Combustion Related Fire Products: A Review

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Summary

1. A systematic and detailed evidence base of combustion related fire products has been developed and the issues relating to the dispersion and toxicity of these compounds reviewed. Combustion related fire products from four different combustion environments were studied to develop an understanding of the effects of the materials burned and the combustion environment on the compounds generated and their yields. Due to the need to link combustion related fire products to the source material and combustion environment, studies which reported only gas phase concentrations of combustion related fire products were excluded from this review.

2. A review of the dispersion (transport) of combustion related fire products was included to identify issue relation to the deposition of such compounds. Toxicology impacts were also evaluated.

3. This review included studies covering 197 source materials with 298 unique compounds emitted during combustion of these materials but encountered a two important limitations: data were influenced by selection bias; and yields were reported in only a subset of the studies evaluated. Extrapolation of these results to other conditions cannot be done confidently and as a result, this review was able to make only general statements about potential combustion related fire products.

4. The primary conclusions of the review are:

    - There are no strong relationships between the compounds present in the combustion related fire products and the source material. An important exception is the production of hydrogen halides during combustion of halogenated source materials and some specific source material formulations).
    - Yields of combustion related fire products are strongly dependent on the local combustion conditions which are generally not known for a given fire.
    - No obvious correlations were established between compound yields and source material burning.
    - Plume dynamics associated to fires are not well known with key uncertainties around plume injection; local flow conditions; and atmospheric dynamics. These uncertainties combine to result in large uncertainties around dilution of combustion related fire products at the point of deposition.

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Part 1:
Introduction, background and combustion related fire product summary

1. Introduction

1. This report has been prepared for the Ministry of Housing, Communities and Local Government under Contract Number CPD/004/120/109.

2. This report provides a review of the academic literature on the topic of combustion-related fire products. Specially, as set out in the Requirement (Attachment 3 – Statement of Requirements Allocations Evidence Collection Exercise Contract Reference: CCZZ19A27), the report provides a review of combustion related fire products generated in small and large scale experiments and from the incineration and burning of municipal waste. In addition, review of the relevant toxicology and environmental impacts is presented and an overview of the relevant issues pertaining to atmospheric dispersion is given.

3. The report is structure in two parts.

4. In Part 1, an overview of the scope and structure of the report is given followed by a brief overview of the methodology employed when undertaking the literature review. A brief overview of the relevant combustion chemistry is given. This is intended to orientate the reader and provide a high-level overview of the relevant phenomena.

5. The data on the combustion related fire products, are presented based on the combustion environment. These studies then cross-referenced with materials known to be present at Grenfell Tower.

6. A brief overview of the relevant phenomena associated to the atmospheric dispersion of fire products is then given. Finally, an assessment of the toxicological impacts of the compounds identified is given.

7. Part 2 is comprised of annotated bibliographies relating to each of the four combustion environments identified in the Requirement.

1.1. Scope and structure

8. The Statement of Requirement defines the scope of the literature review to be undertaken to cover fire chemistry and effluents to provide a systematic and detailed evidence base on the subject. In summary there are seven steps involved in the requirement:

    1. Identify combustion products from small scale laboratory studies.
    2. Identify combustion products from large scale fire experiments.
    3. Identify the studies measuring the combustion products from incineration of municipal solid waste.
    4. Identify the studies measuring the combustion products from uncontrolled incineration of wastes.
    5. Identify the toxicological impacts of the compounds identified above
    6. Identify the compounds above that are likely to have been present due to the fire at Grenfell Tower.
    7. Evaluate the studies on dispersion to assess dispersion and area of interest for future site investigations.

9. The report is broadly structured around these key themes. In addition, a review of the combustion processes and their effects on the emissions from fires is given. A brief overview of common diagnostic techniques is also presented to highlight the limitations in some approaches.

1.2. Methodology of review

10. The review was undertaken by addressing items 1–7 as defined in the Requirement in parallel.

11. When discussing the literature, the following terms are used:

    - *Source* is used to refer to academic peer reviewed papers or reports that contain information.

- *Study* refers to the burning of a material under a specific set of conditions.
- *Compound* is used to refer to the combustion related fire products.

12. The literature was review was undertaken in two steps.

13. Initially a search of the academic literature using Google Scholar and Web of Knowledge was undertaken. Variants on the phrases *combustion product, emissions, emission factors, combustion product yields, combustion yields* and *fire emissions* were used. The cross-referencing nature of the literature was then used to identify further sources to be explored (i.e. using the references and citations from individual studies).

14. Secondly a detailed review of the sources from established scientists in this field was undertaken. The cross-referencing nature of the literature was once again used to identify further sources to be explored.

15. Only sources which reported yields of compounds for a given study are presented in this report. Although there are many studies which report concentrations of compounds, these are not reported here as it is not possible to use this metric to make comparisons between studies.

16. To address the needs of the Requirement, the data are presented grouped by combustion type (i.e. small scale experiment, large scale experiment, municipal waste incineration, municipal waste burning. In each section the compounds which have been measured with the highest yields and the compounds which have been identified most frequently are given.

17. Compounds which were identified in multiple studies have been the primary focus of the toxicology assessments. Where appropriate, additional compounds that have been identified in only one study have been cross referenced against materials known to be present at Grenfell Tower – particularly the construction materials. This approach allowed a screening of compounds identified.

18. Studies on dispersion are reviewed to guide further site analysis.

1.3. Assisted by

19. Dr Hadden and Dr Switzer have been assisted in the preparation of this report by the following persons:

- Dr Eric Mueller
- Mr Zakary Campbell-Lochrie
- Mr Carlos Walker-Ravena
- Mr Georgios Kanellopoulos
- Mr Vasileios Koutsomarkos

20. Further details are available in Appendix A.

1.4. Nomenclature

Compound

21. A substance in which two or more chemical elements are bonded together chemically. In this report the term compound is generally used in relation to combustion related fire products.

Pyrolysis

22. The thermal decomposition of a solid fuel.

Analytes

23. Compounds which are specifically searched for in a chemical analysis.

Flammability

24. An assessment of the ease of ignition and heat released during the burning of a material. Frequently used to identify the fire hazard posed by a material.

Equivalence ratio

25. The ratio of fuel to oxygen relative to the stoichiometric mixture in a combustion system.

Product

26. The compounds produced following a chemical reaction.

Combustion

27. The reaction between a fuel and oxygen.

2. Combustion chemistry

28. A fire is the result of combustion of a compound by reaction with oxygen from the air. A fire is a manifestation of a chemical processes that releases energy (in the form of heat and light) and generates smoke. It is important to note that a fire is very often controlled by the physical state and distribution of the fuel and its environment rather than on the chemical nature of the fuel. That is to say it is generally more important to understand *how* something is burning rather than *what* is burning (Drysdale, 2011, p. 1). This principle extends to evaluating the emissions from a fire.

29. The reason for this is that most combustion processes are controlled by how the fuel and oxidiser, which are initially separated, are mixed. In a fire, this process is limited by the rate of diffusion of the fuel and the oxygen to form a flammable mixture (Quintiere, 2006). This process is relatively slow, resulting in low temperatures in the combustion zone and incomplete combustion i.e. not all the fuel is oxidised to produce carbon dioxide and water. As a result, products of incomplete combustion are formed (Drysdale, 2011).

30. Most materials which are involved in fires are polymers. These may be natural polymers e.g. wood, or synthetic polymers e.g. polyethylene. Under ideal conditions of complete combustion of a hydrocarbon or carbohydrate (i.e. those polymers containing only carbon, hydrogen and oxygen) will result in the production of two stable gaseous species: carbon dioxide and water (Drysdale, 2011; Khan, Tewarson and Chaos, 2016).

31. Some polymers include other elements e.g. nitrogen, halogens, metals, phosphorous. These impart specific material properties (Hurley *et al.*, 2016) and the inclusion of these elements complicates the combustion chemistry and even in the case of complete combustion will result in generation of multiple compounds.

32. In a fire, the nature by which the oxygen and fuel are mixed do not favour complete combustion and a complex mixture of combustion products is formed depending on the local combustion conditions. In order to evaluate the parameters that control the compounds formed, it is necessary to describe the process of burning.

2.1. Combustion stoichiometry

33. For simple fuels, it is possible to develop an understanding of the combustion stoichiometry. This is defined as the ratio of oxygen (within air) required to completely react with all of the fuel present to produce known combustion products (usually carbon dioxide and water).

34. In a fire, the complete mixing of fuel and air does not occur (see Section 2.4 below) and generally the mixture is characterised by large gradients in concentration of fuel and oxygen between the reaction zone and the surrounding environment. The rate of transport of the fuel and oxygen is proportional to the gradient in concentration. As the rate of transport is generally slower than the characteristic time of the chemistry, insufficient oxygen can be provided to the reaction and hence the combustion process will not be complete, and products of incomplete combustion are formed within the flame. The ratio of a mixture to the ideal, stoichiometric mixture is referred to as the equivalence ratio.

35. The equivalence ratio is defined as (McAllister, Chen and Fernandez-Pello, 2011):

36. $$\phi = \frac{(fuel/air)_{actual}}{(fuel/air)_{stoichiometric}}$$

37. If the equivalence ratio is less than one, then the mixture is said to be fuel lean and if the mixture is greater than one the mixture is defined as fuel rich. With all other factors equal, the burning of a lean mixture will in general have a higher degree of completeness compared to the burning of a fuel rich mixture. This is because there is insufficient oxygen available in a rich mixture to allow the conversion of the fuel to stable, fully oxidised compounds such as carbon dioxide and water. Consequently, a large quantity of partially oxygenated species (e.g. carbon monoxide) and fuel will be present among the combustion products.

38. This indicates that the availability of air in the reaction zone, and hence the nature of the mixing of fuel and air, will have a significant, often dominant, effect on determining the composition and yields of combustion products.

2.2. Smoke

39. The definition of smoke given by the National Fire Protection Association is "*The airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass*" (NFPA, 2018).

40. The complex mixture of compounds which form smoke has long been known to pose a threat to life during a fire. Early studies on fire safety in buildings reflected this, and smoke management is a key pillar of fire safety regulation and design.

41. The composition of the smoke produced during burning is strongly dependent on the burning processes and particularly the temperature and the ratio of fuel to oxygen available within the combustion zone.

42. In order to make meaningful assessment of the quantity of combustion products, it is necessary to related the mass of material produced to the mass of material that is degrading, per unit time. This is defined as the yield, Y_i.

43. $Y_i = \frac{\dot{m}_i}{\dot{m}_f}$

44. where $\dot{m}_i$ is the rate of production of species i, and $\dot{m}_f$ is the rate of degradation of the fuel. Other means of characterising the quantity of combustion product, such as concentrations, are not useful as they give no indication of the mass of fuel that was burning.

2.3. The processes of burning

45. The process of flaming combustion arises due to the gas phase oxidation of a fuel. This process, and those leading up to it, include complex chemical processes with multiple reaction steps, heat and mass transport in the gas and solid phases. There are strong couplings between these processes resulting in a highly complex process.

46. The burning of solids is characterised by four steps which are necessary to generate a flammable mixture of gaseous fuel and air (Drysdale, 2011).

    1) The heating of the solid.
    2) The thermal decomposition (pyrolysis) of the solid to produce gaseous (or vapour) phase fuel (pyrolyzate).
    3) The ignition of the flammable mixture of air and pyrolyzate.
    4) The sustained burning of the material due to continued heating and pyrolysis of the solid fuel by the energy evolved from the combustion process.

2.3.1. Heating

47. In most cases, an external heat source is required to initiate the heating of a solid fuel to a temperature where thermal decomposition will occur. In a fire this is often due to the flaming combustion of an adjacent material or object.

48. The response of a material to heating is dictated by the thermal properties of the material (density, heat capacity and thermal conductivity), its geometric dimensions, and the heating scenario e.g. convective or radiative heating). The rate of heating may also be influenced by the chemical composition as some polymeric materials will deform and melt before they undergo chemical decomposition.

2.3.2. Thermal decomposition

49. The thermal decomposition (pyrolysis) of a combustible solid occurs when the temperature of the material corresponds to an energy state which is sufficient to break the chemical bonds between the atoms which form the molecule. The precise decomposition mechanisms – and hence the products of pyrolysis – are not presently understood but are known to depend on the composition of the material, the rate of heating and the pyrolysis and combustion environment (Hurley *et al.*, 2016).

50. There are three commonly accepted mechanisms of pyrolysis: chain scission, chain stripping and cross-linking (Hurley *et al.*, 2016).

51. Chain scission is the breaking of the polymer molecule at points along its length. This may be either at random locations forming a mixture of molecules with varying molecular weights or specific locations corresponding to decomposition back to the monomer unit of the polymer. Compounds such as polyethylene and polystyrene will undergo random chain scission. Polymethyl methacrylate (plexiglass) and polytetrafluoroethylene (Teflon) will undergo end chain scission and produce a high fraction of monomer units in the decomposition products (Hurley *et al.*, 2016).

52. Chain stripping occurs in polymers where the main chain remains intact and side groups break off to form low molecular weight compounds. A common example is polyvinylchloride (PVC).

53. Cross-linking occurs in polymers which produce a char on heating e.g. wood. As molecules are released from the polymer chain, reactive sites on the polymer molecule react with other polymer molecules resulting in cross-linking and promoting the formation of char.

54. The precise nature of the compounds produced by these processes is not well known (Drysdale, 2011). However, it is common for these to range from simple molecules such as hydrogen and methane to compounds of higher molecular weight that are only vapours at the high temperatures of the surface of the solid and cool rapidly upon expulsion from the surface to form an aerosol. During faming combustion most of the pyrolysis products will be oxidised in the flame. In some scenarios e.g. where the oxygen concentration is limited, these may not be oxidised and will be emitted as aerosol smoke.

55. The process of thermal decomposition is a series of chemical reactions. Therefore, the rate is characterised by the temperature of the polymer and the energy required to initiate the reaction. It is common therefore to define a decomposition temperature at which the polymer chain will begin to decompose. Typically, decomposition temperatures range from 200°C to 550°C.

2.3.3. Ignition

56. If the solid is heated sufficiently then the pyrolysis products will be generated at a rate which will form a flammable mixture with air from the surroundings. If an ignition source (e.g. spark or flame) is present, then a premixed flame will propagate through the mixture (Hurley *et al.*, 2016).

57. If the pyrolysis products are produced at a sufficient rate, then the flame will anchor to the solid surface and transition to a diffusion flame.

2.3.4. Sustained burning

58. After ignition, the diffusion flame will generally be anchored on the fuel surface, the feedback may support further pyrolysis of the fuel and/or the spread of flame across the fuel surface. In this case the products generated will be the products of incomplete combustion. In locations where the conditions are such that the flame is partially anchored, the products will be a combination of pyrolysis products and the products of incomplete combustion. In other locations, the flame will not have established, and the products are only those of pyrolysis. In some scenarios, these pyrolysis products may ignite and burn far from the fuel surface if the conditions (oxidiser, temperature) permit.

59. In order to understand the products of combustion from the burning of a solid it is necessary to evaluate the processes which control the diffusion flame and the impact these have on the combustion chemistry.

2.4. Diffusion flames

60. In a fire, the gaseous fuel and air are not mixed before they react. This means that the process of burning is largely dominated by the rate at which oxygen from the surrounding air diffuses into the fuel rich vapours produced by the thermal decomposition of a solid. Consequently, fires are characterised by diffusion flames (Glassman, 1977).

61. The dynamics of a diffusion flame which arises from the burning of a solid fuel are controlled by buoyancy. The buoyant motion is generated by the high temperatures achieved in the combustion zone resulting in low density of the combustion species causing them to rise relative to the surrounding air.

62. The flame sheet in a diffusion flame has a temperature of approximately 1200–1500°C. The characteristic orange-yellow colour is a result of radiation from soot particles (which are produced in a diffusion flame) being heated to these temperatures (Drysdale, 2011).

63. The buoyant forces generated by diffusion flames from small samples (0.01 m) generally result in a flow field that is laminar in nature. As the fire size is increased the flow field becomes turbulent. Fires which are larger than approximately 0.3 m in diameter are considered to be fully turbulent. Higher degrees of turbulence generally enhance the mixing of fuel and oxygen (Drysdale, 2011). Consequently, the chemical processes and hence combustion products, are expected to be different as the fire grows in size. This also implies that the buoyancy induced turbulence will be dependent on location of the flame (and the location within the flame). As a result, buoyancy-induced turbulence in the region of the flame (and hence combustion environment) is extremely challenging to predict. This generally precludes prediction of species produced from the burning of condensed-phase fuels.

2.5. The role of fire retardants

64. Fire retardants are compounds which are included within a material to alter (reduce) the material's flammability. Fire retardants may operate in the gas phase to inhibit the flame i.e. reduce the energy released, or in the solid phase to increase the energy required for pyrolysis of the solid.

65. Both of these mechanisms of action have the potential to increase the yields of products of incomplete combustion. A discussion of the value of fire retardants in the framework of fire safety is beyond the scope of this work.

2.6. Sources of combustion related fire products

66. From the above it is clear that combustion products may be generated at several stages of the combustion process.

2.6.1. Pyrolysis

67. Any pyrolyzate that is not oxidised in the flame will be considered as a combustion-related fire product. As detailed above, the composition of pyrolyzate is not well defined and depends on the rate of heating of the material. These compounds are transported by buoyancy but may not pass through the high temperature region of the flame. They will then be released to the atmosphere.

2.6.2. Incomplete gas-phase combustion

68. The structure of a diffusion flame means that the oxidation process is not complete. The mixing of the fuel and vapours is dependent on the turbulence induced by the buoyant flow. This results in substantial concentration and temperature gradients within the flame region and consequently the formation of pockets of fuel rich mixtures.

69. The high temperature environment of these fuel rich zones can promote further pyrolysis and reaction between the fuel molecules resulting eventually in the production of aromatic compounds. These may further react with each other to form polycyclic aromatic hydrocarbons, the molecules of which agglomerate and ultimately form solid soot particles. If the conditions are such that these aromatic species and soot do not oxidise in the flame e.g. the temperature or oxygen concentration is too low, they will be emitted as smoke.

2.7. The combustion environment

70. The production of combustion related fire products depends on the local phenomena. For example, in a compartment fire, the burning conditions are likely to vary spatially and in time. In waste incineration, transient events such as start up or changes in the fuel composition are likely to impact these conditions. Therefore, the use of integrated (in space or time) measurements are unlikely to allow accurate description of emissions from specific materials. Additionally, as a fire grows, the flow fields (and hence oxygen availability) within a compartment is likely to become a strong function of the fire.

71. These factors result in a problem with generally poor spatial and temporal descriptions of important factors that govern the formation of combustion related fire products – temperature, and oxygen availability. As a result, it is challenging to disentangle the effects of the combustion environment and the material burning on the production of combustion related fire products.

72. As a result, this review explores combustion related fire products generated in four different combustion environments in order to cover as wide a range as possible of combustion conditions and materials burnt.

73. Small scale experiments cover scenarios with low turbulence and well-defined mixing and thermal environments. Typically, these involve simple fuels. Large scale experiments have, in general, a higher degree of turbulence, poorly defined mixing conditions and realistic, though poorly defined fuel sources. Studies on outdoor waste burning explore the emissions from uncontrolled fires using typical domestic materials with poor description of the combustion environment. Studies relating to incineration again allow exploration of the emissions from the burning of common domestic items but under optimised conditions. These four scenarios therefore cover the range of expected materials and burning conditions relevant to a large fire in a domestic building.

3. Measurement of combustion products

74. There are many measurement techniques that can be used to measure combustion related fire products. These are not reviewed here. The studies reported here were not evaluated critically for the quality of the analytical chemistry. Their findings were accepted as reported.

75. It is important to note that it is not currently possible to run a diagnostic system that will identify all the species generated as combustion products. In most cases, sources only report results from a list of analytes that have been decided a priori.

76. This introduces potential for significant observation bias in the results whereby some compounds may appear frequently as they are commonly included in lists of analytes; however, others may not be reported at all despite being produced in large quantities.

3.1. Relating combustion products to materials burning

77. The methods by which the products of combustion are related to the material(s) burning are relatively non standardised. In a small scale experiment the yield is often used. This is a measure of the mass of product produced per mass of fuel consumed.

78. In a compartment scale fire, it is common to relate the emissions generated to the equivalence ratio (although this has some limitations).

79. In a large, outdoor fire, the emissions factor may be quoted. This is calculated in the same way as a yield although frequently the mass loss is not recorded and so the fraction is given as the mass of product released to the total mass of material available burning.

80. Sources or studies in which only the concentration in air is reported are not considered in this review as it is not possible to make meaningful comparisons between such studies. This is due to the inability to link concentrations to the source when entrainment of air and the burning conditions are not described.

3.2. Limitations

81. The preceding sections highlight a number of limitations that are present in this review. These are summarised below.

    - Observational bias. The analysis of combustion related fire products requires researchers to define the compounds of interest ahead of time. This means that a compound not being detected does not mean it was not present. Observational bias also extends to the scope of the application. For example, the section on incineration of waste, it is reasonable to assume that requirements of environmental permits will drive the compounds of interest.
    - Knowledge gaps. Several apparent knowledge gaps have been identified in the course of this review. Of particular relevance is existing studies in which the release of species from a fire has been explicitly linked to deposition and hence concentration in soils. No information has been found relating to deposition mechanisms or concentrations in soils in studies other than those relating to Grenfell Tower. An additional knowledge gap exists around the ability to predict the plume dynamics at Grenfell Tower due to the lack of publicly available information on the fire size and hence plume characteristics.

4. Overview of combustion related fire products

82. The literature covering the combustion products generated in fires is highly varied in application, intent and scope. Many studies measure concentrations of species at a fixed location form the fire; others record the yields of compounds. In many cases the combustion environment is inadequately quantified to allow clear interpretation of the measurement. In this review studies which report yields of combustion products are prioritised as these allow the most robust interpretation and comparison. Although the yield alone does not cover all the details of the combustion environment, it nevertheless provides a useful metric to compare materials burning under different conditions as it allows the degradation rate of the materials (which will depend on the combustion conditions) to be implicitly incorporated in the analysis.

83. Initially a list of species is presented that includes data from all the studies that have been reviewed in the production of this report. This list is then priorities based on the number of studies that report the species and, in Section 4.3, to the materials known to be present at Grenfell Tower.

84. The detailed findings from each of the Objectives 1–4 in the Statement of Requirement are discussed separately in Sections 9–12 below.

4.1. Species of interest

85. Compounds which have been detected following the burning of materials or products are reported. These include compounds that are classified as volatile organic compounds, polycyclic aromatic hydrocarbons, acidic gases, dioxins, furans among others.

86. Occurrences and yields of carbon monoxide and carbon dioxide are not included.

87. The yields presented are the maximum reported in a study.

88. This section first reports and overview of all the species analysed and the associated maximum yields. Each objective is then presented to allow comparison between the frequency with which compounds are detected and the compounds which are generated with high yields. Studies which report the aggregated measurement of combustion products e.g. total hydrocarbon, aggregated measurements of volatile organic compounds (VOC), polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB), are not included.

4.2. Overview

89. A total of 298 unique compounds were identified from the burning of 197 individual materials. These are listed in Appendix B.

90. Some materials for which yields of combustion related fire products are labelled using generic terms only e.g. ‘Airplane seat cover’, ‘car’, ‘Domestic waste’. No materials have been excluded based on this as many of these materials may be present in other forms in common domestic settings (fireworks, insecticides, and herbicides were excluded at the request of the Client).

91. Details of the literature consulted is available in Part 2 of this report.

92. Table 1 identifies the twenty compounds identified with the highest yields. These are shown graphically in Figure 1.

93. Table 2 lists the seventy compounds which occur in five or more studies.

94. In addition, the following general observations are made:

    - There are no strong correlations between the material burning and the combustion related fire products. This may be due to observation bias in the selection of products for which analysis is undertaken.
    - There are no strong relationships between the scale at which the combustion was undertaken, and the products collected. It is hypothesised that this is due to the high sensitivity of the combustion environment.

- Many aromatic compounds are identified. These are formed during the combustion of a wide rate of hydrocarbon-derived fuels.
- Chlorinated combustion products are found when the materials burned contain chlorine.
- Some compounds appear to be emitted in a manner that is relatively insensitive to the burning conditions. In particular, these include halogenated species (hydrogen bromide, hydrogen chloride and hydrogen fluoride).
- In general terms the yields of oxygenated species such as sulphur dioxide and nitrogen dioxide, increase with increasing availability of oxygen and by inference the yields of other products must decrease e.g. hydrogen cyanide, acrolein, formaldehyde and other hydrocarbons.

Table 1 The 20 compounds identified with the highest yields.

Compound	Max yield, mg/kg	Material burning
Sulfur dioxide	1752632	Li-ion battery
Hydrogen cyanide	584210	PVC
Isocyanate acid	210000	Car
Hydrogen fluoride	59500	Li-ion battery (LiPF6)
PCDF	56000	Car
Styrene	49400	Fiberglass Materials (Building Industry)
Benzene	47800	MDI/polyester foam, fire retarded
Toluene	29800	MDI/polyester foam
Propene	16270	Rigid Polyurethane (PAPI,TMP)
Methane	15310	Rigid Polyurethane (PAPI,TMP)
Naphthalene	15100	MDI/polyester foam, fire retarded
NOx	15000	Car Part (Polyamide 6,6)
Ammonia	15000	Airplane Wall/floor cover
Benzonitrile	14900	MDI/polyether polyol foam
Ethene	11440	Rigid Polyurethane (PAPI,TMP)
PCDD/PCDF	10000	Municipal waste
Phenyl isocyanate	9800	Car
Freon	9410	Rigid Polyurethane (PAPI,TMP)

Ethyl Benzene	9300	Fiberglass Materials (Building Industry)
Ethanal	9070	Rigid Polyurethane (PAPI,TMP)
Acetone	8140	Rigid Polyurethane (PAPI,TMP)
Acetic acid	7400	Landfill waste

95. The combustion related fire products exhibiting the highest yields are primarily generated from materials that could be expected to be present at Grenfell Tower.

96. PCDF and phenyl isocyanate are generated during the burning of a car. Although further details are not available on the specific material burning, these are considered relevant due to the presence of common polymeric materials within a car.

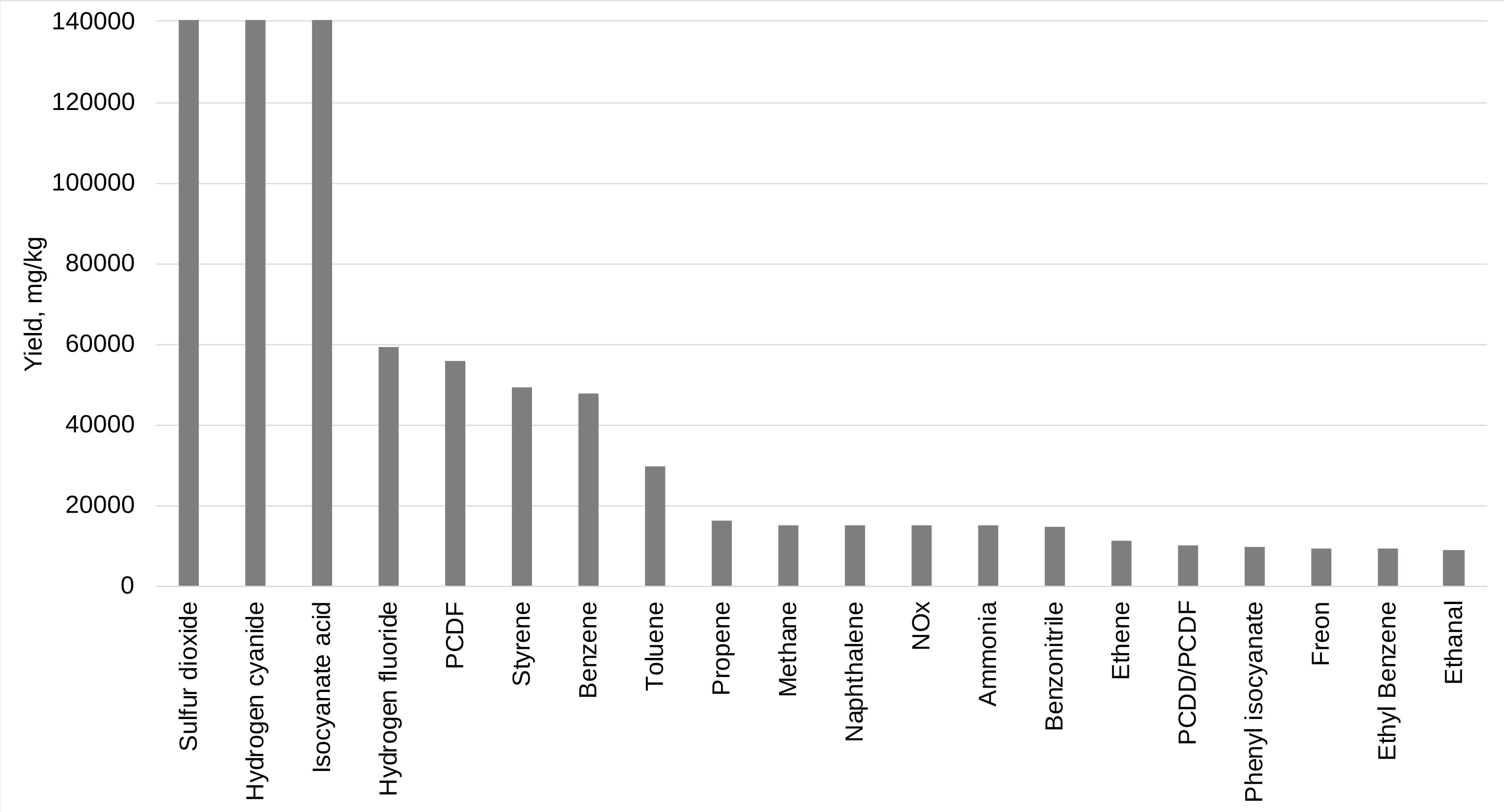
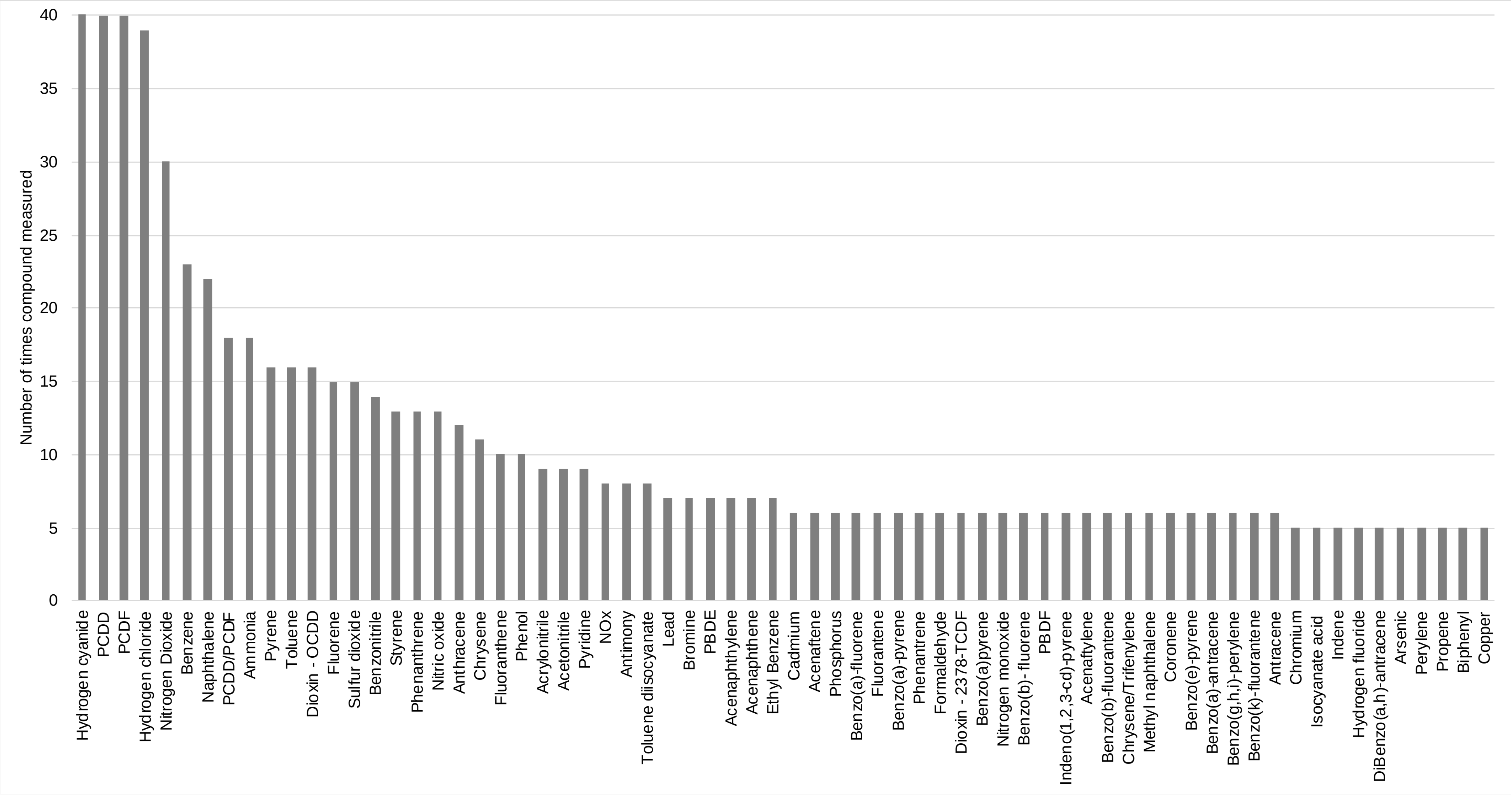


Figure 1 The twenty species detected with the highest maximum reported yields. Yields of sulfur dioxide (1 752 632 mg/kg), hydrogen chloride (1 162 000 mg/kg), hydrogen cyanide (584 210 mg/kg) and isocyanate acid (210 000 mg/kg) exceed the y-axis limit.

Table 2 The 68 compounds detected in five or more studies

Compound	Number of times compound measured	Max yield, mg/kg
Hydrogen cyanide	115	584210
PCDD	40	2100
PCDF	40	56000
Hydrogen chloride	39	1162000
Nitrogen Dioxide	30	3300
Benzene	23	47800
Naphthalene	22	15100
Ammonia	18	15000
PCDD/PCDF	18	10000
Pyrene	16	597
Toluene	16	29800
Dioxin - OCDD	16	0
Fluorene	15	534
Sulfur dioxide	15	1752632
Benzonitrile	14	14900
Styrene	13	49400
Phenanthrene	13	2156
Nitric oxide	13	121000
Anthracene	12	596
Chrysene	11	597
Phenol	10	6830
Fluoranthene	10	844
Pyridine	9	1500
Acrylonitrile	9	4500
Acetonitrile	9	5510
NOx	8	15000
Toluene diisocyanate	8	7200
Antimony	8	15
Bromine	7	260
PBDE	7	57
Acenaphthene	7	23
Lead	7	820
Ethyl Benzene	7	9300
Acenaphthylene	7	634
Phenantrene	6	103
Benzo(a)-antracene	6	9
Benzo(e)-pyrene	6	9
Indeno(1,2,3-cd)-pyrene	6	13
Benzo(b)- fluorene	6	2
Benzo(a)-fluorene	6	3
Phosphorus	6	25
Methyl naphthalene	6	429
Benzo(k)-fluorantene	6	5
Benzo(a)-pyrene	6	10
Dioxin - 2378-TCDF	6	0
Cadmium	6	2
Benzo(b)-fluorantene	6	16

Benzo(a)pyrene	6	503
Fluorantene	6	49
Nitrogen monoxide	6	4500
Antracene	6	12
Chrysene/Trifenylene	6	12
Benzo(g,h,i)-perylene	6	11
Coronene	6	4
Acenaftylene	6	125
PBDF	6	5
Acenaftene	6	1
Formaldehyde	6	7400
Biphenyl	5	1936
Isocyanate acid	5	6027
Chromium	5	14
DiBenzo(a,h)-antracene	5	1
Propene	5	16270
Arsenic	5	48
Perylene	5	2
Hydrogen fluoride	5	59500
Indene	5	140
Copper	5	27



97.

Figure 2 The frequency with which compounds reported in 5 or more studies are documented. Counts of hydrogen cyanide (115) exceed the y-axis limit

4.3. The influence of combustion conditions

98. In this section the yields and number of studies which report the measurement of a compound is given. These metrics are used to identify compounds which are anticipated to be generated in large quantities and also those which are most frequently reported in the fire products literature.

99. For each of the objectives listed in Table 3, the twenty compounds with the highest yields are reported in graphical and tabular format.

100. The total number of occurrences presented varies between the objectives. A summary of the number of occurrences used as the cut off is given in Table 3. Small- and large-scale fire experiments were the larges body of literature and therefore compounds which are reported in six or more studies are reported. For the solid waste incineration, which had the smallest body of associated literature and typically smallest ranges of compounds searched for, compounds reported in two or more studies are reported and for solid waste burning, compounds reported in four or more studies are presented.

101. It is acknowledged that these limits are arbitrary, and a full list of all compounds measured and the maximum reported yields under each combustion environment is given in Appendix D-G.

Table 3 The number of occurrences used as a cut off for reassessment of the most common compounds for each combustion condition

Combustion environment	Number of occurrences presented	Number of compounds
Small scale experiments	6 or more	20
Large scale experiments	6 or more	31
Solid waste incineration	2 or more	22
Solid waste burning	4 or more	17

4.3.1. Small scale experiments

102. Small scale experiments typically include laboratory studies using single materials under well-defined conditions. Common apparatuses used include the cone calorimeter, Fire Propagation Apparatus and the Purser (Tube) Furnace.

103. From the literature reviewed, a total of 91 unique compounds detected in small scale studies and a total of 121 unique materials were studied. A complete list of the compounds identified, material burning and maximum yields are given in Appendix D.

104. Maximum yields from these studies are shown in Figure 3. A summary of the data, including the material burning is given in Table 4.

105. The highest yields are associated to compounds that are generated due to the burning of materials which contain sulphur, chlorine or nitrogen – sulfur dioxide (material burning: lithium ion battery), hydrogen chloride (material burning: Car Part (Polyvinylchloride)), hydrogen cyanide (material burning: PVC), hydrogen fluoride (material burning: Li-ion battery (LiPF6). Aromatics (benzene, toluene) are also reported with high yields during the burning of MDI/polyester foam, fire retarded.

106. Following these species, aromatic and short chained aliphatic molecules are also reported at high yields along side partially oxygenated species such as ehtanal and acetone.

107. Since chlorine and sulfur are not present in the atmosphere and molecular nitrogen is relatively unreactive at the temperatures associated to diffusion flames, their production must arise due to the presence of these elements within the materials burnt.

108. The compounds which are reported in six more studies are shown in Figure 4. There are twenty such compounds.

109. The most frequently detected species is hydrogen cyanide which was detected in 89 studies.

110. There is a relatively large degree of overlap between the most commonly reported compounds and compounds measured with the highest yields. Primarily these are compounds generated due to the combustion processes associated to materials containing chlorine, sulfur and nitrogen. In addition, aromatic and polycyclic aromatic compounds are frequently reported.

111. There is a strong overlap between the commonly found species and the species which are generated with high yields. Hydrogen cyanide, hydrogen chloride, sulfur dioxide, naphthalene, ammonia, and benzonitrile appear as both frequently detected and present in high concentrations.

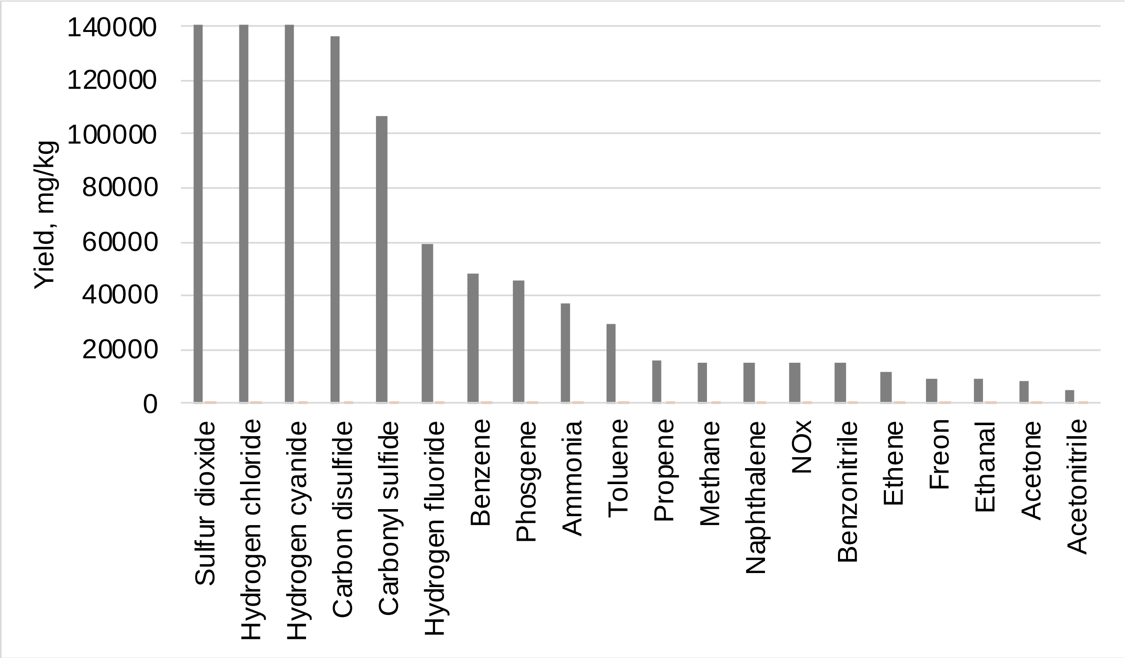


Figure 3 The twenty highest maximum yields of compounds identified in small scale experimental studies. Yields of sulfur dioxide (1 752 632 mg/kg), hydrogen chloride (1 162 000 mg/kg) and hydrogen cyanide (584 210 mg/kg) exceed the y-axis limit.

Table 4 The 20 compounds identified with the highest maximum yields in small scale experimental studies.

Compound	Max yield, mg/kg	Material burning
Sulfur dioxide	1752632	Li-ion battery
Hydrogen chloride	1162000	Car Part (Polyvinylchloride)
Hydrogen cyanide	584210	PVC
Hydrogen fluoride	59500	Li-ion battery (LiPF6)
Benzene	47800	MDI/polyester foam, fire retarded
Toluene	29800	MDI/polyester foam
Propene	16270	Rigid Polyurethane (PAPI,TMP)
Methane	15310	Rigid Polyurethane (PAPI,TMP)

Naphthalene	15100	MDI/polyester foam, fire retarded
NOx	15000	Car Part (Polyamide 6,6)
Ammonia	15000	Airplane Wall/floor cover
Benzonitrile	14900	MDI/polyether polyol foam
Ethene	11440	Rigid Polyurethane (PAPI,TMP)
Freon	9410	Rigid Polyurethane (PAPI,TMP)
Ethanal	9070	Rigid Polyurethane (PAPI,TMP)
Acetone	8140	Rigid Polyurethane (PAPI,TMP)
Acetonitrile	4800	MDI/polyester foam
Acrylonitrile	4500	MDI/polyether polyol foam
Hydrogen sulfide	3000	Carpet (Wool, Polyester)
Acetylene	2900	Li-ion battery (LiPF6)

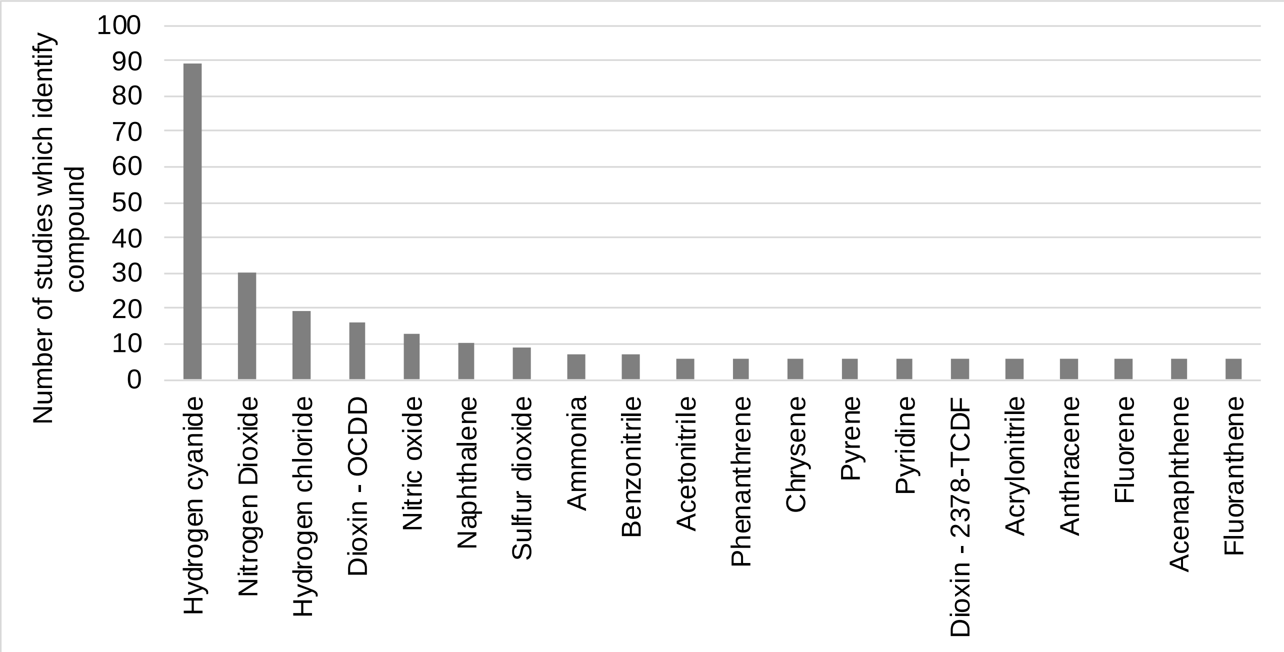


Figure 4 The twenty compounds which are identified in six or more small scale experimental studies.

4.3.2. Large scale experiments

112. Large scale experiments typically include a mixture of studies of burning single objects (vehicles, furniture) in open conditions or within compartments. Often a large calorimeter is used and analysis of the smoke collected is used to determine the yields of fire products.

113. From the literature reviewed, a total of 76 unique compounds or types of compounds detected in large scale studies and a total of 40 unique materials or items were studied. A complete list of the compounds identified, material burning and maximum yields are given in Appendix E.

114. The twenty compounds with the highest maximum yields from these studies are shown in Figure 5.

115. As with the small-scale experiments, the highest yields are associated to compounds that are generated due to the burning of materials which contain sulphur, chlorine or nitrogen – sulfur dioxide, hydrogen chloride, hydrogen cyanide, carbon disulphide and carbonyl sulphide. The yields of these compounds are significantly higher than the other compounds in this list.

116. Since chlorine, sulfur are not present in the atmosphere and molecular nitrogen is relatively unreactive at the temperatures associated to diffusion flames, their production must arise due to the presence of these elements within the materials burnt.

117. There appears to be a bias in this list with high yields of various isocyanates present. These arise due to a small number of studies in which these were specifically of interest, highlighting the bias that may be introduced based on decisions taken by individual report authors.

118. The compounds which are reported in six more studies are shown in Figure 6. There are 31 such compounds.

119. The most frequently detected species is hydrogen cyanide which was detected in 26 studies.

120. There is a small degree of overlap between the compounds most frequently reported and those with the highest yield. In particular hydrogen cyanide and hydrogen chloride, benzene, ammonia and polychlorinated dibenzodioxins (PCDD) are reported in high concentration and with relatively high measurement occurrences. However, the most frequently reported species are dominated by polycyclic aromatic hydrocarbons

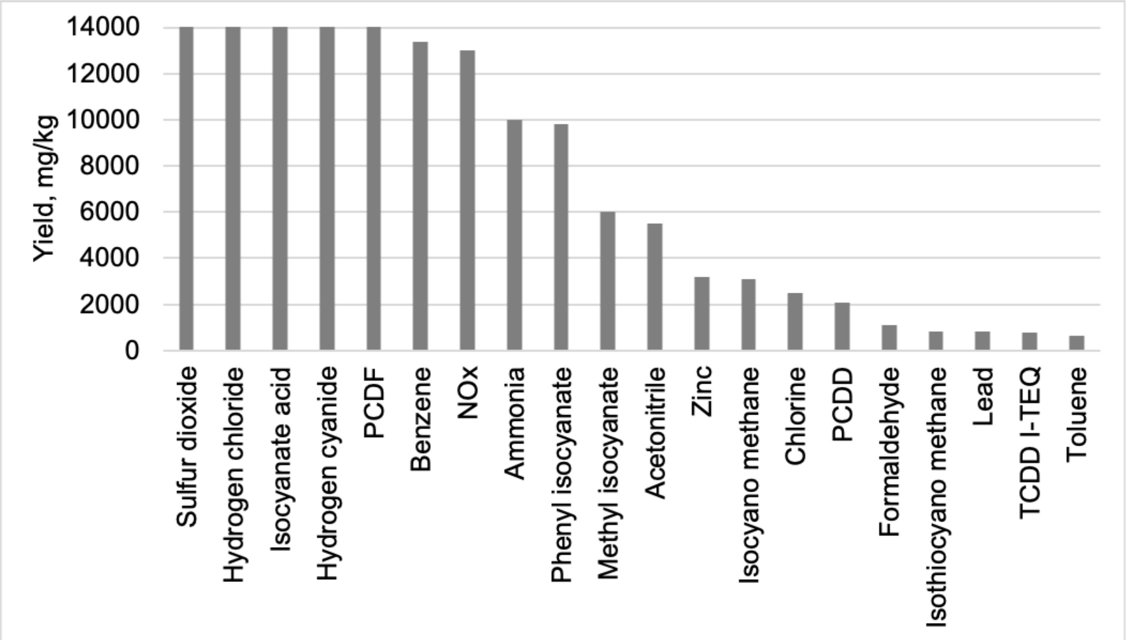


Figure 5 The twenty highest maximum yields reported for large scale fire experiments. Yields of sulfur dioxide (1 050 000 mg/kg), hydrogen chloride (246 000 mg/kg), isocyanate acid (210 000 mg/kg), Hydrogen cyanide (70 000 mg/kg) and PCDF (56 000 mg/kg) exceed the y-axis limit.

Table 5 The 20 compounds identified with the highest maximum yields in large scale experimental studies.

Compound	Max yield, mg/kg	Material burning
Sulfur dioxide	1050000	Tetramethylthiuram monosulphide
Isocyanate acid	210000	Car
Hydrogen cyanide	70000	MDF
PCDF	56000	Car
Benzene	13384	Television (US)
NOx	13000	Tetramethylthiuram monosulphide
Ammonia	10000	Nylon 6.6
Phenyl isocyanate	9800	Car
Methyl isocyanate	6000	Car
Acetonitrile	5510	Tetramethylthiuram monosulphide
Zinc	3200	Car
Isocyano methane	3100	Tetramethylthiuram monosulphide
Chlorine	2500	Car
PCDD	2100	Car
Formaldehyde	1100	Automobile
Isothiocyano methane	840	Tetramethylthiuram monosulphide
Lead	820	Car
TCDD I-TEQ	800	Car
Toluene	660	Automobile
Hexamethyl diisocyanate	620	Car

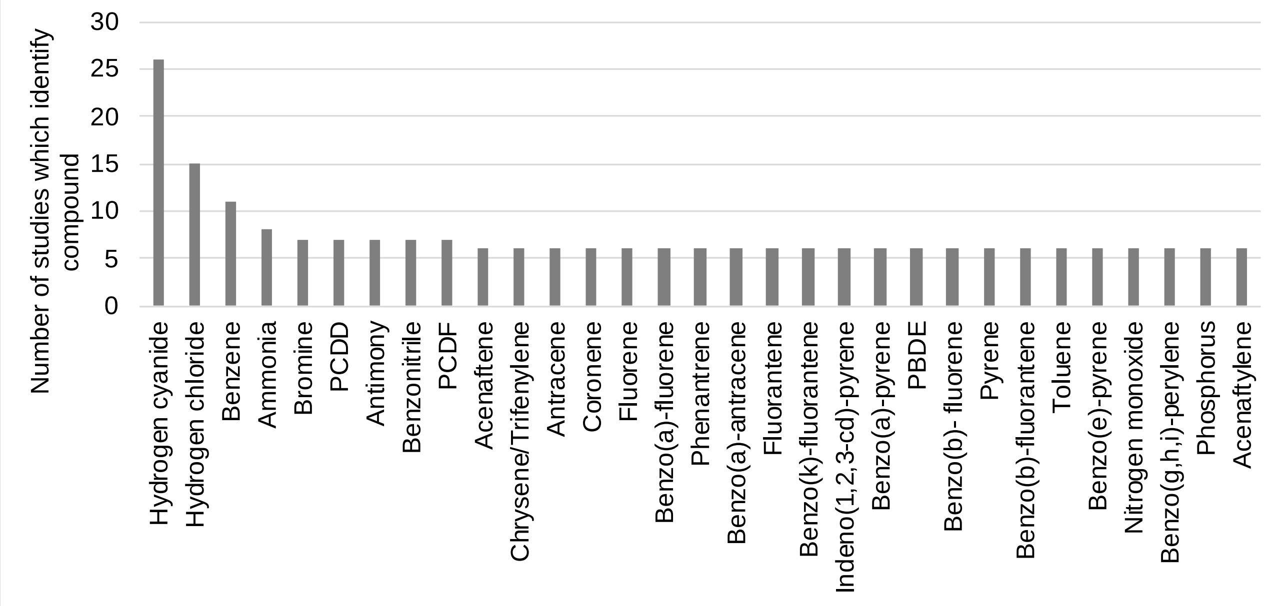


Figure 6 The 31 compounds which were measured in six or more large scale experimental studies.

4.3.3. Municipal waste incineration

121. Emissions form municipal waste incineration usually are measured in the exhaust treatment stream of incinerator plant, typically downstream of exhaust treatment systems. As such, the yields reported are generally lower than would be expected in the absence of exhaust treatment. However, some studies reported the emissions during transient operation (start up, shut down) and these have been included. See the Annotated Bibliography for more details.

122. From the literature reviewed, a total of 53 unique compounds detected in small scale studies and a total of 7 types of waste were studied. A complete list of the compounds identified, material burning and maximum yields are given in Appendix F.

123. The twenty compounds with the highest maximum yields from these studies are shown in Figure 7.

124. As before high yields are obtained for species that are generated during the combustion of materials which contain sulfur, chlorine or fluorine – hydrogen fluoride, hydrogen chloride and sulfur dioxide. Since these are not present in the atmosphere, the generation of these compounds must depend on the materials burnt.

125. The highest yield is associated to polychlorinated dibenzofurans (PCDF) and polychlorinated dibenzodioxins (PCDD). These are reported to be generated during the transient stage of incinerator operation (e.g. startup).

126. Yields of elemental compounds given in Figure 7 are all less than 10 mg/kg.

127. The compounds which are reported in two more studies are shown in Figure 8. There are 22 such compounds.

128. The most frequently detected compounds are PCDD and PCDF which combined were detected in sixteen studies (either individually as PCDDs or PCDFs or as a total). Hydrogen chloride is the fourth most frequently reported compounds. The remaining frequency reported compounds are characterised by heavy metals and aromatics.

129. PCDD and PCDF, hydrogen chloride and heavy metals are frequently measured and reported with high yields. This may be due to the relatively small number of primary literature associated to this space.

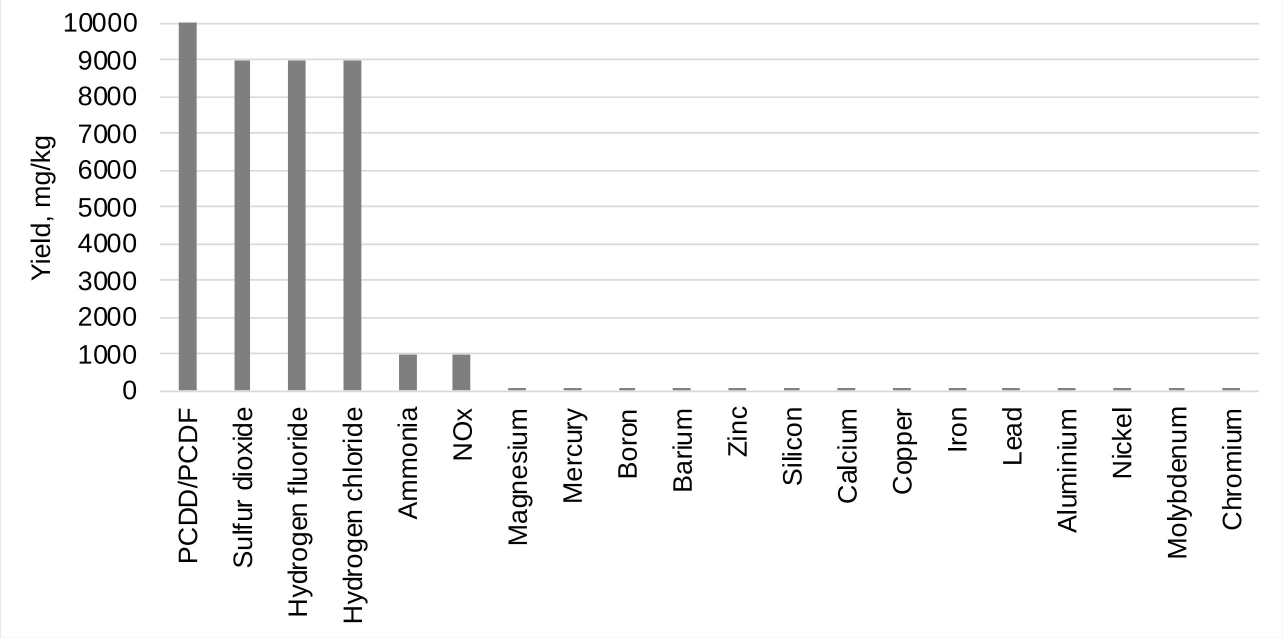


Figure 7 The twenty highest maximum yields reported for solid municipal waste incineration. Yields species from Magnesium on were less than 10 mg/kg.

Table 6 The 20 compounds identified with the highest maximum yields in large scale experimental studies.

Compound	**Max yield, mg/kg**	**Material burning**
PCDD/PCDF	10000	Municipal waste
Sulfur dioxide	9000	Municipal waste
Hydrogen fluoride	9000	Municipal waste
Hydrogen chloride	9000	Municipal waste
Ammonia	1000	Municipal waste
NOx	1000	Municipal waste
Magnesium	9.8	Municipal waste
Mercury	8.8	Municipal waste
Boron	6.2	Municipal waste
Barium	4.2	Municipal waste
Zinc	3.3	Municipal waste
Silicon	2.4	Municipal waste
Calcium	2.0	Municipal waste
Copper	2.0	Municipal waste
Iron	2.0	Municipal waste
Lead	1.6	Municipal waste
Aluminium	0.6	Municipal waste
Nickel	0.5	Municipal waste
Molybdenum	0.5	Municipal waste
Chromium	0.4	Municipal waste

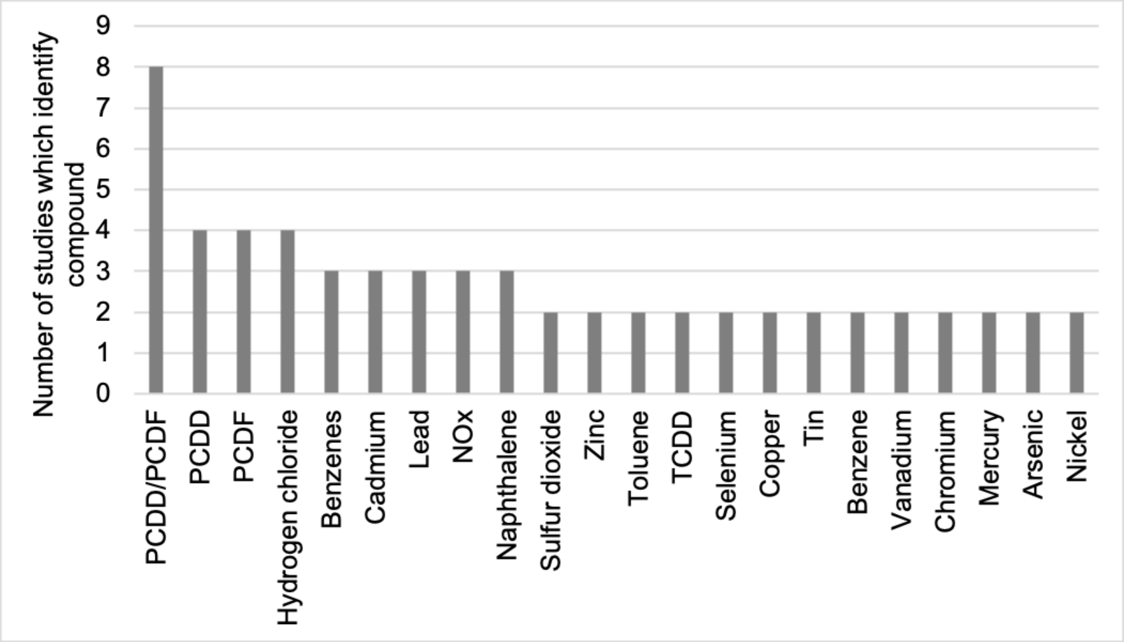


Figure 8 The 22 compounds which were measured in two or more studies on the emissions from solid waste incineration.

4.3.4. Municipal waste burning

130. The open burning of municipal waste is reported in a number of scenarios all of which offer limited or no control of the burning conditions. Mixtures of natural and synthetic polymers are typically burnt. Little information is given regarding the combustion conditions in the studies.

131. From the literature reviewed, a total of 166 unique compounds detected in small scale studies and a total of 37 types of waste were studied. A complete list of the compounds identified, material burning and maximum yields are given in Appendix G.

132. The twenty compounds with the highest maximum yields from these studies are shown in Figure 9.

133. The highest yields are associated to styrene, benzene and toluene. The remaining highest yields are made up of aromatic hydrocarbons, polycyclic aromatic hydrocarbons and partially oxygenated compounds. In general, these are of smaller molecular weight than those detected in other conditions.

134. The compounds which are reported in four more studies are shown in Figure 10. There are 17 such compounds.

135. The most frequently detected compounds are PCDD and PCDF which combined were detected in 66 studies (either individually as PPCDDs or PCDFs or as a total). The remaining most frequently detected compounds are aromatic and polycyclic aromatic hydrocarbons.

There is a relatively low degree of overlap between the specific species found to be present in high yields and in a large number of studies. However, in general terms, these burning conditions, aromatic and polycyclic aromatic compounds appear to be key fire products and PCDD and PCDF due to large number of times these are detected.

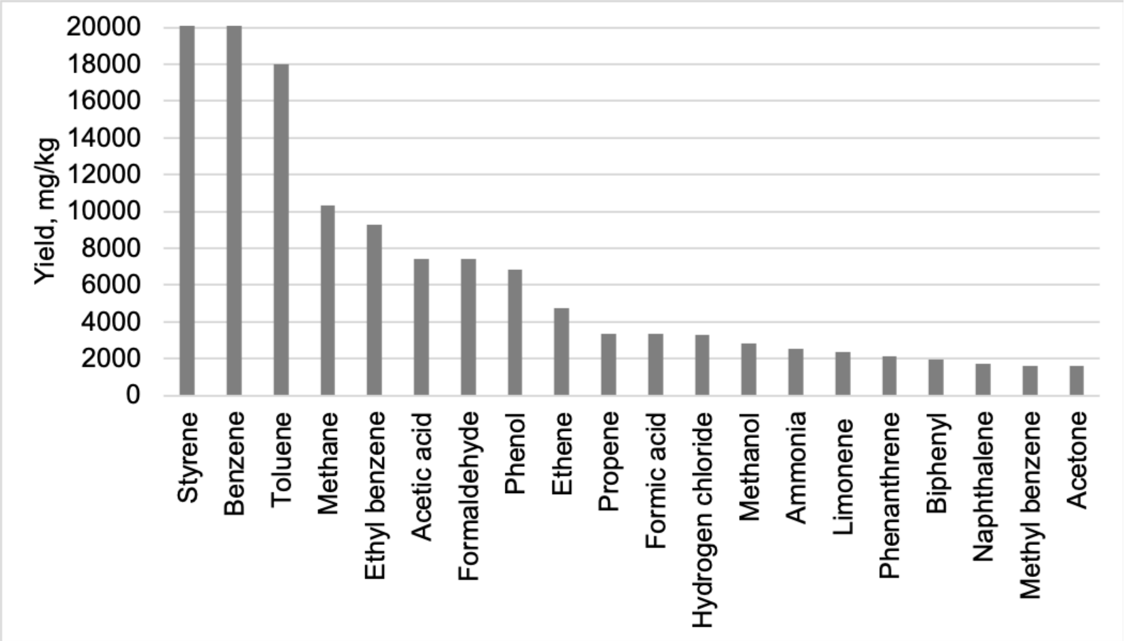


Figure 9 The twenty highest maximum yields reported for municipal solid waste burning. The yields of styrene (49 400 mg/kg) and benzene (34 800 mg/kg) exceed the y-axis limit.

Table 7 The 20 compounds identified with the highest maximum yields in large scale experimental studies.

Compound	**Max yield, mg/kg**	**Material burning**
Styrene	49400	Fiberglass Materials (Building Industry)
Benzene	34800	Fiberglass Materials (Boating Industry)
Toluene	18000	Fiberglass Materials (Building Industry)
Methane	10300	Fiberglass Materials (Building Industry)
Ethyl Benzene	9300	Landfill waste
Acetic acid	7400	Landfill waste
Formaldehyde	7400	Fiberglass Materials (Building Industry)
Phenol	6830	Landfill waste
Ethene	4750	Landfill waste
Propene	3340	Landfill waste
Formic acid	3340	Household waste
Hydrogen chloride	3280	Landfill waste
Methanol	2810	Landfill waste
Ammonia	2520	Tire Shred

Limonene	2345.5	Fiberglass Materials (Building Industry)
Phenanthrene	2156	Fiberglass Materials (Building Industry)
Biphenyl	1936	Tire Chunk
Naphthalene	1697.9	Tire Chunk
Methyl benzene	1606.4	Military waste with PET plastics
Acetone	1600	Fiberglass Materials (Building Industry)

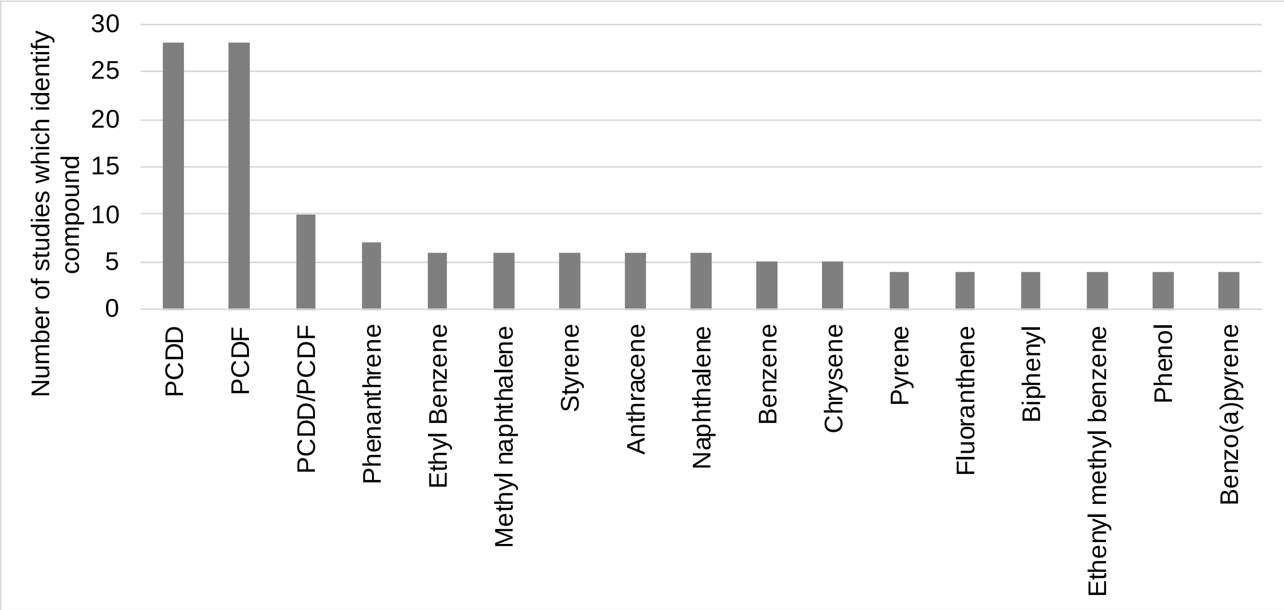


Figure 10 The 17 compounds which were measured in four or more studies on the emissions from municipal solid waste burning.

4.4. Summary

136. The yields and number of studies which reported compounds for the burning of materials in small scale experiments, large scale experiments, solid waste incineration and solid waste burning have been reported.

137. In summarising these results it is important to consider that the results are largely influenced by the burning, conditions, the materials burnt and the compounds which individual investigators have chosen to measure.

138. Comparison of small- and large-scale fire behaviour indicates that the highest yields are consistently associated to hydrogen chloride, hydrogen cyanide, and sulfur dioxide. Other compounds which are detected frequently or in large quantities include a range of aromatic and polycyclic aromatic hydrocarbons.

139. There is a reasonable consistency in the magnitude of yields across these studies with yields typically in the orders of 1 000 to 10 000 mg/kg.

140. The relatively few studies on municipal solid waste incineration suggest that PCDD and PCDF are of significance being reported with high yields and with highest frequency. This however may be

due to bias introduced in this field. These compounds are known have adverse environmental and health impacts so have been the primary focus of these studies. Studies on emissions from incineration also focus on release of heavy metals due to known health and environmental impacts. In general, these are not reported in studies including fire experiments. This does not mean that such compound groups will not be present however, the yields will depend on the nature of the combustion environment.

141. There is relatively little overlap between the yields of fire products in the burning of waste compared to the incineration of waste. Studies on burning of wastes show high yields of aromatic and polycyclic aromatic hydrocarbons. There is however generally agreement that PCDD and PCFD are compounds of significance as these are measured in a large number of studies.

142. The yields of species from burning of municipal solid waste are comparable to those obtained in small and large scale fire experiments (in the orders of 1 000 to 10 000 mg/kg).

143. In general, across the four objectives, the highest yields are of species which cannot be further oxidised by reaction with oxygen under the temperature and species conditions typical of a fire.

5. Correlation of products identified to products known to be present at Grenfell Tower

5.1. Contents of flats

144. The contents of the individual flats at Grenfell Tower are not known and no studies evaluating the detailed composition of materials present have been found in the literature.

145. A list of the 190 materials on which the review is based is given in Appendix C. Given the widespread use of many of these materials it is assumed that these are representative of those which may be found within a domestic or commercial premises.

146. The descriptions of the materials given in Appendix C are those used in the reference literature Some of the descriptions of the material burned may seem irrelevant, it is important to note that these do not provide detailed descriptions of the chemical composition of the materials so it is considered that these materials remain relevant.

147. This is further supported by the hypothesis that the conditions of burning are more important in determining the combustion related fire products than the material which is burning.

148. Therefore, we propose the species identified Appendix B are likely to have been present during the Grenfell Tower fire.

5.2. Construction materials

149. Using the information available from the Grenfell Tower Inquiry (Grenfell Tower Inquiry, 2020), and particularly the Expert Witness Report of Professor Luke Bisby (Bisby, 2018), the materials identified to be present on the external structure of Grenfell Tower are listed in Table 8 alongside relevant references which present information on the yields of fire products.

150. It is notable that of the eight primary materials identified, five of these do not appear in the literature reviewed and hence there are no data available on the likely combustion related fire products that may be expected.

Table 8 The materials present on the external structure of Grenfell Tower and

Material	**Reference**
Polyisocyanurate foam	(Blomqvist *et al.*, 2003) (Purser and Purser, 2008) (McKenna *et al.*, 2019)
Polyethylene	None
EPDM membrane	None
Phenolic foam	None
Polyurethane foam insulation	(Paabo and Levin, 1987) (Blomqvist *et al.*, 2007) (Paabo and Levin, 1987) (Blomqvist *et al.*, 2003)
(u)PVC	(Griffith, Janssens and Willson, 2005) (Blomqvist *et al.*, 2007) (Vikelsùe and Johansen, 2000) (Hull, Lebek and Stec, 2008) (Stec *et al.*, 2008)
Mineral wool	None
Expanded polystyrene	None

151. The combustion products detected from studies which have investigated the burning polyisocyanurate foam (PIR), polyurethane foam and polyvinyl chloride (PVC) and the associated maximum yields are listed below in Table 9.

152. These data should be used carefully. As already identified, the mode of combustion will significantly influence the yields of combustion products. The form of the materials and the burning conditions relevant to the yields produced in Table 9 are not reported in detail and given the lack of information available regarding the conditions at Grenfell tower, it is not possible to infer that these yields would be applicable to the fire at Grenfell Tower.

153. Nevertheless, it is noteworthy that hydrogen cyanide, hydrogen chloride and isocyanates are present. Again, this seems to indicate that the material burning is important in quantifying the production of a combustion related fire product, but the burning conditions will dictate the yields.

Table 9 The maximum yields of compounds measured in studies which consider materials similar to those which were present on the external structure of Grenfell Tower

Material burning	**Compound**	**Max. of Yield, mg/kg**
Cable (Polyvinylchloride)	Hydrogen chloride	320000
Car Part (Polyvinylchloride)	Hydrogen chloride	1162000
PIR (rigid foam)	Methylenediphenyl isocyanate	40
	Isocyanate acid	6027
	Phenyl isocyanate	877
	Methyl isocyanate	22
	Ethyl isocyanate	9
	Methylenedianiline	177
Polyisicyanurate foam	Hydrogen cyanide	25000
Polyisocyanurate foam	Hydrogen chloride	19000
	Hydrogen cyanide	20000
		17000
	Phosphoric acid	3000
	Nitric oxide	3000
Polyurethane Insulation	Ammonia	1000
	Hydrogen cyanide	17000
	Nitric oxide	3000
Polyurethane mattress	Ammonia	1500
	Hydrogen cyanide	9000
	Nitric oxide	4000
Polyvinylchloride carpet	Hydrogen chloride	240000
Polyvinylchloride Pellets	Hydrogen chloride	170000
		500000
PUR (flexible foam)	Toluene diisocyanate	220
	Hexamethyl diisocyanate	1
	Isoforon diisocyanate	19
	Methylenediphenyl isocyanate	37
	Isocyanate acid	395
	Phenyl isocyanate	27

	Toluene aminoisocyanate	111
	Toluenediamine	5
	Methylendiphenyl aminoisocyanate	10
PUR (rigid foam)	Isoforon diisocyanate	1
	Methylenediphenyl isocyanate	15
	Isocyanate acid	1483
	Phenyl isocyanate	1174
	Methyl isocyanate	9
	Ethyl isocyanate	3
	Methylendiphenyl aminoisocyanate	35
	Methylenedianiline	455
Rigid Polyurethane (PAPI,TMP)	Acetone	8140
	Allene	2250
	Benzene	7380
	Benzonitrile	7730
	Butadiene	1110
	Ethanal	9070
	Ethane	2020
	Ethene	11440
	Ethyne	1400
	Freon	9410
	Methane	15310
	Propene	16270
	Propenitrile	2780
	Propyne	1100
	Styrene	1220
	Toluene	3730
	Xylene	1980
	Butenyne	130
	Methyl propenal	1750
	Methylbutene	3570

6. Review of mechanisms for dispersion of emissions

154. The transport and dispersion of airborne material (gaseous species or fine particulate matter) is an important topic for many issues related to public and environmental health. Therefore, the mechanisms which govern dispersion have been widely studied in a variety of contexts, including stack emissions from industrial processes, point source emissions from chemical attacks, and disperse emissions from common pollution sources (e.g. traffic). Many of the core concepts have been laid out in the past decades in texts such as the Handbook on Atmospheric Diffusion (Hanna, Briggs and Hosker, 1982), and these still form the basis of current modelling approaches. This appears to be due to the following: that they adequately describe the most dominant processes, and that collection of detailed data for model testing and development is difficult to obtain (particularly in a repeatable manner).

155. Many approaches have been proposed for modelling dispersion, from simple correlations to complex computational fluid dynamic (CFD) approaches with detailed transport models (Hanna, Briggs and Hosker, 1982; Belcher *et al.*, 2013). However, the Gaussian plume model is most typically employed, owing to its ability to accurately predict experimental measurements with a relatively simple formulation. This model assumes a Gaussian distribution of concentration in the plume, which depends on the emission rate and prevailing wind speed. The plume is assumed to originate from a point source and be advected horizontally in the direction of the prevailing wind (taken here as the x direction). The width of the plume in the horizontal (σ_y) and vertical (σ_z) directions grows as it travels along distance from the source. This leads to a decay in maximum concentration, which can be described (to a first approximation, particularly for smaller distances) as inversely proportional to the square of the distance ($C \propto x^{-2}$) (Briggs, 1973). For a horizontally transported plume which does not interact with the ground, the centreline (and therefore maximum) concentration is described as:

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z}$$

156. where u is the wind speed, Q is the release rate, and the growth in cross-sectional area ($2\pi\sigma_y\sigma_z$) is dependent on a number of factors, but is roughly proportional to x^2 at small distances (both σ_y and σ_z proportional to x). The key then becomes determining which factors can alter the plume growth and cause the decay in concentration to deviate from this trend.

157. For the problem of dispersion and deposition of combustion products from Grenfell Tower, the context is that of an elevated point source (though emission is likely to have occurred across a range of heights) with an elevated temperature (implying buoyancy effects) in an urban environment. Dispersion in open environments historically received more attention than in urban settings, partially due to the simplification of the flow. However, more mechanistic evaluations of flow and dispersion through so-called ‘urban canopies’ have also been developed more recently (e.g. Belcher, 2005).

158. While a simple Gaussian model can adequately describe dispersion, based on the available body of knowledge, we have identified the following mechanisms which can impact dispersion, and are relevant to the Grenfell Tower fire.

6.1. Injection height/plume rise

159. As the Gaussian model involves a vertical component of dispersion (σ_z), it is expected that the concentration at a given height above the ground will depend on the distance between that height and the plume centreline (as well as the distance from the source). The plume centreline is defined by the height of the source, and thus determining the concentration at an arbitrary height above the ground depends on this injection height (h). Using the Gaussian model, it is possible to then predict the concentration at ground level at a given distance (assuming the plume is reflected when it reaches ground level). This is particularly important for understanding deposition of emissions. If

the plume grows proportionally in the horizontal and vertical direction, this should occur at the distance when $\sigma_z = h/\sqrt{2}$, and is given by (Hanna, Briggs and Hosker, 1982):

$$C = \frac{2Q}{\pi u e h^2} \frac{\sigma_z}{\sigma_y}$$

160. However, while useful for understanding ambient temperature emissions injected at height, this does not account for buoyancy effects, such as those that would be expected from a fire source (or initial momentum, as often encountered in industrial emissions). Buoyancy will serve to further increase the height that the plume reaches before horizontal advection becomes dominant. The rise of a plume will eventually be limited by interaction with a stable layer of air (the ambient atmospheric temperature profile inhibits vertical motion) or by dilution through turbulent mixing. The relationship between initial plume velocity and temperature and the ambient conditions will determine if a plume is vertical or bent over. Guidance for different conditions can be found in a variety of formulations which are used to calculate stack emissions (e.g. Brummage, 1968; Hanna, Briggs and Hosker, 1982). These are based on first principles, but generally require a degree of empirical fitting.

161. A simplistic approach is to calculate the plume rise and add this to the initial injection height, creating a new effective height, and proceeding as before to determine ground level concentrations. In its most basic form, this does not account for dilution during the plume rise stage. This may be important for plume rises which are relatively large compared to the distance to the maximum concentration, however, modification of the initial size of the horizontal Gaussian plume could be used to account for this initial growth.

162. Calculating plume rise may present the biggest challenge for large fire scenarios, particularly when the burning dynamics and thus condition of the plume at the source are not well-quantified. For this reason, more complex models are often adopted when considering fire sources (e.g. burning of crude oil (McGrattan 2003) or wildland fires (Goodrick *et al.*, 2013)). These involve more detailed solutions of the transport equations than the Gaussian approaches based on idealized sources but require correspondingly more information regarding the source at atmospheric conditions. Therefore, an empirical Gaussian approach can provide a first estimate of dispersion (particularly where visual observations may be used to supplement predictions of plume rise), and for more detailed predictions models such as ALOFT (NIST), HYSPLIT (NOAA), or ADMS (CERC) may be considered.

6.2. Atmospheric conditions

163. Important atmospheric conditions include the wind speed, direction, and turbulent characteristics. Of these, the influence of the wind speed and direction are the most easily accounted for. The basic Gaussian concentration has an inverse linear dependence on wind speed (see above), and the wind direction will determine the direction of the plume centreline.

164. This simple picture provides a baseline for dispersion considerations; however, reality may be more complex. For example, wind speed is generally not uniform along height. The speed at the effective plume height is often used. If not known, this can be estimated from measurements at another height by an assumed power-law profile

$$u = u_{10} \left(\frac{z}{10}\right)^p$$

165. where the power p can be chosen for different atmospheric stability conditions (Irwin, 1979). It is also worth noting that the wind direction may only dictate the dispersion direction at longer distances, particularly when considering low-elevation sources in urban settings. For example, in the 2007 DAPPLE urban tracer experiment in London, elevated tracer concentrations were recorded up to two blocks away regardless of the prevailing wind direction (implying upwind dispersion) (Wood *et al.*, 2009).

166. The turbulent characteristics of the wind are also important to capture, as these can influence the nature of the plume growth (σ_y, σ_z). To truly capture this behaviour, detailed quantification of the turbulence is required (boundary layer shear, convective heat flux, etc.). However, simple classifications of the atmospheric stability (known as Pasquill types A-F) are often used to generate a first approximation, as they are easily obtained from observations of mean wind speed and cloudiness in day or night conditions (Gifford, 1976). Briggs (Briggs, 1973) proposed simple correlations for the plume growth for all Pasquill types, for both rural and urban settings. Those relevant to at least the initial stages of the Grenfell Tower fire (nighttime, urban) follow the form of both σ_y and σ_z proportional to distance (x) close to the source. Further away, both are proportional to $x^{1/2}$.

167. However, there may be a limit to the usefulness of these correlations. For example, they were obtained for injection heights of <100 m (Hanna, Briggs and Hosker, 1982). More recent work by (Connan *et al.*, 2011) compared measurements of high temperature (buoyant) emissions from a 40 m stack in a rural environment to both the Briggs (Briggs, 1973) approach and ADMS model (also a Gaussian approach, but employs more detailed turbulence characteristics to determine dispersion and more detailed plume rise calculations) ('ADMS 5 - Atmospheric Dispersion Modelling System User Guide', 2016). The atmospheric stability had little effect on horizontal dispersion (σ_y), which was predicted within an error factor <2 by both approaches. However, the maximum concentration (which therefore includes vertical dispersion) was more reliably predicted by ADMS in neutral conditions, and neither approach could be reliably used for near-field (<1.5 km) estimates in unstable conditions.

168. Another study by Gryning and Lyck (Gryning and Lyck, 1984) investigated non-buoyant tracer measurements, recorded between 2-6 km from an elevated release (115 m) in an urban area (Copenhagen). They compared models which use stability classes to quantify plume growth (such as Briggs (Briggs, 1973)) to those which use direct measurements of turbulent statistics during the release. They found that certain methods based on the wind variances resulted in lower prediction error (for both horizontal growth and maximum concentration at a downwind distance) than those using stability classes (including Briggs), though not necessarily for all models considered.

169. It is not necessarily surprising that approaches which included more direct quantification of relevant phenomena have the potential to produce more accurate results. Indeed, a recent evaluation of the Pasquill stability types against more detailed characterizations of the atmosphere indicated that they tended to incorrectly classify the conditions (particularly in daytime) (Kahl and Chapman, 2018). While simple approaches such as this can offer a first estimate, correct characterization of the atmospheric turbulence is important, given its role in vertical mixing, particularly with buoyant emissions from an elevated source.

6.3. The urban canopy

170. Dispersion in urban environments is of particular interest for this case. A majority of past research into flow and dispersion in such contexts, however, has focused on non-buoyant ground-level sources. This is because most interest is directed to predicting dispersion in the case of chemical attacks, though some investigation of traffic-based pollution has also been conducted. Elevated buoyant sources, which are more representative of a high-rise fire, are more often studied in the context of the models above. That is, the effect of the urban environment is treated as a surface condition which alters the downwind growth rate of the plume. For example, in some approaches a correction may be applied to the vertical growth of the plume to account of the effect of the urban heat island (Gryning and Lyck, 1984). Nevertheless, studies which focus on street level dispersion can still provide interesting insight for this case, particularly as some emissions may have been generated close to ground level.

171. The review by Belcher (Belcher, 2005) provides an overview of some of the important street-level mechanisms. Generally, streets and intersections are considered to be the major elements for flow in the near-field. Flow can either be channelled along streets if oriented in a parallel manner, or

cause shear-induced mixing circulations within the street canyon if the overhead flow is perpendicular to the street direction. At intersections, more complicated flow patterns emerge as jets channelled down one street either impinge on a building face (t-intersection) or induce vortices in cross-streets (4-way intersections).

172. A number of highly involved experimental campaigns have been conducted to monitor the dispersion of tracers released in urban settings. Examples include tests in London (Arnold *et al.*, 2004; Wood *et al.*, 2009; Martin, Nickless, *et al.*, 2010; Martin, Price, *et al.*, 2010), Oklahoma City (Flaherty *et al.*, 2007), Salt Lake City (Allwine *et al.*, 2002), Toulouse (Masson *et al.*, 2008). These have produced some observations of street-scale mechanisms. For example, a number of studies observed channelling of flow down streets which served to modify the plume direction, particularly close to the source (Allwine *et al.*, 2002; Arnold *et al.*, 2004; Flaherty *et al.*, 2007). A detailed analysis of data from one of the London releases also determined that the role of channelling and mixing circulations could be understood by decomposing the above-building wind vector into along-street and cross-street components (Dobre *et al.*, 2005).

173. While such mechanisms are key for understanding street-level dispersion, particularly close to the source, they are difficult to incorporate in a generalized model as each city configuration will differ from the next. Therefore, measurements are often compared to a simplified Gaussian model which assumes linear plume growth in both the horizontal and vertical directions. This gives the familiar form for maximum concentration:

$$C = \frac{KQ}{U_H R^2}$$

174. with K taken as a constant between 5-20 and U_H as the characteristic above-building wind speed (Belcher, 2005). This approach has been shown to provide a reasonable estimate when compared to data from a number of urban releases (keeping in mind that sampling in these cases is usually within 1 km of the source) (Neophytou and Britter, 2004; Wood *et al.*, 2009; Martin, Nickless, *et al.*, 2010). However, analysis of horizontal plume width in an Oklahoma City experiment indicated that a correction factor was needed for wind direction, as wind oriented 45 degrees to the street grid could serve to roughly double horizontal plume growth (Flaherty *et al.*, 2007). Similarly, the Salt Lake City experiments produced a plume width greater than the linear model (Hanna, Britter and Franzese, 2003). Therefore, the general agreement of the simple concentration model may be masking some more complex behaviour.

6.4. Summary

175. The sources referenced above indicate that dispersion of fire related combustion products should be a strong function of the prevailing wind (direction and speed) during the time of the fire. However, a monotonic decay of concentration of emissions from the fire should not be expected. The settlement of compounds from the plume depend on a number of factors but in particular the buoyant vertical flow may result in comparatively low concentrations in the immediate vicinity of the tower with maximum concentrations of fire products being found some distance from the base of Grenfell Tower. This is further complicated by local flow phenomena near the ground such as channelling. However, the role of dilution is strong – and potentially increased by mixing induced by the urban canopy – and it is likely that concentrations in the soil will be very low. Furthermore, characterising the plume injection characteristics from the fire at Grenfell Tower has not been possible using available information in the public domain limiting the application of these observations.

176. No data have been found pertaining to soil contamination following large fires. Perhaps the best characterisation available to date is following the Buncefield Fire and Explosion however, due to the atmospheric conditions present, the buoyant plume was trapped between stable layers in the atmosphere and sporadically came into contact with the ground (Targa *et al.*, 2006). Further to this point, no studies exploring the deposition from the plume and corresponding soil concentrations were not found in the scientific literature.

7. Toxicology assessment

7.1. High Yield Compounds

7.1.1. Overview

177. Where data exist to quantify yield, maximum yield (mg/kg) was calculated for each substance and high yield substances were identified. Total potential yield (mg/kg) was calculated by adding maximum yields so that relative amounts of each compound could be examined. Individual compounds are listed in Table 10. Yields of all compounds identified are listed in Appendix B. These compounds were evaluated for toxicity, carcinogenicity and chemical properties that may cause them to be retained in soil. Because of their persistence in the environment, PTEs and SVOCs deposited by emissions are likely to be retained in soil. Because of their volatility and relatively fast rates of degradation in the environment, gases and some VOCs may not be retained in soil, although VOCs may be present as constituents of complex, less volatile mixtures. This review aims to identify substances that may be present as a result of the fire. Many of these substances may also be present in soils as a result of other human activities and/or natural occurrence. Unless compelling reasons were identified to eliminate these substances from further consideration, recommendations are made for the parties undertaking the Phase 2 Site Investigation and Risk Assessment to consider these substances and decide based on all available information, whether these substances should be included in that investigation. Detailed evaluation of toxic and carcinogenic mechanisms related to human exposure to substances retained by soil is outside of the scope of this report and is normally undertaken as part of the Phase 2 Site Investigation and Risk Assessment.

Among high yield compounds, gases account for 84.1% of total potential yield, volatiles account for 12.9%, and semi-volatiles account for 2.9% (

178. Table 11).

Table 10 High yield substances in fire emissions grouped as semi-volatile organic compounds, volatile organic compounds, and gases.

Semi-volatiles	**Max yield, mg/kg**	**Volatiles**	**Max yield, mg/kg**	**Gases**	**Max yield, mg/kg**
PCDF	5600	Isocyanate acid	210000	Sulfur dioxide	1752632
Styrene	49400	Carbon disulfide	136000	Hydrogen chloride	1162000
Naphthalene	15100	Hydrogen cyanide	110000	Nitric oxide	121000
		Benzene	47800	Carbonyl sulphide	107000
		Toluene	29800	Hydrogen fluoride	59500
				Phosgene	46000
				Nitrous oxide	45000
				Ammonia	37000
				Propene	16270
				Methane	15310
				NOx	15000

Table 11 Total potential yield and relative amounts by compound

Compound type	**Total Yield, %**
SVOC	2.9
VOC	12.9
Gas	84.1

7.2. Substances to consider for testing

179. The semi-volatile organic compounds with highest yields are **polychlorinated dibenzofurans** (PCDF), styrene, and naphthalene. Among these, naphthalene is already planned for testing among the **USEPA 16 Priority PAHs**. PCDF (along with PCDD) are among the most frequently detected compounds in our literature survey. IARC classify 2,3,7,8-TCDD as a known carcinogen (Group 1) and other PCDD/F as not classifiable (Group 3) due to lack of data. IARC classifies styrene as a probable carcinogen (Group 2A). **PCDF** and **styrene** are suggested for further consideration in developing the soil testing programme.

180. Volatile organic compounds include two cyanide compounds (isocyanate acid and hydrogen cyanide), carbon disulphide, benzene, and toluene. Cyanide compounds are highly toxic. Neither hydrogen cyanide nor isocyanic acid are classified for carcinogenicity by IARC. Isocyanic acid reacts readily with water. Hydrogen cyanide has a half-life of 1-5 years in the atmosphere. In the gas phase, it is slightly lighter than air. Degradation of cyanide compounds is slower in soil than in the atmosphere. Carbon disulphide is toxic and not evaluated for carcinogenicity by IARC or other agencies. Benzene is highly toxic at low doses and a known carcinogen (IARC Group 1). Toluene is toxic but significantly less so than benzene and not classified as carcinogenic (IARC Group 3). Benzene and toluene seem unlikely to be present on their own but may be present in complex mixtures. **Cyanide compounds**, **carbon disulphide**, and **benzene** are suggested for further consideration in developing the soil testing programme. Based on significantly lower toxicity than benzene, toluene is not suggested for further consideration.

181. None of the gases were evaluated directly; however, based on high yields of SO_2, carbonyl sulphide, and carbon disulphide, excess **sulphur** is suggested for further consideration. Elemental sulphur is not particularly harmful; however, its presence may be a potential indicator that an area was affected by airborne deposition of fire effluent constituents.

182. In summary, based on yield calculations, **PCDF, styrene, cyanide compounds, carbon disulphide, benzene, and sulphur** are suggested for further consideration during development of the soil testing programme. Site-specific evaluation should follow to determine if any of these substances should be eliminated before undertaking the Phase 2 investigation.

7.3. Frequently Detected Compounds

7.3.1. Overview

183. Literature review identified hundreds of possible substances or types of substances. This initial list was narrowed by counting the frequency of reports. Substances that were reported in five or more studies are listed in Table 12, which also disaggregates these substances by type (potentially toxic elements (PTEs), semi-volatile organic compounds (SVOCs), volatile organic compounds (VOCs), and gases.

184. This analysis relies heavily on researchers choosing to analyse specific substances. If a substance was not included, it would not be detected. As such, this approach risks missing substances that are not common analytes, leaving an important gap in this work. A short section follows about notable omissions (Section 7.4); however, the knowledge gap remains. Further, the studies reported here were not evaluated critically for the quality of the analytical chemistry. In this review, findings were accepted as reported. If using background or non-detect levels from the previous site investigation to exclude substances, practitioners should be convinced that the previous site investigation found the areas impacted by fire effluent before making those decisions.

185. We did not attempt to establish frequency of detection in the review. Science has a culture that biases against reporting of negative results (Fanelli, 2012). We do not know if substances reported only five times (or fewer) were unique analytes or measured as widely as the most frequent substances (PCDD/Fs).

Table 12 Substances identified five or more times during the literature review listed by type (potentially toxic elements (PTEs), semi-volatile organic compounds, volatile organic compounds, and gases). Substances currently planned for quantification in Phase 2 Site Investigation (lead and 16 USEPA Priority PAHs) are highlighted in blue.

PTEs	**Count**	**Semi-volatiles**	**Count**	**Volatiles**	**Count**	**Gases**	**Count**
Antimony	8	PCDF	40	Hydrogen cyanide	54	Hydrogen chloride	39
Lead	7	PCDD	40	Benzene	23	Nitric oxide	26
Bromine	7	PCDD/PCDF	34	Toluene	16	Ammonia	19
Cadmium	6	Naphthalene	20	Acrylonitrile	9	Sulfur dioxide	17
Phosphorous	6	Phenanthrene	17	Acetonitrile	9	NOx	8
Chromium	5	Fluoranthene	14	Ethyl benzene	7	Formaldehyde	6
Arsenic	5	Pyrene	14	Isocyanate acid	5	Hydrogen fluoride	5
Copper	5	Acenaphthylene	13			Nitrous oxide	5
		Fluorene	13			Methane	5
		Styrene	13			Propene	5
		Acenaphthene	11			Hydrogen fluoride	5
		Benzonitrile	11				
		Anthracene	10				
		Phenol	10				
		Chrysene	9				
		Pyridine	9				
		Toluene diisocyanate	8				
		PBDE	7				
		Chrysene/ Triphenylene	6				
		Benzo(a)-anthracene	6				
		Coronene	6				
		Benzo(b)-fluoranthene	6				
		Benzo(e)pyrene	6				
		Benzo(g,h,i)-perylene	6				
		PBDF	6				
		Indene	5				
		Dibenzo(a,h)-anthracene	5				
		Biphenyl	5				
		Perylene	5				

7.3.2. Substances to consider for testing

186. Analysis for **potentially toxic element (PTE)** loads usually focuses on the most toxic elements (Suvarapu and Baek, 2016). In this literature review, antimony, lead, bromine, cadmium, phosphorus, arsenic, and copper were the most frequently detected substances. **Lead** is already planned for inclusion. **Arsenic**, **cadmium**, **chromium** (in its Cr_{6+} form) are highly toxic and carcinogenic, and therefore should be considered for inclusion. **Antimony** and **bromine** may be worth further evaluation as well, particularly if total bromine can be used in initial screening for poly-brominated SVOC. Further study is needed to determine if this is possible. **Phosphorus** and copper are essential elements that do not become toxic until very high doses (e.g. copper >5000mg/kg in animal studies). From a toxicity perspective, inclusion may not be necessary; however, phosphorus-based flame retardants are common. If mobilised phosphorus is in a form that is retained on soil, excess phosphorus may be an indicator that an area was affected by airborne deposition of fire effluent constituents. As with bromine, further study is needed to determine if total phosphorus is beneficial as a screening tool.

187. **Semi-Volatile Organic Compounds (SVOCs)** in Table 12 include dioxins and furans (PCDD/F), polycyclic aromatic hydrocarbons (PAHs); other cyclic and heterocyclic compounds; brominated fire retardants such as polybrominated diphenyl ethers (PBDEs); and polybrominated dibenzofurans (PBDF). PAHs are among the most widely studied substances in environmental analysis and their presence in fire effluents is unsurprising. The 16 USEPA Priority PAHs test is already planned for the Phase 2 Site Investigation. The 16 PAHs are well represented in Table 12, accounting for nearly 50% of the SVOCs listed. Over-representation may be the result of selection bias because the 16 PAHs is a well-known and widely used standard test. Similarly, PCDD/Fs are well-known toxic by-products of processes such as incineration so their inclusion in fire effluent studies would be expected. All of the substances listed among the frequently detected SVOCs are toxic. Some are known or suspected carcinogens. Some substances do not have much information about toxicity or carcinogenicity. None should be eliminated from consideration based on low toxicity.

188. **Volatile Organic Compounds:** The list of frequently detected compounds has significant overlap with the list of high-yield VOCs. **Cyanide compounds** and **benzene** are already recommended for further consideration. Ethyl benzene, acrylonitrile, acetonitrile, and toluene are all considerably less toxic than other VOCs.

7.4. Notable Omissions

189. Some substances were notable for their absence in the lists of commonly detected and/or high yield substances.

190. Combustion processes are an important source of global **mercury** emissions (Chen *et al.*, 2016); however, analysis for mercury is inherently challenging and often cannot be conducted in the same manner other PTEs (Reis *et al.*, 2016). In the environment, mercury cycles between inorganic, organic, and elemental forms as a result of environmental processes. Instrumentation is not the only problem; sample collection, preparation, and digestion methods often need to be different. Due to these difficulties, mercury may be excluded from analytes or, when included, not analysed properly. Mercury should be considered for further evaluation.

191. Among **SVOCs**, **polychlorinated biphenyls (PCBs)** and **polybrominated biphenyls (PBBs)** are notable omissions. PCBs are more commonly studied as constituents within the fuel load (e.g. incineration processes). Along with PCDD/F, PCBs may be formed as by-products of incomplete combustion. PBBs may also be possible. The US banned manufacturing of PBBs in the 1970s, but it continued elsewhere. In the European Union, the Restriction of Hazardous Substances Directive came into effect in 2006 putting restrictions on PBB use. Their presence is possible. Lastly, degradation products are potential omissions. For example, PBDEs and other BFRs may follow a number of potential degradation pathways at elevated temperatures and/or in the environment (Eljarrat, Feo and Barceló, 2011). Heat and photodegradation lead to debromination of higher-

brominated PBDEs to form lower brominated PBDEs and diphenyl ether. Cleavage at the epoxide can form brominated benzenes and phenols. Degradation processes for some substances (e.g. PAHs) are more widely studied than others.

7.5. Key Observations and Conclusions

192. This review identified a number of high yield and frequently detected substances. These substances were evaluated for toxicity, carcinogenicity, and chemical properties that contribute to their potential retention in soil. Substances that may be present in soils impacted by fire effluent are listed in Table 13. This list is not exhaustive. Selection bias weighs heavily in substances evaluated by previous studies.

193. The USEPA 16 Priority PAHs test is already planned for the Phase 2 Site Investigation. Interestingly, benzo(a)pyrene, one of the Priority PAHs, does not appear in Table 12 or Table 13, but its isomer benzo(e)pyrene does. Some practitioners use benzo(a)pyrene as a marker for all PAH(s) in detailed quantitative risk assessments to evaluate potential risks from exposure to PAHs in soil. Based on frequent detection of other PAHs and absence of benzo(a)pyrene among both frequent and high yield substances, this practice may not be appropriate as part of the Phase 2 Site Investigation and subsequent evaluation.

194. Testing for all of the substances listed in Table 13 is probably unfeasible in every soil sample. The team developing the Phase 2 Site Investigation may wish to develop a tiered screening process involving specific markers to determine if a particular sample is impacted by fire effluent. Samples with elevated levels of these markers can then be analysed for other substances. Subsequent analysis can use quantitative methods for specific substances or qualitative/semi-quantitative screening methods such as ICP-MS (PTEs) and/or two-dimensional gas (or liquid) chromatography with mass spectroscopy (SVOCs) to identify substances that are present.

195. Determining which markers may be suitable is outside of the scope of this review.

Table 13 Substances that may be present in soils impacted by fire effluent.

PTEs	**Semi-volatiles**	**Volatiles**
Lead	PCDD/PCDF	Benzene
Cadmium	Naphthalene	Carbon disulfide
Chromium	Phenanthrene	Cyanide compounds
Arsenic	Fluoranthene	
Mercury	Pyrene	
Antimony	Acenaphthylene	
Bromine	Fluorene	
Phosphorous	Styrene	
Sulfur	Acenaphthene	
Copper	Benzonitrile	
	Anthracene	
	Phenol	
	Chrysene	
	Pyridine	
	Toluene diisocyanate	
	PBDE	
	Chrysene/ Triphenylene	
	Benzo(a)-anthracene	
	Coronene	
	Benzo(b)-fluoranthene	
	Benzo(e)pyrene	
	Benzo(g,h,i)-perylene	
	PBDF	
	Indene	
	Dibenzo(a,h)-anthracene	
	Biphenyl	
	Perylene	

8. Conclusions

196. Combustion related fire products from a range of different combustion environments have been reviewed. This review accounts for 197 materials and 298 unique combustion related fire products.

197. There are two general observations from the data presented that must be considered when making interpretations.

- The data is subject to observer bias. Only compounds which are searched for will be detected. Those which are not searched for will not be detected even if they are present.
- Extrapolating these results to other conditions cannot be done confidently. The yields and compounds produced by the burning of a specific material is strongly dependent on the local combustion environment.

198. These observations mean that it is only possible to make general statements regarding the likely combustion related fire products. The highest yields of compounds produced in conditions similar to those of a building fire are those which inhibit or do not participate readily in combustion reactions. These include hydrogen chloride, hydrogen cyanide, hydrogen fluoride and sulphur dioxide. These are reported with yields in the range 100 000 to 1 000 000 mg/kg.

199. Following these, aromatic and polycyclic aromatic hydrocarbons were frequently measured with yields on the order of 10 000 to 100 000 mg/kg.

200. There was no obvious correlation between the material burning and the yields of hydrocarbon compounds produced. Compounds which contained elements other than hydrogen, carbon and oxygen were only measured when the material burnt contained these elements. For example, high yields of hydrogen chloride are obtained when burning polyvinyl chloride. This was found to be relatively independent of the combustion environment.

201. Review of the literature on dispersion studies has indicated that the highest concentrations of combustion related fire products are be found in the direction of the prevailing wind at the time of the fire. In general, the concertation will decrease with distance from the point of release; however, given the height and buoyant upwards flow, this decrease may not be monotonic and urban topography plays a strong role. It should be noted that previous studies of contamination from previous large scale fires could not be identified. The exception to this was plume characterisation following the Buncefield explosion and fire however the atmospheric conditions present at the time resulted in the bulk of the plume was trapped above stable layers of the atmosphere and did not come into contact with the ground.

202. Analysis of the compounds reported allowed a prioritised screening list to be developed. This includes relevant combustion related fire products. If further investigation is required then a tiered screening process involving specific markers should be developed and used to determine if a particular sample is impacted by fire effluent is recommended.

Part 2:
Annotated bibliographies

9. Combustion products from small scale experiments

(Tewarson, Jiang and Morikawa, 1993). "Ventilation-Controlled Combustion of Polymers"

203. Polymers investigated were PE, PP, PS, PMMA, Nylon and Pine Wood. Thermal and airflow conditions provided by Factory Mutual Research Corporation's (FMRC) 50kW scale flammability apparatus and Fire Research Institute (FRI) 0.0.22 and 8m3 enclosures. Gas analysis was achieved in FMRC by IR analyser (CO, CO2), Paramagnetic analyser (O2) and Flame Ionisation analyser (CH) whereas in FRI it was by Gas chromatograph (CO, CO2, O2, N2, acrolein) and Colorimetry (HCN, NOx, HCHO) . This allowed the authors to investigate the effect of the equivalence ratio (0.005-4.0) on the production of effluents. Yields not given but parameters for an exponential fit is given. Authors found that all showed decrease in co2 production with increase in equivalence ratio. Furthermore, there was a decrease in o2 consumed with increase in equivalence ratio. In terms of products of incomplete combustion, these followed similar trends. There was an increase in co-production with increase in equivalence ratio. However, there was divergence with preferential production in the following order wood>PMMM>nylon>PE>PP>PS. This trend was similar for hydrocarbons where there was an increase in HC production with equivalence ratio. Divergence similar to CO but wood different due to charring. The resultant production order is PMMA>nylon>PE=PP>wood>PS**.** The least divergent of the incomplete combustion products was soot. This was seen to increase with equivalence ratio in the following order PS>wood>PE=PP>nylon>PMMA. The authors found that HCHO will oxidise if there is enough oxidiser. Shown to increase with equivalence ratio. Prioritised in CHO materials

204. HCN is formed in CHON structures with its ox. producing NOx. Hence, HCN increases with equivalence ratio. (until non flaming conditions). Naturally if there is less ox. Then there is less oxidation of HCN to produce NOx. Other products other than CO, CO_2 soot and hydrocarbons are produced with a preference: PS<PE/PP<wood<Nylon<PMMA. Conclusion is that CH materials are converted mostly to CO, soot and HC. Whereas CHO and CHON structures to products other than co, co2, soot and HC for example HCHO and HCN.

205. Yields not presented.

(Martinka et al., 2012) "Experimental determination of the effect of temperature and oxygen concentration on the production of birchwood main fire emissions"

206. Authors tested birch wood in a Setchki furnace at temperatures of 450 and 600°C and at O2 concentrations of 9, 15 and 21%. Gas analysis was conducted for CO and TOC. This allowed the authors to investigate the production of effluents with T and O2 concentrations as variables. At 450°C O2 concentration did not affect their production however at 600°C TOC and CO production is seen to increase with decrease in O2. This is true except for CO when decreasing to 9% from 15% where it is seen to decrease.

207. Yields not presented.

(Luche *et al.*, 2011) Characterisation of thermal properties and analysis of combustion behaviour of PMMA in a cone calorimeter.

208. Authors used the cone calorimeter under atmospheric conditions to test how effluent production is influenced by incident heat flux (11-60 kW/m2). To analyse the gases produced the authors used an FTIR in the exhaust duct of the apparatus. Yields are given for the main emissions (CO, CO2 and H2O). Implication being that at atmospheric conditions only CO, CO2 and H2O produced at substantial quantities. Whereas HC around 10ppm and SO2/N2O/NH3<1ppm. As heat flux was increased the yield of CO and H2O decreased slightly (0.0008 to 0.0006 mg/kg and 0.7 to 0.6 mg/kg). Conversely as HF was increased the yield of co2 increased slightly from 2.0->2.2. To summarise the Mean yield values for CO/CO2/H2O are 0.007/2.148/0.658 [g/g].

(Brohez, Marlair and Delvosalle, 2006)**. Fire calorimetry relying on the use of the fire propagation apparatus. Part I and 2: Early learning from use in Europe.**

209. Comparison of recorded yields with theoretical maximum. However, there are no tabulated yields. It appears that they are using theoretical maximum yields in order to assess the validity of using the FPA as an instrument.

210. Yields not presented.

(Hietaniemi, Kallonen and Mikkola, 1999) Burning characteristics of selected substances production of heat smoke and chemical species.

211. Authors used the cone calorimeter at 50 and 25 kW/m2 and altered the equivalence ratio by changing airflow (estimating this value using O2 in and O2 out). The substances investigated were Lindane (C6H6Cl6) , Dimethoate (DMMP)(C5H12NO3PS2) , Dichlobenil (DCBN) (C7H3Cl2N) , .4-Chloro-3-nitrobenzoic acid (CNBA)(C7H4ClNO4), Tetramethylthiuram monosulfide (TMTM) (C6H12N2S3), Chlorobenzene (CB) (C6H5Cl) , Nylon 66. (C12H22N2O2) and polypropylene (PP) (C3H6).

212. Assertion that the flammability and toxicity properties are majorly influenced by the presence of CL. I.e. Lindane did not ignite and it is the most chlorinated. This is in both well and under ventilated conditions. The also assert that CL compounds are not affected by ventilation. Furthermore they observed that at lower heat flux the dependence on ventilation is less but they are unsure whether this is an experimental artefact. Authors compared Cone and DIN furnace results and were given concordant results. Therefore, comparison of different experimental setups is ok. Results are given as Tewarson style exponential fit parameters.

213. Yields not presented.

(Jørgensen and Smith-Hansen, 1995) TOXFIRE Flash pyrolysis and DIN 53436 experiments.

214. Authors investigated emissions in some common insecticide/pesticides/herbicides. They used a DIN furnace with an FTIR to produce yields of low-weight molecules (CO2, CO, COCl2, HCl, HCN, NO, N2O, NH3, SO2, CS2, COS and CH4). GCMS was used in the flash pyrolysis studies however these results are given as binary values rather than actual yields. Substances investigates were Lindane, Dichlobenil, Glyphosate, Thiram, Atrazine and Dimethoate. Equivalence ratio was changed by altering the ratio of air and N2 flows into the furnace.

(Ribière *et al.*, 2012) “Investigation on the fire-induced hazards of Li-ion battery cells by fire calorimetry”

215. Authors used FPA at 35kw/m2 with an airflow of Air 350l/min to investigate the changes in emissions under 3 states of charge(0 50% 100%). Emissions were detected using an FTIR (HF, CO, NO, SO2 and HCl). It was found that the electrochemical energy stored in a Li-Ion battery influences the products of combustion particular warning was given at the production of HF.

(Hull *et al.*, 2008) Comparison of toxic product yields of burning cables in bench and large-scale experiments “

216. Authors aimed to compare bench scale to large scale tests involving PVC and LSZH cables. For the bench scale the Steady State Tube Furnace (SSTF) (also termed the Purser Furnace) was used. Three conditions were defined as per IEC 60695-7-50: Oxidative pyrolysis, well ventilated flaming and under ventilated flaming-post flashover. These corresponded to [T; airflow] = 350C, 650C, 825C; 1.1l/min, 22.6l/min, 2.7l/min.

217. Additionally a NFX-70-100 test was performed using equipment developed by the SNCF (French Railway). This is a similar tube furnace and was performed at 800C with an airflow of 21l/min. For gas analysis an FTIR was used. Yields for CO2 CO and HCL are given as bar charts and the maximum of each type (PVC or LSZH) cable was extracted.

(Eshetu et al., 2014) "Fire behavior of carbonates-based electrolytes used in Li-ion rechargeable batteries with a focus on the role of the LiPF6 and LiFSI salts"

218. Authors used FPA at 25kW/m2 and an airflow of 350l/min coupled with an FTIR to investigate the production of effluents of different li-ion compositions. The analysis emphasized the interest of using LiFSI for decreasing HF gases evolution (3.6 times less). However, others toxic gases are produced along with HF as SO2, CO, NO, HCN, which may enhance the toxicity hazards (cumulative effect).

(Griffith, Janssens and Willson, 2005) "Evaluation of Smoke Toxicity of Automotive Materials According to Standard Small-Scale Test Procedures"

219. Authors use Cone Calorimeter at 50 kW/m_2 on certain car materials (Polyamide 6,6, Polyamide 6 , and Polyvinylchloride). An FTIR is used for analysis and CO and HCl yields reported. In general, they are using CO measurements as a proxy for toxicity. Furthermore, they summarise that the generation of products is highly dependent on the fire conditions.

(Branka *et al.*, 2009) "Characterisation of sparklers and Bengal flames using the fire propagation apparatus"

220. Use of the FPA in air and in N2 for FTIR analysis of gas components produced by fireworks. No mention of heat flux but they suggested that all the samples were ignited.

(Alarifi et al., 2013) "Ignition and Toxicity Evaluation of Selected Aircraft Interior Materials Using the Cone Calorimeter and FTIR Analysis"

221. Cone calorimeter was used at 40 kW/m2 to investigate the combustions products for aircraft materials. The cone chamber was adapted to allow for 15 air changes an hour – this is the similar to an aircraft. FTIR measurements were given in graphical form and the average value was estimated. They assessed that SO2 was a major toxic gas and was most likely generated due to fire retardants added to the material. The second most important toxic gas was HCN. The authors noted that CO was not a dominant species although the material was subjected to oxygen starved conditions.

(Paabo and Levin, 1987) "A Review of the Literature on the Gaseous Product sand Toxicity Generated from the Pyrolysis and Combustion of Rigid Polyurethane Foams"

222. Carbon monoxide (CO) and hydrogen cyanide (HCN) were the predominant toxicants found among more than a hundred other gaseous products. The generation of CO and HCN was found to increase with increasing combustion temperatures.

(Blomqvist *et al.*, 2003) "Isocyanates, aminoisocyanates and amines from Fires - a screening of common materials found in buildings"

223. Using the cone to apply a 35 kW/m2 heat flux on common materials found in buildings. Both total yields and specific yields are reported. Impinger filter was used to measure the isocyanates.

(Bustamante Valencia et al., 2009) "Analysis of principal gas products during combustion of polyether polyurethane foam at different irradiance levels"

224. Cone calorimeter was used at several heat fluxes in order to investigate the gases produced, from polyether polyurethane foam, as a function of the incident heat flux. They used an FTIR to measure the gas products (CO2 H2O CO NO THC).

(Huggett and Levin, 1987) "Toxicity of the Pyrolysis and Combustion Products of Poly (Vinyl Chlorides): A Literature Assessment"

225. Literature review of PVC. Includes GCMS data but only binary. They conclude that the major products of thermal decomposition include hydrogen chloride, benzene and unsaturated hydrocarbons.

(Bhargava, Dlugogorski and Kennedy, 2002) "Emission of polyaromatic hydrocarbons, polychlorinated biphenyls and polychlorinated dibenzo-p-dioxins and furans from fires of wood chips"

226. Authors modified a cone calorimeter through the addition of a GCMS allowing them to sample more obscure gas products. A heat flux of 50 kW/m2 was used on samples of untreated pine, camphor laurel, MDF, chipboard. It was found that treated wood resulted in higher emissions. There was also a suggestion that chlorine content might be positively correlated with dioxin production.

(Vikelsùe and Johansen, 2000) "Estimation of dioxin emission from fires in chemicals"

227. The authors sought to compare gas production at different scales using three incremental experimental setups – DIN 53436 furnace, cone calorimeter and ISO 9705 room test. Test in the furnace had an initial mass of 2.5g and T = 500 and 900C. An airflow of 100l/hr was imposed leading to over ventilated conditions.

228. The influence of scale was studied for chlorobenzene and 4-chloro-3-nitro-benzoic acid in additional experiments, carried out in a cone calorimeter burning 20 g substance, and in ISO 9705 room test burning about 50 kg. The cone was calibrated to 25 and 50kw/m2 and airflows of 60 and 180l/min were used. For the analysis of gases, a high resolution GCMS was used.

229. A good agreement between the results for large and small scale indicated that formation of PCCD/F during a ®re may be estimated from laboratory experiments. This suggest laboratory test may be used to screen for chemicals posing a hazard for release of PCDD/F during fires.

(Braun and Levin, 1986) "Polyesters: A Review of the Literature on Products of Combustion and Toxicity "

230. Review paper. 'The thermal decomposition products of polyesters are a function of temperature and oxygen content of the atmosphere. In general, as the temperature increases, the quantity of heavier hydrocarbons decreases and the production of CO and CO, increases. The presence of flame-retardant additives, such as bromine and chlorine-containing compounds, produce halogenated combustion products. The use of phosphorus and bromine together in the same flame-retardant finish increases the concentration of low molecular weight compounds. '

(Gurman, Baier and Levin, 1987) "Polystyrenes: A Review of the Literature on the Products of Thermal Decomposition and Toxicity"

231. Review paper. From the analysis conducted they concluded that The main volatile component is the styrene monomer. Evidence is provided that the mass fraction of styrene increases with furnace temperatures at least through 500°C. At 800°C and above, the concentration of styrene decreases. In oxidative atmospheres, carbon monoxide (CO), carbon dioxide (CO2) and oxidative hydrocarbons are formed.

232. Yields not presented.

(Wu *et al.*, 2016) Experimental study on polystyrene with intumescent flame retardants from different scale experiments

233. This study investigated the effect of different flame retardant treatments on the combustion behaviour of polystyrene. Experiments were conducted at both bench-scale (Microscale combustion calorimeter and cone calorimeter) and full-scale (ISO 9705 fire test room). Combustion gases (O_2, CO_2 and CO) were collected with an exhaust hood and continuously measured. No other combustion products were analysed or reported however and therefore this study is not considered further.

(Molyneux, Stec and Hull, 2014) The effect of gas phase flame retardants on fire effluent toxicity

234. This study evaluated the emissions of toxic products from the combustion of two types of glass fibre composites (polyamide 6 (PA 6) and polyamide 6.6 (PA 6.6.)) in a steady state tube furnace.

For each composite the effect of two types of flame retardant treatments was evaluated; an aluminium phosphinate – melamine polyphosphate (AlPiM) and brominated polystyrene – antimony oxide blend respectively. The equivalence ratio was also varied between experiments by varying the airflow for a constant fuel feed rate.

235. The yields of CO, CO_2, HCN, NO_2 and HBr were measured and expressed in terms of mass-charge for each experimental condition. In both cases, the untreated composites produced measurable, but very low, levels of HCN, with the yield increasing with the addition of either flame retardant. Different mechanisms are discussed to explain the observed decrease in HCN yields at higher temperatures (825°C) for the untreated composite and also the AlPiM retardant, but observed increase in yield at this temperature for the BrSb retardant. Explanations for the decreased yield include the identification of more complete oxidation as the temperature increases from 650 to 850°C, as well as the indicated presence of gas phase inhibition which is removed at 825°C. The BrSb cases resulted in significantly greater HCN yields, with a greater dependence on equivalence ratio also observed at lower furnace temperatures, with the yield almost independent of equivalence ratio at higher temperature. An increase in NO_2 yields with gas phase inhibition was also observed however these measurements are at times stated to be close to detection limits. The HBr yields are also reported for cases involving the addition of the BrSb retardant.

(Hu *et al.*, 2014) Flame retardant polystyrene copolymers: Preparation, thermal properties, and fire toxicities

236. This study describes experiments conducted at multiple scales to characterise the properties and toxicity of a copolymer consisting of styrene and novel phosphorous and nitrogen containing monomer DMPMA. The experiments conducted included TGA, microscale combustion calorimeter and steady state furnace experiments. The yields of CO, CO_2 and smoke were measured and reported, with increased smoke and CO yields measured and attributed to incomplete combustion of the copolymer, however the yields of any other emissions products were not measured and therefore this study is not considered further.

(Hull et al., 2001) Combustion toxicity of fire retarded EVA

237. This study investigates the emissions from the steady-state flaming combustion of ethylene-vinyl acetate (EVA) in a Purser furnace, both with and without fire retardants. The effect of different fire conditions was also considered by varying the equivalence ration between 0.5 and 1.5. With some exceptions, higher CO yields were reported for fire retarded EVA samples than the untreated samples in the more fuel rich cases, however the CO yields were similar in well-ventilated cases. The yields are reported for CO and CO_2 only, with the residual mass used to estimate the total volatised carbon not in either of these forms, however additional species are not identified and therefore this study is not considered further.

(Zhang et al., 2015) The influence of carbon nanotubes on the combustion toxicity of PP/intumescent flame retardant composites

238. This study investigates the effect of adding Carbon Nanotubes (CNTs) and/or intumescent flame retardants to polypropylene composites, on the combustion related emissions. The experiments are conducted in a steady state tube furnace at varying equivalence ratios. The authors highlight the significant contribution of ventilation and combustion temperature on the production of fire effluents and soot particle morphology, with the effect of CNT addition on smoke profuction and hydrocarbon production varying with the equivalence ratio. While the yield of CO and CO_2 are reported (along with smoke density and particulate analysis), hydrocarbons produced are reported in total terms as concentration only (without species identification) and therefore this study is not considered further.

(Stec *et al.*, 2013) Analysis of toxic effluents released from PVC carpet under different fire conditions

239. This study investigates the combustion and oxidative pyrolysis related emissions for PVC carpet material in a steady state furnace. A wide range of emission compound types are monitored

including CO, CO_2, HCl, PAHs, PCDD/Fs, as well as soot production, with combustion experiments conducted at both under-ventilated and well-ventilated conditions. Various gas species were continuously sampled and analysed using FTIR spectrometry, with the yields of CO, CO_2 and HCL reported at each condition (based on the average for 2 or 3 replicate cases at each condition). PAHs, chlorine contend and PCDD/Fs were analysed using various methods including gas chromatography – mass spectrometry and X-ray fluoresce spectrometry. The PCDD/F and PAH emissions are reported either as concentrations are as TEQ yields.

(Rhodes, Smith and Stec, 2011) Characterisation of soot particulates from fire retarded and nanocomposite materials, and their toxicological impact

240. This study investigates the effect of combining nanofillers and/or fire retardants with polyamide 6 and polypropylene, on the combustion related emissions and soot production. Experiments were conducted in the steady state furnace in under-ventilated and well-ventilated conditions with the total soot yield, particle distribution and agglomeration analysed and reported. The yields of specific compounds produced are not studied or reported and therefore his study is not considered further.

(Stec and Rhodes, 2011) Smoke and hydrocarbon yields from fire retarded polymer nanocomposites

241. This study investigates the effect of combining nanofillers and/or fire retardants with polyamide 6 and polypropylene. The combustion experiments were conducted in the steady state furnace under different fire conditions and the yields of CO, smoke and hydrocarbons were investigated. The highest yields of CO were recorded for under-ventilated fires in which both fire retardant and nanofillers were present. The yields of effluents are reported for CO and smoke, while the yield of hydrocarbons is reported as a single total value without species identification and therefore is not considered further.

9.1. Reviews

(Hull and Stec, 2016) Generation, Sampling and Quantification of Toxic Combustion Products

242. This chapter describes past and ongoing efforts to characterise the emissions of toxic products of combustion. It focuses on the practical challenges associated with the measurement and analysis involved in the quantification of toxic products. The lack of adequate characterisation of the combustion conditions in much of the past research into toxic combustion emissions is highlighted. Past studies, and sampling and analysis methods relevant to various experimental scales are discussed.

(McKenna and Hull, 2016) The fire toxicity of polyurethane foams

243. This study provides a detailed overview of the generation of toxic emission products from polyurethane foams. A detailed description of the formation and decomposition of polyurethane foams is included. Using the available literature, typical products of polyurethane foams are discussed along with a discussion of their associated toxicity. Typical experimental and analytical methods for the sampling and analysis of emissions from polyurethane foams are described, including a summary of relevant studies.

(Paul et al., 2008) Fire Smoke Toxicity: The Effect of Nitrogen Oxides

244. This paper reviews a variety of past studies covering different aspects of the properties, formation and toxicity of Nitrogen Oxides formed in combustion fire products. It summarises the existing knowledge, discusses and compares results from past experimental studies. As a result, a number of recommendations for changes to practice and identification of areas requiring further research are outlined.

10. Combustion products from large scale experiments

245. Large scale experiments provide an opportunity for the measurement of combustion products under free burning of the material of interest. Often large-scale experiments use products e.g. sofas, rather than pure materials. This can lead to complexities in analysis as the burning is highly scenario dependent.

246. The most common method for correlating the yields of combustion products from compartment fires is to use the equivalence ratio. This provides a relationship between the quantity of air available for combustion and the quantity of air required for combustion. It is hypothesised that as the equivalence ratio is increased beyond the stoichiometric limit then the production of products of incomplete combustion will rapidly increase. Beyler (Beyler, 1986) was the first to apply this concept to steady-state fires and developed relationships between the equivalence ratio and the yields of carbon monoxide and total hydrocarbons in the smoke. Pitts (Pitts, 1995) has subsequently demonstrated that the equivalence ratio approach is not suitable for predicting the yields of carbon monoxide (and by extension other species) away from the source of the fire. The mixing and flow conditions are identified as being key to making accurate predictions and scaling assessments. This is particularly relevant when considering real compartment fires where multiple objects are burning generating co-dependent plumes and complex mixing.

247. The following studies present data on the measurement of combustion products from compartment-scale fires. References are given at the end of the document.

(Hull *et al.*, 2008) "Comparison of toxic product yields of burning cables in bench and large-scale experiments"

248. Attempt of correlation of Purser furnace testing of cables to large-scale testing; when ventilation, temperature, extent of burning, residue, and geometry are accounted for, a correlation is plausible.

(Crewe *et al.*, 2014) "Experimental Results of a Residential House Fire Test on Tenability: Temperature, Smoke, and Gas Analyses"

249. A 1950-style house was used for the experiment of tenability conditions; furnishing used was typical of that found in a modern era house. A potential egress path was identified based on measurement of effluents (CO, CO2, HCN).

(Stec, 2017) "Fire toxicity: The elephant in the room?"

250. Review paper presenting the toxicity risk. Carbon monoxide yields are presented for comparison from multi-scale testing of PA 6.6.

(Blomqvist *et al.*, 2003) "Isocyanates, aminoisocyanates and amines from fires: a screening of common materials found in buildings"

251. Multi-scale testing undertaken. A sofa was burnt as part of the large-scale experimentation. Total isocyanates are reported (ppb units); no yields available for this experimentation. PUR foam mattresses were also tested for sprinkler systems; no reported yield data.

(Hewitt et al., 2017) "Release of volatile and semi-volatile toxicants during house fires"

252. Full-scale experimentation undertaken to study the species produced. VOCs, SVOCs, and PAHs were detected. Qualitative species formation for different ignition packages, room geometries and ventilation conditions; species formation can be attributed to various sources and detected in most scenarios.

(Lönnermark and Blomqvist, 2006) "Emissions from an automobile fire"

253. Small- and large-scale experiments conducted on parts of and whole car fires. Effluents measured indicate adverse effects for humans, the environment; some species were compared to literature data.

(Beyler, 1986) "Major Species Production by Diffusion Flames in a Two-layer Compartment Fire Environment"

254. Small-scale experiments were performed under a hood. Propane was used as a fuel initially; CO, CO2 and THC are reported. Normalised CO data are reported from later experiments using propene, hexanes, toluene, methanol, ethanol, isopropanol, and acetone.

(Pitts, 1995) "The global equivalence ratio concept and the formation mechanisms of carbon monoxide in enclosure fires"

255. Correlation of the Global Equivalence Ratio (GER) with the formation of CO is discussed; GER was presented as an adequate means to predict CO formation in the enclosure fire. Data from Gottuk and co-workers were compared to Beyler's dataset.

(Hull and Paul, 2007) "Bench-scale assessment of combustion toxicity - A critical analysis of current protocols"

256. Materials on fire and the environmental conditions during this burning are assessed. Toxic severity is addressed either based on the yields of different species or as the potency of the effluents on testing animals. Suggestion for a more global, harmonised testing protocol is presented. Multi-scale data are shown within.

(Blomqvist and Lonnermark, 2001) "Characterization of the Combustion Products in Large-scale Fire Tests Comparison of Three Experimental Configurations"

257. Various polymers were tested in large-scale (ISO room 9705) fires to inform the understanding of the effect of the ventilation conditions to fire chemistry; yields of different combustion products as a function of the ventilation (equivalence ratio) were reported.

(Ko *et al.*, 2009) "Mixture fraction analysis of combustion products in the upper layer of reduced-scale compartment fires"

258. Medium-scale experiments (based on the ISO room 9705) were conducted using condensed-phase hydrocarbons; unitless CO yields are shown in figures as a relationship to the equivalence ratio. A relationship between the mixture fraction and the local composition of effluents was established for various compartment conditions and HRR values. Inclusion of soot in the mixture fraction is suggested to lead to a better characterisation of under- or over-ventilated conditions.

(Stec et al., 2009) "Comparison of toxic product yields from bench-scale to ISO room"

259. Five materials were burnt in a tube furnace and an ISO room; data were compared, with plastics in the pool fire giving a better agreement between scales. When materials were used as linings, correlation was poor. Yields of CO, CO2, HCN, and hydrocarbons were plotted as a function of the CO2/CO ratio.

(Stec *et al.*, 2014) "Fire Toxicity Assessment: Comparison of Asphyxiant Yields from Laboratory and Large Scale Flaming Fires"

260. Multi-scale experimentation of thermoplastics. Experiments showed cases where small-scale tests were more suitable for comparison to full-scale tests. SSTF and FPA show the best agreement to the different fire conditions; other apparatuses fail to capture the under-ventilated conditions.

(Blomqvist et al., 2014) Detailed study of distribution patterns of polycyclic aromatic hydrocarbons and isocyanates under different fire conditions

261.

(Stec et al., no date) Environmental contamination following the Grenfell Tower fire

262. This study involved the collection and analysis of soil, char and fire debris at distances of up to 1.2 km from the tower (with locations in the direction of the prevailing wind during the fire), at periods of 1 and 6 months after the fire. Additional samples (dust and condensates) were also collected from a flat, located 160 m away from the tower, 17 months after the fire. Analysis

including Gas Chromatography-Mass Spectrometry and Thermogravimetric Analysis – Fourier Transform Infrared Spectroscopy was used for identification and measurement of semi-volatile and volatile organic compounds, and for quantitative analysis of PCDD/F, PAHs, benzene and metals.

263. Elevated levels of phosphorous, benzene and PAH concentrations were identified in soil samples and decreased with increasing distance from the tower. PCDD/Fs concentrations were at a maximum at a distance of 100 m from the tower. Phosphate compounds, not naturally occurring in the soil but commonly used in insulation and furniture foam were found in soil, debris and char samples. Methyl isocyanate, isocyanic acid, ethyl isocyanate and propyl isocyanate were also found in a flat located 160 m from the tower. The characteristics of particulates primarily contributing to toxic contamination were observed to vary with distance, with particulates > 100 µm deposited up to 200 m from the tower, and 10 µm particulates deposited up to 2 km form the tower. Given the nature of the study, results are reported as concentrations, with no yields reported.

(McKenna *et al.*, 2019) Fire behaviour of modern façade materials – Understanding the Grenfell Tower fire

264. This study investigated the fire behaviour and toxic emissions, at both the micro- (microscale combustion calorimetry) and bench-scale (cone calorimetry), of various façade materials including ACM products, phenolic and PIR foams, and non-combustible insulation materials (Glass and Stone Wool). Some materials were chosen due to their reported presence at Grenfell Tower, with other materials chosen for comparison purposes. Additional measurement of the smoke toxicity of insulation materials was conducted using the Steady State Tube Furnace (SSTF), at three different flaming conditions (well-ventilated, small and large under-ventilated).

265. A variety of results are presented including yields of emission products for each of the SSTF combustion ventilation conditions, with potential implications for toxicity also discussed. Observations include a low yield of HCN for phenolic foams (due to their low Nitrogen content) which increases at under-ventilated conditions. Direct comparisons with mineral wool are limited as ignition was not observed.

(Crewe *et al.*, 2018) Fire Performance of Sandwich Panels in a Modified ISO 13784-1 Small Room Test: The Influence of Increased Fire Load for Different Insulation Materials

266. This study investigated the fire behaviour of two different sandwich panel types (comprising of PIR foam and stone wool cores respectively) in a modified version of the ISO-12784-1 test. For the four experiments conducted, the toxicity of emissions (O_2, CO_2, O_2 and HCN) were measured below the room doorway, in addition to the various fire behaviour measurements. The authors report an increased yield of toxic effluents in under-ventilated flaming conditions however gas measurements are reported in terms of concentration only, and therefore this study is not considered further.

(McKenna *et al.*, 2018) Flame retardants in UK furniture increase smoke toxicity more than they reduce fire growth rate

267. This study investigated the fire behaviour and emissions products from the combustion of sofas, with varying levels and types of flame retardancy, at both small (cone calorimeter) and large scales (whole sofa in test room). Four sofa types were used, three of which contained polyurethane foam and a polyester layer and either fire-retardant or untreated fabric cover. The fourth sofa was made of natural materials including a polycotton pad and cotton and wool covers. Continuous measurement of CO, CO2 and O2 was undertaken, along with analysis of HCN emissions. The yields of combustion gases and HCN were reported for both small and large scale tests (based on the flow rate of exhaust gases which was calculated form the measured temperature profiles and vent openings). The authors conclude that flame retardants affect flammability and toxicity but that the observed variations are not consistent between the scales investigated.

(Crewe *et al.*, 2017) Asphyxiant yields from common polymers in under-ventilated fires in the large instrumented fire enclosure (LIFE)

268. This study investigates the yield of combustion gases from the combustion of polymer pellets (LDPE, PMMA. PS and polyamide 6.6. (PA6.6.)) in 12 large scale, fire enclosure experiments involving under-ventilated conditions. The gas products were measured, at the end of a corridor connected to the fire enclosure, using NDIR and electrochemical cells (CO, CO_2 and O_2) and spectrophotometric analysis (HCN). The emissions data is reported relative to two different types of equivalence ratio based on a global and plume approach respectively, with the plume approach expected to be more comparable to results from smaller-scale studies. The yield of HCN is reported in comparison with the equivalence ratio for experiments involving PA6.6 pellets and compared with results from past experimental studies.

11. Review of combustion products from incineration of MSW

11.1. Experimental work

(Olie, Vermeulen and Hutzinger, 1977) "Chlorodibenzo-p-Dioxins and chlorodibenzofurans are trace components of fly ash and flue gas of some municipal incinerators in the Netherlands"

269. In this work the first notice of Chlorodibenzo-p-Dioxins and chlorodibenzofurans as trace components in the flue gas of municipal incinerators is taken. GC-MS experiments were carried out in three large incinerators geographically distributed in the Netherlands. Variations in the effectivity of electrostatic precipitators made it extremely difficult to obtain accurate quantitative data. Qualitative data are presented, and yields were not further considered.

(Benestad et al., 1990) "Emissions of organic micropollutants from discontinuously operated municipal incinerators"

270. Data are presented on the burning of municipal waste (household waste as well as office and store waste) in intermittently operated medium scale grate-fire type incinerators. One of the aims was the measurement of the emission variations during various periods of the combustion cycles through stack gas sampling. The study found much higher PAH yield emissions at the start of the combustion cycle, but there was no correlation between the PAH and PCDD/PCDF emissions.

(Benestad, 1989) Incineration of hazardous waste in cement kilns

271. This work presents the results from two experiments burning hazardous waste in cement kilns. Different fuels were tried and compared. Both studies concluded that the type of fuel incinerated does not influence the emission of organic micropollutants, but the operating conditions are a key-parameter. Flue gas emissions are presented for PAH, PCB, and PCDD's and their respective congeners. The yields were not further considered.

(Hasselriis and Licata, 1996) "Analysis of heavy metal emission data from municipal waste combustion"

272. In this work, the link between the levels of heavy metals in the waste composition and stack emissions is studied. Particulate matter is also explored as a surrogate option to indirectly regulate heavy metal emissions, with good correlation. Data from one facility are analysed for a 3-4 year period and results are compared with individual tests of another twenty facilities. Yields measured in the boiler and stack emissions are provided in separate tables that showcase the efficiency of the air control units. An increase of lead and cadmium in the feed had a marginal effect in stack emissions, not supporting a cause and effect relationship. It is noted that since it is not possible to obtain simultaneous samples of the waste and the discharges all the mass balances cannot be closed exactly.

(Zhang, 1998) "The effect of the oxygen fraction on volatile organic compound emissions from waste combustion"

273. An experimental laboratory boiler with a stationary grate which was continuously fed with household refuse was used to study the effect of the oxygen fraction on Volatile Organic Compound emissions during the combustion processes. The identification and analysis of organic pollutants were performed by thermal desorption Gas Chromatography and Mass Spectrometry (GC/MS) with a Tenax sampling train from gas samples taken at the flue gas duct. The emission of benzene, toluene, m-xylene, 1,3,5-methylbenzene and total volatile organic compounds tended to decrease with increasing oxygen concentration although the temperature change was a confounding factor. VOC emissions and carbon monoxide concentration also correlated each other confirming the fact that oxygen deficiency is the main cause resulting in the formation of VOC emissions and carbon monoxide. Caution is advised when using the results since similar trends, but different concentrations are expected in full scale boilers. Yields are not further considered.

(Zhang, 1997) "Emissions from waste combustion - An application of statistical experimental design in a laboratory-scale boiler and an investigation from large-scale incineration plants" PhD Thesis

274. The previous 1998 paper by Zhang originates from this doctoral research work. Additionally, full-scale tests on seven Swedish incineration plants were analysed. The data were used to evaluate the emissions from large-scale incineration plants with various type of fuels and incinerators, and were also compared with the laboratory results, however yields were not further considered.

(Chen *et al.*, 2015) Dioxins from medical waste incineration: Normal operation and transient conditions

275. Polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) are key pollutants in waste incineration and their emissions are monitored only during steady-state operation. This work investigates how the emissions are affected due to poor combustion, plant shutdown, and especially when starting-up from cold, in the case of medical waste incineration. Memory effects possibly affected the results making the analysis difficult. It was found that during start-up the PCDD/Fs concentrations are much higher than the local emission standard and 20 times higher than during normal operation and 4 times higher during shut down conditions. The stack concentrations are presented and yields were not further considered.

(Šyc *et al.*, 2015) The effect of transient operations on the levels and congener profiles of PCBz, PCPh and PCDD/F in raw flue gases of MSWI plant

276. The data presented in this work are from a continuously operating large scale MSWI plant. Sampling and analysis were done based on EN 1948 for the whole operation of three different runs. It was found that the rates of pollutants concentration increase, along with the length of the memory effect, since both are strongly affected by the period prior to shut-down. Congeners were measured to analyse the mechanisms of PCDD/F formation during the transient conditions and the results imply that under transient operations de novo synthesis formation is taking place in a greater extent. Yields were not further considered.

(Guo *et al.*, 2014) Emissions of PCDD/Fs and PCBs during the Cold Start-up of Municipal Solid Waste Incinerators

277. This work focused on the start-up conditions in a large municipal waste incinerator. The modified U.S. EPA Modified Method 23 was employed. It was found that the peak total (PCDD/F + PCB) concentration occurred when the temperature in the combustion chamber reached the window (250°C–450°C) for the PCDD/F de novo synthesis. Reducing unnecessary start-ups could be more important with regard to controlling the PCDD/F and PCB emissions than only attempting to increase the pollutant removal efficiency in the steady operations of MSWIs. Yields were not further considered.

(Yang *et al.*, 2015) Emissions of polychlorinated diphenyl ethers from a municipal solid waste incinerator during the start-up operation

278. This study focuses on the formation of PCDEs during start-up conditions, since they act as precursors for the formation of the more toxic PCDD/Fs. In the absence of a standard method for PCDE analysis, the modified U.S. EPA Modified Method 23 was employed. The samples were taken from a municipal solid waste incinerator. It was shown that the effect of controlling the furnace temperature during start-up is greater than the effects of changing fuels or waste feeding method for the MSWI. The peak PCDE measurement took place in the temperature range that de novo synthesis of PCDD/F's is occurring, exhibiting a correlation of the two. Yields were not further considered.

(Victorin, Ståhlberg and Ahlborg, 1988) Emission of mutagenic substances from waste incineration plants

279. This work aims to populate the literature around the emission of mutagenic substances from municipal solid waste incineration, and correlate them with CO and PAH emissions. Four

incinerators in Sweden, throughout different combustion conditions are experimentally studied. Flue gas concentrations are provided, but the yields were not further considered.

(Faengmark *et al.*, 1993) Influence of combustion parameters on the formation of polychlorinated dibenzo-p-dioxins, dibenzofurans, benzenes, and biphenyls and polyaromatic hydrocarbons in a pilot incinerator

280. This experimental work used a laboratory scale incinerator and a synthetic fuel of municipal waste to explore the impact of combustion parameters on the formation of PCDD/F's, PCBz, and PAH's. The flue gas concentrations for every congener are presented and correlations are made. Residence time in the cooling section was attributed to be the most important parameter for the formation of the compounds. The yields are not further considered.

(Marklund *et al.*, 1986) Chapter 6 - Determination of PCDDs and PCDFs in Incineration Samples and Pyrolytic Products

281. This book chapter presents the results from four experiments in municipal waste incinerators in Sweden. Temperatures and operating conditions are linked to flue gas concentrations of total PCDD/F's and broken down into their most toxic congeners. Victorin et al. analysed the same experiments. The yields were not further considered.

11.2. Literature reviews

(Neuwahl *et al.*, 2019) "Best Available Techniques (BAT) Reference Document for Waste Incineration: Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)"

282. The document provides an up-to-date overview of the processes involved in waste incineration and collated data from a 2014-2015 survey. In the appendices a list of the UK incinerators that participated in the survey can be found, along with their yield data. Yields found in the stack emissions on HCl, HF, SO2, NOx, NH3, and TVOC's are given in graphical form.

(Buekens and Huang, 1998) Comparative evaluation of techniques for controlling the formation and emission of chlorinated dioxins-furnas in municipal waste incineration

283. This comparative review of the available literature focuses on control measures on the emissions of PCDD/F's by removal of the substances in the flue gas, treatment of the fly ash, prevention of formation in the post combustion zone, improvement of the combustion conditions, or control of the waste composition and properties. The latter three are of interest in our study. For the post combustion zone, the rate of cooling the flue gases appears to be the key parameter in PCDD/F formation. Some reservations about the reliability of experimental results throughout the different decades are expressed. It is also found that the results from different testing programmes are contradictory possibly because "different types of incinerators have quite different behaviour, and no general, universally applicable correlation can be found". The yields for the various conditions were not further considered.

(Jones and Harrison, 2016) Emission of ultrafine particles from the incineration of municipal solid waste: A review

284. This work is a literature review focusing on the emission of ultrafine particles (diameter <100 nm) from municipal waste incineration. It was noted that the incinerator emissions are not impacting significantly upon concentrations of ultrafine particles in the locality which tend to be dominated by sources such as road traffic and domestic combustion. The low emissions of ultrafine particles from MSW incinerators can be attributed to the use of high efficiency filtration at the end of the process. Yields were not further considered.

(Obaid *et al.*, 2017) Obaid et al. 2017 - Comparing Non-Steady State Emissions under Start-Up and Shut-Down Operating Conditions with Steady State Emissions for Several Industrial Sectors: A Literature Review

285. This literature review contains a section on waste incineration. The authors compared the emissions under start-up, shut-down, and normal operation of the incinerators. There were many differences in the emission variables and units, so for the comparison to happen they normalised the emissions to the normal operating scenario of each case. Some trends were defined, but investigation of further facilities is advised. The yields were not further considered.

12. Review of combustion products from uncontrolled burning of MSW and other large fires

286. A wide variety of combustion related products are identified across the various reviewed studies describing the uncontrolled or informal burning of waste. This can partly be explained by the wide variety of 'fuels' used depending on the study of each focus and this is observed within the selected studies of other relevant wastes (for example waste tires). Even within single studies there is often variation between the fuel composition and/or limited quantification of the exact composition given the complex nature of municipal waste. Results from many of the studies indicate significant variation in measured yields across replicate experiments, and this variation is highlighted by several of the authors included in this summary.

287. In addition to variations in the waste fuel composition, authors also highlight the potential influence of other factors which may affect combustion quality and resultant emissions. This includes variation in air flow paths and in the global and local packing and compression of the waste fuel. While many of the studies provide qualitative observations of the relationship between emissions productions and the combustion behaviour (particularly comparing the smouldering and flaming phases), only in a smaller number of studies are suitable measurements incorporated to allow quantitative conclusions regarding combustion quality to be made. Where possible it has been indicated in this review when such measurements are present.

12.1. Municipal Waste

(Lutes et al., 1998) "Emissions of Polynuclear Aromatic Hydrocarbons from the Open Burning of Household Waste in Barrels"

288. This study evaluated the emissions of Polynuclear Aromatic Hydrocarbons from the experimental burning of household waste in 55 gallon burn barrels, representative of common domestic practices. Emissions from duplicate experiments for two different waste compositions, representative of 'avid recyclers' and non-recyclers', were compared.

289. Air sampling was conducted within the experimental burn hut, with a Graseby PS-1 sampler, incorporating a XAD-2 vapour trap, used for the collection of total particulate phase organics. Semi-volatile and particulate phase organics were sampled with a separate 110 mm diameter filter containing resin sorbent. Analysis incorporated gas chromatography/mass spectroscopy and selective ion monitoring.

290. Estimated emissions of PAHs are reported per kg of waste consumed by combustion. Significant variability in emissions were observed for duplicate experiments involving the same waste stream. Total PAH emissions from the 'non-recycler' waste stream were roughly twice those of the 'avid recycler' stream however this does not account for the reduced initial mass of waste in the 'avid recycler' waste stream. No additional information on combustion conditions in each experiment is provided.

(Christian *et al.*, 2010) Trace gas and particle emissions from domestic and industrial biofuel use and garbage burning in central Mexico

291. This study presents emissions data for various elemental organic carbon das and aerosol species, metals, chlorine, nitrate and anhydrosugars for multiple types of combustion activities. The most relevant cases involve garbage fires in Mexican landfill sites, one of which was accidental and another three which were deliberately ignited experimental fires. Estimates of waste composition are provided while it is noted that for a variety of reasons tires, wood and recyclables were partially or wholly removed prior to burning.

292. Measurements of emissions were conducted primarily using a Fourier transform infrared spectrometer. Additionally, particulate matter filters were used as well as thermal optical transmission analyser (for continuous carbon analysis) and an anion-exchange chromatography (for anhydrosugars).

293. Emission factors are presented for these various particle species (per kg of fuel) for each of the four fires, with sampling at the accidental fire starting significantly after ignition at which time primarily smouldering combustion was observed. While the smouldering : flaming ratio was not quantified it was observed that three experimental fires displayed mostly flaming combustion across the sampling duration. The reported emission factors are compared with a variety of other studies including other forms of garbage burning (barrels) and other combustion types (including forest fires, biomass burning, charcoal production).

(Wevers, De Fré and Desmedt, 2004) Effect of backyard burning on dioxin deposition and air concentrations

294. This study measures the dioxin deposition and air concentrations from a number of experimental fires involving the combustion of garden and household waste. This includes a comparison of the combustion of garden waste in barrels and as an open fire, and the combustion of household waste in empty oil drums. The use of different barrel types (with varying number of holes and differing construction features) also promoted different combustion conditions by altering the ventilation profile.

295. Dioxin air concentrations were measured within the plume, at a fixed distance above the fire, with simultaneous continuous monitoring of CO_2 concentration using a Nondispersive Infrared Sensor (NDIR). Air emissions measurements are reported in terms of concentration or as overall combined TEQ emission factors. This study was therefore not considered further.

(Hedman *et al.*, 2005) Emissions of Polychlorinated Dibenzodioxins and Dibenzofurans and Polychlorinated Biphenyls from Uncontrolled Burning of Garden and Domestic Waste (Backyard Burning)

296. This study measured the emissions of dioxins and PCB from the experimental combustion of garden and domestic waste (both in barrels and open fires), in a manner representative of ‘backyard burning’. The majority of burns were conducted in a 200 L steel barrel, with 12 small air supply holes around 50 mm from the base of the barrel, while an additional two open burning experiments were also conducted. The waste compositions varied between experiments but consisted of either garden waste, paper, plastic, refuse derived fuel, motor oil, straw or a mixture of these components.

297. Emissions from barrel burns were collected in a fuel hood above the barrel for sampling. Infrared detectors and an electrochemical cell provided continuous measurements of CO, CO_2 and O_2. The barrel experiments involved stirring of the smouldering fuel remains (at a specified temperature drop) to encourage further combustion, and this effect can be observed in the recorded thermocouple data for each barrel burn. For open fires, a thin layer of fuel was positioned on a $1m_2$ steel plate. Flue gas emissions in the flue gas were sampled according to EN 1948 1-3 and are reported relative to the mass unit of fuel consumed by combustion.

298. Temperature measurements from within the barrels showed a similar trend with peak temperatures (circa. 600 – 700 °C) observed within 5 - 10 minutes of ignition, with temperatures greater than 600 °C generally maintained for less than 10 minutes. A decrease in temperature is subsequently observed reaching a temperature of less than 100 °C after 20 – 30 minutes, after which stirring was initiated resulting in temporary temperature spikes.

299. Emission factors are provided for PCDD/F in the flue gas, with emission factors for specific homologues also reported for each case. Low chlorinated PCDF was dominant in the emissions and was identified as an indicator of de novo synthesis and an unavailability of catalytic sites for these species. A case in which motor oil was added to waste fuels, resulted in generally reduced emissions, which the authors suggest may be as result of ‘more effective combustion’ as a result of the higher energy content of oil. Similarly, a reduction in combustion efficiency due to a decrease in heat retention was suggested as a possible explanation for the relatively high PCB and dioxin concentrations observed for the open fire cases.

(Lemieux *et al.*, 2000) Emissions of Polychlorinated Dibenzo-p-dioxins and Polychlorinated Dibenzofurans from the Open Burning of Household Waste in Barrels

300. This study measured the emissions of various pollutants from the experimental burning of household waste in barrels, and focuses on the analysis of emitted PCDD/PCDF species. Separate waste samples, representative of recycling and non-recycling households respectively, were burned in 208 L barrels representing typical ‘backyard burning’ practices. All experiments were conducted within the EPA open burning test facility, with the barrel positioned on a load cell to record the mass loss rate throughout the experimental duration, while dilution air was supplied into the burn facility. A brief discussion of existing theories and past studies into the effect of combustion conditions and formation theories on PCDD/F emissions is included in the introduction to the study.

301. Continuous emissions monitors within the sampling duct monitored combustion gas emissions (CO, CO_2, O_2 and THC), with additional ambient air samplers present in the burn facility with metals, PM and HCL sampled. Temperature and continuous emissions data are provided for each test, with total PCDD/F emissions data reported along with specific emission factors for each compound and isomer, and for sampled metals. Some emissions were however outside the detection limits, while contamination may have influenced the measured emissions of OCDD.

302. Four combustion experiments with waste fuel loads varying from 6.4 to 13.6 kg resulted in PCDD/PCDF emissions ranging from 0.0046 and 0.48 mg/kg of waste burned. PCDD/F emission factors for the ’avid recylcer’ waste stream were greater than those for the ‘non-recycler’ samples. This was partly attributed to the greater proportion of PVC present potentially resulting in increased chlorinated organic compounds production. The potential influence of combustion conditions (mixing patterns, temperature profiles, oxygen availability) was also highlighted as important factors affecting PCDD/F formation.

303. The results from the experimental study are compared to and observed to be greater than typical available PCDD/PCDF emissions estimates (from other studies) for municipal waste combustors (on the basis of waste mass burned).

(Zhang *et al.*, 2009) Emission of PCDD/PCDF from Open Burning of Municipal Solid Waste in China: Field Test Zhang

304. This study involved the sampling of emissions from the experimental open burning of municipal waste, representative of the waste stream compositions of different parts of China (urban, semi-urban and rural). Five different experiments were conducted with the waste fuel loads ranging from 100 -150 kg, with a novel high-volume sampler to collect combustion fumes, with additional monitoring of combustion gases. While dominant PCDD/F congeners are identified, the emission factors are reported as total TEQ only and therefore this study is not considered further.

(Ruokojarvi *et al.*, 1995) Formation of polyaromatic hydrocarbons and polychlorinated organic compounds in municipal waste landfill fires

305. This study involved the measurement of polyaromatic hydrocarbons (PAH) and polychlorinated biphenyl (PCB) concentrations in both the air and waste samples of landfill fires. Two landfill fires were studied, one of which was an experimental burn ignited deliberately, while the other was an accidental ‘spontaneous’ fire.

306. Air samplers were used to measure PAH and PCB concentrations in the ambient air, while burnt waste samples were collected from each fire. For the experimental fires, air sampling was conducted pre, during and post-fire, and increased PAH and PCB concentrations were measured during the fires. PCB concentrations varied between the ‘spontaneous’ and experimental fires however this may partly be due to the increases presence of industrial (de-inking waste) at the ‘spontaneous’ fire site. The emissions data is presented only in the form of concentration and this study was therefore not considered further.

(Solorzano-Ochoa *et al.*, 2012) Open burning of household waste: Effect of experimental condition on combustion quality and emission of PCDD, PCDF and PCB

307. This study explores the emissions from the open burning of municipal waste and the effect of compaction, stirring and moisture on combustion quality and the subsequent effect on emissions of PCDD, PCDF and PCB. This study presents the results from six new open burning experiments (each involving circa. 100 kg municipal waste, collected from a Mexican landfill site) with half involving waste lightly compacted and moistened prior to burning, two involving loose waste without added moisture, and a final experiment also without added moisture but incorporating stirring of the waste during combustion. The results of these studies are compared with results from various past experimental campaigns at landfill sites in both China and Mexico, in which waste composition alone accounted for very little of the observed variability in emissions.

308. Emissions of PCDD, PCDF and PCB in the combustion gases were analysed, along with continuous monitoring of CO, CO_2, HCl and H_2O using an FTIR spectrometer. While total emissions factors are provided in terms of TEQ in the text, an additional detailed breakdown of homolog-specific emission factors is provided (in terms of mass of Carbon burned) for each experiment in the Supporting Information. Experiment specific mass loss data and ash sample composition is also provided within the Supporting Information.

309. The study observed that the lowest air emission factors were yielded by the stirred experiment, followed by the loosened waste experiments, while the CO/CO_2 ratio also decreased with increased stirring. The experiments in which waste was both compacted and moistened yielded the greatest air emission factors. Relatedly, both air emission factors and CO/CO_2 ratio were highest in the latter stages of the burns characterised by still elevated temperatures but little mass loss, which the authors suggest can be considered as the smouldering phase.

(Zhang *et al.*, 2011) Emissions of unintentional persistent organic pollutants from open burning of municipal solid waste from developing countries

310. This study reports the emissions from 20 experiments conducted in China and Mexico, in which a high volume sampler (introduced in Zhang 2009) was used to study the emissions from pen burning of municipal landfill waste. These experiments involved different waste compositions which reflected the observed waste streams in different areas of each country (rural, semi-urban, urban, urban-industrial).

311. Monitoring and analysis varied slightly between the experiments conducted in Mexico and those in China. In both cases though CO and CO_2 concentrations were monitored during the experiment, with post-experiment PCDD/PCDF analysis conducted according to EN 1948. Each experiment involved an initial waste fuel load of around 100 kg, with two of the experimental sites in China involving a small wall to help contain the waste (present in four experiments).

312. Emissions data is presented both for specific experiments and in some cases as averages by country and waste type only. Some yields are reported (per unit mass of waste), while for some compound classes the data is presented only as TEQ or in terms of concentration. While some variation in emission factors between the Mexico and China samples was observed, they were not statistically different given the large scatter and differences even between replicate experiments.

(Lemieux *et al.*, 2003) Variables affecting emissions of PCDD/Fs from uncontrolled combustion of household waste in barrels

313. This study investigated the emissions of PCDD/Fs from 25 experimental barrel burns of domestic waste, with polychlorinated biphenyls (PCBs) also measured in a subset of experiments. These experiments involved the combustion of waste representative of domestic waste (including mixtures of paper, plastic, food waste, glass/ceramics, wood and metals) in 208 L steel barrels, with 12 small ventilation holes around the base, in a manner representative of typical residential waste burning. The effect of varying waste compositions on emissions was investigated as well as the effect of compressing or wetting the fuel and of burning double the initial fuel load. A single

open burning experiment was also conducted in which the waste was burned in an open pile rather than in a barrel.

314. All experiments were conducted in the EPA Open Burn Test Facility, with a measured supply of ambient air into the burn facility. The mass of the burning waste was continuously monitored, while six thermocouples were positioned at various heights within the barrel. PCDD/F sample collection was conducted according to Method T09, with analysis by gas chromatography and mass spectrometry according to EPA Test Method 8290.

315. Combustion gas and in-fuel temperature measurements are presented for each experimental case. Similarly the total PCDD/F and PCB emissions are provided for each case, based on the mass of waste burned. A large variation in emissions results was noted across the seven baseline experiments conducted. It was suggested that random factors including waste orientation and air flow paths may significantly affect emissions of PCDD/Fs across these baseline experiments. Total emissions from the single open burn were within the variability range of the baseline experiments. Conclusions were however drawn from the observations of burn behaviour, with the majority of emissions stated to have occurred in the latter stages of the experimental period, during which smouldering combustion was dominant, except in the case of wetted wasted fuel, where the majority of emissions occurred during the early phases of the fire during the period of moisture evaporation.

(Gullett *et al.*, 1999) "PCDD/F Emissions from uncontrolled, domestic waste burning"

316. This study investigated PCDD/F emissions from experimental barrel burning of domestic waste, exploring the effect of small variation in waste composition on both combustion conditions and overall emissions. This involved a series of baseline experiments followed by subsequent experiment in which the organic or inorganic Chlorine level in the waste fuel was varied.

317. Continuous monitoring of combustion gases in the exhaust duct was undertaken for O_2, CO_2, and CO, with a PM sampler also present. Estimated PCDD/F emissions were based on the concentration measured by an ambient air sampler, along with dilution air supply rate into the burn facility and the mass of waste burned. PCDD/F emissions are however reported only as TEQ (based on EPA Toxic Equivalent Factors (TEF)) for each experiment and therefore this study is not considered further.

(Gullett *et al.*, 2010) PCDD/F, PBDD/F, and PBDE Emissions from Open Burning of a Residential Waste Dump

318. This study involves the characterisation of emissions from two experimental open fires involving municipal waste at two different waste dump facilities in Mexico. At both sites there was some removal of recyclables (certain plastics, aluminium, cardboard and glass) from the waste prior to burning.

319. Each experiment involved the ignition of a waste pile of around 5 m_3 volume, with four air samples recorded for each site across the three day experimental duration, using high volume samplers. The CO and CO_2 concentrations above the fire were also monitored.

320. The emission factors of PBDD/Fs and PBDEs are reported on the basis of carbon burned, while the emission factors for specific PCDD/F homolouges are similarly reported for each experiment in the Supporting Information. The PBDD/F and PCDD/F emissions (in terms of TEQ per unit mass of carbon burned) are also compared with combustion quality (base on CO/CO_2 ratio). A trend of increasing PCDD/F emission factor with higher CO/CO_2 ratio ('poor combustion quality') was observed, and this was also the case, but to a lesser extent, for PBDD/F emissions.

(Sidhu *et al.*, 2005) Endocrine disrupting chemical emissions from combustion sources: Diesel particulate emissions and domestic waste open burn emissions

321. This study investigates the emissions from the experimental (uncontrolled) open burning of domestic waste, with a specific focus on the emissions of endocrine disrupting chemicals (EDCs),

characterised using gas chromatography – mass spectrometry. These emissions are compared with those from additional experiments involving controlled burning in a diesel engine.

322. For the domestic waste experiments, the waste fuel was composed of household waste (including shoes, packaging and plastics) were burned in 55 gal steel drums. A list of compounds identified in these burns is presented along with their associated emissions rate. Additional comparison with industrial emissions is provided, along with information regarding identified toxicants.

(Gullett *et al.*, 2001) Emissions of PCDD/F from uncontrolled, domestic waste burning

323. This study describes similar experiments to those in Gullet et al, 1999, with domestic waste burned in 55 gal steel barrels. The baseline waste composition is well described, with additional experiments including waste of varying PVC, inorganic chlorine or copper levels, and waste of differing moisture content and compression.

324. All experiments were conducted at the EPA Open Burning Test Facility, with mass loss and combustion gasses (O_2, CO and CO_2) monitored throughout the experimental duration. HCl and chlorine were sampled and analysed following EPA Methods 26, while a separate sampler measured PM. PCDD/Fs and PCBs were sampled and analysed using gas chromatography – mass spectrometry. The PCB data is not discussed in this study, while the total PCDD/F emissions are discussed they are presented only as TEQ, and are therefore not considered further.

(Ruokojgtrvi *et al.*, 1995) Polychlorinated Dibenzo-P-Dioxins and –Furans (PCDDs and PCDFs) in Municipal Waste Landfill Fires

325. This paper, similarly to Ruokojarvi *et al,* 1995 (a) studies the emissions from municipal waste in two landfill fires, one of which was deliberately ignited (for purposes of the experiment) with the other fire occurring accidentally. This paper focuses on reporting the PCDD and PCDF measurements from both fires, based on measurements of both the ambient air and samples of burnt waste. The PCDD/F analysis used gas chromatography and mass spectrometry however while specific congeners are identified, all data is provided in terms of concentration and is therefore not considered further.

(Lönnermark, Blomqvist and Marklund, 2008) Emissions from simulated deep-seated fires in domestic waste

326. This study presents the emissions from a series of experiments involving the combustion of domestic waste in 1 m_3 container, in which only the top surface of the waste is exposed. This was designed as a well-controlled manner in which to investigate emissions from the type of 'deep-seated' fires typical of landfill fires. Estimated compositions of the domestic waste used in this study are provided based on recent analysis of waste production around the region from which the domestic waste was obtained.

327. The yield of PAH, PCDD/F, PCB, HCB, PM, hexachlorobenzene and metals in the gas phase were measured, while samples of the burned waste were also analysed in a subset of experiments. Mass loss was recorded throughout the experimental duration, with combustion gas collected in an exhaust hood, with flow, duct temperature and gas concentrations (O_2, CO_2, CO) measured within the exhaust duct.

328. The total mass loss for each experiment is presented, along with the gas phase yields of PAH, PCDD/F, PCB, HCB, PM, hexachlorobenzene and metals in terms of the mass lost, with information for specific congeners and isomers also presented for each experiment.

12.2. Other Relevant Wastes

(Lemieux and Ryan, 1993) "Characterization of Air Pollutants Emitted from a Simulated Scrap Tire Fire"

329. This study evaluated the organic and inorganic emissions from the experimental burning of tire samples, within a large burn hut. Two tire sample types of varying size are considered: a tire

‘chunk’ (1/4 to 1/6 of an entire tire) and a tire ‘shred’ [2 in by 2 in piece], with two experiments conducted at each condition.

330. Combustion gases (O2, CO2, THCs and SO2) were monitored using the US Environmental Protection Agency (EPA) Hazardous Air Pollutants Mobile Laboratory (HAPML). Organics and particulates collection used both the Volatile Organic Sampling Train (VOST) and XAD-2 and particulate filters (for collection of semi-volatiles). Background measurements were recorded for all sampling methods. Subsequent analysis involved gas chromatography/mass spectroscopy, flame ionization detection, and gravimetric methodologies.

331. Continuous combustion gas data across the experimental duration is provided for each experiment, where these deviated significantly from the ambient concentrations. Estimated emissions are presented for an extensive range of volatiles and semi-volatile organics and for airborne metals (often beyond maximum detection limits) and small particulates. The experimental setup allows the comparison of emission rates with burning rate of the samples, with the amount of CO, SO_2 and unburned hydrocarbons increasing with increasing burn rate however, the mass of specific organic compounds emitted relative to tire mass consumption generally decreased as the burn rate decreased. The authors suggest this may be as a result of the lower temperature burn regime in the later stages of the combustion period in which pyrolysis may continue but reduced combustion may occur.

(Woodall *et al.*, 2012) “Emissions from small-scale burns of simulated deployed U.S. military waste”

332. This study characterises the emissions from the experimental open burning of military waste at the EPA Open Burn Testing Facility. While the focus of the study is on military waste, the described composition is somewhat similar in composition to municipal waste, containing many similar waste products e.g. plastics, wood, paper and cardboard, food waste. Seven experimental burns were conducted involving 10 kg waste samples, with PET #1 water bottles included in 3 cases but not the others (to simulate targeted recycling efforts). In all cases, waste was loosely packed onto a burn platform positioned on a load cell to monitor the mass loss rate.

333. Sampling and analysis of emissions were conducted with flow rate and temperature measured within the extraction duct. A wide variety of EPA methods were used to sample different compound classes (PXDD/PXDF, PAHs, VOCs, SVOCs, PM) with subsequent analysis involving gas chromatography/ mass spectroscopy and gravimetric analysis. Combustion gases (O_2, CO_2, CO, SO_2, NO_x) were analysed using a combustion environmental monitoring system.

334. Emission factors are reported (per unit mass of Carbon burned) for various polycyclic aromatic hydrocarbons, volatile organic compounds, metals and particulate matter, with additional detailed information provided (per test) in the Supporting Information. The lack of a significant decrease in VOC emissions for the cases in which PET #1 plastic bottles were removed, prompted the authors to suggest that both cases burned with similar combustion quality.

(Gullett *et al.*, 2007) “Characterization of air emissions and residual ash from open burning of electronic wastes during simulated rudimentary recycling operations”

335. This study characterises both air emissions and ash samples from the experimental open burning of two types of electronic waste (printed circuit boards and insulated wires) typical of basic recycling and metal recovery practices. The experiments were conducted in an enclosed open burnt test facility, with the supply of exterior dilution air to avoid oxygen depletion and better simulate open burning conditions.

336. Ten experiments were conducted, with combustion gases (CO, CO_2, O_2, THC)continuously monitored throughout the experimental duration. Sampling of PCDD/Fs was conducted in a subset of experiments and analysed using EPA Method 8290, with PBDD/F compounds measured in a single case. Emission factors (based on the initial mass of the e-waste, as e-waste consumption could not be separated from that of the charcoal, present to sustain combustion) were reported for the particulate matter and metals in the combustion fly ash samples and for emissions of PCDD/F.

Additional graphical emissions factor information is provided (including for PBDD/Fs where measured), while the composition of residual ash samples are also provided.

337. Notably high emissions from PCDD/PCDF were reported for the insulated wire case, which was attributed to both the uncontrolled nature of combustion and the high chlorine content. For the circuit boards very high levels of PBDD/PBDF were reported and attributed to the presence of brominated flame retardants.

(Lutes and Ryan, 1994) Characterization of Air Emissions from the Simulated Open Combustion of Fiberglass Materials

338. This report summarises a project in which the emissions from experimental open burning of two types of fiberglass material (from the boating and building industries respectively) are characterised. Experiments were conducted in the EPA Open Burn Test Facility, with an elemental analysis of the fiberglass materials conducted prior to testing, while during experiments there was continuous monitoring of combustion gases (CO_2, CO, NO, O_2, THC). Mass loss and various temperature measurements were also recorded throughout the experimental duration.

339. A VOST sample train was used for the sampling of volatile organics, while separate samplers collected semi-volatiles and PM, with analysis primarily in the form of gas chromatography / Mass Spectrometry. Estimated emissions of CO, CO_2, THC, PAH and various metals are presented for each experiment along with average estimated emissions of selected volatiles, semi-volatiles for each material. Authors note that there may be a significant error associated with parts of this dataset as result of limitations in both the mass loss measurements (as a result of the low initial sample mass) and potential overloading of sample trains and the preventative measures taken to limit this.

12.3. Reviewed but not further considered

(Kjeldsen and Christensen, 1990) Leaching tests to evaluate pollution potential of combustion residues from an iron recycling industry

340. No relevant information presented.

(Owusu Boadi and Kuitunen, 2005) Environmental and health impacts of household solid waste handling and disposal practices in Third World cities: The case of the Accra Metropolitan Area, Ghana

341. No relevant information presented.

(Stearnst and Petoyant, 1984) Identifying and controlling landfill fires

342. No relevant information presented.

(Carrico *et al.*, 2010) Water uptake and chemical composition of fresh aerosols generated in open burning of biomass

343. No relevant information presented.

(Simoneit, Medeiros and Didyk, 2005) Combustion products of plastics as indicators for refuse burning in the atmosphere

344. No relevant information presented.

(Rushbrook and Finnecy, 1988) Planning for Future Waste Management Operations in Developing Countries

345. No relevant information presented.

(Wiedinmyer *et al.*, 2011) The Fire INventory from NCAR (FINN): A high resolution global model to estimate the emissions from open burning

346. No relevant information presented.

(Neurath and Neurath, 2004) PVC's role in dioxin emissions from open burning: New analysis of US EPA data

347. No relevant information presented.

(El-Halwagi *et al.*, 1987) Solid waste management in Egypt: Problems, Planning and National Trends

348. No relevant information presented.

(Escobar-Arnanz *et al.*, 2018) Characterization of organic aromatic compounds in soils affected by an uncontrolled tire landfill fire through the use of comprehensive two-dimensional gas chromatography–time-of-flight mass spectrometry

349. No relevant information presented.

(Yhdego, 1988) Urban Solid Waste Management in Tanzania

350. No relevant information presented.

(Pansuk, Junpen and Garivait, 2018) Assessment of Air Pollution from Household Solid Waste Open Burning in Thailand

1. No relevant information presented.

12.4. Reviews

(Estrellan and Iino, 2010) Toxic emissions from open burning

351. This review provides a summary of recent experimental and numerical studies of toxic emissions from a variety of open burning fire and fuel types. This includes a brief summary of recent studies investigating the emissions from the open burning of domestic waste.

(Lemieux, Lutes and Santoianni, 2004) Emissions of organic air toxics from open burning: A comprehensive review

352. This review provides a summary of open burning practices and past studies focused on the measurement of emissions from various open burning fire and fuel types. This includes separate sections on the open burning of household waste and landfill fires, as well as other potentially relevant fire types. A summary of selected emissions study is provided for each study area. A general review of the methods used in the measurement and reporting of emissions is also provided.

(Hutzinger and Fiedler, 1989) Sources and Emissions of PCDD/PCDF

353. This review provides a summary of key sources responsible for PCDD/PCDF emissions, including the contribution of combustion related activities. Some older emissions studies are summarised, while the nature of PCDD and PCDFs and their formation processes are also discussed.

(EPA (Environmental Protection Agency), 2006) An inventory of sources and environmental releases of dioxin- like compounds in the United States for the years 1987, 1995, and 2000.

354. This report provides a detailed overview of the release of dioxin-like compounds and the contributing sources within the United States. Emissions estimates are provided for various sources including combustion related production, and specifically for uncontrolled or minimally controlled combustion with key studies identified and discusses.

(Akagi *et al.*, 2011) Emission factors for open and domestic biomass burning for use in atmospheric models

355. This study provides an overview of available emissions data for open and domestic burning including specific emissions factors for garbage burning. The focus is on providing emissions factors for use in modelling efforts. The experimental or theoretical studies used to inform the selection of emission factors and guidance for their use are also included.

(Wiedinmyer, Yokelson and Gullett, 2014) Global Emissions of Trace Gases, Particulate Matter, and Hazardous Air Pollutants from Open Burning of Domestic Waste

356. This study presents a model to estimate the global contribution of open burning of domestic waste to various emissions types. A useful summary of existing relevant studies is provided in the process of defining emissions factors for use in the model.

(Verma *et al.*, 2016) Toxic Pollutants from Plastic Waste- A Review

2. This review provides an introduction to the role of plastic as a contributor to various forms of emissions and related toxicology.

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502.

Appendix A: Personnel

Person: Dr Eric Mueller
Education

- Doctor of Philosophy, Fire Safety Engineering, University of Edinburgh, July 2017
- Master of Science, Fire Protection Engineering, Worcester Polytechnic Institute, 2012
- Bachelor of Science (Summa Cum Laude), Engineering Physics, Tufts University, 2010

Experience
Dr Mueller has significant experience in the dynamics of fires and combustion processes. He has experience in using numerical tools to predict fire behaviour and the transport of smoke. His experience in the design of combustion experiments will allow him to critically evaluate the data obtained from the literature review. Dr Mueller has significant experience in data analysis, data synthesis and data presentation.

Person: Zakary Campbell-Lochrie
Education

- MEng, Mechanical Engineering, University of Edinburgh, 2017

Experience
Mr Campbell-Lochrie has experience in undertaking detailed reviews of the literature associated to the effects of the combustion environment. He has a background in experimental design and data analysis which are directly relevant to the literature review.

Person: Carlos Walker-Ravena
Education

- MEng, Mechanical Engineering, Imperial College London, 2016

Experience
Mr Walker-Ravena has experience in undertaking detailed reviews of the literature associated to the effects of the combustion environment on the burning of a range of materials at bench scale. He has a background in thermodynamics and pyrolysis which are directly relevant to the requirement of the literature review.

Person: Georgios Kanelopolous
Education:

- MEng, Civil Engineering, The Aristotle University of Thessaloniki

Experience:
Mr Kanelopolous has experience in the dynamics of fires in compartments and the impact of the burning conditions on the fire behaviours. He is experienced in reviewing the technical literature associated with large-scale fire dynamics are directly relevant to the requirement of this literature review.

Person: Vasileios Koutsomarkos
Education:

- MEng, Civil Engineering, The Aristotle University of Thessaloniki

Experience:
Mr Koutsomarkos has experience in the detailed review of fire science literature across a range of topics and disciplines. His skills in data synthesis, literature searches and literature analysis are core to the requirements of this review.

Appendix B: List of fire related combustion products

An alphabetic list of the 295 individual compounds identified as combustion related fire products. These are separated based on the combustion environment in Appendices D-G.

Compound	**Number of times detected**	**Max yield, mg/kg**
4,40-Methylenediphenyl diisocyanate	1	1
Acenaftene	6	1
Acenaftylene	6	125
Acenaphtalene	1	87
Acenaphtene	1	14
Acenaphthalene	2	1000
Acenaphthene	7	23
Acenaphthylene	7	634
Acenaphthylene	1	89
Acetaldehyde	2	580
Acetic acid	4	7400
Acetone	2	8140
Acetonitrile	9	5510
Acetoxymethylfuraldehyde	1	1
Acetylaminofluorene	1	9
Acetylene	4	2900
Acrolein	3	1200
Acrylonitrile	9	4500
Allene	1	2250
Aluminium	1	1
Ammonia	18	15000
Anthracene	12	596
Anthracenedione	1	0
Antimony	8	15
Antracene	6	12
Arsenic	5	48
Barium	1	4
Benz(ghi)perylene	2	0
Benz[de]anthracenone	1	1
Benzaldehyde	3	334
Benzene	23	47800
Benzenedicarboxylic acid	1	1
Benzenediol	1	13
Benzenes	3	
Benzisothiazole	1	174
Benzo fluoranthene	1	3
Benzo(a) anthracene	2	534

Benzo(a)-antracene	6	9
Benzo(a)-fluorene	6	3
Benzo(a)-pyrene	6	10
Benzo(a)anthracene	3	11
Benzo(a)pyrene	6	503
Benzo(b) fluoranthene	2	628
Benzo(b)- fluorene	6	2
Benzo(b)-fluorantene	6	16
Benzo(b)fluoranthene	1	4
Benzo(b)thiophene	1	44
Benzo(e)-pyrene	6	9
Benzo(g,h,i) perylene	2	100
Benzo(g,h,i)-perylene	6	11
Benzo(g,h,i)perylene	2	3
Benzo(k) fluoranthene	2	534
Benzo(k)-fluorantene	6	5
Benzo(k)fluoranthene	1	2
Benzo[a]anthracene	4	1
Benzo[b]fluoranthene	4	1
Benzo[e]pyrene	1	1
Benzo[k]fluoranthene	4	1
Benzo[k]fluoranthene	1	2
Benzodiazine	2	17
Benzofuran	2	25
Benzoic acid	1	5
Benzonitrile	14	14900
Benzonitriles	1	
Benzothlophene	2	26
Beryllium	1	0
Biphenyl	5	1936
Biphenyl carboxaldehyde	1	1
Biphenylene	1	6
Bismuth	1	0
Bisphenol A	1	10
Boron	1	6
Bromine	7	260
Butadiene	3	1110
Butadiene	1	540
Butanone	1	540
Butenyne	1	130
Cadmium	6	2
Calcium	1	2

Carbon disulfide	2	250
Carbon tetrachloride	1	2
CDE-141	1	
CDE-180	1	
CDE-209	1	
CDE-28	1	
CDE-77	1	
CDE-99	1	
Chlorine	1	2500
Chlorobenzene	1	
Chlorobenzenes	1	2
Chloromethane	1	220
Chloronaphthalene	1	4
Chlorophenols	1	2
Chromium	5	14
Chrysene	11	597
Chrysene/Trifenylene	6	12
Cobalt	2	0
Copper	5	27
Coronene	6	4
Cumene	2	33
Cyanobenzene	2	517
Cyclopentadiene	1	49
Dibenz (a,h) anthracene	2	72
Dibenz(a,h)anthracene	2	0
DiBenzo(a,h)-antracene	5	1
Dibenzofuran	1	3
dihydro indenone	1	2
Dihydroindene	2	43
Dimethoxy phenol	1	1
Dimethoxytoluene	1	0
Dimethyl benzene	2	1078
Dimethyl hexadiene	2	91
Dimethyl naphthalene	2	178
dimethyl, methlpropyl benzene	1	15
Dimethylbenz(a)anthracene	1	2
Dimethyldibenzothiophene	1	1
Dimethyldihydro indene	2	22
Dioctyl phthalate	1	336
Dioxin - 1234678-HpCDD	2	1
Dioxin - 1234678-HpCDF	2	0
Dioxin - 12378-PeCDF	2	0

Dioxin - 234678-HxCDF	2	0
Dioxin - 2378-TCDF	6	0
Dioxin - OCDD	16	0
Dioxin - OCDF	4	0
Diphenyl methanone	1	2
Diphenylpropene	1	2
Ethanal	1	9070
Ethane	1	2020
Ethanone, 1-phenyl-	1	4
Ethene	3	11440
Ethenyl benzene	2	942
Ethenyl cyclohexene	2	108
Ethenyl dimethyl benzene	2	24
Ethenyl methyl benzene	4	222
Ethenyldimethyl cyclohexane	1	350
Ethyl Benzene	7	9300
Ethyl bromide	1	1570
Ethyl dimethyl benzene	1	272
Ethyl isocyanate	3	250
Ethyl isocyanate	3	9
Ethyl methyl benzene	2	476
Ethylene	1	1800
Ethylene bromide	2	2710
Ethyne	1	1400
Ethynyl benzene	2	276
Ethynyl methyl benzene	2	531
Ethynylbenzene	2	180
Fluorantene	6	49
Fluoranthene	10	844
Fluorene	15	534
Fluorenone	1	4
Fluorine	3	308
Formaldehyde	6	7400
Formic acid	2	3340
Freon	1	9410
H-benzo[b]fluorine	1	1
Heptadiene	2	51
hexahydro azepinone	2	749
Hexaklorbensen	1	0
Hexamethyl diisocyanate	2	620
Hexamethyl diisocyanate	1	1
Hydrgoen bromide	4	5000

Hydrogen bromide	4	33279
Hydrogen chloride	39	#REF!
Hydrogen cyanide	115	584210
Hydrogen fluoride	5	59500
Hydrogen sulfide	2	3000
Hydroxy benzaldehyde	1	1
Hydroxymethoxy benzaldehyde	1	7
Hydroxymethoxy benzoic acid	1	1
Idene	2	503
Indene	5	140
Indeno(1,2,3-c,d)pyrene	3	100
Indeno(1,2,3-cd)-pyrene	6	13
Indeno(1,2,3-cd)pyren	1	2
Indeo(123cd)pyrene	2	0
Iron	2	4
Isobenzofurandione	1	4
Isocyanate acid	2	210000
Isocyanate acid	5	6027
Isocyanic acid	2	763
Isocyano benzene	2	347
Isocyano methane	1	3100
Isocyano naphthalene	1	9
Isoforon diisocyanate	2	19
Isothiocyano methane	1	840
Lead	7	820
Limonene	2	2346
m-p-Xylene	2	1100
m-Xylene	1	
m,p-Xylenes	1	150
Magnesium	1	10
Manganese	2	6
Mercury	3	17
Methane	4	15310
Methanol	3	2810
Methoxy phenol	1	16
Methyl benzaldehyde	1	87
Methyl benzene	2	1606
Methyl biphenyl	1	11
Methyl bromide	1	780
Methyl catechol	1	3
Methyl cyclohexene	2	40
Methyl furfural	1	8

Methyl hexadiene	2	127
Methyl indene	2	401
Methyl isocyanate	3	6000
Methyl isocyanate	3	30
Methyl naphthalene	6	429
Methyl Phenol	2	400
Methyl propenal	1	1750
Methyl thiophene	2	13
Methyl, ethenyl benzene	2	77
Methyl, methylethenyl benzene	2	684
Methyl, methylethyl benzene	3	1426
Methyl, methylethyl c.h.	1	170
Methyl, propyl benzene	1	42
Methylbutene	1	3570
Methylcholanthrene	1	4
Methylendiphenyl aminoisocyanate	2	35
Methylene chloride	2	8
Methylene indene	2	49
Methylenedianiline	2	455
Methylenediphenyl isocyanate	4	40
Methylethyl benzene	3	229
Methylnaphthalene	1	16
Molybdenum	1	0
Naphthalene	22	15100
Naphthalenol	1	0
Nickel	4	3
Nitric oxide	13	121000
Nitric oxide	2	93158
Nitrogen Dioxide	30	3300
Nitrogen monoxide	6	4500
NOx	8	15000
o-xylene	2	80
PBDD	3	0
PBDE	7	57
PBDF	6	5
PCDD	40	2100
PCDD/PCDF	18	10000
PCDE	1	
PCDF	40	56000
Pentadiene	2	1163
Perylene	5	2
Phenalenone	1	1

Phenanthrene	13	2156
Phenantrene	6	103
Phenol	10	6830
Phenyl acetylene	3	58
Phenyl isocyanate	3	9800
Phenyl isocyanate	3	1174
Phosphoric acid	4	3000
Phosphorus	6	25
Polyoxymethylene	1	
Propene	5	16270
Propenitrile	1	2780
Propenyl naphthalene	1	24
Propenyl, methyl benzene	1	524
Propyl benzene	2	220
Propylbenzene	2	34
Propyne	1	1100
Pyrene	16	597
Pyridine	9	1500
Selenium	2	0
Silicon	1	2
Silicon tetrafluoride	1	10600
Silver	2	14
Styrene	13	49400
Sulfur dioxide	15	1752632
TCDD	2	
TCDD I-TEQ	2	800
TCDF	1	
Terphenyl	1	4
Tetramethyl benzene	1	256
Thallium	1	5
Thiophene	4	110
Tin	2	0
Toluene	16	29800
Toluene aminoisocyanate	4	4100
Toluene aminoisocyanate	3	111
Toluene diisocyanate	8	7200
Toluenediamine	1	5
Tribromo phenol	1	5
Trichloro/flouromethane	1	58
Trimethyl benzene	2	751
Trimethyl naphthalene	1	316
Trimethylbenzene	1	

Triphenylene	1	2
Ultrafine particles	1	
Vanadium	3	0
Vinyl acetate	1	1500
Xylene	1	1980
Zinc	3	3200

Appendix C: List of materials from which combustion related fire products were measured

An alphabetic list of the 190 individual materials from which combustion related fire products are measured.

Acetone
Airplane seat cover (fabric)
Airplane Wall/floor cover
Atrazin
Automobile
Bitumen
Boucle (acrylic, wool, polyester)
Boucle (acrylic, wool, polyester) (FR)
Brominated Polyester
C1meqCl
Cable (LSZH)
Cable (NO7V-K)
Cable (NYM)
Cable (Polyvinylchloride)
Cable (Polyvinylchloride)
Cable (RV-K)
Camphor Laurel
Captan
Car
Car - Carpet
Car - Dashboard
Car - Door Panel
Car - Electrical Wirings
Car - Lacquered Plate From Car Body
Car - Polymer From Vent System
Car - Tyre
Car - Upholster Material From Back Seat
Car - Upholster Material From Drivers Seat
Car Part (Polyamide 6,6)
Car Part (Polyamide 6)
Car Part (Polyvinylchloride)
Carpet (Wool, Polyester, Polyurethane)
Carpet (Wool, Polyester)
CB
Chipboard
Chlorobenzene
Clthalonil

CMHR polyurethane foam (FR)
CNBA
Controlled synthetic fuel - municipal waste
DCPP
Dichlobenil
DimethaC1
Dimethoate
Diuron
Domestic Waste
Domestic Waste
Ethanol
Fiberglass Materials (Boating Industry)
Fiberglass Materials (Building Industry)
Flexible Lab formulated foam (2,4and 2,6TDI)
Fluoropolymer
Fluoropolymer-cable
FP Cable
FR4 laminate
FRPE Pellets
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)
Garden and Domestic Waste
Garden and Industrial Waste
Garden and Refuse Waste
Garden waste
Garden Waste and Motor Oil
Glass wool
Hazardous waste
Hexanes
Household refuse
Household waste
Household Waste (1% Polyvinylchloride)
Household Waste (7.5 % Polyvinylchloride)
Household waste (Compacted/Moistened)
Household waste (Compacted/Moistened/Stirred)
Household Waste (Compressed)
Household Waste (High Copper Content)
Household Waste (Including CaCl2 Soaked Newspaper)
Household waste (Loosened)

Household Waste (No Polyvinylchloride)
Household Waste (Open Fire)
Household Waste (Wetted)
Insulated wires
Isopropanol
Landfill waste
LDPE
Li-ion battery
Li-ion battery (LiFSI)
Li-ion battery (LiPF6)
Lindane
Low-density polyethylene pellets
MCPA
MDF
MDF - Fire resistant
MDF (FR)
MDI/polyester foam
MDI/polyester foam, fire retarded
MDI/polyether polyol foam
MDI/polyether polyol foam, fire retarded
Medical waste
Melamine
Methanol
Military waste with PET plastics
Military waste without PET plastics
Mineral wool
Municipal solid, organic, laboratory, industrial, liquid, and medical waste
Municipal waste
Municipal waste
Municipal waste & Electronic Waste
Nitrile rubber
Nylon 6.6
Nylon 6.6/6
Optical cable
PA 6.6
Particleboard
PCP
Phenolic foam
Pine Wood
PIR
PIR (rigid foam)
Plywood

PMMA
Polyacrylonitrile
Polyamide 6
Polyamide 6 (AlPiM Retardant)
Polyamide 6 (BrSb Retardant)
Polyamide 6 (No Retardant)
Polyamide 6.6
Polyamide 6.6 (AlPiM Retardant)
Polyamide 6.6 (BrSb Retardant)
Polyamide 6.6 (No Retardant)
Polyetherpolyurethane (PPUF)
Polyethylene based cable
Polyethylene based pellets
Polyisicyanurate foam
Polyisocyanurate foam
Polypropene
Polypropylene
Polystyrene
polystyrene pellets
Polyurethane (flexible)
Polyurethane (rigid)
Polyurethane Insulation
Polyurethane mattress
Polyvinylchloride
Polyvinylchloride cable
Polyvinylchloride carpet
Polyvinylchloride Pellets
Polyvinylchloride+fluoropolymer cable
Printed circuit boards
Propane
Propene
PUR (flexible foam)
PUR (rigid foam)
PVC
PVC Carpet (contains polyurethane components)
PVC chloride carpet
Refuse Waste & Domestic Waste
Refuse Waste & Domestic Waste (Air-Dried)
Refuse Waste & Domestic Waste & Electronic Waste
Refuse Waste & Domestic Waste & Misc.
Rigid Lab formulated foam (2,4and 2,6TDI)
Rigid Polyurethane (PAPI,TMP)

Sofa (Polycotton pad, woolen layer, woven cotton and wool cover, No fire retardant treatment)
Sofa (Polyurethane foam, polyester layer, Chinese fire retardant fabric cover)
Sofa (Polyurethane foam, polyester layer, UK fire retardant fabric cover)
Sofa (Polyurethane foam, polyester layer, Untreated EU fabric cover)
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)
Sparkler
Stone wool
Straw
Straw (Moistured Fuel)
Straw & Industrial Waste
Television (EU)
Television (US)
Television set (EU)
Television set (US)
Tetramethylthiuram monosulphide
Tire Chunk
Tire Shred
TMTM
Toluene
Untreated Pine
Velour (acrylic, cotton, polyester)
Wood
Wood (Pine)
Wood Board
Wool

Appendix D: Small scale experiments: Compounds identified, material burning and maximum yield

Compound Material burning	**Yield, mg/kg**
4,40-Methylenediphenyl diisocyanate	
Wood Board	0.5
Acenaphthalene	
PVC chloride carpet	1000
Wood Board	0.69
Acenaphthene	
Camphor Laurel	0.064
Chipboard	0.212
MDF	0.197
PVC chloride carpet	23
Untreated Pine	0.05
Wood Board	3.39
Acenaphthylene	
Camphor Laurel	0.843
Chipboard	2.466
MDF	2.026
Untreated Pine	0.636
Acetone	
Rigid Polyurethane (PAPI,TMP)	8140
Acetonitrile	
Flexible Lab formulated foam (2,4and 2,6TDI)	1100
MDI/polyester foam	4800
MDI/polyester foam, fire retarded	3300
MDI/polyether polyol foam	3800
MDI/polyether polyol foam, fire retarded	3000
Rigid Lab formulated foam (2,4and 2,6TDI)	1100
Acetylene	
Li-ion battery (LiFSI)	800
Li-ion battery (LiPF6)	2900
Acrylonitrile	
Flexible Lab formulated foam (2,4and 2,6TDI)	300
MDI/polyester foam	2500
MDI/polyester foam, fire retarded	3300
MDI/polyether polyol foam	4500
MDI/polyether polyol foam, fire retarded	3600
Rigid Lab formulated foam (2,4and 2,6TDI)	400

Allene	
Rigid Polyurethane (PAPI,TMP)	2250
Ammonia	
Airplane seat cover (fabric)	5000
Airplane Wall/floor cover	15000
Car - Tyre	2300
Car - Upholster Material From Back Seat	350
Car - Upholster Material From Drivers Seat	400
Polyurethane Insulation	1000
Polyurethane mattress	1500
Anthracene	
Camphor Laurel	0.15
Chipboard	0.581
MDF	0.499
PVC chloride carpet	596
Untreated Pine	0.098
Wood Board	2.1
Benz(ghi)perylene	
Chipboard	0.227
MDF	0.143
Benzene	
MDI/polyester foam	43800
MDI/polyester foam, fire retarded	47800
MDI/polyether polyol foam	33900
MDI/polyether polyol foam, fire retarded	37800
Rigid Polyurethane (PAPI,TMP)	7380
Benzo(a) anthracene	
PVC chloride carpet	534
Wood Board	57.8
Benzo(a)pyrene	
PVC chloride carpet	503
Wood Board	83.5
Benzo(b) fluoranthene	
PVC chloride carpet	628
Wood Board	78.3
Benzo(g,h,i) perylene	
PVC chloride carpet	100
Wood Board	32
Benzo(k) fluoranthene	
PVC chloride carpet	534
Wood Board	43.1
Benzo[a]anthracene	

Camphor Laurel	0.132
Chipboard	0.614
MDF	0.484
Untreated Pine	0.082
Benzo[b]fluoranthene	
Camphor Laurel	0.251
Chipboard	0.612
MDF	0.696
Untreated Pine	0.326
Benzo[k]fluoranthene	
Camphor Laurel	0.046
Chipboard	0.085
MDF	0.917
Untreated Pine	0.032
Benzonitrile	
Flexible Lab formulated foam (2,4and 2,6TDI)	2400
MDI/polyester foam	12600
MDI/polyester foam, fire retarded	11400
MDI/polyether polyol foam	14900
MDI/polyether polyol foam, fire retarded	9300
Rigid Lab formulated foam (2,4and 2,6TDI)	3900
Rigid Polyurethane (PAPI,TMP)	7730
Butadiene	
Rigid Polyurethane (PAPI,TMP)	1110
Butenyne	
Rigid Polyurethane (PAPI,TMP)	130
Chrysene	
Camphor Laurel	0.059
Chipboard	0.23
MDF	0.287
PVC chloride carpet	597
Untreated Pine	0.035
Wood Board	50.4
Dibenz (a,h) anthracene	
PVC chloride carpet	72
Wood Board	5.4
Dioxin - 1234678-HpCDD	
PCP	0.74
Dioxin - 1234678-HpCDF	
Polyvinylchloride	0.0001
Dioxin - 12378-PeCDF	
MCPA	0.0049

Dioxin - 234678-HxCDF	
CB	0.0042
Dioxin - 2378-TCDF	
CNBA	0.0079
Diuron	0.0052
TMTM	0.0007
Dioxin - OCDD	
Captan	0.0006
CB	0.018
Clthalonil	0.019
CNBA	0.23
DCPP	0.057
Dichlobenil	0.000001
DimethaC1	0.024
Dimethoate	0.0021
Lindane	0.0013
Dioxin - OCDF	
Atrazin	0.001
C1meqCl	0.0001
Ethanal	
Rigid Polyurethane (PAPI,TMP)	9070
Ethane	
Rigid Polyurethane (PAPI,TMP)	2020
Ethene	
Rigid Polyurethane (PAPI,TMP)	11440
Ethyl Benzene	
Brominated Polyester	440
Ethyl bromide	
Brominated Polyester	1570
Ethyl isocyanate	
Wood Board	1.1
Ethyl isocyanate	
PIR (rigid foam)	9.386763074
PUR (rigid foam)	3.279867027
Wood (Pine)	0.972086514
Ethylene	
Li-ion battery (LiPF6)	1800
Ethylene bromide	
Brominated Polyester	2710
Ethyne	
Rigid Polyurethane (PAPI,TMP)	1400
Fluoranthene	

Camphor Laurel	0.389
Chipboard	0.708
MDF	1.008
PVC chloride carpet	844
Untreated Pine	0.296
Wood Board	76.12
Fluorene	
Camphor Laurel	0.2
Chipboard	0.841
MDF	0.64
PVC chloride carpet	534
Untreated Pine	0.297
Wood Board	0.53
Formaldehyde	
Li-ion battery (LiFSI)	900
Li-ion battery (LiPF6)	900
Freon	
Rigid Polyurethane (PAPI,TMP)	9410
Hexamethyl diisocyanate	
PUR (flexible foam)	1.102258098
Hydrgoen bromide	
Polyamide 6.6 (BrSb Retardant)	5000
Hydrogen bromide	
Polyamide 6 (BrSb Retardant)	33279
Hydrogen chloride	
Cable (Polyvinylchloride)	320000
Car - Door Panel	160000
Car - Electrical Wirings	390000
Car - Upholster Material From Back Seat	8100
Car - Upholster Material From Drivers Seat	66000
Car Part (Polyvinylchloride)	1162000
Carpet (Wool, Polyester, Polyurethane)	11800
Carpet (Wool, Polyester)	7100
FP Cable	130000
Glass wool	0
Li-ion battery	1315.789
Phenolic foam	7000
Polyisocyanurate foam	19000
Polyvinylchloride carpet	240000
Polyvinylchloride Pellets	500000
PVC Carpet (contains polyurethane components)	316000
Stone wool	0

Hydrogen cyanide	
Airplane seat cover (fabric)	5000
Airplane Wall/floor cover	20000
Boucle (acrylic, wool, polyester)	37500
Boucle (acrylic, wool, polyester) (FR)	26000
Car - Carpet	4900
Car - Dashboard	3800
Car - Door Panel	2900
Car - Lacquered Plate From Car Body	2700
Car - Upholster Material From Back Seat	5300
Car - Upholster Material From Drivers Seat	2400
Car Part (Polyamide 6,6)	5000
Car Part (Polyamide 6)	5000
Carpet (Wool, Polyester, Polyurethane)	2600
Carpet (Wool, Polyester)	3000
CMHR polyurethane foam (FR)	17000
Flexible Lab formulated foam (2,4and 2,6TDI)	28000
Glass wool	0
Li-ion battery (LiFSI)	400
MDF	7500
MDF (FR)	12500
MDI/polyester foam	73200
MDI/polyester foam, fire retarded	50900
MDI/polyether polyol foam	38100
MDI/polyether polyol foam, fire retarded	50800
Nylon 6.6/6	66300
Phenolic foam	5000
Plywood	0
Polyacrylonitrile	85500
Polyamide 6	110000
Polyamide 6 (AlPiM Retardant)	2800
Polyamide 6 (BrSb Retardant)	22800
Polyamide 6 (No Retardant)	400
Polyamide 6.6	70000
Polyamide 6.6 (AlPiM Retardant)	2476
Polyamide 6.6 (BrSb Retardant)	12590
Polyamide 6.6 (No Retardant)	381
Polyisocyanurate foam	20000
Polyurethane Insulation	17000
Polyurethane mattress	9000
PVC	584210
Rigid Lab formulated foam (2,4and 2,6TDI)	36000

Sofa (Polycotton pad, woolen layer, woven cotton and wool cover, No fire retardant treatment)	90
Sofa (Polyurethane foam, polyester layer, Chinese fire retardant fabric cover)	970
Sofa (Polyurethane foam, polyester layer, UK fire retardant fabric cover)	420
Sofa (Polyurethane foam, polyester layer, Untreated EU fabric cover)	310
Stone wool	0
Velour (acrylic, cotton, polyester)	35000
Hydrogen fluoride	
FP Cable	20000
Li-ion battery	39842.105
Li-ion battery (LiFSI)	17600
Li-ion battery (LiPF6)	59500
Hydrogen sulfide	
Carpet (Wool, Polyester, Polyurethane)	500
Carpet (Wool, Polyester)	3000
Indeno(1,2,3-c,d)pyrene	
PVC chloride carpet	100
Wood Board	39.4
Indeo(123cd)pyrene	
Chipboard	0.113
MDF	0.081
Isocyanate acid	
Particleboard	722.1153176
PIR (rigid foam)	6027.35609
Plywood	17.69908519
PUR (flexible foam)	394.6340033
PUR (rigid foam)	1483.36271
Isocyanic acid	
PVC chloride carpet	71.6
Wood Board	763.2
Isoforon diisocyanate	
PUR (flexible foam)	18.55662293
PUR (rigid foam)	0.546818944
Methane	
Li-ion battery (LiPF6)	100
Rigid Polyurethane (PAPI,TMP)	15310
Methanol	
Brominated Polyester	1650
Methyl bromide	
Brominated Polyester	780

Methyl isocyanate	
Wood Board	715.8
Methyl isocyanate	
Particleboard	30.30800687
PIR (rigid foam)	22.1110252
PUR (rigid foam)	8.683388214
Methyl propenal	
Rigid Polyurethane (PAPI,TMP)	1750
Methylbutene	
Rigid Polyurethane (PAPI,TMP)	3570
Methylendiphenyl aminoisocyanate	
PUR (flexible foam)	9.615384615
PUR (rigid foam)	34.61538462
Methylenedianiline	
PIR (rigid foam)	176.9230769
PUR (rigid foam)	455
Methylenediphenyl isocyanate	
Particleboard	0.433805528
PIR (rigid foam)	39.65597828
PUR (flexible foam)	36.68445147
PUR (rigid foam)	14.97875396
Naphthalene	
Camphor Laurel	24.171
Chipboard	60.393
MDF	49.909
MDI/polyester foam	10400
MDI/polyester foam, fire retarded	15100
MDI/polyether polyol foam	14100
MDI/polyether polyol foam, fire retarded	6500
PVC chloride carpet	7429
Untreated Pine	18.36
Wood Board	0.2
Nitric oxide	
Car - Carpet	9500
Car - Dashboard	6400
Car - Door Panel	7400
Car - Upholster Material From Back Seat	7500
Car - Upholster Material From Drivers Seat	5700
Glass wool	0
Phenolic foam	0
Polyetherpolyurethane (PPUF)	3000
Polyisocyanurate foam	3000

Polyurethane Insulation	3000
Polyurethane mattress	4000
Stone wool	0
Nitric oxide	
Li-ion battery	93158
Li-ion battery (LiFSI)	3000
Nitrogen Dioxide	
Carpet (Wool, Polyester, Polyurethane)	130
Carpet (Wool, Polyester)	140
Glass wool	0
Phenolic foam	0
Polyamide 6 (AlPiM Retardant)	3300
Polyamide 6 (BrSb Retardant)	2292
Polyamide 6 (No Retardant)	1000
Polyamide 6.6 (AlPiM Retardant)	1620
Polyamide 6.6 (BrSb Retardant)	677
Polyamide 6.6 (No Retardant)	305
Polyisocyanurate foam	0
Stone wool	0
NOx	
Car Part (Polyamide 6,6)	15000
Car Part (Polyamide 6)	12000
Phenanthrene	
Camphor Laurel	0.482
Chipboard	1.379
MDF	1.519
PVC chloride carpet	1620
Untreated Pine	0.379
Wood Board	6.69
Phenyl isocyanate	
Wood Board	3.8
Phenyl isocyanate	
PIR (rigid foam)	876.8343351
PUR (flexible foam)	26.86429672
PUR (rigid foam)	1174.268583
Phosphoric acid	
Glass wool	0
Phenolic foam	2000
Polyisocyanurate foam	3000
Stone wool	0
Propene	
Rigid Polyurethane (PAPI,TMP)	16270

Propenitrile	
Rigid Polyurethane (PAPI,TMP)	2780
Propyne	
Rigid Polyurethane (PAPI,TMP)	1100
Pyrene	
Camphor Laurel	0.262
Chipboard	0.457
MDF	0.439
PVC chloride carpet	597
Untreated Pine	0.197
Wood Board	76.12
Pyridine	
Flexible Lab formulated foam (2,4and 2,6TDI)	200
MDI/polyester foam	1500
MDI/polyester foam, fire retarded	1100
MDI/polyether polyol foam	700
MDI/polyether polyol foam, fire retarded	400
Rigid Lab formulated foam (2,4and 2,6TDI)	200
Silicon tetrafluoride	
Li-ion battery (LiPF6)	10600
Styrene	
Brominated Polyester	640
Rigid Polyurethane (PAPI, TMP)	1220
Sulfur dioxide	
Airplane seat cover (fabric)	30000
Airplane Wall/floor cover	10000
Car - Tyre	21000
Car - Upholster Material From Back Seat	10000
Car - Upholster Material From Drivers Seat	9900
Carpet (Wool, Polyester, Polyurethane)	15800
Carpet (Wool, Polyester)	17000
Li-ion battery	1752631.579
Li-ion battery (LiFSI)	70700
Toluene	
MDI/polyester foam	29800
MDI/polyester foam, fire retarded	10100
MDI/polyether polyol foam	4700
MDI/polyether polyol foam, fire retarded	2900
Rigid Polyurethane (PAPI,TMP)	3730
Toluene aminoisocyanate	
PUR (flexible foam)	110.8974359
Toluene diisocyanate	

PUR (flexible foam)	220.0364931
Wood (Pine)	15.58199106
Toluenediamine	
PUR (flexible foam)	5.128205128
Xylene	
Rigid Polyurethane (PAPI, TMP)	1980

Appendix E: Large scale experiments: Compounds identified, material burning and maximum yield

Compound Material burning	**Yield, mg/kg**
Acenaftene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.6
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.9
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1.1
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	1.1
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.5
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.2
Acenaftylene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	105
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	96
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	125
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	20
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	10
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	6
Acetaldehyde	
Car	580
Acetic acid	
Tetramethylthiuram monosulphide	540
Acetonitrile	
Tetramethylthiuram monosulphide	5510
Acrolein	
Automobile	300
Car	300

Acrylonitrile	
Tetramethylthiuram monosulphide	130
Ammonia	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1100
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	800
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	500
Nylon 6.6	10000
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	700
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	400
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	600
Antimony	
Car	15
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1.1
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.7
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.7
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	12.4
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.4
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.3
Antracene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	11
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	12
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	11
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	2

Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	1
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.6
Arsenic	
Car	0.26
Benzene	
Automobile	3000
Car	3000
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1337
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1305
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1296
Television (EU)	5908
Television (US)	13384
Tetramethylthiuram monosulphide	120
Benzo(a)-antracene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	7.5
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	8
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	9.2
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	1.3
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.6
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.4
Benzo(a)-fluorene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1.9
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	2.7
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	2.7
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	0.5

Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.3
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.2
Benzo(a)-pyrene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	9.7
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	8.5
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	7.1
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	0.7
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.4
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.3
Benzo(b)- fluorene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1.9
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	2.4
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	2.4
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	0.4
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.3
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.2
Benzo(b)-fluorantene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	13
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	13
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	16
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	1.9

Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.7
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.6
Benzo(e)-pyrene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	7.5
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	6.4
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	8.7
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	0.8
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.3
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.3
Benzo(g,h,i)-perylene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	11
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	8
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	11
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	0.8
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.4
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.3
Benzo(k)-fluorantene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	4
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	3.9
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	5.1
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	0.5

Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.2
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.2
Benzonitrile	
Automobile	230
Car	230
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	101
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	96
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	55
Tetramethylthiuram monosulphide	90
Bromine	
Car	260
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	5.3
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1.5
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1.7
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	62
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	12
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	18
Cadmium	
Car	1.7
Carbon disulfide	
Tetramethylthiuram monosulphide	250
Chlorine	
Car	2500
Chromium	
Car	3.8
Chrysene/Trifenylene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	11

Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	10
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	12
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	1.7
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.6
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.5
Cobalt	
Car	0.32
Copper	
Car	27
Coronene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	3.8
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	2.6
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	3.4
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	0.4
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.1
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.1
DiBenzo(a,h)-antracene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.9
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.7
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.9
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	0.1
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.1
Ethyl isocyanate	
Automobile	0.25

Car	250
Ethynylbenzene	
Automobile	180
Car	180
Fluorantene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	37
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	38
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	49
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	5.8
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	2.5
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	1
Fluorene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	15
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	15
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	18
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	2.4
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	1.7
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	1
Fluorine	
Car	33
Formaldehyde	
Automobile	1100
Car	1100
Hexamethyl diisocyanate	
Automobile	0.62
Car	620
Hydrogen chloride	
Automobile	13000
Cable (NO7V-K)	246000

Cable (NYM)	25300
Cable (RV-K)	100000
Car	13000
Chlorobenzene	190000
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	600
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	800
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	600
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	8300
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	7600
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	5700
Television set (EU)	6000
Television set (US)	15000
Hydrogen cyanide	
Automobile	1600
Car	1600
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1400
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1000
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	900
MDF	70000
Nylon 6.6	35000
PA 6.6	20000
Polyamide 6.6	33750
Polyisicyanurate foam	25000
Sofa (Polyurethane foam, polyester layer, Chinese fire retardant fabric cover)	9000
Sofa (Polyurethane foam, polyester layer, UK fire retardant fabric cover)	10000
Sofa (Polyurethane foam, polyester layer, Untreated EU fabric cover)	4000
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	900
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	500

Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	400
Indene	
Automobile	140
Car	140
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	32
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	56
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	46
Indeno(1,2,3-cd)-pyrene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	11
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	9
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	13
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	1
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.4
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.3
Isocyanate acid	
Automobile	210
Car	210000
Isocyano methane	
Tetramethylthiuram monosulphide	3100
Isothiocyano methane	
Tetramethylthiuram monosulphide	840
Lead	
Car	820
Manganese	
Car	5.7
Methyl isocyanate	
Automobile	6
Car	6000
Naphthalene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	377

Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	341
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	284
Nickel	
Car	2.8
Nitrogen monoxide	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	500
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	700
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	900
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	3100
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	4500
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	4000
NOx	
Nylon 6.6	5000
Tetramethylthiuram monosulphide	13000
PBDD	
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.00002
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.00087
PBDE	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.16542
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.0108
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.00132
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	57.1605
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	6.7734
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.0076
PBDF	

Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.0029
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.0002
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	5.053
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.101
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.00013
PCDD	
Car	2100
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.000015
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.000018
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.000016
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	0.00102
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.000016
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.000003
PCDF	
Car	56000
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.0033
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.001
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	0.0002
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	0.0133
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.0003
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	0.0003
Perylene	

Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1.6
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1.4
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	1.4
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	0.1
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	0.1
Phenantrene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	92
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	90
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	103
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	17
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	7.1
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	4.8
Phenol	
Automobile	360
Car	360
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	72
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	81
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	55
Phenyl acetylene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	58
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	54
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	41
Phenyl isocyanate	

Automobile	9.8
Car	9800
Phosphorus	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	6.5
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	25
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	15
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	13
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	11
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	2.6
Propene	
Tetramethylthiuram monosulphide	490
Pyrene	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	38
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	37
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	46
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine Foam with Brominated Fire Retardant Coating)	4.6
Sofa (Wood Frame, Cotton Covering, Decorative Cover,TCPP-melamine treted foam with Phosphorus-based Fire Retardant Treatment)	2.4
Sofa (Wood Frame, Cotton Covering, No Fire Retardant)	1.7
Pyridine	
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	35
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	56
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	19
Styrene	
Automobile	500
Car	500

Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	130
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	139
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	75
Sulfur dioxide	
Automobile	5000
Car	5000
Tetramethylthiuram monosulphide	1050000
TCDD I-TEQ	
Car	800
Thallium	
Car	5.1
Thiophene	
Tetramethylthiuram monosulphide	110
Toluene	
Automobile	660
Car	660
Furniture (Fire Retarded Armchair & Bromine Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	154
Furniture (Fire Retarded Armchair & Phosphorus Fire Retardant Sofa, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	130
Furniture (Non-Fire Retarded Sofa & Armchair, plus Bookshelfs, Table, Carpet, Curtains, TV, Books)	118
Toluene aminoisocyanate	
Automobile	4.1
Car	4100
Toluene diisocyanate	
Automobile	7.2
Car	7200
Vanadium	
Car	0.45
Zinc	
Car	3200

Appendix F: Municipal waste incineration: Compounds identified, material burning and maximum yield

503.

Compound Material burning	**Yield, mg/kg**
Aluminium	
Municipal waste	1
Ammonia	
Municipal waste	1000
Antimony	
Municipal waste	0
Arsenic	
Municipal waste	0
Barium	
Municipal waste	4
Benzene	
Hazardous waste	
Household refuse	
Benzenes	
Hazardous waste	
Municipal waste	
Benzonitriles	
Hazardous waste	
Beryllium	
Municipal waste	0
Biphenyl	
Hazardous waste	
Bismuth	
Municipal waste	0
Boron	
Municipal waste	6
Cadmium	
Hazardous waste	
Municipal waste	0
Calcium	
Municipal waste	2
CDE-141	
Municipal waste	
CDE-180	
Municipal waste	
CDE-209	

Municipal waste	
CDE-28	
Municipal waste	
CDE-77	
Municipal waste	
CDE-99	
Municipal waste	
Chlorobenzene	
Municipal solid, organic, laboratory, industrial, liquid, and medical waste	
Chromium	
Municipal waste	0
Cobalt	
Municipal waste	0
Copper	
Municipal waste	2
Hydrogen chloride	
Controlled synthetic fuel - municipal waste	
Hazardous waste	
Municipal solid, organic, laboratory, industrial, liquid, and medical waste	
Municipal waste	9000
Hydrogen fluoride	
Municipal waste	9000
Iron	
Municipal waste	2
Lead	
Hazardous waste	
Municipal waste	2
m-Xylene	
Household refuse	
Magnesium	
Municipal waste	10
Manganese	
Municipal waste	0
Mercury	
Municipal waste	9
Molybdenum	
Municipal waste	0
Naphthalene	
Hazardous waste	
Household refuse	

Nickel	
Municipal waste	0
NOx	
Medical waste	
Municipal solid, organic, laboratory, industrial, liquid, and medical waste	
Municipal waste	1000
PCDD	
Controlled synthetic fuel - municipal waste	
Hazardous waste	
Medical waste	
Municipal waste	
PCDD/PCDF	
Municipal solid, organic, laboratory, industrial, liquid, and medical waste	
Municipal waste	10000
Municipal waste	
PCDE	
Municipal waste	
PCDF	
Controlled synthetic fuel - municipal waste	
Hazardous waste	
Medical waste	
Municipal waste	
Phenol	
Household refuse	
Polyoxymethylene	
Hazardous waste	
Selenium	
Municipal waste	0
Silicon	
Municipal waste	2
Sulfur dioxide	
Medical waste	
Municipal waste	9000
TCDD	
Hazardous waste	
Medical waste	
TCDF	
Medical waste	
Tin	
Municipal waste	0

Toluene	
Hazardous waste	
Household refuse	
Trimethylbenzene	
Household refuse	
Ultrafine particles	
Municipal waste	
Vanadium	
Municipal waste	0
Zinc	
Municipal waste	3

Appendix G: Municipal waste burning: Compounds identified, material burning and maximum yield

Compound Material burning	**Yield, mg/kg**
Acenaphtalene	
Domestic Waste	87
Acenaphtene	
Domestic Waste	14
Acenaphthene	
Household waste	1
Acenaphthylene	
Household waste	26
Tire Chunk	634
Tire Shred	531
Acenaphthylene	
Military waste with PET plastics	89
Acetic acid	
Landfill waste	7400
Acetone	
Military waste with PET plastics	1600
Acetonitrile	
Military waste with PET plastics	100
Acetoxymethylfuraldehyde	
Domestic Waste	1
Acetylaminofluorene	
Household waste	9
Acetylene	
Landfill waste	720
Acrolein	
Military waste with PET plastics	1200
Acrylonitrile	
Military waste with PET plastics	44
Ammonia	
Landfill waste	2520
Anthracene	
Domestic Waste	14
Fiberglass Materials (Boating Industry)	353
Fiberglass Materials (Building Industry)	202
Household waste	3
Military waste with PET plastics	21
Anthracenedione	

Domestic Waste	0
Arsenic	
Fiberglass Materials (Boating Industry)	1
Fiberglass Materials (Building Industry)	48
Benz[de]anthracenone	
Domestic Waste	1
Benzaldehyde	
Domestic Waste	6
Tire Chunk	299
Tire Shred	334
Benzene	
Fiberglass Materials (Boating Industry)	5900
Fiberglass Materials (Building Industry)	34800
Military waste with PET plastics	2000
Tire Chunk	2156
Tire Shred	2205
Benzenedicarboxylic acid	
Domestic Waste	1
Benzenediol	
Domestic Waste	13
Benzisothiazole	
Tire Shred	174
benzo fluoranthene	
Domestic Waste	3
Benzo(a)anthracene	
Domestic Waste	4
Household waste	3
Military waste with PET plastics	11
Benzo(a)pyrene	
Domestic Waste	1
Fiberglass Materials (Boating Industry)	86
Fiberglass Materials (Building Industry)	72
Household waste	3
Benzo(b)fluoranthene	
Household waste	4
Benzo(b)thiophene	
Tire Chunk	44
Benzo(g,h,i)perylene	
Domestic Waste	1
Household waste	3
Benzo(k)fluoranthene	
Household waste	2

Benzo[e]pyrene	
Domestic Waste	1
Benzo[k]fluoranthene	
Domestic Waste	2
Benzodiazine	
Tire Chunk	14
Tire Shred	17
Benzofuran	
Domestic Waste	3
Tire Chunk	25
Benzoic acid	
Domestic Waste	5
Benzothlophene	
Tire Chunk	26
Tire Shred	15
Biphenyl	
Fiberglass Materials (Boating Industry)	689
Fiberglass Materials (Building Industry)	1936
Tire Chunk	210
Tire Shred	330
Biphenyl carboxaldehyde	
Domestic Waste	1
Biphenylene	
Domestic Waste	6
Bisphenol A	
Domestic Waste	10
Butadiene	
Tire Chunk	308
Tire Shred	161
Butadiene	
Military waste with PET plastics	540
Butanone	
Military waste with PET plastics	540
Cadmium	
Fiberglass Materials (Boating Industry)	0
Fiberglass Materials (Building Industry)	1
Carbon disulfide	
Military waste with PET plastics	160
Carbon tetrachloride	
Military waste with PET plastics	2
Chlorobenzenes	
Household waste	2

Chloromethane	
Military waste with PET plastics	220
Chloronaphthalene	
Household waste	4
Chlorophenols	
Household waste	2
Chromium	
Fiberglass Materials (Boating Industry)	2
Fiberglass Materials (Building Industry)	14
Chrysene	
Domestic Waste	3
Fiberglass Materials (Boating Industry)	323
Fiberglass Materials (Building Industry)	458
Household waste	4
Military waste with PET plastics	18
Copper	
Household waste	15
Military waste with PET plastics	2
Cumene	
Military waste with PET plastics	18
Military waste without PET plastics	33
Cyanobenzene	
Tire Chunk	224
Tire Shred	517
Cyclopentadiene	
Tire Chunk	49
Dibenz(a,h)anthracene	
Domestic Waste	0
Household waste	0
Dibenzofuran	
Domestic Waste	3
dihydro indenone	
Domestic Waste	2
Dihydroindene	
Tire Chunk	41
Tire Shred	43
Dimethoxy phenol	
Domestic Waste	1
Dimethoxytoluene	
Domestic Waste	0
Dimethyl benzene	
Tire Chunk	780

Tire Shred	1078
Dimethyl hexadiene	
Tire Chunk	28
Tire Shred	91
Dimethyl naphthalene	
Tire Chunk	41
Tire Shred	178
dimethyl, methlpropyl benzene	
Tire Shred	15
Dimethylbenz(a)anthracene	
Household waste	2
Dimethyldibenzothiophene	
Domestic Waste	1
Dimethyldihydro indene	
Tire Chunk	22
Tire Shred	18
Dioctyl phthalate	
Domestic Waste	336
Diphenyl methanone	
Domestic Waste	2
Diphenylpropene	
Domestic Waste	2
Ethanone, 1-phenyl-	
Domestic Waste	4
Ethene	
Landfill waste	4750
Ethenyl benzene	
Tire Chunk	942
Tire Shred	611
Ethenyl cyclohexene	
Tire Chunk	26
Tire Shred	108
Ethenyl dimethyl benzene	
Tire Chunk	7
Tire Shred	24
Ethenyl methyl benzene	
Tire Chunk	222
Tire Shred	41
Ethenyldimethyl cyclohexane	
Tire Shred	350
Ethyl Benzene	
Fiberglass Materials (Boating Industry)	700

Fiberglass Materials (Building Industry)	9300
Military waste with PET plastics	340
Military waste without PET plastics	510
Tire Chunk	461
Tire Shred	338
Ethyl dimethyl benzene	
Tire Shred	272
Ethyl methyl benzene	
Tire Chunk	335
Tire Shred	476
Ethynyl benzene	
Tire Chunk	276
Tire Shred	187
Ethynyl methyl benzene	
Tire Chunk	531
Tire Shred	259
Fluoranthene	
Domestic Waste	16
Household waste	7
Military waste with PET plastics	30
Fluorene	
Domestic Waste	23
Household waste	7
Military waste with PET plastics	40
Fluorenone	
Domestic Waste	4
Fluorine	
Tire Chunk	210
Tire Shred	308
Formaldehyde	
Landfill waste	7400
Formic acid	
Landfill waste	3340
H-benzo[b]fluorine	
Domestic Waste	1
Heptadiene	
Tire Chunk	25
Tire Shred	51
hexahydro azepinone	
Tire Chunk	75
Tire Shred	749
Hexaklorbensen	

Domestic Waste	0
Hydrogen chloride	
Household waste	3280
Hydroxy benzaldehyde	
Domestic Waste	1
Hydroxymethoxy benzaldehyde	
Domestic Waste	7
Hydroxymethoxy benzoic acid	
Domestic Waste	1
Idene	
Tire Chunk	503
Tire Shred	339
Indeno(1,2,3-c,d)pyrene	
Household waste	3
Indeno(1,2,3-cd)pyren	
Domestic Waste	2
Iron	
Military waste with PET plastics	4
Isobenzofurandione	
Domestic Waste	4
Isocyano benzene	
Tire Chunk	347
Tire Shred	290
Isocyano naphthalene	
Tire Chunk	9
Lead	
Fiberglass Materials (Boating Industry)	39
Fiberglass Materials (Building Industry)	8
Military waste with PET plastics	24
Limonene	
Tire Chunk	56
Tire Shred	2346
m-p-Xylene	
Fiberglass Materials (Boating Industry)	500
Fiberglass Materials (Building Industry)	1100
m,p-Xylenes	
Military waste with PET plastics	150
Mercury	
Military waste with PET plastics	17
Methane	
Landfill waste	10300
Methanol	

Landfill waste	2810
Methoxy phenol	
Domestic Waste	16
Methyl benzaldehyde	
Tire Shred	87
Methyl benzene	
Tire Chunk	1606
Tire Shred	1390
Methyl biphenyl	
Tire Chunk	11
Methyl catechol	
Domestic Waste	3
Methyl cyclohexene	
Tire Chunk	21
Tire Shred	40
Methyl furfural	
Domestic Waste	8
Methyl hexadiene	
Tire Chunk	71
Tire Shred	127
Methyl indene	
Tire Chunk	316
Tire Shred	401
Methyl naphthalene	
Tire Chunk	351
Tire Shred	429
Methyl Phenol	
Fiberglass Materials (Boating Industry)	125
Fiberglass Materials (Building Industry)	400
Methyl thiophene	
Tire Chunk	6
Tire Shred	13
Methyl, ethenyl benzene	
Tire Chunk	56
Tire Shred	77
Methyl, methylethenyl benzene	
Tire Chunk	98
Tire Shred	684
Methyl, methylethyl benzene	
Tire Chunk	128
Tire Shred	1426
Methyl, methylethyl c.h.	

Tire Shred	170
Methyl, propyl benzene	
Tire Shred	42
Methylcholanthrene	
Household waste	4
Methylene chloride	
Military waste with PET plastics	8
Military waste without PET plastics	5
Methylene indene	
Tire Chunk	49
Tire Shred	34
Methylethyl benzene	
Tire Chunk	135
Tire Shred	229
Methylnaphthalene	
Household waste	16
Naphthalene	
Domestic Waste	390
Household waste	54
Military waste with PET plastics	410
Tire Chunk	1698
Tire Shred	1131
Naphthalenol	
Domestic Waste	0
Nickel	
Military waste with PET plastics	2
o-xylene	
Military waste with PET plastics	49
Military waste without PET plastics	80
PBDD	
Municipal waste	0
PBDE	
Municipal waste	2
PBDF	
Municipal waste	0
PCDD	
Domestic Waste	0
Domestic Waste	0
Garden and Domestic Waste	0
Garden and Industrial Waste	0
Garden and Refuse Waste	0
Garden waste	0

Garden Waste and Motor Oil	0
Household waste	0
Household waste (Compacted/Moistened)	0
Household waste (Compacted/Moistened/Stirred)	0
Household waste (Loosened)	0
Insulated wires	0
Municipal waste	0
Municipal waste & Electronic Waste	0
Printed circuit boards	0
Refuse Waste & Domestic Waste	0
Refuse Waste & Domestic Waste (Air-Dried)	0
Refuse Waste & Domestic Waste & Electronic Waste	0
Refuse Waste & Domestic Waste & Misc.	0
Straw	0
Straw (Moistured Fuel)	0
Straw & Industrial Waste	0
PCDD/PCDF	
Household waste	0
Household Waste (1% Polyvinylchloride)	0
Household Waste (7.5 % Polyvinylchloride)	0
Household Waste (Compressed)	0
Household Waste (High Copper Content)	0
Household Waste (Including CaCl2 Soaked Newspaper)	0
Household Waste (No Polyvinylchloride)	0
Household Waste (Open Fire)	0
Household Waste (Wetted)	0
PCDF	
Domestic Waste	0
Domestic Waste	0
Garden and Domestic Waste	0
Garden and Industrial Waste	0
Garden and Refuse Waste	0
Garden waste	0
Garden Waste and Motor Oil	0
Household waste	0
Household waste (Compacted/Moistened)	1
Household waste (Compacted/Moistened/Stirred)	0
Household waste (Loosened)	0
Insulated wires	1
Municipal waste	0
Municipal waste & Electronic Waste	0

Printed circuit boards	0
Refuse Waste & Domestic Waste	0
Refuse Waste & Domestic Waste (Air-Dried)	0
Refuse Waste & Domestic Waste & Electronic Waste	2
Refuse Waste & Domestic Waste & Misc.	0
Straw	0
Straw (Moistured Fuel)	0
Straw & Industrial Waste	0
Pentadiene	
Tire Chunk	164
Tire Shred	1163
Phenalenone	
Domestic Waste	1
Phenanthrene	
Domestic Waste	62
Fiberglass Materials (Boating Industry)	902
Fiberglass Materials (Building Industry)	2156
Household waste	27
Military waste with PET plastics	120
Tire Chunk	184
Tire Shred	187
Phenol	
Fiberglass Materials (Boating Industry)	328
Fiberglass Materials (Building Industry)	6830
Tire Chunk	366
Tire Shred	700
Propene	
Landfill waste	3340
Military waste with PET plastics	1700
Propenyl naphthalene	
Tire Chunk	24
Propenyl, methyl benzene	
Tire Shred	524
Propyl benzene	
Tire Chunk	72
Tire Shred	220
Propylbenzene	
Military waste with PET plastics	21
Military waste without PET plastics	34
Pyrene	
Domestic Waste	14
Household waste	11

Military waste with PET plastics	25
Silver	
Fiberglass Materials (Boating Industry)	5
Fiberglass Materials (Building Industry)	14
Styrene	
Fiberglass Materials (Boating Industry)	4500
Fiberglass Materials (Building Industry)	49400
Military waste with PET plastics	3500
Military waste without PET plastics	4200
Tire Chunk	660
Tire Shred	646
Terphenyl	
Domestic Waste	4
Tetramethyl benzene	
Tire Shred	256
Thiophene	
Tire Chunk	55
Tire Shred	28
Toluene	
Fiberglass Materials (Boating Industry)	3600
Fiberglass Materials (Building Industry)	18000
Military waste with PET plastics	860
Tribromo phenol	
Domestic Waste	5
Trichloro/flouromethane	
Tire Chunk	58
Trimethyl benzene	
Tire Chunk	209
Tire Shred	751
Trimethyl naphthalene	
Tire Shred	316
Triphenylene	
Domestic Waste	2
Vinyl acetate	
Military waste with PET plastics	1500