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Review of emission factors for incident fires

Innovation for efficiency science programme

Science report: SC060037/SR3

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Steve Killeen

Head of Science

Executive summary

The Environment Agency regulates a variety of industrial, agricultural and waste management premises across England and Wales. At such premises in the year 2006-07 there were over 450 recorded incidents involving fires and the consequent emission of air pollutants. Incidents are recorded on the Environment Agency's National Incident Recording System (NIRS). This prompts a response from local Environment Agency staff which may involve an officer visiting the site.

The aim of this study was to review emission factors for air pollutants from burning various materials in an incident fire. If, as part of the Environment Agency's response to an incident fire, a predictive environmental impact assessment is required, information would be needed on the materials being consumed, the products of combustion and the rate of their generation. This study attempted to seek out emission factors from uncontrolled or "open" burning events which are likely to be encountered by Environment Agency staff when responding to a reported incident. The search focused on fourteen categories of incident listed in the NIRS report for 2006-07.

In a fire, prevalent combustion conditions determine the level of pollutant emissions and such conditions are usually not ideal. Non-ideal combustion conditions tend to result in incomplete combustion and the production of volatile organic compounds and particulate matter (soot).

Government databases have been developed to feed into pollution inventories for the territories they represent. The United States Environment Protection Agency (USEPA) has a system (AP-42) which contains a significant amount of information on criteria pollutants from a limited number of open burning sources. This system is referenced in UK Government publications on bonfire emissions (Department for Environment, Food and Rural Affairs - Defra, 2006a). AP-42 applies quality assurance and quality control aspects to the derivation of its data. However, the highest quality data are not always available for many of the incident categories encountered in the UK, resulting in factors that can best be expected to give only an indication of the likely emissions.

There are also gaps within published emission factor databases, particularly for metals and chemicals. For example, a fire at a chemicals factory could emit a variety of pollutants depending on the materials stored on site. The diversity of the chemicals sector across England and Wales means that a fire at one of these sites could produce a wide variety of pollutants at unknown emission rates.

It is possible that sub-surface fires at landfill sites are becoming more common; this may be related to an increased emphasis on landfill gas extraction resulting in greater air ingress to the waste mass (Environment Agency, 2007). Sub-surface fires have been identified as a potential source of dioxin and furan (PCDD/F) emissions but the emissions are not well quantified. For example, the NIRS report does not include PCDD/F emission rates or related information on the types and masses of waste involved. Also, these emission rates cannot be readily obtained from the wider technical literature because of a lack of data on types of sub-surface fire, the areal extent of such fires and the amounts of combustion products released at the surface.

The findings of this report are particularly timely given that the Environment Agency is taking a lead role in coordinating air quality monitoring and modelling in major incidents (which can include incident fires) in England and Wales.

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1 Introduction

The Environment Agency regulates a variety of industrial, agricultural and waste management premises across England and Wales. At such premises in the financial year 2006-2007 there were over 450 recorded incidents involving fires.

The Environment Agency is often required to carry out predictive modelling studies of fire incidents. In order to accurately model the resulting emissions information is required on a number of variables including emission factors and the amount / type of material involved in the fire. An emission factor is a numerical value that relates the amount of pollutant produced and released to the atmosphere to the activity associated with the release of that pollutant. Emission factors from point sources are readily available in the literature but emission factors from fires at open, uncontained sources are less prominent.

This study reviews the Environment Agency's National Incident Recording System (NIRS) in order to identify the main categories of report fires. Emission factors for these sources have then been identified from a detailed literature review.

The Buncefield incident, in December 2005, highlighted the need for a more coherent approach to air monitoring during major incidents. The Environment Agency has agreed to take a lead role in coordinating air quality monitoring and modelling in major incidents such as major incident fires and so this review of emission factors is timely.

1.1 National Incident Recording System (NIRS)

NIRS is used to capture details on each recorded incident whether or not it relates to a facility regulated by the Environment Agency. Entry of information onto NIRS begins when the Regional Communications Centre (RCC) receives a report of a potential incident. After entry onto NIRS the report is passed to the local officer for the relevant function to assess and determine the local incident response. NIRS reports can inform how local teams and the Environment Agency nationally manage incidents.

Seventy per cent of all recorded incidents in 2006-07 involved emissions of air pollutants (reported as visual 'smoke') to the atmosphere. By categorising this subset of incidents, the majority of which occurred at sites regulated by the Environment Agency, it is possible to identify the most prominent sectors (Figure 1.1).

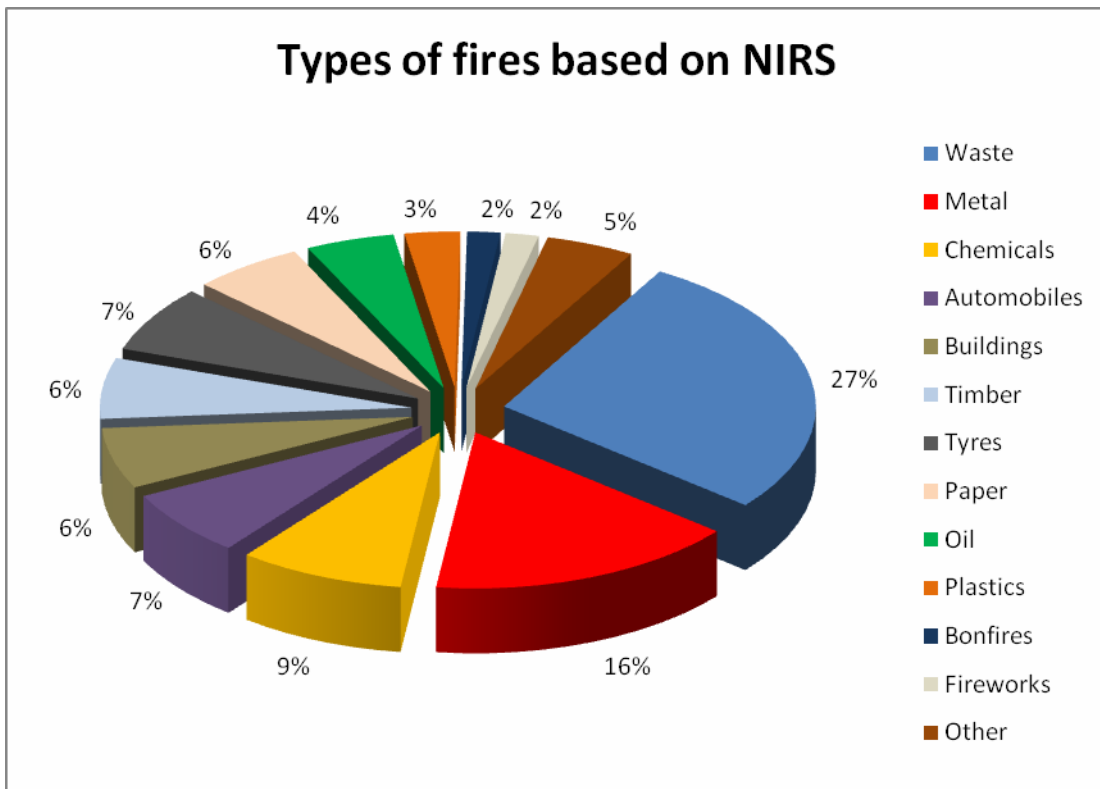


Figure 1.1 Premises that emitted smoke in 2006-07.

For this purpose it is helpful to discount categories with only a single entry, which still leaves 97 per cent of the incidents for categorisation. To assess the pollution emanating from such fires, it is first necessary to identify typical pollutants resulting from the combustion of the relevant materials and to consider the media to which they are released. The ecological impact of a pollutant depends on its bioavailability; Meharg (1994) reminds us that from experience at Bhopal, gaseous pollutants make the highest initial impact on terrestrial organisms. To assess the impact of combustion products on the local environment in this study, it was necessary to carry out a literature search to locate relevant emission factors.

1.2 Literature Search – Methodology

A literature search was carried out to identify emission factors to air for the pollutants generated when materials are subject to open burning. Open burning is described as the unenclosed combustion of materials in an ambient environment (Persson and Simonson, 1998) and includes the burning of material in drums, skips, fields or in large open spaces (USEPA 1995).

Data on emission factors were found in a number of sources, which include the United States Environment Protection Agency (USEPA) website and a search of additional databases covering a range of publications.

Commercial bibliographic databases include:

- Publisher websites: Elsevier (Science Direct), Wiley, Blackwell.
- NAEI website (National Atmospheric Emissions Inventory).
- Web search engines, Google and Dogpile.
- Scirus.
- Environment Agency Information Services Unit.

The key terms used to search the databases were: fire, burn, pallet, litter, tyre, car, household waste and grass fire, each with emission factor. Searches often provided duplication of earlier found documents, suggesting that only a limited number of documents are available on emission factors from open sources. The abstract from each article was reviewed to determine the article's suitability. If considered relevant, the whole article was then reviewed. Where access to the full article was available only via subscription, documents were excluded from the study. Relevant data identified during the literature search are presented in Chapter 2.

1.3 Combustion Products

Ideal combustion conditions comprise excess oxygen, effective mixing of fuel and air and sufficient gas-phase residence time above the substance ignition temperature. Under these conditions conversion of organic substances to carbon dioxide and water, with minimal production of other pollutants, may be expected. However, open burning, with its less than ideal combustion conditions, often produces soot and particulate matter (evident as a visible plume), carbon monoxide, methane and volatile organic compounds including polycyclic aromatic hydrocarbons (PAHs). Heavy metals such as lead, cadmium or mercury may also be emitted depending on the source, whilst any sulphur present is usually converted to sulphur dioxide. Some of these compounds are persistent, bioaccumulative and toxic, such as polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDDs/Fs) and polychlorinated biphenyls (PCBs) (Lemieux *et al.*, 2004).

2 Generic Emission Factors

An emission factor is described as a numerical value that relates the amount of pollutant released to atmosphere as a consequence of an activity associated with the release of that pollutant. Emission factors are usually expressed as the mean value of a distribution of data (USEPA, 2007) and expressed as a mass of pollutant per mass of fuel burned, for example g kg^{-1} .

There are a range of primary sources of data on emission factors relevant to emissions from incident fires. The USEPA AP-42 database (USEPA, 1995) is one of the primary sources of emission factors. There are other minor sources of data from a variety of scientific publications such as Lemieux *et al.* (2004), Persson and Simonson (1998) and Entec (2006).

The United Kingdom's (UK) National Atmospheric Emissions Inventory (NAEI) compiles estimates of emissions to the atmosphere from UK sources such as cars, trucks, power stations and industrial plants. The estimates are intended to help find ways of quantifying the impact of human activities on the environment and our health. The factors, however, are based on mass emissions per year for a range of economic and industrial sectors. They do not therefore have the short-term resolution required for incident fires, such as resolution down to days, hours or minutes. The California state government's Air Resources Board (ARB) has developed emission estimates and factors to support California's Emission Inventory and Air Quality Models but they are specific to prescribed industrial sectors and are not relevant to incident fires.

In their introduction document to AP-42, the USEPA defines an emission factor as a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant, such as kilograms (kg) of particulate emitted per mega gram (Mg) of coal burned. Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in the source category (a population average).

The general equation for emissions estimation is:

$$E = A \times EF \times (1 - ER/100)$$

where:

E = emissions; A = activity rate; EF = emission factor; and ER = overall efficiency of any relevant emission abatement system (%).

USEPA makes it clear that emissions factors are generally developed to represent long-term emissions and that where short-term fluctuations in emission rates are likely (as will be probable for incident fires), a higher uncertainty is expected. USEPA emission factors are based on source tests, modelling, mass balance or other information and some have been subject to more rigorous quality assurance. Each emission factor has therefore been assigned a reliability or robustness rating of A through to E with A being the best.

The rating determination for each factor is a two-step assessment process. The first step is an appraisal of data quality, the second an appraisal of the factor's robustness to stand as a national average across that source activity, that is, an appraisal of how representative it is.

The AP-42 emission factor ratings can be summarised as follows:

- “A” Excellent - developed from the most robust source test data from many randomly chosen installations across the industry. Variability is minimised by selecting a specific source category population.
- “B” Above average - developed from the most robust test data from a reasonable number of installations. Although the data do not display any specific bias, it is not obvious that tested installations represent a random sample of the industry. Variability is minimised, consistent with level A.
- “C” Average - developed from less robust test data than A and B, but from a reasonable number of installations. Although the data do not display any specific bias, it is not obvious that tested installations represent a random sample of the industry. Variability is minimised, consistent with level A.
- “D” Below average - developed from less robust test data and from a small number of installations which may not represent a random sample of the industry. Source population may also exhibit variability.
- “E” Poor - developed from the least robust test data and tested installations may not represent a random sample of the industry. Source population may also exhibit variability.

The bulk of the USEPA emission factors for open burning are assigned factor ratings “C” and “D”.

Open burning emissions can be presented as raw plume or ambient concentrations to give a perspective on local health effects, but these ambient concentrations provide no information on the rate of pollutant generation (Lemieux *et al.*, 2004). By contrast, emission factors presented as mass of pollutant per unit mass of material burned enable comparison on a mass basis. Knowing the activity factor, which describes the rate of burning of a material, a pollutant emission rate may be determined. To counter the uncertainty of emission factors (EF) for organic air toxins driven by the varying combustion conditions, emission ratios (ER) are used where a carbon balance defines the concentration of a chemical species against that of a reference chemical. For example:

$$ER_{\text{species} / \text{CO}} = \frac{(\text{Species})_{\text{smoke}} - (\text{Species})_{\text{ambient}}}{(\text{CO})_{\text{smoke}} - (\text{CO})_{\text{ambient}}}$$

This example corrects for background concentrations and then expresses species emissions as a fraction of CO emissions. For smouldering fires the reference is carbon monoxide and for open fires carbon dioxide. Emission ratios require only the measurement of the reference species and the species of interest in the smoke, and no information is required about fuel composition, burning rates or quantities combusted. However, to be valid, the ratios depend on there being a consistent relationship between the species of interest and the reference species.

Where data are not available in units of EF, data may be converted from ER into EF using:

$$EF_x = ER_{(x/y)} \frac{MW_x}{MW_y} EF_y$$

where:

EF_x is the emission factor for species x; $ER_{(x/y)}$ the molar emission ratio of species x relative to species y; EF_y the emission factor of species y; MW_x and MW_y the molecular weights of species x and y respectively. If the molecular weights of the species are known then:

$$EF_x = ER_{(x/y)} / EF_y$$

where:

$ER_{(x/y)}$ becomes the mass ER of species x relative to species y.

As a result of the literature search, open burning emission factors have been located for a range of pollutants for the following sources:

- municipal and household waste (Lemieux *et al.*, 2004);
- nitrogen-based pesticides, for organophosphorus insecticides (Marlair *et al.*, 1996a, 1996b);
- the burning of buildings (Persson and Simonson, 1998);
- the burning of automobiles (Lönnemark and Blomqvist, 2006);
- timber (Wasson *et al.*, 2005);
- scrap tyres (USEPA, 1995);
- paper (Entec, 2006);
- oils (Booher and Janke, 1997);
- agricultural plastic film (USEPA, 1995);
- plastic bags (Lemieux *et al.*, 2004);
- bonfires (Department for Environment, Food and Rural Affairs - Defra, 2006a);
- a range of materials used in training fire fighters at the Fire Service College in Moreton-in-Marsh near Gloucester (Entec, 2006).

Some data sources (such as Lemieux *et al.*, 2004) provide data on individual compounds within a chemical class, although the general trend is towards grouping emissions. However, the variety of materials consumed and difficulties in acquiring representative environmental samples means there is considerable uncertainty in estimated emission factors from open burning activities.

Difficulties in directly sampling smoke plumes from a fire and the temporal shift in flame fronts has resulted in a hypothetical approach to the development of emission factors (Lemieux *et al.*, 2004). This manifests itself in the undertaking of laboratory experiments under controlled conditions. Using well-ventilated fires in a laboratory setting, combustion efficiencies approaching 80 per cent can be achieved, whereas underventilated fires can see combustion efficiencies as low as 10 per cent, with a larger associated emission of unburnt hydrocarbons and particulate matter (Persson and Simonson, 1998).

Open burning tends to raise public health concerns for the following reasons:

- pollutants are typically released at ground-level which hinders dispersion;
- fires tend to be episodic in nature and localised with increasing pollutant exposure;
- non-point pollutant sources are not amenable to common abatement techniques;
- it is difficult to enforce restrictions on open burning;
- when fired with heterogeneous fuels, it can be difficult to attribute emissions to a single component.

Open burning, with its less than ideal combustion conditions, tends to produce soot and particulate matter that materialise as a visible plume. Such visible emissions and their impact on local air quality can be expected to prompt local residents to report the emission to the regulator (Lemieux *et al.*, 2004). Emissions of particulate matter from fires are of the order of 20 to 400 times the acceptable level for a controlled combustion source. Where a fire has a poor supply of oxygen, or is smouldering, the particulate emissions are even greater (Persson and Simonson, 1998). It should be noted that open burning is not a permitted activity at Agency-regulated facilities. All regulated facilities are required to have an accident management plan requiring action to be taken to minimise the potential causes and consequences of fires (Environment Agency, 2008).

In the following sections, emission factors identified by the literature review are presented to reflect the sectoral order presented in Figure 1.1.

2.1 Emission Factors – Waste

Waste-related fires comprise open burning of waste together and sub-surface fires at landfill sites. At 27 per cent, waste-related fires constitute the largest category of recorded incidents in the NIRS 2006-07 database. The term ‘landfill fire’ is often used to describe a wide range of incidents regardless of the type of incident (Environment Agency, 2007).

Open burning of household waste in the United States is known to produce one of the largest airborne sources of PCDD/F (USEPA, 1995). Within the USEPA system, open burning is defined through a series of Source Classification Codes (SCC) and waste codes are defined under the sub-headings of ‘Government’, ‘Commercial/Institutional’ and ‘Industrial’. However, species pollutant emission factors are consistent across each sub-sector.

Refuse combustion involves the burning of domestic waste and non-hazardous solids; this is collectively described as municipal solid waste. Emission factors (Table 2.1) are presented by Defra (2006a).

Table 2.1 Emission factors – open burning of municipal solid waste (Defra, 2006a).

Source	Particulate	Sulphur oxides	Carbon monoxide	Total organic compounds (TOC) ^a		Nitrogen oxides
				Methane	Non-methane	
Municipal refuse						
kg Mg ⁻¹	8	0.5	42	6.5	15	3

^a Data indicates that TOC emissions are approximately 25% methane, 8% other saturates, 18% olefins, 42% others (oxygenates, acetylene, aromatics, trace formaldehyde).

Lemieux *et al.* (2004) characterised emissions from the burning of household waste using repeated laboratory simulations of 'barrel burning', a common waste management technique used in the United States where waste collection is not universally provided through local service (Table 2.2).

Chlorinated benzenes and phenols are precursors to the formation of PCDD/F (Fleischer *et al.*, 1999) and so it is usual to see the concentration of these substances displayed in organic compound analysis resulting from the open burning of materials.

Table 2.2 Emission factors from the barrel burning of household waste (Lemieux *et al.*, 2004).

Class	Compound	Emission (mg kg ⁻¹ material burned)
VOC	1,3 Butadiene	141.25
	2-Butanone	38.75
	Benzene	979.75
	Chloromethane	163.25
	Ethyl benzene	1812.75
	m,p-Xylene	21.75
	Methylene chloride	17.00
	o-Xylene	16.25
	Styrene	527.50
	Toluene	372.00
	SVOC	2,4,6-Trichlorophenol
2,4-Dichlorophenol		0.24
2,4-Dimethylphenol		17.58
2,6-Dichlorophenol		0.04
2-Chlorophenol		0.95
2-Methylnaphthalene		8.53
2-Cresol		24.59
3- or 4-Cresol		44.18
Acetophenone		4.69
Benzyl alcohol		4.46
Bis(2-ethylhexyl) phthalate		23.79
Di- <i>n</i> -butyl phthalate		3.45
Dibenzofurans		3.64
Isophorone		9.25
Pentachloro nitrobenzene		0.01
Phenol		112.66
Chlorobenzene		1,3-Dichlorobenzene
	1,4-Dichlorobenzene	0.03
	1,2-Dichlorobenzene	0.16
	1,3,5-Trichlorobenzene	0.01
	1,2,4-Trichlorobenzene	0.10
	1,2,3-Trichlorobenzene	0.11
	1,2,3,5-Tetrachlorobenzene	0.03
	1,2,4,5-Tetrachlorobenzene	0.02
	1,2,3,4-Tetrachlorobenzene	0.08
	1,2,3,4,5-Pentachlorobenzene	0.08
Hexachlorobenzene	0.04	

VOC = Volatile organic compound; SVOC = Semi-volatile organic compound

Table 2.2 cont. Emission factors from the barrel burning of household waste (Lemieux *et al.*, 2004).

Class	Compound	Emission (mg kg ⁻¹ material burned)
PAH	Acenaphene	0.64
	Acenaphthylene	7.34
	Anthracene	1.30
	Benzo (a) anthracene	1.51
	Benzo (a) pyrene	1.40
	Benzo (a) fluroanthene	1.86
	Benzo (ghi) perylene	1.30
	Benzo (k) fluroanthene	0.67
	Chrysene	1.80
	Dibenzo (ah) anthracene	0.27
	Fluroanthene	2.77
	Fluorine	2.99
	Indenol (1,2,3-cd) pyrene	1.27
	Naphthalene	11.36
	Phenathrene	5.33
	Pyrene	3.18
	Carbonyl	Acetaldehyde
Acetone		253.75
Acrolein		26.65
Benzylaldehyde		152.03
Butyraldehyde		1.80
Crotonaldehyde		33.53
Formaldehyde		443.65
Isovaleraldehyde		10.20
<i>p</i> -Tolualdehyde		5.85
Propionaldehyde		112.60
PCDD/F and PCB	Total PCDD/F	5.80 x 10 ⁻³
	TEQ PCDD/F	7.68 x 10 ⁻⁵
	Total PCB	1.26 x 10 ⁻¹
	TEQ PCB	1.34 x 10 ⁻⁶

PAH = Polycyclic aromatic hydrocarbon; PCB = Polychlorinated biphenyl
PCDD/F = Polychlorinated dibenzo-p-dioxins/polychlorinated dibenzofurans

Fires within the body of landfill sites (sub-surface fires thus not open burning) accounted for four per cent of recorded incidents (18 out of 450) in the waste section of the 2006-07 NIRS report. Evidence suggests that the occurrence of these fires may be increasing as a result of a greater emphasis on landfill gas extraction, resulting in greater air ingress to the waste mass (Environment Agency, 2008). This may be caused by poor management of the landfill gas extraction system.

The presence of a sub-surface fire is likely to result in an increase in the range of trace gases in any bulk gas emitted to the atmosphere (including volatilised materials, combustion and partial combustion products). If the sub-surface fire is excavated then there will be a short period of exposed waste and increased emissions to the atmosphere (Environment Agency, 2007). The exact nature of the emissions from such fires will depend on the waste type. Excavation is likely to introduce additional oxygen to the fire which will modify its combustion conditions and thus emissions.

Lönnermark *et al.* (2008) carried out a series of tests to measure gas phase emissions from simulated sub-surface fires in domestic waste. Table 2.3a summarises the types of materials present in this domestic waste. [Discharges to water from extinguishing the fire are also available but not presented here.]

Table 2.3a Analysis of domestic waste* used in the fire experiments (Lönnermark *et al.*, 2008).

Waste Type	Mass (kg)	Fraction (%)	Minimum (%)	Maximum (%)
Newspapers	503	14.1	1.1	36.1
Paper packages	352	9.9	5.2	23.1
Compostable	1177	33.0	15.5	50.4
Other bio fuel	334	9.4	2.0	22.8
Sum of bio fuel		66.4	51.7	84.9
Hard plastic	111	3.1	0.4	9.5
Soft plastic	306	8.6	3.9	15.2
Diapers	232	6.5	0.0	33.5
Other fossil fuels	112	3.1	0.4	11.4
Sum fossil fuels		21.3	8.6	44.2
Glass packages	85.8	2.4	0.0	8.9
Metal packages	80.0	2.2	0.4	5.2
Other non-combustion	250	7.0	0.8	21.7
Sum non-combustion		11.6	2.9	25.7
Dangerous waste	22.6	0.6	0.0	3.2
Total	3566	100	-	-

*250 waste sacks from 25 truck loads were analysed; maximum and minimum values across five bags per truck load.

The tests consisted of placing compressed and baled domestic waste in a 1m³ cubic container with an open top. Prior to the test burns waste bulk density was 220-260 kg m⁻³ and moisture content 50 ± 5 per cent by weight. For the purposes of repeatability, two burns for each test type were performed, giving six burns in all. Tests 1a, 1b were fire tests without extinguishment; sampling of gases commenced at ignition and continued for two hours. Tests 2a, 2b were fire tests with removal of overlying layers followed by water application; layers were removed after 90 and 95 minutes and water applied (0.5 litres min⁻¹) 100 minutes after ignition. Gas sampling lasted for two hours after ignition. Tests 3a, 3b were fire tests with extinguishment; gases were sampled for two hours from ignition. Water was applied (0.5 l min⁻¹) 90 minutes after ignition and continued for 30 minutes. Analysis of the gas sampling programme for each test is given in Table 2.3b.

Table 2.3b Summary of results from the analysis of fire gases presented as yields (Lönnermark *et al.*, 2008).

Analysis	1a	1b	2a	2b	3a	3b
PCDD/F (µg kg ⁻¹) TCDD I-TEQ	0.15	0.048 ^a - 0.049 ^b	0.44	0.028 ^a - 0.039 ^b	0.20	0.003 ^a - 0.016 ^b
PCB (µg kg ⁻¹) PCB 7	16	22	140	14	28	18
Σ WHO-PCB	1.8	2.6	16	1.9	3.2	2.1
WHO-TEQ	0.004	0.001	0.060	0.004	0.004	0.002
HCB (µg kg ⁻¹) HCB	19	<5.7	<96	<10	<12	<12
PAH (g kg ⁻¹) Σ PAH	0.45	0.52	0.11	0.38	0.58	0.33
Σ PAH (exc. Naphthalene)	0.20	0.23	0.035	0.11	0.19	0.10

^a Congeners below the detection limit set to zero

^b Congeners below the detection limit set equal to the detection limit

WHO = World Health Organisation

The simulated data recorded by Lönnermark *et al.* (2008) are not sufficient to estimate emissions from landfills in general because such an estimation would need considerable data on landfill fire types and extents. A recent review by the Environment Agency (2007)

has confirmed the lack of such information. In addition, actual sub-surface landfill fires are likely to only result in emissions to air where they either reached the surface (such as on a waste flank) or through contact with the surface (for example through a leachate well).

2.2 Emission Factors – Metals

It is common practice in some parts of the world to use open burning to remove plastic insulation from copper cable, so that the underlying copper can be reclaimed for cash. Whilst the presence of copper and volatile organics makes for the likely production of PCDD/F, no data on emission factors to air from this activity were found.

In the NIRS report, a regular feature is the burning of waste in skips at metal recycling sites. However it is uncommon for the level of description to pinpoint the actual waste being burned. The metals section includes integrated steelworks where fugitive emissions are recorded. Lemieux *et al.* (2004) identifies the reclamation of copper wire as one area where additional data on emissions would be useful.

2.3 Emission Factors – Chemical Pesticides

To test the hazard of generic liquids and their fire behaviour in bulk storage facilities, a pool fire configuration was established at the INERIS facility in France (Marlair *et al.*, 1996a). Large-scale tests were undertaken using two commercially important nitrogen-based pesticides, diuron and dimethoate. Emissions factors were developed and compared with factors produced using other European methods, specifically Rhone Poulenc and VTT (Safety Engineering Laboratory, Tampere, Finland) and the results are shown in Table 2.4a. However, accurate comparisons between lab-scale methods (Rhone Poulenc & VTT) and INERIS are difficult because lab-scale methods use pure chemicals and INERIS use fully commercial grades.

Table 2.4a Emission factors – nitrogen-based pesticides (Marlair *et al.*, 1996a).

Substance	Fire tests on diuron (mg g ⁻¹)		Fire tests on dimethoate (mg g ⁻¹)		
	INERIS (large scale) (b)	Rhone-Poulenc (Tewarson)	INERIS (large scale) (b)	VTT (50 kW m ⁻²)	VTT (25 kW m ⁻²)
CO ₂	1,136	843	(a)	(a)	(a)
CO	68	78	(a)	(a)	(a)
NO _x	25	5	2	14	4.5
HCN	13	13	8	6.7	5.2
HCL	160	144	-	-	-
SO ₂	-	-	175	560	510
CH ₃ SH	-	-	88	Not determined	Not determined
Soot	Yes	Yes	Yes	-	-
Residue	Yes	Yes	Yes	Not reported	Not reported

(a) Not relevant, tests done on pure substance, contrary to large scale INERIS tests

(b) Refers to the pure active chemical

Further analysis at INERIS (Marlair *et al.*, 1996b) has revealed emission factors for the burning of organophosphorus insecticides (Table 2.4b).

Table 2.4b Emission factors – organophosphorus insecticides^a (Marlair *et al.*, 1996b).

Substance	Fire tests on chlormephos (g g ⁻¹)	Fire tests on phosalone (g g ⁻¹)
CO ₂	0.508	0.531
CO	0.075	0.093
NO _x	Not pertinent	0.004
HCN	Not pertinent	0.004
HCL	0.150	0.062
SO ₂	0.237	0.277

Tests carried out on the AT CRIT calorimeter.

2.4 Emission Factors – Automobiles

Although there are only 12 recorded automobile-related fires in the NIRS list for 2006-07, reports from Sweden (Lönnermark and Blomqvist, 2006) suggest that in the period 1985-1999, 11 per cent of all fires reported to their fire and rescue service were vehicle-related. The amount of combustible material within an automobile is given as 150-200 kg and almost all is consumed in the fire. Depending on the size of automobile, this mass includes up to 115 kg of polymer, the remainder being oil and fuel. Tests showed that many automobile components contained nitrogen (such as polyurethane) and were capable of producing hydrogen cyanide and other nitrogen-containing compounds (Tables 2.5a, 2.5b and 2.5c). Potentially harmful compounds are present in seat upholstery, which on combustion produce hydrogen chloride and sulphur dioxide. Although hydrogen bromide was not detected, brominated flame retardants are components of modern day automobiles and hydrogen bromide could have been present at levels below the 10 ppm detection limit.

Table 2.5a Yield (mass of species produced relative to mass of combustible material consumed) of inorganic gas components from burning automobiles (Lönnermark and Blomqvist, 2006).

Species	Total amount (kg)	Yield (g kg ⁻¹)
CO ₂	265	2400
CO	6.9	63
HCN	0.17	1.6
HCl	1.4	13
SO ₂	0.54	5.0

Table 2.5b Volatile organic compounds (VOC)^a expressed as toluene equivalents from burning automobiles (Lönnermark and Blomqvist, 2006).

Compound	Total amount (g)	Yield (g kg ⁻¹)
Benzene	322	3.0
Toluene	71.9	0.66
Styrene	54.1	0.50
Ethyl benzene	19.2	0.18
Phenol	39.1	0.36
Benzonitrile	25.0	0.23
Indene	15.3	0.14
Total VOC ^b	928	8.5

^a Naphthalene is included with the other PAH compounds (Table 2.7).

^b VOC includes xylene, ethyl benzene, alpha-methyl styrene, limonene, phthalic anhydride and biphenyl.

Polycyclic aromatic hydrocarbons (PAH) were adsorbed and analysed during the tests. The total adsorbed amount comprised 21 species, dominated by the lighter PAHs (naphthalene and acenaphthalene) which were expected to be gaseous. Particle-bound PAHs were generated in greatest quantity when the fire was burning vigorously.

Table 2.5c Compounds in fire gas analysis from burning automobiles (Lönnermark and Blomqvist, 2006).

Compounds	Total amount (g)	Yield (mg kg ⁻¹)
Formaldehyde	118	1,100
Acetaldehyde	63	580
Acrolein	<30	<300
Isocyanate acid	22.6	210
Methyl Isocyanate	0.65	6.0
Ethyl isocyanate	0.027	0.25
Phenyl isocyanate	1.07	9.8
2,4-Toluene di-isocyanate	0.786	7.2
2,6-Toluene di-isocyanate	0.569	5.2
Hexamethyl di-isocyanate	0.068	0.62
2,4-Toluene aminoisocyanate	0.068	0.62
2,6-Toluene aminoisocyanate	0.447	4.1
PAH total	119	1100
PAH (particle bound)	10.1	93
Total PCDD	2.34 x 10 ⁻⁴	2.1 x 10 ⁻³
Total PCDF	6.13 x 10 ⁻³	5.6 x 10 ⁻²
TCDD I-TEQ ^c max ^a	8.68 x 10 ⁻⁵	8 x 10 ⁻⁴
TCDD I-TEQ ^c min ^b	7.1 x 10 ⁻⁵	6.5 x 10 ⁻⁴

^a Mass of congeners below detection limit was set equal to the detection limit

^b Mass of congeners below the detection limit was set equal to zero.

^c Toxic equivalent factors.

Particles in the fire gases were analysed by Lönnermark *et al.* (2005) and the size fraction with the highest number count was found to be around 0.1 µm, that is, respirable particles that can penetrate deep into the lungs. The filtered captured particles were analysed for metals and halogens and revealed high concentrations of zinc, lead and chlorine (Table 2.6).

Table 2.6 Analysis of particulate matter in fire gases from burning automobiles (Lönnermark and Blomqvist, 2006). Total yield is the amount of particle bound species produced per amount of combusted automobile.

Compound	Amount on the particles (mg kg ⁻¹)	Total yield (mg kg ⁻¹)
Arsenic (As)	4	0.26
Cadmium (Cd)	26	1.7
Cobalt (Co)	5	0.32
Chromium (Cr)	59	3.8
Copper (Cu)	430	27
Manganese (Mn)	89	5.7
Nickel (Ni)	44	2.8
Lead (Pb)	12,800	820
Antimony (Sb)	230	15
Thallium (Th)	<80	<5.1
Vanadium (V)	7	0.45
Zinc (Zn)	50,300	3,200
Fluorine (F)	510	33
Chlorine (Cl)	39,000	2,500
Bromine (Br)	4,000	260

Lozo (1999) updated the USEPA AP-42 data and assumed that tyres are burned in 60 per cent of automobile fires, that the average car body weighs 3,700 lbs (1,678 kg) and the components (upholstery, belts, hoses and tyres) weigh 500 pounds (227 kg). The composite emission factors listed in Table 2.7 are produced in this case.

Table 2.7 Composite emissions for automobile fires (lb fire⁻¹) (Lozo, 1999).

Total Organics (TOG)	CO	NO _x	SO _x	PM
7.21	21.25	0.7	0	17.0

2.5 Emission Factors – Buildings

The Swedish Fire Protection Association (Persson and Simonson, 1998) has collected statistics on damage from fires based on details reported to their nation's insurance agencies (Tables 2.8a, 2.8b and 2.8c). The statistics include all reported occurrences from the inconsequential to the major event; major events are defined where the financial cost is greater than one million Kronor. The scale of fire is defined by the amount of material consumed in the fire. Data from 1994 are used as the basis for annual emission calculations and buildings are subdivided into commercial and domestic premises. It was found that materials within houses and apartments are composed of wood, paper and textiles and that their distribution within buildings is not critical to the emissions. These data enabled extrapolation to schools. The values for emissions from wood are likely to be higher than those that would be experienced in the UK because of the high wood composition of Swedish buildings.

Table 2.8a Emissions (kg/house) from the burning of houses (Persson and Simonson, 1998).

Material	CO ₂	CO	NO _x	HCN	HCl
Wood	4,531.4	161.2	3.9	0.028	0.0
Paper	1,180.8	41.8	1.0	0.007	0.0
Textiles	1,029.6	36.7	0.9	0.006	0.0
PVC	350.4	27.8	0.1	0.002	76.8
Polyurethane	477.6	38.4	21.6	0.432	0.0
Polyethylene	282.0	6.0	0.2	0.002	0.0

Table 2.8b Emissions (kg/apartment) from the burning of apartments (Persson and Simonson, 1998).

Material	CO ₂	CO	NO _x	HCN	HCl
Wood	3,031.8	107.9	2.6	0.019	0.0
Paper	787.2	27.8	0.7	0.005	0.0
Textiles	686.4	24.5	0.6	0.004	0.0
PVC	233.6	18.6	0.1	0.001	51.2
Polyurethane	318.4	25.6	14.4	0.288	0.0
Polyethylene	169.2	3.6	0.1	0.001	0.0

Table 2.8c Emissions (kg/school) from the burning of schools (Persson and Simonson, 1998).

Material	CO ₂	CO	NO _x	HCN	HCl
Wood	6,520.0	232.0	5.6	0.040	0.0
Paper	2,624.0	92.8	2.2	0.016	0.0
Textiles	1,144.0	40.8	1.0	0.007	0.0
PVC	2,336.0	185.6	1.0	0.014	512.0
Polyurethane	0.0	0.0	0.0	0.0	0.0
Polyethylene	0.0	0.0	0.0	0.0	0.0

If the period of burning is known, an emission rate of pollutant may be determined for each material present in the building.

In a report to assess the impact of training scenarios at the Fire Service College in Moreton-in-Marsh (Entec, 2006), a modelling scenario was compiled to reflect the effects of burning within a commercial building. Theoretical mass burning rates have been assimilated from the literature and used to develop ADMS 3.3 model input rates (Table 2.9).

Table 2.9 Volume emission rates for buildings (Entec, 2006).

Pollutant	Building type emission rate ($\text{g m}^{-3} \text{s}^{-1}$)	
	Commercial	Industrial
CO	1.44×10^{-4}	2.41×10^{-4}
SO ₂	1.52×10^{-6}	2.54×10^{-6}
NO _x	6.49×10^{-5}	1.08×10^{-4}
PM ₁₀	1.03×10^{-5}	1.73×10^{-5}

2.6 Emission Factors – Timber

The pressure treatment of timber with copper, chromium and arsenic (CCA) solutions results in metal concentrations of 0.1-0.3 per cent of the treated wood mass. On combustion the metals partition to the fly ash or residual ash. Between 11-14 per cent of the arsenic (As) is emitted with fly ash, but less than one per cent of the copper (Cu) and chromium (Cr). This reflects the lower boiling point of As (613°C) compared with Cr (2672°C) and Cu (2567°C). Limited sampling for dioxins and furans indicates that the burning of CCA-treated wood results in atmospheric emissions consistent with the burning of untreated wood. Emission factors (Table 2.10) are quoted by Wasson *et al.* (2005) as milligrams of pollutant per kilogram of wood burned.

Table 2.10 Emission factors within fly ash for burning of aged CCA-treated wood fly ash samples (mg kg^{-1}) (Wasson *et al.*, 2005).

Substance	Iso-kinetic sampling
Total particulate	$1.46 - 1.95 \times 10^3$
Copper	8.7 - 13.4
Chromium	8.4 - 22
Arsenic	188 - 237
PCDD/F	8×10^{-5}

A range of PCDD/F emission factors are presented (Defra, 2006b) for domestic wood burning which do not differentiate between seasoned and unseasoned wood (Table 2.11).

Table 2.11 Emission factors for domestic wood burning (Defra, 2006b).

Type of wood	Emission factor
Clean	$0.043 - 11 \mu\text{g ITEQ tonne}^{-1}$ to air ^a
	$0.01 - 0.6 \mu\text{g ITEQ tonne}^{-1}$ in residues (range of three values).
Contaminated	$11 - 400 \mu\text{g ITEQ tonne}^{-1}$ to air ^b
	$1 - 60 \mu\text{g ITEQ tonne}^{-1}$ in residues (range of three values).

^a Expressed as the 5th to 95th percentile range of 11 values.

^b Expressed as the 5th to 95th percentile range of seven values.

Studies in India (Venkataraman *et al.*, 2002) on wood-burning in open stoves has generated emission factors subdivided into a range of PAH groups (Figure 2.12).

Table 2.12 PAH emission factors (EF) from wood-burning stoves (Venkataraman *et al.*, 2002).

Number of repeat experiments	Total EF (mg kg ⁻¹)	Semi-volatile ^a EF (mg kg ⁻¹)	Non-volatile ^b EF (mg kg ⁻¹)
4	2.3	1.5	0.8
4	2.0	1.3	0.7
4	2.3	1.5	0.8
4	3.2	1.9	1.3

^a Fluroanthene, pyrene, benz(a)anthracene, chrysene.

^b Benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, dibenzanthracene, benzo(ghi)perylene, indeno(c,d)pyrene.

2.7 Emission Factors – Tyre Burning

Rubber tyres are made of very combustible materials, including carbon, oil, benzene, toluene, rubber and sulphur. Tyres are not easy to ignite because they are designed to absorb heat generated by the friction resulting from contact with the road. However, the property to absorb heat also makes it difficult to extinguish a fire once a tyre ignites. The high carbon content and steel cords serve as a heat sink within the tyre and although extinguishing cools the tyre from a flaming to a smouldering stage, the stored heat can re-ignite the tyre. Burning tyres decompose into heavy metals, gases and oils and tyres burn with a higher heat output per kg than most coals. When tyres burn in the smouldering stage, vast amounts of smoke, combustion products and toxic chemicals are produced. When tyre fires burn freely, fewer products of combustion are produced and most toxic chemicals are consumed (Poole, 1998).

Burning tyre emissions (Tables 2.13a, 2.13b and 2.13c) are dependent upon the burn rate of the tyre (AP-42 Section 2.5.4). It is recommended to use tyre in the form of “chunks” as opposed to “shredded” to estimate emissions from an accidental tyre fire.

Table 2.13a Particulate mass emission factors from open burning of tyres (USEPA, 1995), emission factor rating D.

Pollutant	Chunks^b mg kg⁻¹ tyre	Shredded^b mg kg⁻¹ tyre
Aluminium	3.07	2.37
Antimony	2.94	2.37
Arsenic	0.05	0.20
Barium	1.46	1.18
Calcium	7.15	4.73
Chromium	1.97	1.72
Copper	0.31	0.29
Iron	11.80	8.00
Lead	0.34	0.10
Magnesium	1.04	0.75
Nickel	2.37	1.08
Selenium	0.06	0.20
Silicon	41.00	27.52
Sodium	7.68	5.82
Titanium	7.35	5.92
Vanadium	7.35	5.92
Zinc	44.96	24.75

^b Weighted average.

Table 2.13b PAH mass emission factors from open burning of tyres (USEPA, 1995), emission factor rating D.

Pollutant	Chunks^{bc} mg kg⁻¹ tyre	Shredded^{bc} mg kg⁻¹ tyre
Acenaphthene	718.20	2,385.60
Acenaphthylene	570.20	568.08
Anthracene	265.60	49.61
Benzo(a)pyrene	173.80	115.16
Benzo(b)fluoranthene	183.10	89.07
Benzo(g,h,i)perylene	36.20	160.84
Benzo(k)fluoranthene	281.80	100.24
Benz(a)anthracene	7.90	103.71
Chrysene	48.30	94.83
Dibenz(a,h)anthracene	54.50	0.00
Fluranthene	42.30	463.35
Fluorene	43.40	189.49
Indeno(1,2,3-cd)pyrene	58.60	86.38
Naphthalene	0.00	490.85
Phenanthrene	28.00	252.73
Pyrene	35.20	153.49

^b Weighted average.

^c 0.00 values indicate pollutant was not found

Table 2.13c Emission factors for organic compounds from open burning of tyres (USEPA, 1995), emission factor rating C.

Pollutant	Chunks^{bc} mg kg⁻¹ tyre	Shredded^{bc} mg kg⁻¹ tyre
1,1' Biphenyl, methyl	12.71	0.00
1h Fluorene	191.27	315.18
1-Methyl naphthalene	299.20	227.87
Acenaphthalene	592.70	549.32
Benzaldehyde	223.34	322.05
Benzene	1,526.39	1,929.93
Benzodiazine	13.12	17.43
Benzofuran	40.62	0.00
Benzothiophene	10.31	914.91
Benzo(b)thiophene	50.37	0.00
Benzisothiazole	0.00	151.66
Biphenyl	190.08	329.65
Butadiene	117.14	138.97
Cyanobenzene	203.81	509.34
Cyclopentadiene	67.40	0.00
Dihydroindene	9.82	30.77
Dimethyl benzene	323.58	940.91
Dimethyl hexadiene	6.22	73.08
Dimethyl naphthalene	35.28	155.28
Dimethyldihydro indene	5.02	27.60
Ethenyl dimethyl benzene	11.50	196.34
Ethenyl methyl benzene	12.48	21.99
Ethenyl benzene	539.72	593.15
Ethenyl cyclohexene	4.85	89.11
Ethylenylmethyl benzene	103.13	234.59
Ethyl, methyl benzene	79.29	223.79
Ethyl benzene	138.94	335.12
Ethynyl, methyl benzene	459.31	345.25
Ethynyl benzene	259.82	193.49
Heptadiene	6.40	42.12
Hexahydro azepinone	64.35	764.03

Table 2.13c continued. Emission factors for organic compounds from open burning of tyres (USEPA, 1995), emission factor rating C.

Pollutant	Chunks^{bc} mg kg⁻¹ tyre	Shredded^{bc} mg kg⁻¹ tyre
Indene	472.74	346.23
Isocyano benzene	283.78	281.13
Isocyano naphthalene	10.75	0.00
Limonene	48.11	2,309.57
Methyl, ethenyl benzene	21.15	67.05
Methyl, methylethenyl benzene	35.57	393.78
Methyl, methylethyl benzene	109.69	1,385.03
Methyl benzaldehyde	0.00	75.49
Methyl benzene	1,129.80	1,395.04
Methyl cyclohexene	3.91	33.44
Methyl hexadiene	15.59	102.20
Methyl indene	50.04	286.68
Methyl, methylethyl benzene	11.76	114.33
Methyl naphthalene	144.78	122.68
Methyl, propyl benzene	0.00	30.14
Methyl thiophene	4.39	10.52
Methylene indene	30.37	58.91
Methylethyl benzene	41.40	224.23
Phenol	337.71	704.90
Propenyl, methyl benzene	0.00	456.59
Propenyl naphthalene	26.80	0.00
Propyl benzene	19.43	215.13
Styrene	618.77	649.92
Tetramethyl benzene	0.00	121.72
Thiophene	17.51	31.11
Trichlorofluoromethane	138.10	0.00
Trimethyl benzene	195.59	334.80
Trimethyl naphthalene	0.00	316.26

^b Weighted average.

^c 0.00 values indicate pollutant was not found

2.8 Emission Factors – Paper

A report by Entec (2006) which assesses the impact of atmospheric emissions from training activities at the Fire Service College includes emission factors for paper taken from the National Atmospheric Emissions Inventory (NAEI) database using their data on wood combustion (Table 2.14).

Table 2.14 Emission factors (g kg⁻¹) from paper combustion (Entec, 2006).

NO_x as NO₂	PM₁₀	CO	SO₂	Benzene (as VOC)
1,640	11	58	0.03	0.24

2.9 Emission Factors – Oil

Following ambient sampling of hydrocarbon emissions from the controlled burning of 500 gallons of crude and fuel oils in large open tanks, emission ratios relative to carbon dioxide were identified and the emission factors listed in Table 2.15 constructed (Booher and Janke, 1997). It is stated that the majority of carbon from hydrocarbon fires is emitted

as CO₂ (92%), CO (3%) and smoke (elemental carbon) (5%). Lesser amounts of uncombusted volatile organic compounds (<1%), aldehydes and ketones (<1%), NO_x and SO_x are also emitted. No metals were detected.

Table 2.15 Emissions from burning pools of liquid fuels (Booher and Janke, 1997).

Class	Compound	Emission (mg kg ⁻¹ material burned)		
		Fuel oil	Crude oil	
VOC	Benzene	1,022	251	
	Toluene	42	-	
	Ethyl benzene	10	-	
	Xylenes	25	-	
	Nonane	13	-	
	Ethyl toluene	22	-	
	1,2,4-Trimethylbenzene	32	-	
	Carbonyl	Formaldehyde	303	139
Acetaldehyde		63	32	
Acrolein		39	11	
Crotonaldehyde		6	-	
Methylketone		13	7	
Benzaldehyde		104	44	
Isovaleraldehyde		17	5	
<i>p</i> -Tolualdehyde		-	13	
Methylisobutylketone		11	-	
2,5-Dimethylbenzaldehyde		13	-	
PAH		Naphthalene	1,623	44
		Acenaphthylene	99	4
	Acenaphthene	10	-	
	Fluorene	1	0.5	
	1-Methylfluorene	26	0.2	
	Phenanthrene	13	6	
	Anthracene	15	1	
	Fluoranthene	20	4	
	Pyrene	2	5	
	Benzo(<i>a,b</i>)fluorine	4	0.3	
	Benzo(<i>a</i>)anthracene	5	1	
	Chrysene	9	1	
	Benzo(<i>b&k</i>)fluoranthene	7	2	
	Benzo(<i>a</i>)pyrene	5	1	
	Indenol(1,2,3- <i>cd</i>)pyrene	5	1	
	PCDD/F	TCDD	-	-
		PeCDD	-	-
HxCDD		-	-	
HpCDD		-	7.07 x 10 ⁻⁵	
OCDD		-	1.34 x 10 ⁻⁴	
TCDF		-	2.05 x 10 ⁻⁴	
PeCDF		-	-	
HxCDF		-	1.86 x 10 ⁻⁵	
HpCDF		-	-	
OCDF		-	-	
Total PCDD/F		-	4.28 x 10 ⁻⁴	

In addition, Entec (2006) includes emission factors for red diesel (agricultural gas oil) taken from the NAEI database (Table 2.16).

Table 2.16 Emission factors (g kg⁻¹) from red diesel combustion (Booher and Janke, 1997).

NO _x as NO ₂	PM ₁₀	CO	SO ₂	Benzene (as VOC)
2.4	0.22	0.61	2.27	-

- Indicates that no emission values are available.

2.10 Emission Factors – Plastics

Agricultural plastic film is used in ground cover activities to help maintain soil moisture content and to prevent the propagation of weeds. The material is burned either in piles or in forced air conditions in an air curtain. The condition of the plastic influences the emission factors. Emission factors in Tables 2.17a/b are taken from USEPA (1995).

Table 2.17a Emissions factors (mg kg⁻¹) for organic compounds from burning agricultural plastic film (USEPA, 1995), emission factor rating C.

Pollutant	Condition of plastic			
	Unused		Used	
	Pile ^a	Forced air ^b	Pile ^a	Forced air ^b
Benzene	0.0478	0.0288	0.0123	0.0244
Toluene	0.0046	0.0081	0.0033	0.0124
Ethyl Benzene	0.0006	0.0029	0.0012	0.0056
1-Hexane	0.0010	0.0148	0.0043	0.0220

^a Emission factors for plastic gathered into a pile.

^b Emission factors for plastic burned in a pile with a forced air current.

Table 2.17b PAH emission factors (µg kg⁻¹ plastic film) from open burning of agricultural plastic film (USEPA, 1995), emission factor rating C.

Pollutant	Conditions of plastic			
	Unused		Used	
	Pile ^a	Forced air ^b	Pile ^a	Forced air ^b
Anthracene	7.14	0.66	1.32	0.40
Benzo(A)pyrene	41.76	1.45	7.53	0
Benzo(B)fluoranthene	34.63	1.59	9.25	0.93
Benzo(e)pyrene	32.38	1.45	9.65	0
Benzo(G,H,I)perylene	49.43	2.11	14.93	0
Benzo(K)fluoranthene	13.74	0.66	2.51	0
Benz(A)anthracene	52.73	2.91	14.41	1.19
Chrysene	54.98	3.70	17.18	1.19
Fluoranthene	313.08	53.39	107.05	39.12
Indeno(1,2,3-CD)pyrene	40.04	2.78	10.70	0
Phenanthrene	60.40	12.56	24.05	8.72
Pyrene	203.26	18.24	58.81	5.95
Retene	32.38	2.91	18.77	3.04

^a Emission factors for plastic gathered into a pile.

^b Emission factors for plastic burned in a pile with a forced air current.

Other agricultural activities result in the burning of plastic bags which previously contained pesticides. Emission factors are given in Table 2.18 (Lemieux *et al.*, 2004).

Table 2.18 Emissions from the open burning of plastic pesticide bags^a (mg kg⁻¹ burned) (Lemieux *et al.*, 2004).

Class	Compound	Empty thimet bags	Thimet bags	Empty atrazine bags	Atrazine bags	
VOC	Acetone	140	630	140	220	
	Benzene	50	850	120	220	
	2-Butanone	120	100	20	30	
	Chloromethane	10	70	10	10	
	Ethyl benzene	50	50	10	20	
	Methylene chloride	40	840	30	220	
	Styrene	140	120	20	90	
	Toluene	70	360	20	120	
	Xylenes	110	110	-	10	
	SVOC	Phenol	84	130	8	20
2-Cresol		-	60	-	-	
4-Cresol		37	100	-	3	
2,4-Dimethylphenol		12	30	-	-	
2-Methylnaphthalene		8	20	-	10	
Benzoic acid		-	-	-	90	
Dibenzofuran		4	8	-	-	
Diethylphthalate		-	-	-	3	
Bis(2-ethylhexyl)phthalate		-	8	-	-	
Thimet		-	180	-	-	
Atrazine		-	-	-	420	
PAH		Naphthalene	370	230	49	130
		Acenaphthalene	12	30	-	-
	Fluorene	4	9	-	-	
	Phenanthrene	13	20	-	-	
	Fluoranthene	3	6	-	-	
	Pyrene	3	6	-	-	
	PCDD/F	TCDD	-	-	-	8 x 10 ⁻⁶
PeCDD		-	-	-	-	
HxCDD		-	-	-	2.7 x 10 ⁻⁵	
HpCDD		-	-	-	1 x 10 ⁻⁴	
OCDD		-	-	-	4 x 10 ⁻⁵	
TCDF		-	-	-	6.7 x 10 ⁻⁶	
PeCDF		-	-	-	-	
HxCDF		-	-	-	3.3 x 10 ⁻⁵	
HpCDF		-	-	-	3.3 x 10 ⁻⁵	
OCDF		-	-	-	-	
TEQ		-	-	-	9 x 10 ⁻⁶	

^a Bags assumed to weigh 0.1 kg

2.11 Emission Factors – Bonfires

The substances of greatest concern that are generated by bonfires and fireworks are polychlorinated dibenzo-p-dioxins (dioxins), polychlorinated dibenzofurans (furans) and co-planar dioxin-like polychlorinated biphenyls (PCB).

A report by Defra (2006b) states that the potential for domestic combustion processes to generate dioxins and dioxin-like PCBs is increased by:

- poor combustion conditions, such as low oxygen levels, low flame temperature, poor mixing of oxygen and fuel;
- increased moisture level in the fuel;
- increased chlorine content of the fuel;
- presence of metals and absence of sulphur in the fuel.

Polycyclic aromatic hydrocarbons (PAH) and dioxins/dioxin-like PCBs are products of incomplete combustion. Elements of incomplete combustion, which are all likely to exist in bonfires and open burning of waste include:

- low flame temperatures;
- incomplete mixing of fuel and oxygen;
- low residence times at high temperatures.

Bonfire combustion conditions are seen to influence emission factor ranges (Table 2.20). Poorly constructed bonfires (with wet wood and poor air flow) are thought to comprise half of all bonfires. The use of contaminated materials (wood coated with pesticides or preservatives), damp wood, wet ground and low supplies of air results in smouldering. Smouldering wood is responsible for relatively high dioxin and furan emissions (Defra, 2006b).

Table 2.20 PCDD/F emission factors from bonfires (Defra, 2006b).

Bonfire combustion condition	Emission factor
Good	0.5 - 20 µg ITEQ tonne ⁻¹ to air ^a
Poor	20 - 30 µg ITEQ tonne ⁻¹ to air ^a
All bonfires	10 µg ITEQ tonne ⁻¹ to air ^b

^a Range of two values.

^b Single value.

Using several assumptions about the construction and burning time of bonfires, Defra (2006a) proposed typical emission factors and pollutant emission rates for the burning of green waste in a typical domestic bonfire (3 m³) (Table 2.21).

Table 2.21 Green waste bonfire emission factors (Defra, 2006a).

	PM ₁₀	CO	Methane TOC	Non-Methane TOC
Emission factor (kg t ⁻¹)	4.8	42	1.7	5.4

Defra (2006a) has also given emission factors for the open burning of a range of agricultural materials (Table 2.22).

Table 2.22 Emission factors from open burning of agricultural material and leaves (kg t⁻¹) (Defra, 2006a).

Refuse category	PM₁₀	CO	Methane TOC	Non-Methane TOC
Unspecified field crops	11	58	2.7	9
Corn	7	54	2	6
Weeds	8	42	1.5	7.2
Forest residues	8	70	2.8	9
Leaves	19	56	6	14

2.12 Emission Factors – Fireworks

Laboratory scale deflagration of a variety of popular fireworks was carried out by Fleischer *et al.* (1999). On deflagration, very small levels of contaminants were found to transfer from the firework to the remaining ash and paper. The most toxic contaminant, 2,3,7,8-TCDD, could not be detected in any of the samples and there were no indications that PCDD/F emissions from fireworks may cause air pollution.

3 Emission Factors Gap Analysis

Of the various sectors of open burning that have featured in this review, the principal gaps in emission factor data lie within the following sectors:

- Fireworks – emissions of inorganic substances (metallic salts) in particulate form.
- Chemicals – factors are limited to the combustion of a few substances.
- Copper wire – limited factors on PCDD/F emissions resulting from the removal of insulation.
- Buildings – factors are generic for houses, apartments and schools and the variability is unknown.
- Vehicles – factors are based on Swedish vehicles from 1985-1999.
- Domestic waste – large range between maximum and minimum constituent groups.
- Landfill cells – emissions from sub-surface fires.

The development or identification of emission factors in these areas would assist the Environment Agency in forming a more complete picture of emissions from the open burning of materials.

A further difficulty in using the emission factors listed in this report is the need to estimate the stock at risk (such as the amount of material in a house and amount of plastic/pesticide in a typical pesticide drum) and the rate of burn. Future studies should aim to draw together a database of such values.

Emission factors from forest fires and biomass burning were not considered in this report as no fires from such sources were recorded by NIRS during 2006-07. However, as a result of the Agency's recent new role as the lead in coordinating air quality monitoring during major incidents, it would be useful to undertake further work to identify emission factors from such fires.

4 Summary and Conclusions

Emission factors are presented in the literature in a variety of units. From the original categorisation of NIRS reported incidents in 2006-07, it has been possible to identify emission factors for most categories. Although emission factors for the burning of insulation from copper wire are missing, the principal source of metal combustion would appear to be the burning of vehicles which are covered in more detail.

Testing in under-ventilated large scale combustion facilities (Mansson *et al.*, 1996) has shown that predicted outcomes can be taken as a model for real-life fires providing studies are limited to burning systems of modest complexity.

Anthropogenic emissions from some open-burning sources can make a significant contribution to the national inventories of some pollutants (Lemieux *et al.*, 2004). For example, while emissions of PCDD/F from incineration have fallen due to tighter legislation, the production of these persistent organic chemicals from open-burning sources can be expected to increase. Persson and Simonson (1998) add that by studying emissions from fires, the importance of fires as a pollutant source may be established, and the information can influence the choice of whether to fight fires or not based on environmental grounds.

Studies have identified sub-surface landfill fires as a potential source of dioxin and furan emissions but these emissions have generally not yet been quantified due to a lack of information (such as on quantity/type of waste consumed and combustion conditions) on the fires themselves (Environment Agency, 2007).

The derivation of emission factors by the USEPA and Defra are based on USEPA emissions data. It is unknown how emission factors developed in North America relate to scenarios in the UK. Defra (2006a) recommends measures to develop emission factors across a range of pollutants from the various stages in a bonfire's life. Such factors would assist the Environment Agency in estimating emissions to atmosphere from the most prominent sector within the latest complete record of incident recordings.

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List of abbreviations

Defra	Department for Environment, Food and Rural Affairs
EF	Emissions factors
ER	Emissions ratios
INERIS	French National Institute for Industrial Environment and Risks
ITEQ	International Toxic Equivalent
kg	Kilogram 1×10^3
mg	Milligram 1×10^{-3}
Mg	Megagram 1×10^6
NAEI	National Atmospheric Emissions Inventory
NIRS	National Incident Recording System
PAHs	Polycyclic aromatic hydrocarbons
PCBs	Polychlorinated biphenyls
PCDDs	Polychlorinated dibenzo- <i>p</i> -dioxins (dioxins)
PCDFs	Polychlorinated dibenzofurans (furans)
ppm	Parts per million
PVC	Polyvinyl chloride
RCC	Regional Control Centre
SCC	Source Classification Codes
SVOCs	Semi-volatile organic compounds
TCDD	Tetrachlorodibenzo- <i>p</i> -dioxin
TOC	Total organic compounds
USEPA	United States Environmental Protection Agency
VOCs	Volatile organic compounds

Appendix A

Dioxins, furans, PCBs and their toxic equivalency quotient (TEQ)

Dioxins, furans and dioxin-like PCB are unwanted byproducts of combustion. When emissions from a combustion process are measured, it is usual to report the levels of individual chemicals multiplied by a factor to reflect the toxicity of each individual substance. This is the “toxic equivalent” or “toxic equivalency quotient” (TEQ) value. There is more than one scheme for toxic equivalence factors. The most widespread are the NATO Committee on the Challenges of Modern Society (NATO-CCMS) values (dioxins and furans only) and the World Health Organisation (WHO) values from 1998. The WHO98 scheme includes updated toxic equivalence values for PCBs. The NATO-CCMS values are also known as International TEQ values, referred to as ITEQ (Defra, 2006b).

Table of toxic equivalence factors.

	ITEQ	NATO-CCMS	WHO98
2,3,7,8-TetraCDD	1	1	1
1,2,3,7,8-PentaCDD	0.5	0.5	1
1,2,3,4,7,8-HexaCDD	0.1	0.1	0.1
1,2,3,6,7,8-HexaCDD	0.1	0.1	0.1
1,2,3,7,8,9-HexaCDD	0.1	0.1	0.1
1,2,3,4,6,7,8-HeptaCDD	0.01	0.01	0.01
1,2,3,4,6,7,8,9-OctaCDD	0.001	0.001	0.001
2,3,7,8-TetraCDF	0.1	0.1	0.1
1,2,3,7,8-PentaCDF	0.05	0.05	0.05
2,3,4,7,8-PentaCDF	0.5	0.5	0.5
1,2,3,4,7,8-HexaCDF	0.1	0.1	0.1
1,2,3,6,7,8-HexaCDF	0.1	0.1	0.1
2,3,4,6,7,8-HexaCDF	0.1	0.1	0.1
1,2,3,7,8,9-HexaCDF	0.1	0.1	0.1
1,2,3,4,6,7,8-HeptaCDF	0.01	0.01	0.01
1,2,3,4,7,8,9-HeptaCDF	0.001	0.001	0.001
1,2,3,4,6,7,8,9-OctaCDF	0.001	0.001	0.001
3,3',4,4'-TetraCB (PCB 77)	-	-	0.0001
3,4,4',5'-TetraCB (PCB 81)	-	-	0.0001
2,3,3',4,4'-PentaCB (PCB 105)	-	-	0.0001
2,3,4,4',5'-PentaCB (PCB 114)	-	-	0.0005
2,3',4,4',5'-PentaCB (PCB 118)	-	-	0.0001
2',3,4,4',5'-PentaCB (PCB 123)	-	-	0.0001
3,3',4,4',5'-PentaCB (PCB 126)	-	-	0.1
2,3,3',4,4',5'-HexaCB (PCB 156)	-	-	0.0005
2,3,3',4,4',5',5'-HexaCB (PCB 157)	-	-	0.0005
2,3',4,4',5,5'-HexaCB (PCB 167)	-	-	0.00001
3,3',4,4',5,5'-HexaCB (PCB 169)	-	-	0.01
2,3,3',4,4',5,5'-HeptaCB (PCB 189)	-	-	0.0001

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