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Estimation of Uncertainties in the National Atmospheric Emissions Inventory

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

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Executive Summary

The National Atmospheric Emissions Inventory (NAEI) contains estimates of emissions to air of 39 pollutants (including seven pollutant groups) covering greenhouse gases, air quality strategy pollutants, acidifying gases, tropospheric ozone precursors, and hazardous air pollutants.

As part of the programme of work to maintain the NAEI, a detailed assessment has been made of the uncertainty in the national emission totals for each pollutant covered by the NAEI. A complete assessment of uncertainty has been made for estimates from the 1999 NAEI and, where the NAEI methodology has subsequently changed, the analysis has been repeated for the 2000 NAEI. These uncertainty estimates have been made using a direct simulation approach which corresponds to the IPCC Tier 2 approach discussed in the Good Practice Guidance (IPCC, 2000), as well as the Tier 2 method proposed in the draft 'Good Practice Guidance for CLRTAP Emission Inventories', produced for inclusion in the EMEP/CORINAIR Guidebook on Emission Inventories. The analysis also identifies those 'key sources', which contribute most to inventory uncertainty. The uncertainty estimates presented in this report replace the 'expert judgements' of uncertainty which were included with earlier versions of the NAEI. The work also identified sources which are, potentially, omitted from the NAEI. None of these 'missing' sources is, however, considered significant.

Results of the analysis for selected pollutants are shown below. The table shows the most recent uncertainty in the national emission total for each pollutant expressed as a percentage relative to the mean or best estimate. The range given is limited to the 95% confidence limits as recommended in the IPCC Good Practice Guidance.

Pollutant	Uncertainty
Sulphur dioxide	+/- 3%
Oxides of nitrogen	+/- 7%
Volatile organic compounds	+/- 10%
Ammonia	+/- 20%
1,3-butadiene	+/- 20%
Benzene	+/- 30%
Carbon monoxide	+/- 20%
PM_{10}	-20% to +50%
Cadmium	-20% to +30%
Mercury	-30% to +40%
Lead	+/- 10%
Benzo[a]pyrene	-60% to +200%
Dioxins	-40% to +90%

It must be noted that the uncertainty estimates quoted above and throughout this report relate to the uncertainty in the national annual emission totals only, and should not be applied to emissions of a given pollutant from individual source sectors or to sub-national emission estimates made using national emission inventory data. In general, the uncertainty in these cases would be expected to be higher than the national emission totals although no analysis has been carried out to confirm this.

In general, sources of gaseous pollutant emissions are better characterised and hence inventories for gaseous pollutants are less uncertain than inventories for particulate matter and metals, which, in turn, are less uncertain than the inventories for persistent organic pollutants and base cations. This ordering of uncertainty was expected and was, by and large, already embodied in the expert judgements previously used to express uncertainty (most recently in Goodwin *et al*, 2001).

Where results are available for pollutant emission totals for both the 1999 and 2000 versions of the NAEI, these are generally the same or similar. This reflects the fact that only relatively minor changes were made to the NAEI methodology for the 2000 version, compared with more far reaching changes in the previous two versions. A like-for-like comparison of current 'numerical' estimates and numerical estimates from 1995 would, we believe, show more dramatic improvements due to the investment of DEFRA in emission factor and inventory development work.

Further refinement of the uncertainty analysis is desirable, especially the need to improve the understanding of the characterisation of emission sources and uncertainty in emissions data provided directly by industry or regulators. Nonetheless the current approach allows the uncertainty in the NAEI to be monitored from year to year and also provides useful data for an assessment of priorities for further inventory development. A method for identifying and prioritising research options for inventory development has been developed and is presented here.

A number of recommendations can be made:

- analysis of uncertainty in inventories should be repeated on an annual basis for future versions of the NAEI using a comparable methodology to that used in the current study in order to monitor year by year improvement;
- repetition of the uncertainty analysis should be carried out periodically for each pollutant covered by the NAEI regardless of whether the inventory methodology for that pollutant has been updated in the intervening period since the previous analysis to guard against deterioration of data due to obsolete assumptions e.g. sources of NMVOC, NOx, SO_2, particulate matter, and heavy metals etc. where changing process technologies and/or the implementation of control strategies are expected to reduce emissions with time;
- efforts should be made to better characterise uncertainty and possible systematic/methodological bias in emissions data provided directly by industry or regulators in order to improve assist inventory compilers to generate reasonable uncertainty estimates;
- research covering all aspects affecting inventory uncertainty should be considered, including improvements to emission factors, activity data, or information on industry structure or process technology, in order to make the most cost-effective improvements to the inventory;
- detailed research priorities should be identified using a methodology that takes account of the likely cost of the research, the likelihood of the research leading to improvements in inventory data, and the desirability of such improvements;
- To ensure completeness of the inventory, emission estimates should be made for missing sources identified as part of this work and included in the next revision of the NAEI.

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1 Background

The National Atmospheric Emissions Inventory (NAEI) contains estimates of emissions to air of 39 pollutants (including seven pollutant groups) covering greenhouse gases, air quality strategy pollutants, acidifying gases, tropospheric ozone precursors, and hazardous air pollutants. The NAEI is updated each year, with results reported in an annual report (most recently in Goodwin *et al*, 2002).

Each annual report includes expert judgements of uncertainty in the national emission total for each pollutant. These are intended as 'ball-park' estimates of the overall uncertainty in each inventory and are made by the NAEI team member responsible for compilation of that inventory.

With limited exceptions, these 'ball-park' estimates have not appeared to change in recent years, giving the impression that the NAEI has not improved in that period despite the considerable research into emission factors carried out. In reality, the inventory is more complete, detailed and accurate now than in the past; it is more useful and national emission totals are more likely to be 'right' i.e. accurate. The problem lies in the mode of presentation of uncertainty; the current expression of uncertainty is simplistic and lacks rigour in its use of quasi-statistical terminology and so it is not capable of reflecting improvement.

A more complete expression of uncertainty is needed. Therefore, as part of the programme of work to maintain the NAEI, a more detailed assessment has been made of the uncertainty in the NAEI using software better able to manipulate and display statistical information. This detailed approach provides a more quantitative measure of uncertainty which will allow the uncertainty in individual emission estimates to be assessed and, if the analysis is repeated each year, is more suitable for the description and monitoring of certain types of improvement.

The uncertainty assessment has covered all pollutants in the NAEI, except for greenhouse gases, which have been the subject of separate studies, reported in the annual greenhouse gas inventory report (most recently in Salway *et al*, 2001).

This paper describes the detailed approach used to quantify uncertainties (Section 2), gives details of the input data used in the analysis (Section 3) and gives results (Section 4 and Appendices A & B). Discussion of the results, conclusions, and recommendations follow in Sections 5, 6 and 7 respectively. A methodology for prioritising future research to improve the NAEI is given in Appendix C.

2 Method for quantification of uncertainty

2.1 GENERAL APPROACH

To address the problem described above, more quantitative estimates of the uncertainties in the NAEI have been calculated using a direct simulation approach. This procedure corresponds to the IPCC Tier 2 approach discussed in the Good Practice Guidance (IPCC, 2000), as well as the Tier 2 method proposed in the draft 'Good Practice Guidance for CLRTAP Emission Inventories', produced for inclusion in the EMEP/CORINAIR Guidebook on Emission Inventories. The approach, as applied to the UK greenhouse gas inventory, has also been described in detail by Charles *et al* (1998). A brief summary of the method is given below.

- An uncertainty distribution is allocated to each emission factor and each activity rate. The distributions used were drawn from a limited set of either uniform, normal, triangular, beta, or log-normal. The parameters of the distributions for each emission factor or activity rate were set either by analysing the available data on emission factors and activity data or by expert judgement.
- A calculation was set up to estimate the emission of each pollutant by sampling individual data values from each of the emission factor and activity rate distributions on the basis of probability density and evaluating the resulting emission. Using the software tool @RISK™, this process could be repeated many times in order to build up an output distribution of emission estimates both for individual sources but also for total UK emissions of each pollutant.
- The mean value for each emission estimate and the national total was recorded, as well as the standard deviation and the 95% confidence limits i.e. the emission values at the 2.5% cumulative probability and the 97.5% cumulative probability.
- The process was carried out first using data for 1999, taken from the 1999 version of the NAEI (published in Goodwin *et al*, 2001). The analysis was then extended to data for the year 2000, taken from the 2000 version of the NAEI (published in Goodwin *et al*, 2002) for those pollutants where changes had been made to the methodology used to estimate emissions. For this repeat of the analysis it was necessary to re-evaluate the probability distributions used for emission factors and activity rates and make modifications to the assumptions where appropriate.
- A key source analysis was undertaken, following the IPCC Tier 2 method (IPCC, 2000). The key source analysis identifies the major contributors to inventory uncertainty[1].

2.2 DISTRIBUTION TYPES AND DEFAULT DISTRIBUTIONS

Five distribution types have been used in this work: uniform, normal, triangular, beta and log normal. These five types were felt to cover the range of probability distributions needed to describe the uncertainty in the NAEI data.

[1] For a fuller description of the key source analysis see Appendix A.

a) Uniform distributions are defined using the form **Uniform (minimum, maximum)** and describe a distribution with an equal probability of any value between the minimum and maximum. This type of distribution is used relatively infrequently, being considered most applicable for those parameters which are considered very uncertain within a fairly limited range relative to the mean value.
b) Normal distributions are defined using the form **Normal (mean, standard deviation)** and describe a normal distribution having those parameters. This type of distribution has been used as the standard type for parameters considered to have a symmetrical uncertainty distribution and a fairly limited range relative to the mean value.
c) Triangular distributions are defined using the form **Triangular (minimum, most likely, maximum)** and describe a triangular distribution with probability highest at the most likely value and equal to zero at the minimum and maximum. This type of distribution has been used for parameters considered to have an asymmetrical uncertainty distribution and a fairly limited range relative to the mean value.
d) Beta distributions are defined using the form **Beta (minimum, most likely, mean, maximum)** and describe beta distributions with the defined parameters. This type of distribution is used for asymmetrical distributions with wider ranges relative to the mean value compared with the triangular distribution.
e) Lognormal distributions are defined using the form **Lognormal (mean, standard deviation)** and describe lognormal distributions with the defined parameters. This type of distribution is used for asymmetrical distributions with very wide ranges relative to the mean value compared with the triangular and beta distributions.

The distributions used in the work are always specified so that the mean value is equal to 1 since the calculations are performed by multiplying the output from each distribution by the fixed emission factor or activity rate normally used in the NAEI.

For parameters with very high levels of uncertainty, a small number of default distributions have been used to model uncertainty. In most cases one of the following beta or lognormal distributions is used.

- Beta (0.5,0.75,1,2)
- Beta (0.3,0.5,1,3)
- Beta (0.2,0.5,1,5)
- Lognormal (1,1.725)

These four distributions are used in most cases where uncertainty in parameters is estimated by the inventory compiler to be a factor of two or worse. The lognormal distribution was chosen because the central 95% of values obtained using it showed a range of two orders of magnitude (0.05-5).

2.3 UNCERTAINTY DUE TO MISSING SOURCES

The direct simulation method described in section 2.1 is useful for investigating the likely impact of uncertainties in emission estimates. It is not, however, helpful for identifying the likelihood of important sources being omitted from the inventory. While in the long run, continued emission inventory research complemented by inventory verification are needed to

ensure that the NAEI is complete, this paper considers what sources are currently being omitted and whether these sources are likely to be significant.

3 Assumptions used in the analysis

3.1 GENERAL

Emission estimates are generally calculated by applying an emission factor to an appropriate activity statistic.

That is:

$$\text{Emission} = \text{Factor} \times \text{Activity}$$

In such cases, uncertainty in the emission estimate derives from uncertainty in both the emission factor and the activity rate used in the calculation. In some cases, however, emission estimates are supplied directly by outside bodies (e.g. process operators, regulators, trade associations) and the emission factors and activity data or other parameters used to generate these emission estimates are not known to us. In these cases, the emission estimate still has to be converted to an emission factor and activity rate so that it can be incorporated within the NAEI database format. For example, emissions from copper refining are available in the Environment Agency's Pollution Inventory and are converted to emission factors by dividing the emission estimates by refined copper production given in the British Geological Survey publication 'UK Mineral Statistics'. In cases such as these, the emission estimate is not affected by uncertainty in the activity rate and any uncertainty in this parameter is ignored. Instead, an uncertainty distribution is selected for the emission factor which reflects the uncertainty in the original emission estimate.

3.2 FUELS

Fuel use data are obtained from the Digest of UK Energy Statistics, published annually (most recent publication was DTI, 2001)

Uncertainty in fuel statistics has been represented using normal distributions. The distribution parameters are taken from Salway *et al*, 2001 and were estimated based from the statistical differences data in DTI (1996). Appendix A gives further details of the distributions used for each fuel type. It should be noted that the uncertainty estimates given are for the uncertainty in total consumption of each fuel type. Although in reality the uncertainty in estimates of fuel used in the detailed sectors included in the NAEI (such as domestic, public services etc.) could be more or less uncertain, this is assumed not to be the case. Instead, the activity data for each data are assumed to be fully correlated with the overall uncertainty.

3.3 NON FUEL ACTIVITY DATA

Non fuel activity data may be split into the following categories:

- Government or other 'official' statistics, such as those obtained from standard references such as the Annual Abstract of Statistics or the UK Minerals Yearbook;
- Activity data collected routinely by trade associations or other industry representatives;
- Estimates provided on an ad-hoc basis by trade associations or other industry representatives;
- Estimates made by members of the inventory team

In addition, activity data may be divided into data which accurately describe the activity which causes the emission e.g. paint consumption for solvent emissions from paint use, and 'surrogate' activity data which are assumed to be related to the activity giving rise to the emission e.g. population is assumed to be directly proportional to the use of consumer products such as polishes and detergents.

In general, official statistics have been assumed to be subject to very limited uncertainty (typically normally distributed with a standard deviation equal to 0.005% of the mean). Uncertainty associated with other non-fuel activity data has been estimated on a case by case basis by NAEI experts. It is recommended that, in future, organisations providing data be asked for their assessments of the uncertainty in the data they provide. Estimates of activity levels made by members of the inventory team are generally consider to be more uncertain than estimates provided by industry, although as with industry data, assessment of uncertainty is on a case by case basis.

3.4 EMISSION FACTORS

Uncertainty estimates for emission factors are largely based on expert judgement although in some cases, such as road transport and stationary combustion sources, distributions have been chosen which reflect the range of reported emission factors. The expert judgements have been provided by AEA Technology staff involved in the generation of the NAEI as shown below:

Expert	**Pollutants/sources considered**
Peter Coleman	Persistent organic pollutants
Chris Dore	Ammonia (non-agricultural)
Tim Murrells	Road transport
Neil Passant	NMVOC, PM_{10}, metals, benzene, 1,3-butadiene
Geoff Salway	NOx, SO_2, CO, HCl

Some literature sources have been useful, providing either expert judgements made by other inventory workers, or background data which have been considered when deciding what uncertainty distributions to use. The major sources are listed in Table 1.

Table 1 Literature sources consulted as part of the analysis

Source	Comments
US EPA, 2001	The US EPA compilation of emission factors, which includes data quality ratings for emission factors and, in some cases, ranges for emission factors
EMEP/CORINAIR, 2000	The EMEP/CORINAIR Emission Inventory Guidebook which includes data quality ratings for emission factors and, in some cases, ranges for emission factors
Simpson *et al*, 1999	Includes discussion of uncertainty in emission estimates for natural sources of NMVOC.
Sutton *et al*, 2000	Gives ranges for estimates of emissions of ammonia from non-agricultural sources
Smith, 1987	Gives ranges of metal contents of coals
Passant, 2002	Includes discussion of species profiles used to generate NAEI emission estimates for benzene and 1,3-butadiene
CPL Laboratories, 2002	Results of measurement of emission factors for domestic combustion of coal and wood, including estimates of uncertainty
Misselbrook, 1999	Estimation of uncertainty in estimates of ammonia emitted from agricultural sources
Passant *et al*, 2002	Review of emission factors for particulate matter and heavy metal emissions from industrial processes
Thistlethwaite, 2002(a)	Results of measurement of emission factors for industrial wood combustion including discussion of uncertainty
Thistlethwaite, 2002(b)	Results of measurement of emission factors for a small, coal-fired, boiler including discussion of uncertainty
Wood, 1996	Analyses of metal contents of liquid fuels involving between 2 and 4 results for each fuel/metal combination
DNV Technica, 1992	Gives ranges for metal contents of orimulsion, heavy fuel oil and UK coal
Lloyd's Register, 1995	Includes data on metal contents of three samples each of gas oil and fuel oil
Barlow *et al*, 2001	Gives ranges of measured emission factors for road transport

Industrial trade associations and industrial process operators provided a final source of expert opinion, a small number of contacts being made in order to obtain information on the uncertainty in emission estimates provided directly by industry.

4 Results

4.1 UNCERTAINTY IN NAEI ESTIMATES

Results of the analysis are summarised in Tables 2 to 6. These tables give the mean emission estimate for each pollutant, as well as the 95% confidence limits. The standard deviation (SD in the tables) and the 95% limit as a percentage of the mean are also shown. A number of pollutants have been excluded from the uncertainty analysis - this was because the inventories for these pollutants are currently very crude. A sophisticated uncertainty analysis was therefore inappropriate. These pollutants are short-chain chlorinated paraffins and polybrominated diphenyl ethers. The level of uncertainty in these inventories will be very high and certainly no better than that obtained for other heavy metals and persistent organic pollutants. As a rough guide, the uncertainty could be expressed as one order of magnitude either way (i.e. -90% to +1000% of the mean).

Key sources, identified using the IPCC Tier 2 method, are listed in Appendix A.

Table 2 Results of uncertainty analysis for gaseous pollutants (emissions in ktonnes)

Pollutant	Year	Mean	95% limits	S.D.	95% limits as % of mean
Hydrogen chloride	1999	98.1	80.4 - 116	9.0	+/- 18%
Ammonia	1999	348	284 - 417	34	+ 20% / - 18%
Ammonia	2000	320	262 - 383	31	+ 19% / - 18%
Oxides of nitrogen	1999	1605	1497 - 1718	57	+/- 7%
Oxides of nitrogen	2000	1525	1421 - 1634	54	+/- 7%
Sulphur dioxide	1999	1187	1149 - 1225	19	+/- 3%
Sulphur dioxide	2000	1156	1117 - 1197	21	+ 4% / - 3%
Volatile organic compounds	1999	1744	1583 - 1935	93	+ 11% / - 9%
Volatile organic compounds	2000	1678	1520 - 1866	91	+ 11% / - 9%
1,3-butadiene	1999	6.17	5.04 - 7.44	0.61	+ 21% / - 18%
Benzene	1999	29.7	24.1 - 35.9	3.0	+ 21% / - 19%
Benzene	2000	16.5	12.7 - 21.0	2.2	+ 28% / - 23%
Carbon monoxide	1999	4760	3898 - 5747	472	+ 21% / - 18%
Carbon monoxide	2000	4179	3345 - 5140	456	+ 23% / - 20%

Table 3 Results of uncertainty analysis for particulate matter (emissions in ktonnes)

Pollutant	Year	Mean	95% limits	S.D.	95% limits as % of mean
Black smoke	1999	271	136 - 476	89	+ 76% / - 50%
$PM_{0.1}$	1999	31.9	27.8 - 36.5	2.2	+ 14% / - 13%
PM_1	1999	77.0	66.2 - 91.2	6.7	+ 18% / - 14%
$PM_{2.5}$	1999	107	90.3 - 136	13	+ 27% / - 16%
PM_{10}	1999	186	150 - 276	39	+ 48% / - 19%
PM_{10}	2000	172	138 - 259	38	+ 51% / - 20%

Table 4 Results of uncertainty analysis for heavy metals (emissions in tonnes)

Pollutant	Year	Mean	95% limits	S.D.	95% limits as % of mean
Arsenic	1999	46.8	29.2 - 76.4	13	+ 63% / - 38%
Arsenic	2000	34.6	21.0 - 58.8	9.7	+ 70% / - 39%
Beryllium	2000	16.2	4.87 - 48.5	13	+ 199% / - 70%
Cadmium	1999	6.47	4.68 - 9.45	1.4	+ 46% / - 28%
Cadmium	2000	5.22	4.03 - 6.93	0.74	+ 33% / - 23%
Chromium	1999	66.7	51.7 - 90.3	10	+ 35% / - 23%
Chromium	2000	62.8	53.4 - 73.4	5.1	+ 17% / - 15%
Copper	1999	59.1	44.3 - 82.1	11	+ 39% / - 25%
Copper	2000	45.7	35.3 - 65.0	8.8	+ 42% / - 23%
Lead	1999	553	474 - 740	82	+ 34% / - 14%
Lead	2000	496	452 - 552	26	+ 11% / - 9%
Manganese	2000	303	65.9 - 1120	340	+ 270% / - 78%
Mercury	1999	8.53	6.21 - 11.6	1.4	+ 36% / - 27%
Mercury	2000	8.54	6.26 - 11.6	1.4	+ 36% / - 27%
Nickel	1999	147	98.4 - 213	29	+ 44% / - 33%
Nickel	2000	115	80.8 - 161	21	+ 40% / - 30%
Selenium	1999	44.3	20.1 - 127	36	+ 186% / - 55%
Selenium	2000	49.9	29.8 - 85.3	15	+ 71% / - 40%
Tin	2000	74.4	10.5 - 301	96	+ 305% / - 86%
Vanadium	1999	225	110 - 428	85	+ 90% / - 51%
Vanadium	2000	157	81.8 - 289	55	+ 84% / - 48%
Zinc	1999	442	282 - 699	120	+ 58% / - 36%
Zinc	2000	336	234 - 525	88	+ 56% / - 31%

Table 5 Results of uncertainty analysis for persistent organic pollutants (emissions in tonnes except dioxins where units are grammes TEQ)

Pollutant	Year	Mean	95% limits	S.D.	Range as % of mean
Benzo[a]pyrene	1999	15.9	6.39 - 40.2	10	+ 154% / - 60%
Hexachlorobenzene	1999	786	299 - 1870	400	+ 138% / - 62%
Lindane	1999	33.2	7.7 - 126	40	+ 278% / - 77%
Polychlorinated biphenyls	1999	2.07	1.23 - 2.99	0.49	+ 45% / - 40%
Dioxins	1999	346	213 - 646	125	+ 87% / - 38%
Pentachlorophenol	1999	482	121 - 1230	293	+ 155% / - 75%

Table 6 Results of uncertainty analysis for base cations (emissions in ktonnes)

Pollutant	Year	Mean	95% limits	S.D.	Range as % of mean
Calcium	2000	7.52	3.71 - 18.4	4.6	+ 145% / - 51%
Magnesium	2000	0.958	0.622 - 1.71	0.33	+ 78% / - 35%
Potassium	2000	2.16	0.821 - 6.69	1.9	+ 209% / - 62%
Sodium	2000	1.18	0.698 - 2.41	0.52	+ 105% / - 41%

4.2 MISSING SOURCES

An attempt has been made to identify sources which are, potentially, omitted from the NAEI. This has been done mainly by checking whether, for each source category used in the NAEI, all pollutants of interest are included. For example, clinical waste incinerators are included in the NAEI for many pollutants but not for NMVOC, selenium, vanadium, benzene and 1,3-butadiene and the possibility exists that releases of these pollutants do actually occur. A small number of additional sources which are not considered in the NAEI for any pollutants have also been identified. A full list of source/pollutant combinations which are not included in the NAEI and which should be considered for inclusion is given in Appendix B. It must be stressed that none of these 'missing' sources is considered significant (i.e. none are expected to increase the inventory for any pollutant by more than a few percent). However, since in many cases it would be relatively easy to include emission estimates in the next revision of the NAEI, it is recommended that this is done.

5 Discussion

The uncertainty in inventories, when expressed relative to the mean value, differ widely, from +/- 3% for sulphur dioxide in the 1999 version of the NAEI to +278% & -77% of the mean for lindane. It must be noted that the uncertainty estimates quoted in this report relate to the uncertainty in the national annual emission totals only, and should not be applied to emissions of a given pollutant from individual source sectors or to sub-national emission estimates made using national emission inventory data. In general, the uncertainty in these cases would be expected to be higher than the national emission totals although no analysis has been carried out to confirm this.

In general, sources of gaseous pollutant emissions are better characterised and hence the inventories for gaseous pollutants are less uncertain than the inventories for particulate matter and metals, which, in turn, are less uncertain than the inventories for persistent organic pollutants and base cations. This ordering of uncertainty was expected and was, by and large, already embodied in the expert judgements previously used to express uncertainty (most recently in Goodwin *et al*, 2001). The differences in the uncertainty for the various inventories can be explained by the level of resource used to compile the inventory and the volume and quality of activity data and emission factors which are then available. Table 7 assesses these factors for selected inventories.

Table 7. Assessment of the level and quality of resources and data used to generate NAEI pollutant inventories and their influence on inventory quality

Pollutant	Resourcing level	Data availability	Data quality	Inventory quality
SO_2	High	High	High	High
NO_x	High	High	High	High
NMVOC	High	High	High	High
HCl	Low	Medium	High	Medium
PM_{10}	High	Medium	Medium	Medium
Cd	Medium	Medium	Medium	Medium
Se	Low	Low	Low	Low
Dioxins	High	Low	Low	Low
B[a]P	High	Low	Low	Low
HCB	Low	Low	Low	Low
Ca	Low	Low	Low	Low

Table 7 does indicate that, in cases where the level of uncertainty in an inventory is assessed as 'low' or 'medium', this can be due to scarcity of data, poor data quality, low resource levels, or a combination of these factors. This suggests that it is more difficult to improve some inventories than others. For example, the inventories for hydrogen chloride and selenium do not receive as much resource as do the inventories for sulphur dioxide, and it is likely that significant improvements could be made to these inventories even with limited additional resources. In comparison, the inventories for dioxins and benzo[a]pyrene have received high levels of resource but, due to the paucity of good data, are still very uncertain and considerable additional resources would be needed in order to make any improvement at all. On the other hand, the

inventories for dioxins and benzo[a]pyrene might be considered 'more important' than those for hydrogen chloride or selenium and therefore improvement of these inventories might be considered more desirable.

The picture given above for inventories is also true within each inventory i.e. there will be emission estimates which are uncertain, despite research, due to inadequate data and estimates which are uncertain due to a lack of research. It is likely that the latter can be improved more cost-effectively.

Research can involve either a) measurement of emission factors or other parameters by means of laboratory-based experiments or in-situ measurement of emission sources, or b) desk-based studies involving consultation with industry, Government and regulators. Of these two approaches it is generally true that, while measurements can provide detailed and accurate data, they are fairly resource-intensive. Historically, many measurements have been made for emissions of gaseous pollutants, while relatively few have been made for other pollutants. While this might suggest that measurements would be desirable, it should be noted that measurement techniques commonly used for pollutants such as PM_{10} and persistent organic pollutants can give variable results when checked against standards, and that emission rates for these pollutants will vary from one process to another in any case. A single measurement exercise will usually not significantly improve the certainty in emission factors, except perhaps for sources where no measurements have previously been made. The cost of carrying out repeated measurements at a large number of sites can be prohibitive unless borne by many different organisations. In future much greater attention should be given to working with regulatory authorities involved in compliance measurement in order to explore the possibility of data sharing. In addition, a more sophisticated approach to the use of measurement-based data, including perhaps the setting up of a database of measurement-based emission factors, would help the identification of areas where new measurements would be most beneficial.

Desk-based consultation exercises can vary from simple telephone contact with a single or small number of process operators or regulatory bodies through to more extensive programmes, similar in resource needs to measurement work. In some cases, simple, cheap options could bring major benefits to inventories. For example, flat glass production is a key source for cadmium, chromium, lead, selenium and zinc. Emission estimates are very uncertain because the emission factors used are old, relate to general glass manufacture, and may be inappropriate for flat glass production. There is one UK producer and it should be a relatively minor exercise to contact the operator and obtain better data. It should also be remembered that improvements to inventories can be effected by improving activity data as well as by improving emission factors.

A further issue to consider is that emissions of most pollutants are believed to be declining as a result of environmental protection legislation and it is vital that the NAEI reflects any reductions that occur. This is especially important for pollutants such as non-methane volatile organic compounds (NMVOC), where legislation requires reductions in emissions from many industrial processes, such as industrial coatings, cleaning solvent use, and petrol stations. These reductions will play an important role toward the UK meeting internationally-agreed emission ceilings. Detailed research has to be carried out in order to provide evidence for any reductions, allowing revisions to be made to the NAEI. Similar research will be required to measure reductions in emissions of other important air pollutants such as sulphur dioxide, oxides of nitrogen, ammonia, PM_{10} and dioxins.

Prioritisation of research is needed. It needs to take account of:

- the level of uncertainty in emission estimates;
- the relative costs of research options;
- the practicality of research options and the likelihood of the research providing improved data
- the sensitivity of the underlying policy requirements and the need to monitor emission levels or emission reductions.

Appendix C gives a method for prioritising research and gives a worked example of how this method can be used to plan a research programme. Discussion of the results of this prioritisation are given in Appendix C.

The key source analysis has identified the most important sources in terms of contribution to inventory uncertainty. Clearly, improvement of the emission estimates for these key sources should be a priority. However, it should be borne in mind that some key sources may very well be 'key' simply because it is difficult or impossible to estimate emissions accurately and that cost-effective improvement of the estimates may not be possible.

The repetition of the analysis for both the 1999 and 2000 versions of the NAEI allows the investigation of whether the NAEI is improving. In fact the results for 1999 and 2000 are generally the same or similar. This, in part, reflects the fact that only relatively minor changes were made to the NAEI methodology for the 2000 version, compared with more far reaching changes in the previous two versions. For those pollutants where revisions were most widespread, e.g. metals, the changes in uncertainty between 1999 and 2000 are most significant. A similar comparison of current 'numerical' estimates and numerical estimates from 1995 (were that possible) would, we believe, show more dramatic improvements due to the investment of DEFRA in emission factor and inventory development work. Analysis of uncertainty in future versions of the NAEI will allow trends in inventory quality to be monitored. Uncertainty analysis should be carried out periodically both to monitor the impact of changes in inventory methodology but also to assess the impact on quality where inventory methods have not been updated and are potentially becoming 'out of date'.

In principle, the results of the current uncertainty analysis could be compared with expert judgements made for the 1995 version of the NAEI. In practice, the two forms of uncertainty assessment are not equivalent as can be clearly seen by comparing the results of the numerical approach with expert judgements made for the 1999 NAEI report (*ibid*), as shown in Table 8. In general the expert judgements significantly overestimated the uncertainty in inventories, although in the case of black smoke emissions, the uncertainty has previously been underestimated compared with the figures given by the current analysis.

Table 8 Comparison of uncertainty according to expert judgement and by detailed analysis

Pollutant	Expert judgement	This analysis
Sulphur dioxide	+/- 10-15%	+/- 3%
Oxides of nitrogen	+/- 30%	+/- 7%
Volatile organic compounds	+/- 30%	+ 11% / - 9%
Ammonia	> +/- 30%	+ 20% / - 18%
Carbon monoxide	+/- 40%	+ 21% / - 18%

Black smoke	+/- 20-25%	+ 76% / - 50%
PM_{10}	'high'	+ 48% / - 19%
Persistent organic pollutants	'order of magnitude'	+ 45% / - 40% to + 278% / - 77%

Further development of the uncertainty analysis methodology is required, particularly in terms of collecting more information on the characteristics of emission sources and the uncertainty in emission factors and emission estimates. One important issue which was encountered during the work was that inventory compilers often had little information on the methods used to calculate emission estimates provided directly by industry or regulators, or the uncertainties that these data are subject to. As a result of current CEN and EA work, better information is now becoming available. In the absence of firm information, it was generally necessary to assume a fairly high level of uncertainty in these data. Important sources of data include the Environment Agency's Pollution Inventory, and trade associations such as UK Offshore Operators Association (UKOOA), UK Petroleum Industry Association (UKPIA), National Sulphuric Acid Association (NSAA), British Coatings Federation (BCF) and Solvent Industry Association (SIA).

6 Conclusions

The direct simulation approach to uncertainty analysis has successfully been used to quantify levels of uncertainty in the NAEI. This has shown that levels of uncertainty vary widely between pollutants, with inventories for gaseous pollutants being less uncertain than inventories for particulate matter and associated pollutants.

The repetition of the analysis for both the 1999 and 2000 versions of the NAEI did not show any major changes in inventory quality between the two. This is to be expected since the NAEI methodology did not undergo many significant changes for the 2000 version. More radical changes in the previous two versions of the NAEI are likely to have resulting in larger changes in uncertainty, although this cannot be quantified. This is because the 'expert best estimate' approach formerly used was qualitative while the current method is analytical.

Repeating the uncertainty analysis for future versions of the NAEI would allow the monitoring of trends in inventory uncertainty and would highlight key areas of uncertainty.

The uncertainty in inventories is a reflection both of the level of resource used to compile the inventory but also the quantity and quality of data which are obtained when compiling the inventory. As a result, further improvement of some inventories will be more challenging, especially in cases where considerable research has already been carried out.

Similarly, in each inventory, there will be differences in the ease with which emission estimates can be improved. A method is needed for prioritising research so as to identify the most cost-effective means of improving the NAEI. Such a method has been developed and is presented in Appendix C. This shows that some 'low cost/high gain' desk-based research options exist which can readily be incorporated into the ongoing programme of research. More resource-intensive options, including measurement-based research and complex desk-based research can be ordered in terms of likely cost-effectiveness and, as a general rule, measurement-based studies are less cost-effective unless a) no measurements have previously been made for that type of source; b) a single or small number of measurements will significantly improve emission factors (e.g. analyses of representative samples of fuel); c) a measurement is carried out as part of a collaborative effort to gather data and will complement work funded by other organisations.

Some further refinement of the uncertainty analysis is desirable, especially the need to improve understanding of uncertainty in emissions data provided directly by industry or regulators.

7 Recommendations

A number of recommendations can be made:

- analysis of uncertainty in inventories should be repeated on an annual basis for future versions of the NAEI using a comparable methodology to that used in the current study in order to monitor year by year improvement;
- repetition of the uncertainty analysis should be carried out periodically for each pollutant covered by the NAEI regardless of whether the inventory methodology for that pollutant has been updated in the intervening period since the previous analysis to guard against deterioration of data due to obsolete assumptions e.g. sources of NMVOC, NOx, SO_2, particulate matter, and heavy metals etc. where changing process technologies and/or the implementation of control strategies are expected to reduce emissions with time;
- efforts should be made to better characterise uncertainty and possible systematic/methodological bias in emissions data provided directly by industry or regulators in order to improve assist inventory compilers to generate reasonable uncertainty estimates;
- research covering all aspects affecting inventory uncertainty should be considered, including improvements to emission factors, activity data, or information on industry structure or process technology, in order to make the most cost-effective improvements to the inventory;
- detailed research priorities should be identified using a methodology that takes account of the likely cost of the research, the likelihood of the research leading to improvements in inventory data, and the desirability of such improvements;
- To ensure completeness of the inventory, emission estimates should be made for missing sources identified as part of this work and included in the next revision of the NAEI.

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Appendices

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Appendix A Results of key source analysis
Appendix B Missing sources
Appendix C Prioritisation of emission factor research

Appendix A
Key Source Analysis

This appendix describes the method used to identify 'key sources' i.e. those sources which contribute most to the uncertainty within the inventory for each pollutant. Key sources will often, but not always, be those sources which contribute most to national emissions of a given pollutant. Some small sources can be key sources if the emission estimate for them is very uncertain. Equally, some sources which are significant at a national level may not be key sources if the emission estimates are less uncertain than estimates made for other sources.

Key sources have been identified using a method based on that recommended by IPCC in their Good Practice Guidance. This involves performing the following calculation for each emission estimate.

$$LU_{x,p} = E_{x,p} / E_p \times U_{x,p}$$

Where:

$LU_{x,p}$ is the level assessment with uncertainty for the emission estimate for pollutant p from source x
$E_{x,p}$ is the mean of the emission estimate for pollutant p from source x
E_p is the mean of the emission estimate of pollutant p from all sources
$U_{x,p}$ is the uncertainty in the emission estimate for pollutant p from source x, which is taken to be the larger difference between the mean and either the 2.5% or the 97.5% confidence limits from the uncertainty analysis.

When calculated for each emission estimate, the values of $LU_{x,p}$ can be used as a measure of the significance of the uncertainty in a given estimate. Those sources which have the largest values of LU_x,p for a given pollutant have the greatest influence on uncertainty in the inventory for that pollutant. These 'key sources' can be used in the prioritisation of research to improve inventories. Key sources in the NAEI have been defined as those sources with the largest values of $LU_{x,p}$ for each pollutant and which collectively have 95% of the sum of the $LU_{x,p}$ values for that pollutant.

Key sources for ammonia and volatile organic compounds follow in the lists below, while key sources for other gaseous pollutants, particulate matter and heavy metals, persistent organic pollutants, and base cations are shown in Tables A1, A2, A3 and A4 respectively.

Key sources for ammonia

- Emissions from soils
- Non-dairy cattle wastes
- Pig wastes
- Sheep wastes
- Wastes of other poultry

Key sources for volatile organic compounds

- Car refuelling using unleaded petrol
- Chemicals manufacture
- Cold start emissions from catalyst cars
- Cold start emissions from non-catalyst cars
- Evaporative emissions from catalyst cars
- Evaporative emissions from non-catalyst cars
- Forests & other vegetation
- Industrial adhesives use
- Leakage from gas distribution network
- Loading of crude oil at offshore facilities
- Loading of crude oil at onshore facilities
- Maturation of whisky
- Metal and plastic coatings
- Non-aerosol carcare products
- Other solvent use
- Process emissions from crude oil refineries
- Road construction
- Tailpipe emissions from catalyst cars on urban roads
- Tailpipe emissions from non-catalyst cars on rural roads
- Tailpipe emissions from non-catalyst cars on urban roads
- Use of petrol in garden vehicles and machinery
- Use of petrol in industrial off-road vehicles and machinery
- Use of trichloroethylene as a cleaning solvent

Table A1 Key sources for other gaseous pollutants

Source	1,3-BD	Benzene	CO	HCl	NOx	SO_2
Chemicals manufacture	X	X				
Cold start emissions from catalyst cars	X	X	X		X	
Cold start emissions from non-catalyst cars	X	X	X			
Domestic use of coal as a fuel		X				
Domestic use of natural gas as a fuel		X			X	
Domestic use of wood as a fuel		X				
Process emissions from cement production					X	
Process emissions from crude oil refineries		X				
Tailpipe emissions from articulated HGVs on motorways	X				X	
Tailpipe emissions from articulated HGVs on rural roads					X	
Tailpipe emissions from buses	X				X	
Tailpipe emissions from catalyst cars on motorways					X	
Tailpipe emissions from catalyst cars on rural roads			X		X	
Tailpipe emissions from catalyst cars on urban roads	X	X	X		X	
Tailpipe emissions from non-catalyst cars on motorways	X				X	
Tailpipe emissions from non-catalyst cars on rural roads	X		X		X	
Tailpipe emissions from non-catalyst cars on urban roads	X	X	X		X	
Tailpipe emissions from rigid HGVs on rural roads	X				X	
Tailpipe emissions from rigid HGVs on urban roads	X					
Use of coal by power stations				X	X	X
Use of coke in sinter production			X			
Use of gas oil by coastal shipping		X			X	
Use of gas oil in agricultural vehicles and machinery					X	
Use of gas oil in industrial off-road vehicles and machinery	X				X	
Use of landfill gas by power stations					X	
Use of natural gas by the general industry sector					X	
Use of petrol in garden vehicles and machinery		X	X			
Use of petrol in industrial off-road vehicles and machinery	X	X	X			
Use of process gases as fuels on offshore oil & gas installations					X	

Table A2 Key sources for particulate matter and metals

Source	As	Cd	Cr	Cu	Pb	Hg	Ni	PM_{10}	Se	V	Zn
Basic oxygen furnaces		X									X
Brake wear emissions from DERV cars								X			
Chemicals manufacture			X	X							
Chlorine production using mercury cells						X					
Clinical waste incineration		X				X					
Construction								X			
Copper alloys and semis production				X							X
Crematoria						X					
Disposal of measurement equipment						X					
Domestic use of anthracite as a fuel	X			X	X	X	X	X			
Domestic use of coal as a fuel							X	X			
Domestic use of natural gas as a fuel								X			
Domestic use of solid smokeless fuel as a fuel	X					X	X				
Domestic use of wood as a fuel								X			
Electric arc furnaces		X	X		X						X
Flat glass production		X	X		X				X		X
Glass fibre manufacture			X								
Housing of broilers								X			
Iron and steel foundries						X					
Manufacture of alkyl lead compounds					X						
Manufacture of chromium based chemicals			X								
Nickel refining							X				
Part B processes								X			
Primary aluminium production							X				
Primary lead/zinc production		X			X	X					X
Process emissions from blast furnaces		X		X						X	X
Process emissions from coke ovens			X								
Process emissions from sinter strands		X		X	X	X					
Production of special glass									X		
Quarrying								X			
Secondary lead production		X									
Sewage sludge incineration		X									
Tailpipe emissions from catalyst cars on motorways					X						
Tailpipe emissions from catalyst cars on rural roads					X						
Tailpipe emissions from catalyst cars on urban roads					X						
Tailpipe emissions from non-catalyst cars on urban roads					X						
Use of coal by autogenerators	X	X		X	X	X	X	X		X	X
Use of coal by power stations		X	X	X	X	X	X	X	X		
Use of coal by public service providers				X							
Use of coal by the general industry sector	X		X	X	X	X	X				X
Use of fuel oil by coastal shipping										X	
Use of fuel oil by crude oil refineries							X			X	
Use of fuel oil by public service providers							X			X	
Use of fuel oil by the 'miscellaneous' sector										X	
Use of fuel oil by the general industry sector							X			X	
Use of fuel oil by the iron & steel industry							X			X	
Use of gas oil in industrial off-road vehicles and machinery								X			
Use of petroleum coke by crude oil refineries							X				
Use of treated wood as a fuel by industry	X										

Table A3 Key sources for persistent organic pollutants

Source	B[a]P	Dioxins	Lindane	HCB	PCBs	PCP
Accidental fires		X				
Accidental vehicle fires		X				
Anode manufacture for aluinium smelting	X					
Capacitors					X	
Carbon tetrachloride manufacture				X		
Clinical waste incineration		X				
Crematoria		X				
Domestic use of coal as a fuel	X					
Domestic use of wood as a fuel	X					
Electric arc furnaces		X				
Forest & moorland fires	X					
Petrol engined road transport	X					
Process emissions from sinter strands		X				
Sewage sludge incineration		X				
Use of Chlorothalonil as a pesticide				X		
Use of coal by power stations		X				
Use of coal by public service providers		X				
Use of coal by the general industry sector	X					
Use of fuel oil by crude oil refineries		X				
Use of gas oil by the general industry sector		X				
Use of treated wood as a fuel by the general industry sector		X				
Use of wood as a fuel by the general industry sector		X				
Wood impregnated with HCH			X			
Wood previously impregnated with PCP						X

Table A4 Key sources for base cations

Source	Ca	K	Mg	Na
Construction	X			
Domestic combustion of coal			X	X
Lime manufacture	X			
Non-fletton brick manufacture			X	
Other industry (Part B processes)			X	
Quarrying	X		X	X
Process emissions from sinter strands		X		X
Resuspension of dust from roads	X	X		X
Use of coal by autogenerators			X	
Use of coal by power stations			X	X

Appendix B
Missing sources

A small number of sources not previously included in the NAEI have been identified None are expected to be significant sources of pollution but, where possible, emission estimates should be included in the next revision of the NAEI. The list below provides details of the sources and principle pollutants emitted.

Animal carcass incineration	CO, NOx, NMVOC, PM_{10}
Flaring of wastes in chemical industry	CO, NOx, SO_2, NMVOC, HCl, PM_{10}, PAHs, dioxins
Use of chemical process wastes as fuel	CO, NOx, SO_2, NMVOC, HCl, PM_{10}, PAHs, dioxins
Part B chemical processes	NMVOC

The following sectors are used in the NAEI but do not include emission estimates for the pollutants listed. Emissions of these pollutants either do occur or may occur. Although none of these emissions are likely to be especially significant, estimates should be included in the next revision of the NAEI.

Source	Pollutants
Accidental fires (vehicle & non-vehicle)	CO, NOx, SO_2, NMVOC, metals, HCl, NH_3, benzene, 1,3-butadiene, PM_{10}, PAHs, PCBs, PCP
Use of fuel oil by agricultural sector	benzene, PCBs
Use of gas oil by agricultural sector	benzene, 1,3-butadiene
Straw used as fuel by agricultural sector	benzene, PAHs, PCP
Gas oil engined farm machinery	V
Petrol engined farm machinery	As, Hg, V, NH_3
Military aircraft	metals, PM10, PAHs, dioxins, PCBs, PCP
Commercial aircraft	V, PAHs, dioxins, PCBs
Use of natural gas in ammonia production	PM_{10}
Use of coal by autogenerators	NH_3, benzene
Use of natural gas by autogenerators	benzene
Use of coal, scrap tyres or waste oils in cement works	PAHs, PCP
Use of petroleum coke by cement works	PAHs, PCBs
Fuel oil powered coastal shipping	HCl, PCBs
Gas oil powered coastal shipping	1,3-butadiene, dioxins
Burning of coal by coke manufacturers	HCl, PCP
Coke production	Se, V
Use of anthracite as a domestic fuel	1,3-butadiene
Use of burning oil as a domestic fuel	PAHs, dioxins
Use of premier burning oil as a domestic fuel	V, PAHs, dioxins, PCBs
Use of coke as a domestic fuel	PAHs, PCBs
Use of fuel oil as a domestic fuel	PAHs, dioxins, PCBs
Use of gas oil as a domestic fuel	1,3-butadiene, PAHs, dioxins
Petrol powered garden equipment	As, Hg, V, NH_3, 1,3-butadiene
Gas oil powered fishing vessels	1,3-butadiene, PAHs, dioxins

Chemical waste incineration	CO, NOx, SO_2, NMVOC, metals, HCl, benzene, 1,3-butadiene, PM_{10}, PCP
Clinical waste incineration	NMVOC, Se, V, benzene, 1,3-butadiene, PCP
Crematoria	PAHs, PCBs
Sewage sludge incineration	benzene
Use of coke oven gas in blast furnaces	1,3-butadiene
Use of coke as fuel in iron & steel industry	metals, PM_{10}, PCBs, PCP
Use of coke oven gas in iron & steel industry	1,3-butadiene
Use of fuel oil in iron & steel industry	benzene, PCBs
Use of gas oil in iron & steel industry	benzene, 1,3-butadiene
Flaring of coke oven gas	1,3-butadiene
Use of coke as a fuel in sinter plant	metals, PM_{10}, PAHs, dioxins, PCBs, PCP
Combustion in lime manufacturing process	NMVOC, metals, PAHs, PCBs, PCP
Use of burning oil as fuel by miscellaneous users	PAHs, dioxins
Use of fuel oil as fuel by miscellaneous users	benzene, PAHs, dioxins, PCBs
Use of gas oil as fuel by miscellaneous users	benzene, 1,3-butadiene, PAHs, dioxins
MSW incineration without electricity generation	1,3-butadiene
Natural fires	CO, NOx, NMVOC, metals, benzene, 1,3-butadiene, PM_{10}, PCBs, PCP
Offshore flares	PAHs, dioxins, PCBs, PCP
Offshore well testing	metals, benzene, 1,3-butadiene, PM_{10}, PAHs, dioxins, PCBs, PCP
Coke use as a fuel in other industries	PAHs, PCBs
Coke oven gas use as a fuel in other industries	1,3-butadiene
Fuel oil use as a fuel in other industries	benzene, PCBs
Gas oil use as a fuel in other industries	benzene, 1,3-butadiene
Waste lubricant use as a fuel in other industries	PAHs, PCBs, PCP
Use of wood as a fuel in other industries	NH_3
Gas oil powered industrial off-road vehicles	V
Petrol powered industrial off-road vehicles	As, Hg, V, NH_3
Use of fuel oil in power stations	HCl, benzene

Use of gas oil in power stations	benzene, 1,3-butadiene
MSW incineration with electricity generation	1,3-butadiene
Use of natural gas in power stations	benzene
Use of landfill gas or sewage gas in power stations	1,3-butadiene
Use of coal slurry in power stations	HCl, benzene, 1,3-butadiene, PAHs, PCBs, PCP
Use of sour gas in power stations	PM_{10}
Use of burning oil as fuel by public service providers	PAHs, dioxins
Use of fuel oil as fuel by public service providers	benzene, PAHs, dioxins, PCBs
Use of gas oil as fuel by public service providers	benzene, 1,3-butadiene, PAHs, dioxins
Use of sewage gas as fuel by public service providers	1,3-butadiene
Trains	PAHs, dioxins
Use of burning oil as fuel by railway operators	PAHs, dioxins
Use of natural gas as fuel by railway operators	PM_{10}
Refineries (flares)	CO, NOx, SO_2, benzene, 1,3-butadiene, PM_{10}, PAHs, dioxins, PCBs, PCP
Use of fuel oil at refineries	benzene, PCBs
Use of gas oil at refineries	benzene, 1,3-butadiene
Use of naphtha & miscellaneous fuels at refineries	benzene, 1,3-butadiene, PAHs, PCBs, PCP
Cracker catalyst regeneration at refineries	Se, HCl, 1,3-butadiene, PCBs
Motorcycles & mopeds	As, Hg, V, PAHs
DERV-engined road vehicles	As
Petrol-engined cars & LGVs	As, Hg, V
Naval shipping	metals, 1,3-butadiene, PAHs, dioxins
Small-scale waste burning	CO, NOx, NMVOC, metals, benzene, 1,3-butadiene, PM_{10}, PCP
Use of coal as fuel by SSF manufacturers	HCl, benzene, 1,3-butadiene, PAHs, PCP
SSF production	Se, V
Brick manufacture (Fletton & non Fletton)	metals
Coal, tar & bitumen processes	SO_2
Glass (all types)	NOx, SO_2

Ceramics & non-chromite based refractories	metals
Landfill flares	NOx, NMVOC
Part B processes not covered elsewhere	CO, SO_2, metals, HCl, NH_3
Refractories (chromite based)	metals (except chromium)
Wood products manufacture	PM_{10}

Appendix C
Prioritisation of Emission Factor Research

Introduction

A method is proposed for prioritising research work aimed at improvement of data used in the NAEI. This method can take account of the level of uncertainty in individual emission estimates, the cost of research options, the likelihood of the research bringing improvements, and the desirability of improving the inventory for a given pollutant. Provisional results are available from the method and these indicate possible priority research areas.

Method

The proposed prioritisation method calculates a score for each of the key sources identified by the key source analysis as shown below:

$$\text{Score} = LU_{x,p} \times D_p \times I_{y,p,x}/C_y$$

Where:

$LU_{x,p}$ is the level assessment with uncertainty for the estimate of emissions of pollutant p from source x (see Appendix C for a description of the calculation of this term).

D_p is a measure of the desirability of improvement to the national inventory for pollutant p

$I_{y,p,x}$ is a measure of the likely improvement in the certainty of the estimate of emissions of pollutant p from source x resulting from a research option y

C_y is the cost of research option y

A single piece of research can, of course, impact on more than one area of the inventory e.g. stack monitoring of metal emissions from a power station could result in improvements in all ten metal inventories. The equation given above can be modified so as to take account of all improvements resulting from a given piece of research:

$$\text{Score} = (LU_{x,p} \times D_p \times I_{y,p,x} + LU_{x,q} \times D_q \times I_{y,q,x})/C_y$$

Where

$LU_{x,p}$ is the level assessment with uncertainty for the estimate of emissions of pollutant q from source x.

D_p is a measure of the desirability of improvement to the national inventory for pollutant q

$I_{y,p,x}$ is a measure of the likely improvement in the certainty of the estimate of emissions of pollutant q from source x resulting from a research option y

The research options which have the highest scores are those which would most cost effectively improve the NAEI.

Input data

The values for the level assessment with uncertainty are provided by the key source analysis (see Appendix A). In order that the prioritisation method can examine research options which affect more than one pollutant, the level assessments with uncertainty have been normalised for each pollutant by dividing the value for each source by the sum of the values for all sources.

The measure of the desirability for improving each inventory should be provided by DEFRA. For illustrative purposes, the following values have been used for this provisional analysis:

1.0 for inventories where improvement is 'more important';
0.5 for inventories where improvement is 'less important'
0.1 for inventories where improvement is 'not important'

It has been assumed that improvement of all inventories where the uncertainty is worse than +/- 30% is 'more important', except for black smoke, which is ignored from the analysis. This group includes PM_{10}, arsenic, copper, mercury, nickel, selenium, vanadium, zinc and all persistent organic pollutants. The SO_2 inventory, which is +/-3%, is treated as 'not important', while the NOx inventory, which is +/- 7%, is treated as 'less important'.

The remaining inventories are subject to uncertainty ranging from +/-10% to +/- 30% and these have been subjectively divided into 'more important' and 'less important' as follows:

More important	**Less important**
Ammonia	Carbon monoxide
Cadmium	Chromium
NMVOC	Hydrogen chloride
Benzene	Lead (because already +/- 10%)
1,3-butadiene	

The assignment of pollutants to a particular category could, of course, be changed from time to time, as the importance of having accurate data were made more or less vital by the timing of, for example, international discussions or compliance deadlines.

Research options have been identified for each key source or for groups of key sources. In practice, there may be more than one way to improve each emission estimate e.g. emission estimates for cadmium emissions from the use of anthracite could be improved both by means of chemical analysis of samples of anthracite, or by talking to anthracite producers and obtaining any data they hold. The costs and the likelihood of success are different in each case - contacting the anthracite suppliers will be inexpensive but they might not have any data or might be unwilling to supply it, whereas chemical analysis of anthracite samples, although expensive, will certainly yield usable data. For this provisional analysis, only one

research option is modelled for each key source. These are distinguished as being of one of four basic options:

DB-S	A simple desk-based exercise, involving a single or limited contacts, taking no more than a few hours
DB-C	A complex desk-based exercise, involving many contacts or involving complex issues, taking more than a few hours and probably many days
M	Monitoring of sources in-situ for determination of emission factors
L	Laboratory based experiments, including chemical analyses

A factor representing the likely improvement in the uncertainty of each emission estimate as a result of research is then estimated. This factor takes into account both the likelihood that the research will 'work' as expected e.g. that the contacts made will be helpful, and the impact that successful completion of the research will have on the uncertainty.

In general, monitoring and laboratory based work are easier to assess. The barriers to successful completion of the work are better understood and the output of the work is obvious. In the case of desk-based consultation work, both the likelihood of finding helpful contacts and the probability that these contacts will be able to provide usable data are difficult to estimate. For the provisional analysis, fairly cautious estimates have been used for the improvement resulting from desk-based studies (typically 10% or 20% improvement).

The costs of these options have been estimated. In principle, these costs do not have to be real costs, as long as the relative size of the cost for each option is correctly modelled. For the provisional analysis the following general rules have been applied:

1. For simple desk-based work, a cost of 0.2 has been used
2. For complex desk-based work, costs are chosen from a limited set of values (2,5,10,20,50) corresponding to the costs for increasingly complex studies. In practice, the smallest and largest values were rarely used.
3. For monitoring studies, costs are chosen from a limited set of values (20,50,100) corresponding to the costs for increasingly complex work.
4. For laboratory work, costs are chosen from a limited set of values (5,10,20) corresponding to the costs for increasingly complex work.

Results

Illustrative results of the prioritisation are shown in Table E1. These results are presented for illustrative purposes only and further consideration of the possible research options, their costs and the improvements they could bring would be needed before a final list of priority research could be compiled. DEFRA might also wish to suggest weighting factors for the desirability of improvements to inventories for each pollutant.

Table C1 Provisional prioritisation of research for improved inventory data

Source	Research	Score	Pollutants
Flat glass production	DB-S	1010	Cd, Cr, Pb, Se, Zn
Primary lead/zinc production	DB-S	401	Cd, Pb, Hg, Zn
All sources	DB-C	75	Sn, Be, Mn
Manufacture of chromium based chemicals	DB-S	51	Cr
Use of coal by autogenerators	DB-C	34	As, Cd, Cu, Hg, Ni, Pb, V, Zn, PM10, Mg
Use of fuel oil by the general industry sector	DB-C	33	Ni, V
Glass fibre manufacture	DB-S	29	Cr
Process emissions from sinter strands	DB-C	23	Cd, Cu, Hg, Pb, dioxins, K, Na
Lime production	DB-S	22	Ca
Use of Chlorothalonil as a pesticide	L	18	HCB
Process emissions from blast furnaces	DB-C	18	Cd, Cu, V, Zn
Domestic use of anthracite as a fuel	DB-C	15	As, Cu, Pb, Hg, Ni
Treated wood use as fuel by the general industry sector	DB-C	14	As, dioxins
Car refuelling using unleaded petrol	DB-S	13	VOC
Use of fuel oil by crude oil refineries	DB-C	13	Ni, V
Nickel refining	DB-S	13	Ni
Domestic use of coal as a fuel	DB-C	12	Ni, Mg, Na
Carbon tetrachloride manufacture	DB-C	11	HCB
All sources	DB-C	10	SCCPs
All sources	DB-C	10	PBDE
Wood previously impregnated with PCP	L	9.8	PCP
Capacitors	DB-C	9.6	PCBs
Wood impregnated with HCH	L	9.5	gamma HCH
Process emissions from crude oil refineries	DB-S	9.2	Benzene
Use of fuel oil by public service providers	DB-C	8.6	Ni, V
Use of coal by the general industry sector	DB-C	8.4	As, Cr, Cu, Pb, Hg, Ni, Zn
Use of coal by power stations	DB-C	6.9	SO2, NOx, HCl, Cd, Cr, Cu, Hg, Ni, Pb, Se, PM10, dioxins, Mg, Na
Non-aerosol carcare products	DB-S	6.4	VOC
Maturation of whisky	DB-S	6.3	VOC
Chlorine production using mercury cells	DB-C	6.2	Hg
Accidental fires	DB-C	5.8	Dioxins
Basic oxygen furnaces	DB-C	5.1	Cd, Zn
All sources	DB-C	5.0	PCN
Crematoria	DB-C	3.5	Hg
Electric arc furnaces	DB-C	3.1	Cd, Cr, Pb, Zn
Chemicals manufacture	DB-C	3.0	Cu
Forest & moorland fires	DB-C	2.9	B[a]P
Use of petroleum coke by crude oil refineries	DB-C	2.6	Ni
Use of fuel oil by the iron & steel industry	DB-C	2.5	Ni, V
Construction	DB-C	2.3	PM10, Ca
Quarrying	M	2.1	PM10, Ca, Mg, Na
Other solvent use	DB-C	2.0	VOC

The example prioritisation shown in Table C1 shows a number of features.

- simple desk-based studies are generally very cost-effective (five of the top ten measures fall into this category);
- desk-based work is generally more cost-effective than laboratory-based experimental work and source measurement work (only three of the former and one of the latter appear in Table C1);
- research which can tackle more than one pollutant will be more cost-effective than research which considers only one (note that many of the top options look at sources which emit metals so that research can lead to improvements in many or all of the ten metal inventories).

The ordering of measures is very dependent upon the value assigned to the importance of improving a particular inventory. It is therefore recommended that DEFRA should consider what 'score' should be given to each pollutant so that prioritisation of research will properly reflect DEFRA's requirements.

The prioritisation illustrated in Table C1 considers each option in isolation, whereas cost savings and/or benefits in terms of additional data might be obtained by carrying out certain options in combination. A final stage is therefore required to group these options into a programme of research. As an example, it might be considered best to group together the three laboratory-based studies into one research project and similarly to treat all of the simple desk-based studies as a single project. A final costing and ordering of research projects would then be required before a decision could be reached on which projects should be funded.