AEAT/R/ENV/0518 Issue 1

# Determination of Atmospheric Pollutant Emission Factors at a Small Industrial Wood-Burning Furnace

A report produced for the Department of the Environment, Transport and the Regions, the National Assembly for Wales, the Scottish Executive and the Department of the Environment for Northern Ireland

AEA Technology Environment

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# Executive Summary

AEA Technology has undertaken a programme of measurements at a wood-burning plant to determine pollutant emission factors for the Department of Environment, Transport and the Regions (DETR), the National Assembly for Wales, the Scottish Executive and the Department of the Environment for Northern Ireland. The emission factor data are intended for further development of the UK National Atmospheric Emissions Inventory (NAEI) which is maintained by AEA Technology on behalf of DETR.

Emission measurements were undertaken at a furnace burning joinery waste from a furniture factory. The SNAP code for the furnace is 020103. Emission factors were determined for the following determinands :

- Polychlorinated dibenzo-p-dioxins (PCDD)
- Polychlorinated dibenzofurans (PCDF)
- Polychlorinated biphenyls (PCB)
- Polycyclic aromatic hydrocarbons (PAH)
- $PM_{10}$
- $PM_{2.5}$
- Carbon Monoxide
- Total Particulate Matter (TPM)

A summary of the emission factors determined in the programme is provided in the following table.

| **Pollutant** | **Emission factor** | |
|---|---|---|
| | **ng $kg^{-1}$** | **ng $MJ^{-1}$** |
| | | |
| Total PCDD/F (ITEQ) | 13 | 0.72 |
| Total PCB | 556 | 32 |
| Total PCB (ITEQ) | 0.37 | 0.021 |
| Total PAH | 41,000 | 2,300 |
| | **g $kg^{-1}$** | **g $MJ^{-1}$** |
| $PM_{10}$ | 0.44 | 0.025 |
| $PM_{2.5}$ | 0.37 | 0.021 |
| TPM | 0.46 | 0.026 |
| CO | 2.58 | 0.150 |

**Notes :**
1. Factors are calculated for mass of wood **as burned** and for **net** thermal input.
2. See main text for speciated PCDD/F, PCB and PAH emission factors.

This work indicates that the NAEI PAH data may overestimate emissions from industrial wood combustion by several orders of magnitude. It is recommended that the NAEI considers adopting PAH emission factors from this investigation or from USEPA. The Naphthalene emission factor determined in this investigation is not proposed for inclusion in the NAEI as it likely to underestimate emissions.

In the absence of other PAH data, the conservative approach may be to adopt the highest factors for each compound. The data should be assessed by the NAEI to determine if emissions are significant and if further emission measurements are required to improve uncertainty for the source sector.

This work indicates that the PAH data published by EMEP/Corinair may overestimate emissions from industrial wood combustion by several orders of magnitude. In addition, the PAH emission factors determined for this wood furnace indicate that the EMEP/Corinair PAH emission profile may not be applicable to UK industrial wood combustion.

Emission factors for dioxins and furans from wood combustion are higher than the current NAEI factor and USEPA default factors. In the absence of data specific to UK processes and to provide a 'worst case' emission inventory it is recommended that the NAEI adopt emission factors from this investigation. The significance of the emission from industrial wood combustion should be assessed by the NAEI and the need for further investigation determined.

In the absence of other published data for PCB emissions from wood combustion,
AEA Technology recommends inclusion of the emission factors determined in this investigation into the NAEI. The contribution of industrial wood combustion to UK PCB emissions should be assessed by NAEI to determine if further source monitoring is required.

The NAEI emission factor for CO from industrial wood burning processes is higher than the emission factor determined at this plant. The CO emission concentration found at the furnace was higher than the emission limit value for new plant. Consequently the NAEI factor may overestimate current emissions and is likely to overestimate future emissions from such plant. If CO emissions are significant from this sector, further investigation may be required to improve uncertainty for the sector.

The NAEI does not currently estimate $PM_{10}$ , particulate or black smoke emission factors for wood combustion. The $PM_{10}$ and $PM_{2.5}$ emission factors determined in this investigation should be assessed by the NAEI to determine if emissions are significant and if further investigation is required to improve uncertainty for the source sector.

Benzene measurements provided limited information and it is recommended that the USEPA default factor is adopted by the NAEI to determine if emissions are significant and if further investigation is required to improve uncertainty for the source sector.

# Contents

# 1 Introduction

AEA Technology has undertaken a programme of measurements at a wood-burning furnace to determine pollutant emission factors for the Department of Environment, Transport and the Regions (DETR) , the National Assembly for Wales, the Scottish Executive and the Department of the Environment for Northern Ireland. The emission factor data are intended for development of the UK National Atmospheric Emissions Inventory (NAEI) which is maintained by AEA Technology on behalf of DETR.

This report summarises a work programme undertaken to determine emission factors for the following determinands:

- Polychlorinated dibenzo-p-dioxins (PCDD)
- Polychlorinated dibenzofurans (PCDF)
- Polychlorinated biphenyls (PCB)
- Polycyclic aromatic hydrocarbons (PAH)
- $PM_{10}$
- $PM_{2.5}$
- Carbon Monoxide
- Total Particulate Matter (TPM)

The existing information on emission factors from wood-burning sources in the NAEI for the above substances is either highly uncertain or absent altogether. This set of tests was required in order to allow the NAEI to assess the significance of industrial wood-burning processes as a source of these substances.

The emission factors derived from the emission measurements are compared with emission factors currently used in the NAEI and emission factors published by the US Environmental Protection Agency (USEPA) and in the UNECE EMEP/Corinair Atmospheric emissions inventory guidebook.

# 2 Plant Description

Emissions to atmosphere from a wood-fired air-heater at a furniture factory was investigated. The boiler burns waste soft and hard wood from machining processes, at a rate of approximately 0.25 te/hr. The system is refractory lined, has no secondary burner fitted and has a cyclone installed to abate particulate emissions. Heat is recovered from the unit in the form of hot air used for heating and drying purposes, and the system has a maximum heat output of 5 million BTU/hr (about 1.5 MW).

The SNAP (Selected Nomenclature of Air Pollution) source code for the furnace is **020103**.
Solid waste combustion processes between 0.4 and 3MW (net thermal input) are prescribed for local authority control under the UK Environmental Protection Act 1990.

Selection of the process was based on several criteria. Ideally, the site chosen was to be representative of UK wood burning processes. However, it is clear that whilst this is a comparatively modest industry sector, there is wide variation both in the type of materials burned and in the process plant.

The plant selected was chosen following a survey of Local Authorities (the regulatory authority for this category of process in the UK). Selection was based on the cooperation offered by regulators and operators, ease of access to the site, the operating regime of the plant (continuous preferred to batch in this instance), the availability of sampling facilities, a reasonably constant supply of feed material and the ease of installation of sampling equipment.

# 3 Emission factors

## 3.1 DEFINITION

An emission factor enables the calculation of the quantity of a pollutant discharged to atmosphere from a specified process with a known production activity, and has been defined[1] as, "a statistical average of the rate at which a pollutant is released to the atmosphere as a result of some activity such as combustion or industrial production divided by the rate of that activity".

## 3.2 DERIVATION

There are several ways of deriving (and expressing) emission factors. The method which has been used to derive the emission factors at combustion plant in this measurement programme is based on a knowledge of the fuel composition, via chemical analysis, and an analysis of the flue gas.

For combustion processes, the ultimate analysis of the fuel can be used to provide the theoretical (stoichiometric) flue gas volume and composition associated with a unit of the fuel (for example for a kg of wood). The relationship between the oxygen concentration and the excess air is then determined. The flue gas oxygen analysis is then used to calculate the total volume of flue gas (per unit of fuel). The mass of pollutant emitted per unit of fuel (the pollutant emission factor) can then be calculated from the flue gas analysis and the derived flue gas volume.

This approach has the advantage that it can be applied almost universally to combustion processes. Other techniques for measurement of emission factors require information that may not be readily available or cannot be accurately measured at all plant.

## 3.3 EXPRESSION

Emission factors for combustion sources are usually expressed as the mass of pollutant emitted divided by the mass or volume of fuel burned (for example, g CO per kg wood).

When comparing emission factors it is necessary to express the emission factors in comparable terms for example, g pollutant per kg dry, ash-free coal, g pollutant per $m^3$ gas at STP (0°C, 101.3 kPa), or per unit of heat input, g $GJ^{-1}$ (on a Net or Inferior basis).

The emission factors for wood combustion in this report are expressed as a mass of pollutant per mass of wood as burned (for example g $kg^{-1}$) and, as a mass of pollutant per unit of net thermal input (for example g $GJ^{-1}$).

# 4 Experimental

## 4.1 SAMPLING POSITION

The sampling position is installed in a vertical section of the ductwork, downstream from the abatement plant.

Ideally, the selected sampling position should be located downstream of all abatement kit and sources of flow disturbances where the velocity profile is even across the duct and the flue gases are homogeneous. The sampling position should allow sampling methodologies to be conducted to recognised standards.

Most of the target pollutants have a significant particulate fraction and the sampling methodologies require multi-point isokinetic sampling on a grid pattern across two or more traverses (dioxins, furans, PCBs, PAHs, TPM, $PM_{10}$ and $PM_{2.5}$). However, multi-point sampling could not be conducted in full accordance with the standard methods, as there was only a single access port fitted at the sampling position, due to access constraints about the stack.

## 4.2 AIR EMISSIONS SAMPLING METHODS

The releases to air were monitored using AEA Technology documented procedures, shown in Table 1. Many of the procedures employed by AEA Technology are UKAS accredited however, deviations from the procedures were necessary for most of the measurements.

## 4.3 FUEL ANALYSIS METHODOLOGY

Wood fuel samples (both hard and soft wood samples) were obtained during the visit and submitted for ultimate analysis. However, due to the limited supply of waste and the large size of the material, a sampling protocol to ensure that the sample was representative could not be followed.

Analysis of these fuel samples was undertaken by TES Bretby, P.O. Box 100, Burton-on-Trent, Staffordshire.

## Table 1 – Source sampling methods

| Determinand | AEAT WI | Source Document | Other Details | UKAS accreditation | |
|---|---|---|---|---|---|
| | | | | Sampling | Analysis |
| Dioxins and furans | 105 | EN 1948 | Multi-component sampling train. Min. 6hr isokinetic sampling. Triplicate sampling and analysis. HR GCMS analysis for 2,3,7,8 isomers. | Yes | Yes |
| PAHs | 105 | EN 1948 | Multi-component sampling train. Min. 6hr isokinetic sampling. Triplicate sampling and analysis. HR GCMS analysis for 33 priority PAHs. | Applied | Yes |
| PCBs | 105 | EN 1948 | Multi-component sampling train. Min. 6hr isokinetic sampling. Triplicate sampling and analysis. HR GCMS analysis for 23 priority congeners. | Applied | Yes |
| Benzene | 113 | NIOSH 1501 | Sample for 1-60 mins @ 0.1 $l.min^{-1}$ onto 2 x charcoal sorbent tubes in series. Triplicate sampling and analysis. | Yes | Applied |
| Carbon Monoxide | 116 | ISO12039 | On-line tests using heated line, IR detection. Throughout all tests. | Yes | Yes |
| Carbon Dioxide | 122 | ISO 12039 | On-line tests using heated line, IR detection. Throughout all tests. | Yes | Yes |
| Oxygen | 117 | ISO12039 | On-line tests using heated line, paramagnetic detection. Throughout all tests. | Yes | Yes |
| $PM_{10}$ | 134 | USEPA 201A | Gravimetric method, using multi-point sampling. Triplicate sampling and analysis. Min. 1 hr tests. | No | No |
| $PM_{2.5}$ | (Based on 134) | (Based on USEPA 201A) | Gravimetric method, using multi-point sampling. Triplicate sampling and analysis. Min. 1 hr tests. | No | No |
| TPM | 118 | ISO 9096 | Gravimetric method, using multi-point sampling. Triplicate sampling and analysis. Min. 1 hr tests. | Yes | Yes |

# 5 Emission Factor Results

The determined emission factors are summarised in the Tables 2 to 5. Spreadsheet calculations used in the determination of these factors are included in Appendix A to E of this report. The figures in the tables below have been calculated using emission concentrations corrected to reference conditions of STP (273K, 101.3 kPa), dry, 11 % oxygen. The emission factors are given relative to the mass of wood as burned. The thermal emission factors are calculated using a net (inferior) calorific value of 18 MJ/kg for the wood as burned (see fuel analysis at Appendix F). Unless otherwise stated, the results are derived from the average of three similar tests for each determinand.

**Table 2 - Dioxin and Furan Emission Factors**

| Determinand | Average Emission Concentration ng (ITEQ)/$m^3$ | Thermal Emission Factor ng (ITEQ)/MJ | Emission Factor ng (ITEQ)/kg |
|---|---|---|---|
| 2378 T4CDD | 0.22 | 0.114 | 2.00 |
| 12378 P5CDD | 0.25 | 0.127 | 2.22 |
| 123478 H6CDD | 0.03 | 0.015 | 0.27 |
| 123678 H6CDD | 0.04 | 0.023 | 0.41 |
| 123789 H6CDD | 0.03 | 0.018 | 0.31 |
| 1234678 H7CDD | 0.01 | 0.007 | 0.12 |
| O8CDD | 0.00 | 0.000 | 0.01 |
| 2378 T4CDF | 0.14 | 0.074 | 1.30 |
| 12378 P5CDF | 0.06 | 0.029 | 0.50 |
| 23478 P5CDF | 0.47 | 0.243 | 4.25 |
| 123478 H6CDF | 0.04 | 0.019 | 0.33 |
| 123678 H6CDF | 0.04 | 0.021 | 0.36 |
| 123789 H6CDF | 0.01 | 0.004 | 0.07 |
| 234678 H6CDF | 0.04 | 0.020 | 0.36 |
| 1234678 H7CDF | 0.01 | 0.003 | 0.06 |
| 1234789 H7CDF | 0.00 | 0.000 | 0.01 |
| O8CDF | 0.00 | 0.000 | 0.00 |
| **Total** | **1.39** | **0.718** | **12.6** |

**Table 3 - Polycyclic Aromatic Hydrocarbons (PAH) Emissions Factors**

| Determinand | Average Emission Concentration µg/m$^3$ | Thermal Emission Factor µg/MJ | Emission Factor µg/kg |
|---|---|---|---|
| Naphthalene | 2.32 | 1.200 | 21.0 |
| Acenaphthylene | 0.285 | 0.147 | 2.58 |
| Acenaphthene | 0.012 | 0.006 | 0.11 |
| Fluorene | 0.028 | 0.015 | 0.25 |
| Phenanthrene | 1.07 | 0.554 | 9.71 |
| Anthracene | 0.019 | 0.010 | 0.18 |
| 2-methyl phenanthrene | 0.147 | 0.076 | 1.33 |
| 2-methyl anthracene | 0.047 | 0.024 | 0.42 |
| 1-methyl anthracene | 0.071 | 0.036 | 0.64 |
| 1-methyl phenanthrene | 0.069 | 0.035 | 0.62 |
| 9-methyl anthracene | 0.002 | 0.001 | 0.02 |
| 4,5-methylene phenanthrene | 0.005 | 0.003 | 0.05 |
| Fluoranthene | 0.128 | 0.066 | 1.16 |
| Pyrene | 0.088 | 0.046 | 0.80 |
| Retene | 0.096 | 0.049 | 0.87 |
| benzo(c)phenanthrene | 0.002 | 0.001 | 0.02 |
| Benzo(a)anthracene | 0.002 | 0.001 | 0.02 |
| Chrysene | 0.017 | 0.009 | 0.15 |
| Cyclopenta(c,d)pyrene | 0.004 | 0.002 | 0.04 |
| Benzo(b)naph (2,1-d) thiophene | 0.006 | 0.003 | 0.05 |
| 5-methyl chrysene | 0.000 | 0.000 | 0.00 |
| Benzo(b)fluoranthene | 0.009 | 0.005 | 0.09 |
| Benzo(k)fluoranthene | 0.009 | 0.005 | 0.09 |
| Benzo(e)pyrene | 0.012 | 0.006 | 0.11 |
| Benzo(a)pyrene | 0.008 | 0.004 | 0.07 |
| Indeno(123cd)pyrene | 0.006 | 0.003 | 0.06 |
| Dibenzo(ah/ac)anthracene | 0.000 | 0.000 | 0.00 |
| Benzo(ghi)perylene | 0.013 | 0.007 | 0.11 |
| Anthanthrene | 0.000 | 0.000 | 0.00 |
| dibenzo(al)pyrene | 0.000 | 0.000 | 0.00 |
| dibenzo(ae)pyrene | 0.007 | 0.004 | 0.07 |
| dibenzo(ai)pyrene | 0.000 | 0.000 | 0.00 |
| dibenzo(ah)pyrene | 0.000 | 0.000 | 0.00 |
| **Total** | **4.49** | **2.32** | **40.6** |

**Table 4 - Polychlorinated Biphenyl (PCB) Emission Factors**

| PCB IUPAC No. | Average Emission Concentration ng/m$^3$ | Thermal Emission Factor ng/MJ | Thermal Emission Factor ng(TEF)/MJ | Emission Factor ng/kg | Emission Factor ng(TEF)/kg |
|---|---|---|---|---|---|
| 18 | 6.64 | 3.430 | - | 60.1 | - |
| 31 | 13.82 | 7.142 | - | 125.1 | - |
| 28 | 13.89 | 7.177 | - | 125.7 | - |
| 51 | 1.00 | 0.518 | - | 9.1 | - |
| 52 | 6.50 | 3.360 | - | 58.9 | - |
| 49 | 4.42 | 2.284 | - | 40.0 | - |
| 47 | 4.15 | 2.143 | - | 37.5 | - |
| 101 | 2.19 | 1.131 | - | 19.8 | - |
| 99 | 0.50 | 0.259 | - | 4.5 | - |
| 77 | 1.30 | 0.669 | 0.000067 | 11.7 | 0.00117 |
| 123 | 0.20 | 0.106 | 0.000011 | 1.9 | 0.00019 |
| 118 | 0.87 | 0.451 | 0.000045 | 7.9 | 0.00079 |
| 114 | 0.20 | 0.106 | 0.000053 | 1.9 | 0.00093 |
| 153 | 1.65 | 0.854 | - | 15.0 | - |
| 105 | 0.56 | 0.287 | 0.000029 | 5.0 | 0.00050 |
| 138 | 1.20 | 0.620 | - | 10.9 | - |
| 126 | 0.38 | 0.197 | 0.019660 | 3.4 | 0.34444 |
| 167 | 0.24 | 0.123 | 0.000001 | 2.1 | 0.00002 |
| 156 | 0.30 | 0.156 | 0.000078 | 2.7 | 0.00137 |
| 157 | 0.22 | 0.111 | 0.000056 | 2.0 | 0.00098 |
| 180 | 0.82 | 0.423 | 0.000004 | 7.4 | 0.00007 |
| 169 | 0.20 | 0.106 | 0.001058 | 1.9 | 0.0185 |
| 189 | 0.20 | 0.106 | 0.000011 | 1.9 | 0.00019 |
| **Total** | **61.5** | **31.8** | **0.0211** | **556** | **0.369** |

**Table 5 - Particulate, Benzene and Carbon Monoxide Emission Factors**

| Determinand | Average Emission Concentration (mg/m$^3$) | Emission Factor (g/kg wood as burned) | Thermal Emission Factor (g/MJ) |
|---|---|---|---|
| Total Particulate Matter | 51 | 0.46 | 0.026 |
| $PM_{10}$ | 96 (% of TPM) | 0.44 | 0.025 |
| $PM_{2.5}$ | 81 (% of TPM) | 0.37 | 0.021 |
| Benzene | < 2 | < 0.02 | <0.001 |
| Carbon Monoxide | 290 | 2.58 | 0.15 |

# 6 Emission limit values

Table 6 compares the standardised emission concentrations with the emission limit values applied to **new** waste wood burning processes detailed in the process guidance note[2].

**Table 6 Comparison with new plant emission limit values**

| Pollutant | Measured concentration | Emission limit value |
|---|---|---|
| | **$mg.m^{-3}$ at 11% $O_2$ , dry and STP (0°C, 101.3 kPa)** | |
| | | |
| Total particulate matter | 51 | 200 |
| Carbon monoxide | 290 | 150 |

Emission limits for formaldehyde, hydrogen chloride and hydrogen cyanide may also be applied but only where furnaces are burning plywood, chipboard, fibreboard or coated wood.

The furnace would exceed the CO emission limit value for new plant but is well below the particulate emission limit value applied at new plant.

# 7 Comparison with NAEI, USEPA and UNECE Emission Factors

## 7.1 COMPARISON WITH NAEI EMISSION FACTORS

Table 7 summarises the latest published (1998)[3] NAEI emission factors for industrial wood combustion and compares the data with the factor determined at the wood furnace.

**Table 7 – Comparison with NAEI 1998 emission factors**

| **Pollutants** | **Emission factors,** | |
|---|---|---|
| | **NAEI** | **AEAT** |
| | **Other Industry** | **1.5MW wood burner** |
| | **kt Mt$^{-1}$** | |
| Acenaphthene | 1.6 | 0.00011 |
| Acenaphthylene | 39.3 | 0.00258 |
| Anthracene | 3.3 | 0.00018 |
| Benz[a]anthracene | 2.5 | 0.00002 |
| Benzo[a]pyrene | 0.65 | 0.00007 |
| Benzo[b]fluoranthene | 0.8 | 0.00009 |
| Benzo[ghi]perylene | 0.5 | 0.00011 |
| Benzo[k]fluoranthene | 0.3 | 0.00009 |
| Chrysene | 1.9 | 0.00015 |
| Dibenzo[ah]anthracene | 0.01 | <0.00001 |
| Fluoranthene | 3.4 | 0.00116 |
| Fluorene | 4.2 | 0.00025 |
| Indeno[1,2,3-cd]pyrene | 0.04 | 0.00006 |
| Naphthalene | 46.6 | 0.021 |
| Phenanthrene | 12.3 | 0.00971 |
| Pyrene | 3.7 | 0.0008 |
| | **kt Mt$^{-1}$** | |
| Benzene | 0.244819 | <0.02 |
| CO | 7.063 | 2.58 |
| | **g Mt$^{-1}$** | **gITEQ Mt$^{-1}$** |
| Dioxins | 1.5 | 12.6 |

The average CO and benzene emission factors determined at the wood furnace are lower than the NAEI factors. The PAH emission factors are several orders of magnitude lower than the current NAEI emission factors. The emission factor determined in this investigation for Naphthalene is likely to underestimate emissions of this comparatively volatile PAH. The dioxin emission factor determined by AEA Technology is significantly higher than the current NAEI factor.

## 7.2 COMPARISON WITH EMEP/CORINAIR EMISSION FACTORS

Emission factors from the UNECE EMEP/Corinair atmospheric emission inventory guidebook[4] published by the EEA are compared with the emission factors determined in this investigation in Table 8.

The EMEP/Corinair PAH factors are for only four species and these are derived from Benzo(a)pyrene concentrations and PAH profiles for each emission source. Although the PAH factors determined at the wood furnace are much lower than the EMEP/Corinair factors, the published factors are derived from maximum potential emissions from sources without abatement and illustrate the high uncertainty in PAH emissions from this source category. The PAH emission profile determined in this investigation differs from that published by EMEP/Corinair.

The determined CO emission factor is similar to the EMEP/Corinair default factor. The determined $CO_2$ emission factor (based on fuel analysis) is within the range of published $CO_2$ emission factors. The range of published $CO_2$ emission factors is surprising for a thermal emission factor.

**Table 8 - Comparison with EMEP/Corinair Atmospheric Emission Inventory Guidebook**

| **Pollutant** | **Emission factors, mg $t^{-1}$** | |
|---|---|---|
| | **EMEP/Corinair** | **AEAT** |
| Benzo(a)pyrene | 1300 (650) | 0.07 |
| Benzo(b)fluoranthene | 1560 (780) | 0.09 |
| Benzo(k)fluoranthene | 520 (260) | 0.09 |
| Indeno(123cd)pyrene | 130 (65) | 0.06 |
| | **g $GJ^{-1}$** | |
| CO | 199 | 150 |
| | **kg $GJ^{-1}$** | |
| $CO_2$ | 83-323 | 98 |

**Notes :**

1. Main figures for EMEP/Corinair PAH emission factors are maximum figures assigned to wood combustion plant with no emission controls. The factors in parentheses represent default 'best estimates' for wood combustion plant.
2. EMEP/Corinair factors for PAH compounds other than Benz(a)pyrene are based on emission ratio profiles for wood combustion.

## 7.3 COMPARISON WITH USEPA EMISSION FACTORS

### 7.3.1 Overview

Table 9 compares the emission factors for the wood furnace with factors published by USEPA[5]. The USEPA has published a large number of factors for industrial wood combustion. Although a comparison of mass based emission factors has been prepared, the thermal emission factors provide a better means for comparing data from differing fuels.

The USEPA recommends comparing thermal emission factors where the wood burned is substantially different from the US 'typical' wood/wood waste which has about 50% moisture content. The wood waste burned at the furnace in this investigation was derived from seasoned wood at furniture factory and had a lower moisture content. It should be noted that the thermal factors are calculated from the gross (superior) heat input.

### 7.3.2 Total Particulate and $PM_{10}$

The TPM and $PM_{10}$ emission factors are lower than the published USEPA factors.

### 7.3.3 Carbon monoxide and carbon dioxide

The average CO emission factor determined at the wood furnace is lower than the USEPA factor but the $CO_2$ emission factors (based on fuel calculation) are similar.

### 7.3.4 PAH Emission factors

In general the PAH emission factors were lower than the USEPA emission factors however the determined factor for Benzo (a) pyrene and Benzofluoranthenes are higher than the default USEPA emission factor. The emission factors determined in this investigation for Naphthalene are likely to underestimate emissions of this comparatively volatile PAH.

### 7.3.5 Dioxins and furans

The USEPA total PCDD and PCDF emission factors may include other compounds outwith the suite of seventeen dioxins and furans determined in this investigation. However, the emission factors determined by AEA Technology are generally higher than the USEPA default emission factors. In particular the USEPA emission factor for 2,3,7,8 Tetrachlorodibenzo-p-dioxin (the most significant dioxin congener) is less than 2% of factor determined by AEA Technology.

### 7.3.6 Benzene

The measurements for Benzene have a high uncertainty as all concentrations were below the analytical LOD however, the determined emission factor is consistent with the USEPA factor.

## Table 9 – Comparison with USEPA emission factors

| Pollutant | Emission factors | | | |
|---|---|---|---|---|
| | kg $t^{-1}$ | | kg $GJ^{-1}$ | |
| | **USEPA** | **AEAT** | **USEPA** | **AEAT** |
| PM | 2.1 | 0.46 | 0.20 | 0.025 |
| $PM_{10}$ | 1.3 | 0.44 | 0.12 | 0.023 |
| CO | 6.8 (0.95-40) | 2.58 | 0.65 (0.091-3.8) | 0.14 |
| $CO_2$ | 1000 | 1700 | 100 | 91 |
| | mg $t^{-1}$ | | mg $GJ^{-1}$ | |
| Acenaphthene | 2.05 | 0.11 | 0.196 | 0.0059 |
| Fluorene | 4.11 | 0.25 | 0.393 | 0.013 |
| Phenanthrene | 25.1 | 9.71 | 2.40 | 0.518 |
| Anthracene | 1.7 | 0.18 | 0.16 | 0.096 |
| Fluoranthene | 9.15 | 1.16 | 0.875 | 0.062 |
| Benzo(a)anthracene | 1.64 | 0.02 | 0.157 | 0.001 |
| Benzo(k)fluoranthene | 0.383 | 0.09 | 0.0366 | 0.005 |
| Benzofluoranthenes | 0.54 | 0.18 | 0.052 | 0.096 |
| Benzo(a)pyrene | 0.0338 | 0.07 | 0.00323 | 0.004 |
| Benzo(g,h,I)perylene | 0.705 | 0.11 | 0.0674 | 0.0059 |
| Chrysene | 0.226 | 0.15 | 0.0216 | 0.0080 |
| Indeno(1,2,3,c,d)pyrene | 0.18 | 0.06 | 0.017 | 0.003 |
| Acenaphthylene | 23.8 | 2.58 | 2.28 | 0.138 |
| Methyl anthracene | 70 | 1.1 | 6.7 | 0.059 |
| Pyrene | 8.40 | 0.80 | 0.80 | 0.043 |
| Naphthalene | 1700 | 21 | 160 | 1.1 |
| 2,3,7,8 Tetrachlorodibenzo-p-dioxin | 0.000018 | 0.002 (0.002 ITEQ) | 0.0000017 | 0.0001 (0.0001 ITEQ) |
| Polychlorinated dibenzo-p-dioxins | 0.006 | 0.036 (0.00534 ITEQ) | 0.0006 | 0.0019 (0.000285 ITEQ) |
| Polychlorinated dibenzo-p-furans | 0.015 | 0.050 (0.00724 ITEQ) | 0.0014 | 0.0027 (0.000386 ITEQ) |
| Benzene | 4980 | <20000 | 476 | <1000 |

**Notes :**

1. USEPA Emission factors are based on as-fired wood waste with average 50% moisture and gross calorific value of 10.5 MJ/kg. The wood waste burnt at this plant is joinery off cuts and has a comparatively low moisture content (10.4 %) and high gross calorific value (18.8 MJ/kg).
2. All PCDD and PCDF emission factors determined by AEA Technology are expressed as ITEQ equivalents and the total PCDD and PCDF data are based on a suite of seventeen 2,3,7,8 substituted compounds.
3. Carbon dioxide emission factors are calculated from average fuel analysis.

# 8 Uncertainty of Emission Factors

The overall uncertainty of the emission factors have not been determined. Some guidance on the likely uncertainties is provided in the analytical uncertainties associated with measured concentrations (Appendices A to E). However, these uncertainties are limited as they do not include a provision for the deviations from the particulate sampling protocol which affects almost all of the species measured. For example, the sampling of particulate material may have an uncertainty of up to 45%. The calculation of the emission factor introduces additional uncertainty from the sampling and analysis of the fuel.

The determined emission factors are based on a single furnace burning wood waste. Although the factors are considered to be representative of normal operation of the process tested, extension of the factors to other UK wood waste combustion processes is likely to increase uncertainty. Nonetheless, the emission factors determined in this investigation help to address the uncertainty associated with emissions from wood combustion in the NAEI.

For all of the dioxin and furan congeners, the analysis results were well above the Limit of Detection (LOD) for the analysis technique employed. The emission concentration results were very consistent across the three tests, which would suggest that the process is quite consistent in terms of dioxin emissions over time. The three tests gave a mean concentration of 1.4 ng(ITEQ).$m^{-3}$, with a relative standard deviation over the three tests of 18%.

The analysis results indicate that the pattern of PAH emissions is similar across the three tests, with the predominant species being naphthalene in each case. Other species such as phenanthrene, acenaphthylene, 2-methyl phenanthrene, fluoranthene, pyrene and retene also found at levels well above their respective LODs in each test. Around half of the species analysed for were found at levels that were very close to the LOD. The variability of figures across the three tests is greater than in the case of dioxins and furans, with a mean emission concentration of total PAHs of 4.5 μg.$m^{-3}$, with a relative standard deviation over the three tests of 32%.

The PCB analysis indicated that the repeatability of these results was far less than that for the dioxins, furans and PAHs. Consequently these data are likely to have a high uncertainty.

Benzene concentrations were below the LOD of the analysis method and consequently have a very high uncertainty.

The uncertainty of particulate, $PM_{10}$ and $PM_{2.5}$ measurements may be as high as 45 %.

# 9 Findings and Recommendations

## 9.1 PAH EMISSIONS

This work indicates that the NAEI PAH data and factors published by EMEP/Corinair may overestimate emissions from industrial wood combustion by several orders of magnitude. In addition, the PAH emission factors determined for this wood furnace indicate that the EMEP/Corinair PAH emission profile may not be applicable to UK industrial wood combustion.

The determined Benzo(a)pyrene and Benzofluoranthenes emission factors are similar to the USEPA default factors however most other PAH emission factors are lower than the default USEPA factors. The differences between USEPA and the emission factors determined in this investigation suggest that USEPA emission factors may not be applicable to UK industry and/or there may be large differences in PAH emissions from different wood or wood waste combustion facilities.

It is recommended that the NAEI considers adopting PAH factors from this investigation or from USEPA. In general, the PAH emission factors determined at the wood furnace are recommended for inclusion in the Inventory. However, the Naphthalene emission factor determined in this investigation is not proposed for inclusion in the NAEI as it is likely to underestimate emissions.

In the absence of other data, the conservative approach may be to adopt the highest factors for each compound. The data should be assessed by the NAEI to determine if emissions are significant and if further emission measurements are required to improve uncertainty for the source sector.

## 9.2 DIOXINS AND FURANS EMISSION FACTORS

Emission data for dioxins and furans from wood combustion are higher than in the current NAEI. The determined emission concentrations are comparatively high (compared to emission limits for waste incineration) and indicate that wood combustion could be a significant source of dioxins and furans emission.

The USEPA default emission factor for 2,3,7,8 Tetrachlorodibenzo-p-dioxin is about 2% of the factor determined in this investigation. Similarly, the total dioxin and furan emission factors determined at this process are higher than published USEPA emission factors for industrial wood combustion. However, the USEPA has not applied toxicity factors to its total dioxins and furans emission factors and consequently comparison may not be meaningful.

In the absence of other data specific to UK processes and to provide a ‘worst case’ emission inventory it is recommended that the NAEI adopt emission factors from this investigation. The significance of the emission from industrial wood combustion should be assessed by the NAEI and the need for further investigation determined.

## 9.3 PCB EMISSION FACTORS

In the absence of other published data for PCB emissions from wood combustion, AEA Technology recommends inclusion of the emission factors determined in this investigation into the NAEI. The contribution of industrial wood combustion to UK PCB emissions should be assessed by NAEI to determine if further source monitoring is required.

## 9.4 CARBON MONOXIDE AND BENZENE

The NAEI emission factor for CO from industrial wood burning processes is higher than the emission factor determined at this plant. The CO emission concentration found at the furnace was higher than the emission limit value for new plant. Consequently the NAEI factor may overestimate current emissions and is likely to overestimate future emissions from such plant. If CO emissions are significant from this sector, further investigation may be required to improve uncertainty for the sector.

Benzene measurements provided limited information and it is recommended that the USEPA default factor is adopted by the NAEI to determine if emissions are significant and if further investigation is required to improve uncertainty for the source sector.

## 9.5 PARTICULATE, $PM_{10}$ AND $PM_{2.5}$

The NAEI does not currently estimate emissions of these components for wood combustion. The $PM_{10}$ and $PM_{2.5}$ emission factors determined in this investigation should be assessed by the NAEI to determine if emissions are significant and if further investigation is required to improve uncertainty for the source sector.

# 10 Acknowledgement

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# Appendix A
# Summary of test data – 30 October 2000

# Appendix B
# Summary of test data – 31 October 2000

# Appendix C
# Summary of test data – 1 November 2000

# Appendix D
# Summary of test data – 2 November 2000

# Appendix E
# Summary of test data – 3 November 2000

# Appendix F
# Fuel Analysis

# Fuel analysis

Table F1 – Summary of fuel analysis

| Sample | Douglas fir, 3/11 | Cedar, 30/10 | Cedar, 30/10 | Softwood, 3/11 | Kerding, 3/11 | Average | Average |
|---|---|---|---|---|---|---|---|
| | Analysis, % as received | | | | | | Analysis, % dry, ash-free |
| Moisture | 9.00 | 11.60 | 9.00 | 10.30 | 12.10 | 10.4 | |
| Ash | 0.20 | 1.00 | 0.10 | 0.30 | 0.70 | 0.46 | |
| Volatile Matter | 77.30 | 74.40 | 75.90 | 77.50 | 74.10 | 75.8 | 85.1 |
| Fixed Carbon | 13.50 | 13.00 | 15.00 | 11.90 | 13.10 | 13.3 | 14.9 |
| | | | | | | | |
| Carbon | 47.10 | 45.50 | 49.10 | 47.20 | 46.10 | 47.00 | 52.7 |
| Hydrogen | 4.95 | 4.62 | 4.77 | 4.99 | 4.66 | 4.80 | 5.38 |
| Nitrogen | <0.30 | <0.30 | <0.30 | <0.30 | <0.30 | <0.3 | <0.34 |
| Chlorine | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Sulfur | <0.04 | <0.04 | <0.04 | 0.18 | <0.04 | 0.07 | <0.08 |
| | MJ $kg^{-1}$ | | | | | | MJ $kg^{-1}$ |
| CV (Gross) | 18.59 | 18.02 | 19.38 | 19.27 | 18.47 | 18.75 | 21.03 |
| CV (Net) | 17.36 | 16.80 | 18.19 | 18.00 | 17.23 | 17.52 | 19.65 |