50 MWth	Oil	ESP	£3.5/kWth	Not available
50 MWth	Oil	Fabric filter	£5.7/kWth	Not available
10 MWth	Coal	ESP	£12.0/kWth	Not available
10 MWth	Coal	Fabric filter	£19.7/kWth	Not available
10 MWth	Oil	ESP	£10.5/kWth	Not available
10 MWth	Oil	Fabric filter	£17.7/kWth	Not available
5 MWth	Coal	ESP	£16.9/kWth	Not available
5 MWth	Coal	Fabric filter	£29.6/kWth	Not available
5 MWth	Oil	ESP	£15.5/kWth	Not available
5 MWth	Oil	Fabric filter	£28.2/kWth	Not available

Costs have also been obtained from an equipment supplier for ceramic filters for smaller oil-fired boilers. Prices are £7,500 for a 200 kW plant, £9,500 for a 500 kW plant, and £19,000 for a 1000 kW plant. These equate to £37.5/kW, £19/kW and £19/kW respectively. The efficiency in each case is quoted as 99.95% for particulate matter. These costs are not very different from those given in Table for fabric filters which range from £6/kW to £30/kW. However as stated above, these costs may overstate the current cost. For the cost curves, it has been assumed that, given that costs for ceramic filters are £19/kW for plant of greater than 500 kW, and that fabric filters would be less expensive, a figure of £15/kW will be used.

The total industrial combustion consumption of coal, manufactured solid fuel, petroleum products and renewables and waste is given in DUKES [DTI 1999] as 9.5 million tonnes of oil

equivalent (1998 figures). Assuming that 1 tonne of oil is equivalent to 11,630 kWh, and that the average plant is operated for 6000 hours per year, this implies a total capacity of 18,400 MW. Taking £15/kWh (at year 2000 prices, the total cost of installing filters would be £276M.

Effectiveness

Emissions would be reduced by about 99% or more for particulate and particulate-related pollutants compared with an unabated combustion plant. In reality, most combustion plant of a reasonable size would have some abatement (cyclones or cyclones plus filters or ESPs) and so a lower efficiency should be used. As no reliable data are available, the efficiency has been estimated at 50%.

5.1.8 Natural fires

Remarks

Natural fires of (mostly coniferous) forests and moorland are a major source of some PAHs and a fairly minor source of dioxins.

1. Abatement Measure: Fire Prevention

Description

A wide range of measures are available to reduce the risk and consequences of natural fires. These include public information and education, restrictions on public access, the use of fire-breaks and fire-belts, controlled burns, development of fire plans, use of fire prediction tools, and the provision of fire-fighting equipment and resources (including water supplies).

It is important to note that for some land types, especially moorland, a certain amount of burning is essential for the ecological health of the site, so this source can never be eliminated completely.

Cost and effectiveness

Because this source is spread among a very large number of landowners, and because a large part of the costs of controlling fires is management time rather than capital, it is difficult to quantify the total costs involved accurately. As an example, the National Trust's High Peak Estate covers an area of about 12,600 ha, has approximately £50,000 worth of capital equipment (allowing for some dual-use equipment), and spends approximately £10,000 per year on management time for fire control [personal communication]. Investment is likely to be lower for more remote and privately-owned areas.

According to the DEFRA's Countryside Information System, the total UK land area covered by coniferous woodland is about 1,400,000 ha, and that covered by moorland is 1,200,000 ha, giving a total land area at risk of 2,500,000 ha. As a first approximation, we assume that the annual cost (including annualised capital costs) of current fire prevention is about £1,500 per thousand hectares. Then the total current investment is £3.8M per year. It is assumed that investing the same amount again would reduce the number and extent of fires by a quarter, and therefore reduce emissions from this source by 25% for all pollutants.

5.1.9 Non-industrial Combustion

Remarks

This sector, which covers combustion processes operated by public services (e.g. schools, hospitals and sports centres) and commercial premises (mainly offices), is a source of heavy metals, dioxins and PAHs. Most of the coal fired boilers in the public sector are in schools.

1. Abatement Measure: Switch to Gas

Description

Conversion of combustion plant from coal, wood or oil-fired to gas-fired significantly reduces emissions of heavy metals, PAHs and dioxins. It also offers commercial benefits due to the relatively low cost of gas and easier fuel handling and storage. Consequently, there is a steady shift towards the use of gas, especially as plants reach the end of their lives. In particular, new coal-fired boilers are no longer made and replacements will be either gas-fired or dual fuel (gas and oil) fired.

The typical annual energy consumption for heating and hot water in the buildings in this sector is in the range 100 to 200 kWh/m² of treated floor area per year [EEO, 1998]. Most office buildings are in the range 2,500 to 12,000 m² of net floor area and would require a boiler in the range 200 kW to 1 MW (assuming 2,000 hours per year operation). Sites such as shopping malls or business parks may have a larger boiler supplying several buildings.

Coal and wood-fired boilers cannot be converted to another fuel and would need to be replaced. Oil-fired boilers can be converted to gas simply by replacing the burner, and this is relatively cheap. The major constraint on conversion to gas is the provision of a gas supply where it does not already exist. This can be very expensive, but this factor is of course very site-specific.

Cost

Approximate costs for installing dual-fuel boilers are given in Table 5.12 [manufacturers' estimates]. Gas-only burners are about £3,000 each cheaper.

Table 5.12 Costs of Converting Oil Burners to Natural Gas

Size of burner	Approximate cost
0.5 MW or less	£5k
0.5 to 1 MW	£6-7k
2 MW	£10k
3 MW	£12k
5 MW	£15k
10 MW	£20k

The cost of installing a gas pipeline, where necessary, is roughly in the range £20-50,000 [manufacturers' estimates]. Not all plants will need this, so it is assumed that the cost per plant averaged over all plants is £20,000.

The total non-industrial use of fuels for public administration, commercial and miscellaneous sectors, is given in DUKES [DTI 2001] and reproduced in Table 5.13. The equivalent number

of 1 MW installations is then calculated assuming that the average plant has an operating time of 2000 hours per year. Given the cost of conversion for a 1 MW plant of £5k, the total cost of converting all the installations to gas can then be calculated.

Table 5.13 Costs of converting to gas (excluding gas connection)

Fuel	Consumption	Conversion factor	Consumption	Equivalent number of installations	Conversion cost
Coal	355 kt	29.2 GJ/t	2880 GWh	1440	£7.2M
Petroleum	2,146 kt	11,630 kWh/toe	26,400 GWh	13200	£66M

The total conversion cost is £73.2M excluding gas connection. Including gas connection the total cost is $£73.2M + 14,640 \times £20,000 = £366M$.

Effectiveness

The costs above relate to conversion of the whole industrial combustion sector to gas. All emissions from non-gas fuels will therefore be eliminated, although some emissions of particulate matter will occur from the burning of gas. The reduction in particulate matter emissions is calculated on the same basis as for industrial combustion as 90%

2. Abatement Measure: Ceramic Filters

Description

Fabric filters, ESPs and ceramic filters can be applied to coal or oil-fired boilers. For this size of boiler, ceramic filters are preferred as they are more compact and, because they can operate at higher temperatures, do not require extra ducting or facilities for cooling.

This measure is an alternative to (exclusive of) the above measure, conversion to gas.

Cost

Costs have been obtained from an equipment supplier for ceramic filters for smaller oil-fired boilers. Prices are £7,500 for a 200 kW plant, £9,500 for a 500 kW plant, and £19,000 for a 1000 kW plant.

The total number of plants is estimated in Section 0 as about 14640, based on the assumption that each plant is 1MW. Taking £19,000 as a typical price for ceramic filters in this size range, the total cost of installing fabric or ceramic filters would be £278M.

Effectiveness

The efficiency of ceramic filters is quoted as 99.95%. We assume that emissions would be reduced by about 99% or more for particulate and particulate-related pollutants.

5.1.10 Power Stations

Remarks

Power stations are sources of PAH, dioxins, and heavy metals. Emissions result mainly from combustion of coal and fuel oil rather than gas. Almost all of the emissions are emitted from

stacks with the only potential sources of fugitive emissions being handling of fuels, additives, and any ash. Potentially, emissions might be reduced through application of more efficient end-of-pipe abatement. The use of flue gas desulphurisation on power stations would enable particulate matter emissions of 20 mg/m³ to be reached as well as reducing emissions of SO₂. However, in discussions, the electricity industry have pointed out that it is cheaper to build new CCGT plant than retrofit FGD to old plant. This has been tested by inclusion of cost data for both options in the cost curve.

1. Abatement Measure: Switch to Gas

Description

This measure is to switch from coal-fired power generation to gas (CCGT). The discussion here is expressed in terms of generating the same quantity of electricity using gas rather than coal. Most quantitative information below comes from the Digest of UK Energy Statistics (DUKES) [DTI, 2001].

Cost

Electricity generated by major producers in coal-fired plant in 1999 was 102 TWh, using 39.6 Mtonnes of coal. In the same year, 282 TWh of gas was used to generate 128 TWh of electricity in stations with a total capacity of 17058 MW. Therefore, 225 TWh of additional gas would need to be burnt in order to generate the electricity produced in coal fired power stations in plants with a capacity of 13600 MW.

The capital cost of building gas plant is £300/kW, based on an estimated cost of “less than £450M” to build the 1,500 MWe CCGT plant at Staythorpe [National Power, 1998 Annual Report, p. 4]. Therefore the total capital cost is $13,600 \times 1000 \times 300 = \text{£}4080\text{M}$.

Operating costs include the cost of fuel. In 1999 fuel costs were 0.405 pence/kWh for coal and 0.613 pence/kWh for gas. The extra cost of fuel is therefore £212M.

Effectiveness

100% of emissions from coal-burning power stations will be eliminated. Emissions of particulate matter, metals and toxic organic pollutants from the gas-fired plant are considered to be effectively zero.

2. Abatement Measure: Flue Gas Desulphurisation

Description of measure

This measure assumes that wet flue gas desulphurisation is fitted to all coal fired power stations in operation in May 2001.

Cost

Costs are taken from the methodology developed by the International Institute for Applied Systems Analysis (IIASA), reported in Cofala *et al.* (1998). The assumptions in Table 5.14 are used to calculate costs:

Table 5.14 Input parameters for calculation of costs for wet flue gas desulphurisation at UK power stations

Parameter	Value
-----------	-------

Sulphur content of coal	1.55%
Thermal input per set	1300 MWth
Plant annual load factor	36.5%
Design efficiency of FGD	75% ^a
Lifetime of plant	5 ^b

Notes (a) FGD can achieve higher efficiencies than 75% but the low load factors at UK coal-fired power stations would make this difficult; (b) UK coal-fired power stations are all already over 25 years old (check this) and so the remaining lifetime is debatable. A short lifetime is assumed here, but to demonstrate the importance of this parameter, using a value of 10 years instead would decrease overall annual costs by one third.

The capital costs of fitting existing power stations with wet flue gas desulphurisation are estimated to be £1940 million, with annual operating costs of £110 million.

Effectiveness

It is assumed that the technology can reduce particulate matter emissions by 60% (from 50 mg/m³ to 20 mg/m³).

5.1.11 Primary Lead/Zinc

Remarks

There is only one UK plant involved in the production of primary lead and zinc and it is a significant source of heavy metals and dioxins. The plant uses the Imperial Smelting Process (ISP) in which lead and zinc-bearing materials are first sintered with coke and then smelted. The sintering process is a source of particulate matter and cadmium, mercury and arsenic and the smelter is a source of emissions of arsenic, cadmium, copper, lead and zinc. Further fugitive sources of emissions include furnace tapping, slag granulation and drossing pots.

1. Abatement Measure: Reduce particulate matter emissions to 10 mg m⁻³

Description of Measure

This scenario is taken from the Calculation of UK Costs of Complying with the Proposed UNECE Protocols on Heavy Metals and Pops (Entec, 1998). A range of measures were identified to reduce the emissions from the sole UK lead/zinc process to 10 mg m⁻³. The measures included:

- *For the sinter plant:*
 - Partial replacement of crusher house particulate abatement equipment with bag filters
 - Improvements to venturi scrubbing equipment for moisture-laden gas streams from the sinter machine / mixing drum
- *For the smelting/refining process:*
 - Replacement of wet scrubbing equipment for condenser floor operations with a bag filter
 - Improvements to wet venturi scrubbing equipment for the slag granulation system
 - Installation of additional scrubbing equipment for excess LCV gas to atmosphere

Cost

Investment costs quoted by Entec, based on information provided by the process operators, are £5.3M (1998). Running costs are assumed by Entec to be 10% of the capital cost, i.e. £530,000/y (1998).

Effectiveness

Entec estimate that emissions of particulate matter would be reduced by 41%. They assume that emissions of lead and cadmium would be reduced by the same percentage; we further assume here that the same is true of zinc and other heavy metals except mercury. Entec assume that the overall removal efficiency of mercury is 25% that of particulate matter, that is, 10%.

5.1.12 Refineries**Remarks**

This sector covers fuel usage at refineries. As would be expected, almost all of the fuel burnt is either fuel oil or other liquid fuel. Refineries are sources of heavy metals, dioxins, and PAHs. Because of their significant usage of fuel oil, refineries are major sources of nickel, which is present in higher concentrations in liquid fuels than in solid fuels.

1. Abatement Measure: The Strategic Review's "Likely Best Options"**Description**

This scenario is taken from A Strategic Review of the Petroleum Refinery Industry Sector (Foster Wheeler Energy Ltd, 1999). It is the "Likely Best Option", in which for each refinery, the best option from Options 1 to 4 is chosen, and the results aggregated. Note that the best option is chosen on the basis of sulphur reduction, not heavy metal reduction.

The four options are, briefly:

1. Reduction of sulphur in fuel oil. (This would have negligible impact on heavy metal emissions.)
2. Substituting fuel oil firing with LPG or natural gas.
3. Abating key stacks using wet gas scrubbing.
4. A combination of Options 2 and 3.

Cost

The Strategic Review gives the following costs:

Capital cost	£47.9M
Operating cost	£16.8M/y

Effectiveness

The Strategic Review quotes a reduction in emissions of particulate matter of 48% (equivalent to 1231 t/y from a 1996 baseline). Reductions in heavy metals is likely to be at least as great (especially where fuel oil burning is replaced with LPG or natural gas), but detailed information is not available.

2. Abatement Measure: The Strategic Review's Option 5

Description

This scenario is taken from A Strategic Review of the Petroleum Refinery Industry Sector (Foster Wheeler Energy Ltd, 1999). It is “Option 5”, which is designed to meet the requirements of the EU’s proposed Communication on Acidification and the Large Combustion Installations Directive, and is more stringent than the “Likely Best Option” described elsewhere. Note that these requirements are oriented towards sulphur and NO_x emissions, not heavy metal reduction. In brief, the measures considered were:

- All combustion plant to be fired on zero-sulphur gas with ultra-low-NO_x burners
- Selective Catalytic Reduction to be fitted to major furnaces and boilers
- Recovery of waste streams containing sulphur for processing in the sulphur recovery unit
- Sulphur recovery units operating at 99.9% efficiency
- Fluidised Catalytic Cracking feed hydrotreatment fitted to major Fluidised Catalytic Cracking Units (FCCUs) on two refineries, and wet gas scrubbing fitted to remaining FCCUs.
- Use of high integrity trip systems to minimise the frequency and quantity of releases from flares.

Cost

The Strategic Review gives the following costs:

Capital cost	£450M
Operating cost	£100M/y

Effectiveness

The Strategic Review does not quote the reduction in emissions of heavy metals or particulate matter. However, it will be at least as great as the 48% achieved by the “Likely Best Option”.

For comparison reductions in SO₂ and NO_x are 52% and 39% for the Likely Best Option, and 90% and 85% for Option 5. Option 5 is optimised for sulphur and NO_x reductions, so heavy metal reductions of 85 to 90% are unlikely, but nevertheless they are likely to be significantly better than 48%. Therefore, we shall assume an intermediate value of 75% reduction in heavy metal emissions.

2. Abatement Measure: Fabric Filters

Description

Entec (1996) describes the potential application of measures comparable to those for oil-fired boilers in the power generation sector — essentially the addition of fabric filters to the flue gases from the process heaters.

Cost

Entec assumes that the cost per tonne abated would be the same as for the oil-fired power stations sector. The annualised cost is given as £161M/y (it is not clear exactly how this is calculated).

Effectiveness

Lead and cadmium are stated to be reduced by 93% and mercury by 35%. For the cost curve, other pollutants are assumed to be reduced by 93% as well.

5.1.13 Road Transport**Remarks**

Emissions occur due to a variety of mechanisms. Heavy metal, PAH and dioxin emissions occur as a result of the combustion of fuel. Emissions of heavy metals are all fairly low with the exception of lead, which is present in anti-knocking additives such as tetraethyl lead. Tyre wear is considered separately in this report.

Lead emissions formerly arose from due to the presence of the additives tetraethyl lead or tetramethyl lead in leaded petrol. Since the mid-1980s, the level of lead allowable in leaded petrol has fallen and since the early 1990s unleaded fuel has become increasingly common. From the beginning of 2000, leaded petrol was prohibited in the UK except for “specialist interest groups” such as classic car clubs, and must account for no more than 0.5% of total petrol sales. Lead emissions from this sector are therefore considered effectively negligible.

The other main pollutants of relevance to this study are PAHs and dioxins. In July 2000 the Government published its ten-year transport plan. This includes a large number of measures, the focus of which is to reduce congestion and CO₂ emissions. The effect of the measures in the plan on PAH and dioxin emissions are, however, relatively small.

In addition to this, there are a number of additional techniques, for example converting buses to run on liquid natural gas, that are not included in the plan that could be applied to further reduce PAH and dioxin emissions. Details and costs for these technologies are not yet finalised and are therefore not reported in this report.

1. Abatement Measure: Mandatory Particulate Traps for New Light and Heavy Duty Diesel Vehicles**Description**

Costs for this and other options for road transport have been provided by DLTR. These have been described fully in a previous report for DEFRA and DTI (AEA Technology, 2001) and the data are summarised here. In all cases, the efficiency of the measures was originally given for particulate matter only. We have assumed that emissions of all heavy metals except mercury are abated with the same efficiency of removal, while mercury removal is assumed to be half of the rate for other metals.

This option involves the mandatory fitting of particulate traps to diesel vehicles. The overall efficiency of this measure has been calculated at 11.5% for light duty vehicles, assuming implementation is by 2010.

The estimates of the costs to manufacturers of meeting this standard for light duty vehicles are highly uncertain and the DLTR have provided a range of possible costs. The lifetime of the equipment is assumed to be 6 years for a light duty trap. The traps are expected to lead to a small

increase in fuel consumption. An increase of 1% has been assumed and the additional resource cost included in the cost estimates. Table 5.15 shows the results of the cost analysis for light duty vehicles in 2010.

Table 5.15 Estimated Costs for Particle Traps and Light Duty Vehicles.

Particulate traps, £	Diesel cars	Diesel cars	Light vans	Light vans
	Low cost	High cost	Low cost	High cost
Trap cost	300	750	300	750
Lifetime (years)	6	6	6	6
Discount rate	6%	6%	6%	6%
Annualised capital cost	61	153	61	153
Annual fuel cost	7	7	11	11
Total annual cost per vehicle	68	159	72	163
Total annual cost	166 million	390 million	83 million	190 million

Source: DTLR

In the case of heavy-duty vehicles, traps are calculated to give an additional reduction in particulate matter emissions of 15.3%, if implemented by 2010. The cost of a trap is assumed to be between £2,000 and £3,000. An annual maintenance cost of £288 is also assumed, in line with experience from retrofitted vehicles.

Table 5.16 shows the relative cost-effectiveness for rigid and articulated heavy goods vehicles (HGVs) and buses for the high and low trap cost scenarios.

Table 5.16 Estimated Costs for Particle Traps and Heavy Duty Vehicles

Particulate traps, £	Rigid HGV	Rigid HGV	Artic HGV	Artic HGV	Buses
	Low cost	High cost	Low cost	High cost	
Trap cost	2,000	3,000	2,000	3,000	3,000
Lifetime (years)	7	7	7	7	7
Discount rate	6%	6%	6%	6%	6%
Annualised capital cost	358	537	358	537	537
Annual fuel cost	22	22	64	64	21
Annual maintenance cost	288	288	288	288	288
Annual cost per vehicle	668	847	710	889	845
Total annual cost	104,007,837	131,896,509	66,254,027	82,973,898	36,871,496

Source: DTLR

2. Abatement Measure: Introduction of 10ppm sulphur Limit in Diesel

Description

This option has modelled the impact of the widespread introduction of 'sulphur free' (10ppm) diesel. It has been assumed that sulphur free diesel will reduce PM₁₀ and heavy metal emissions from Euro I/II/III light and heavy duty diesel vehicles by 5%. It is not expected to have an additional impact on top of Euro IV standards (all new cars coming onto the market from 1st January 2006). It is also unlikely to have an additional impact on top of particulate traps, although for the purposes of the cost analysis the two measures have been estimated in isolation.

Overall, the estimated efficiency of the measure is 2.1%. The estimated cost to refineries from producing 10ppm diesel has been assumed to be between 0.2 – 1 pence per litre, with a central estimate of 0.4p.

3. Abatement Measure: Promotion of CNG for new Heavy Goods Vehicles

Description

This scenario has assumed the further encouragement of CNG in the HGV sector. The additional cost per new CNG vehicle is estimated to be between £20,000 to £30,000. The modelling has assumed the following number of CNG vehicles are introduced each year, as shown in Table 5.17.

Table 5.17 Assumed numbers of introduced CNG vehicles.

Year	2001	2002	2003	2004	2005+
Number of new CNG HGVs	100	200	300	500	500

Source: DTLR

It is unlikely that a new CNG vehicle would have any additional PM10 benefits on top of a heavy duty vehicle with a particulate filter. However, as with sulphur free diesel, for the purposes of the cost analysis the measures have been modelled independently. This measure has been estimated to achieve a reduction in emissions of 0.3% in 2010. Table 5.18 shows the estimated cost-effectiveness in 2010 for a range of estimates of the additional costs of new CNG vehicles.

Table 5.18 Estimated Cost-effectiveness for a Range of Cost Estimates for New CNG vehicles

New CNG HGVs, £	Rigid HGV	Rigid HGV	Artic HGV	Artic HGV
	Low cost	High cost	Low cost	High cost
Additional CNG cost	20,000	30,000	20,000	30,000
Lifetime (years)	10	10	10	10
Discount rate	6%	6%	6%	6%
Annualised capital cost	2,717	4,076	2,717	4,076
Annual fuel cost	3,760	3,760	7,359	7,359
Total annual cost per vehicle	6,477	7,836	10,077	11,435
Total annual cost	13,277,651	16,062,944	20,657,330	23,442,623

Source: DTLR

5.1.14 Secondary Lead

Remarks

This sector is a source of heavy metals and dioxins. The secondary lead industry is concentrated on the recovery of lead from batteries, although other processes include the recovery of lead from scrap pipes, sheet or drosses. Emissions can occur from the handling and fragmentation of batteries and other scrap materials but occur primarily during smelting.

1. Abatement Measure: Improvements to Fabric Filters and Fugitive Emission Control

Description

A study by Entec (1996) quotes the costs for achieving current standards (a 50% reduction in emissions) of about £2.32M per tonne of lead abated, for a representative plant. Given the reported emissions of 33.1 t/y, this implies a total annualised cost of £38M/y. These measures are assumed to be incorporated into the baseline for the cost curve. The Entec report also argues

that further reductions would have a high cost impact with little lead emitted. However the sector remains a relatively large source of lead, especially with the elimination of lead from petrol.

It has proved difficult to find a reliable source of further measures with costs specifically for this sector. It is therefore assumed here that achieving a further 50% cut in emissions is possible using further improvements to fabric filters and fugitive emission control.

Cost

The cost is assumed to be the same as for the first 50% reduction, as quoted in the Entec report, that is £38M/y (annualised).

Effectiveness

It is assumed that this measure would achieve a 50% reduction in each pollutant from the cost curve baseline.

5.1.15 Sinter Plant

Remarks

Sinter production is a source of heavy metals. Emissions of metals occur during handling of raw materials, crushing, screening and conveying of sinter feedstock and products, during sintering, and during cooling of the finished sinter. Emissions of dioxins and PAH occur during sintering.

One abatement option is the use of fabric filters on sinter plant, but this is currently required as an upgrade to UK plant and is therefore in the baseline.

1. Abatement Measure: Process Optimisation for Minimisation of Dioxins

Description

BREF [EIPPCB 2000a] reports that the only specific measure to reduce formation and emission of dioxins from sintering are improved process control for operational consistency. It also notes that UK plants are as good as any in Europe in this respect. Since there is no significant installation or running cost to further such improvements, and there are operational benefits, there is a net benefit to operators, and it will not be considered further for this cost curve.

2. Abatement Measure: Emission Optimised Sintering (EOS)

Description

Emission Optimised Sintering (EOS) essentially consists of re-circulating part of the waste gas from the sinter strand (see BREF [EIPPCB 2000a] for details). A side benefit is that waste gas discharge volumes are reduced so the required capacity of end-of-pipe abatement is reduced.

Cost

The capital cost quoted in BREF is 17 MEURO (1996), or approx. £10M (assuming £1 = 1.6 EURO approx.).

There are likely to be operational savings, but BREF indicates that the values achieved at the reference plant (2.5 MEURO (1996)/y) may not be achievable elsewhere for various reasons.

Therefore, since there clearly will be some savings, an intermediate value of £1M/y (cost saving) is assumed here.

Effectiveness

BREF reports reductions in emissions of particulate matter and hydrocarbons of around 50%, and reductions in dioxins (PCCD/F) of around 65–70%.

3. Abatement Measure: Sectional Waste Gas Re-circulation

Description

This measure essentially consists of re-circulating part of the waste gas from the sinter strand, dealing with different sections of the strand separately. See BREF [EIPPCB 2000a] for details. It is similar in concept to Emission Optimised Sintering (q.v.) with similar results but slightly cheaper.

Cost

The capital cost quoted in BREF is 8–10 MEURO (1997), or approx. £5–6M (assuming £1 = 1.6 EURO approx.).

Operational costs are not given, but there are likely to be slight savings in coke consumption. It is therefore assumed here that the operational costs are zero.

Effectiveness

BREF reports reductions in emissions of particulate matter of 56%.

5.1.16 Tyre Wear

Remarks

Tyre wear from road transport results in emissions of zinc due to the use of zinc oxide in tyres and cadmium which is present as a contaminant in the zinc used to manufacture of zinc oxide.

Zinc emissions occur mainly from dust generated as a result of tyre wear. The tyres contain zinc oxide (2–5% of total). The British Rubber Manufacturers Association states (personal communication, 2000) that no alternatives to the use of zinc in tyres can be foreseen. Furthermore, although the rate of tyre wear has improved significantly over recent years, it is not clear whether there is scope for further improvement (the commercial nature of the issue means that information is not publicly available). It might be possible to reduce tyre wear by encouraging drivers to maintain their tyres better (e.g. maintaining the correct pressure) and improve their driving; this would provide a variety of environmental and safety benefits but it has not been possible to quantify them for this report.

1. Abatement Measure: Use Zinc with Lower Cadmium Levels

Description

The zinc used in tyres mainly comes from scrap zinc, which contains cadmium as a trace contaminant (Entec 1996). Use of higher grade zinc would reduce cadmium emissions.

Cost

Entec estimate that the cost of replacing scrap zinc with Grade 1 zinc would be around £160 per tonne used; with 6,000 tonnes of zinc oxide used annually, or approximately 5,000 tonnes of zinc, the total cost of the upgrade in zinc quality would be £800,000/y.

Effectiveness

Currently, cadmium contents of zinc oxide specified by tyre manufacturers are typically between 0.1% and 0.5% cadmium. Grade 1 zinc contains about 30 ppm cadmium, some 30 times less. This measure will therefore reduce cadmium emissions from this source by 97%. No other pollutants will be affected.

5.2 MEASURES EQUIVALENT TO OR BELOW BAT**5.2.1 Alkyl Lead Production**

The production of tetraethyl lead and tetramethyl lead is a source of emissions of lead. The process involves the alloying of lead with sodium, the reaction of this alloy with alkyl chlorides to produce the alkyl lead, and the treatment of the residues from the second stage, in order to recover lead. Emissions of lead can occur from all three stages.

The phase-out of lead additives in petrol around the world means that this sector is shrinking rapidly. There is only a single plant in the UK producing lead additives, and production is down more than 90% since 1990 [Richard Shone, Associated Octel, personal communication, 2000]. Lead emissions have fallen roughly in proportion. The plant is managing the ongoing reduction in demand with a view to its pending closure at some time in the medium-term future. It is likely that lead emissions will continue to decline significantly until the plant finally closes. Therefore, no specific additional abatement measures are included here.

5.2.2 Anode Baking

Anode baking refers to the preparation of pre-baked anodes, for use in the production of primary aluminium by electrolysis of alumina. The anodes are manufactured from coal tar pitch and petroleum coke, and are baked at temperatures of up to 1150 °C, for about three weeks. The baking process is a major source of PAH emissions. Anodes are baked at two sites in the UK, for use by the UK's three primary aluminium plants.

Emissions from anode baking have been significantly reduced at one plant by the adoption of a range of measures including improved containment, better combustion control and by gas cooling and particulate matter arrestment. Similar measures are planned at the remaining anode baking plant. These measures form part of the baseline inventory. Measures for achieving significant further abatement beyond this baseline have not been identified.

5.2.3 Basic Oxygen Furnaces

Basic oxygen steel-making furnaces are sources of heavy metals. Emissions occur during metal pre-treatment, during oxygen blowing, charging and tapping of the oxygen converter and during secondary metallurgy processes. Emissions are most significant during oxygen blowing.

Some primary measures are available, for example by improving the design or control of the furnace. But the most important control strategy involves the use of particulate matter abatement plant. Options include use of venturi scrubbers and ESPs for de-dusting of the furnace off-gases. Fabric filters or ESPs are commonly used for de-dusting of secondary off-gases. In the UK, all plants have primary gas cleaning using wet scrubbers. These systems are reported to achieve particulate emission levels of around 10–50 mg/Nm³. In addition, there are secondary fume extraction systems, which operate at low level near to the converters and at roof level to capture those emissions it was not possible to capture at or near the source; these use either bag filters, wet scrubbers or ESPs. No further options have been identified for this sector.

5.2.4 Blast Furnaces

Blast furnaces are a source of heavy metal emissions. Emissions occur during blast furnace charging, from blast furnace top gas use (although most particulate matter is removed from blast furnace gas prior to reuse), and from the tapping and pig iron/slag separation processes which occur in the casting bay area. Zinc present in the blast furnace feedstocks is largely transferred to blast furnace gas [EIPPCB 2000a]. Abatement measures can include enclosing the hot metal route with carefully designed screening structures, and filling the remaining spaces with nitrogen in order to prevent oxidation of molten iron, producing fume. However such systems should be considered as being in the baseline (Powlesland, 2001) i.e. either in place or to be implemented under existing legislation. No further options have been identified.

5.2.5 Cement

Cement production is a source of heavy metal and dioxin emissions. The main sources of emissions are the milling of raw materials and the kilning of the raw materials.

ESPs, or less commonly, fabric filters, are used to control dust emissions from the milling and kilning. Emissions of dust also occur from the handling of materials and in this case good housekeeping can help as well as use of filters to treat dust-laden gases. Heavy metals, dioxins and PAHs are reported to be strongly adsorbed to the clinker dust, so measures to reduce particulate emissions also reduce these emissions efficiently. The principal abatement option is therefore to upgrade ESPs or fabric filters. However this should be included in the baseline and so no costs are included.

Some other possible measures include use of feedstocks without dioxin precursors or volatile metals, temperature control to prevent dioxin formation, and use of activated carbon to remove mercury, other volatile metals and/or dioxins. Since emissions of these pollutants are low, they are not considered further here. Further options include the use of dry kiln/pre-heater technology with fabric filtration and carbon injection rather than the wet or semi-wet process, thus cutting fuel use and therefore emissions. No cost data have been obtained for these measures.

5.2.6 Chromium chemicals

This sector includes the manufacture of chemicals based on chromium and is a significant source of chromium. There is one UK plant which uses fabric filtration, and wet scrubbing to dedust the various particulate matter emissions from the plant. No information on further abatement options for this plant have been found.

5.2.7 Clinical Waste Incineration

Clinical waste incinerators emit heavy metals and dioxins, and very small amounts of PAH. The Waste Incineration Directive (WID) provides mandatory maximum permissible emission levels for particles of 10 mg m^{-3} , for mercury of 0.05 mg.m^{-3} , for cadmium and thallium there is a combined limit of 0.05 mg.m^{-3} and for other heavy metals there is a combined limit of 0.5 mg m^{-3} . Finally for dioxins there is a limit of 0.1 ngTEQ m^{-3} . Fabric filters have to be used to meet these limits and carbon injection is deployed to meet the mercury and dioxin limits. Further tightening of limits under WID will require increased reagent injection.

5.2.8 Coke Production

Coke ovens are sources of heavy metals, PAH, and dioxins. Emissions occur during coke oven charging, from coke oven doors and lids during coking, and during pushing and quenching. Control of emissions during quenching using lamella stack baffles and good design of the quenching tower to minimise emissions is considered part of the baseline (Powlesland, 2001)

There is a wide range of emission factors reported between different coke plants. This is partly due to the design of the plant and installed equipment, but maintenance can often be a determining factor. As the European IPPC Bureau (2000a) puts it: "The wide range of values for emission factors can primarily be explained by the maintenance programme, the degree of care taken in its performance (enabling smooth and stable operation conditions) and the abatement techniques applied." As explained in the introduction, maintenance issues are generally beyond the scope of this work, being regarded as BAT already.

5.2.9 Foundries

Foundries are sources of heavy metal emissions. Emissions can occur during melting of metals, pouring into moulds and during fettling (cleaning and finishing of the casting).

Primary methods for reducing emissions include replacement of cupolas with induction furnaces which have lower emission rates. (Use of natural gas as a fuel in cupolas rather than coke will also lower particulate matter emissions). No costs have been obtained for this measure

A number of process controls can be implemented to reduce emissions, for example avoidance of excessive heating of the melt or prolonged holding of the melt at high temperature, and use of raw materials containing lower levels of heavy metals. Such measures are likely to be cost-neutral, or very nearly, but the likely emission reduction is very difficult to quantify. This type of measure will, most probably be already in use in many foundries.

Secondary methods of abatement include the use of either wet scrubbing or fabric filters for hot blast cupolas. Fabric filters are also used for cold blast cupolas, induction furnaces and electric arc furnaces. ESPs are only used very occasionally. Entec (1996) gives fabric filtration as being BAT for foundries. Entec suggest that the current/impending commitments in 1996 would achieve 10 mg m^{-3} , which is as good as currently achievable.

5.2.10 MSW Incineration

Municipal solid waste (MSW) incinerators are significant sources of dioxins and heavy metal emissions. Although some emissions of heavy metals could result from handling of waste feedstocks and combustion residues, the bulk of emissions of heavy metals and all of the emissions of dioxins result from the incineration process itself. One UK plant has ESPs while the rest have fabric filters and all have carbon injection. Under the Waste Incineration Directive, some upgrading of bag filters may be required at some sites and increased levels of carbon injection may also be required. No further options for abatement have been identified.

5.2.11 Other non-ferrous metals

This sector includes non-ferrous metal processes with lower emissions, making only a small contribution to the total inventory. Abatement measures for these small sources have not been included in this study.

5.2.12 Other Sources

This sector includes a wide range of (mainly minor) sources of heavy metals, PAHs and dioxins which do not fit into any of the other categories used in the cost curves. Sources include miscellaneous chemical processes, miscellaneous non ferrous metals processes, use of wood preservatives, emissions of mercury from electrical and measuring equipment, and landfill sites. This is a very diverse collection of sources and although it should be technically possible to abate emissions from some or all of these processes, such abatement measures have not been included in the cost curves.

5.2.13 Other transport

This category includes shipping, aircraft, railways, and off-road vehicles, and is a source of heavy metals, dioxins, and PAHs. Emissions occur as a result of fuel combustion. This is another diverse collection of sources which makes a small contribution to the inventory. Therefore, although it should be technically possible to abate emissions from some or all of these processes, such abatement measures have not been included in the cost curves..

5.2.14 Primary Aluminium

The primary aluminium industry is a major source of PAH emissions as well as being a source of emissions of some heavy metals. Emissions of PAH occur due to the use of anodes manufactured from coal tar pitch and petroleum coke in the electrolysis of the aluminium. The three remaining UK plants all use the pre-baked anode process, which makes use of previously baked anodes (see Section 5.2.2). A UK Soderburg plant, which baked anodes in-situ, closed in 2000.

Emissions have been significantly reduced at one plant by the adoption of a range of measures including improved containment, better combustion control and by gas cooling and particulate matter arrestment. Similar measures are planned at the remaining plants. These measures form part of the baseline inventory. Measures for achieving significant further abatement beyond this baseline have not been identified.

5.2.15 Secondary Copper

There was one secondary copper process in the UK but this has recently closed down.

6 Cost curves

Single pollutant cost curves have been prepared as well as cost curves for “weighted mixes” of pollutants. The principle underlying the weighted-mix cost curves is that the priority for implementing measures is optimised based on reducing more than one pollutant, and the effects on emissions of many of the pollutants included in this study are shown on a single graph.

6.1 SINGLE-POLLUTANT COST CURVES

6.1.1 Underlying Idea

The purpose of a cost curve is to show which are the most cost-effective measures to achieve a particular reduction in emissions. The available abatement measures are ranked according to their cost-effectiveness (tonnes of emission abated divided by the annual cost of implementing the measure). The cumulative cost and the emissions remaining are calculated as running totals, starting with the most cost-effective measure and ending at the least. The cumulative cost is then plotted against the emissions remaining on a graph.

6.1.2 The Cost Curves

Single pollutant cost curves have been prepared for the following pollutants: Arsenic, Benzo[a]pyrene, Benzo[b]fluoranthene, Benzo[ghi]perylene, Cadmium, Chromium, Copper, Dioxins, Mercury, Nickel, Lead, Selenium, Vanadium and Zinc. An example of the cost curve prepared for Arsenic is shown in Figure 6.1. A complete graphical set of cost curves, representing the results of the measures presented in Section 5, is included as Appendix D.

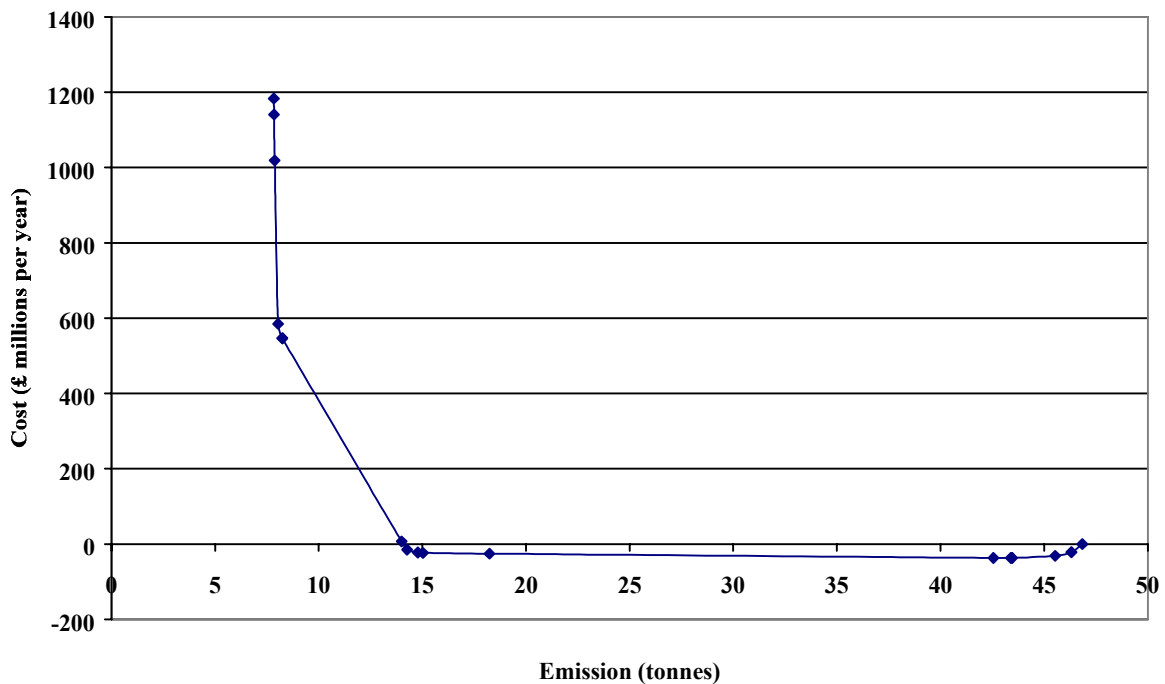


Figure 6.1 Cost Curve constructed for Arsenic.

6.1.3 Interpreting the Cost Curves

Conventional single-pollutant cost curves illustrate the most cost-effective way of reducing emissions. They show the cost of achieving any required level of emission. The x axis shows emissions remaining in kilotonnes, kilograms or grams depending on pollutant. (Sometimes cost curves are presented with the cumulative emission reduction achieved on the x axis, resulting in J-shaped curves which are the mirror image of the graphs in Appendix D. The advantage of the method used here is that it includes the current emission level on the curve and makes visual comparisons with the status quo easier.) The y axis shows the cumulative cost required to achieve the level of emissions on the x axis.

As an example of the interpretation of the graphs, consider the arsenic cost curve in Figure 6.1. The graph is best read from right to left. The point at the right-hand end of the line represents the current baseline situation. The x -value is the current total emission of arsenic from all sectors: 46.8 t per year. The y -value is zero, because this point represents the situation where no extra money is spent.

Moving left along the line, it drops below the y axis. This indicates that there are measures which reduce emissions and save money. Checking the graph's source table (not included in this report) shows that the measure is improved insulation in the domestic combustion sector. This is reasonable: improved insulation reduces the amount of fuel used and can pay for itself over the medium term. Although this is a win-win measure (reduced emissions and cost savings), it is poorly implemented at present for a number of reasons, such as the requirement for up-front capital expenditure with relatively long pay-back time, lack of awareness, lack of external pressure, inertia, *etc.*

Moving further left along the line, there are two more measures which both reduce emissions and save money, but the cost saving per unit emission reduction is progressively lower. These measures are switching to gas in the domestic combustion sector (to which the above comments apply again), and emission optimised sintering, which has only a very small effect. Finally, measures begin to cost money and the line turns upwards. The next most cost-effective measures are “primary measures in melting activities” in the glass sector, and then switching to burning gas in the industrial combustion sector. The latter achieves the greatest single reduction of any measure — from 42 t per year to 18 t per year.

Continuing to move left along the line, measures become increasingly less cost-effective as the line steepens (the gradient becomes more negative). At the left-hand end there are measures such as upgrading filtration in clinical waste incinerators and improving fabric filters in the secondary lead sector. These cost tens of millions per year, but result in very small reductions of just a few kilograms per year.

6.1.4 Using the Graphs

There are two main ways to read information off the graphs:

- For a given expenditure, see how far emissions can be reduced.
- See how much it would cost to achieve a given emission level.

Continuing to look at the arsenic example, suppose £100M per year were available to spend on abatement measures. In that case emissions could be reduced to just under 10 t per year, a reduction of about 80 per cent. Looking at the graph’s source table provides a list of the sectors affected and the specific measures which would need to be implemented (there are twelve measures across ten different sectors).

Alternatively, suppose there were a target to reduce emissions by 50 per cent — that is, from 47 t per year to 23 t per year. The graph shows that this can be done while still saving money overall. The measures that would need to be implemented are:

- Domestic combustion: Improved insulation.
- Domestic combustion: Switch to gas.
- Sinter plant: Emission optimised sintering.
- Glass: Primary measures in melting activities.
- Industrial combustion: Switch to gas (with 80% penetration).

Note that, in this scenario, some sectors (specifically the industrial combustion sector) would lose money. As noted above, there are also non-financial obstacles to implementing the measures.

6.1.5 Further points

Penetration

For most measures, penetration can be less than 100%. This was shown in the previous example, where the target can be met with 80% penetration of the last measure. This is meaningful, since it is possible for 80% of the numerous, small industrial combustion units to convert while the

other 20% are left as they are. On the other hand, however, some measures are discrete and are implemented in whole or not at all. For example, the primary lead/zinc sector consists of a single plant which would either be upgraded or not. Generally, these are small sources, but this may not always be the case for certain pollutants.

This means that when looking at a cost curve graph, it is usually possible to read off values from anywhere along a line segment, but sometimes it is necessary to read off from an adjacent node (corner) instead.

Successive Sets of Measures

After implementing a set of measures, the cost curve needs to be redrawn and, in general, further measures will be less cost-effective than they seem on the original cost curve.

The underlying reason for this is that it is usually more cost-effective to make a large change all in one go, than to take a succession of smaller steps to the same end. For example, suppose a power station currently has a PM₁₀ stack concentration of 140 mg/m³. Upgrading its electrostatic precipitators to achieve 20 mg/m³ it might cost £5M (say). Alternatively, if they first upgraded from 140 mg/m³ to 50 mg/m³ it might cost £3M, and then later upgraded from 50 mg/m³ to 20 mg/m³, the second upgrade might cost a further £3M.

The cost curves are designed to allow for this effect. This is in fact a special case of mutually exclusive measures, discussed below.

Mutually Exclusive Measures

Sometimes, available measures within a sector are incompatible (mutually exclusive); in other cases, they can be applied simultaneously. For example, emission optimised sintering and sectional waste gas re-circulation are both ways of improving sinter emissions, but only one can be applied at any given plant. On the other hand, either can be used in tandem with improved ESPs or fabric filters.

To handle exclusive measures, it is necessary to introduce the concepts of marginal cost and marginal abatement. Consider for example the hypothetical measures in Table 6.1. ESPs and fabric filters are assumed to be mutually exclusive; either can be used in conjunction with the process control.

Table 6.1 Example of Mutually-Exclusive Abatement Measures.

Measure	Cost	Emission abated	Cost-effectiveness	Marginal cost	Marginal abatement	Marginal cost-effectiveness
ESPs	£2M	10 t	5 t/£M	£2M	10 t	5 t/£M
Fabric filters	£3M	12 t	4 t/£M	£1M	2 t	2 t/£M
Process control	£1M	3 t	3 t/£M	£1M	3 t	3 t/£M

The ESPs are more cost-effective than the fabric filters, but are unable to achieve as great a reduction in emissions. (If ESPs were both more cost effective and able to achieve a greater reduction, then fabric filters would be completely excluded from the cost curve, since there are no circumstances in which it would be worth using them.) For the ESPs (the most cost-

effective of the exclusive measures) and for the process control (which is not exclusive), the marginal cost and marginal abatement are the same as the raw cost and abatement. For the less cost-effective fabric filters, the marginal cost (compared with the ESPs) is $\pounds 3\text{M} - \pounds 2\text{M} = \pounds 1\text{M}$. The marginal abatement is $12\text{ t} - 10\text{ t} = 2\text{ t}$. The marginal cost-effectiveness is therefore $2\text{ t} / \pounds 1\text{M} = 2\text{ t} / \pounds \text{M}$.

When ranking measures for the cost curve, it is the marginal cost-effectiveness that is used (in this case, $5\text{ t} / \pounds \text{M}$, $3\text{ t} / \pounds \text{M}$ and $2\text{ t} / \pounds \text{M}$). When plotting the graph, the marginal costs and marginal abatements are used. The result is the cost curve illustrated in Figure 6.2.

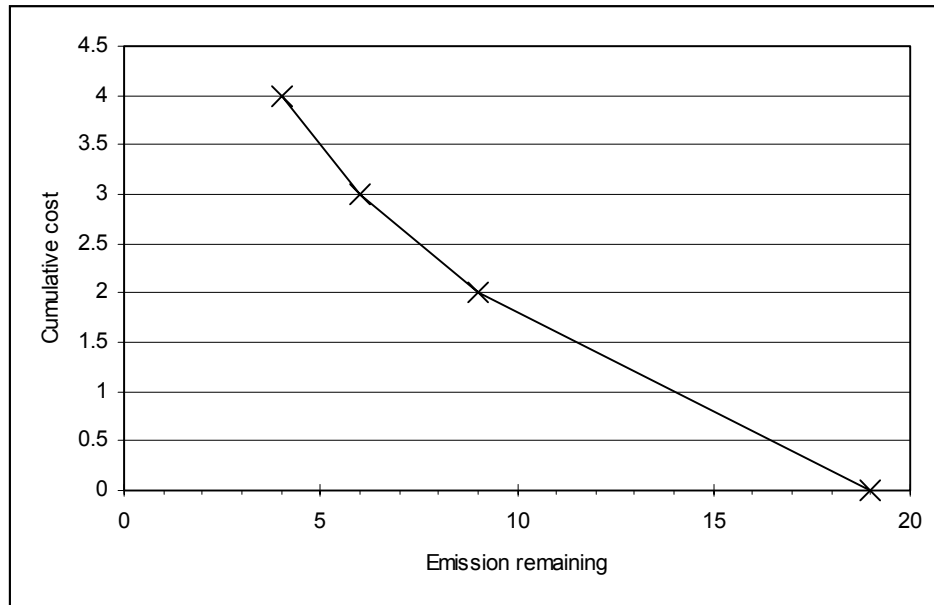


Figure 6.2 Example Cost Curve for Mutually-exclusive Abatement Measures.

6.2 THE WEIGHTED MIX COST CURVES

As well as conventional single-pollutant cost curves, this report presents so-called weighted mix cost curves. The purpose of these is to assess and illustrate the effects of measures on multiple pollutants.

The weighted mix cost curves can be used in two ways:

- To assess strategies aimed at controlling a number of pollutants simultaneously (true weighted mix).
- To see how measures aimed at reducing a single pollutant affect emissions of other pollutants (“side-effects”).

6.2.1 True Weighted Mix Pollutant Cost Curve

Generally, targets to reduce emissions of pollution will include several pollutants, some of which will be considered a higher priority than others. As an example, perhaps emissions of mercury are considered unacceptable, dioxins are a concern, zinc is a minor issue, and all other pollutants are at tolerable levels. In this case, you would want to give a high priority to measures for

controlling mercury, medium priority to measures that abate dioxins, and low priority to those that only affect zinc. You can express these priorities as numerical weightings, as in Table 6.2. Note that the total of the weightings is exactly 1.

Table 6.2 Example Weightings

Pollutant	Weighting
Mercury	0.6
Dioxins	0.3
Zinc	0.1
Others	0
Total	1.0

The software tool developed for this study uses these weightings to develop a cost curve that shows the most cost-effective way of meeting the combined target, prioritising the measures according to their effects on the different pollutants as described above.

An example of a weighted-mix cost curve is shown in Figure 6.3, using the 1999 NAEI emission inventory and the information contained in 5. The cost curve is optimised for a combination of several pollutants and show the effects on all pollutants considered in this study. The weightings used in this example are given in Table 6.3.

Figure 6.3 Cost curve for “Weighted Mix 1”

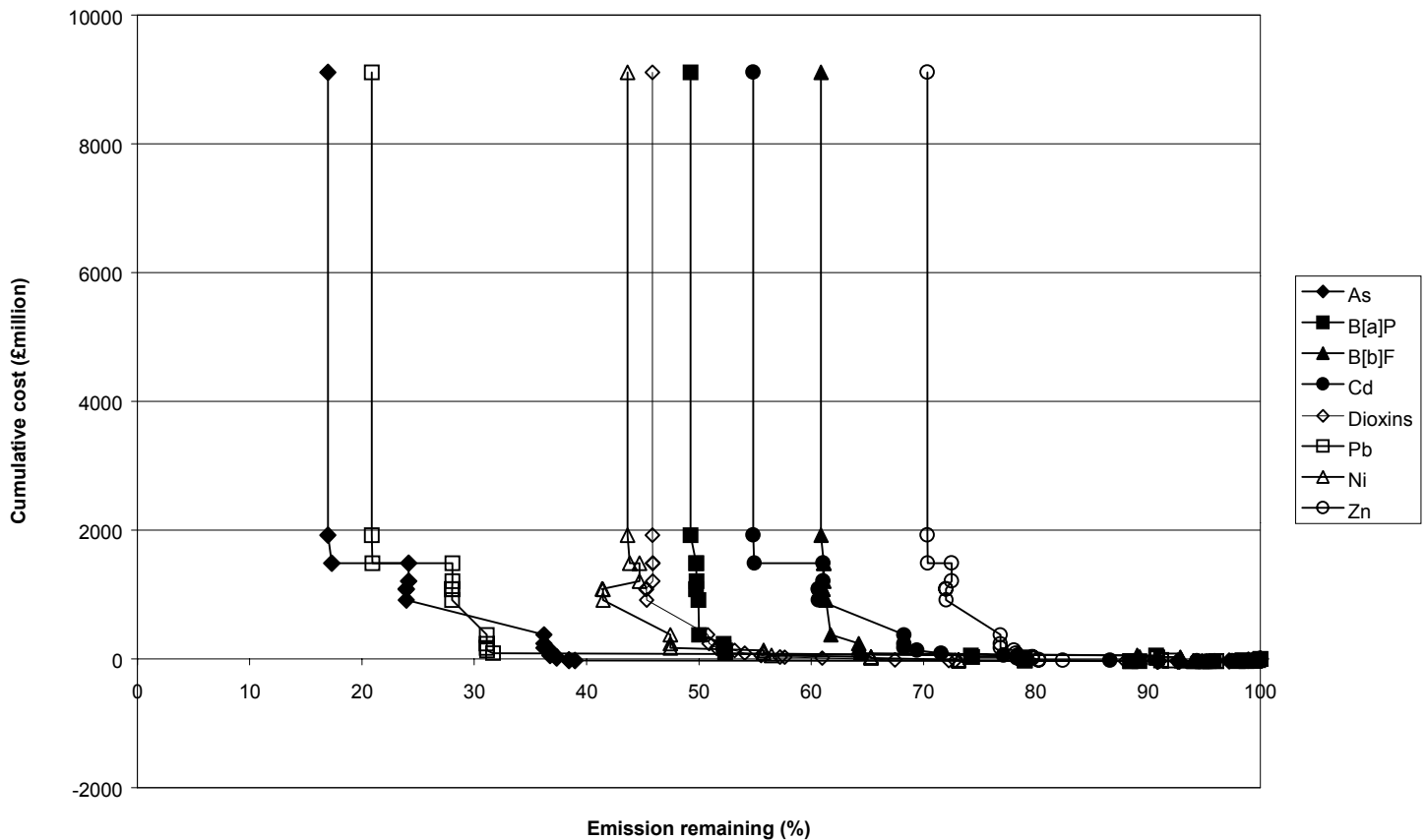


Table 6.3 Pollutant Weightings

Pollutant	Weighted Mix 1	Weighted Mix 2
Benzo[a]pyrene	0.34	0
Benzo[b]fluoranthene	0.33	0
Benzo[ghi]perylene	0.33	0
Dioxins	0	1
Others	0	0

Each line in Figure 6.3 represents a different pollutant, and can be read off in exactly the same way as on a conventional cost curve. Because the absolute amounts of emissions vary by orders of magnitude between different pollutants, the mixed weight cost curves are presented in terms of the percentage of the baseline emission remaining, rather than the absolute amount.

It should be noted that

1. the lines on the graph are much less smooth-looking than for simple cost curves because, for a given pollutant, the order in which the measures are applied may not reflect their cost-effectiveness *for that pollutant*. Pollutants with higher priority will have smoother curves, in general.
2. in order to reduce visual clutter on the graph and make it reasonably readable, it only shows a selection of the twenty-eight pollutants included in this study.

In the example given, the first measures involve the reduction in use of fuels in the domestic sector through energy efficiency measures, followed by a switch from coal to gas as fuel, again in the domestic sector. The remaining measures relate to the use of end-of-pipe technology or process changes by industry and particulate matter abatement equipment and alternative fuels for road transport, with the road transport measures generally among the least cost effective.

6.2.2 Side-effects of Single-pollutant Measures

Pollutants such as the heavy metals, dioxins and PAHs often have the same sources and can be controlled by the same abatement measures, hence their inclusion in this study. This means that any abatement programme aimed at reducing a single one of these pollutants is likely, as a side-effect, to reduce emissions of other pollutants as well. It would sometimes be useful to see these side-effects on the same graph as the main pollutant cost curve.

Using the weighted mix facility in the software tool, it is simple to produce such plots. Rather than entering a true weighted mix, assign all priority to a single pollutant. This has the effect of calculating a conventional cost curve for that pollutant, while also calculating the effects of the ranked measures on the other pollutants.

An example is shown in Figure 6.4. This uses dioxins as the key pollutant (see second column of Table). The following should be noted:

1. the line for dioxins is a smooth curve, like a conventional cost curve, whereas for the other pollutants, the lines are crooked.
2. to reduce the visual clutter from having twenty-eight lines plotted, only a selection of pollutants are shown in the figure.

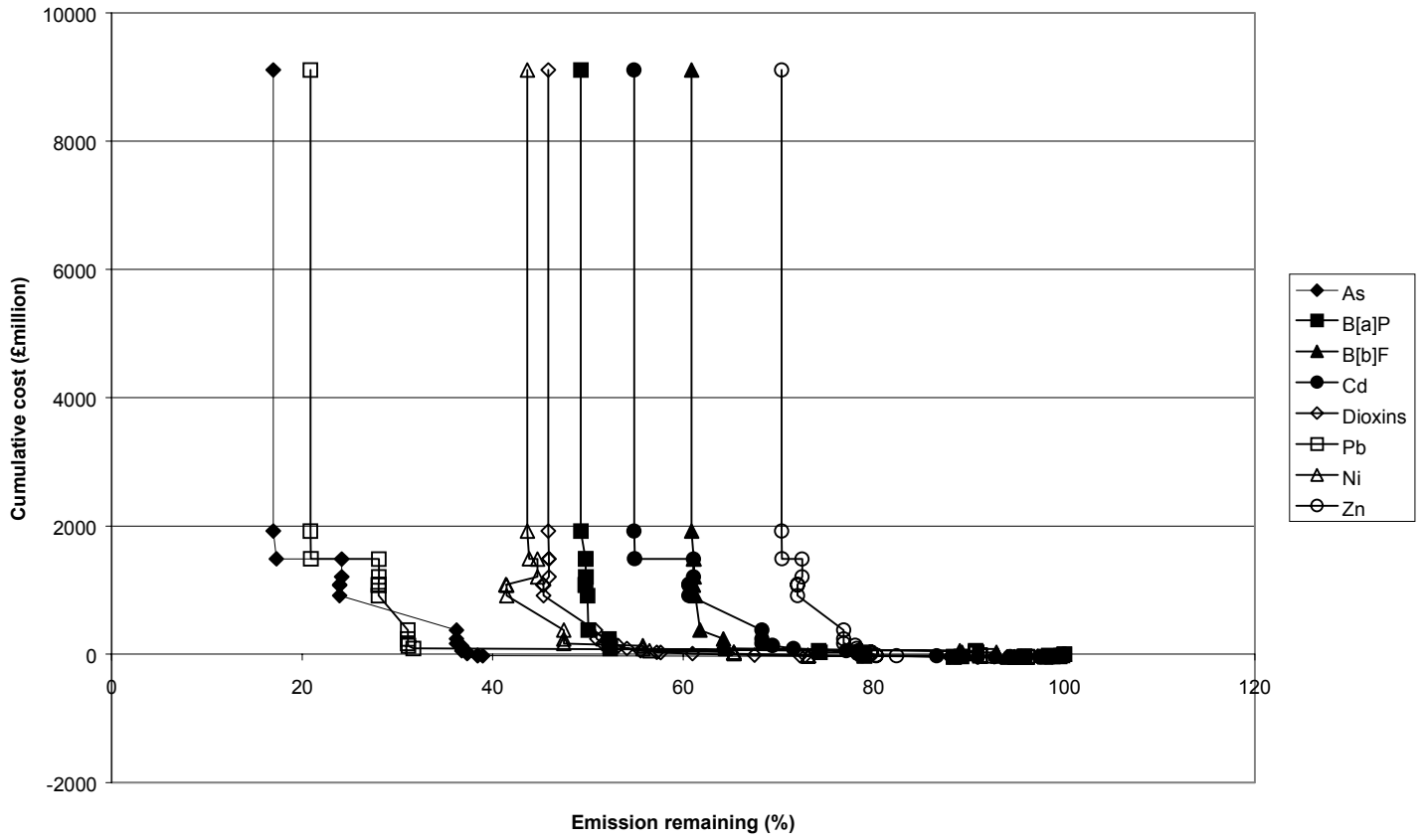


Figure 6.4 Cost Curve for "Weighted Mix 2"

7 Uncertainty in the cost curves

7.1 SOURCES OF UNCERTAINTY IN THE COST-CURVES

The scope of this study was to identify the sources and emissions of trace air pollutants and to identify and cost possible measures to control them. The cost-curves so generated represent a first step, and will be subject to refinement over time. This section reviews the main uncertainties with the cost-curves as they currently stand, in order to provide focus for future improvement, and to indicate their likely reliability at the present time.

Uncertainty arises at many points in the development of a cost-curve. The key areas where uncertainties arise for TOMPS and heavy metals are:

- **Quantification of emissions data and projections**
For most other air pollutants uncertainties at this stage are relatively unimportant, compared to uncertainties at other stages of cost-curve development. However, uncertainties are (proportionally) larger for trace pollutants, partly because of the use of non-continuous monitoring, and partly because of variability in emissions according to the quality of input materials, systems maintenance, etc.
- **Identification of abatement options**
Ideally a cost-curve would include all potential abatement options for reducing the pollutant in question, though this is rarely possible in practice. In this study, for example, no account has been taken of the potential for significant technological such as the introduction of fuel cells that could have a major impact on emissions.

Any omission is likely to have two effects on the cost-curve. First, the maximum feasible reduction in emissions will be underestimated. Second, the estimated costs of reaching any given level of emissions control may increase (if cheaper options could be applied to reach a particular point than those included in the cost-curve). Clearly, therefore, this source of error will bias towards overestimation of costs and future emissions.

- **Applicability of abatement techniques.**
Uncertainties in applicability vary according to the source and abatement technique under consideration. For sectors that cover large industrial installations (e.g. iron and steel, power generation, refineries) the existing state of technology is well characterised and the potential for further refinement reasonably well understood. Problems increase as one starts to consider technologies deployed in smaller installations (e.g. small industrial processes or the residential sector), and cases where technologies have a very long life expectancy (this would include the residential sector, but exclude transport). The problem is probably most marked in this report with respect to energy efficiency options, which, in view of their importance to the cost-curves, are discussed in a separate section below. Overall, the likely bias from this source is towards underestimation of costs and future emissions as a result of the uncertainty in applicability of energy efficiency options.

Some options will not be available at all sites— this being the case for fuel switching to natural gas at some plant where the existing gas infrastructure is not sufficient to cope with

major new sources of demand at the present time. [This does, of course, raise another uncertainty – will the infrastructure be developed over time to be able to satisfy demand, possibly as a result of legislation to control emissions.]

- Efficiency of abatement techniques

In general, the efficiencies of techniques, and certainly those applied to the major sources (stationary combustion; transport) are relatively well known for TSP and PM₁₀. Therefore, in the context of the report on PM₁₀ abatement (Holland *et al*, 2001), it was considered that this source of uncertainty was relatively unimportant. In the context of trace pollutant control, it is more problematic, as heavy metals, dioxins and PAHs tend to associate with particular size fractions of particles, and information on abatement of each size fraction by each different control option is generally lacking. In this report it is assumed that abatement efficiencies for each species will be the same as for PM₁₀, with the exception of Hg where a 50% efficiency has been adopted². This assumption is reasonable for low-volatility metals such as As, Cu, Cr and V. However, it is less satisfactory for semi-volatile species such as Cd, Pb, POPs, Se and Zn which may be concentrated on particles less than 2.5 microns in diameter. Also, for Hg, which is emitted as a gas.

Here, we make a general estimate of 50% uncertainty in estimates of abatement efficiencies. We accept that this will overestimate uncertainty for the less volatile species (e.g. As, Cr, Cu and V, as already mentioned), and underestimate uncertainty for the more volatile species (e.g. mercury, and some of the PAHs, such as fluoranthene).

- Technology unit costs

For large stationary sources, the costs of many of the measures are derived from UK BAT or the BREF notes, and so have been subject to careful and widespread review by industry and regulators. However, these costs are for representative firms and will likely to vary according to the size of industry and plant. Uncertainties are higher for other sectors which have so far been subject to a lower level of analysis and review in the context of IPPC.

There is evidence that estimated abatement costs tend to fall over time – for example as more suppliers enter the market creating competition and development costs are recouped. Furthermore costs may decrease as the market for a given technique matures. Finally, it may be difficult to know how to attribute the cost of an abatement technique if it reduces emissions of other pollutants concurrently, or if measures would be undertaken in any case through IPPC.

7.2 QUANTIFIABLE UNCERTAINTIES

A formal uncertainty analysis was not carried out specifically for this study. However, given similarities in the measures available for control of the trace pollutants of interest here as for PM₁₀, it is possible to use earlier work on particle control (Holland *et al*, 2001) to derive a first estimate of the overall reliability of the data generated. Accordingly parts of that study are reproduced below, with additional commentary to make the findings more relevant to this report.

² Recent work on the NAEI suggests that the 50% figure is too high by a considerable margin. For most sources a figure of 5 or 10% would appear more appropriate.

A previous study on the potential and costs for abatement of ammonia from non-agricultural sources (Handley *et al*, 2001) demonstrated that the use of Monte-Carlo techniques greatly reduces the range in estimates, compared to the simpler approach of combining all high estimates and all low estimates to generate ranges. Holland *et al* therefore applied Monte-Carlo analysis on the national cost-curve for reductions in PM₁₀ emissions in 2010 to take into account uncertainty in the following factors:

- costs (£ per tonne) of abatement technologies.
- baseline emissions;
- efficiency of abatement technologies;
- applicability of abatement technologies;

Quantification of the uncertainties in the above factors for individual emission control options is constrained by available data. In some cases (though by no means all), for example, it is necessary to draw on single estimates of costs for a given technology – information that cannot provide guidance on the potential spread of data. However, some estimation of likely uncertainties can be made by drawing on the ranges defined for other measures. The method is not perfect, but at the same time, it is clearly preferable to an assumption of no uncertainty.

The analysis was carried out in two parts. First, the effects of the combined uncertainties of the costs of abatement were assessed (Figure 5). The second analysis looked at the other three factors listed above (Figure 6). In both cases the analysis was based on a ‘high’ cost scenario for transport options. The figures describe the 90% confidence interval around the best estimate. Simultaneous analysis of all sources of uncertainty was not carried out, though could be factored into future exercises of this nature.

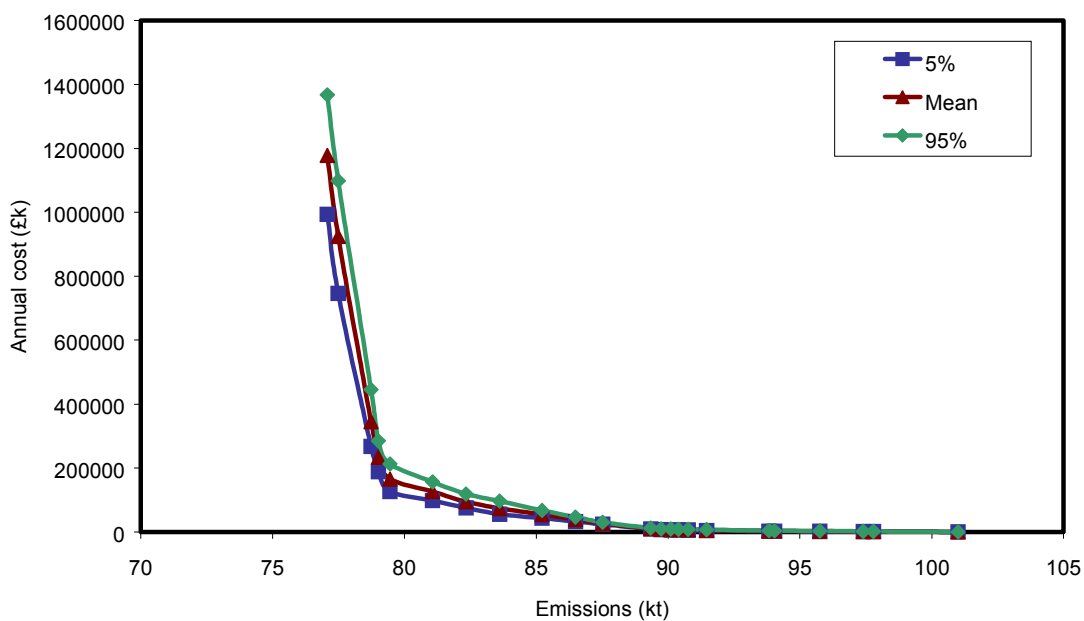


Figure 5 – The impact of uncertainty in costs of abatement measures on the total annual costs of the measures contained in the PM₁₀ cost-curve (Holland *et al*, 2001).

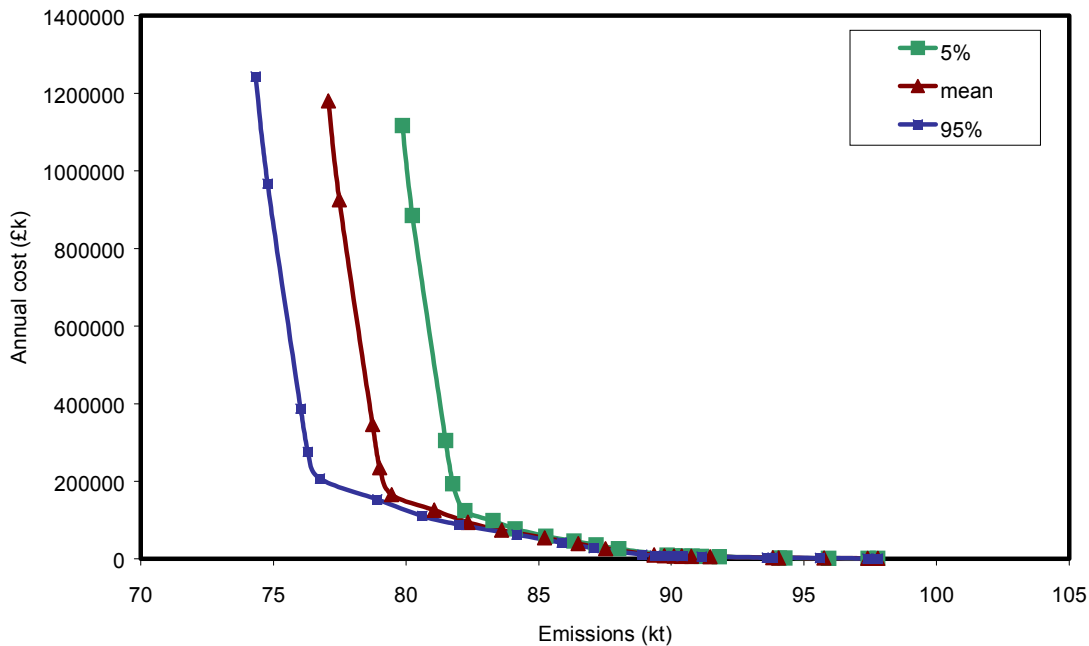


Figure 6 – The impact of uncertainty in abatement levels on the total annual costs of the measures contained in the PM₁₀ cost-curve (Holland *et al*, 2001).

Figure 5 demonstrates that there is a maximum uncertainty (as 90% confidence interval) in the costings of +30%, -24% around the mean. Results in Figure 6, to the extent that measures are comparable between the two studies, suggest a similar (additional) level of variation in emissions data.

Having seen these data for PM₁₀, it is necessary to consider how they might apply to the pollutants considered here, bearing in mind that there is greater variability in emissions data and the likely efficiency of options, depending on the effectiveness of measures in controlling the specific particle fractions in which each trace pollutant will preferentially concentrate. Without firm data on the latter in particular, it is not possible to come to a view that is well supported by available information. However, we make a conservative estimate that, for the uncertainties considered to this point, errors in costs and emissions are likely to be twice as high for the trace pollutants as for particles, giving a 90% confidence interval around the best estimates so far derived of $\pm 60\%$. This is not intended as the final word on this matter, but does provide some guidance prior to a more complete investigation of the problem.

Uncertainties will of course vary between pollutants, with information on some, not surprisingly, being of a higher quality than for others. For example, uncertainties in baseline emission estimates will be greater for those pollutants for which sources are less well characterised, for example where emissions are dominated by industrial processes rather than fuel use. Such pollutants include Cd, Cr, Hg, Se and Zn. Fugitive emissions pose a particular problem as the difficulties in including them in the NAEI (through imperfect reporting systems) introduce a tendency for underestimation in baseline emissions. In the same area, there is additional uncertainty through possible incompleteness of the inventory, and possible misunderstanding of the importance of historical residues. This seems likely to be of limited significance but could be important for POPs.

The analysis presented thus far does not include consideration of the effects of variation in the discount rate. Given that the choice of discount rate is typically made on an either/or basis, rather than considered through continual ranges this is best done using sensitivity analysis. Moving from a rate of 6%, consistent with current Treasury guidance, to 3% would reduce overall costs for an average measure by about 20%. The measures most sensitive to discount rate are those with high initial costs and low operating and maintenance costs. For measures for which initial costs are low, there is, not surprisingly, little difference in costs between the two discount rates. Further information is provided by Holland *et al* (2001).

It is clearly essential that account is also taken of issues that cannot currently be quantified with a reasonable level of confidence, as is done below. Although there is no satisfactory basis for quantifying the effects of these uncertainties in this report they should not be forgotten.

7.3 UNCERTAINTY IN THE APPLICABILITY OF ENERGY EFFICIENCY MEASURES

The existence of variability in the applicability of some measures was discussed above, specifically in relation to fuel switching and current issues of gas supply. In the context of this report the problem is probably most pronounced in relation to energy efficiency measures. As the cost-curves show, these could lead to significant cost-savings whilst at the same time reducing emissions. It is sometimes said that there is now very limited potential for additional energy and other efficiency measures to be introduced. However, this is not the case – as the best practice programmes for the UK Government have demonstrated over many years. Accepting that there is *potential*, however, is not the same as saying that people will be willing to undertake the measures identified. There may be several reasons why uptake of measures is limited, including but certainly not limited to, the following.

- Lack of awareness of the benefits of energy efficiency, or a lack of belief in claimed financial benefits.
- Inaffordability of the high initial costs of some energy efficiency measures. Unfortunately this may apply most to those living in properties where energy efficiency measures could be most beneficial. Some may simply be put off by high initial costs, even though they could afford them.
- Personal estimates of the useful life of equipment or the length of time that people may live in a particular property – are they long enough to recoup costs?
- Unwillingness to accept the disruption caused by significant building works (e.g. replacement of windows).

The study by Holland *et al* (2001) omitted energy efficiency measures on the grounds that the level of uncertainty in associated uptake and hence costs and emission reductions were too great to be used in a study which was to be applied directly and immediately in relation to the IGCB's (2001) review of the Air Quality Strategy. The issue was discussed in the context of a probable underestimation of the potential for abatement and reduction in control costs, but not taken further. In the context of this study, however, it is appropriate to include the measures in order that the issue is properly debated. For future work, it is recommended that a more extensive review of the potential for energy efficiency is undertaken, in consultation with relevant government departments in particular, as these are already driving forward policy in this area.

7.4 UNQUANTIFIED UNCERTAINTIES

These arise from the following sources:

1. Omission of options, either because of advances in existing technologies (e.g., replacement of heavy metals by other chemicals, for example for use as stabilisers in some plastics, or in battery manufacture), radical technological change (e.g. introduction of fuel cells in vehicles), or a lack of data on current application of a valid option
2. Availability of some non-technical options for reducing emissions in the UK, for example, changing the source of fuels
3. Possible errors in scenarios of future energy use, of the effectiveness in the implementation of existing legislation, and of future market trends
4. The extent to which the costs identified here will be borne as a result of concern over other problems, for example, global warming, particle control, and waste management.

Issues 1, 2 and 4 in this list bias the existing cost-curves towards under-estimation of the maximum feasible reduction in emissions, and to overestimation of the costs of reaching any given level of abatement. Issue 3 may lead to over or under-estimation.

Issue 4 indicates the need for going beyond the concept of single pollutant cost-curves, to a more multi-dimensional framework.. The single-pollutant methodology was adequate for the times when problems and solutions were sensibly addressed on a pollutant by pollutant basis— in other words when certain pollution problems were so manifestly bad that it was clear that they needed to be tackled without reference to anything else. However, the success of action to control pollution means that now it is not nearly so clear where the biggest benefits to be gained through pollution control lie. This study has defined a preliminary method for introducing the multi-pollutant dimension. The methods applied could be extended to include other pollutants also (here, they are confined to heavy metals and TOMPS). Whilst we believe that the method applied here is useful in generating new perspectives on abatement, additional methods, for example, more explicit inclusion of impacts assessment, should also be considered for the future.

Some of the uncertainties listed provide additional ideas for refinement of cost/benefit decision-making models such as the cost-curves generated in this study. It would appear appropriate to develop a much broader scenario-based approach to quantifying such uncertainties in the future – one that could be applied consistently across all pollutants, and be compatible with a statistical treatment of those uncertainties that can be quantified. Such an approach may be useful in identifying areas where alternative approaches to encouraging abatement, such as the use of fiscal incentives, could be useful. It may also assist in defining general levels of risk of different strategies – for example, some approaches may work well only under certain energy scenarios.

7.5 CONCLUSIONS

This section has demonstrated that the development of cost-curves is subject to a number of sources of uncertainty, some of which are likely to cause underestimation of potential abatement and/or overestimation of costs, and some which will act in the opposite manner. The acknowledgement and quantification of these uncertainties is in many ways an indication of the growing maturity of cost-curve development – previous use has often given readers a false sense of security in the data presented. Given that the cheapest options for pollution control have

generally been adopted already, it is time that a more strategic approach to the application of cost-curves was established to reduce the risks of taking options that are less cost-effective than possible. This needs to go beyond the quantification of individual sources of uncertainty in the cost-curve to include sensitivity analysis around energy and other types of scenario. Such developments need to be considered alongside DEFRA's continuing work on Integrated Assessment Modelling – adding to the transparency of that work, whilst not duplicating it.

The estimates made in this section of the extent of uncertainties in the cost-curves should be regarded as preliminary, though they do indicate where future refinements may be most useful in reducing uncertainty.

The need to factor in other policies more effectively than has been possible here, particularly those relating to climate change (given the potential effect of energy efficiency measures on the cost-curves) and particle control (given the link to most of the pollutants considered here) is suggested as the highest priority. The cost data used in the cost curves is not always robust and it is likely that measures which could play significant roles in reducing emissions of pollutants are missing from the analysis. Therefore the identification of areas for collection of further cost data is of great importance as well. Emissions data, particularly for persistent organic pollutants is very uncertain and cost curves could be made more reliable by addressing these uncertainties. Finally, improvement of the knowledge of which size fraction of particles each of the pollutants tend to condense onto in the flue gas stream is needed.

8 Recommendations

We would make the following recommendations for further development of cost curves. The recommendations are split into three areas for improvement and are ranked by high and medium priority.

Raw data for cost curves

High priority

- A detailed review of the *major* sources of emissions of heavy metals, persistent organic pollutants, benzene and 1,3-butadiene should be carried out to identify gaps and weaknesses in the available cost data and to prioritise areas for further research. This review should consider all types of control option including end-of-pipe equipment, process changes and process management techniques and should include both currently available techniques and developing techniques.
- On the basis of this review, further research should be carried out to establish costs of implementation, both capital and operating, for each identified emission reduction technique, together with potential cost savings e.g. through reduced resource consumption and compared with the expected emission reductions.
- Further research is required on the efficiency of particulate matter control equipment at reducing emissions of metals and persistent organic pollutants.
- Further analysis of uncertainty in cost curves is required, to identify areas where better data are required and to provide a better understanding of the likely reliability of the curves at present.

Medium priority

- The detailed review of available cost data referred to above should be extended to all sources of heavy metals, persistent organic pollutants, benzene and 1,3-butadiene. When considering minor sources of emissions the emphasis should be on identifying whether any measures might be available that could contribute in a significant and cost effective way to reductions in UK emissions of relevant pollutants.
- Further review of the main sources of emissions of heavy metals and persistent organic pollutants should be considered to further refine emission factors for these sources and thus reduce uncertainties in the emission inventory.

Scope of cost curves

High priority

- The cost curves should be modified so as to factor in emission reductions which might occur as a result of other policies, such as those aimed at promoting energy efficiency or reductions in other pollutants.
- In addition, existing cost curve data for other pollutants, in particular non methane volatile organic compounds (NMVOC), NO_x, SO₂, and non-agricultural sources of ammonia should be combined with the existing metals and persistent organic pollutant cost curves.
- The impact on the cost curves of different projection scenarios should be examined.

- Consideration should be given to options for the development of a model framework in order to provide effective integration of multi-pollutant issues into cost curves.

Medium priority

- The benefits to human health of expected emission reductions should be identified and evaluated on both a qualitative and quantitative basis.

Development of the cost curve tool

High priority

- Linking of emissions data within the NAEI with the cost curve tool would facilitate annual updating of cost curves as new inventory data become available, and would help to maintain consistency between the inventory and cost curve work. It would also assist in the efficient production of future or regional cost curves, speciated cost curves or temporally resolved cost curves through interaction with the spatial mapping, speciation, projections and temporally disaggregated elements of the NAEI database.
- The cost curve tool should be configured so as to provide flexible output which is suitable for use by other DEFRA contractors (for example in integrated assessment modelling work).

Medium priority

- Consideration should be given to expressing the performance of control measures in terms of emission factors in a manner consistent with the NAEI, rather than expressing performance in terms of a percentage reduction.

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Appendix A. Software tool for implementing of the cost curves

A.1 INTRODUCTION

A software tool has been developed using Microsoft Access to rank the measures identified in this report and present them as cost curves. Microsoft Access is a relational database management system with a sophisticated user interface, which makes the development and maintenance of this sort of tool reasonably simple.

Another reason for using Access is that the NAEI database is already implemented in Access. In future it may be possible to link the cost curve tool with the NAEI directly, either by importing the cost curve tool into the NAEI database, or by modifying the cost curve tool to link to the NAEI's data tables.

This appendix provides a simplified overview of the tool's structure and outlines its use.

At present, the tool contains information on the following pollutants:

- Acenaphthene
- Anthracene
- Benz[a]anthracene
- Benzo[b]fluoranthene
- Benzo[k]fluoranthene
- Chromium
- Copper
- Dioxins (PCDD/F)
- Fluorene
- Lead
- Naphthalene
- Particulate Matter < 10µm
- Pyrene
- Vanadium
- Acenaphthylene
- Arsenic
- Benzo[a]pyrene
- Benzo[ghi]perylene
- Cadmium
- Chrysene
- Dibenz[ah]anthracene
- Fluoranthene
- Indeno[1,2,3-cd]pyrene
- Mercury
- Nickel
- Phenanthrene
- Selenium
- Zinc

It currently contains emissions data for the years: 1990, 1995 and 1999.

A.2 EMISSIONS DATA

The tool uses NAEI emissions inventory data as the baseline to calculate emissions reductions. These are stored in the table *tblInventory*. At present, the table is set up by exporting data from the NAEI database, but in future it could be modified to contain a direct link to the NAEI. This table contains data for all years, all pollutants and all NAEI sectors.

Because the cost curves use a reduced set of sectors compared with the NAEI, there is a table called *tblNAEISectorsToTccSectors* which relates the 250 NAEI sectors to the 31 sectors used in this study. This table is in fact the same as Table C.1 in Appendix C. The tool is then able to use a query to create a set of emissions based on the 31 sectors used in this study.

A.3 ABATEMENT DATA

Information on the costs and effectiveness of the various abatement measures available is entered through the *frmAbatement* form and stored in the *tblAbatement* and *tblRemovalEfficiencies* tables. This data is taken from Section 5 of this report.

Each abatement measure corresponds to a record in the *tblAbatement* table. New measures are entered as new records in the *frmAbatement* form.

When entering data into the form, some values can be calculated for you automatically. For example, when you enter a discount rate and the plant lifetime, the capital recovery factor is automatically calculated. Similarly, whenever the capital cost or the capital recovery factor is updated, the annualised capital cost is recalculated. You can override the calculated values by entering a new value directly into the field. For example, for some measures, only the total annual cost is known, not the raw capital and operating costs.

For each abatement measure, it is necessary to enter removal efficiencies for each of the pollutants in the system. There are three ways to do this:

1. Set the removal efficiencies based on the PM₁₀ removal efficiencies. It is a common assumption that most heavy metals are removed at the same rate as PM₁₀, but mercury is only removed at half the rate, for example.
2. Set uniform removal efficiencies. It is sometimes the case that all pollutants are removed by a blanket amount, for example when a source is completely eliminated.
3. Set removal efficiencies individually. This can be done after using one of the above functions.

Where measures are mutually exclusive, this should be indicated by entering an “exclusion group identifier” (a suitably descriptive text string) in the Exclusion Group field. Measures with the same exclusion group identifier will be taken as mutually exclusive, and marginal costs calculated in the cost curve. (Some measures may be excluded from the cost curves if other measures in the exclusion group are always better.)

A.4 INDIVIDUAL COST CURVES AND GRAPHS

Calculated individual cost curves are stored in the *tblCostCurveParents* and *tblCostCurves* tables. These tables store the calculated rankings, cumulative costs and emissions remaining needed to plot the graphs, as well as supplementary data used in the calculation and occasionally useful to inspect.

Users can access the cost curves most easily through the *frmCostCurves* form. This presents data for all the individual cost curves in both tabular and graphical form. Cost curves depend on pollutant and on the baseline inventory year used. Whenever changes are made to the data underlying the cost curves – that is the abatement measures or the emissions inventory – the cost

curves should be recalculated by pressing the Calculate button on the frmCostCurves form. This will calculate a complete set of individual cost curves – one for each baseline inventory year and each pollutant.

Note that the Calculate button recalculates *all* the individual cost curves possible from the data in the system (i.e. each combination of baseline inventory year and pollutant).

A.5 WEIGHTED MIX COST CURVE

Information to manage weighted mix cost curves is stored in the *tblMixEmRem*, *tblMixParents*, *tblMixResults* and *tblMixWeights* tables. To set up or view weighted mix cost curves, open the *frmWeightedMix* form.

Each weighted mix cost curve corresponds to a record on the *frmWeightedMix* form. To see existing weighted mix curves, navigate through the records on this form.

To create a new weighted mix cost curve, reflecting a new control strategy scenario:

1. Open the *frmWeightedMix* form.
2. Create a new record by opening the Insert menu and choosing New Record.
3. Choose a Baseline Inventory Year and enter a suitable text Description.
4. Enter a weight for each pollutant. The weights must add up to exactly 1.
5. Choose the Calculate button. This will calculate the weighted mix cost curve.

Note that the Calculate button only calculates the *current* weighted mix cost curve. This is unlike the Calculate button on the individual cost curves form, which recalculates *all* the individual cost curves.

You must also press the Calculate button after making changes to abatement measures or emission inventory data.

Appendix B. Organisations contacted

In the course of this work, a number of organisations were contacted to obtain and/or review information. These included:

- Associated Octel
- British Cement Association
- British Non-Ferrous Metals Federation
- Britannia Zinc Limited
- Coalite
- CPL Industries
- Electricity Association
- Energy From Waste Association
- Environmental Industries Commission
- Forestry Commission
- Hamworthy Combustion Engineering
- IMechE Environmental & Safety Engineering group
- Ofgem
- Solid Fuel Association
- UK Steel Association
- Association of Electricity Producers
- British Glass Manufacturers Confederation
- British Rubber Manufacturers Association
- Chemical Industries Association
- Country Landowners Association
- Department of Trade and Industry
- Elementis Chromium
- Environment Agency
- Federation of British Cremation Authorities
- Hays Chemicals
- ICI Chemicals and Polymers
- National Trust
- Rhodia Eco Services
- Timber Growers Association

Appendix C. Definitions of sectors

The sectors used for this study are based on those used in the NAEI, but grouped in order to reduce the 250 NAEI sectors to a more manageable number. These groupings were based on similarities in the processes and in the abatement measures which might be applied. The “Other sources” category includes miscellaneous minor sources, such as ceramic manufacture and construction, generally contributing less than one per cent of total UK emissions of any of the featured pollutants, plus a few sources which are not readily amenable to abatement controls.

The complete list of NAEI sectors and the sectors to which they are assigned for this study are given in Table C.1.

Table C.1. Assignment of NAEI categories to cost curve categories

NAEI Source	NAEI Fuel	TOMPs Cost Curve Sector
accidental fires (vehicles)	accidental fires (vehicles)	Other sources
Accidental_Fires	NON-FUEL_COMBUSTION	Accidental fires
AGRICULTURE	Arable farming	Other sources
AGRICULTURE	BURNING_OIL	Domestic combustion
AGRICULTURE	COAL	Domestic combustion
AGRICULTURE	COKE	Domestic combustion
AGRICULTURE	FUEL_OIL	Domestic combustion
AGRICULTURE	GAS_OIL	Domestic combustion
AGRICULTURE	NATURAL_GAS	Domestic combustion
AGRICULTURE	STRAW	Domestic combustion
AGRICULTURE	VAP_OIL	Domestic combustion
AGRICULTURE_POWER_UNITS	GAS_OIL	Other transport
AGRICULTURE_POWER_UNITS	PETROL	Other transport
AIRCRAFT_SUPPORT	GAS_OIL	Other transport
Aircraft_TOL_(Domestic)	AVIATION_TURBINE_FUEL	Other transport
Aircraft_TOL_(international)	AVIATION_TURBINE_FUEL	Other transport
AUTOGENERATORS	COAL	Industrial combustion
AUTOGENERATORS	NATURAL_GAS	Industrial combustion
Broilers	Housed Livestock	Other sources
Cement_(Fuel_Combustion)	FUEL_OIL	Industrial combustion
Cement_(Fuel_Combustion)	PETROLEUM_COKE	Industrial combustion
Cement_(Non-decarbonising)	Clinker_Production	Cement
Cement_and_Concrete_batching	NON_FUEL_PROCESSES	Other sources
Ceramic_manufacture	NON_FUEL_PROCESSES	Other sources
Chemical industry	Index of Output (Chemicals)	Other sources
Chemical industry	Non fuel bitumen use	Other sources
Chemical Industry (Chrome chemicals)	NON_FUEL_PROCESSES	Chrome chemicals
Chemical_Industry_(Alkyl_Lead)	NON_FUEL_PROCESSES	Alkyl lead production
Chemical_industry_(Pesticide_production)	NON_FUEL_PROCESSES	Other sources
Chemical_industry_(Prod_Halogenated_chemicals)	NON_FUEL_PROCESSES	Other sources
CHLORALKALI_INDUSTRY	No fuel (EF = Emission)	Chloralkali process
COASTAL	FUEL_OIL	Other transport
COASTAL	GAS_OIL	Other transport
COKE_PRODUCTION	BF_GAS	Industrial combustion
COKE_PRODUCTION	COKE-OVEN_GAS	Industrial combustion

NAEI Source	NAEI Fuel	TOMPs Cost Curve Sector
COKE_PRODUCTION	COKE_MADE	Coke production
COKE_PRODUCTION	COLLIERY_CH4	Industrial combustion
COKE_PRODUCTION	NATURAL_GAS	Industrial combustion
COLLIERIES	COAL	Other sources
COLLIERIES	COKE-OVEN_GAS	Industrial combustion
COLLIERIES	COLLIERY_CH4	Industrial combustion
COLLIERIES	NATURAL_GAS	Industrial combustion
CONSTRUCTION	CONSTRUCTION_VALUE_1990	Other sources
Creosote_use	NON_FUEL_PROCESSES	Other sources
Dairy Cattle	Housed Livestock	Other sources
DOMESTIC	ANTHRACITE	Domestic combustion
DOMESTIC	BURNING_OIL	Domestic combustion
DOMESTIC	BURNING_OIL_(P)	Domestic combustion
DOMESTIC	COAL	Domestic combustion
DOMESTIC	COKE	Domestic combustion
DOMESTIC	FUEL_OIL	Domestic combustion
DOMESTIC	GAS_OIL	Domestic combustion
DOMESTIC	LPG	Domestic combustion
DOMESTIC	NATURAL_GAS	Domestic combustion
DOMESTIC	SSF	Domestic combustion
DOMESTIC	TOWN_GAS	Domestic combustion
DOMESTIC	WOOD	Domestic combustion
DOMESTIC_HOUSE&GARDEN	DERV	Other transport
DOMESTIC_HOUSE&GARDEN	PETROL	Other transport
FIELD_BURNING	BARLEY_RESIDUE	Other sources
FIELD_BURNING	LINSEED_RESIDUE	Other sources
FIELD_BURNING	OATS_RESIDUE	Other sources
FIELD_BURNING	WHEAT_RESIDUE	Other sources
FISHING	FUEL_OIL	Other transport
FISHING	GAS_OIL	Other transport
GAS_PRODUCTION	COLLIERY_CH4	Industrial combustion
GAS_PRODUCTION	LPG	Industrial combustion
GAS_PRODUCTION	NATURAL_GAS	Industrial combustion
GAS_PRODUCTION	OPG	Industrial combustion
GAS_PRODUCTION	TOWN_GAS	Industrial combustion
GLASS_PRODUCTION	Glass Production (Cont flat fibre spec)	Glass
INCINERATION	Chemical_waste	Other incineration
INCINERATION	CLINICAL_WASTE	Clinical waste incineration
INCINERATION	CREMATION	Cremation
INCINERATION	MSW	MSW incineration
INCINERATION	Sewage_Sludge_Combustion	Other incineration
IPCC_Domestic_Aviation	AVIATION_SPIRIT	Other transport
IPCC_Domestic_Aviation	AVIATION_TURBINE_FUEL	Other transport
IPCC_International_Aviation	AVIATION_TURBINE_FUEL	Other transport
IPCC_International_Marine	FUEL_OIL	Other transport
IPCC_International_Marine	GAS_OIL	Other transport
Iron_and_Steel_(Basic_Oxygen_Furnace)	Steel Production (oxygen converters)	Basic oxygen furnaces
Iron_and_Steel_(Blast_Furnaces)	BF_GAS	Industrial combustion
Iron_and_Steel_(Blast_Furnaces)	COKE-OVEN_GAS	Industrial combustion
Iron_and_Steel_(Blast_Furnaces)	Iron Production (Blast furnace)	Blast furnaces
Iron_and_Steel_(Blast_Furnaces)	NATURAL_GAS	Industrial combustion
Iron_and_Steel_(Combustion)	BF_GAS	Industrial combustion

NAEI Source	NAEI Fuel	TOMPs Cost Curve Sector
Iron_and_Steel_(Combustion)	COAL	Industrial combustion
Iron_and_Steel_(Combustion)	COKE	Industrial combustion
Iron_and_Steel_(Combustion)	COKE-OVEN_GAS	Industrial combustion
Iron_and_Steel_(Combustion)	FUEL_OIL	Industrial combustion
Iron_and_Steel_(Combustion)	GAS_OIL	Industrial combustion
Iron_and_Steel_(Combustion)	LPG	Industrial combustion
Iron_and_Steel_(Combustion)	NATURAL_GAS	Industrial combustion
Iron_and_Steel_(Combustion)	TOWN_GAS	Industrial combustion
Iron_and_Steel_(Electric_Arc_Furnace)	Steel Production (Electric Arc)	Electric arc furnaces
Iron_and_Steel_(Flaring)	BF_GAS	Industrial combustion
Iron_and_Steel_(Flaring)	COKE-OVEN_GAS	Industrial combustion
Iron_and_Steel_(Grey_Iron_Foundary)	Iron castings	Foundries
Iron_and_Steel_(Sinter_Plant)	Iron_Production	Sinter
LANDFILL	Escaping_Methane	Other sources
LANDFILL	Flared_Methane	Other sources
Laying hens	Housed Livestock	Other sources
LEAD_CRYSTAL_GLASS	NON-FUEL_COMBUSTION	Glass
LEAD_MINING_DEWATERING	Lead_Mined	Other sources
LIME_PRODUCTION_(Combustion)	LIME_PRODUCTION	Other sources
LIME_PRODUCTION_(Combustion)	NON-FUEL_COMBUSTION	Other sources
MAGNESIUM_alloying	NON_FUEL_PROCESSES	Other NFM
MISCELLANEOUS	COAL	Industrial combustion
MISCELLANEOUS	COKE	Industrial combustion
MISCELLANEOUS	FUEL_OIL	Industrial combustion
MISCELLANEOUS	GAS_OIL	Industrial combustion
MISCELLANEOUS	NATURAL_GAS	Industrial combustion
MISCELLANEOUS	NON-FUEL_LANDFILL_GAS	Industrial combustion
MISCELLANEOUS	SSF	Industrial combustion
MISCELLANEOUS	TOWN_GAS	Industrial combustion
NATURAL FIRES	Forest_&_Moorland	Natural fires
Non-Ferrous Metals (Nickel production)	Nickel production	Other NFM
Non-Ferrous Metals (Nickel production)	NON_FUEL_PROCESSES	Other NFM
Non-Ferrous Metals (other non-ferrous metals)	Index of Output (Basic Metals)	Other NFM
Non-Ferrous Metals (Primary Lead/Zinc)	Slab zinc and lead bullion	Primary lead/zinc
Non-Ferrous Metals (Secondary Copper)	Refined copper	Secondary copper
Non-Ferrous Metals (Secondary Lead)	Refined lead	Secondary lead
Non-Ferrous Metals (ALUMINIUM_PRODUCT ION_(Anode_baking))	NON_FUEL_PROCESSES	Primary aluminium
Non-Ferrous Metals (ALUMINIUM_PRODUCT ION_(General))	Primary Aluminium production	Primary aluminium
Non-Ferrous Metals (ALUMINIUM_PRODUCT ION_(using_pre-bake_anodes))	NON_FUEL_PROCESSES	Primary aluminium
Non-Ferrous Metals (ALUMINIUM_PRODUCT ION_(VSS_process))	NON_FUEL_PROCESSES	Primary aluminium
Non-Ferrous Metals (Primary_Lead_Production)	NON_FUEL_PROCESSES	Primary lead/zinc
Non-Ferrous Metals (Primary_Zinc_Production)	NON_FUEL_PROCESSES	Primary lead/zinc

NAEI Source	NAEI Fuel	TOMPs Cost Curve Sector
Non-Ferrous_Metals_(Secondary_Aluminium_Smelting_(Total_Al_prod)	NON_FUEL_PROCESSES	Other NFM
Non-Ferrous_Metals_(Tin_Production)	NON_FUEL_PROCESSES	Other NFM
NUCLEAR_FUEL_PROD	NATURAL_GAS	Other sources
OFFSHORE_FLARING	NON-FUEL_COMBUSTION	Other sources
OFFSHORE_OWN_GAS_USE	NATURAL_GAS	Industrial combustion
Other Cattle	Housed Livestock	Other sources
Other poultry	Housed Livestock	Other sources
Other_Industry_(Asphalt_manufacture)	Asphalt_produced	Other sources
Other_industry_(Combustion)	BURNING_OIL	Industrial combustion
Other_industry_(Combustion)	COAL	Industrial combustion
Other_industry_(Combustion)	COKE	Industrial combustion
Other_industry_(Combustion)	COKE-OVEN_GAS	Industrial combustion
Other_industry_(Combustion)	COLLIERY_CH4	Industrial combustion
Other_industry_(Combustion)	FUEL_OIL	Industrial combustion
Other_industry_(Combustion)	GAS_OIL	Industrial combustion
Other_industry_(Combustion)	LPG	Industrial combustion
Other_industry_(Combustion)	LUBRICANTS	Industrial combustion
Other_industry_(Combustion)	NATURAL_GAS	Industrial combustion
Other_industry_(Combustion)	OPG	Industrial combustion
Other_industry_(Combustion)	PETROLEUM_COKE	Industrial combustion
Other_industry_(Combustion)	SSF	Industrial combustion
Other_industry_(Combustion)	TOWN_GAS	Industrial combustion
Other_industry_(Combustion)	TREATED_WOOD	Industrial combustion
Other_industry_(Combustion)	WOOD	Industrial combustion
Other_Industry_(Part_B_Processes)	NON_FUEL_PROCESSES	Other sources
OTHER_INDUSTRY_OFFROAD	GAS_OIL	Other transport
OTHER_INDUSTRY_OFFROAD	PETROL	Other transport
OTHER_UK_SHIPPING	FUEL_OIL	Other transport
OTHER_UK_SHIPPING	GAS_OIL	Other transport
PHOSPHATE_FERTILIZERS	phosphate rock imports	Other sources
PIGMENTS_&_STABILIZERS	NON-FUEL_COMBUSTION	Other sources
Pigs	Housed Livestock	Other sources
POWER STATIONS	COAL	Power stations
POWER STATIONS	COKE	Power stations
POWER STATIONS	FUEL_OIL	Power stations
POWER STATIONS	GAS_OIL	Power stations
POWER STATIONS	LPG	Power stations
POWER STATIONS	MSW	Power stations
POWER STATIONS	NATURAL_GAS	Power stations
POWER STATIONS	NON-FUEL_LANDFILL_GAS	Power stations
POWER STATIONS	NON-FUEL_SEWAGE_GAS	Power stations
POWER STATIONS	OPG	Power stations
POWER STATIONS	ORIMULSION	Power stations
POWER STATIONS	PETROLEUM_COKE	Power stations
POWER STATIONS	POULTRY_LITTER	Power stations
POWER STATIONS	SCRAP_TYRES	Power stations
POWER STATIONS	SLURRY	Power stations
PUBLIC_SERVICES	BURNING_OIL	Industrial combustion
PUBLIC_SERVICES	COAL	Industrial combustion
PUBLIC_SERVICES	COKE	Industrial combustion
PUBLIC_SERVICES	FUEL_OIL	Industrial combustion

NAEI Source	NAEI Fuel	TOMPs Cost Curve Sector
PUBLIC_SERVICES	GAS_OIL	Industrial combustion
PUBLIC_SERVICES	NATURAL_GAS	Industrial combustion
PUBLIC_SERVICES	NON-FUEL_SEWAGE_GAS	Industrial combustion
PUBLIC_SERVICES	TOWN_GAS	Industrial combustion
QUARRYING	TOTAL_AGGREGATE	Other sources
Railways_(Freight)	GAS_OIL	Other transport
Railways_(intercity)	GAS_OIL	Other transport
Railways_(Regional)	GAS_OIL	Other transport
Railways_(Stationary_sources)	BURNING_OIL	Other transport
Railways_(Stationary_sources)	COAL	Other transport
Railways_(Stationary_sources)	COKE	Other transport
Railways_(Stationary_sources)	FUEL_OIL	Other transport
Refineries_(Combustion)	FUEL_OIL	Refineries
Refineries_(Combustion)	GAS_OIL	Refineries
Refineries_(Combustion)	LPG	Refineries
Refineries_(Combustion)	MISC	Refineries
Refineries_(Combustion)	NAPHTHA	Refineries
Refineries_(Combustion)	NATURAL_GAS	Refineries
Refineries_(Combustion)	OPG	Refineries
Refineries_(Combustion)	PETROL	Refineries
Refineries_(Combustion)	PETROLEUM_COKE	Refineries
Regeneration_of_Activated_Carbon	NON_FUEL_PROCESSES	Other sources
Road Transport: M/cycle (>50cc, 2st)	BRAKE_WEAR	Road transport
Road Transport: M/cycle (>50cc, 2st)	PETROL	Road transport
Road Transport: M/cycle (>50cc, 2st)	TYRE_WEAR	Tyre wear
Road Transport: M/cycle (>50cc, 4st)	BRAKE_WEAR	Road transport
Road Transport: M/cycle (>50cc, 4st)	PETROL	Road transport
Road Transport: M/cycle (>50cc, 4st)	TYRE_WEAR	Tyre wear
Road Transport: Mopeds (<50cc, 2st)	BRAKE_WEAR	Road transport
Road Transport: Mopeds (<50cc, 2st)	PETROL	Road transport
Road Transport: Mopeds (<50cc, 2st)	TYRE_WEAR	Tyre wear
Road_transport (coaches)	BRAKE_WEAR	Road transport
Road_transport (coaches)	DERV	Road transport
Road_transport (coaches)	TYRE_WEAR	Tyre wear
Road_transport_(All_cars)	BRAKE_WEAR	Road transport
Road_transport_(All_cars)	DERV	Road transport
Road_transport_(All_cars)	TYRE_WEAR	Tyre wear
Road_transport_(All_LGVs)	BRAKE_WEAR	Road transport
Road_transport_(All_LGVs)	DERV	Road transport
Road_transport_(All_LGVs)	TYRE_WEAR	Tyre wear
ROAD_TRANSPORT_(all_road_transport)	DERV	Road transport
ROAD_TRANSPORT_(all_road_transport)	PETROL	Road transport
ROAD_TRANSPORT_(all_road_transport)	TYRE_WEAR	Tyre wear
Road_transport_(buses)	BRAKE_WEAR	Road transport
Road_transport_(buses)	DERV	Road transport
Road_transport_(buses)	TYRE_WEAR	Tyre wear
Road_transport_(cars_cat)	PETROL	Road transport
Road_transport_(cars_non_cat)	PETROL	Road transport
Road_transport_(HGV_Artic)	BRAKE_WEAR	Road transport
Road_transport_(HGV_Artic)	DERV	Road transport
Road_transport_(HGV_Artic)	TYRE_WEAR	Tyre wear
Road_transport_(HGV_rigid)	BRAKE_WEAR	Road transport
Road_transport_(HGV_rigid)	DERV	Road transport

NAEI Source	NAEI Fuel	TOMPs Cost Curve Sector
Road_transport_(HGV_rigid)	TYRE_WEAR	Tyre wear
Road_transport_(LGVs_cat)	PETROL	Road transport
Road_transport_(LGVs_non_cat)	PETROL	Road transport
Road_Transport_(Resuspension)	Vehicle kilometers	Road transport
SHIPPING_NAVAL	GAS_OIL	Other transport
SSF_PRODUCTION	COAL	Industrial combustion
SSF_PRODUCTION	COKE	Industrial combustion
SSF_PRODUCTION	NATURAL_GAS	Industrial combustion
SSF_PRODUCTION	PETROLEUM_COKE	Industrial combustion
SSF_PRODUCTION	SSF_MADE	Coke production
TOWN_GAS_PRODUCTION	BURNING_OIL	Industrial combustion
TOWN_GAS_PRODUCTION	COAL	Industrial combustion
TOWN_GAS_PRODUCTION	COKE	Industrial combustion
TOWN_GAS_PRODUCTION	COKE-OVEN_GAS	Industrial combustion
TOWN_GAS_PRODUCTION	LPG	Industrial combustion
TOWN_GAS_PRODUCTION	NATURAL_GAS	Industrial combustion
Waste Disposal (Batteries)	NON-FUEL_COMBUSTION	Other sources
Waste Disposal (Electrical_Equipment)	NON-FUEL_COMBUSTION	Other sources
Waste Disposal (Lighting)	NON-FUEL_COMBUSTION	Other sources
Waste Disposal (Measurement_and_Control_Equipment)	NON-FUEL_COMBUSTION	Other sources
Wood impregnation	PCP_treatment	Other sources

Appendix D. Cost curve graphs

Cost curve graphs are presented for the following cases:

• Arsenic.....	Page 75
• Benzo[a]pyrene.....	Page 76
• Benzo[b]fluoranthene.....	Page 77
• Benzo[ghi]perylene.....	Page 78
• Cadmium.....	Page 79
• Chromium.....	Page 80
• Copper.....	Page 81
• Dioxins.....	Page 82
• Mercury.....	Page 83
• Nickel.....	Page 84
• Lead.....	Page 85
• Selenium.....	Page 86
• Vanadium.....	Page 87
• Zinc.....	Page 88

The cost curves are based on optimising for a single pollutant, and show the effects on the emissions of that pollutant only. For conciseness, only three of the sixteen PAHs are included here. All the cost curves are based on the 1999 NAEI emissions inventory.

For a general discussion of the interpretation of cost curves, see Section 6. The curves presented here are based on the use of an annualisation period of 10 years for energy efficiency measures in the domestic sector and, as discussed in section 5.1.4, this may be considered too long to drive peoples purchasing decisions. Using a shorter annualisation period would change the cost effectiveness of the measure leading to a reordering of the measures in the cost curve and the shape of the curves themselves. In the curves presented here, there is a small cost saving from the adoption of the energy efficiency measures and, since the next few measures can be implemented at low cost, in the case of many pollutants, a large reduction in emissions can be achieved before the cumulative cost exceeds zero. If a short annualisation period such as two years were used, then there would be only a very small reduction achieved before cumulative cost exceeded zero, however it would still be possible to achieve very significant reductions for relatively small costs (i.e. tens of £million per year).

Figure D.1. Cost Curve for Arsenic

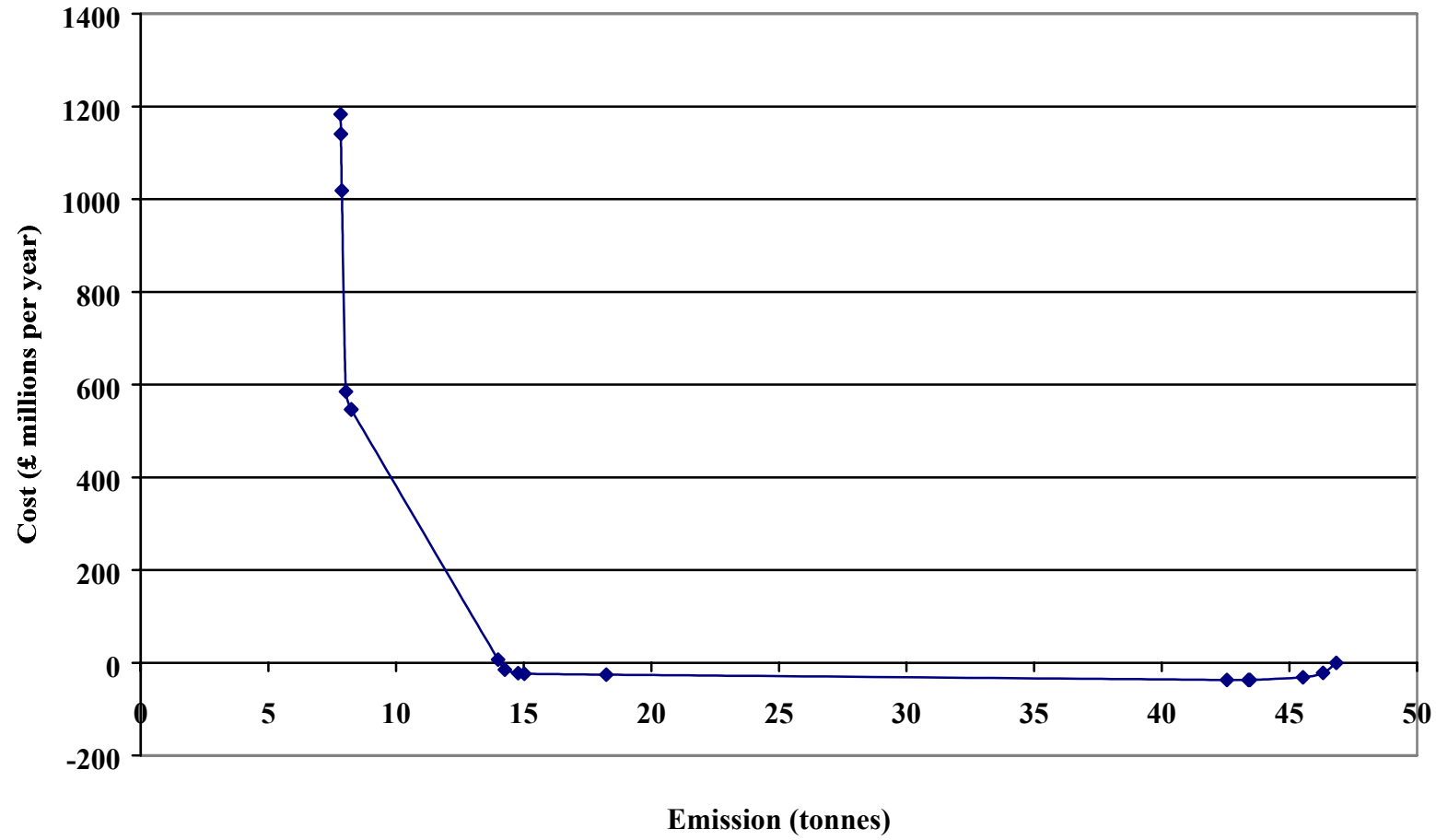


Figure D.2. Cost curve for benzo[a]pyrene

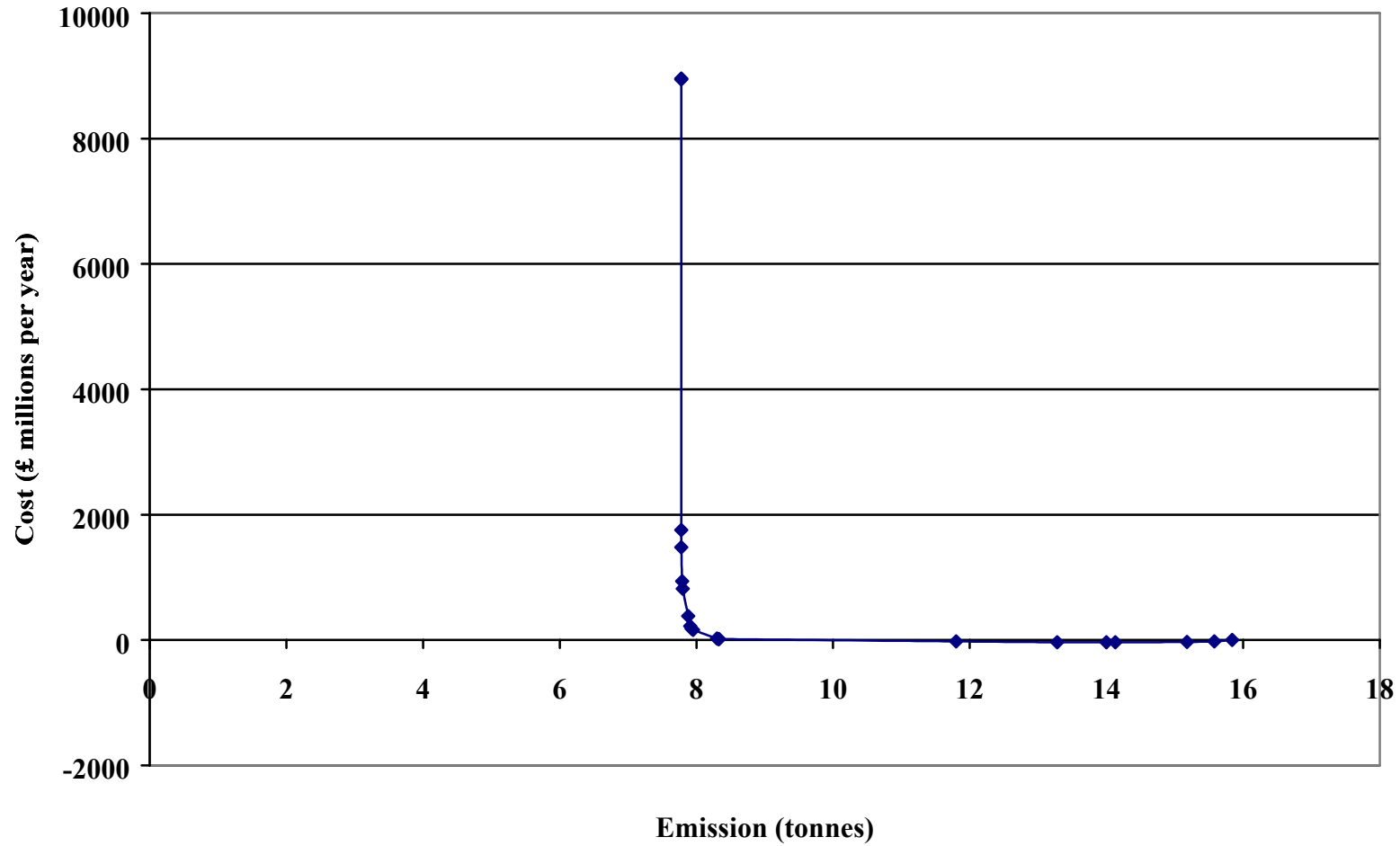


Figure D.3. Cost curve for benzo[b]fluoranthene

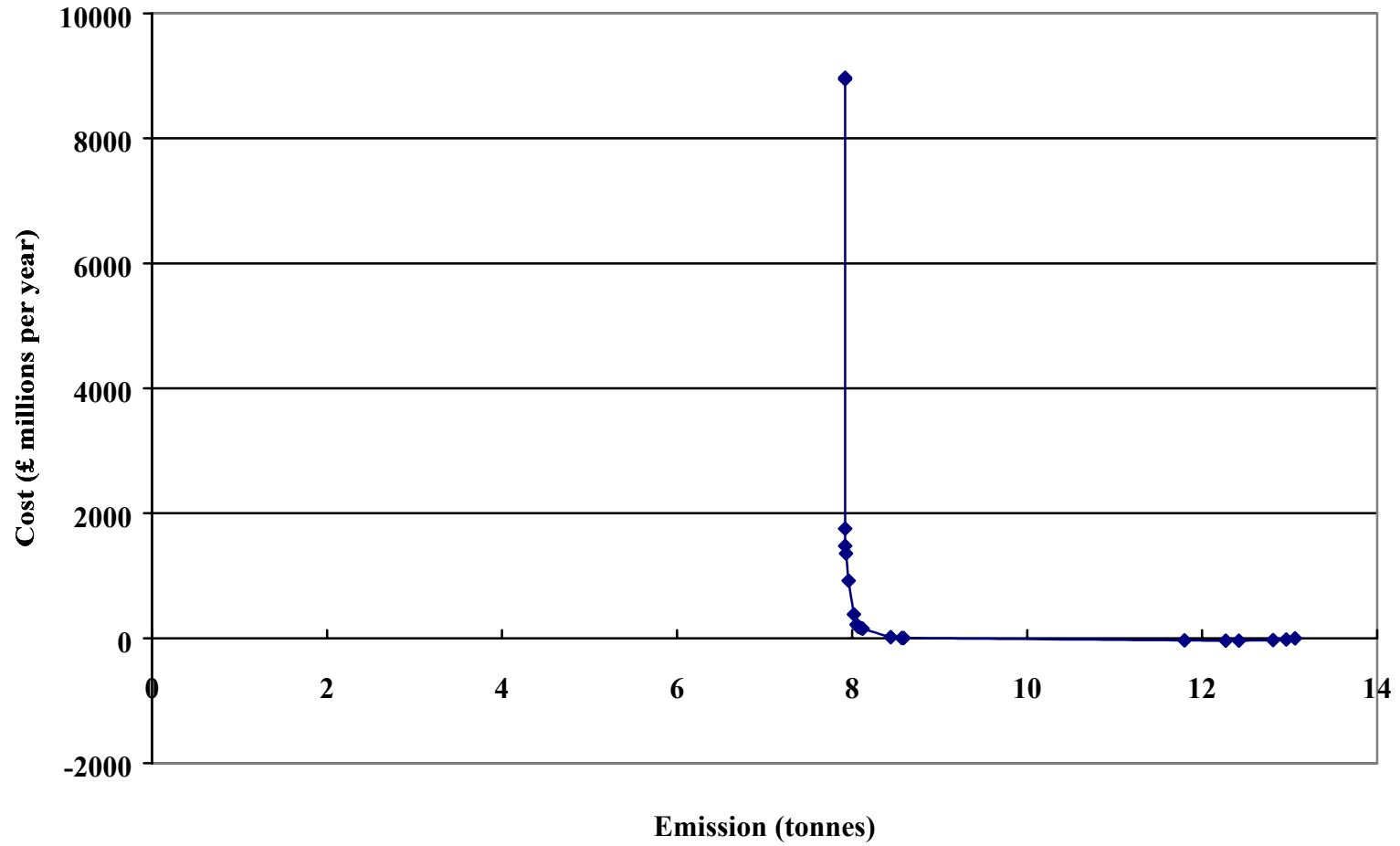


Figure D.4. Cost curve for benzo[ghi]perylene

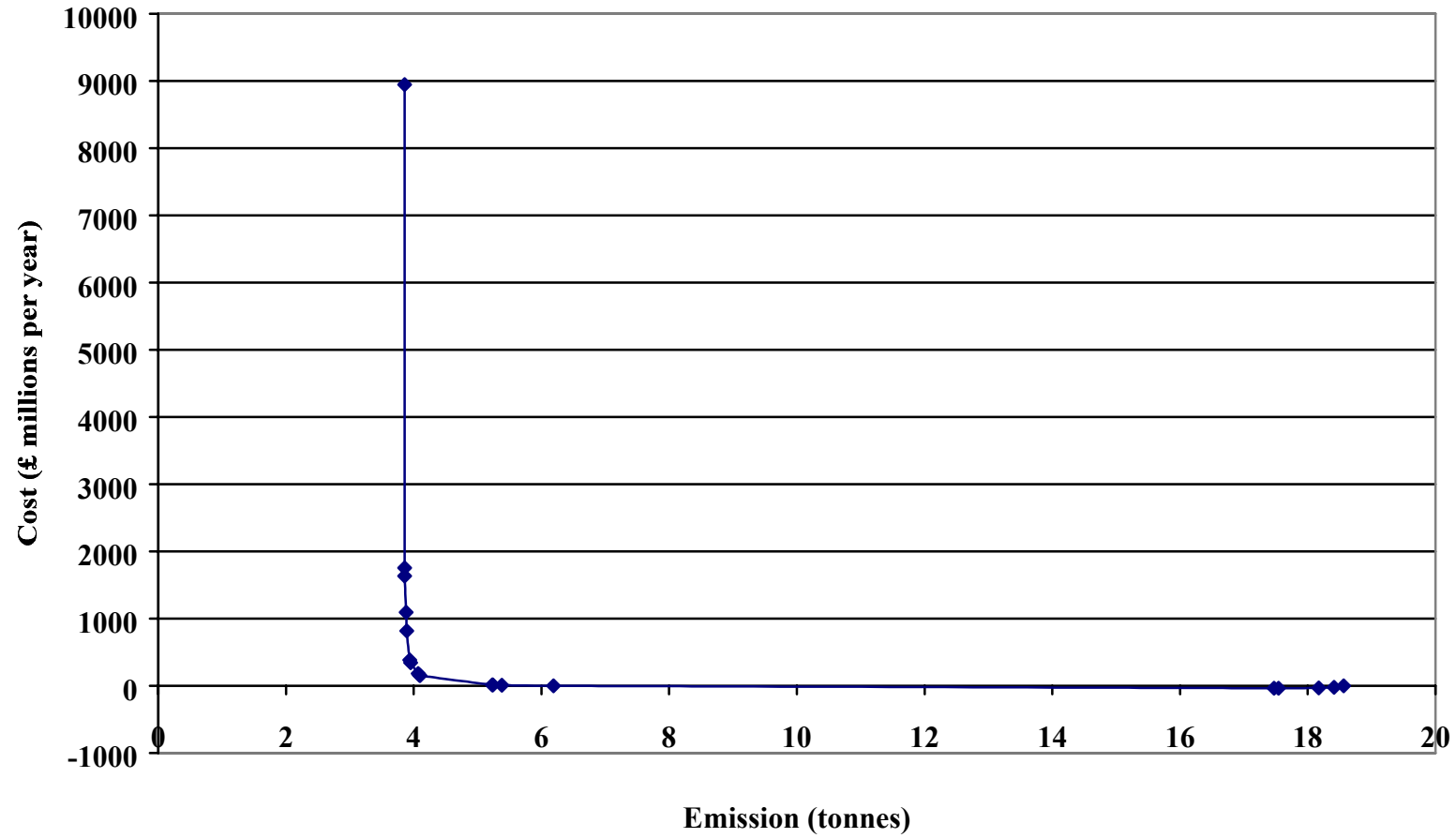


Figure D.5. Cost curve for cadmium

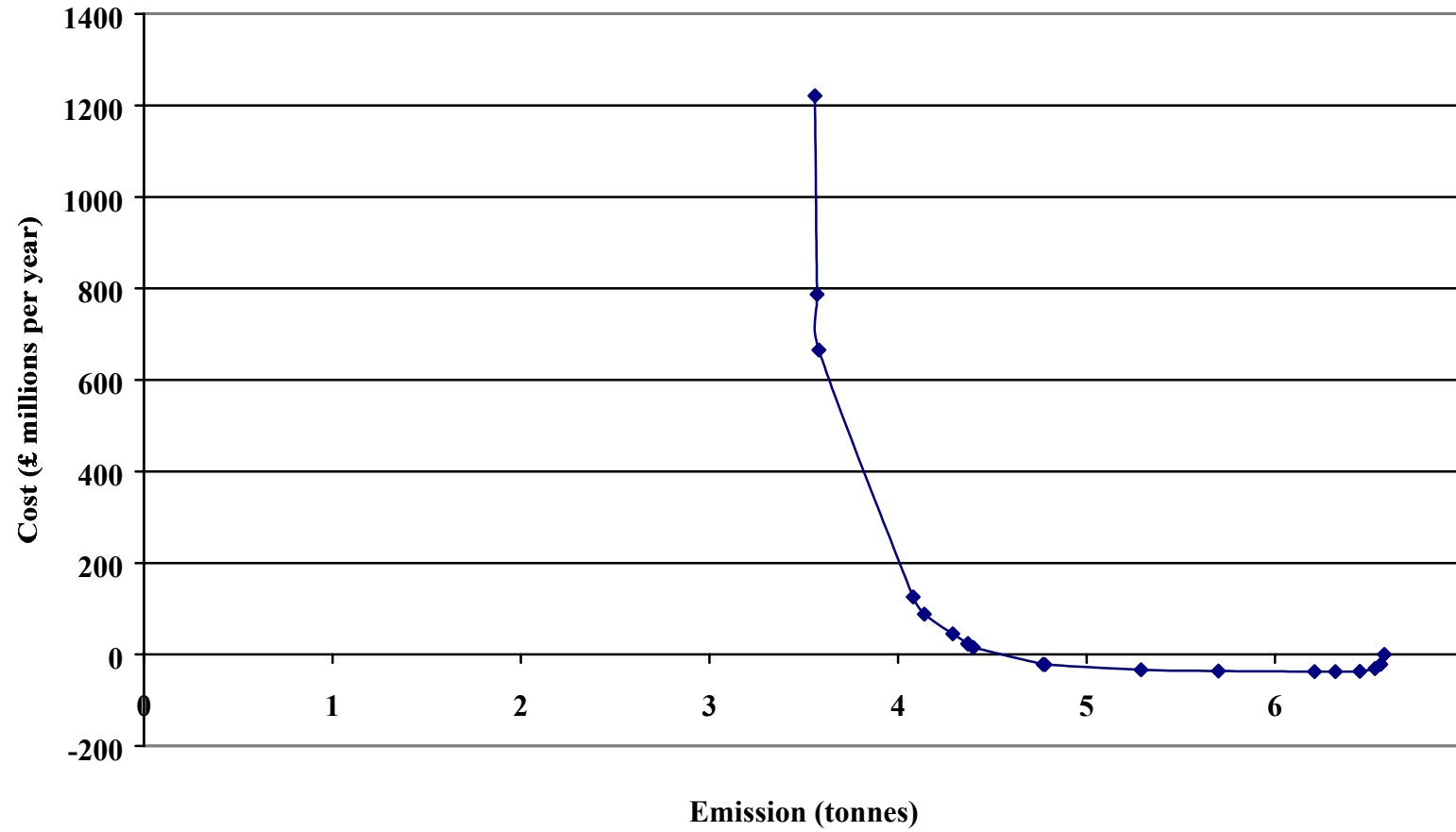


Figure D.6. Cost curve for chromium

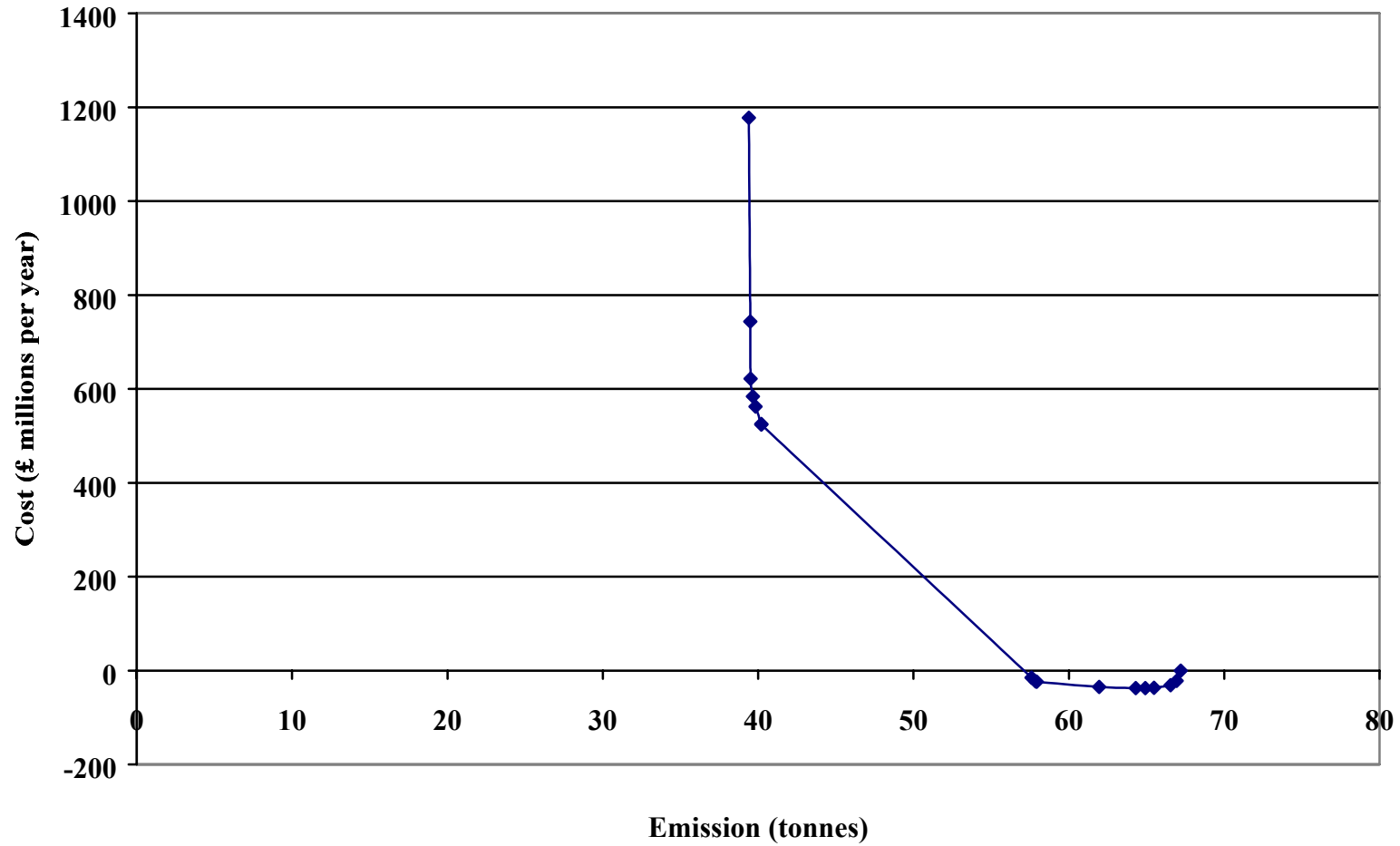


Figure D.7. Cost curve for copper

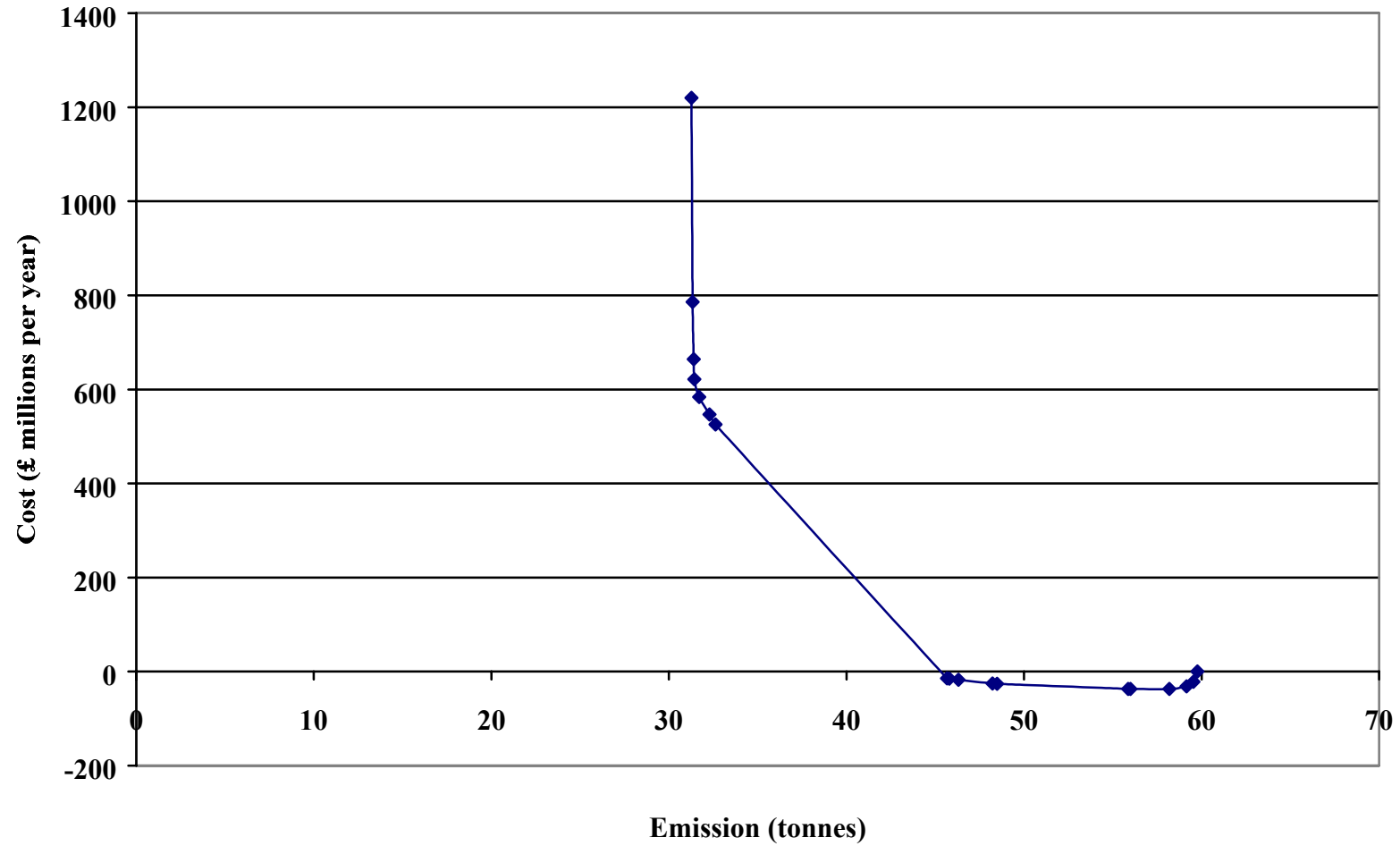


Figure D.8. Cost curve for dioxins

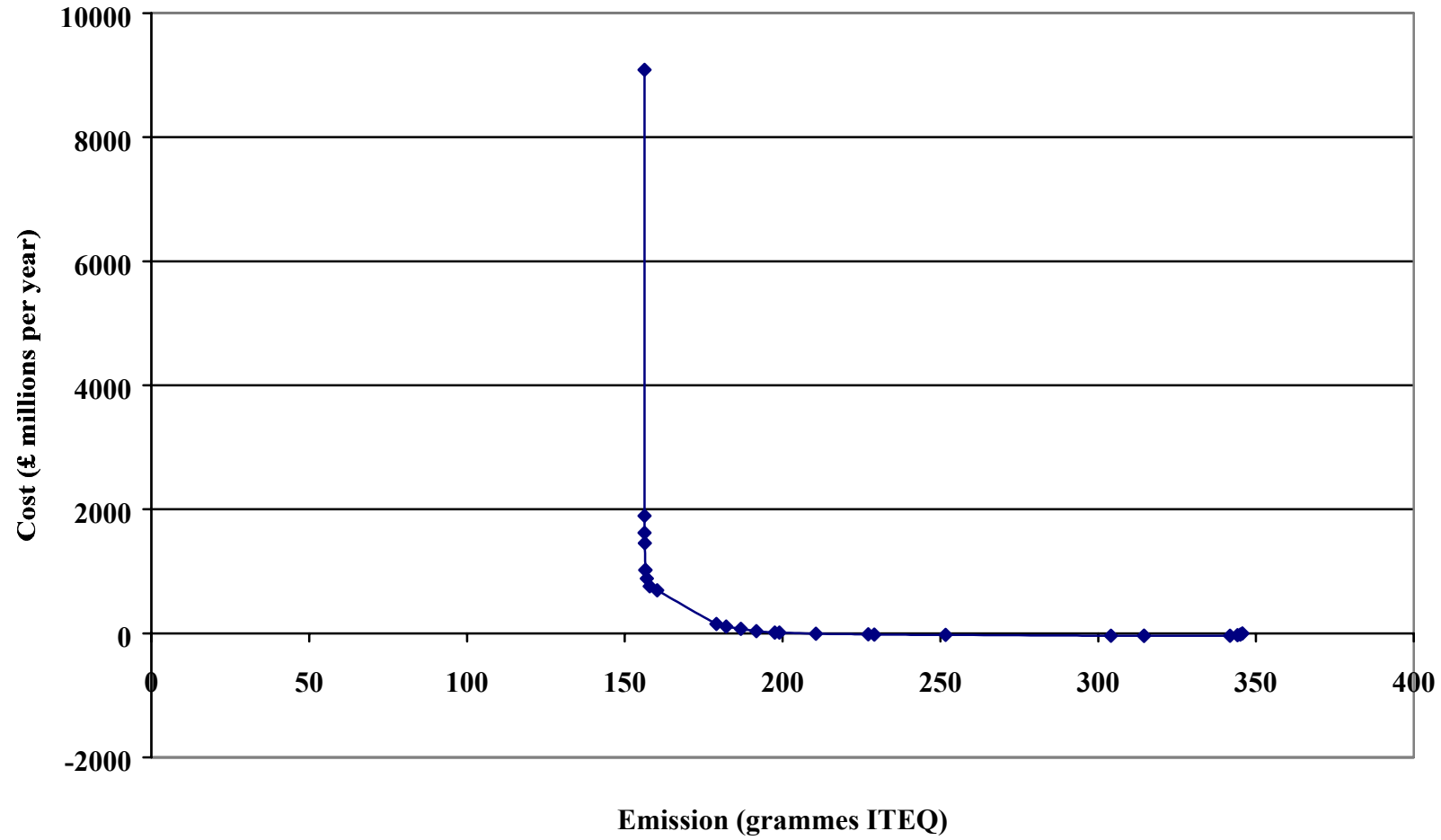


Figure D.9. Cost curve for mercury

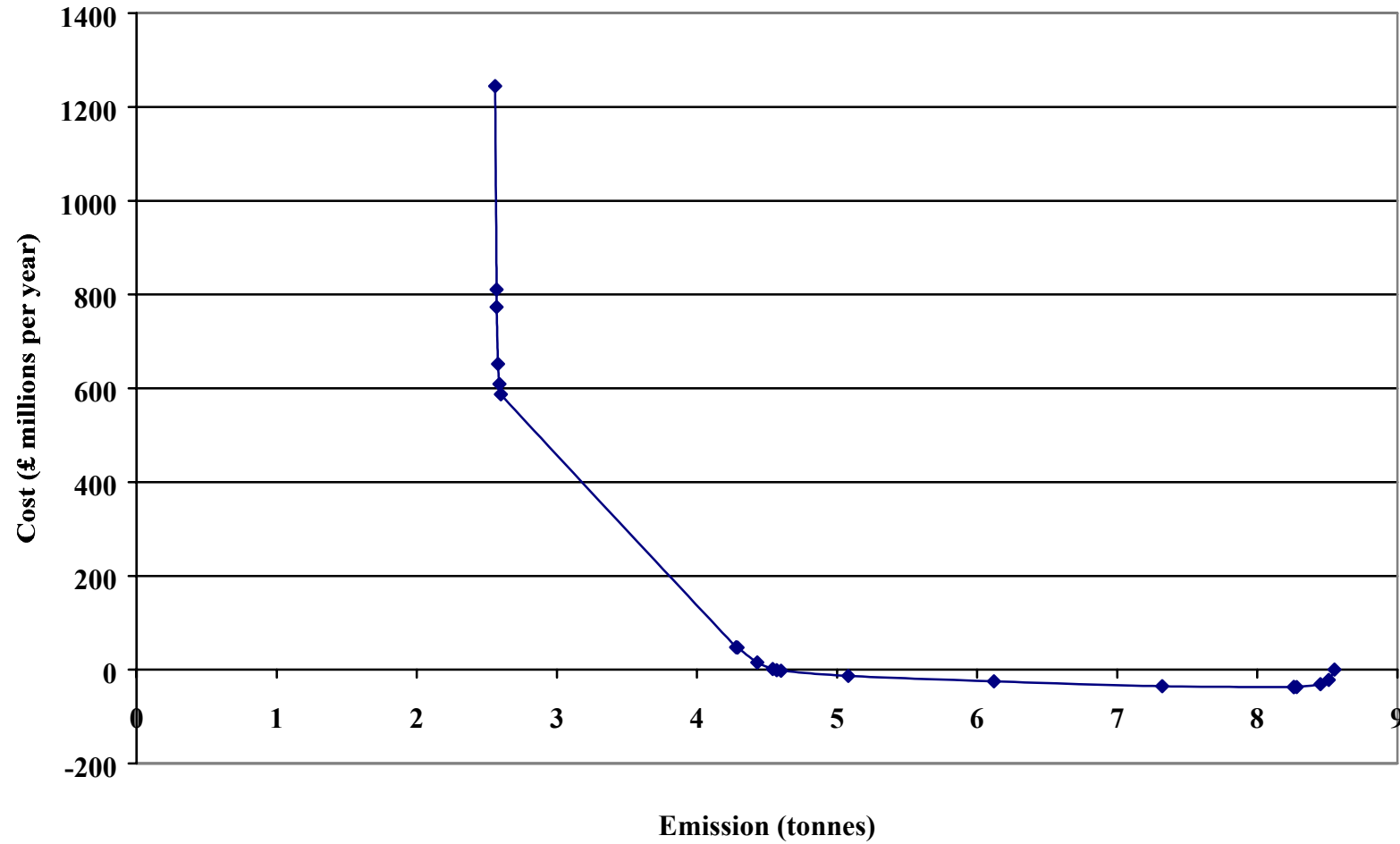


Figure D.10. Cost curve for nickel

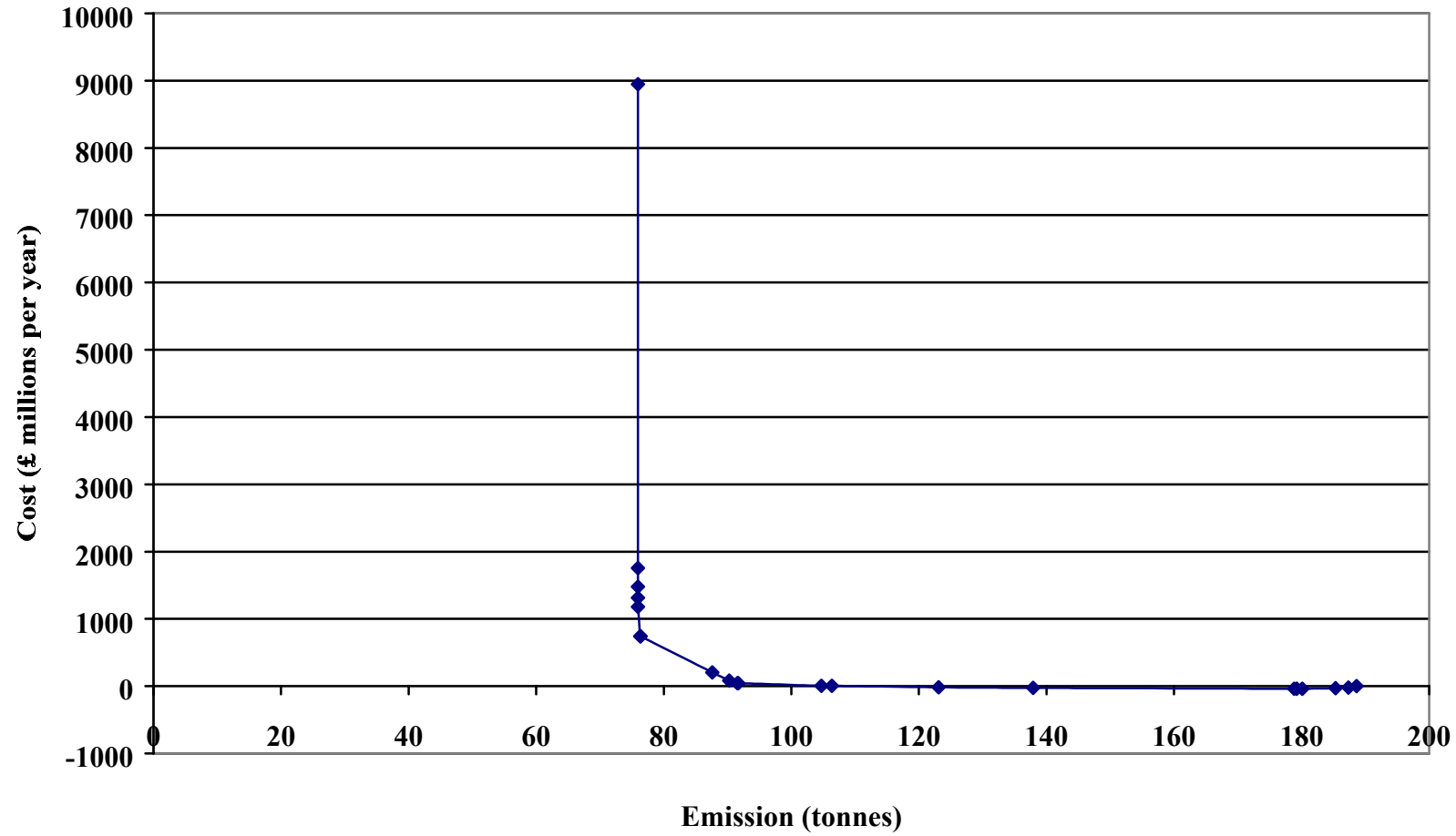


Figure D.11. Cost curve for lead

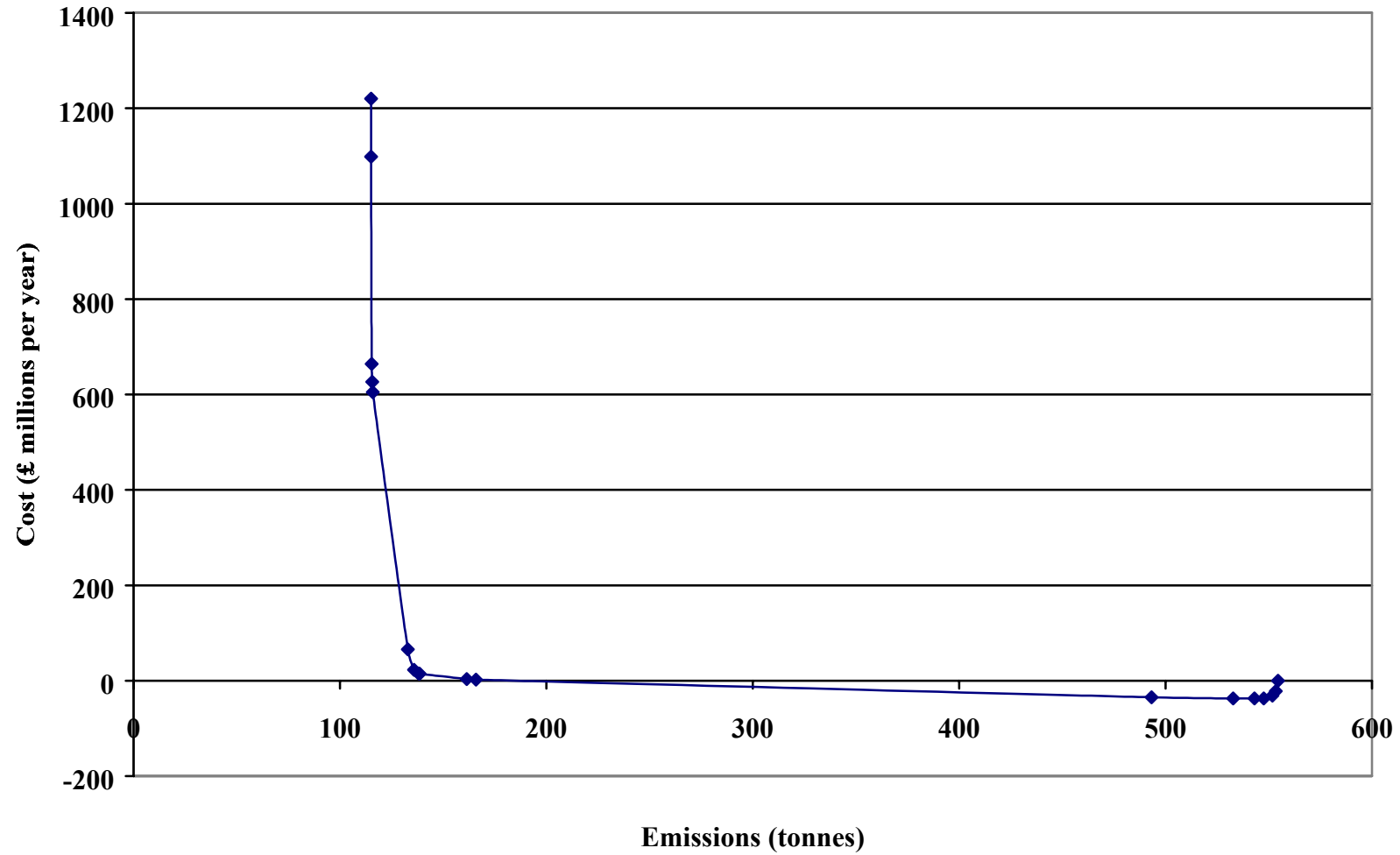


Figure D.12. Cost curve for selenium

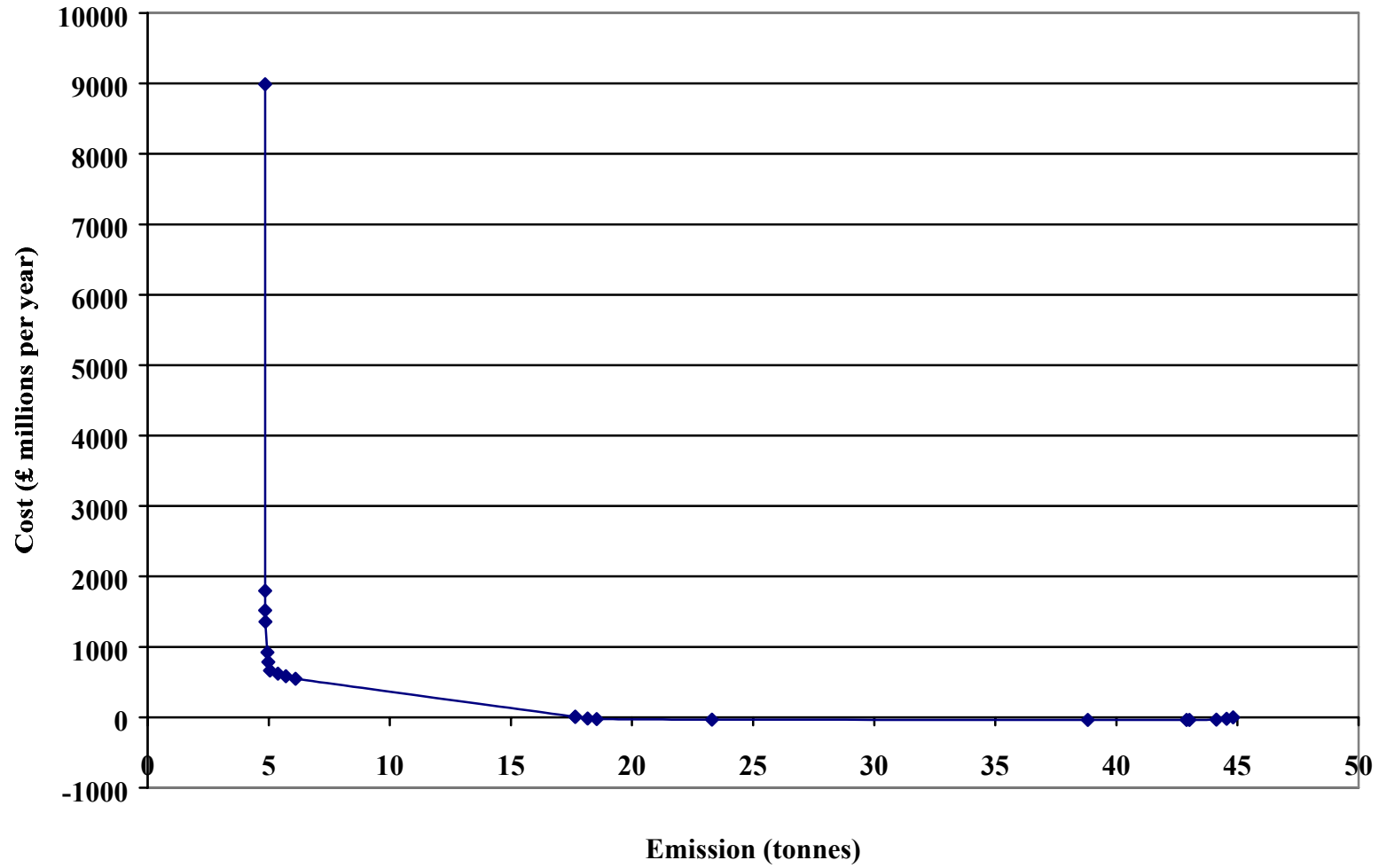


Figure D.13. Cost curve for vanadium

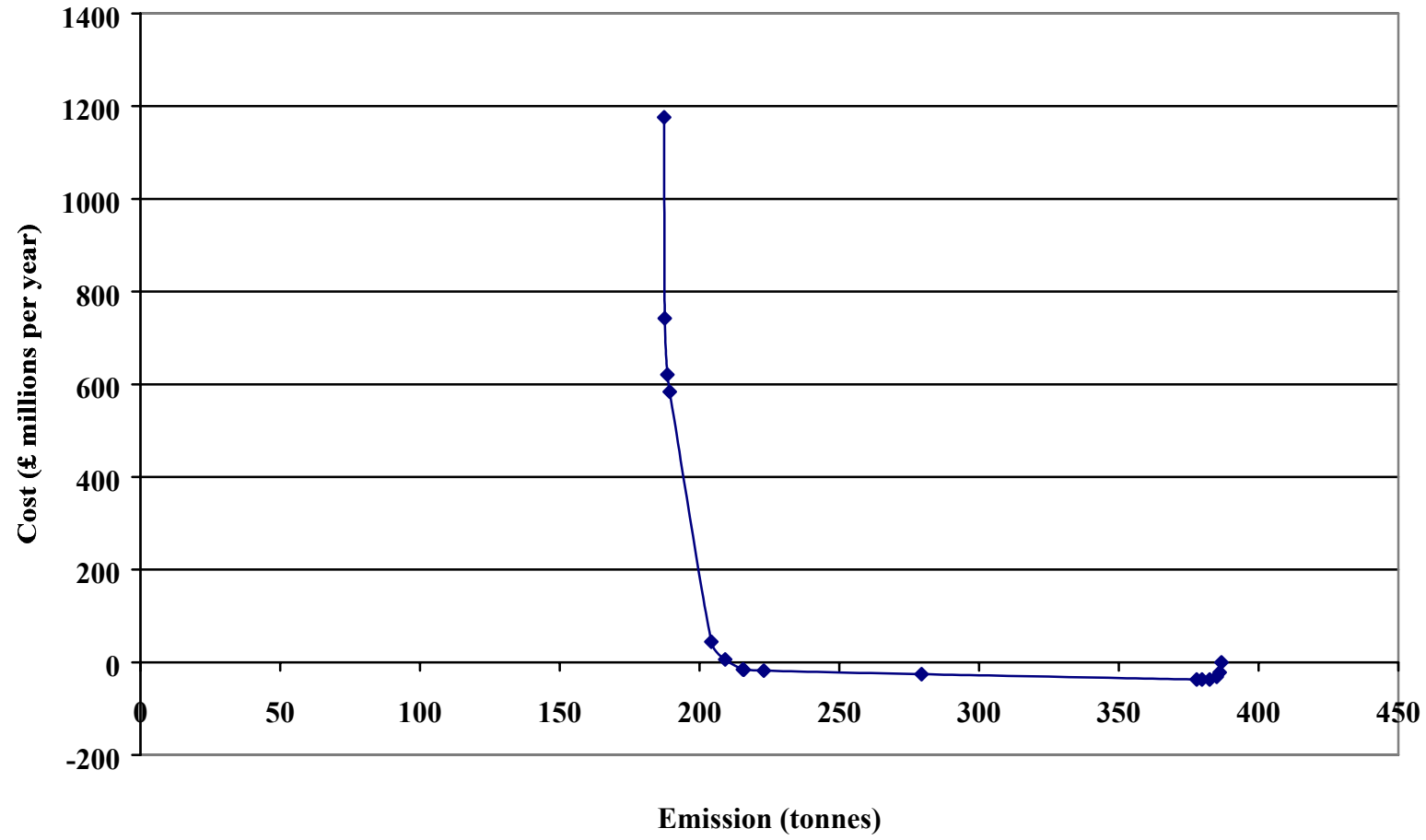


Figure D.14. Cost curve for zinc

