Department for Environment, Food and Rural Affairs

Development of UK Cost Curves for Abatement of Dioxin Emissions to Air

Final Report – draft for consultation

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Entec UK Limited

Executive Summary

Introduction

This report presents the results of the research to develop UK cost curves for abatement of dioxin emissions to air. The research was completed for DEFRA by Entec under the current "Cost Curves for Air Pollutants" contract.

Dioxins are a group of structurally related chemicals which persist in the environment, are bio-accumulative and are toxic to humans and animals. Dioxins and dioxin-like PCBs are being addressed as a high priority under a number of international conventions. Although UK dioxin emissions to air have decreased by around 70% since 1990, further action is likely to be required to abate remaining emission sources.

Objectives

The aim of this study is to provide information on the likely costs and emissions reductions from measures to abate dioxin emissions. This data will support further work by DEFRA to develop a Regulatory Impact Assessment (RIA) for a national dioxins action plan, including a cost-benefit assessment. The study scope is limited to dioxin and furan emissions (collectively termed 'dioxins') to air within the UK. Dioxin-like PCBs are not considered within the scope of this study since the sources and abatement measures are different to those for dioxins. The study builds upon previous dioxin cost curves developed for DEFRA with the aim of making the cost curves more transparent, robust and comprehensive.

Methodology

Dioxin sources have been identified using the latest data available from the National Atmospheric Emissions Inventory (NAEI). The 111 individual sources listed in the NAEI have been grouped into 15 source categories which together cover 98% of total UK emissions. Detailed investigations of each source category were carried out to establish what abatement measures are required by policy instruments under the business as usual (BAU) scenario, including the requirements to use Best Available Techniques (BAT). Measures that go beyond BAU are also assessed. The costs of these abatement measures and emissions reductions achievable were evaluated through consultation with key stakeholders, and reference to sector guidance documents and other recent national and international literature on the subject. Secondary benefits of the measures and issues such as affordability and impact on competitiveness were are also noted. The data collected was fed into a dioxins cost curve spreadsheet which has been developed with transparency and ease of future updating in mind.

Results & Conclusions

The key findings from the research to develop the UK cost curves for abatement of dioxin emission to air are summarised as follows:

i) During the detailed investigation and review of certain sources of dioxins it became clear that some of the NAEI emissions estimates for 2000 were inaccurate.

ii) Dioxin emissions from waste incineration, cremation, public services combustion, and refinery combustion were re-evaluated and were found to be negligible.

iii) The corrected UK total dioxin emissions figure for 2000 is 276 gTEQ. This represents a significant reduction of 23% from the current NAEI estimate of 360 gTEQ for 2000.

iv) A total of 10 BAU measures which will lead to dioxin emissions reductions were identified (see Table 3.1). Together these measures will cost £14.6 million/year and will reduce dioxin emissions from 276 to 225 gTEQ/year. Therefore, BAU measures will reduce total emissions by 18% compared to the corrected baseline emissions of 276 gTEQ/year.

v) Unit abatement costs for BAU measures range from around £0.1 to 2.3 million per gTEQ of dioxins abated. As expected, these unit costs are very high compared to those for other pollutants but they must be put into context by considering the environmental and human health benefits that may arise.

vi) A total of 9 realistic[1] beyond BAU measures which would lead to dioxin emissions reductions were identified (see Table 3.1). Together these measures would cost £37.8 million/year and would reduce dioxin emissions from 225 to 188 gTEQ/year. Therefore, beyond BAU measures would reduce total emissions by 14% compared to the corrected baseline emissions of 276 gTEQ/year.

vii) Unit abatement costs for beyond BAU measures range from around £0.2 to 6.0 million per gTEQ of dioxins abated.

viii) The effect on competitiveness of imposing beyond BAU measures in certain sectors must also be considered when formulating a dioxins action plan.

ix) Overall, the revised UK cost curves are considered to represent the most accurate picture presented to date of the potential for further dioxin abatement, and the associated costs.

The revised dioxin cost curves should be used to inform policy makers and other stakeholders in any decision-making process that leads to the formulation of a national dioxins action plan.

Benefits

The main benefit of this work is the provision of a set of up-to-date, transparent and accurate cost curves for dioxin abatement in the UK. This information is needed in order to assess the implications of particular policies and assist in the development of policies which focus on the most cost-effective ways of reducing emissions.

[1] Although 12 beyond BAU measures were identified, 3 of these measures had unit abatement costs which were an order of magnitude higher than those of the other beyond BAU measures. Therefore, only 9 of the beyond BAU measures identified were considered to be realistic.

Contents

Glossary

2,3,7,8 TCDD	2,3,7,8 tetrachlorodibenzo-*p*-dioxin (the most toxic dioxin congener)
BAT	Best available techniques
BATNEEC	Best available techniques not entailing excessive cost
BAU	Business as usual
BREF	BAT reference document
COT	Commission on the Toxicity of Chemicals in Food, Consumer Products and the Environment
Dioxin	Polychlorinated dibenzo-*p*-dioxin (PCDD for short)
Dioxins	Term used to refer to dioxin and furan congeners collectively
ELV	Emission limit value (i.e. dioxin concentration in stack gas)
Furan	Polychlorinated dibenzofuran (PCDF for short)
FGD	Flue gas desulphurisation
HGVs	Heavy goods vehicles
IPC	Integrated Pollution Control
IPCC	Intergovernmental Panel on Climate Change
IPPC	Integrated Pollution Prevention and Control
LAPC	Local Air Pollution Control
LAPPC	Local Air Pollution Prevention and Control
LCPD	Large Combustion Plant Directive
LGVs	Light goods vehicles
mg	milligram (10^{-3} g)
MSW	Municipal solid waste
NAEI	National Atmospheric Emissions Inventory
ng	nanogram (10^{-9} g)
NO_x	Nitrogen oxides (expressed as NO_2)
PCB	Polychlorinated biphenyl
PCDD/Fs	Abbreviation used to refer to dioxin and furan congeners collectively
pg	picogram (10^{-12} g)
PPC	Pollution Prevention and Control (i.e. title of UK legislation to implement IPPC)
SO_2	Sulphur dioxide
SSF	Smokeless solid fuel
TDI	Tolerable daily intake
TEFs	Toxic equivalency factors (the International (I-TEF) system is used within this report)
TEQ	Toxic equivalent (mass of dioxins and furans as 2,3,7,8 TCDD equivalent, calculated using the TEF system)

1. Introduction

1.1 Background

1.1.1 The Cost Curves Project

It is essential for policy makers to have reliable information on the sources of air pollution, on trends in emissions and on the current and possible future costs of abatement. Entec's overall project for DEFRA on "Cost Curves for Air Pollutants" focuses on the provision of UK estimates of the costs of emission reductions in the form of 'cost curves'. This information is needed in order to assess the implications of particular policies and assist in the development of policies which focus on the most cost-effective ways of reducing emissions. With this in mind, the aim of the overall project is to:

"*characterise and quantify the costs and impact of control measures on current and possible future emissions, and the resulting costs and benefits in support of the development, implementation and monitoring of domestic and international air pollution policies*" [2].

A previous project for DEFRA to produce an initial set of UK cost curves for heavy metal and dioxin abatement was completed by AEA in early 2002[3]. However, these cost curves were considered to be a 'first-pass' assessment. Further work is required to develop more comprehensive, transparent and accurate cost curves for dioxins abatement using the latest available data and research findings in this area.

This study was carried out in parallel with, and is complementary to, a second dioxins study for the Environment Agency which focuses on dioxin releases from industrial sites. The second study entitled 'Cost Curve for the Reduction of Agency Regulated Dioxins & Dioxin like PCB Releases' was carried out by AEA Technology.

1.1.2 Dioxins in the UK Environment

Dioxins are a group of structurally related chemicals which persist in the environment, are bio-accumulative and are toxic to humans and animals (DEFRA 2002a). Dioxins are usually grouped together with furans and dioxin-like PCBs when considering potential risks to health and the environment since they have similar mechanisms of toxicity. A description of the two systems for presenting dioxin emission figures (i.e. I-TEQ and WHO-TEQ) is given in Appendix A[4].

[2] Review of Cost Curves and Proposed Work Plan, Entec UK Ltd, Draft Report, July 2002.

[3] Cost Curves for the Abatement of Heavy Metal, PAH and Dioxin Emissions, AEA Technology, AEAT/R/ENV/0159 Issue 1, February 2002.

[4] Throughout this report the term 'dioxin(s)' is used synonymously with the term 'dioxin(s) and furan(s)'. The I-TEQ system is used to quote dioxin mass emission figures unless otherwise stated.

Dioxins and furans are emitted to atmosphere by wide range of combustion processes whereas PCBs are most commonly emitted from PCB insulated electrical equipment. A summary of the mechanisms for dioxin and furan formation is given in Appendix C.

Research indicates that the major route of human exposure to dioxins (>90% of exposure) is through the food chain. In simplistic terms, the dioxin pathway from air emissions → deposition on land → uptake by plants → livestock → the human food chain is important in determining human uptake rates. Historic reservoir sources of dioxins in soils and sediments and long-range environmental transport play a role in uptake (DEFRA 2002a). However, it is clear from the available data that measures taken in the past to reduce dioxin emissions to air have led to declining human exposure levels (DEFRA 2002a).

Data from the National Atmospheric Emissions Inventory (NAEI) indicates that over the period 1990-1999 total UK emissions of dioxins to air have fallen by 70% as shown in Figure 1.1.

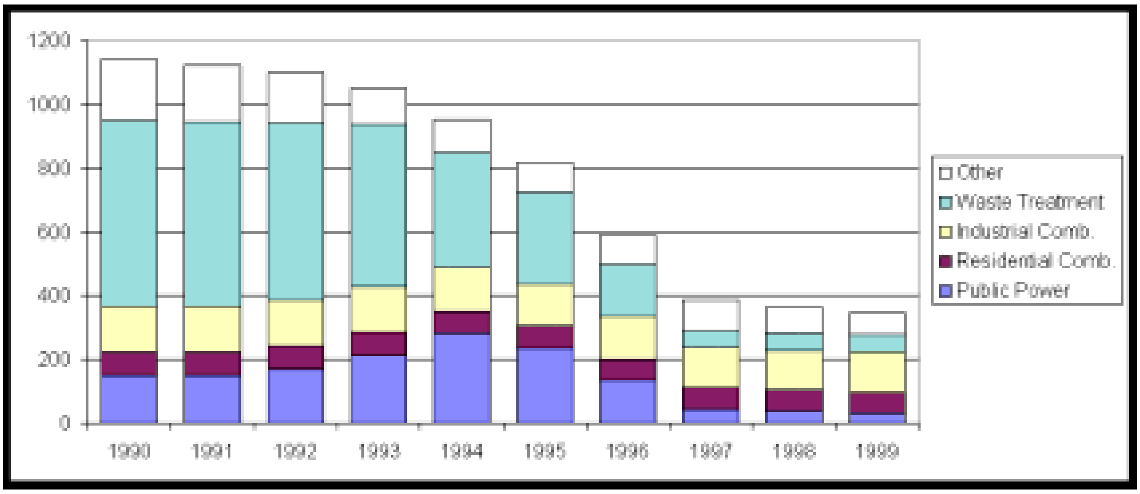

Figure 1.1 - Historical Trends in UK Dioxin Emissions to Air in gI-TEQ (NAEI 2002a)

Despite these significant reductions in dioxin emissions, some population groups remain at risk of elevated exposure levels, as illustrated in Table 1.1.

Table 1.1 - UK Dioxin Exposure Levels and Tolerable Daily Intake (DEFRA 2002a)

Parameter	**Value** (pgWHO-TEQ/kg body weight/day)*
COT Recommended Tolerable Daily Intake (TDI)	**2.0**
Exposure of toddlers (1.5-2.5 years)	5.1
Exposure of schoolchildren	2.2
Exposure of adults	1.8

* Total for dioxins and dioxin-like PCBs. Exposure levels are upper bound mean values for 1997.

This picture of declining but still significant dioxin emissions to air and elevated human exposure levels is similar across all industrialised nations (EC 1997; USEPA 2000). Given the transboundary nature of air pollution the international community is taking action to address the dioxins issue. Under the requirements of the Stockholm Convention and other international regulatory action, the UK Government have proposed creating a national dioxins plan to further cut human exposure to dioxins and dioxin-like PCBs (DEFRA 2002a). As a result a consultation document and a partial RIA on dioxins and dioxin-like PCBs have recently been issued by DEFRA and devolved Administrations and feedback was expected by the end of January 2003. This follows publication of an EC strategy on dioxins and dioxin-like PCBs which recommended reducing average human exposure to 14 pg WHO-TEQ per kg of body weight per week (DEFRA 2002a).

A new UK initiative could shift the focus of attention to a large number of relatively small sources of dioxins which are currently unregulated. These constitute a significant share of total emissions since previously significant sources such as municipal solid waste incineration have been abated. However, it is recognised that abatement of unregulated, diffuse dioxin sources may be difficult to achieve in a cost-effective manner, compared to abatement of certain industrial dioxin sources. Therefore, an essential part of the dioxins RIA will be an assessment of the likely costs and benefits of a dioxins action plan covering all significant sources. The recently issued partial RIA (DEFRA 2002b) contained only limited data on costs and benefits and this study will provide additional data for the full RIA. The dioxins consultation document (DEFRA 2002a) should be referred to for further background information.

1.2 Study Scope and Aims

The aim of this study is to develop UK cost curves for abatement of dioxin emissions to air which will support further work to enable the UK to develop a dioxins action plan.

The work will address the gaps in the 'first-pass' cost curves that have been developed for DEFRA and will take account of feedback from the current dioxins consultation and the latest UK and international research in this area. The study involves the following tasks:

1. Reviewing the key sources of dioxins based on NAEI data and other recently published research;
2. Identifying the current policy measures to reduce dioxin emissions and associated policies which impact on emissions;
3. Establishing the business as usual (BAU) scenario for abatement (including consideration of BAT) and identifying measures that go beyond BAU;
4. Identifying a complete set of potential dioxin abatement measures including associated costs, additional benefits and practicalities of implementation; and,
5. Generation of a series of cost curves for dioxin abatement (for BAU and beyond BAU scenarios) based on the detailed research completed above.

The study scope is limited to abatement of dioxin and furan emissions. Dioxin-like PCBs are excluded from scope as the sources and abatement methods applicable are generally different to those for dioxins.

1.3 Study Benefits

Anticipated benefits from revision of the dioxin cost curves are expected to include:

- Identification of the BAU position (not covered by the previous cost curves report) including a clear statement of control measures required (including BAT measures) and associated emission reductions and costs;
- More robust consideration of measures (including BAT) that go beyond BAU and the associated costs;
- Identification of a wider range of measures and improved understanding of the applicability of measures;
- Improvement in accuracy of cost estimates;
- Consideration of affordability, impacts on industry competitiveness and secondary pollutants; and,
- Reduction in uncertainty in targeted areas.

The cost curves will be developed with transparency in mind and this will bring a number of benefits which are expected to include:

- Better consideration of assumptions (e.g. basis of abatement efficiency figures);
- Reduced familiarisation time with data supporting cost curves;
- Easier manipulation of cost curves to customise the input and output data, which would facilitate integration with GIS and cost-benefit analysis;
- Potential improvements to policy relevance;
- More effective peer review; and,
- Improved integration with other areas of research on air pollutant abatement.

1.4 Outline of Report Structure

A summary of the structure and content of the main sections of this report is given below.

Table 1.2 - Outline of Report Structure

Section	Content
Section 1 - Introduction (this section)	Presents the background to the study and the associated objectives.
Section 2 - Methodology	Describes the methodology employed within the study and presents the key data sources.
Section 3 - Cost Curves for Dioxins	Presents the revised UK cost curves for dioxins abatement and the associated results. Results for BAU measures and beyond BAU measures are presented.

Section	Content
Section 4 - Discussion	Provides a qualitative analysis of the cost curves and explains the key issues, uncertainties and significance of the findings.
Section 5 - Conclusions	Summarises the key findings of the study.
References	Cites all references employed within the main part of the report. Additional references for specific source category data are listed in Appendix D.
Appendix A	Presents information on the different dioxin and furan congeners and their relative toxicity factors.
Appendix B	Presents the complete inventory of UK dioxin sources for the year 2000 based on NAEI data.
Appendix C	Provides a summary of the mechanisms of dioxin/furan formation and the generic abatement measures that are available.
Appendix D	Presents the results of the detailed investigation of dioxin sources, abatement measures and costs. A separate sub-section is used for each source category and the data presented is used to generate the revised UK cost curves.

2. Methodology

2.1 Review of Dioxin Sources

2.1.1 The UK Emissions Inventory

The UK National Atmospheric Emission Inventory (NAEI) is compiled by the National Environmental Technology Centre on behalf of DEFRA Air and Environment Quality Division and the devolved administrations. The NAEI is the standard reference for air emissions data for the UK and includes emission estimates for a wide range of important pollutants including SO_2, NO_x, VOCs and dioxins. Therefore, the NAEI is a primary source of data for development of dioxin cost curves.

The current NAEI data presents annual emission estimates for the 1970-1999 time series although estimates from 1990 onwards are more accurate (NAEI 2002a). The most recent available emission estimates for the year 2000 have also been obtained from the NAEI for use in this study (2002b). Throughout the compilation of the inventory, considerable effort has been made to ensure that the inventory is consistent with other national statistics and that all available data sources are considered (NAEI 2002a). One important source of data used in the NAEI is the Environment Agency Pollution Inventory which includes dioxin emissions from IPC Part A processes. Where specific point source emissions data are unavailable, or in the case of diffuse/mobile sources, emissions are estimated from other activity data such as fuel consumption, distance travelled, production or some other indicator (e.g. sector economic output) that is directly related to the emissions. Emission estimates for a particular source are calculated by applying an emission factor to an appropriate activity statistic as follows:

Total Dioxin Emission (e.g. gTEQ/year) = Emission Factor (e.g. gTEQ/Te product) × Activity Data (e.g. Te of product/year)

Emission factors are generally derived from measurements of a number of sources that are assumed to be representative of a particular source type. Activity data is often based on fuel consumption (e.g. using data from the Digest of UK Energy Statistics) since this relates directly to emissions. To estimate road transport emissions the NAEI uses a model based on distances travelled combined with emission factors that are calculated based on a range of parameters such as vehicle type, vehicle age, engine size and average speed.

The NAEI dioxins inventory was first developed in 1995 and uses the International Toxic Equivalency (I-TEQ) Factor system to report the total mass emission of dioxin and furan congeners as 2,3,7,8 TCDD equivalent for each source. Since 1995 work has been carried out to improve the data and measure emissions factors for key sources. However, the uncertainty in the dioxins emission inventory remains high compared to that for other air pollutants such as SO_2 and NO_x. The reasons for this include:

- Emission factors are highly variable and there are several important sources that are not well characterised (e.g. accidental fires);

- There is little robust data on congener profiles (which can be highly variable) for certain emission sources;
- Scientific knowledge of dioxin/furan generation mechanisms and sources is still developing; and,
- There may be some anthropogenic sources which have yet to be identified or have been significantly underestimated.

Nevertheless, the existing NAEI data provides the best available baseline from which to develop cost curves for emissions reductions. Projections to 2010 for dioxins emissions are not available from the NAEI but historical trends (see Figure 1.1) indicate that:

- The waste treatment sector (particularly MSW incineration) was a major dioxins source but emissions have dropped by around 90% over the past 10 years due to implementation of abatement measures;
- Emission from the public power sector have dropped by about 80% over the last 10 years;
- Emissions from industrial and residential combustion and 'other' sources have remained fairly static over the past 10 years; and,
- There has been a 70% drop in total emissions in the past 10 years but this rate of improvement is unlikely to be sustained in future years.

The complete inventory of UK dioxin sources for the year 2000 (i.e. latest data available from the NAEI) is presented in Appendix B. There are 111 *individual sources* listed but the first 22 of these contribute 90% of the UK total emissions. The inventory indicates that total dioxins emissions were 360 gTEQ in 2000, which compares to 346 gTEQ in 1999, and 361 gTEQ in 1998 (NAEI 2002a). In addition to traditional industrial and domestic fuel combustion activities it is evident that accidental fires, small-scale waste burning, metals production and waste incineration are the largest sources of dioxins. A detailed study by the European Commission to establish a European dioxins inventory also identifies these as key sources (EC 1997). A recent study by the US Environmental Protection Agency presents a similar picture for key sources in the US (USEPA 2000).

2.1.2 Selection of Sources Categories for Cost Curve Development

Having reviewed the current UK inventory of dioxin emissions, it is possible to identify several types of source which make a significant contribution to total emissions. These sources can be usefully grouped together to enable efficient development of the cost curves. The grouping of individual sources into *source categories* ensures that they are similar in terms of:

- Process technology and mechanisms of dioxin formation;
- Abatement measures applicable; and,
- Regulatory controls and policy measures applicable.

The selected source categories, which are similar to those used in previous cost curve studies, are shown below.

Table 2.1 - UK Dioxins Emissions for the Year 2000 (NAEI 2002b) - Split by Source Category

No.	Source Category	Fuel Type/Activity	Emissions (mgTEQ)	% of UK Total	Cumulative %
1	Accidental fires	All including vehicle fires	64850	18.0	18
2	Iron & steel sector	All sector activities	57869	16.1	34
3	Small-scale waste burning	All uncontrolled waste burning	49961	13.9	48
4	Other combustion in industry	All other combustion of fuels	41282	11.5	59
5	Waste Incineration	All controlled incineration	35454	9.8	69
6	Non-ferrous metals sector	All sector activities	20561	5.7	75
7	Cremation	All cremation	18388	5.1	80
8	Power stations	All fuels	14319	4.0	84
9	Public services combustion	Coal	13949	3.9	88
10	Refinery combustion	All fuels	9125	2.5	90
11	Domestic fuel combustion	All fuels	6876	1.9	92
12	Agricultural combustion	Straw	6700	1.9	94
13	Natural fires	All natural fires	5800	1.6	96
14	Road transport	All fuel combustion	4741	1.3	97
15	Cement manufacture	Clinker production	4627	1.3	98
16	All other sources	See note 1	5578	1.5	100
	Total		**360,080**	**100.0**	**100**

Notes:

1. The 'all other sources' category comprises a total of 28 individual sources, none of which individually contribute more than 0.3% of total UK emissions.

2. The emissions data in this table should be read in the context of Section 4.1 of this report since some of the figures have been revised downwards as a result of the detailed investigation of source categories.

3. The definition of source categories used here is slightly different to that used in Figure 1.1, which is taken from the NAEI.

There are 15 *source categories* to consider which together account for 98% of total dioxin emissions. Development of the cost curves will focus on the collection and analysis of data for these source categories.

2.2 Review of Policy Requirements

2.2.1 Review of Key Policy Instruments

Dioxins and dioxin-like PCBs are being addressed as a high priority under a number of international conventions including the:

- United Nations Environment Programme (UNEP) Stockholm Convention on Persistent Organic Pollutants (POPs);
- United Nations Economic Commission for Europe (UNECE) Convention on the Long Range Transboundary Air Pollution (LRTAP) Protocol on POPs; and the,
- Oslo and Paris Commission (OSPAR) Convention for the Protection of the Marine Environment of the North East Atlantic.

The UK has obligations under these to continue to reduce emissions of dioxins and dioxin-like PCBs and for the production of source inventories, action plans and continued environmental monitoring (DEFRA 2002a). A review of key European and national policy instruments identified the following policies as being directly relevant to securing reductions in dioxin emissions:

- Environmental Protection Act 1990 (Part I) - Integrated Pollution Control (IPC) and Local Air Pollution Control (LAPC) regulations;
- 1996/61/EC - Integrated Pollution Prevention and Control (IPPC) Directive[5]; and,
- 2000/76/EC - Waste Incineration Directive (WID)[6].

In addition, certain policies are likely to have an impact on the consumption of fuels for heat and power generation, and for transport. These policies will have an indirect effect on dioxin emissions and include:

- 2001/80/EC - Large Combustion Plant Directive (LCPD);
- 1999/32/EC - Sulphur Content of Certain Liquid Fuels Directive (SCLFD);
- 1998/70/EC - European Fuels Directive on petrol and diesel sold after 2000;
- Utilities Act 2000 - Renewables Obligation and Energy Efficiency Commitment;
- Climate Change Levy and the associated sectoral Climate Change Agreements;
- Home Energy Conservation Act 1995 and Home Energy Efficiency Scheme;
- Building Regulations 2000 - Part L (conservation of heat and power); and,
- The '10 Year Plan for Transport' (DETR 2000).

Finally, certain policies are aimed at reducing emissions of other air pollutants such as SO_2, NO_x and particulates. Abatement measures implemented to comply with these policies will also tend to reduce dioxin emissions. These policies include:

- 2001/80/EC - Large Combustion Plant Directive (LCPD);
- 96/62/EC - Air Quality Framework Directive;
- 1999/13/EC - Solvents Emissions Directive (SED);

[5] In the UK the IPPC Directive is implemented through the Pollution Prevention and Control (England and Wales) Regulations (SI 2000, No. 1973) as amended, and similarly-titled 2000 instruments for Scotland and for Northern Ireland. Under IPPC, a new Local Air Pollution Prevention and Control (LAPPC) regime has been introduced to replace LAPC.

[6] In the UK the WID is implemented through the Waste Incineration (England and Wales) Regulations (SI 2002, No. 2980), and through related Directions. Similar 2003 Regulations and Directions for Scotland and for Northern Ireland are being introduced.

- 2001/81/EC - National Emissions Ceilings Directive; and,
- 98/69/EC - Euro IV standards for vehicles.

2.2.2 Determination of Policy Requirements

From the above, there are three key BAU policies (i.e. IPC/LAPC, IPPC/LAPPC and the WID) that directly address dioxin emissions and the impact of these policies on emissions is relatively simple to assess. Several other policies are in place which may have an indirect effect on dioxin emissions and their impact is more difficult to assess. Therefore, the determination of the business as usual (BAU) scenario for dioxin emissions abatement will:

i) Focus on quantifying the impact of the policies which directly address dioxin emissions;

ii) Assume that these directives/policies will be fully complied with by the various UK sectors; and,

iii) Where there is reliable data to calculate the effect of other policies on dioxin emissions, this will be taken into account.

The approach to BAU is therefore one of examining the detailed text of the relevant policies, and the associated guidance in the case of IPC/IPPC, to determine what benchmark emission limit values (ELVs) and abatement standards apply. Particular attention is paid to the activities covered, any derogations, threshold sizes, compliance dates and other conditions specified in the regulations. It is noted that the purpose of this task is not to assess the degree of implementation/enforcement of benchmark ELVs across the relevant sectors, rather it is to assess what ELVs would be achieved if the conditions of the statutory instruments were met by these sectors. One of the key over-arching requirements of air pollution policy is the application of best available techniques (BAT). BAT is defined in the guidance as (EA 2001):

"the most effective and advanced stage in the development of activities and their methods of operation which indicates the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent, and where that is not practicable, generally to reduce emissions and the impact on the environment as a whole".

Under IPPC, the requirements to employ BAT are clearly defined and the benchmark ELVs achievable for dioxins are set out in a growing series of European BAT References Documents (BREFs). These are either supplemented by, or, where not yet finalised at European level, are preceded by Environment Agency Sector/Process Guidance Notes. An operator must demonstrate that BAT for dioxin abatement is being applied if such emissions are considered to be significant. If benchmark ELVs are not being met, a technical and economic justification for less stringent emission limits at a particular installation must be made and will be considered by the regulator (taking into account the technical characteristics of the installation, its geographical location and the local environmental conditions).

In considering dioxin abatement measures that go beyond BAU, the assessment will:

i) Examine measures which deliver lower emission levels than those specified by policy instruments;

ii) Include measures which could be implemented voluntarily by operators to improve environmental performance (i.e. greater uptake of measures already in use) or could be imposed mandatorily by regulators; and,

iii) Include measures which operators may foreseeably take for other reasons such as cost savings, improved safety or competitive advantage.

2.3 Evaluation of Abatement Measures

2.3.1 Review of Abatement Measures

This study is concerned with currently available technologies or measures for abatement of dioxin emissions to air. A review of the literature identified those measures for each source category which are:

1. Capable of meeting the tight dioxin emission limit values;
2. Proven to work on a reasonably large/commercial scale;
3. Technically understood - allowing accurate design and reliable operation; and,
4. Currently in use in either the UK or Europe.

Key sources of data on dioxin abatement measures included the following:

- IPPC BREFs and Environment Agency Sector/Process Guidance Notes;
- Discussions with key stakeholders such as industrial operators, sector associations and regulatory bodies;
- The British Library on-line bibliographic database (covering papers, research reports, theses, technical publications);
- Other bibliographic databases, technical indexes and reputable websites;
- Previous cost curves reports for DEFRA (e.g. AEA 2002; Entec 2002)
- In-house knowledge of abatement measure design, costs and performance, and data from previous policy studies;
- Discussions with academics, industry contacts and equipment vendors involved in abatement technology supply and research; and,
- Various other technical and industry sector publications.

A description of the generic measures for dioxin emissions abatement is given in Appendix C. These measures generally fall into two categories:

i) **Primary or process-integrated -** these measures seek to prevent dioxins being generated and emitted from the main process. They include: the prevention of precursors (e.g. chlorinated compounds) being present in the first place; the destruction or removal of precursors before they become available for dioxin formation; fuel switching; and the avoidance of conditions suitable for dioxin formation.

ii) **Secondary or end-of-pipe -** these measures attempt to destroy or recapture dioxins after they have been emitted from the main process. They include: particulate matter arrestment plant such as electrostatic precipitators and fabric filters; acid gas scrubbers; and injection of lignite coke powder or other adsorbents upstream of particulate abatement units.

2.3.2 Determination of Applicable Abatement Measures

Not all of the abatement measures identified during the review are applicable to certain activities or sources. Primary measures are most economically incorporated during the design stage of a process since they require optimisation of the fundamental process parameters and size and type of equipment. Alternatively they can be retrofitted to an existing process but practical issues such as size of the existing combustion chamber, space limitations, and excessive costs for modifications can be an issue. Primary measures can also include fuel switching, energy efficiency measures and changes to raw material composition.

Even when primary measures have been installed, dioxin emissions can remain at elevated levels. Therefore, for both new and existing plant, secondary measures may be required to meet tight emission limit values for dioxins (e.g. 0.1 ng/m^3). Secondary measures involve fitting abatement equipment such as fabric filters in the flue gas system. Again there may be practical problems in installing abatement equipment due to space limitations, pressure drop considerations and excessive costs for modifications to plant, especially if the existing plant is nearing the end of its economic lifetime.

There is also the possibility of combining two or more abatement measures. In some applications additional abatement measures may not be applicable for technical or safety reasons, or because of an incompatibility with existing abatement measures. Those measures that are considered to be applicable based on literature, guidance documents and consultations with operators are detailed in Appendix D for each source category.

2.3.3 Calculation of Emissions Reductions Achievable

The emissions reductions achievable through installing a specific abatement measure (or combination of measures) across a source category (or individual source) is generally assessed by:

i) Examining the current typical dioxin emission levels (= a ng/m^3);

ii) Identifying the ELVs that are achievable with the measure (= b ng/m^3);

iii) Estimating the *uptake* of the measure across the sector (= c %); and,

iv) Combining this data with the 2000 mass emission figure (= d mgTEQ) to calculate the reduction in dioxin emissions across the source category (= $[a-b]/a * c/100 * d$ mgTEQ).

The value $[a-b]/a$ is normally referred to as the *abatement efficiency*. For the BAU scenario, the uptake of a measure is that required by policy instruments. For the beyond BAU scenario, the uptake of a measure is a realistic estimate of the potential for *additional* implementation (i.e. the uptake is considered to be either technically or economically feasible, or a possible requirement that future policy could specify).

For some abatement measures a more complex calculation procedure is used to take account of the particular characteristics of the source and the applicability of the abatement measure.

2.3.4 Evaluation of Secondary Benefits and Other Impacts

Abatement measures are rarely installed with the sole purpose of abating dioxin emissions. Where data is available, the secondary benefits such as reduced emissions of PM_{10}, PAH, heavy metals and acid gases are noted (see Appendix D).

Abatement measures may lead to an increase or decrease in energy use and where data is available this is noted. Other impacts of abatement measures such as improved/reduced product quality, affordability of measures, and effect on competitiveness in a particular sector are also considered where appropriate (see Appendix D).

2.4 Generation of Cost Curves

2.4.1 Treatment of Abatement Cost Data

The *baseline* for the dioxin cost curves is the NAEI data for dioxin emissions during the year ending 31st December 2000, at which point the costs are set at zero. Any further emissions reductions and costs of abatement are relative to this baseline (i.e. expenditure and emissions reductions already made during 2001/02 will be shown on the curve). Where the investigation of source categories indicates that a *correction* to the NAEI emission baseline is required, then this will be clearly documented in Appendix D and will be shown on the cost curve (at zero cost) to provide an audit trail.

The costs of abatement measures are estimated based on available data and experience of previous cost-benefit assessment. The costs are annualised using the following equation:

Annualised cost (£/yr) = [Capital Cost (£) * Annualisation Factor] + Change in Operating Costs (£/yr)

The annualisation factor (e) is given by: $$e = \left[\frac{r}{(1+r)^n - 1}\right] + r$$

Where r is the annual discount rate (taken as 6%) and n is the estimated lifetime of the measure (normally in the range 5-20 years). The change in operating costs is positive for additional expenditure (e.g. increased waste disposal costs) and negative for savings (e.g. decreased fuel bills).

To ensure that the cost curves are as realistic as possible for the pollutant of interest, when considering any measures to be implemented under BAU policies, the cost is set to zero if the measure is to be implemented anyway to satisfy a policy requirement not related to the pollutant of interest (Entec 2002). A good example of this is the Large Combustion Plant Directive which require measures to abate SO_2, NO_x and particulate emissions - the cost of these measures are not attributable to dioxins abatement but they will lead to reductions in dioxin emissions and will appear on the BAU cost curve at zero cost.

2.4.2 Calculation of Cost Curves

Much consideration has been given to the most transparent way in which the revised cost curve could be presented. The existing cost curve for DEFRA (AEA 2002) was developed in Microsoft Access format and due to the large amount of data and number of forms in this database, it is difficult to manipulate and interrogate the results. Therefore, the cost curves presented in this report have been developed in Microsoft Excel format. The spreadsheet for the revised dioxin costs curves builds upon previous cost curve work and presents the results in a transparent manner. The worksheets within the spreadsheet include:

- **Module 1 (Sectors)** - It is important to know which sectors (or source categories) contribute to and dominate UK dioxin emissions so that relevant policy decisions can be taken. This module is fully consistent with current NAEI emissions data baseline for 2000 to facilitate future updating and improve transparency. The sectors/source categories to be considered in the cost curve were identified using NAEI data and are listed in Table 2.1.

- **Module 2 (Sources)** - This module focuses in on the individual sources that contribute to the overall emissions from each specific sector/source category. These contributors are listed by NAEI 'Source Code' and 'Fuel Code'. The data allows those sources that dominate a specific sector to be clearly identified. Again, this module is fully consistent with current NAEI baseline for 2000 to facilitate future updating and improve transparency. A full listing of dioxin sources is presented in Appendix B.

- **Module 3 (Measures)** - This module lists the abatement measures applicable to each source along with data on the abatement efficiency, uptake, capital and operating costs. Corrections required to the NAEI baseline are also listed. The annualised cost and emission reduction are calculated along with the unit abatement cost (£k per mgTEQ abated). The abatement measure data builds on that from previous cost curve work and presents the results in a transparent manner that allows updating.

- **Module 4 (Cost Curve)** - The cost curve module presents the raw data for inclusion in the cost curve itself, allowing ranking and ordering of abatement measures according to unit abatement cost and whether the measure is a baseline correction, BAU or beyond BAU. The cost curve can easily be modified to include additional measures and present the data on either an absolute or relative basis using this module.

3. Cost Curves for Dioxins

3.1 Introduction

The tables and graphs in this section present the results of the research to develop the UK cost curves for abatement of dioxin emissions to air. Abatement measures for each of the 15 source categories identified in Table 2.1 are listed in order of increasing unit abatement cost (£k per mgTEQ abated). The starting point for the dioxin cost curve is the NAEI 2000 emissions data which is the baseline for the overall cost curves project. The *measures* and *corrections* to emissions data are listed in the following order:

1. **Corrections to the NAEI baseline** - during the investigation of some source categories it became apparent that the existing NAEI emissions estimate for 2000 was inaccurate. Therefore, the baseline had to be corrected to reflect the latest available data;
2. **BAU measures** - measures that will deliver reductions in dioxin emissions under the requirements of existing policies; and,
3. **Beyond BAU measures** - measures that could realistically be taken up in future to allow further reductions in dioxin emissions that are beyond existing policy requirements.

The cost curves present this data graphically so that the remaining UK dioxin emissions and the cost associated with achieving a certain level of emissions can be evaluated.

3.2 Cost Curve Data

The cost curve data obtained from the detailed investigation of the 15 source categories is shown in Table 3.1.

Table 3.1 - Data for Revised UK Cost Curves for Abatement of Dioxin Emissions to Air (2000 Baseline)

Measure/ Correction Number	Source Category	Description	Emissions Reduction (mgTEQ/yr)[1]	Annualised Cost (£k/yr)	Unit Abatement Cost (£k/mgTEQ)	Total UK Emissions Remaining (gTEQ/yr)	Cumulative Annualised Cost (£M/yr)	Cumulative Emission Reduction c.f. Baseline (%)
NAEI Baseline								
0	All UK Sources	NAEI 2000 emissions baseline	-	-	-	360.1	-	-
Corrections to NAEI Baseline								
1	Waste incineration	Revision of NAEI estimate based on latest data	33800	0	0.00	326.3	0.0	9.4
2	Cremation	Revision of NAEI estimate based on latest data	18320	0	0.00	308.0	0.0	14.5
3	Public service combustion	Revision of NAEI estimate based on latest data	13260	0	0.00	294.7	0.0	18.2
4	Iron & steel sector	Closure of the two Llanwern sinter plants	11730	0	0.00	283.0	0.0	21.4
5	Refinery combustion	Revision of NAEI estimate based on latest data	7300	0	0.00	275.7	0.0	23.4
BAU Measures								
6	Power stations	FGD, load factor changes and plant closures[2]	5550	Note 2	0.00	270.1	0.0	25.0
7	Domestic fuel combustion	Energy drivers and home energy efficiency policy[3]	4520	Note 3	0.00	265.6	0.0	26.2
8	Other combustion in industry	Climate Change Agreements to reduce energy use[4]	1250	Note 4	0.00	264.4	0.0	26.6
9	Road transport	Gradual replacement of UK petrol fuelled vehicle fleet with vehicles meeting Euro IV standard[5]	1200	Note 5	0.00	263.2	0.0	26.9
10	Road transport	Gradual replacement of UK diesel fuelled vehicle fleet with vehicles meeting Euro IV standard[5]	120	Note 5	0.00	263.0	0.0	26.9
11	Iron & steel sector	Urea addition at sinter plants[6]	12090	850	0.07	250.9	0.8	30.3
12	Non-ferrous metals sector	Carbon injection upstream of filters[6]	9250	3610	0.39	241.7	4.5	32.9
13	Cement manufacture	Installation of bag filters[6]	2400	1010	0.42	239.3	5.5	33.5
14	Other combustion in industry	Diverting treated wood to landfill[7]	14300	8870	0.62	225.0	14.3	37.5
15	Other combustion in industry	Diverting waste oil to specialist incineration facilities[8]	120	265	2.30	224.9	14.6	37.6
Beyond BAU Measures								
16	Iron & steel sector	Carbon injection at EAFs	11330	1880	0.17	213.5	16.5	40.7
17	Small-scale waste burning	Education campaign to disseminate best practice for waste burning	1750	500	0.29	211.8	17.0	41.2
18	Domestic fuel combustion	Best practice education campaign for hearths	240	100	0.42	211.5	17.1	41.2

Measure/ Correction Number	Source Category	Description	Emissions Reduction (mgTEQ/yr)[1]	Annualised Cost (£k/yr)	Unit Abatement Cost (£k/mgTEQ)	Total UK Emissions Remaining (gTEQ/yr)	Cumulative Annualised Cost (£M/yr)	Cumulative Emission Reduction c.f. Baseline (%)
19	Other combustion in industry	Switch from solid/liquid fuel to gas for heat & power	4420	2070	0.47	207.1	19.1	42.5
20	Accidental fires	Improved fire prevention education campaign[9]	3240	2060	0.64	203.9	21.2	43.4
21	Iron & steel sector	Metallic mesh filter installation with carbon injection at sinter plants	9680	6820	0.70	194.2	28.0	46.1
22	Natural fires	National education campaign on prevention of accidental fires in forests and on heath/moorland	580	500	0.86	193.6	28.5	46.2
23	Power stations	Carbon injection at remaining coal-fired plant	3260	6480	1.99	190.4	35.0	47.1
24	Accidental fires	Increased uptake of smoke alarms in domestic properties[9]	2900	17440	6.02	187.5	52.4	47.9
25	Domestic fuel combustion	Switch from solid/liquid fuel to gas/LPG fired heating	1200	69300	57.91	186.3	121.7	48.3
26	Accidental fires	Increased uptake of fire extinguishers & fire blankets in domestic properties[9]	530	30700	58.04	185.7	152.5	48.4
27	Domestic fuel combustion	Increased uptake of energy efficiency measures	340	21600	63.12	185.4	174.0	48.5

Notes:

1. Where there is more than one dioxin abatement measure for a particular source category, emissions reductions are calculated assuming that the measures are implemented in the above order for that source category.
2. This measure is required under the LCPD and costs have been estimated to be in the region £430-800 million as a net present value. However, these costs are not attributable to dioxin abatement as the LCPD is primarily intended to reduce emissions of SO_2, NO_x and particulates.
3. The costs of the energy efficiency measures are in the region of £665 million over the period 2000 to 2004. However, these costs are not attributable to dioxin abatement since the BAU policies involved are primarily intended to reduce domestic energy use in accordance with climate change targets.
4. The costs of this measure are in the region of £60 million/year. However, these costs are not attributable to dioxin abatement since the BAU policies involved are primarily intended to reduce industrial energy use in accordance with climate change targets.
5. The costs of these road transport measures are estimated to be in the region of £2.0 billion/year. However, these costs are not attributable to dioxin abatement since the BAU policies involved are primarily designed to reduce emissions of other air pollutants from road transport.
6. These measures are required under IPC/IPPC regulation in order to meet benchmark ELVs for dioxins that are specified under the BAT requirements.
7. This measure is required under the WID in order to meet the benchmark ELVs that are specified for dioxins. It is expected that operators covered by the WID will cease on-site combustion of treated wood and divert the waste stream to landfill (or alternatively to specialist incineration facilities).
8. This measure is required under the WID in order to meet the benchmark ELVs that are specified for dioxins. It is expected that operators covered by the WID will send waste oil to specialist incineration facilities rather than burn this on-site.
9. The primary benefit of fire safety measures is a reduction in fire-related deaths and damage to property. However, the benefit in terms of dioxins abatement is evaluated above.

3.3 Overall Revised UK Cost Curve

The overall revised UK dioxin cost curve is shown in Figure 3.1. Corrections to the NAEI emissions data are shown in order to provide an audit trail relative to the original baseline for the cost curves project. All measures are shown, except for measures 26-28, which have very high unit abatement costs and are off the selected scale range on the y-axis. The x-axis indicates the total annual UK dioxin emissions remaining after implementation of each measure. The y-axis indicate the cumulative annualised cost of the measures implemented. Data points are labelled by their measure number as shown in Table 3.1. Datapoint '0' is the NAEI baseline emission figure for 2000. Several BAU dioxin emission reductions are shown at zero cost. This is because they will be achieved through policy measures that are intended to abate emissions of other air pollutants and, therefore, the costs are not attributable to dioxins.

3.4 BAU Cost Curve

The BAU cost curve is shown in Figure 3.2. This is an enlargement of the overall cost curve shown in Figure 3.1. The corrections to the NAEI baseline are also indicated.

3.5 Beyond BAU Cost Curve

The beyond BAU cost curve is shown in Figure 3.3. The starting point is the BAU emissions which are shown at zero cost. Therefore, this graph shows the additional cumulative cost of measures beyond those that are already required under BAU.

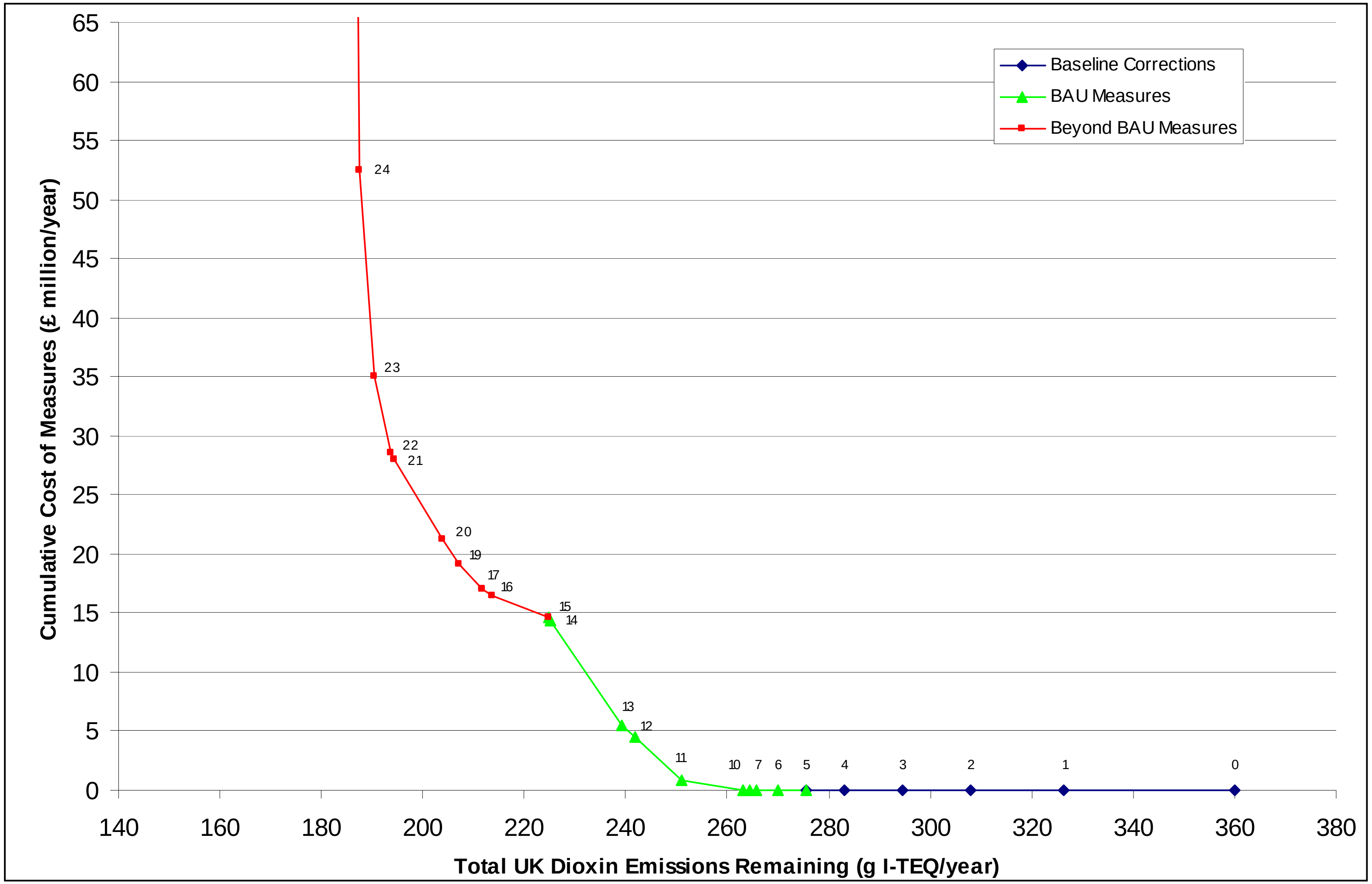

Figure 3.1 - Overall Revised UK Dioxin Cost Curve (2000 Baseline)

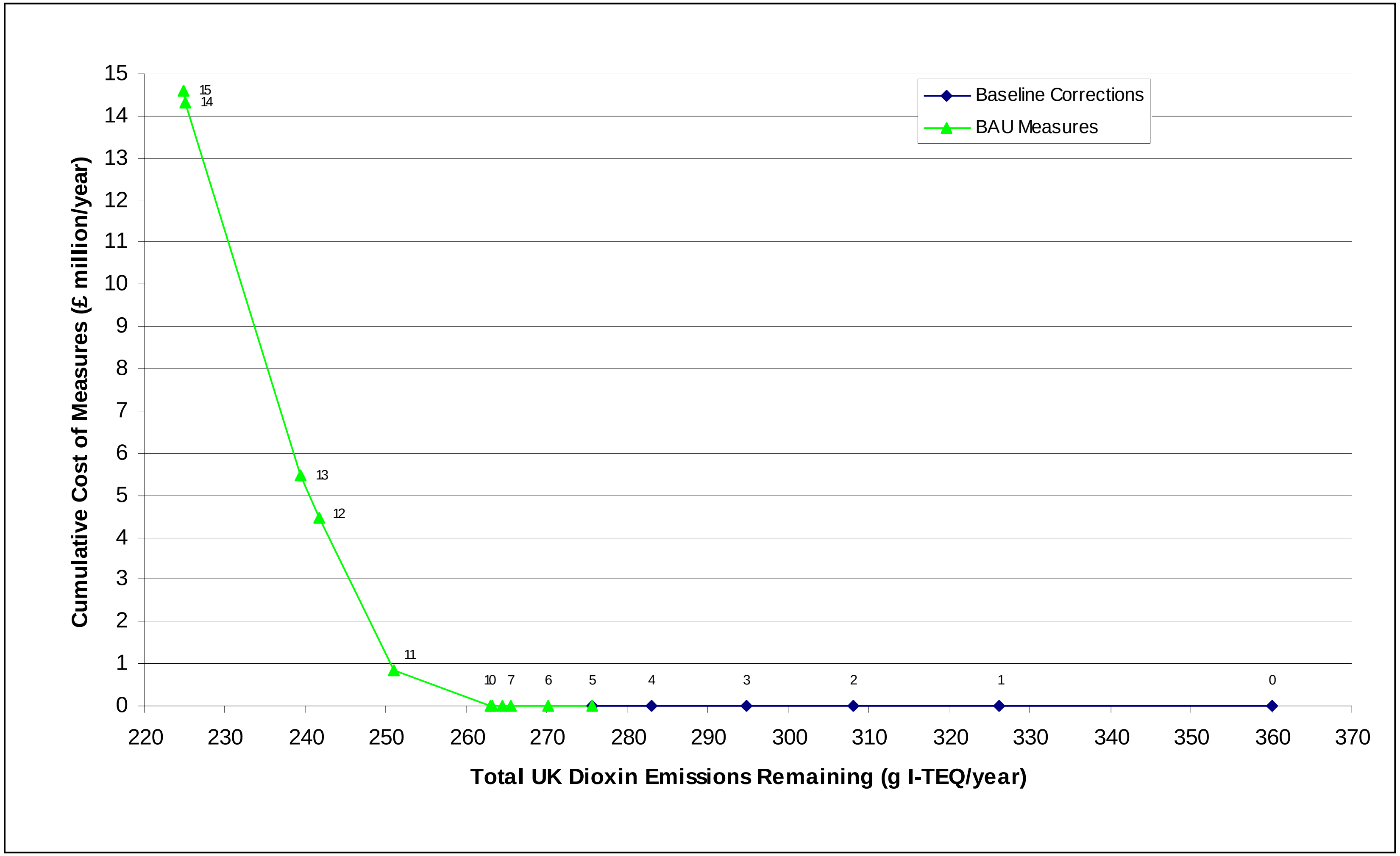

Figure 3.2 - Revised Dioxin Cost Curve for BAU Measures (2000 Baseline)

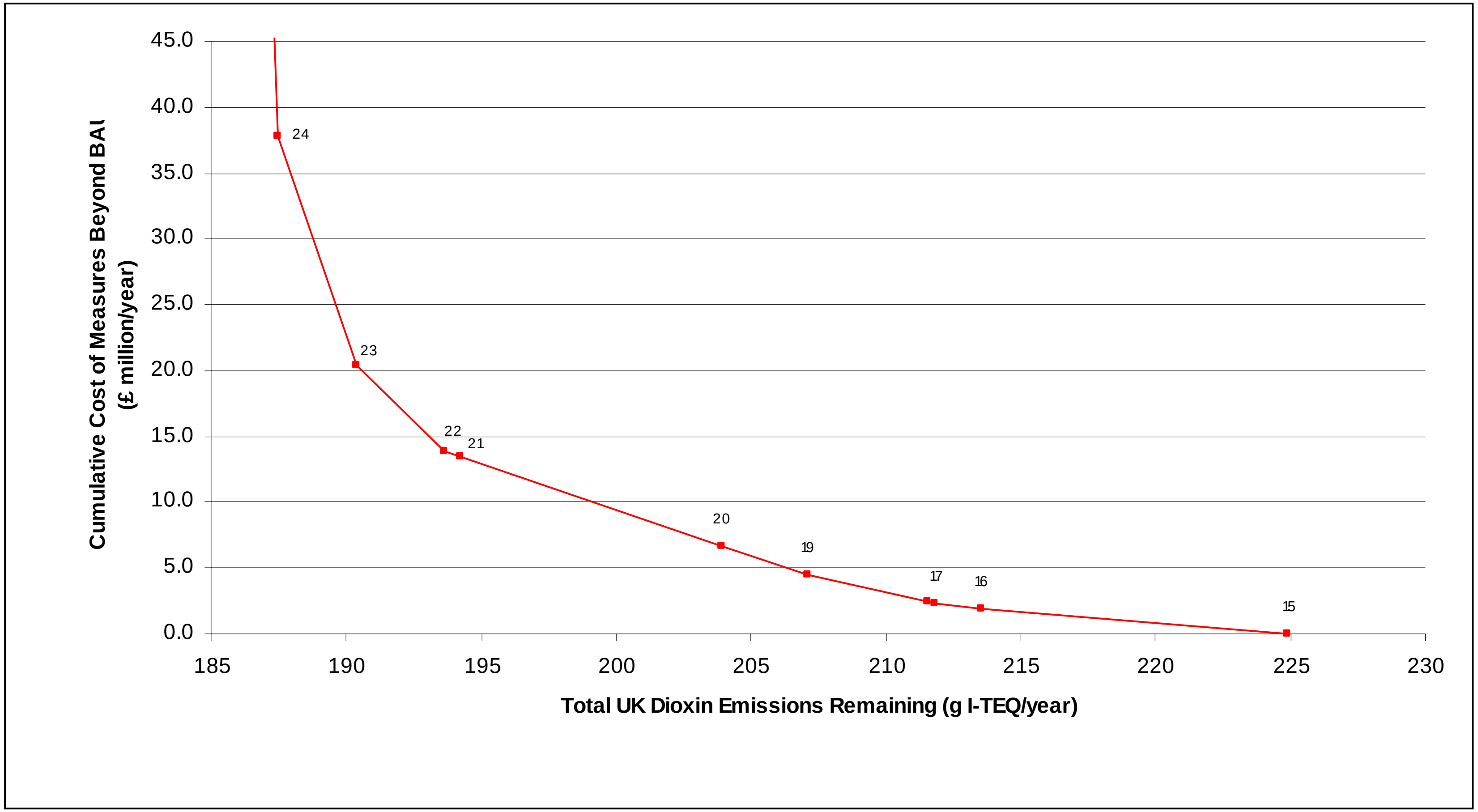

Figure 3.3 - Revised Dioxin Cost Curve for Beyond BAU Measures (2000 Baseline)

4. Discussion

4.1 Baseline Corrections

The baseline for the cost curves project is the NAEI data for 2000. However, during the detailed investigation and review of certain sources of dioxins it became clear that some of the NAEI emissions data was based on old emission factors and inaccurate activity statistics which do not accurately reflect the situation during the year 2000. In some cases the NAEI data did not correspond even approximately with the Environment Agency's Pollution Inventory which lists emissions data that is statutorily reported by operators of major industrial dioxin sources in England and Wales (EA 2003). In other cases, the dioxin ELVs (i.e. ng/m^3) that are implied by the NAEI are orders of magnitude higher than the most recent literature suggests.

In particular, the emission estimates for the following source categories required correction:

- **Waste Incineration** - Previous detailed studies on the Waste Incineration Directive indicate that the vast majority of UK incinerators (i.e. those handling clinical, municipal and chemical wastes) were complying with a dioxin ELV of 0.1 ng/m^3 by the end of 1999. The NAEI emission estimate of 35.5 gTEQ in 2000 (i.e. 9.8% of the UK total) suggests a much higher ELV. The emissions from this sector have been re-calculated at 1.7 gTEQ for 2000. Therefore, it is concluded that the sector contributes <1% of the UK total dioxin emissions.

- **Cremation** - the NAEI emission figure of 18.4 gTEQ in 2000 (5.1% of the UK total) is based on old emission factors which do not represent the significant improvements made in this sector under LAPC regulation. The revised emission estimate for this source based on recent studies is <0.1 gTEQ in 2000. Therefore, it is concluded that this source contributes <0.1% of the UK total dioxin emissions.

- **Public Services Combustion** - the NAEI emission figure of 13.9 gTEQ in 2000 (3.9% of the UK total) appears to be based on old emission factors and inaccurate activity data since coal is no longer widely used in this sector. The revised emission estimate for this source is 0.6 gTEQ in 2000. Therefore, it is concluded that this source contributes <0.2% of the UK total dioxin emissions.

- **Iron & Steel Sector** - closure of the two sinter plants at the Corus Llanwern works during 2001 will lead to a reduction in dioxin emissions of 11.7 gTEQ/year. Therefore, this reduction is shown in the cost curve as a correction to the baseline so that future emissions under BAU can be accurately represented.

- **Refinery Combustion** - the NAEI emission figure of 9.1 gTEQ in 2000 (2.5% of the UK total) appears to be based on old emission factors which do not represent current operations. The revised emission estimate for this sector is 1.8 gTEQ in 2000. Therefore, it is concluded that the sector contributes <1% of the UK total dioxin emissions.

On this basis, the corrected UK total dioxin emissions figure for 2000 is 276 gTEQ. This represents a significant reduction of **23%** from the current NAEI estimate of 360 gTEQ for 2000. It is recognised that there will always be a relatively high level of uncertainty in dioxin emission inventories. However, the above corrections to the baseline are considered to be reasonable based on a detailed review of the most recently available data.

4.2 BAU Measures

A total of 10 BAU measures which will lead to dioxin emissions reductions were identified. Together these measures will cost **£14.6 million/year** and will reduce dioxin emissions from 276 to **225 gTEQ/year**. Therefore, BAU measures will reduce total emissions by **18%** compared to the corrected baseline. Under BAU, total UK emissions will reduce to **62%** of the NAEI baseline for 2000 when baseline corrections are included. This indicates a better picture for the UK than previous studies indicate in terms of reducing dioxin emissions from historically high levels. Unit abatement costs for BAU measures range from around £0.1-2.3 million per gTEQ of dioxins abated. As expected, these unit costs are very high compared to those for other pollutants but they must be put into context by considering the environmental and human health benefits that may arise. The total cost of BAU measures appears to be quite low when compared to the previous cost curve (AEA 2002). However, previous work has under-estimated the emission reductions that were made (and already paid for) prior to 2000 and has incorrectly attributed the costs of some measures to dioxin abatement.

Around 46% of the total BAU emissions reductions will be delivered by the industrial sector under IPPC regulation. Under IPPC operators must demonstrate that they are using BAT for abatement and achieve stringent benchmark ELVs for dioxin emissions (typically 0.1 ng/m^3) over the next 3 to 6 years. Previously, under IPC regulation these industries were typically only required to meet ELVs of around 1 ng/m^3. All of the relevant industrial sectors, including some operations that were not previously covered by IPC, will come under IPPC regulation by 2007 (e.g. the Iron & Steel sector are currently in the process of transferring from IPC to IPPC). LAPC/LAPPC also has a role to play in reducing dioxin emissions from smaller operations under BAU.

Around 28% of the total BAU emissions reductions are from ‘other combustion in industry’ and will be delivered under the requirements of the WID. Operators covered by the WID will have to comply with a 0.1 ng/m^3 dioxin ELV for on-site combustion of treated wood and waste oils. In practice the majority of treated wood is likely to be segregated from untreated wood and diverted to either landfill or specialist incineration facilities. Operators covered by the WID and burning waste oil are likely to divert this waste stream to specialist incineration facilities.

In the public power sector, the LCPD will require measures such as flue gas desulphurisation and reduced load factors at some coal-fired plants, and closure of other plants. The UK has not yet decided on the implementation route for the LCPD (i.e. ELV route or National Plan). However, based on previous and ongoing LCPD studies, both routes will deliver similar but significant reductions in particulate emissions and this will lead to reductions in dioxin emissions.

In the industrial and domestic sectors, energy efficiency measures and fuel-switching under BAU will lead to reductions in coal and oil combustion which are significant sources of dioxins. In the road transport sector improvements in engine efficiency (Euro IV standards) due to gradual vehicle fleet replacement, and transport policy measures to reduce the use of cars will lead to some reduction in dioxin emissions. Leaded petrol consumption no longer contributes significantly to dioxin emissions since sales are limited to 0.5% of total UK petrol sales under the European Fuels Directive.

4.3 Beyond BAU measures

A total of 12 beyond BAU measures which would lead to dioxin emissions reductions were identified. Together these measures would cost **£159.4 million/year** and would reduce dioxin emissions from 225 to **185 gTEQ/year**. Therefore, all possible beyond BAU measures would reduce total emissions by **14.3%** compared to the corrected baseline. If all BAU and beyond BAU measures were implemented, total UK emissions would reduce to **52%** of the NAEI baseline for 2000 when baseline corrections are included.

It is worth noting that measures 25-27 have excessively high unit abatement costs. For this reason alone they are unlikely to be implemented. Therefore, it can be assumed that only measures 16-24 could be implemented. In this case the beyond BAU measures would cost **£37.8 million/year** and would reduce dioxin emissions from 225 to **188 gTEQ/year**. Therefore, implementation of beyond BAU measures 16-24 would reduce total emissions by **13.6%** compared to the corrected baseline. These results indicate that significant further reductions in dioxin emissions are possible if measures beyond BAU are implemented.

The beyond BAU measures include additional abatement at industrial sites, education campaigns to disseminate best practice for combustion and for prevention of fires, and fuel-switching. Unit abatement costs for beyond BAU measures (excluding measures 25-27) range from around £0.2-6.0 million per gTEQ of dioxins abated. As expected, these unit costs are very high compared to those for other pollutants but they must be put into context by considering the environmental and human health benefits that may arise.

The effects on competitiveness of imposing beyond BAU measures would have to be considered. Available information on economics and affordability is given under the relevant source category headings in Appendix D.

4.4 Uncertainty

There is a high level of uncertainty in dioxin emission inventories when compared to emission inventories for other air pollutants such as SO_2, NO_x and particulates. The main reasons for this uncertainty were discussed in Section 2.1.1.

The NAEI data for 2000 was taken as the most accurate baseline to work from in developing the cost curves. This remains the case but it is recommended that the NAEI data be revised in light of the data presented in Section 4.1. Other source categories for which the NAEI data is most uncertain are:

- Accidental fires;
- Small-scale waste burning; and,

- Non-ferrous metals.

For these sources, further work is required to better quantify emission factors and activity rates. In particular, further work on the small-scale waste burning sector would be useful to confirm the significance of this dioxin emissions source. At present there is a high level of uncertainty in the quantity of waste burnt on a small-scale and the dioxin emission factors that apply. In addition some potentially significant sources of dioxins do not appear to be quantified in the NAEI, including:

- Animal carcass incineration (an expanding sector as a result of controls on disposal in landfills);
- Biomass incineration and biomass power plants;
- Food & animal feed processing;
- Cremation of pets (listed in the Pollution Inventory as a dioxin source); and,
- Oil & gas extraction (inland and offshore).

It is recommended that the NAEI data be reviewed to account for emissions from these sectors.

Recent work indicates that the uncertainty in the NAEI dioxins emission inventory (95% confidence limits) is of the order -40% to +90% (NAEI 2003). However, the corrections to the NAEI outlined in Section 4.1 and the potential source omissions discussed above must also be considered. Therefore, it is difficult to estimate the uncertainty in the dioxins inventory but it is considered that the *corrected* baseline represents the best-estimate of emissions based on currently available data (overall uncertainty is likely to be of the order ± 50%).

The cost curve is based on the corrected baseline and further emissions reductions can be calculated with a reasonably high degree of certainty as they are calculated from published abatement efficiency data, regulatory ELVs, and first principles (estimated uncertainty is of the order ± 30%). The costs of abatement measures are reasonably well documented and can also be estimated with some certainty (estimated uncertainty is of the order ± 20%).

The discount rate used for calculation of annualised costs in the cost curves was the standard treasury rate at the time of commencement of this study of 6% (n.b. the treasury discount rate has recently been revised to 3.5%). However, in the private sector, discount rates of 10-15 % are more commonly used to reflect the cost of capital (e.g. the Corus discount rate is 13%). Since most measures require private investment then the annualised costs may be underestimated by use of the treasury discount rate.

Detailed uncertainty analysis of the data is not considered to be worthwhile at this early stage in developing UK cost curves for dioxins and further significant work to improve the accuracy of dioxins data may be required in future. Overall, the revised UK cost curves are considered to represent the most accurate picture presented to date of the potential for further dioxin abatement, and the associated costs.

5. Conclusions

The key findings from the research to develop the UK cost curves for abatement of dioxin emission to air are presented below:

5.1 Cost Curve Development

i) The degree of uncertainty in the historical dioxins emissions data is higher than that for other air pollutants. However, the NAEI dioxins emissions data represents the most accurate available baseline from which to develop the cost curves.

ii) In addition to the traditional industrial and domestic combustion activities it is apparent that accidental fires, small-scale waste burning and metals production are significant dioxin sources (both in the UK and across Europe). Although substantial emissions reductions have been made in recent years these sources remain a priority for abatement.

iii) A detailed investigation of abatement measures for the 15 source categories which account for 98% of UK dioxin emissions has been carried out. The latest national and international research and literature on the subject has been reviewed and data has been obtained from key stakeholders. The updated cost curves presented as a result of this research are considered to be more comprehensive, transparent and accurate than the previous curves developed for DEFRA.

iv) The revised dioxin cost curves should be used to inform policy makers and other stakeholders in any decision-making process that leads to the formulation of a national dioxins action plan.

5.2 Baseline Corrections

v) The starting point for the dioxin cost curve is the NAEI 2000 emissions data which is the baseline for the overall cost curves project.

vi) During the detailed investigation and review of certain sources of dioxins it became clear that some of the NAEI emissions data was based on old emission factors and inaccurate activity statistics which do not accurately reflect the situation during the year 2000.

vii) Dioxin emissions from waste incineration, cremation, public services combustion, and refinery combustion were re-evaluated and were found to be negligible. The revised emission estimates are based on the latest available data and are factored into the cost curve as corrections to the baseline to provide an audit trail.

viii) The corrected UK total dioxin emissions figure for 2000 is 276 gTEQ. This represents a significant reduction of **23%** from the current NAEI estimate of 360 gTEQ for 2000.

5.3 BAU Measures

ix) A total of 10 BAU measures which will lead to dioxin emissions reductions were identified. Together these measures will cost **£14.6 million/year** and will reduce dioxin emissions from 276 to **225 gTEQ/year**. Therefore, BAU measures will reduce total emissions by **18%** compared to the corrected baseline.

x) Unit abatement costs for BAU measures range from around £0.1 to 2.3 million per gTEQ of dioxins abated. As expected, these unit costs are very high compared to those for other pollutants but they must be put into context by considering the environmental and human health benefits that may arise.

xi) The majority of the BAU emissions reductions will be delivered by the industrial sector under IPPC/LAPPC regulation and by the waste incineration sector under the WID. However, the vast majority of the emissions reductions required in the waste incineration sector under the WID were made prior to 2000.

xii) In the industrial, commercial and domestic sectors, energy efficiency measures and fuel-switching under BAU policy measures will also lead to reductions in dioxin emissions.

5.4 Beyond BAU Measures

xiii) A total of 9 realistic beyond BAU measures which would lead to dioxin emissions reductions were identified. Together these measures would cost **£37.8 million/year** and would reduce dioxin emissions from 225 to **188 gTEQ/year**. Therefore, beyond BAU measures would reduce total emissions by **14%** compared to the corrected baseline. These results indicate that significant further reductions in dioxin emissions are possible if measures beyond BAU are implemented.

xiv) The beyond BAU measures include: additional abatement at industrial sites; education campaigns to disseminate best practice for domestic combustion, small-scale waste burning and fire prevention; and, fuel-switching.

xv) Unit abatement costs for beyond BAU measures (excluding measures 25-27) range from around £0.2 to 6.0 million per gTEQ of dioxins abated. As expected, these unit costs are very high compared to those for other pollutants but they must be put into context by considering the environmental and human health benefits that may arise.

xvi) The effect on competitiveness of imposing beyond BAU measures in certain sectors must also be considered when formulating a dioxins action plan.

5.5 Uncertainty

xvii) There is a high level of uncertainty in dioxin emission inventories when compared to emission inventories for other air pollutants such as SO_2, NO_x and particulates. Further work is required to better quantify dioxin emission factors and activity rates for accidental fires, small-scale waste burning and non-ferrous metals manufacture.

xviii) Some potentially significant sources of dioxins do not appear to be quantified in the NAEI. Therefore, the NAEI dioxins inventory should be reviewed, especially in light of the baseline corrections detailed above.

xix) It is difficult to estimate the uncertainty in the dioxins inventory but it is considered that the *corrected* baseline represents the best-estimate of emissions based on currently available data.

xx) The cost curve is based on the corrected baseline and further emissions reductions can be calculated with a reasonably high degree of certainty. The costs of abatement measures are well documented and can also be estimated with a reasonably high degree of certainty.

xxi) The discount rate of 6% used for calculation of annualised costs in the cost curves is lower than typical private investment discount rates. Therefore the annualised costs may be underestimated by use of the treasury discount rate.

xxii) Overall, the revised UK cost curves are considered to represent the most accurate picture presented to date of the potential for further dioxin abatement, and the associated costs.

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Appendix A - Dioxin and Furan Congeners and Toxicity Factors

In order to indicate the overall toxicity of dioxin and furan emissions a system of Toxic Equivalency Factors (TEFs) for the various dioxin and furan congeners is commonly used. The two systems in use are the International TEFs (I-TEFs) which were developed in 1988 and the World Health Organisation TEFs (WHO-TEFs) which were published in 1994 and take account of more recent toxicity data (DEFRA 2002a). Total mass emissions from a source are quoted as toxic equivalent (I-TEQ or WHO-TEQ), for example gI-TEQ, and are calculated using the TEFs. The table below lists the congeners which are known to be toxic and gives their assigned TEFs for exposure of humans/mammals.

Table A1.1 - Toxic Equivalency Factors for Dioxin and Furan Congeners (NAEI 2002a)

Congener	I-TEFs	WHO-TEFs
Dioxins		
2,3,7,8 tetrachlorodibenzo-*p*-dioxin*	1	1
1,2,3,7,8 pentachlorodibenzo-*p*-dioxin	**0.5**	**1**
1,2,3,4,7,8 hexachlorodibenzo-*p*-dioxin	0.1	0.1
1,2,3,6,7,8 hexachlorodibenzo-*p*-dioxin	0.1	0.1
1,2,3,7,8,9 hexachlorodibenzo-*p*-dioxin	0.1	0.1
1,2,3,4,6,7,8 heptachlorodibenzo-*p*-dioxin	0.01	0.01
Octachlorodibenzo-*p*-dioxin	**0.001**	**0.0001**
Furans		
2,3,7,8 tetrachlorodibenzofuran	0.1	0.1
1,2,3,7,8 pentachlorodibenzofuran	0.05	0.05
2,3,4,7,8 pentachlorodibenzofuran	0.5	0.5
1,2,3,4,7,8 hexachlorodibenzofuran	0.1	0.1
1,2,3,6,7,8 hexachlorodibenzofuran	0.1	0.1
1,2,3,7,8,9 hexachlorodibenzofuran	0.1	0.1
2,3,4,6,7,8 hexachlorodibenzofuran	0.1	0.1
1,2,3,4,6,7,8 heptachlorodibenzofuran	0.01	0.01
1,2,3,4,7,8,9 heptachlorodibenzofuran	0.01	0.01
Octachlorodibenzofuran	**0.001**	**0.0001**

Note: Differences between I-TEFs and WHO-TEFs are highlighted in bold.

* 2,3,7,8 tetrachlorodibenzo-*p*-dioxin (2,3,7,8 TCDD) is the most toxic dioxin congener and is used as the reference for the TEFs.

This report uses the I-TEF system in order to ensure consistency with the NAEI data. Although the WHO-TEF system is now recognised as the preferred system, the I-TEF system remains in wide use internationally. For development of the cost curves the choice of TEF system is not critical given the high level of uncertainty in the dioxins emissions inventory and the lack of detailed data on congener profiles for certain emission sources.

Appendix B - UK Dioxins Emissions Inventory for the Year 2000

Table B1.1 - UK Dioxins Emissions Inventory for the Year 2000 (NAEI 2002b)

No.	Source	Fuel Type/Activity	Emissions (mgTEQ)*	% of UK Total	Cumulative %
1	Accidental fires	Non-fuel combustion	57800	16.05	16
2	Small-scale waste burning	Waste	49961	13.87	30
3	Iron and steel (sinter plant)	Iron production	35943	9.98	40
4	Incineration	Clinical waste	24070	6.68	47
5	Incineration	Cremation	18388	5.11	52
6	Iron and steel (electric arc furnace)	Steel production (electric arc)	16989	4.72	56
7	Other industry (combustion)	Treated wood	14300	3.97	60
8	Public services	Coal	13949	3.87	64
9	Power stations	Coal	13107	3.64	68
10	Other industry (combustion)	Wood	9302	2.58	70
11	Incineration	Sewage sludge combustion	7709	2.14	73
12	Accidental fires (vehicles)	Accidental fires (vehicles)	7050	1.96	75
13	Other industry (combustion)	Gas oil	6766	1.88	76
14	Agriculture	Straw	6700	1.86	78
15	Refineries (combustion)	Fuel oil	6321	1.76	80
16	Non-ferrous metals (secondary aluminium)	Secondary aluminium production	5972	1.66	82
17	Non-ferrous metals (secondary lead)	Refined lead	5839	1.62	83
18	Natural fires	Forest & moorland	5800	1.61	85
19	Non-ferrous metals (aluminium production (using pre-bake anodes))	Non fuel processes	5559	1.54	87
20	Other industry (combustion)	Burning oil	5250	1.46	88
21	Cement (non-decarbonising)	Clinker production	4627	1.29	89
22	Incineration	Chemical waste	3675	1.02	90
23	Domestic	Coal	3013	0.84	91
24	Iron and steel (grey iron foundry)	Iron castings	2917	0.81	92
25	Non-ferrous metals (primary lead/zinc)	Slab zinc and lead bullion	2453	0.68	93
26	Refineries (combustion)	Petroleum coke	2345	0.65	93
27	Other industry (combustion)	Coal	2257	0.63	94
28	Domestic	Anthracite	1926	0.53	94
29	Other industry (combustion)	Fuel oil	1483	0.41	95
30	Domestic	SSF	1339	0.37	95
31	Other industry (combustion)	Lubricants	1282	0.36	96
32	Iron and steel (combustion)	Fuel oil	1204	0.33	96
33	Road transport (cars non-catalytic urban)	Petrol	1144	0.32	96
34	Other industry (asphalt manufacture)	Asphalt produced	1024	0.28	96
35	Road transport (cars non-catalytic highway)	Petrol	991	0.28	97
36	Iron and steel (combustion)	Gas oil	765	0.21	97
37	Non-ferrous metals (nickel production)	Nickel production	684	0.19	97

No.	Source	Fuel Type/Activity	Emissions (mgTEQ)*	% of UK Total	Cumulative %
38	Coke production	Coke made	655	0.18	97
39	Power stations	MSW	646	0.18	98
40	Lime production (combustion)	Non-fuel combustion	640	0.18	98
41	Road transport (cars catalytic urban)	Petrol	563	0.16	98
42	Other industry (combustion)	Coke	557	0.15	98
43	Landfill	Escaping methane	541	0.15	98
44	Agriculture	Gas oil	520	0.14	98
45	Road transport (cars catalytic highway)	Petrol	475	0.13	98
46	Power stations	Fuel oil	468	0.13	99
47	Road transport (cars non-catalytic urban)	Petrol	459	0.13	99
48	Ssf production	Petroleum coke	408	0.11	99
49	Wood impregnation	PCP treatment	400	0.11	99
50	Domestic	Coke	348	0.10	99
51	Landfill	Flared methane	334	0.09	99
52	Refineries (combustion)	Gas oil	313	0.09	99
53	Road transport (cars catalytic rural)	Petrol	252	0.07	99
54	Autogenerators	Coal	247	0.07	99
55	Domestic	Wood	216	0.06	99
56	Coastal	Fuel oil	185	0.05	99
57	Road transport (LGVs non-catalytic urban)	Petrol	129	0.04	99
58	Road transport (LGVs non-catalytic highway)	Petrol	123	0.03	100
59	SSF production	SSF manufacture	104	0.03	100
60	SSF production	Coke	89	0.02	100
61	Miscellaneous	MSW	88	0.02	100
62	Other industry (combustion)	SSF	86	0.02	100
63	Refineries (combustion)	Naphtha	82	0.02	100
64	Power stations	Gas oil	78	0.02	100
65	Road transport (HGV articulated urban)	DERV	68	0.02	100
66	Refineries (combustion)	Miscellaneous	65	0.02	100
67	Road transport (LGVs non-catalytic rural)	Petrol	59	0.02	100
68	Other industry off-road	Petrol	57	0.02	100
69	Non-ferrous metals (aluminium production (VSS process))	Non fuel processes	55	0.02	100
70	Road transport (HGV articulated highway)	DERV	54	0.01	100
71	Iron and steel (combustion)	Coke	46	0.01	100
72	Agriculture	Fuel oil	43	0.01	100
73	Chemical industry (prod halogenated chemicals)	Non fuel processes	43	0.01	100
74	Road transport (all LGVs urban)	DERV	41	0.01	100
75	Road transport: m/cycle (>50cc, 4st urban)	Petrol	39	0.01	100
76	Other industry offroad	Gas oil	39	0.01	100
77	Road transport (all LGVs highway)	DERV	38	0.01	100
78	Road transport: m/cycle (>50cc, 4st highway)	Petrol	38	0.01	100
79	Road transport (buses)	DERV	36	0.01	100
80	Miscellaneous	Coal	36	0.01	100
81	Road transport (HGV rigid urban)	DERV	35	0.01	100

No.	Source	Fuel Type/Activity	Emissions (mgTEQ)*	% of UK Total	Cumulative %
82	Domestic house & garden	Petrol	34	0.01	100
83	Ceramic manufacture	Non fuel processes	31	0.01	100
84	Collieries	Coal	29	0.01	100
85	Road transport (all cars urban)	DERV	24	0.01	100
86	Road transport (HGV rigid highway)	DERV	22	0.01	100
87	Road transport (HGV rigid rural)	DERV	22	0.01	100
88	Power stations	Slurry	20	0.01	100
89	Road transport (all LGVs highway)	DERV	19	0.01	100
90	Magnesium alloying	Non fuel processes	18	0.00	100
91	Agriculture	Coal	17	0.00	100
92	Road transport (all cars highway)	DERV	17	0.00	100
93	Agriculture power units	Gas oil	15	0.00	100
94	Road transport (HGV articulated)	DERV	13	0.00	100
95	Road transport (LGVs catalytic urban)	Petrol	13	0.00	100
96	Road transport: m/cycle (>50cc, 4st rural)	Petrol	12	0.00	100
97	Road transport (LGVs catalytic highway)	Petrol	12	0.00	100
98	Glass production	Glass production (all types)	10	0.00	100
99	Road transport (coaches urban)	DERV	9	0.00	100
100	Road transport (all cars rural)	DERV	8	0.00	100
101	Road transport: mopeds (<50cc, 2st urban)	Petrol	8	0.00	100
102	Road transport: m/cycle (>50cc, 2st urban)	Petrol	6	0.00	100
103	Regeneration of activated carbon	Non fuel processes	6	0.00	100
104	Road transport (LGVs catalytic rural)	Petrol	6	0.00	100
105	Road transport: m/cycle (>50cc, 2st highway)	Petrol	6	0.00	100
106	Iron and steel (combustion)	Coal	5	0.00	100
107	Road transport (coaches highway)	DERV	3	0.00	100
108	Aircraft support	Gas oil	1	0.00	100
109	Domestic house & garden	DERV	<1	0.00	100
110	Chemical industry (pesticide production)	Non fuel processes	<1	0.00	100
111	Agriculture power units	Petrol	<1	0.00	100
-	**UK Total**	**-**	**360080**	**-**	**-**

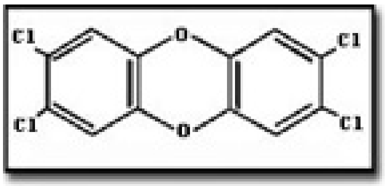
Figures quoted for each source are totals for all dioxin and furan congeners and are calculated using International Toxic Equivalency (I-TEQ) factors.

Appendix C - Mechanisms of Dioxin Formation and Generic Abatement Measures

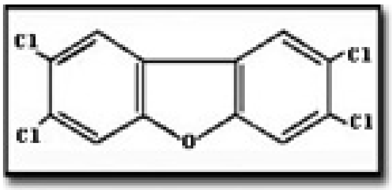
C.1 Mechanisms of Dioxin Formation (USEPA 2000, EC 1997)

This section provides a summary of dioxin formation mechanisms. For a more detailed consideration, the recent USEPA (2000) study on dioxin sources should be referred to.

More than a decade of combustion research has led to a general understanding of the mechanisms for formation of dioxins, furans and other dioxin-like compounds. Current understanding of the conditions necessary to form dioxins is primarily derived from studying municipal solid waste incinerators together with observations involving the experimental combustion of synthetic fuels in the laboratory. However, the formation mechanisms identified during these studies are generally relevant to most combustion systems in which organic material is burned in the presence of chlorine containing materials. The chemical structures of the most toxic dioxin and furan congeners are illustrated below:



2,3,7,8 tetrachlorodibenzo-*p*-dioxin



2,3,7,8 tetrachlorodibenzofuran

There are three principal mechanisms for dioxin and furan formation, which should not be regarded as being mutually exclusive, as follows:

1. Contaminated Feed

This mechanism requires dioxins to be present as contaminants in the combusted organic material (fuel), and to pass through the furnace unaltered. This mechanism is not thought to be a major contributor to emissions since combustion conditions in commercial systems normally lead to destruction of such compounds in the feed and mass balance studies indicate that synthesis is a more important mechanism than pass through.

2. Precusor Mechanism

With this mechanism dioxins are ultimately formed by the thermal breakdown and molecular rearrangement of precursor chlorinated aromatic hydrocarbons with a structural resemblance to the dioxin and furan molecules. Precursors emanated from the combustion zone are a result of the incomplete oxidation of the constituents in the feed.

3. *De novo* Synthesis

De novo synthesis (i.e. synthesis from basic molecules rather than from more complex molecules) is similar to the precursor mechanism. The formation pathway is one of heterogeneous reactions on fly ash involving carbon, oxygen, hydrogen, chorine, and a transition metal catalyst. With these reactions, intermediate compounds having an aromatic ring structure are formed. Studies in this area suggest that aliphatic compounds, which arise as products of incomplete combustion, may play a critical role in initially forming simple ring molecules, which later evolve into complex aromatic precursors. Dioxins are then formed from the intermediate compounds.

In both mechanisms (2) and (3), formation occurs outside the furnace, in the so-called secondary or post-combustion zone as the waste combustion gases begin to cool. The dioxins form when the precursors sorb onto binding sites on the surface of fly ash particles. This reaction has been observed to be catalysed by the presence of a transition metal sorbed to the particulate. The most potent catalyst is copper chloride. Since these reactions involve heterogeneous chemistry, the rate of emissions is less dependent on reactant concentration than conditions that promote formation such as temperature, retention time and availability of catalytic surfaces. Particulate bound carbon is suggested as the primary reagent in the *de novo* syntheses pathway.

Although chlorine is an essential component for the formation of dioxins in combustion systems, empirical evidence indicates that chlorine levels in the feed are not the dominant controlling factor for rates of formation.

It is evident that no clear distinction exists between the precursor and *de novo* synthesis mechanisms for forming dioxins and furans. Both mechanisms depend on the evolution of precursors within combustion gases, the interaction of reactive fly ashes, a generally oxidative environment, the presence of a transition metal catalyst, the presence of gaseous chlorine, and a favourable range of temperature. The temperature of the waste combustion gases is perhaps the single most important factor in forming dioxin-like compounds. Temperatures in the range 200 to 450°C are most conducive for dioxin formation with maximum formation occurring at around 350°C. If temperature falls outside this range, the amount of dioxins formed is minimised.

C.2 Generic Abatement Measures (USEPA 2000, EIPCCB 2002)

C.2.1 Types of Abatement Measure and Applicability

This section provides a summary of generic dioxin abatement measures. Further details can be found in the relevant IPPC BREF documents and Appendix D. Abatement measures can be grouped into two main categories:

i) **Primary or process-integrated** measures avoid formation of dioxins by inhibiting the three mechanisms listed above; and,

ii) **Secondary or end-of-pipe** measures remove dioxins from the waste combustion (flue) gases before discharge to atmosphere.

Primary measures are most economically incorporated during the design stage of a process since they require optimisation of the fundamental process parameters and size and type of equipment. Alternatively they can be retrofitted to an existing process but practical issues such as size of the existing combustion chamber, space limitations, and excessive costs for modifications can be an issue.

Even when primary measures have been installed, dioxin levels can remain at elevated levels. Therefore, for both new and existing plant, secondary measures may be required to meet tight emission limit values for dioxins (e.g. <1 ng/m^3). Secondary measures involve fitting abatement equipment such as fabric filters in the flue gas ductwork such that the dioxins (which sorb onto fly ash particles) are separated from the flue gases before discharge to atmosphere. The dioxin contaminated fly ash that is collected must then be disposed of in a proper manner so that it is not re-released to the environment. Again there may be practical problems in installing abatement equipment due to space limitations, pressure drop considerations and excessive costs for modifications to plant, especially if the existing plant is nearing the end of its economic lifetime.

C.2.2 Primary Abatement Measures

The precursor and *de novo* synthesis mechanisms for dioxin formation both rely on the presence of products of incomplete combustion of the feed material (i.e. unburnt or partially burnt fuel) which result from poor control of combustion conditions. Therefore a key measure in abating any potential dioxins source is to establish conditions for efficient and complete combustion. The requirements for complete combustion are:

- Adequate oxygen content;
- High temperature to promote combustion;
- Sufficient residence time to complete combustion reactions; and,
- Turbulence to promote good mixing of fuel with combustion air.

The above conditions are met when the combustion gases are held at >850°C for at least 2 seconds in the secondary combustion zone. In addition the concentration of oxygen at the outlet of the combustion zone should be >6% by volume (wet basis). Turbulence should be enhanced by strategic introduction of secondary air into the combustion zones. Turbulence and residence time are linked (i.e. good mixing maximises residence time) and the optimisation of combustion air distribution, fuel feed systems and combustion chamber dimensions is essential. Techniques for this optimisation such as CFD simulation are well established and are most usefully applied at the design stage.

However, even with good combustion the *de novo* synthesis route can lead to formation of dioxins, particularly as the flue gases cool downstream of the combustion zone (e.g. in the flue gas ductwork). Attention must also be paid to the post-combustion conditions to ensure that they are not favourable for dioxin formation. These measures typically involve rapid cooling of the flue gases to around 200°C (i.e. below the *de novo* synthesis temperature window) using either a water quench or waste heat boiler (i.e. heat recovery). Flue gas ducting and heat exchange surfaces should be kept clean to prevent build up of fly ash particulates which can act as catalyst sites. Also any material containing copper, iron or magnesium should be excluded from the ductwork (and feed material) as far as possible since these metals can act as catalysts.

Primary measures can also include steps to prevent raw material contamination (e.g. with chlorides or dioxin precursors) although chlorine levels in feed are not normally the limiting factor in dioxin formation. Other primary measures include fuel switching (e.g. switch from coal to gas for domestic heating) and energy efficiency (e.g. home insulation which reduces the need for coal combustion at public power plants) which help to reduce the production of dioxins.

C.2.3 Secondary Abatement Measures

Since dioxins tend to sorb onto particulates that are present in the flue gases, most secondary measures are focused on capture of particulate matter. Secondary abatement measures are rarely installed with the sole purpose of abating dioxin emissions (e.g. heavy metals and acid gas emissions are also reduced). However, injection of certain adsorbents prior to particulate removal can enhance dioxin removal efficiency. The dioxin removal efficiency is also function of the size range of particles removed. Sub-micron particulates and aerosols in the flue gases provide sites for dioxin formation and these may not be removed by coarse particulate abatement measures. The dioxin congener profile also affects removal efficiency since the higher chlorinated congeners tend to sorb onto particulates, whereas the tetra and penta congeners tend to partition to the vapour phase.

The main types of secondary measures employed for dioxin abatement are the:

- **Electrostatic Precipitator (ESP)** - The ESP is generally used to collect and control particulate matter generated in the combustion process by introducing a strong electrical field in the flue gas stream. This charges the particles entrained in the combustion gases and large collection plates receive an opposite charge to attract and collect the particles. Dioxin formation can occur within the ESP at temperatures in the range of 150 to 350°C. Although ESPs in this temperature range efficiently remove most particulates and the associated dioxins, the formation that occurs can result in a net increase in dioxin emissions. Therefore, when considering dioxin abatement efficiency, ESPs are classified as either cold-side (operating below 230°C) or hot-side (operates at an inlet temperature >230°C).

- **Fabric Filter** - This is a particulate matter control device, which removes dioxins associated with particles and any vapours that adsorb onto the particles. Filter bags, made from woven fibreglass material or other fabric, are usually arranged in series and can be used downstream of an ESP. An induction fan forces the combustion gases through the tightly woven fabric. The porosity of the fabric allows the bags to act as filter media and retain a broad range of particles sizes (down to less than 1 micron in diameter). A filter cake builds up until the pressure drop reaches a set point. At this time, the filter comes off-line and is cleaned by either air reversal, shakers or pulse jets. The fabric filter is sensitive to acid gas; therefore, it is usually operated in combination with spray dryer adsorption of acid gases. Problems may also occur due to high flue gas temperatures which can damage the filter and lead to fires in the presence of carbonaceous material in the fly ash. Filters also lead to additional pressure drop in the system and are often prone to blinding with fine particulates and other residues.

- **Dry Scrubber** - Also called spray dryer adsorption, this involves both the removal of acid gas and particulate matter from the post-combustion gases. By themselves, these units probably have little effect on dioxin emissions. However, dry scrubbers are often used in combination with a downstream ESPs (the scrubber reduced the ESP inlet temperatures) and together can be effective at dioxin removal. In a typical dry scrubber system, hot combustion gases enter a scrubbing column and an atomised hydrated lime slurry is injected into the column and rapidly mixes with the combustion gases. The water in the hydrated lime slurry evaporates, and the heat of evaporation causes the combustion gas temperature to rapidly decrease. The neutralising capacity of hydrated lime reduces the combustion gas content of acid gas constituents (e.g. HCl and SO_2). A dry product, consisting of particulate matter and hydrated lime, settles to the bottom of the scrubber.

- **Dry Sorbent Injection (DSI)** - This has traditionally been used to reduce acid gas emissions (see dry scrubber description above). However, recent research has highlighted the role of DSI in enhancing dioxin removal when combined with fabric filtration or ESPs. DSI to remove dioxins involves the injection of activated lignite coke or activated carbon adsorbents either directly into the combustion chamber or into the flue duct of the hot post-combustion gases. In either case, the reagents adsorb the dioxins and precursors and are then themselves removed by downstream particulate abatement equipment. When used in conjunction with fabric filters, powdered lime is also injected to pre-coat the filter with a protective layer and lower the auto-ignition point as the injection of carbon can lead to an increased fire risk.

- **Wet Scrubber** - These devices are designed for acid gas removal but also help to reduce emissions of dioxin in both vapour and particle forms. There are normally two stages. The first stage removes HCl with water scrubbing, and the second stage removes SO_2 using caustic or hydrated lime. Good dioxin removal has been achieved using a two-stage, high pressure drop, venturi scrubber design but consequently energy use is high. The treated flue gases may also need reheating to prevent a visible plume.

The removal efficiency of dioxins using the above abatement measures is process specific. It depends on the inlet dioxins concentration, flue gas temperature and flowrate, flue gas particulate size distribution, and combination of abatement measures used. Details of removal efficiency and capital and operating costs for abatement of specific sources are given in Appendix D.

Appendix D - Detailed Investigation of Dioxin Source Categories and Abatement Measures

Contents List