



Fire Emissions of Organics into the Atmosphere

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Abstract. The mass of dioxins, PAH (polycyclic aromatic hydrocarbons) and VOC (volatile organic compounds) emitted from fires to the atmosphere in Sweden per year has been estimated. The estimate is based on the number of fires in buildings, vehicles, waste and forest fires in Sweden in 1999. It is estimated that the total emission of dioxins from fires is in the range 0.5–1.4 g TEQ. The total emissions of PAH and VOC are in the ranges 2–12 ton and 13–200 ton, respectively.

The estimated emission of dioxins from fires approximately corresponds to the total emission from traffic or half the emissions from municipal waste combustion (Swedish data from 1993).

The fire statistics show that the mass of material combusted in building fires during a year is approximately 7500 ton, while that from forest fires is 2600 ton. Additionally, 2000–3000 tons are combusted in vehicle fires, fires in containers, etc.

In addition to the more common types of fires during a year, individual large incidents may contribute significantly to the total emission. Such incidents include fires in municipal landfills or specific waste storage facilities (such as those for used tyres). An assessment of the consequences of such incidents has been made. This assessment implies that a large contribution to the emission of dioxins could be expected from fires in landfills and from fires in waste plastics (PVC) and tyres. Fires in deposits of wood chips and tyres are also significant potential sources of PAH and VOC.

Keywords: accident statistics, dioxins, emissions, fires, PAH, VOC

1 Introduction

The environmental effect of fires has been the topic of much discussion in recent years. The authors of this paper first published an estimate of the emissions from fires into the atmosphere a typical year in Sweden in 1998 [1]. This work focussed on the emission of some key species including carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x) and sulfur dioxide (SO₂). It was concluded that while large amounts of these species are emitted from fires each year, fires represent a minor part of these emissions with the majority coming from controlled combustion sources including, energy production, industry and transport [2]. Further, it was concluded that while fires are a minor source of these products they potentially represent a major source of some environmentally important species, such as PAH, dioxins and furans, due to the incomplete nature of

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combustion in a fire relative to that under controlled combustion conditions. At the time of the previous study, however, very little information was available in the literature to corroborate this hypothesis.

In the past 5 years, a great deal of new research has provided detailed information concerning the emission of polycyclic aromatic hydrocarbons (PAH), volatile organic compounds (VOC), polychlorinated dibenzodioxins and dibenzofurans (collectively often referred to as dioxins) from fires, with quantitative information now available concerning emissions from typical dwellings [3], burning wood [4, 5], fires in vehicles [6] and fires in waste deposition [7, 8]. These data together with other data, have been combined with new fire statistics from Sweden to provide an estimate of the emission of these species from fires relative to that from other sources. This article collates these data, using the same methods presented in the previous publication, for the most common types of building material located in houses, schools and other occupancies. The levels of emissions calculated are, naturally, uncertain as were those presented in the previous work, but they do indicate the order of magnitude of emissions and provide the basis for a meaningful discussion of the importance of fire emissions relative to other sources.

While it is true that fires give rise to emissions both to water and soil, available data mostly pertains to emissions to the air. The focus of this paper is also on emissions to the air although the authors are involved in measurements of emissions to the soil and water and hope to compile similar emission data to these media in the future.

2 Fire Statistics

The Swedish Fire Protection Association has collected statistics concerning damage from fires since 1980. The statistics encompass the total number of accidents reported to insurance agencies and cover the spectrum from very small accidents to large industrial accidents. In this study large accidents have been defined as those in which the damages exceed 1.5 million Swedish kronor (MSEK). The statistics also provide some information concerning the most frequent causes and victims of fires. These statistics are not, however, detailed enough to allow an accurate estimate of the mass of material that has been burned in each instance. Other sources of information regarding the number and types of fires in Sweden are the collated data from the Insurance Federation and the annual report from the Swedish Rescue Service Agency (SRV) [9] which is based on data from the local rescue services.

Table 1 shows the statistics concerning the number of fires between 1996 and 1999. In 1996 the system for reporting fire incidents to the SRV was changed to better reflect the number of actual fires, e.g., to avoid inclusions of false alarms in the fire statistics. This has caused some difficulty in making direct comparisons between the data used in the previous study (as this was based on a specific search in the SRV database) and those used in this study. In the previous study, 1994 was chosen as the model year. However, in this study, 1999 has been chosen as the model year. The total amount of material consumed in fires used in the present study for 1999 was somewhat lower compared to the estimate for 1994.

Table 1
Number of Fires in Sweden between 1996 and 1999
from Swedish Rescue Services Agency [9]

Year	# Fires in buildings	# Fires not in a building
1996	13,266	17,771
1997	12,290	18,773
1998	11,166	10,974
1999	11,186	14,388

This follows the general trend seen [9], with a decrease in the number of fires in buildings between 1994 and 1999. The choice of 1999 as a new model year is based on the desire to include this decreasing trend in the total number of fires in our evaluation of fire emissions. Unfortunately, the fire statistics are not typically available from the fire authorities until 2 years after the end of the calendar year. Thus, in 2002 when this evaluation was first undertaken, the 1999 statistics were those most recently available. Older data were deemed unsuitable due to the importance of choosing a model year that was recent enough to allow meaningful interviews of fire investigators of large fires. Finally, in the previous study we established that the total emissions of CO, CO₂, NO_x, and SO₂ from fires were significantly lower than other sources (see Table 8 in Persson et al. [1]) and thus new estimates of these emissions were not made for the 1999 data.

Table 1 shows that the number of fires has steadily decreased between 1996 and 1999, although the decrease is small compared to the uncertainty in the estimate of the total amount of material in each fire. The number of large fires in particular varies greatly each year. These statistics need to be broken down further in order to be used to determine the emission from different objects. This information is summarised in Table 2.

In Table 2 “dwelling” refers to houses, semi-detached housing, apartments and vacation houses; “general building” refers to shops, hospitals, service homes,

Table 2
Size of the Fire in Buildings Relative to the Object Burning. Based on
statistics for the year 1999 by the Swedish Rescue Services Agency
[9]

Size	General Building	Dwelling	Industry	Other Building	Other Object	Unknown
Fire extinguished/died out	557	1053	302	63	68	20
Smoke development only	534	1578	327	84	77	17
Fire in object of origin	482	2309	517	307	353	75
Fire in one room	184	854	125	94	125	15
Fire in several rooms	74	511	57	87	61	4
Fire in several fire cells	24	94	22	43	15	4
Unknown size of fire	17	31	5	2	6	9
Total per year	1872	6430	1355	680	705	144
Total potentially large fires	299	1490	209	226	207	32

theatres, museums, movie theatres, churches, hotels, hostels, dormitories, restaurants, storage buildings, military buildings, schools, day care, sports arenas, government buildings and communication buildings; "industry" refers to industrial hotels, chemical industry, food industry, foundries, textile industry, building industry, storage buildings and related production or repairs; "other buildings" refers to power production, service stations, sewage works, farms (excluding dwellings), parking decks, construction sites and condemned buildings.

In most cases the fires are very small with consequently small emissions. When estimating the fire emissions it is, therefore, only those fires that are classified as "fire in one room" or larger that have been included in the calculation. Other fires have been estimated separately. This is particularly important in the case of fires in dwellings, as the category "fires in object of origin" is a large part of the total number of fires.

The statistics summarised in Table 2 provide only coarse guidance when estimating the total emissions from fires any given year, e.g., a "room fire" can refer to a small room in a dwelling or to an industrial location covering an area of several thousand m². Further, the categories do not provide details concerning how much of the item is consumed in the fire. Some information concerning the amount of material consumed can be gleaned from the Swedish Rescue Services Agency Database on Accidents and from statistics from the Insurance Federation. In the statistics from the Insurance Federation there is information concerning when building fires have caused total damage. This is, however, also somewhat uncertain as it can contain cases where large parts of the combustible material have not been consumed but are sufficiently damaged (structurally or due to smoke and water) to require replacement.

Thus, in order to improve the uncertainty, the Insurance Federation statistics have been used to determine the relationship between the cost of a fire and the amount of material involved in the fire. Large fires in 1999 are those where the cost exceeds 1.5 MSEK. In the previous publication we set this limit at 1 MSEK. In certain instances there are fires that have cost insurance companies in excess of 100 MSEK, but the majority of this cost has been connected to costs incurred as a result of the fire rather than due to the fire itself (e.g., loss of market share, down time for a factory, etc).

The statistics from the Insurance Federation show that the total insurance payment for large fires was essentially unchanged between 1994 and 1999, i.e., 1200 MSEK in 1994 and 1156 MSEK in 1999. Note that the costs have not been corrected for inflation during that time. The distribution between dwelling fires and other fires was also essentially unchanged at 22% in 1994 and 19% in 1999.

The majority of emissions from those fires not occurring in buildings emanated from forest and wildland fires, together with fires in vehicles. Some 8918 fires of the total of 14,388 fires not occurring in buildings in 1999 were from these sources. In the case of forest and wildland fires the total area involved in the fire is available but not the percentage of the forest involved that has burned. The estimated emissions from forest fires have been related to the total cost of the fires, 3.7 MSEK in 1999, and related to the type of forest and area burned. Note that the cost of forest fires is small relative to the cost of fires in buildings.

In the case of vehicle fires, the majority are related to cars. The statistics from the Swedish Rescue Services Agency indicate that 3558 fires occurred in cars and 631 in other vehicles in 1999. Similar statistics from the Insurance Federation indicate that there were 9038 fires in vehicles in 1999, 6522 of which occurred in cars. It is reasonable to assume that these statistics indicate that the fires included in the Rescue Services Agency statistics relate to fires consuming the entire vehicle while those from the Insurance Federation relate to both these total fires and other smaller fires.

3 Estimate of the Total Amounts of Materials Involved in Fires

In the previous estimate on fire emissions to the atmosphere [1], there was a detailed study made of the amount of combustible material in different objects. This study has been updated in this new inventory, but only small modifications were necessary.

For the materials found in houses, data have been taken from Adalberth [10]. The estimated mass of the major materials in a 120 m² Swedish standard house, are given in Table 3.

For the combustible materials in the interior of apartments, schools and hospitals there have been detailed studies conducted in order to determine the fire loads [11, 12]. The data in these studies are given as the amount of energy per square meter. The conversion of such data to amount of combustible material developed by Persson et al. [1] has been applied in this study. A novel inventory has been included regarding the most common materials found in houses, semi-detached houses, apartments, and schools. By combining this distribution of materials with the total amounts of combustible material, it was possible to estimate a distribution of the combustible materials found in buildings. The results of this estimate are given in Table 4. It is here assumed that a typical house/semi-detached house has a living area of 120 m², while that of an apartment is 80 m², and that of a typical school is 500 m². In the inventory of large accidents, however, the content of combustible materials has been based on the actual area in each case.

In order to estimate the amount of materials involved in fires for different objects the statistics from the Insurance Federation was used in combination with an inventory of large accidents reported. From the inventory it was possible to set

Table 3
Mass of Materials in a Typical Residence

Material	Mass (kg)
Wood	9000
PVC	50
Polystyrene	300
Polyethylene	110
Plaster	4100

Table 4
The Distribution of Combustible Material in the Interior of Houses (Including Semi-detached Houses), Apartments and Schools (kg/object)

Material	House	Apartment	School
Wood	2780	1860	4000
Paper	720	480	1600
Textile	720	480	800
PVC	240	160	1600
PUR	240	160	0
Polyethylene	100	60	0
ABS	20	20	40

up a relationship between the amount of combustible material for a specific type of building and the insurance costs. Using this method the amount of combustible material involved in large accidents was collated for each type of building.

To the amount of materials from large accidents the contribution from the remaining smaller fires have been added using the information from Table 2. For the group dwellings it was assumed that a fire in one room contributed 5% of the amount of material from the interior of a house, fire in several rooms contributed 35%, and fire in several fire cells contributed 80%. This distribution is a rather coarse estimate, but was based on experience gathered from incident leaders. Fires where the extent of the damage was not reported have been excluded.

For General buildings, Industrial buildings and Other buildings, it was difficult to estimate the distribution of specific materials. The masses of materials given in

Table 5
Total Mass of Material Involved in Building Fires in Sweden During the year 1999 (in tons), Rounded to the Nearest ton

Material	Dwellings	General buildings	Industry buildings	Other building	~Total mass (tons)
Wood	2550	750	1447	1718	6500
Particleboard	64	–	–	–	60
Paper	214	76	7	–	300
Textile	205	23	23	–	250
PVC	82	21	12	2	120
PUR	81	5	–	–	90
Polyethylene	57	5	–	1	60
Polystyrene	76	2	5	–	80
ABS	6	2	1	2	10
Tarred roofing felt	12	30	23	–	70
Linoleum	–	18	–	–	20
Rubber	–	–	7	–	10
Organic solvents	–	11	2	–	10
Petroleum products	–	–	–	2	2
Grain	–	–	–	14	10

Table 6
Total Mass of Material Respective Numbers of
Objects for Fires not in Buildings in Sweden
During the year 1999

Type of object	Mass/number
Forest fires	2600 tons
Garbage cans	13 tons
Containers	250 tons
Vehicles	4189 fires
Trains	42 fires

Table 5 were estimated from the total damage costs for all fires compared to the damage costs for large fires.

For the group "Fire not in a building" no attempt has been made to estimate the distribution of specific materials. Instead, the total amount of combustible materials for each object was estimated, and the emissions were calculated from measurements of emissions per object. The estimated amounts of material involved in fires per object are shown in Table 6. Note that in the case of vehicle or trains the number of fires has been estimated and an emission per fire calculated.

4 Emission Factors for VOC, PAH and Dioxins

Fires represent uncontrolled combustion. In contrast to a controlled combustion situation, e.g., a heating furnace, where the combustion is optimised, a fire typically produces large amounts of the products of incomplete combustion. The yield of products of incomplete combustion and the product distribution (i.e., relative amounts of each species produced) varies depending on the type of fuel, oxygen availability (or ventilation) and temperature of the fire. The oxygen availability and combustion temperature are, to a large degree, determined by the configuration of the fire (i.e., the presence or geometry of an enclosure) and the fuel.

A fire that has ample oxygen available (i.e., well-ventilated) will exhibit a high combustion efficiency and low yield of products of incomplete combustion relative to that of a fire with poor oxygen availability (i.e., vitiated). Well-ventilated fires give a combustion efficiency of 60–80% although the combustion efficiency will drop rapidly as the ventilation decreases and vitiation increases. The products of incomplete combustion included in this study were VOC, PAH and dioxins, the latter two of which are often found adsorbed onto particulate matter.

Traces of dioxins can be found throughout our ecosystem. In contrast to certain environmental toxins like polychlorinated biphenyls (PCBs) and certain polychlorinated pesticides like DDT, dioxins have never been produced and marketed in their own right. This group of chemicals is, however, produced as a bi-product from certain industrial processes and through incomplete combustion (both controlled combustion and fires).

The group of chlorinated dioxins consists of 75 congeners of polychlorinated dibenzo-*p*-dioxins (PCDD) and 135 congeners of polychlorinated dibenzofurans (PCDF). The basic structure for the congeners is the same with only the total num-

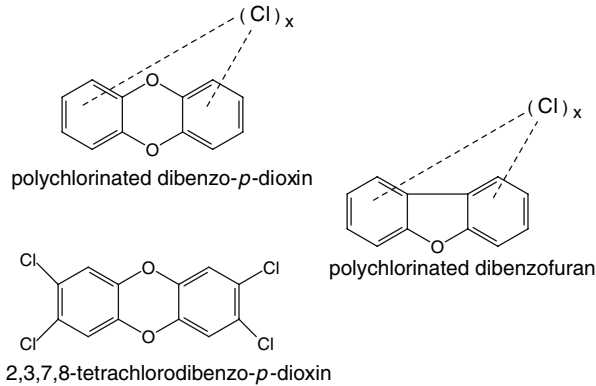


Figure 1. General structure of polychlorinated dibenzodioxins and furans and the specific structure of 2,3,7,8 tetrachlorodibenzo-*p*-dioxin (TCDD), the most toxic of this family of molecules.

ber and positioning of the chlorine atoms in the molecule differing. Figure 1 shows the chemical structure of these molecules. The various congeners are usually summed (referred to as TCDD-equivalents) using weights according to the relative toxicity of the individual chemicals. In this sum it is assumed that 2,3,7,8-tetrachlorodibenzodioxin (2,3,7,8-TCDD) is the most toxic of this group of chemicals and each other member of the group is assigned a toxic equivalency factor (TEF) that describes the toxicity of the species relative to that of 2,3,7,8-TCDD [13].

TCDD-equivalents have been calculated according to various models with some variations in the TEFs applied. Some common schemes that can be found in the literature are the TEFs according to the Eadon model [14], the Nordic model [15], the International model [16] and the more recent WHO model [17]. The TCDD-equivalents found in the literature cannot always be converted to a common basis regarding TEFs, as details regarding the individual congeners are not always reported. Thus, the data regarding dioxins in this work have been included with the units used in the literature source. The collated emission factors reported here are thus expressed as “general” TCDD-equivalents (TEQ) with no specific weighting model specified. Small differences are found when calculating the TCDD-equivalents using the various models but these are probably less than the uncertainty in the calculation of the total emissions from fires.

Polycyclic aromatic hydrocarbons (PAH) are a complex group of chemicals that are comprised of two or more joined aromatic rings. The PAH that has been investigated the most is benzo(a)pyrene (BaP) which can be metabolised to a carcinogen in the body, and is generally considered the most toxic of the PAHs. The toxicity of BaP is lower than that of the dioxin 2,3,7,8-TCDD [18] and, as in the case of PCDD/F, there are TEFs for PAH that allow the calculation of BaP-equivalents [19]. Due to lack of data concerning the make-up of total PAH reported in the literature, BaP equivalents have, however, not been presented.

Fire gases often contain complex mixtures of PAH with the lightest of the PAHs (naphthalene) dominating. The chemical structure of BaP and naphthalene

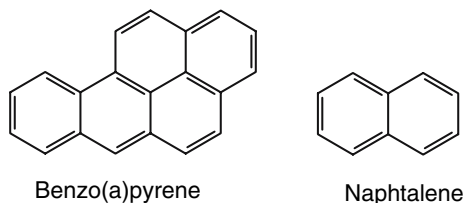


Figure 2. Structure of benzo(a)pyrene and naphthalene.

are shown in Figure 2. The tendency for fuels to form PAH varies depending on the structure of the basic organic fuel. While all organic fuels will form PAH in a fire, the greatest yields are obtained from aromatic fuels followed by cyclic aliphatics, olefins and paraffins in decreasing order of magnitude [20].

Volatile Organic Compounds (VOC) do not have a single, clear definition. WHO has included compounds according to boiling point where polar compounds appear at the higher end of the range [21]:

VVOC (very volatile organic compounds) < 0 to 50–100°C

VOC (volatile organic compounds) 50–100 to 240–260°C

SVOC (semi-volatile organic compounds) 240–260 to 380–400°C

Thus, this group includes a very large and varied number of compounds including benzene, toluene, styrene, xylene, chlorobenzene etc. Indeed, naphthalene is also sometimes included in this group causing some confusion in the reporting of PAH and VOC and difficulty in detailed comparisons between various sources in the literature. One common method for determining the concentration of VOC is to sample using the adsorbent Tenax™ with subsequent GC/MS analysis. In this case VOC is defined as non-polar and mildly polar species in the range of C₅–C₁₈. Another method for determining the total amount of volatile organics is a direct reading total hydrocarbon (THC) analyser. The results from such a measurement are not directly comparable with the summed results from, e.g., a detailed Tenax™ measurement as both lighter and heavier hydrocarbon species might be included in the THC results. There are, however, in many cases only THC results reported in the literature.

The types and amounts of combustible material related to fires in buildings (as defined in the statistics) were estimated in a previous study [2]. The various groups of materials identified as important contributors to the total fuel load were: PVC, wood, wood fibre board, textile, paper, polystyrene, polyurethane (PUR), polyethylene (PE), acrylonitrile butadiene styrene (ABS), petroleum products, tarred roofing felt, linoleum, rubber, organic solvent and grain.

To find a single true emission factor for an organic fire product for each of these groups of materials, that further represents all types of fires, is not feasible. As discussed above, the fire conditions influence the emissions strongly. Further, the exact composition of a certain type of material (e.g., wood, PVC, PUR, etc.) does vary and may influence the outcome of the combustion. In the estimates

presented here, however, general emission factors, or a likely range of values, have been used. These estimates were made by consulting the literature and searching for data from experiments representing conditions found in fires and where fire gases had been quantitatively analysed. In many cases, however, it was not possible to find such information and instead some rather crude assumptions were made. The emission factors use in this study can be found in Table 7 for the materials identified in the fire statistics and in Table 8 for specific objects.

4.1 Emission factors for materials

Relevant quantitative analysis results for dioxins (PCDD/F) were found in the literature for PVC, wood and a halogen-free cable. It was evident that most publications reported only more qualitative results e.g., concentrations found in soot samples taken at fire sites. Such sampling is by its very nature ad hoc and cannot give a full picture of the total emissions. Although analyses of PAH and VOC are considerably less expensive than analyses of dioxins, also for these groups of compounds rather few references were found containing detailed quantitative results. A number of useful references were, however, found for PVC, wood, polystyrene, polyurethane, polyethylene and petroleum products.

The emission factor for dioxins from PVC was largely based on data from two sources, a series of tubular-furnace tests [22] and a series of large-scale test with PVC cables [23]. As the yields of dioxins varied considerably between experiments, the emission factor was expressed as a range, between 0.012 and 2.2 ng TEQ/g, corresponding to the lowest value from the furnace tests and the highest value from the cable-tests. This range of values corresponds rather well to the estimate of dioxin emission from fires with PVC conducted by Carroll [24]. Carroll's investigation was based on the assumption of a soot yield of 0.0065 g soot/g PVC and

Table 7
Estimates of Emission Factors to Air for PCDD/F, PAH and VOC from Fires with Specific Materials

Material	PCDD/F (ng TEQ/g)	PAH (mg/g)	VOC (mg/g)
PVC	0.012–2.2	1–5	10–50
Wood	0.002	0.1–1.0	1–20
Wood fibre board	0.02	0.1–1.0	1–20
Textile	0.002	0.1	1
Paper	0.002	0.1	1
Polystyrene	0.002–0.1	10	5–30
PUR	0.002–0.1	1–10	1–50
PE	0.002–0.1	1	5–30
ABS	0.002–0.1	10	5–30
Petroleum products	0.002–0.1	1	7.5
Tarred roofing felt	0.002–0.1	1	7.5
Linoleum	0.002–0.1	1	7.5
Rubber	0.002–0.1	10	50
Organic solvents	0.002–0.1	1	7.5
Grain	0.002	0.1	1

Table 8
Estimates of Emission Factors to Air for PCDD/F, PAH and VOC from
Fires in Specific Objects

Material	PCDD/F (TEQ)	PAH	VOC
<i>Objects present in the statistics for 1999</i>			
Forest fires	0.002 ng/g	0.1–1.0 mg/g	1–20 mg/g
Waste basket	0.8–3.3 ng/g	0.024–0.066 mg/g	2–4 mg/g
Container	0.8–3.3 ng/g	0.024–0.066 mg/g	2–4 mg/g
Car	0.038 mg	20 g	–
Train	9.2 mg	–	–
<i>Objects not present in the statistics</i>			
Municipal waste dump	0.04–0.9 ng/g	0.0012–0.026 mg/g	–
Room	5.5 µg	494 g	811 g

results from quantitative soot analyses, and gave a dioxin yield in the range of 0.030–3.5 ng TEQ/g combusted PVC. For PAH and VOC, data was found from the cable tests mentioned above and from a test series of large pool-fires with granulated PVC [25, 26]. These sources indicated emission factors in the range 1–5 mg/g for PAH and 10–50 mg/g for VOC. The selected range for VOC was supported by the information given by Tewarson regarding the combustion products from PVC [27]. His review does not give VOC yields, but shows a THC yield of 23 mg/g from one source and an average yield of benzene of 37 mg/g from several sources.

While PVC contains a high amount of chlorine, and it is clear that dioxins can be formed from the combustion of this material, other materials with a much lower content of chlorine can form dioxins as well. Actually, most natural materials (e.g., wood) and artificial products contain low levels of chlorine, originating from the material itself or from contamination from the surroundings. Indeed, the mix of combustible material found in a building always contains some chlorine. An emission factor for dioxins greater than zero has thus been given to all materials identified to be present in building fires (Table 7).

For wood the emission factors for dioxins were mainly based on the results of a series of tests with the cone calorimeter on different wood materials [4]. It was found that the yields of dioxins were a magnitude higher for fibre boards compared to solid wood. From these results an emission factor of 0.002 ng TEQ/g was taken for wood, and 0.02 ng TEQ/g for wood fibre products. The selected emission factor for wood was strengthened by the information given by Thomas et al. [5] regarding non-industrial combustion of wood, which showed an approximate emission factor also of 0.002 ng TEQ/g. Emission factors regarding PAH for wood were found from combustion of birch wood in tubular furnace experiments [28] and tests with different kinds of wood in smaller stoves and furnaces [29]. No data from large-scale fire tests were found. The data found indicated that a reasonable interval for an emission factor would be 0.1–1.0 mg/g for PAH. For VOC data was available from the tests with stoves and furnaces referred to above and from an unpublished large-scale test run by the authors. These data pointed at an

interval for the emission factor in the range of 1–20 mg/g. The selected intervals for the emission factors for both PAH and VOC were corroborated by emission factors given by EPA [30], which were 1.0 mg/g for PAH and 21 mg/g for VOC.

For the remaining groups of materials given in Table 7 emission data regarding dioxins could not be found in the literature and some crude assumptions had to be made. For textile and paper it seemed reasonable to use the emission factor for wood as they are generally similar in terms of their carbon and hydrogen content although their basic chemical structure may vary, in particular in the case of textiles. Similarly, this factor was used for grain and hay. The remaining materials are mainly polymers or petroleum products. For these materials a rather wide range was estimated as possible emission factors for dioxins. In the low end the factor estimated for wood, 0.002 ng TEQ/g, and in the high end a factor of 0.10 ng TEQ/g, originating from full-scale tests with nominally halogen free cables [23]. As no specific data on PAH and VOC from textile, paper, grain and hay was found, the lower limits of the spans for wood were used, i.e., 0.1 mg/g for PAH and 1 mg/g for VOC. However, for polystyrene, polyurethane, polyethylene and petroleum products some experimental data on PAH and particularly VOC was found as given in more detail below.

For polystyrene PAH results were found from tests with a TV containing a large proportion of a non-flame retarded HIPS (high impact polystyrene) [3]. These test included both full-scale tests with the TV and cone calorimeter tests with the HIPS material. The other source of PAH results was contained tubular furnace tests [28]. The yields of PAH reported from these two references were both high and in rather good accordance. The average yield of 10 mg/g was taken as an emission factor for PAH. VOC data was given from the TV-tests and a series of pool fires with expanded polystyrene, both non-fire retarded and fire retarded [25]. These results fit into the interval between 5 and 30 mg/g. The interval selected for VOC was corroborated by the THC-yields between 13 and 16 mg/g reported by Tewarson [27].

Only limited data regarding PAH and VOC from polyurethane was found. Tewarson [27] reports THC results of 2–5 mg/g for flexible foams and 1–4 mg/g for rigid foams. These results refer to small-scale tests from well-ventilated conditions. A well-ventilated large-scale test at SP yielded 1.4 mg/g THC, which further confirms that rather low amounts of VOC are produced from well-ventilated burning of PUR foam. However, under vitiated conditions or during pyrolysis, considerably higher yields of VOC should be expected. A cone calorimeter test run at SP with an MDI-based rigid PUR gave a VOC yield of > 50 mg/g. In this test the sample pyrolysed during the first half of the test before it ignited. Based on a very limited amount of information a wide span of 1–50 mg/g was selected as the emission factor for VOC. No analytical data was found regarding PAH from PUR. Considering the aromatic structure of many PUR materials it is reasonably to assume rather high emission factors in some fires, and an emission factor in the span 1–10 mg/g was assumed.

The only information found on polyethylene (PE) is a THC yield of 7 mg/g given by Tewarson [27] for well-ventilated tests. The THC yield given for polypropylene (PP) is of the same order and the soot yields are very similar for these two

polymers (i.e., PE and PP). Thus, it appears that these polymers have a similar combustion behaviour, which would be expected due to the similarity in their chemical structure. As more information was available regarding polypropylene it was assumed that this information should also be valid for polyethylene. The data available for polypropylene was from large-scale pool fires with varying ventilation conditions that gave THC yields in the range 7–43 mg/g. As THC is generally somewhat higher compared to VOC, a range for VOC of 5–30 mg/g was assumed for polyethylene. For PAH tubular furnace tests gave a yield of 1.2 mg/g [28]. Based on these results an approximate emission factor of 1.0 mg/g was assumed for PAH.

Booher et al. [31] have reviewed data on the emissions from the open combustion of petroleum products including oil, diesel and kerosene. The data for these products were rather consistent and general emission factors of 7.5 mg/g and 1 mg/g can be used for VOC respective PAH. These emission factors were also used for tarred felt, linoleum and organic solvents.

For the remaining materials in Table 7 crude assumptions were made for the emission factors of VOC and PAH. The emission factors for ABS were assumed to be the same as those for polystyrene due to the large proportion of styrene in ABS. For rubber, which typically exhibits sooty and inefficient combustion, the same emission factors as for PUR were selected.

4.2 Emission factors for objects

For the Fires not occurring in buildings, emission factors have been estimated for specific objects, summarised in Table 8. In the case of forest fires no quantitative data could be found. Although there are some data published, they refer to concentrations in soot samples or concentrations in air that are not traceable to the amount of forest material combusted. However, the results from Tashiro et al. [32] show that low, but elevated concentrations of dioxins, can be found both in soil and in the air from forest fires. In a previous inventory of dioxins, emissions data for wood have been used [5]. Hence, in the present inventory the emission factors for wood (from Table 7) will also be used for forest fires.

The US EPA has studied the emissions from open combustion of household waste in a series of experiments where the combustion gases were studied in great detail [7, 8]. The results from these measurements have here been used as emission factors for fires in waste baskets and containers.

For fires in vehicles, quantitative data were found from a series of tests in a tunnel from the EU project EUREKA [6]. Tests were conducted with two different models of cars and the average of these results on dioxins and PAH were used as the emission factors for car fires. There was also one test conducted with a train carriage where only dioxins were measured. VOC were not measured for any of the vehicles in these tests, and have not been reported for any tests in the literature to our knowledge.

Although no fires were reported in municipal waste dumps in the statistics for 1999 in Sweden, fires do occur regularly and present a potential source of emissions. It has been shown that fires in municipal waste dumps can produce dioxins

[33]. The quantity of the emissions depends on the specific waste and on the combustion conditions. A model study on household waste was conducted in Sweden [34] which gave an average emission factor of 1.1 ng Nordic-TEQ/g. In another Swedish study the emissions of both PAH and dioxins were quantified from real waste dump fires [35]. The results for dioxins were in reasonable agreement for both studies. The results from the measurements conducted on the real fires were used as emission factors in this inventory (see Table 8). We were not able to find any quantitative results for VOC emissions from municipal waste dump fires. As we lacked this type of information it was decided not to set an arbitrary factor, although the emissions from these types of fires are probably substantial.

In Table 8 there are data presented for a fire in a single furnished room. These data originate from a test conducted at SP [3]. The room had an area of 16 m³ and the total amount of furnishing etc. was approximately 500 kg. The fuel load in the room included e.g., wood, particleboard, PUR, PS, wool and paper. As the distribution of the material in this fire was known and detailed quantitative measurements were conducted on the fire effluents, this experiment was used as test case for the selected emission factors for organic fire effluents. Combining the amounts of the various materials in the room with the emission factors for these materials in Table 7, gave estimated emissions of 2.4–5.8 µg (TEQ) PCDD/F, 124–528 g PAH, and 292–5660 g VOC for the room. While these emission ranges are quite broad (especially in the case of VOCs) they do correspond well to the actual experimental results (given in Table 8), which implies that the emission factors developed should give reasonable ball park figures for total fire emissions.

5 Results and Discussion

5.1 Total Emissions

An estimate of the total amounts of PCDD/F, PAH and VOC from fires during 1999 was made by combining the amounts of materials involved in building fires (Table 5) and fires in specific objects (Table 6), with the emission factors for these materials (Table 7) and objects (Table 8). The estimates for the emissions are presented in Table 9. Note that in many cases rather broad ranges have been presented for the emissions.

The estimates show that the majority of dioxin emissions were from Fires not in buildings. Large sources were fires in garbage cans and containers, and fires in vehicles. A large source of PAH and VOC, however, was fires in buildings. Forest fires is another large source of PAH and VOC. For dioxins information is available concerning emissions from other sources. In 1999 UNEP published a dioxin inventory [36] including estimates of the emissions in Sweden (for 1994). This inventory showed that the total emission of dioxins in Sweden was between 23 and 93 g TEQ. The only fire related emissions included in this inventory were from fires in municipal waste dumps (3–30 g). Examples of emissions from other sources are: 0.2–1 g TEQ from traffic and 3 g TEQ from municipal waste combustion. Thus, the 0.5–1.4 g estimated in the present inventory reveals that emissions of dioxins from fires is a significant source, in the same range as the emission

Table 9
Estimate of Total Emissions (min/max limits) from Fires in Sweden
During the year 1999

Material	PCDD/F (mg TEQ)	PAH (tons)	VOC (tons)
Dwellings	9/210	1.3/4.8	4.7/65
General building	2/60	0.2/1.0	1.6/17
Industry buildings	3/30	0.3/1.7	2.2/30
Other buildings	4/8	0.2/1.8	1.8/35
Forest fires	~5	0.3/2.6	2.6/52
Garbage cans, containers	210/870	0.006/0.02	0.5/1.0
Vehicles, trains	~220	~0.1	–
Sum	500/1400 mg	2/12 tons	13/200 tons

from traffic and municipal waste combustion. Note that there were no fires in municipal waste dumps reported in the statistics for 1999. This might, however, be an important source and will be discussed further below.

In the case of PAH and VOC emissions there has been no comparison made with emissions from other sources. The data concerning PAH emissions presented in the literature is typically presented as total PAH, with little or no information on the individual compounds. However, the estimate shows that tons of PAH are emitted each year from fires, which should reasonably be a significant source. For the broad group of VOC compounds, there is no system for toxicity- or environmental weighting to our knowledge. As in the case of PAH emissions, however, the emissions of tens of tons of these species, should realistically be environmentally significant.

5.2 Potential Fires

The emissions from fires may vary considerably between different years due to the occurrence of large, catastrophic fires. These would include fires in deposits and storage of waste, wood chips, paper, plastics, textiles, tyres etc. The emissions from such potential fires have been estimated based on the fire-load data given in a recent (2001) investigation of risk objects [37]. The results from the estimate of emissions from potential larger fires are given in Table 10.

Table 10
Estimate of Emissions (min/max limits) from Potential Fires in Various
Storage Facilities

Potential fires	Amount (tons)	PCDD/F (mg TEQ)	PAH (tons)	VOC (tons)
Waste deposit	2500	100/2300	0.003/0.065	–
Wood chips	10,000	~20	1/10	10/200
Paper	4000	~8	~0.4	4
PVC	500	6/1100	0.5/2.5	5/25
Textiles	100	~0.2	0.01	0.1
Tyres	1000	2/100	10	50

During recent years there have been no fires in waste deposits reported in the statistics. Improved methods and increased knowledge of fire risks and waste handling have decreased the number of incidents. Limited surface fires are, however, not uncommon, although these fires are typically extinguished by the personnel on the site without the assistance of the rescue services. The most recent waste deposit fire reported in the statistics is from 1996. Prior to that there were several large waste fires reported, e.g., in 1992 when 2500 tons of waste were burned in a single fire [35].

There are approximately 160 deposits of wood chips in Sweden [37]. In 60 of these there are between 1000 and 6000 tons of material. Four deposits are considerably larger, containing between 10,000 and 24,000 tons. In our estimate of emissions we have assumed a potential fire involving 10,000 tons of wood chips.

For paper and cardboard there are approximately 150 storage facilities in Sweden. The majority contain less than 1000 tons, 30 contain between 1000 and 4000 tons, and the largest contains 53,000 tons. In the estimate of emissions a storage of 4000 tons is assumed.

There are just short of 40 storage facilities for textiles. Approximately 20 are between 10 and 100 tons. The largest contains 140 tons. Here 100 tons is assumed for the estimate of emissions. The storage of used tyres is typically small. There are, however, 7 storage facilities that store between 500 and 1000 tons. The largest deposit contains 5000 tons. We have assumed 1000 tons for the present calculation.

The results from the estimate show that the largest potential emissions of dioxins are from fires in waste deposits, storage of plastics (PVC) and storage of tyres. Fires in deposits of wood chips and storage of tyres would yield the largest emissions of PAH and VOC. Further, single incidents of the size presented in Table 10 could potentially significantly increase the environmental impact of fires any given year.

6 Conclusions

In this article we have presented an estimate of the emission of dioxins, PAH and VOC. The total estimate is based on statistics gathered for the number of fires during a typical year and the nature of these fires, i.e., their size and content. This includes an estimate of the amount of combustible material that has been burned in buildings, or based on direct measurements from certain specific objects (e.g., cars).

The emission estimates are given (in most cases) in terms of an upper and lower bound to indicate the uncertainty in the data concerning emission of these species, in part due to their production being sensitive to the specific combustion conditions. The emission data has, in some cases, been based on controlled combustion but even in the case of controlled combustion the emission determination can vary greatly. This inherent uncertainty in the product distribution from the combustion of the various material involved in the fires is compounded by the added uncertainty of the fire statistics due to a lack of detailed information concerning the amount of material involved in the various fires, which implies that the upper bound should not be taken as absolute.

Despite the obvious uncertainties in the estimates, the emission factors that have been presented have been shown to reliably reproduce estimates for emission from a room fire when compared to available experimental data and it is proposed that they provide a reasonable rule of thumb for determining fire emissions.

The previous publication in this subject indicated that the production of PAH, dioxins and furans, together with the production of particulate matter might be the major environmental impact of fire emissions to the environment although at that time insufficient data was available to test this hypothesis. This present study confirms this hypothesis and indicates that the major source of dioxin emissions is from fires not in buildings while the majority of PAH and VOC come from fires in buildings.

Finally, large fires can have a major effect on the overall emissions. Potential sources of emissions that could be a similar size or larger than the total emissions estimated from other sources include fires in municipal waste deposits, fires in warehouses or storage facilities for plastics (new or waste), chemicals, wood chips, paper, textiles, or tyres. The greatest potential source of dioxins in this category would be a fire in a municipal waste deposit, or a large amount of plastic (PVC) or tyres. The greatest potential source of PAH and VOC, however, would be a fire in wood chips or tyres. Even without these source the emission of PAH, VOC and dioxins from fires is comparable to that from many other sources.

Estimates presented in this paper are all related to emissions to air. Other potential sources of environmental impact from fire include emissions to water and soil. Very little information is presently available concerning these emissions but the authors hope that future research will allow the estimation of the size and importance of such emissions.

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