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EnVIE

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Indoor Air Pollution Exposure

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ENVIE
Co-ordination Action on Indoor Air Quality and Health Effects

WP2 Final Report

Indoor Air Pollution Exposure

by

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1. Introduction: background, objectives and rationale

EnVIE project was built on the foundations formed by the European Collaborative Action (ECA) on Urban Air, Indoor Environment and Human Exposure (2000-…), formerly Indoor Air Quality and its Impact on Man (1986-99), the 26 reports which it has produced covering a wide range of indoor air quality related issues, the STRATEX Report (ECA Report Nº 25), the INDEX Report (Critical Appraisal of the Setting and Implementation of Indoor Exposure Limits in the EU, project funded by DG Sanco and coordinated by JRC/IHCP, Kotzias *et al.* 2005, Koistinen *et al.* 2008) and numerous other EU, WHO and national research projects and coordination actions conducted during the past 30 years and concerning the health effects of various aspects of indoor air quality.

Considering the different approaches of the previous efforts, some starting from the sampling and analyses of indoor air contaminants and assessing their potential impacts on health, some focusing on the building materials, products and equipment, their releases into the indoor air under different environmental challenges, moisture, heat, oxidants, etc, some others focussing on the requirements for building technologies, such as ventilation, heating and air conditioning to maintain a healthy and pleasant indoor environment, yet others evaluating all of the above from the point of view of energy conservation and environmental sustainability.

EnVIE project selected a different approach. The starting point of the project was human health: those health conditions which in Europe appear to have the strongest link to indoor air quality – regardless of whether the indoor air contaminants originate from indoor sources or are transmitted into indoor environments via ventilation from outdoor air. It was then evaluated which indoor air contaminants are the most likely causal agents for these health effects, and which sources are the most likely contributors to these exposures. The objective of the current report is to review the current European status of knowledge about these exposures and their sources.

The indoor exposure agents reviewed in this report include those, originally selected for EnVIE, namely tobacco smoke, (combustion) particles, carbon monoxide, radon, moisture, moulds and dust mites and VOCs. In addition this report reviews the indoor exposures to the *INDEX high priority chemicals*, benzene, formaldehyde, naphthalene, carbon monoxide and nitrogen dioxide, *INDEX second priority chemicals*, acetaldehyde, xylenes, toluene and styrene, *INDEX chemicals requiring further research* (Ammonia), δ-limonene and α-pinene. The small overlap between the EnVIE and INDEX lists is mainly due to the fact that INDEX was limited to specific single chemicals, and EnVIE was not. As VOCs are listed as one exposure in EnVIE, most of the INDEX chemicals belong to this group.

The current EnVIE Report on Indoor Air Exposure reviews mainly European research. Research from elsewhere is reported for issues where, e.g., American results are expected to be equally relevant for our understanding of the indoor exposure and its sources (e.g. tobacco smoke, or accidental CO exposures), or where data from outside of Europe are useful for setting the European data on a scale.

Radon is probably the only indoor air contaminant for which comprehensive and comparable indoor exposure data exist for most of the European countries. For some others representative and comparable data exist for selected cities across Europe (mainly the EXPOLIS, MACBETH, AIRMEX, and PEOPLE studies). The Audit study evaluated the IAQ using harmonised study protocols in selected office buildings in nine countries. Nationally representative studies have been performed in Germany (GerES I…IV, 1986-2006) and France (IAQ Observatory, 2005-…). In the UK indoor air quality was studied repeatedly and comprehensively in a representative sample of homes in one area, Avon. Finally the THADE project has compiled and evaluated existing indoor air quality data from 10 European cities.

The current report relies mostly on the reports of these projects, but presents also relevant data from other studies.

2. Sources of European indoor air exposure data

European Indoor air pollution data come from a multitude of quite heterogeneous sources. EXPOLIS study (Jantunen *et al.* 1998) was performed simultaneously and with identical equipment and work protocols in seven European cities. The representativeness of the EXPOLIS population samples varied considerably between the cities, but it has been analysed and published (Rotko *et al.* 2000). The project had personal exposure as its main target, but in order to understand and develop modelling capability for personal exposures, also residential indoor and outdoor and workplace concentrations of a wide selection of particulate and volatile air pollutants were monitored.

The German Environmental Survey (GerES) (Seifert *et al.* 2000) and the French Indoor Air Observatory (OQAI) (Kirchner *et al.* 2006) projects both provide nationwide representative indoor air quality data. The German study has been repeated 4 times between 1985 and 2006, and, thus, provides a unique set of data for the assessment of indoor air pollution trends. The EC/JRC Institute for Health and Consumer protection has conducted three urban VOC (mainly benzene, toluene, ethylbenzene and m-, p- & o-xylene, BTEX) exposure studies, which covered a range of European cities and have included residential indoor air monitoring, MACBETH (Cocheo *et al.* 2000), AIRMEX (Kotzias *et al.* 2005), PEOPLE (Ballesta *et al.* 2006), and the European Parliament Pilot Project on Exposure to Indoor Air Chemicals and Possible Health Risks (Geiss *et al.* 2008). The EC Audit study focused on a small number of office buildings in 9 European countries, and the English ALSPAC study was a three year follow up of the homes of 170 pregnant women and new born babies in Avon, UK. Besides, there are a few studies which have not generated new data, but instead compiled indoor air quality data from previous studies, surveys and databanks (THADE, INDEX, Radon).

2.1. Surveys

2.1.1. EC Audit

Full name	European Audit Project to Optimize Indoor Air Quality and Energy Consumption in Office Buildings
Time	Heating season 1993-1994
Leading institute and partners	Leading institutes TNO and U. of Porto. Other partners: TNO (NL), Technical University of Denmark (DK), Danish Building Research Institute (DK), Centre Scientifique et Technique du Bâtiment (F), Belgian Building Research Institute (B), Norwegian Building Research Institute (N), Technical Research Centre of Finland (SF), University of Athens (GR), Swiss Federal Institute of Technology Lausanne (CH), EA-Technology (UK) and Building Research Establishment (UK).
Environment	Office buildings
Region (countries, cities)	9 European countries (the Netherlands, Denmark, United Kingdom, Greece, France, Switzerland, Finland, Norway and Germany)

Study character	Field investigation with questionnaire of health and environmental conditions and physical-chemical measurements
Sample size, representativeness	56 buildings (6 per country) selected with criteria's, 6537 occupants representing more than 30000 occupants of the buildings. May not be representative because of the choice criteria and only one day of measurements per building.
Agents	total VOC, CO and CO_2. In some building also particulate matter and individual VOCs. All measurements from outdoor air too.
Exposure	Only concentrations and possible sources defined.
Other data	Characteristics of ventilation system, temperature, operative temperature, relative humidity, air velocity, noise levels.
References	1. Bluyssen, *et al.* Indoor Air. 1996, 6. 2. P. Bluyssen, *et al.*, editors, European Audit Project…: Final Rep., Commission of the European Communities (1995)

2.1.2. GerES

Full name	German Environmental Survey I-IV
Time	GerES I 1985/86, GerES II 1990/91 and 1991/92, GerES III 1998, and GerES IV 2003 to 2006
Leading institute and partners	Institut für Wasser-, Boden- und Lufthygien, Umweltbundesamt, Berlin
Environment	Residences
Region (countries, cities)	Germany
Study character	Field investigation with measurements
Sample size, representativeness	Represents German population
Agents	VOCs, formaldehyde
Exposure	Residential indoor concentrations/exposures and simultaneous occupant biomarkers from blood, hair, scalp.
Other data	(Varies between studies) Tap water concentrations, content of vacuum cleaner, dust.
References	Web page: http://www.umweltbundesamt.de/gesundheit-e/survey/index.htm Seifert B, *et al.* JEA&EE. 2000,10.

2.1.3. EXPOLIS

Full name	Air Pollution Exposure in European Cities
Time	1996-1997
Leading institute and partners	KTL (Finland), University of Athens (Greece), RIVM (Netherlands), Université Joseph-Fourier, (France), VTT (Finland), University of Milan (Italy), Regional Institute of Hygiene of Central Bohemia in Prague (Czech Republic), Universität Basel (Switzerland), Imperial College of Science, Technology and Medicine (UK)
Environment	Workplace, residential buildings, home outdoor
Region (countries, cities)	Greece (Athens), Switzerland (Basel), France (Grenoble, Finland (Helsinki), Italy (Milan) and Czech (Prague)

Study character	Field investigation with measurements and questionnaires
Sample size, representativeness	The target population in each of the original EXPOLIS cities is the 25-55 year old (i.e. working age) people. Several population samples were drawn from target population: 1. random sample for short mailed or interviewed questionnaire 2. random sample for time activity diary and in-depth questionnaires 3. sample for exposure and micro environmental concentration measurements In Helsinki, a larger exposure measurement sample was drawn for more detailed analysis of exposure determinants (n=201). In other centers the exposure sample size was 50. The target size for mailed questionnaire was 2000, the true sample sizes in each city varying up to 3000. Response rates in different cities varied. See Rotko T, *et al.* JEA&EE, 2000, 10.
Agents	VOCs, $PM_{2.5}$, CO and in some places NO_2 and carbonyls
Exposure	48 h personal monitoring, divided between workday and leisure time (incl. night), residential indoor and outdoor, and workplace indoor concentrations during the times of occupancy.
Other data	Questionnaires for time-activity, housing conditions, workplace conditions, meteorological and centrally monitored ambient air quality data.
References	Web page: http://www.ktl.fi/expolis/ Jantunen MJ, *et al.* JEA&EE. 1998, 8. Hänninen O, *et al.* JEA&EE. 2004, 14.

2.1.4. French IAQ Observatory (OQAI)

Full name	National survey of indoor air quality in French dwellings
Time	October 1st 2003 to December 21st 2005
Leading institute and partners	
Environment	Residential buildings
Region (countries, cities)	France
Study character	Field investigations with measurements
Sample size, representativeness	710 buildings, representative of the situation of 24 million principal residences in mainland France
Agents	Volatile organic compounds (VOC), aliphatic hydrocarbons, halogenated hydrocarbons, glycol ethers, aldehydes, carbon monoxide (CO), radon and gamma radiation, allergens, inert particulate matter (PM_{10} and $PM_{2.5}$) and carbon dioxide (CO_2)
Exposure	
Other data	Temperature, relative humidity,
References	Final report: Kirchner S, *et al.* 2006. Available at http://www.air-interieur.org/userdata/documentsUnited_Kingdom/1_document_1.pdf

2.1.5. ALSPAC-study

Full name	The Avon Longitudinal Study of Parents and Children
Time	November 1990 to February 1993

Leading institute	University of Bristol
Environment	Residential buildings
Region (countries, cities)	United Kingdom, Avon
Study character	Field investigations with measurements
Sample size, representativeness	170 homes, selected based on the pregnancy cohort, 3339 samples
Agents	TVOCs, formaldehyde
Exposure	
Other data	Family and household characteristics, parental occupations, other socioeconomic factors, and frequency of use of 9 common household products that contain high proportions of VOCs.
References	Project web-page: www.alspac.bris.ac.uk/ Farrow A, *et al.* Arch Environ Health. 2003, 58.

2.1.6. AirMex

Full name	European Indoor Air Monitoring and Exposure Assessment Study
Time	2003-2005
Leading institute and partners	EC: JRC/IHCP, Ispra, Italy
Environment	Public buildings (town halls, guild halls), schools and kindergartens
Region (countries, cities)	Catania, Athens, Arnhem and Nijmegen, Brussels, Milan, Thessaloniki, Nicosia
Study character	Field investigations with measurements
Sample size, representativeness	
Agents	Hexane, Formaldehyde, Benzene, Acetaldehyde, Toluene, Propanal, Ethylbenzene, Hexanal, m/p-Xylene, o-Xylene, 1,3,5-Trimethylbenzene, alpha-Pinene, d-Limonene
Exposure	Personal measurements
Other data	Outdoor concentrations
References	Kotzias D. Experim Toxicol Pathol. 2005, 57.

2.2. Other data sources

2.2.1. INDEX

Full name	Critical Appraisal of the Setting and Implementation of Indoor Exposure Limits in the EU
Time	December 2002 - December 2004
Leading institute and partners	European Commission, Joint Research Centre, Institute for Health and Consumer Protection, Physical and Chemical Exposure Unit (Italy), University of Milan Italy, National Public Health Institute (Finland)
Environment	Indoor in general
Region (countries, cities)	Worldwide

Study character	Data survey for 1) type and levels of chemicals in indoor air and 2) available toxicological information to allow the assessment of risk to health and comfort
Sample size, representativeness	
Agents	Formaldehyde, carbon monoxide, nitrogen dioxide, benzene, naphthalene, acetaldehyde, toluene, xylenes, styrene, ammonia, limonene and alpha-pinene
Exposure	Only indoor air concentration levels
Other data	Health effect thresholds
References	Final report: http://ec.europa.eu/health/ph_projects/2002/pollution/fp_pollution_2002_frep_02.pdf

2.2.2. THADE

Full name	Towards Healthy Air in Dwellings in Europe
Time	2002-2003
Leading institute and partners	
Environment	Indoor in general
Region (countries, cities)	Europe
Study character	Data survey
Sample size, representativeness	
Agents	Tobacco smoke, indoor-generated particulate matter, carbon monoxide, carbon dioxide, formaldehyde, dust mites, pet allergens, cockroaches, mould, pollen, nitrogen oxide, volatile organic compounds (VOCs), man-made mineral fibers, and radon
Exposure	Only indoor air concentration levels
Other data	Health effects and risks are evaluated
References	Final report: http://www.efanet.org/activities/documents/THADE Report.pdf

2.2.3. Radon levels in Europe

Full name	An overview of radon surveys in Europe
Time	Time varies between data
Leading institute and partners	Joint Research Centre (JRC)
Environment	Residential buildings
Region (countries, cities)	Europe (23 Member States of the European Union, as well as Romania, Croatia, Turkey, Norway, Switzerland, FYROM and Serbia-Montenegro)
Study character	Data survey for measurements done
Sample size, representativeness	Representativeness varies between countries
Agents	Radon
Exposure	Only indoor air concentration levels

Other data	
References	Final report: http://radonmapping.jrc.it/fileadmin/Documents/WorkingDocuments/EU_Reports/EUR_RADON_2005_final.pdf

3. Indoor air pollution exposure levels & attribution to sources

3.1. Particulate matter

3.1.1. Introduction

Particulate matter (PM) is the most heterogeneous air pollution category. It consists of all air suspended material, which in normal indoor and outdoor temperatures is at least partly found in liquid and solid phases, from inorganic minerals to semivolatile organic compounds and biological materials in particle sizes ranging from a few nm to above 100 µm. A comprehensive ambient or indoor air PM measurement would report particle count and PM mass, elemental and/or chemical composition across the whole particle size distribution. This is a very expensive undertaking and, thus, hardly ever done. As a compromise, PM is monitored, analysed and reported as PM_{10} or $PM_{2.5}$ (ca. total mass of particles smaller than 10 or 2.5µm per m^3 of air) or UFP# (the count/number of ultrafine particles per cm^3 of air – depending strongly on the particle counter and the smallest particle it detects).

Since 1993 the interest on PM has increased strongly because relatively low levels of urban ambient air $PM_{2.5}$ has been found in increasing numbers of studies to significantly elevate cardiovascular and respiratory mortality (e.g. WHO, 2006). Similar findings have been reported on the health impacts of indoor environmental tobacco smoke (ETS). Questions have been raised about the role of indoor air PM other than ETS.

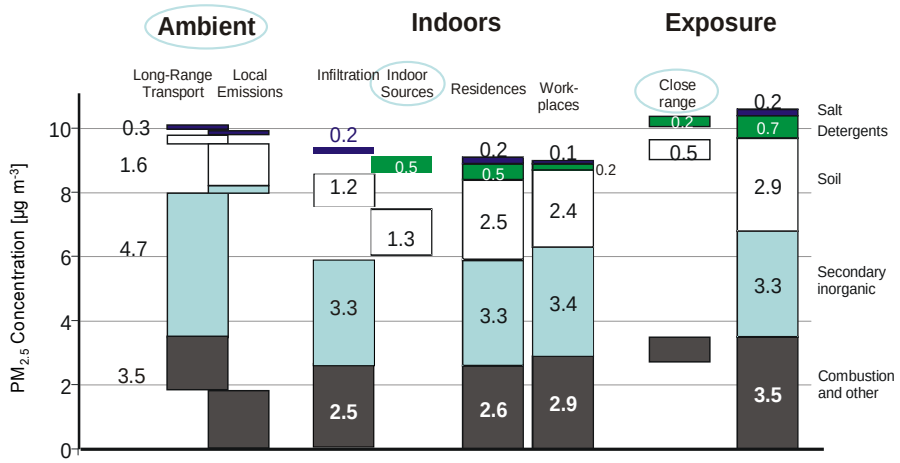


Figure 3.1.1.1. Build-up of average personal $PM_{2.5}$ exposure in Helsinki from PM from different sources in different micro-environments.

From a comprehensive literature review (Morawska and He 2003), ratios of indoor to outdoor concentrations of PM_{10} and $PM_{2.5}$ (with no known indoor sources) for naturally ventilated buildings world wide range from 0.50 to 0.98 (median 0.70) and from 0.54 to 1.08 (median 0.91) respectively. Analysis of the composition and mass relationships between the $PM_{2.5}$ in indoor air and personal exposure to respective ambient air levels in the Helsinki *EXPOLIS* study (Koistinen *et al.* 2004, Hänninen *et al.* 2004), reveals that in ETS free occupied

residential and occupational indoor spaces the $PM_{2.5}$ levels were, in average, ca. 89% of the ambient air levels, that indoor concentration of the $PM_{2.5}$ of ambient origin was 71% of the respective ambient concentration, and only 20% of the indoor $PM_{2.5}$ was, in average, of indoor origin, consisting mostly of mineral dust and phosphates.

Due to the population's time use and infiltration of ambient $PM_{2.5}$ into most indoor environments ca. 90 % of the exposure to $PM_{2.5}$ of outdoor origin occurs indoors, and the results of the epidemiological risk assessment of urban ambient air $PM_{2.5}$ reflect, in fact, more indoor than outdoor exposure. Besides, the most significant indoor sources of PM are tobacco smoking and other combustion processes, and this PM of indoor origin can be considered to be at least as harmful as the urban outdoor air PM. Therefore, the margin of error of using ambient air $PM_{2.5}$ risk assessments for indoor air $PM_{2.5}$ is no bigger that the margin of error in the original assessment. This, however, may not be true for the PM from other than combustion sources indoors, e.g. mineral or detergent dusts.

3.1.2. Results

Table 3.1.2.1. Indoor exposures to $PM_{2.5}$ and attribution to sources

STUDY	AM[A] (µg/m³)	GM sGM[B] (µg/m³)	Median (µg/m³)	Source contributions (no ETS unless mentioned)					
				Dust (%)	Salt (%)	LRT[C] (%)	Primary, traffic[D] (%)	Other (%)	Indoor sources total (%)
EC Audit[1]									
- Netherlands	72								
- Denmark	88								
- UK	20								
- Greece	149								
- France	76								
- Czech Rep.	181								
- Finland	51								
- Norway	20								
- Germany	61								
EXPOLIS[2]									
- Helsinki	12.4	8.8/2.3	7.6	19[3] 27[12]	2[3] 2[12]	25[3] 36[12]	54[3] 30[12]	4[12] deter gents	49 with ETS 33 no ETS
- Athens	28.1	23.1/1.8	22.6	26[3]	10[3]	16[3]	42[3]	6[3] oil combust	22 with ETS 0 no ETS
- Basel	32.2	20.3/2.3	16.6	9[3]	3[2]	30[3]	58[3]		55 with ETS 1 no ETS
- Grenoble	36.7	30.2/2.0	29.3						
- Milan									17
- Oxford	17.0	11.9/2.2	11.0						73 with ETS 11 no ETS
- Prague	30.3	24.7/1.8	22.7						50 with ETS 6 no ETS
French IAQ[4]			19.1 (17.2 - 20.7)						
THADE									
- Pisa[5]	57							ETS	
- Po Delta[5]	63								
- Athens[6]	35.6							outdoor, ETS, gas	
- Basel[6]	21.0								
- Helsinki[6]	9.5								

- Prague[6]	34.4							appli-ances	
- Milan[7]	42.7							ETS	
- Manchester, living room[8]	28.4							ETS	
- Manchester, bedroom[8]	19.0								
- France[9]	22.5								
- Mexico city[10]	29								
- Amsterdam[11]	28.6								
- Helsinki[11]	11.0								

[A] AM = arithmetic mean and average concentration
[B] GM = geometric mean, sGM = standard deviation of geometric mean
[C] LRT = long range transport (usually mostly secondary PM)
[E] Primary particles mostly from traffic and other combustion sources
[1] Bluyssen *et al.* 1996
[2] EXPOLIS 1999
[3] Ilacqua *et al.* 2007 (source attribution by structural equation modelling)
[4] Kirchner at al. 2006
[5] Simoni *et al.* 2002
[6] Gotschi *et al.* 2002
[7] Maroni *et al.* 2002
[8] Gee *et al.* 2002
[9] Zmirou *et al.* 2002
[10] Cortez-Luego *et al.* 2002
[11] Janssen *et al.* 2000
[12] Koistinen *et al.* 2004 (source attribution by source reconstruction)

3.1.3. Environmental and occupational guidelines & standards

WHO Air Quality Guideline (WHO, 2006), which applies for outdoor as well as for indoor air, is 20 µg/m³ for annual mean concentration of PM_{10} and 10 µg/m³ for annual mean concentration of $PM_{2.5}$, and 50 µg/m³ for 24 h mean concentration of PM_{10} and 25 µg/m³ for annual mean concentration of $PM_{2.5}$. The respective first interim WHO targets (IT-1) are 70 µg/m³ for annual mean concentration of PM_{10} and 35 µg/m³ for annual mean concentration of $PM_{2.5}$, and 150 µg/m³ for 24 h mean concentration of PM_{10} and 75 µg/m³ for annual mean concentration of $PM_{2.5}$. The annual IT-1 level is associated with ca. 15% excess mortality and the 24 h level with 5% excess acute mortality. Yet, even these values are often not met indoors, and in the presence of ETS they are met only rarely.

Occupational exposure limits have not been assigned by EU or the Finnish Occupational Health Authorities (STM, 2007) to indoor ait PM_{10} or $PM_{2.5}$ or other chemically unspecific PM metric. INDEX (2005) report does not give any guidelines for PM, because the project only dealt with specific chemicals.

3.1.4. Discussion

In the absence of indoor combustion devices and tobacco smoke, the indoor air PM levels are normally lower than ambient air levels, containing more coarse mineral particles and less secondary and combustion particles than outdoor air at the same location. The contributions of indoor sources to indoor PM levels vary from a few percent to about ⅓ depending as much on the indoor sources [numerator] as the level of outdoor PM that penetrates indoors [denominator].

Indoor smoking or other indoor combustion sources usually increase the indoor source contribution to indoor PM levels up to ½ and above, i.e. when present ETS is usually the dominating source of indoor air PM.

3.2. Environmental tobacco smoke

3.2.1. Introduction

Environmental tobacco smoke (ETS) is one of the most harmful of all indoor pollutants. Burning tobacco releases a complex mixture of more than 4,000 chemicals found in both vapour and particle phases. Many of these chemicals are classified as known human toxic or carcinogenic agents.

Exposure to tobacco smoke via active smoking is a cause of lung and other cancers, emphysema and other chronic obstructive pulmonary diseases, and cardiovascular and other diseases in adults. Passive smoking can also cause lung cancer in otherwise healthy adults who never smoked. Children are even more susceptible to harmful effects from ETS. Infants and young children up to three years exposed to ETS, the exposure causes an approximate doubling in the incidence of pneumonia, bronchitis.

ETS results are also found in chapters 3.1 (particulate matter), 3.5 (benzene), and most other chapters of specific indoor air pollutants.

3.2.2. Results

Most studies are described in Chapter 2 and their results given in Tables 3.2.2.1-3.2.2.2. References for specific data in the tables are given in table footnotes. Two American studies are included, because the available European results are scarce. More data on ETS contributions to specific indoor air pollutants can be found in tables 3.1.2.1, 3.3.1.2.1, 3.3.2.2.1, 3.4.1.2.1, 3.4.2.2.1, and 3.4.5.2.1.

Table 3.2.2.1 Contribution of Environmental Tobacco Smoke to indoor air pollution

STUDY	**Pollutant**	**Contribution (%)**	**Concentration (µg/m^3)**
THADE	Total Particulate	50-90	
US[1]	Formaldehyde	57-84	4.1-26.1
	2-Butanone	44-69	0.9-5.8
	Benzene	37-58	1.3-8.2
	Styrene	20-69	0.5-3
Ohio[2]	PAH	87	
	EOM	49	

[1] Hodgson *et al.* 1996
[2] Mitra *et al.* 1995

Table 3.2.2.2 Nicotine level of Environmental Tobacco Smoke (µg/m³)

STUDY	**AM/sAM** [A] **(µg/m³)**	**GM/sGM** [B] **(µg/m³)**	**Median (µg/m³)**	**Range** [C] **(µg/m³)**	**Sources**	**Other info**
Portugal[2]				5.79-106.31		Discos
Austria [1]						
	154.4			487.10		Discos

				(max)		
	21.3/6.1					Restaurants, smoking area
	23.3/15.9					Restaurants, non-smoking area
	38.0/60.6					Restaurants, without separate smoking area
				45.1 (max)		- Hospitals, next to smoking area
	21.4/39.3			47.7 (max)		Hospitals, smoking room
Basel[3]						
	0.9					Personal, co-workers smoke
	0.6					Personal, spouse smokes
Prague[4]						
	1.6					Personal, co-workers and spouse smokes
	0.15					Personal, no smoking
Bremen[4]						
	0.69					Personal, co-workers smoke

[A] AM = arithmetic mean and average concentration, sAM = standard deviation of arithmetic mean
[B] GM = geometric mean, sGM = standard deviation of geometric mean
[C] Range = Minimum and maximum value
[1] Moshammer *et al.* 2004
[2] Precioso *et al.* 2007
[3] Phillips *et al.* 1999
[4] Phillips *et al.* 1998

3.2.3. Environmental and occupational guidelines & standards

WHO Air Quality Guidelines for Europe (2000) acknowledges that ETS is carcinogenic to humans, and gives a 10^{-3} unit risk of cancer associated with lifetime ETS exposure in a home where one person smokes. ETS also causes acute and chronic respiratory disease for children in particular at levels down to 0.1 µg/m³ [nicotine]. Current occupation exposure limit in Finland and increasing number of other countries forbids any occupational exposure to tobacco smoke.

3.2.4. Discussion

ETS, where present, is usually the main contributor to indoor pollution levels of fine particles, formaldehyde, benzene and polyaromatic hydrocarbons including nicotine.

Indoor air nicotine can be considered as the most specific marker of ETS. The highest concentrations have been found in discos, where the nicotine concentrations show a large variation. In the absence of physical barriers, no substantial differences have been seen between designated smoking and non-smoking areas in restaurants and hospitals.

3.3. Gaseous combustion products

3.3.1. Carbon monoxide

3.3.1.1. Introduction

Carbon monoxide (CO) is produced in incomplete combustion of carbon-containing fuels. While SO_2 emissions from combustion cannot exceed the sulphur contents of the fuel, and NO_X emissions are limited by the maximum combustion temperature, CO emissions from a

poorly controlled combustion process are only limited by the amount of carbon in the fuel. In principle acutely lethal CO concentrations can in unfavourable conditions be generated by any combustion of a carbonaceous fuel, i.e. any fuel. CO exhibits no colour, odour or pungency, it is not detectable by senses.

Combustion of low grade solid and biofuels in a small stove or fireplace generates always high CO emissions, which may become lethal to occupants, unless the flue gases are led outdoors via a chimney through the entire combustion process. In the beginning of the combustion particles, towards the end CO dominates the pollution release. Combustion of high grade fuels, such as natural gas, butane or propane, produces much less CO, but also these devices cause lethal CO intoxications, because they are often not flued and if poorly maintained or improperly adjusted also they can emit high CO concentrations into indoor air. Also tobacco smoke contains high levels of CO.

Exposure to CO reduces the blood's ability to carry oxygen, because it has ca. 200 times higher affinity to haemoglobin than O_2. Depending on the amount inhaled the symptoms can range from fatigue, headache, weakness, confusion, disorientation, nausea, dizziness, loss of consciousness and death. Only ethyl alcohol causes in Europe and worldwide more lethal intoxications than CO – almost always from indoor sources.

Children, elderly, and people with cardiovascular illnesses are particularly at high risk for adverse health effects of carbon monoxide.

3.3.1.2. Results

Recent studies on indoor air CO concentrations and exposure levels are in the Table 3.3.1.2.1. Studies concerning accidental or peak exposures are separated to the end of the list. Representativeness and data quality, as well as the form in which the data are presented vary greatly between the studies, and make detailed comparisons meaningless, except when comparing data within the same study. The general levels of CO, however, vary so much between the locations and studies, that patterns are easily discernible.

References for specific data in the table are given in table footnotes.

Table 3.3.1.2.1 Indoor levels of CO (mg/m³)

STUDY	**AM/StDev (mg/m³)**	**GM/GSD (mg/m³)**	**Median (mg/m³)**	**Range (mg/m³)**	**I/O (range)**	**Sources**	**Other info**
Europe							
Athens [1]	1.3						
Athens [2]		**4**				Smoking	Homes
Basel [1]	2.0						
Helsinki [3]	2.1	1.6/2.3	1.8	**- 15.3**	1.2 - 3.6	Ambient air, gas stoves and ETS	Personal 24 h exposures of children
Helsinki [1]	1.2						
Helsinki [2]	1.2					No ETS	Homes
Prague [1]	0.6						
Anhui [4]				1.6 - **3**			
Milan [1,5]	2.4			2.1-**3.9**		gas cooking	Homes
Milan [6]	1.8/1.3	1.4/2.2			0.85	None	Homes
	2.4/1.5	1.9/1.9			0.89	Gas cooking	Homes
	2.9/1.6	2.4/1.8			1.45	ETS	Homes

	3.4/2.2	2.8/1.9			1.10	Gas cooking & ETS	Homes
	1.9/1.7	1.4/2.2			1.0	None	Offices
	1.6/1.2	1.2/2.0			1.0	ETS	Offices (*
	2.5/2.2	1.8/2.4			1.19	None	Other indoor
	6.5/2.5	**6.2**/1.4			2.95	Gas cooking	Other indoor
	3.5/2.9	2.8/1.9			2.19	ETS	Other indoor
UK [7]				0.2-2.7			Homes
England [8]		0.4					
UK National survey [9]		0.3				All-electric	Home kitchen
		0.8				Gas oven/ cooking	Home kitchen
		0.9				Unflued heater	Home kitchen
		0.7				ETS	Bedroom
		0.4				No ETS	Bedroom
		0.3					Rural
		0.4					Suburban
		0.5					Urban
		0.7					City centre
Spring		0.3					All homes
Summer		0.2					All homes
Autumn		0.5					All homes
Winter		0.5					All homes
London [10]	1.9			- 2.7	1.1	Marylebone rd.	Lounge
	2.3			**- 7.6**	1.4	Gas cooking	Kitchen
	2.0			**- 3.6**	1.2	smoking	Kitchen
London [11]				0.05 – 0.6	0.2 – 4.1	Busy street	Office bldg. 15 min averages
Oxford [12]	1.1	0.5/3.9 1.0/2.3				No smoking smoking	Personal exposure
French IAQ Observatory[13]			2.0 (1.6-15.2)				Main rooms 95% 13.2 (9.5-15.2)
			3.9 (3.0-4.7)	-53..120			Other rooms 95% 21.1(14.4-36.3)
Accidental / peak exposure cases studies							
WHO[14]				**60-115** (peak)			Homes
UK[15]				**10-182** (peak)			Homes
UK[16]				**121** (peak)			Homes
				6-49 (peak)			Homes
				3.5-4 (peak)			all-electric homes
				60 (peak)			Homes
Virginia, USA[17]				COHb % **6.6 - 50**		Portable electric generators	Case studies on CO poisoning
Ice rink in Finland [18]	> **140**			CoHB % **8 - 24**		Ice resurfacing machine	Case study of a CO poisoning epid.

Camping tent [19]	CoHB % 21.5/2.4 @ 120 min			**200 – 550**		Kerosene cooking stove	Experiment

*) problem in the self reported exposures in the offices analysed in ref. 28

1 Maroni *et al.* 2002
2 Georgoulis *et al.* 2002
3 Alm *et al.* 2001
4 Pan *et al.* 2002
5 Maroni *et al.* 1996
6 Bruinen de Bruin *et al.* 2004
7 Ross 1996
8 Raw *et al.* 2002
9 Raw *et al.* 2004
10 Ditmitroulopoulou *et al.* 2006
11 Milner *et al.* 2006
12 Lai *et al.* 2004
13 Kirchner *et al.* 2006
14 WHO. 2000
15 IEH 1998
16 Ross et al .1996
17 Hampson & Zmaeff, 2005
18 Salonen *et al.* 2008
19 Thomassen *et al.* 2004

3.3.1.3. Environmental and occupational guidelines & standards

The WHO Air Quality Guideline (WHO, 2000) for CO concentration in indoor as well as outdoor air is 30 mg/m^3 for 1 h average and 10 mg/m^3 for 8 h average concentration. INDEX (2005) Report supports these same guideline values, and further recommends to:

- Apply the indoor air concentration guideline in the building and ventilation design process, considering the possibility of excessive releases from the sources to be installed.
- Develop building codes, ventilation standards and equipment/appliance standards so that they require all indoor combustion equipment to exhaust into chimneys/hoods/vents leading outdoors.
- Require standardised information CO emission under intended use for all combustion devices which do not exhaust directly into a chimney.
- Require regular mandatory inspections for indoor combustion equipment.
- Recommend alarm systems responding to abnormally high concentrations.
- Raise public awareness about the risks of indoor air CO, and provide public information about its sources, risks and reasons for suspecting high CO levels.

As an example of occupational exposure limit values the Finnish HTP values to carbon monoxide are 35 mg/m³ (8 h average) and 87 mg/m³ (15 min peak value) (HTP-values, 2007).

3.3.1.4. Discussion

In the absence of indoor sources the current indoor air CO concentrations in European cities are only small fractions of the existing air quality guidelines and standards. Still in the 50's and 60's the urban air CO levels often approached and even exceeded these reference values, but drastic reductions in the emissions from space heating and traffic have brought the levels down by an order of magnitude in spite of the growing cities and increasing traffic.

The highest reported non-accidental CO levels are observed in public or residential garages and primitive kitchens. Aside of cooking or heating with open fire, the common sources for elevated indoor air CO concentrations are unvented gas appliances, tobacco smoking and proximity to busy traffic. The lowest concentrations are found in homes, churches and schools at distance from busy traffic and with no indoor sources.

Short time peak concentrations often exceed 100 mg/m^3, and have been published in a few cases. The results are non-representative and vary over a wide range (e.g. IEH 1998, El Fadel *et al.* 2001, Ross *et al.* 1996). CO intoxications are mostly caused by accidentally induced or repetitively generated high short term peaks, which are hardly ever captured in any monitoring programmes. Sometimes the intoxicating concentrations can be estimated from the blood COHb levels measured from the victims (e.g. Hampson & Zmaeff, 2007, Salonen *et al.* 2008), and such values have also been regenerated experimentally to evaluate the incidences (e.g. Thomassen *et al.* 2004, Salonen *et al.* 2008). These values may reach several hundred mg/m^3.

CO is an almost inert gas in the ambient air with atmospheric half life in the order of a month. CO is not absorbed by building materials or ventilation system filters and it is essentially non-reactive with the other outdoor and indoor air pollutants. In principle, therefore, in the absence of any indoor CO source the indoor air CO concentration is the same as the concentration of the ventilated incoming outdoor air, and its minimum I/O ratio is 1.0. In practice the measured I/O concentration ratios for CO vary for two reasons.

- Small scale non-homogeneity of the outdoor air CO concentration, i.e. the outdoor air CO concentration at the point of measurement may be significantly higher or lower than the outdoor air CO concentration at the point of ventilation air intake. Consequently, even in the absence of any indoor sources the 15 min I/O for CO varies from 0.2 to 4.1, and the daily I/O from 0.4 to 1.2.
- Normal indoor sources, gas appliances and tobacco smoking increase the I/O ratios respectively up to 1.5 for ETS and up to 4 for gas appliances. Faulty or improperly operated indoor combustion devices may increase the indoor concentrations to orders of magnitude above the outdoor concentrations. In these situations I/O ratio is no more a meaningful concept.

3.3.2. Nitrogen dioxide

3.3.2.1. Introduction

Nitrogen dioxide (NO_2) is one of the nitrogen oxides (NO_x), a group of air pollutants produced from combustion processes. Indoor NO_2 is produced mainly by unvented heaters and gas stoves but it also can be found in environmental tobacco smoke. It irritates the mucous membranes in the eye, nose and throat and causes shortness of breath after exposure to high concentrations. Prolonged exposure to high levels of NO_2 can damage respiratory tissue and may lead to chronic bronchitis.

3.3.2.2. Results

Most studies are described in Chapter 2 and their results given in Table 3.3.2.2.1. References for specific data in the table are given in table footnotes.

Table 3.3.2.2.1. Levels of NO_2 (µg/m³)

STUDY	AM/sAM [A] (µg/m³)	GM/sGM [B] (µg/m³)	Median (µg/m³)	Range[C] (µg/m³)	Sources	Other info
HEAL (Hungary) [1]					gas cooker (10-30 %), gas heating (21-39 %), tobacco smoke (11-13 %)	

- Győr	25					no indoor sources
- Sopron	8					no indoor sources
6 TOWNS[3]	32					no gas appliances
	78				gas cooker	
	154				gas cooker and heater	
ZUGLO[4]	58,6 /44,6				central heating	
	84,8/52,2				gas heater	
	47,6/31,6					
SZBATTA-BUDAÖRS[5]				5-100		class rooms
				5-130		homes
3 TOWNS[6]	37,9/41					
BUDAPEST SCHOOLS				8-34		no indoor sources
THADE - Pisa[7]	26,3					
- Po Delta[7]	34,8					
- Genoa[8]	47					kitchen
	24,8					bedroom
- UK[9]	21,8					kitchen
	11,9					bedroom
- UK[10]	20,3					bedroom
	27,2					living room
- France[11]	36,1					
- West Germany[12]			17			
- East Germany[12]			15			
- France[13]	41					
- Japan[14]	47,8					
- Australia[15]			11,6			
- Hong Kong[16]	91,6					kitchen
	61					bedroom
- Switzerland[17]	21					
- Kuopio[18]	10,34					
- Kjeller [18]	14,66					
- Geneve [18]	15,6					
- Erfurt [18]	16,97					
- Ottawa [18]	20,12					
- Berlin [18]	23,12					
- Zagreb [18]	31,58					
- Boston [18]	36,1					
- London [18]	40,42					
- Sapporo [18]	43,43					
- Philippines [18]	45,12					
- Beijing [18]	47,75					

- Sosnowiec [18]	64,67					
- Taejon [18]	72,76					
- Bombay [18]	76,7					
- Tokushima [18]	78,77					
- Seoul [18]	71,22					
- Mexico City [18]	117,88					
- Sweden[19]	11,0					urban area
	6,0					control area
- New Mexico[20]	63,9					kitchen
	54,5					living room
	39,5					bedroom
EXPOLIS-INDEX	12.5					no indoor source
	50.25				gas appliances	
- Helsinki	18					
- Basel	27					
- Prague[23]	43					
- UK		21.80		13-40		
INDEX				180-2500 (max)		
- ECRHS II study				25-200		homes with gas cooking
- Po Delta[7]	62					kitchens in winter
	38					kitchens in summer
- Spanish study[21]				12,5-14,7		
- Levy[18]				10-81		
- COMEAP[22]				13-40		homes without gas stove
				25-70		homes with gas stove
- Portage[2]	18				gas stove	above outdoor level
	36				gas stove	above outdoor level
- Boston[24]	10					above homes with electric stove
- Los Angeles[24]	5					above homes with electric stove

[1] Rudnai *et al.* 1993b
[2] Quackenboss *et al.* 1986
[3] Páldy *et al.* 1999
[4] Rudnai *et al.* 1993
[5] Hülsse *et al.* 1989
[6] Viragh *et al.* 2004
[7] Simoni *et al.* 2002
[8] Gallelli *et al.* 2002
[9] Coward *et al.* 2002
[10] Gee *et al.* 2002
[11] Zmirou *et al.* 2002
[12] Cyrys *et al.* 2000

[13] Saintot *et al.* 2000
[14] Shima *et al.* 2000
[15] Garrett *et al.* 1999
[16] Leung *et al.* 1998
[17] Monn *et al.* 1998
[18] Levy *et al.* 1998
[19] Hagenbjork-Gustaffson *et al.* 1996
[20] Lambert *et al.* 1993
[21] Garcia-Algar *et al.* 2003
[22] COMEAP 1997
[23] Kousa *et al.* 2001
[24] Ryan *et al.* 1989

3.3.2.3. Environmental and occupational guidelines & standards

The WHO guideline values to NO_2, applicable to indoor as well as outdoor air are 200 µg/m³ (1 hour) and 40 µg/m³ (annual average) (WHO, 2006). INDEX (2005) Report supports these guideline values and further recommends to:

- Apply the indoor air concentration guideline in the building and ventilation design process.
- Develop building codes, ventilation standards and equipment/appliance standards (design, maintenance and use) so that all indoor combustion equipment will exhaust into chimneys/hoods/vents leading outdoors.
- Require standardised NO2 emission information - for normal use and extreme release - about all combustion devices which do not exhaust directly into a chimney.
- Provide public information about the sources, risks and means of controlling NO2 indoors.

Finnish occupational exposure limits to nitrogen dioxide are 5.7 mg/m³ (8 h average) and 11 mg/m³ (HTP-values, 2007). Directive 2000/39/EC does not specify any European occupational exposure limit value for NO_2.

3.3.2.4. Discussion

Gas cookers and gas heaters without exhaust hood are very important sources of NO_2. Consequently higher exposure was experienced in kitchens than bedrooms and living rooms.

NO_2 concentration showed notable geographical differences. This is probably due to the different customs and circumstances. For instance, if exhaust pipe of the gas heater is conducted to the outdoor air just under the window sill the combustion products can easily re-enter the room resulting the NO_2 level.

Opened windows in summer can contribute to better air quality in the kitchen.

Outside NO_2 concentration played a secondary role in formation of indoor NO_2 level.

Many of the reported NO_2 values were close or exceeded the WHO annual average limit value (40 µg/m³). As a conclusion we can say that indoor concentrations of NO_2 can cause adverse health effects especially to sensitive population.

3.4. Gaseous and volatile organic compounds

3.4.1. Formaldehyde

3.4.1.1. Introduction

Formaldehyde was the first air pollutant, which already in the 1970's emerged as a specifically non-industrial indoor air quality problem. Formaldehyde as an indoor air quality problem emerged from the use of the easily applied and cheap urea-formaldehyde insulation (UFI) to conserve energy in buildings in the aftermath of the first mid and late 1970's energy crisis. Indoor air pollution studies soon detected also the urea-formaldehyde resin in chipboards, quite widely used building materials. In both products formaldehyde is a slowly releasing component in an unstable product. UFI use was soon banned, and the chipboard resins were changed to formaldehyde free alternatives. Yet formaldehyde remained an indoor air quality issue; on one side it was found to be still released from natural fresh wood materials, some interior textile treatment chemicals and in smaller quantities from numerous other household and office products, on the other side, it was classified by IARC as a human carcinogen. Still today the levels of formaldehyde in residential indoor air are among the highest of any indoor air contaminant.

Concentration of 0.2 ppm is known to cause nasal and eye irritation to humans (Andersen and Mølhave, 1983) and 0.12 ppm problems with short term memory (Bach *et al.*, 1990). The OAEL for acute exposure with serious effects is 3.6 ppm (Cassee and Feron, 1994).

In chronic exposure 5.6 ppm causes significantly reduced survival among rats (Swenberg *et al.* 1980, Kerns *et al.* 1983). The LOAEL of chronic exposure with less serious symptoms is calculated to be 0.24 ppm (Holmstrom *et al.* 1989). The LOAEL of chronic exposure with serious symptoms is 5.6 ppm (Swenberg *et al.* 1980, Kerns *et al.* 1983).

3.4.1.2. Results

Results for Formaldehyde measurements are listed in Table 3.4.1.2.1.

Table 3.4.1.2.1. Indoor exposures to formaldehyde and attribution to sources

STUDY	AM/sAM[A] (µg/m³)	GM/sGM [B] (µg/m³)	Median (µg/m³)	Range[C] (µg/m³)	Sources	Other info
EC Audit						
GerES						
- Survey 1985/86	58.6	49.4/1.9		309 (max)		
- Survey 1991/92	79			816 (max)		
EXPOLIS[7]					tobacco smoke, insulation, chipboard, plywood, paints, fabrics, cleaning agents, disinfectants, particle board	
-Helsinki[1]		44.8	25.7	1.5-217.5		
French IAQ[9]			19.6 (18.4-21.0)	86.3 (max)	photochemicals, particle boards, fibre boards, unfinished	

					wood boards, new books and magazines, upholstery fabrics, paint, tobacco smoke, photocopiers	
ALSPAC					Building material, furnishing	
	25/21			1-205		main bedroom
	23/17			1-181		living room
AirMex						
INDEX[8]					[10,11,12,13]tobacco smoke, insulation materials, particle board, plywood, paints, fabrics, cleaning agents, disinfectants, pesticides, paper products, adhesives, plastic surfaces, building materials, gas cookers, open fireplaces	
				7-79		indoor
	12					workplace
THADE[14]					tobacco smoke, combustion, particle board and plywood products, urea-formaldehyde insulation	
- Japan[2]				91.25 - 290		
- UK[3]		22.2 (19.5 - 26.1)				
- Australia[4]			15.8	139 (max)		
- Louisiana, USA[5]				<LOQ[D]- 6.6		
- USA[6]				<LOQ[D]- 575		

[A]AM = arithmetic mean and average concentration, sAM = standard deviation of arithmetic mean
[B] GM = geometric mean, sGM = standard deviation of geometric mean
[C] Range = minimum and maximum value
[D] LOQ = limit of quantification
[1] Jurvelin *et al.* 2001
[2] Minami *et al.* 2002
[3] Brown *et al.* 2002a
[4] Garret *et al.* 1999
[5] Lemus *et al.* 1998
[6] Liu *et al.* 1991
[7] EXPOLIS 1999
[8] INDEX 2005
[9] Kircher *et al.* 2006
[10] WHO 1989
[11] COMEAP 1997
[12] Jurvelin *et al.* 2001
[13] EPA/Cal 2003
[14] THADE 2004

3.4.1.3. Environmental and occupational guidelines & standards

WHO (2000) guideline to prevent significant sensory irritation of formaldehyde in the general population is 100 μg/m^3 as 30-minute average exposure. The no-effect level (acute and chronic) is estimated to be at 30 μg/m^3 as 30-minute average exposure. Pending the outcome of the current IARC revision of the carcinogenicity of formaldehyde, a guideline value should be as low as reasonably achievable. The INDEX (2005) Report further recommends to:

- Minimise the emissions of formaldehyde from building materials, products, furnishings and household/office chemicals.
- Require product labelling to inform about Formaldehyde content and potential formaldehyde release from household and building products
- Discourage the use of any formaldehyde containing products.
- Raise public awareness and provide information to the public about the sources, nature and levels of risks of formaldehyde in indoor air.

The Finnish occupational exposure guidelines for formaldehyde are 0.37 mg/m^3 for 8 h and 1.2 mg/m^3 for 15 min exposure time (STM, 2007). Directive 2000/39/EC does not specify any European occupational exposure limit value for formaldehyde.

3.4.1.4. Discussion

Data for population representative indoor air formaldehyde measurements in European level are quite scarce considering that formaldehyde is the indoor air pollutant which has been acknowledged and measured for decades and broadly across Europe. It remains one of the most common indoor air pollutants with verified acute and chronic health effects.

Building materials and furniture are the main sources of formaldehyde and the maximum values measured indoors vary quite a lot, as can be seen when comparing results between Germany (GerEs study) and France (IAQ-study). Some of the maximum values exceed the occupational exposure limit (8 h average). Several of the maximum values exceed the LOAELs of both less serious symptoms in acute and chronic exposure, possible causing irritation to eyes and nose and memory problems. Exceedances of both the WHO (2000) and INDEX (2005) guideline values appear to be quite common.

3.4.2. Benzene

3.4.2.1. Introduction

Benzene as an indoor air pollutant originate primarily from outdoor air, indoor combustion processes, primarily tobacco smoking, and from some technical solvents, where it can still be found as an impurity.

Benzene is a human carcinogen, and its concentration in indoor air should be kept as low as reasonably achievable. The acute inhalation LC50 for benzene is 13 700 ppm (Drew and Fouts, 1974). Acute inhalation exposure LOAEL is 10 ppm for less serious symptoms (Demster and Snyder, 1991) and 21 ppm for serious symptoms (Toft *et al.*, 1982). For chronic exposure 200 ppm adds mortality of rats (Maltoni *et al.*, 1982). For humans calculated chronic LOAEL for less serious symptoms is 0.57 ppm (Lan *et al.*, 2004). Because of the carcinogenicity, however, much lower levels of benzene in indoor (and outdoor) air are considered a health hazard. Chronic exposure to 1 ppm of benzene is considered sufficient to cause cancer to humans (Aksoy *et al.*, 1987).

3.4.2.2. Results

Results for Benzene measurements are presented in Table 3.4.2.2.1.

Table 3.4.2.2.1. Indoor exposures to benzene and attribution to sources

STUDY	AM/sAM [A] (µg/m³)	GM/sGM [B] (µg/m³)	Median (µg/m³)	Range[c] (µg/m³)	Sources [D] (indoor contrib%)	Other info
GerES II [9]	13.5	10.5	11	5-32		
EXPOLIS[5]						
- Oxford	6.64	3.29/2.75	2.86		35 with ETS 0 no ETS	home
- Athens	11.1	2.2	8.6		10 with ETS 0 no ETS	home
	13.7	2.5	13.8			workplace
- Basel	3.0	2.4/2.2	2.7		50.0	home
	7.8	2.7/2.7	2.5			workplace
- Helsinki	2.2	1.6/2.4	1.9		39 with ETS 12 no ETS	home
	3.8	1.8/2.6	2.1			workplace
- Milan	13.2	9.1/2.6	9.7			home
	14	9.9/2.6	9.8			workplace
- Prague	12.0	8.2/2.0	8.1		43 with ETS 39 no ETS	home
	9.4	8.2/1.7	8.6			workplace
PEOPLE[6]						
- Brussels			6	2-33		home
			3	1-14		office
			2	0-28		school
- Bucharest			8	3-24		home
			10.5	5-19		office
			5			school
- Dublin			1.6	1.1-5.5		home
			1.6	0.9-1.7		office
			2.6	1.0-2.5		school
- Lisbon			3.5	1-9		home
			6	3-11.5		office
			4.5	0.2-11.5		school
- Ljubljana			2.5	1.2-4.8		home
			3.6	2.5-12		office
			2.5	1.8-7		school
- Madrid			5.5	2.5-23		home
			7.5	5-16.5		office
			6			school
French IAQ[7]			2.1 (1.9-2.2)	22.8 (max)	combustion, gasoline vapours, tobacco smoke, do-it-yourself products, furniture, construction and decoration products, incense	
AirMex[1]				2.9-63.7		
INDEX[8]					[8,9,10]consumer products, outdoor sources, fuel	

					component, tobacco smoke	
				2-13		indoor
				4-14		workplace
THADE						
- UK[2]		3.0				
- East-Germany[3]	2.17 [3]					
- West-Germany[3]	1.48					
- Italy[4]		21.2				

[A] AM = arithmetic mean and average concentration, sAM = standard deviation of arithmetic mean
[B] GM = geometric mean, sGM = standard deviation of geometric mean
[C] Range = Minimum and maximum value
[D] Indoor sources include ETS
[1] Public buildings
[2] Brown *et al.* 2002b
[3] Schneider *et al.* 2001
[4] Carrer *et al.* 2000
[5] EXPOLIS 1999
6 Ballesta *et al.* 2006
[7] Kirchner at al. 2006
[7] INDEX 2005
[8] ATSDR 1991
[9] Hoffman *et al.* 2000
[10] Wallace 1989

3.4.2.3. Environmental and occupational guidelines & standards

Benzene is a IARC classified category 1 known human carcinogen, and its concentration in indoor air should, therefore, be kept as low as reasonably achievable. EU outdoor air quality directive sets 5 µg/m³ as an annual mean limit value for benzene. WHO Air Quality Guideline for Europe does not give benzene a guideline value, but instead a lifetime leukemia risk of $6x10^{-6}$ per 1 µg/m³. INDEX (2006) Report requires that indoor exposure to benzene should be kept as low as reasonably achievable, and recommends further to:

- Ban any sources emitting benzene in the indoor environment.
- Lower the permissible benzene content in any building material and consumer product, and report about known benzene levels also when below permissible levels.
- Raise public awareness and provide information to the public about the sources, nature and levels of risks of benzene in indoor air.

Finnish occupational health limit for benzene is 1 ppm or 3.25 mg/m³ (8 h average) (HTP-values, 2007). Directive 2000/39/EC does not specify any European occupational exposure limit value for benzene.

3.4.2.4. Discussion

When comparing the measured indoor air benzene concentrations to LOAELs and occupational exposure limit, one can see that the LOAEL of less serious chronic symptoms is about 80 times bigger that measured maximum concentration.

3.4.3. Naphthalene

3.4.3.1. Introduction

Outdoor sources are the main origin of indoor naphthalene, but the highest indoor concentrations – sometimes orders of magnitude above the outdoor air levels comes from consumer products, such as multipurpose solvents, lubricants, herbicides, charcoal lighter, and hair spray, tobacco smoke, and – most importantly – from naphthalene insect repellents, the moth balls, used to protect textiles stored indoors in closets.

The LOAEL is 10 ppm causing less serious effects in acute exposure (West *et al.*, 2001) and cancer in chronic exposure (Abdo *et al.* 2001).

3.4.3.2. Results

Table 3.4.3.2.1. Indoor exposures to naphthalene and attribution to sources

STUDY	AM/sAM [A] (µg/m³)	GM/sGM [B] (µg/m³)	Median (µg/m³)	Range[C] (µg/m³)	Sources (indoor contrib. % at 90th percentile)	Other info
GerES[1]	2.3	2.1				
EXPOLIS[2]					[8]plasticizers, resins, phthaleins, dyes, pharmaceuticals, moth repellents and insecticides, paints, dyes, deodorizers	
- Oxford	1,3		1.0		21	Home
- Helsinki	0.6		0.5		3.3	Home
- Basel	0.7		0.6		27	Home
- Athens	82		22		98	Home
	7.5	1.7	4.3			workplace
				[5]1.7 - 990		indoor
- Milan	20.1	2.1/2.7	2.0		73	Home
	2.2	1.7/2.2	1.7			workplace
- Prague	2.0		1.6		62	Home
	2.2	2.0/1.6	1.7			workplace
INDEX[3]					[5.6] moth repellents, fungicides, lubricants, preservatives, topical antiseptics	
				1-90		indoor
				2-8		workplace
European offices[4]	6.5	4.3		- 68.5		50 office buildings

[A] AM = arithmetic mean and average concentration, sAM = standard deviation of arithmetic mean
[B] GM = geometric mean, sGM = standard deviation of geometric mean
[C] Range = Minimum and maximum value
[1] Hoffman *et al.* 2000
[2] EXPOLIS 1999
[3] INDEX 2005
[4] Zuraimi *et al.* 2006
[5] EPA/Cal 2003
[6] HSDB 2003
[7] Edwards *et al.* 2004
[8] ATSDR 1995

3.4.3.3. Environmental and occupational guidelines & standards

EU does not provide ambient air quality limits, and WHO does not provide air quality guidelines for naphthalene. INDEX (2005) Report recommends a long term guideline value of 10 μg/m^3 based on irritation/inflammation/hyperplasia. This level is at the lower extreme of the olfactory perception range. The report further recommends to:

- Restrict the use of naphthalene containing household products, particularly mothballs.
- Raise public awareness about the sources, risks, means of detecting and avoiding naphthalene in indoor air.

Finnish occupational exposure limits are for 8 h average, 5 mg/m³ and for 15 min peak exposure 10 mg/m³ (HTP-values, 2007). Directive 2000/39/EC does not specify any European occupational exposure limit value for naphthalene.

3.4.3.4 Discussion

Measured Naphthalene concentrations are basically available only from EXPOLIS study, so there are not that much data available to do any comprehensive conclusions. In general, average levels of Naphthalene are well below the health effect level, yet, occasionally, and specifically in connection to moth ball use the levels can be very high and of clear health concern for individuals with haemolytic anaemia.

3.4.4. Terpenes

3.4.4.1. Introduction

Terpenes are widespread in nature, mainly in plants as constituents of essential oils. Many terpenes are hydrocarbons, but oxygen-containing compounds such as alcohols, aldehydes or ketones (terpenoids) are also found. Their building block is the hydrocarbon isoprene and they are classified according to the number of isoprene units. Although terpenes themselves are not considered toxic, some recent studies have shown that they may react with ozone to produce a number of toxic compounds. Irritating effects are the main health effects associated to terpenes.

3.4.4.2. Results

Table 3.4.4.2.1 Indoor exposures to terpenes and attribution to sources

STUDY	AM/sAM [A] (μg/m³)	GM/sGM [B] (μg/m³)	Median (μg/m³)	Range[C] (μg/m³)	Sources (indoor contrib. %)	Other info
GerES I Survey 1985/86	41.2	27.7 /2.4		362 (max)		α-pinene, β-pinene, α-terpinene, limonene
EXPOLIS[1]						
- Oxford						
· α-Pinene	37.04	11.04/3.24	7.73		[2]air refresher, detergents, fragrances, waxes, polishes	home
· d-Limonene	19.64	9.32/3.61	9.79		[2]air refresher, detergents, fragrances, cleaning products, soaps, colognes 60	home

· 3-Carene	4.98	2.83/2.74	2.37		[2]air refresher, detergents, fragrances 75	home
- Athens						
· α-Pinene	11.4	2.1	8.3		80	home
	17.4	1.7	3.2			workplace
· d-Limonene	82.5	3.4	22.8		98	home
	14.4	2.3	11.0			workplace
· 3-Carene	2.8	0.764	2.4		72	home
	3.1	1.0	1.0			workplace
- Basel						
· α-Pinene	4.1		1.8	37	94	home
						workplace
· d-Limonene					98	home
						workplace
· 3-Carene					66	home
						workplace
- Helsinki						
· α-Pinene	15.9	9.0/2.8	8.9		85	home
	4.7	1.9/3.4	1.9			workplace
· d-Limonene	31.5	11.6/3.9	10.6		97	home
	13.8	2.7/4.3	2.6			workplace
· 3-Carene	5.6	2.6/3.6	2.8		87	home
	1.6	<LOQ [D] /2.5	<LOQ [D]			workplace
- Milan						
· α-Pinene	14.5	3.5/4.2	3.1		34	home
	1.3	0.8/2.3	<LOQ [D]			workplace
· d-Limonene	46.6	12.1/5.2	12.4		49	home
	10.5	4.1/4.6	4.8			workplace
· 3-Carene	2.2	0.7/2.7	<LOQ [D]			home
	0.5	0.5/1.2	<LOQ [D]			workplace
- Prague						
· α-Pinene	11.9	6.0/3.0	5.1		61	home
	4.8	3.5/2.1	3.7			workplace
· d-Limonene	42.2	16.0/3.7	18.8		90	home
	23.1	10.1/3.2	8.1			workplace
· 3-Carene	8.0	3.4/3.4	3.1		18	home
	2.1	1.9/1.8	2.2			workplace
INDEX[3]						
- α-Pinene				11-23	[4,5]paint, cleaning and sanitation products, paint and varnish removers, waterproofing compounds, wood furniture, waxes	indoor
				1-17		workplace
- Limonene				6-83	food, cleaning products, perfumes, solvents	indoor
				11-23		workplace

[A] AM = arithmetic mean and average concentration, sAM = standard deviation of arithmetic mean
[B] GM = geometric mean, sGM = standard deviation of geometric mean
[C] Range = minimum and maximum value
[D] LOQ = limit of quantification
[1] EXPOLIS 1999
[2] Niewenhuijsen *et al.*
[3] INDEX 2005
[4] HSDB 2003
[5] Maroni *et al.* 1995

3.4.4.3. Environmental and occupational guidelines & standards

There are no inhalation toxicological data available about terpenes. The Finnish occupational exposure limits to d-Limonene are: 8 h average, 25 ppm or 140 mg/m³, 15 min peak value, 50 ppm or 280 mg/m³ (HTP-values, 2007).

3.4.4.4. Discussion

Consumer products are the main sources of terpenes in indoor air. D-Limonene is the most common of the terpenes in indoor air and it's mainly originating from air refresher, detergents, fragrances and cleaning products, intentionally added to the products to give a "fresh lemon scent". The monitored indoor air concentrations are low and far below the occupational exposure limits.

3.4.5. Other VOCs

3.4.5.1. Introduction

VOCs are one of the most commonly measured compounds when studying indoor air and this is because of their abundance. VOC's are often used in paint, carpet backing, plastics, and cosmetics. The United States Environmental Protection Agency (EPA) has found concentrations of VOCs in indoor air to be 2 to 5 times greater than in outdoor air. During certain activities indoor levels of VOCs may reach 1,000 times that of the outside air.

Toxicity varies among different VOC compounds, but for example LC50 for toluene is 5320 ppm (Svirbely *et al.*, 1943), 4/30 rats died during week's exposure 700 ppm m-xylene (Ungvary *et al.*, 1980) and LOAEL of n-hexane (acute exposure with serious effects) is 5000 ppm (Mast *et al.*, 1987 and 1988; De Martino *et al.*, 1987). 75 ppm acute exposure to toluene is enough to cause neurological symptoms in humans (Echeverria *et al*., 1991) and 266 ppm exposure abortions to rabbits (Ungvary and Tatrai, 1985). LOAEL of acute exposure with less serious effects for n-hexane is 1000 ppm (Bus *et al.*, 1979; Mast *et al.*, 1987) and for xylene it is 50 ppm (Ernstgard *et al.*, 2002).

For chronic exposure LOAEL for toluene is 29 ppm for less serious effects (Svensson *et al.*, 1992). Chronic exposure to toluene (88 ppm) increases spontaneous abortions among humans (Ng *et al.*, 1992) and 2.5 ppm increases susceptibility to infections among mouse (Aranyi *et al.*, 1985). Chronic exposure LOAEL (less serious effects) for xylenes is 14 ppm (Uchida *et al.*, 1993) and calculated chronic exposure LOAEL (less serious effects) for n-hexane is 58 ppm (Sanagi *et al.*, 1980).

3.4.5.2. Results

Table 3.4.5.2.1. Indoor exposures to VOCs and attribution to sources

STUDY	AM/sAM [A] (µg/m³)	GM/sGM[B] (µg/m³)	Median (µg/m³)	Range[C] (µg/m³)	Sources	Other info
EC Audit [1]					outdoor sources, tobacco smoke, building materials, furnishing, consumer products, equipment	Office buildings

- Netherlands, Total VOC	179					
- Denmark, Total VOC	135					
- United Kingdom, Total VOC	436					
- Greece, Total VOC	495					
- France, Total VOC	413					
- Czech Republic, Total VOC	518					
- Finland, Total VOC	118					
- Norway, Total VOC	528					
- Germany, Total VOC	146					
GerES [2]						
- Total VOC	401	336 /1.8		2665 (max)		
- n-Alkanes	70.0	54.3 / 2.0		498 (max)		n-hexane, n-heptane, n-octane, n-nonane, n-decane, n-undecane, n-dodecane, n-tridecane
- Iso-Alkanes	31.9	25.9 /1.8		293 (max)		isohexanes, isoheptanes, isooctanes, isononanes
- Cycloalkanes	19.1	13.8 /2.0		667 (max)		methylcyclopentane, cyclohexane, methylcyclohexane
- Carbonyls	25.9	20.3 /1.9		347 (max)		ethylacetate, n-butylacetate, isobutylacetate, methyl ethyl ketone, 4-methyl-2-pentanone, hexanal
- Alcohols	6.1	5.2 /1.7		56 (max)		n-butanol, isobutanol, isoamylalcohol, 2-ethylhexanol
- Aromatic compounds	165.7	133.9 / 1.9		1773 (max)		benzene, toluene, ethylbenzene, m-xylene, p-xylene, o-xylene, isopropylbenzene, n-propylbenzene, styrene, 2-ethyltoluene, 3-ethyltoluene, 4-ethyltoluene, 1,2,3-trimethylbenzene, 1,2,4-trimethylbenzene, naphthalene
- Chlorinated compounds	41.7	22.2/ 2.4		1631 (max)		1,1,1-tricholroethane, trichloroethylene, tetrachloroethylene, 1,4-dichlorobenzene
EXPOLIS[3]					VOC: combustion, tobacco smoke, wood and particleboard, building materials, cleaning	

					and maintenance products	
- Oxford						
· Total VOC	331.96	183.70/2.40	147.59			home
· Hexane	17.90	5.12/3.07	3.56		[5]Alkanes, alkenes: combustion	home
				[23]400 – 900 (max)		work place
· Nonane	6.41	2.90/2.87	2.46			home
· Decane	19.11	5.89/3.82	3.89			home
· Undecane	7.35	3.78/2.92	3.66			home
· Cyclohexane	3.38	4.16/2.46	3.06			home
· Toluene	39.13	14.48/3.66	11.17			home
· Ethylbenzene	3.76	2.23/2.20	1.67		[5]traffic emissions, paints, lacquers, printing inks	home
· m,p-Xylene	12.06	5.97/2.59	4.87		[5]traffic emissions, paints, lacquers, printing inks	home
· o-Xylene	6.43	3.68/2.28	2.89		[5]traffic emissions, paints, lacquers, printing inks	home
· Styrene	3.55	2.17/2.26	1.62			home
· Propylbenzene	4.97	1.71/3.27	1.01			home
· Trimethylbenzenes	13.31	6.18/2.97	4.46		[5]traffic emissions, paints, lacquers, printing inks	home
· 2-Methyl-1-propanol	3.22	2.03/2.06	1.75			home
· 1-Butanol	13.19	2.65/3.17	1.85		[5]plastics	home
· 2-Ethylhexanol	13.37	4.76/2.69	3.49			home
· Phenol	7.34	4.57/2.13	3.79			home
· 1-Octanol	4.84	3.06/2.08	2.56			home
· 2-Buthoxyethanol	8.73	4.66/2.42	3.52			home
· Hexanal	17.01	8.22/2.32	6.32			home
- Oxford, home, Benzaldehyde	17.48	6.46/3.55	6.32			home
· Octanal	8.81	4.74/2.18	5.20			home
· Trichloroethene	4.44	2.61/2.22	4.03			home
· Tetrachloroethene	4.66	2.42/2.35	2.10			home
· 1,1,2-Trichloroethane	3.80	2.39/2.06	1.93			home
· 1-Methyl-2-pyrrolidinone	11.13	6.81/2.19	2.07			home

- Athens						
· Nonane	5.6	1.4	4.0			home
	6.9	1.5	3.7			workplace
· Decane	13.8	2.3	9.6			home
	14.0	1.9	5.5			workplace
· Undecane	6.8	1.6	5.1			home
	8.5	1.6	1.2			workplace
· Cyclohexane	4.6	1.4	3.6			home
	7.3	1.7	1.9			workplace
· Ethylbenzene	7.7	1.9	6.9			home
	54.1	2.3	8.1			workplace
· m,p-Xylene	24.0	3.0	21.8			home
	121.2	3.4	26.2			workplace
· o-Xylene	8.3	1.9	2.0			home
	28.7	2.3	9.1			workplace
· Styrene	2.4		2.2			home
	7.1	1.3	3.1			workplace
· Propylbenzene	3.1		3.0			home
	4.1	1.2	3.2			workplace
· Trimethylbenzenes	18.2	2.7	16.1			home
	19.4	2.6	16.6			workplace
· 2-Methyl-1-propanol	7.0	1.8	5.8			home
	6.9	1.7	5.5			workplace
· 2-Ethylhexanol	3.6	1.1	2.9			home
	3.9	1.3	2.9			workplace
· Phenol	25.5	3.3				home
		9.8				workplace
· 2-Buthoxyethanol	14.8	2.2	7.8			home
	12.0	2.4	12.9			workplace
· Hexanal	11.8	2.2	8.1			home
	8.7	2.0	7.8			workplace
· Benzaldehyde	7.4	1.9	6.3			home
	11.0	2.3	10.8			workplace
· Octanal	5.1	1.4	3.1			home
	6.9	1.5	3.6			workplace
· Trichloroethene	11.4	2.0	8.2			home
	7.5	1.8	6.4			workplace
· Tetrachloroethene	7.7	1.4	4.0			home
	4.7	1.3	3.5			workplace
- Basel						
· Nonane	3.4	1.8/2.8	1.3			home
	24.4	1.5/5.3	1.0			workplace
· Decane	8.6	3.5/3.2	2.7			home
	62.9	3.2/5.9	1.9			workplace
· Undecane	8.8	2.9/3.3	2.1			home
	38.8	2.7/5.2	1.7			workplace
· Toluene	20.1	16.9/1.8	14.9			home
	32.4	15.4/2.4	13.0			workplace
· Ethylbenzene	2.7	2.1/1.8	1.8			home
	9.8	2.5/3.0	1.8			workplace
· m,p-Xylene	7.9	6.2/1.8	5.9			home
	34.6	7.1/3.3	5.1			workplace
· o-Xylene	2.7	2.1/1.9	1.9			home
	11.3	2.5/3.2	1.7			workplace
· Propylbenzene	1.0	0.7/2.1	0.6			home
	5.4	0.8/3.6	0.5			workplace

· Trimethylbenzenes	7.4	5.2/2.2	4.3			home
	75.1	5.5/4.3	3.8			workplace
· Hexane	1.5	0.7/3.9	0.7			home
	11.6	1.2/5.8	0.9			workplace
· Heptane	4.2	2.0/2.7	1.8			home
	65.8	3.3/4.6	2.4			workplace
· 1,1,1-Trichloroethan	13.0	1.3/4.1	0.8			workplace
· Trichloroethene	1.0	0.8/2.2	0.8			home
	2.2	1.0/3.0	0.9			workplace
· Tetrachloroethene	1.2	0.6/3.1	0.6			home
	1.4	0.9/3.0	1.2			workplace
- Helsinki						
· Total VOC	290.2	231.5/1.9	226.1		[10] cleaning products (18%), traffic (18%), long-range transport (17%), product emission/ fungi, mould (9%)	home
	432.1	152.9/2.6	125.7		[10] traffic (24%), product emission (21%), long-range transport (19%), air fresheners (7%)	workplace
· Nonane	2.1	1.3/2.4	1.3			home
	7.0	1.2/3.5	<LOQ^{D}			workplace
· Decane	5.2	2.5/3.1	2.6			home
	12.5	1.7/4.5	1.3			workplace
· Undecane	5.1	2.5/3.0	2.5			home
	11.8	1.6/3.9	1.3			workplace
· Cyclohexane	1.3	<LOQ^{D}/2.2	<LOQ^{D}			home
	1.5	<LOQ^{D}/2.2	<LOQ^{D}			workplace
· Toluene	20.3	14.6/2.1	13.5			home
	24.7	<LOQ^{D}/2.8	7.4			workplace
· Ethylbenzene	2.8	2.1/2.2	2.2			home
	15.0	1.9/3.5	1.7	[23]1384 (max)		workplace
· m,p-Xylene	7.8	6.1/2.0	5.9			home
	35.2	6.4/3.2	5.2	[23]1390 (max)		workplace
· o-Xylene	2.4	1.7/2.3	1.7			home
	15.0	1.8/3.5	1.6	[23]2779 (max)		workplace
· Styrene	1.1	<LOQ^{D}/2.0	<LOQ^{D}			home
	<LOQ^{D}	<LOQ^{D}/1.6	<LOQ^{D}			workplace
· Propylbenzene	<LOQ^{D}	<LOQ^{D}/1.8	<LOQ^{D}			home

	3.3	<LOQ[D]/2.8	<LOQ[D]			workplace
· Trimethylbenzenes	4.0	2.1/2.8	2.2			home
	13.8	2.0/4.1	1.7			workplace
· 2-Methyl-1-propanol	8.2	3.3/4.0	4.3			home
	2.8	<LOQ[D]/3.2	<LOQ[D]			workplace
· 2-Ethylhexanol	3.5	1.8/3.2	2.1			home
	2.6	1.4/2.9	1.4			workplace
· 2-Buthoxyethanol	2.0	<LOQ[D]/2.8	<LOQ[D]			home
	18.8	<LOQ[D]/2.8	<LOQ[D]	[23]2422 (max)	[23]spray lacquers, enamels, varnishes, latex paints, paint thinners, paint strippers, varnish removers	workplace
· Hexanal	11.5	8.4/2.4	8.9			home
	3.9	2.1/3.2	2.9			workplace
· Benzaldehyde	5.0	4.2/1.9	4.4			home
	4.9	3.9/2.3	4.7			workplace
· Octanal	4.2	3.2/2.3	3.9			home
	2.2	1.4/2.6	1.7			workplace
· Tetrachloroethene	<LOQ[D]	<LOQ[D]/1.7	<LOQ[D]			home
	<LOQ[D]	<LOQ[D]/1.7	<LOQ[D]			workplace
- Milan						
· Total VOC	689	519.4/2.1	434			home
	511	402.8/2	370			workplace
· Hexane	11.9	0.7/3.9	<LOQ[D]			home
	14.5	0.8/4.4	<LOQ[D]			workplace
· Nonane	6.9	3.5/2.7	2.6			home
	3.1	2.1/2.5	2			workplace
· Decane	7.5	4.2/3.1	4.1			home
	5.2	3.3/2.7	3.6			workplace
· Undecane	5.6	3.6/2.6	3.8			home
	3.6	1.9/3.1	2.4			workplace
· Cyclohexane	7	2.1/4.9	<LOQ[D]			home
	8.3	1.8/5.4	<LOQ[D]			workplace
· Ethylbenzene	10.7	7.5/2.3	6.7			home
	8.8	6.4/2.3	5.7			workplace
· m,p-Xylene	36.5	26.1/2.2	22			home
	28.8	20.4/2.5	18.8			workplace
· o-Xylene	11.5	7.8/2.5	7.3			home
	9.3	6/2.9	6.3			workplace
· Styrene	5.5	3/3.1	3.3			home
	2.9	1.8/3	2.6			workplace
· Propylbenzene	3.1	2/2.5	1.7			home
	2.3	1.6/2.4	1.6			workplace
· Trimethylbenzenes	17.7	13.5/2.1	12.1			home
	15.3	9/3.2	9.1			workplace
· 2-Methyl-1-propanol	16.9	3.5/5.9	5			home
	5.3	1.1/4.4	<LOQ[D]			workplace

· 2-Ethylhexanol	2.2	0.9/3	<LOQ[D]			home
	4.4	1.4/4.2	<LOQ[D]			workplace
· Phenol	0.8	<LOQ[D]	<LOQ[D]			home
	3.7	0.7/3.1	<LOQ[D]			workplace
· 1-Octanol	0.5	<LOQ[D]	<LOQ[D]			home
	0.5	0.5/1.1	<LOQ[D]			workplace
· 2-Buthoxyethanol	7.6	2/5.1	<LOQ[D]			home
	14.7	5.4/6	11.7			workplace
· Hexanal	4.7	1.8/4.2	<LOQ[D]			home
	2.2	1.1/3.1	<LOQ[D]			workplace
· Benzaldehyde	10.6	8.8/2	9.5			home
	12.3	9.4/2.6	10.5			workplace
· Octanal	3	1.5/3.4	<LOQ[D]			home
	3	1.3/3.6	<LOQ[D]			workplace
· Trichloroethene	89.4	6/5.6	7.7			home
	10.2	3.8/4.5	4.7			workplace
· Tetrachloroethene	12.8	7.6/2.7	7.4			home
	7.8	5/2.8	5.4			workplace
· 1,1,2-Trichloroethane	1.1	0.5/1.8	<LOQ[D]			home
		<LOQ[D]	<LOQ[D]			workplace
· 1-Methyl-2-pyrrolidinone	<LOQ[D]	<LOQ[D]	<LOQ[D]			home
	1.5	0.6/2	<LOQ[D]			workplace
· 1-Butanol	4.9	1.1/4.3	<LOQ[D]			home
	3.7	1/3.8	<LOQ[D]			workplace
- Prague						
· Total VOC	451.5	366.7/1.8	388.9			home
	563.6	314.3/2.8	282.2			workplace
· Hexane	35.1	21.8/3.8	15.0			home
	76.2	21.6/4.3	15.1			workplace
· Nonane	5.4	3.0/2.4	2.3			home
	4.1	3.0/2.1	2.3			workplace
· Decane	4.9	3.6/2.2	3.2			home
	3.8	2.8/2.0	2.9			workplace
· Undecane	6.5	3.9/2.6	3.3			home
	4.8	3.8/1.9	3.8			workplace
· Cyclohexane	30.7	9.3/3.6	7.1			home
	17.5	7.8/3.2	5.8			workplace
· Toluene	74.2	60.4/2.6	57.0			home
	69.1	32.3/2.8	31.4			workplace
· Ethylbenzene	9.1	6.0/2.4	6.3			home
	9.6	5.5/2.3	5.1			workplace
· m,p-Xylene	21.5	14.2/2.4	13.2			home
	25.5	14.8/2.3	13.5			workplace
· o-Xylene	7.1	4.8/2.3	4.7			home
	7.7	4.7/2.4	4.5			workplace
· Styrene	3.9	2.4/2.3	2.3			home
	3.7	2.7/2.1	2.2			workplace
· Propylbenzene	3.1	2.2/2.2	2.0			home
	2.7	2.3/1.1	2.2			workplace
· Trimethylbenzenes	12.1	7.9/2.3	7.1			home
	9.5	7.1/2.2	8.0			workplace
· 2-Methyl-1-propanol	11.7	7.6/2.4	7.7			home
	15.4	8.6/2.7	6.5			workplace
· 2-Ethylhexanol	6.8	5.1/2.1	5.4			home

	5.7	5.0/1.7	5.2			workplace
· Phenol	6.4	5.2/2.0	4.4			home
· 1-Octanol	6.8	6.7/1.3	7.0			workplace
· 2-Buthoxyethanol	8.5	6.1/2.2	4.4			home
	10.1	8.2/1.9	7.9			workplace
· Hexanal	10.3	8.0/2.0	7.4			home
	10.0	8.1/1.8	7.5			workplace
· Benzaldehyde	9.5	7.8/1.8	6.8			home
	9.1	8.2/1.6	8.1			workplace
· Octanal	4.5	3.7/1.9	3.9			home
	4.6	4.1/1.7	4.0			workplace
· Trichloroethene	13.6	4.7/4.0	4.2			home
	5.1	4.1/1.9	4.4			workplace
· Tetrachloroethene	12.3	0.4/2.5	8.7			home
	6.2	4.7/2.0	3.7			workplace
French IAQ[4]						
- Acetaldehyde			11.6 (10.8-12.3)	94.6 (max)	photochemicals, tobacco smoke, photocopiers, raw wood panels, particle boards	
- Acrolein			1.1 (1.0-1.2)	12.9 (max)		
- Hexaldehyde			13.6 (12.6-14.7)	368.5 (max)	particle boards, new books and magazines, paint, wood treatment products, untreated wood boards	
- 1,4-dichlorobenzene			4.2 (3.7-4.8)	4809.8 (max)	moth-repellent, deodorant, mole poison	
- Ethylbenzene			2.3 (2.1-2.5)	85.3 (max)	fuel, waxes	
- n-Decane			5.3 (4.8-6.2)	1774.1 (max)	white spirit, floor glues, waxes, wood varnish, cleaners	
- n-Undecane			6.2 (5.6-7.1)	502.1 (max)		
- Styrene			1.0 (0.9-1.0)	35.1 (max)	plastic materials, insulating materials, fuel, tobacco smoke	

- Tetrachloroethylene			1.4 (1.2-1.6)	684.3 (max)	carpets, mats, dry cleaning	
- Toluene			12.2 (11.4-13.7)	414.2 (max)	paints, varnishes, glues, inks, carpets, mats, silicone caulking, gasoline vapour	
- Trichloroethylene			1.0 (<LOQ-1.1)	4087.2 (max)	paints, glues, varnishes, degreasing agents	
- 1,2,4-trimethylbenzene			4.1 (3.7-4.4)	111.7 (max)	oil solvents, fuel, tar, varnishes	
- m/p-xylene			5.6 (5.1-6.0)	232.8 (max)	paints, varnishes, glues, insecticides	
- o-xylene			2.3 (2.1-2.5)	112.3 (max)		
- 2-butoxyethanol			1.6 (<LOQ-1.8)	60.6 (max)	paints, varnishes, lacquers, soaps, cosmetics, fungicides, herbicides, wood treatment products, silicone caulking	
- 2-butoxy-ethylacetate			<LOQ[D]	12.2 (max)		
- 1-methoxy-2-propanol			1.9 (<LOQ[D]-2.3)	170.1 (max)		
- 1-methoxy-2-propylacetate			<LOQ[D]	39.5 (max)		
ALSPAC					Painting, tobacco smoke	
- Total VOC	400 (551)			21-8392		main bedroom
	396 (573)			28-11401		living room
AirMex [12]						
- Total VOC				8 – 281		public buildings
- Catania, Total VOC				25 – 53		kindergartens
- Athens, Total VOC				19 -36		kindergartens
- Total VOC	5.3			>300 (max)		personal exposure
INDEX[6]						

- Styrene				1-6	[8,20,21,22]plastics, tobacco smoke, adhesives	indoor
				3-7		workplace
- Toluene				15-74	[9]outdoor sources, tobacco smoke, paints, thinners	indoor
				25-69		work place
- m,p-Xylene				4-37	[11,12,18]perfumes, pesticides, pharmaceuticals, paints, printed materials, rubber, plastics, leather, polyester	indoor
				25-121		workplace
- o-Xylene				2-12		indoor
				7-29		workplace
- Acetaldehyde				10-18	[7,8]alcoholic beverages, food, tobacco smoke, combustion, cooking, adhesives, coatings, lubricants, inks, rubber, paper, perfumes, dyes	indoor
	3					workplace
THADE[19]					VOC: pressed-wood, interior treatments, dry-cleaned fabrics, floor cover adhesives	
- UK, Toluene [13]		15.1				
- Italy, Toluene [14]		35.2				
- East-Germany, Toluene [15]	37.29					
- West-Germany, Toluene [15]	20.46					
- USA, VOC [16]				5.10 – 130		
- Italy, Total VOC [14]		514				
- Germany, Total VOC [17]				2000 – 3000		house after 2 months
				900 – 1300		house after 10 months

[A] AM = arithmetic mean and average concentration, sAM = standard deviation of arithmetic mean

[B] GM = geometric mean, sGM = standard deviation of geometric mean
[C] Range = minimum and maximum value
[D] LOQ = limit of quantification
[1] Bluyssen *et al.* 1996
[2] Survey 1985/86
[3] EXPOLIS 1999
[4] Kirchner *et al.* 2006
[5] Nieuwenhuijsen *et al.* 2002
[6] INDEX 2005
[7] WHO 1995
[8] EPA/Cal 2003
[9] WHO 2000
[10] Edwards *et al.* 2001
[11] IARC 1989
[12] ECETOC 1986
[13] Brown *et al.* 2002b
[14] Carrer *et al.* 2000
[15] Schneider *et al.* 2001
[16] Cox *et al.* 2001
[17] Pitten *et al.* 2000
[18] Fishbein 1988
[19] THADE 2004
[20] WHO 1983
[21] IARC 1994
[22] IARC 2000
[23] Edwards *et al.* 2004

3.4.5.3. Environmental and occupational guidelines & standards

WHO does not suggest ambient or indoor air guidelines for Xylenes or hexane, but does give an air quality guideline 0.26 mg/m^3 derived from LOAEL for continuous exposure, or a short term guideline of 1.0 mg/m^3 derived from its odour threshold.

EU and Finnish occupational exposure limits are given in table 3.4.5.3.1.

Table 3.4.5.3.1. Finnish occupational exposure limits (HTP-values, 2007)

	Direct. 2000/39/EC	**HTP, 2007**	**Direct. 2000/39/EC**	**HTP, 2007**
	8 h aver. (mg/m^3))	**8 h aver. (mg/m^3)**	**15 min (mg/m^3))**	**15 min (mg/m^3)**
Toluene	-	190	-	380
Xylenes, o-, p-, m-	221	220	442	440
n-Hexane	-	72	-	-

3.4.5.4. Discussion

Generally concentrations of different VOC compounds are quite low, but summing up the total VOC concentration can be significantly larger. Variation of the concentrations in different locations is quite great, so total VOC emissions can possibly have locally effect on sensitive individuals.

3.5. Radon

3.5.1. Introduction: What is Radon (ERRICCA 2)

Radon is a colourless, odourless, radioactive gas. It comes from the radioactive decay of radium, which in turn comes from the radioactive decay of uranium. Uranium acts as a permanent source of radon and is found in small quantities in all soils and rocks, although the amount varies from place to place. It is particularly prevalent in granite areas but not exclusively so. Radon levels vary not only between different parts of the country but even between neighbouring buildings.

Radon in the soil and rocks mixes with air and rises to the surface where it is quickly diluted in the atmosphere. Concentrations in the open air are very low. However, radon concentration in soil-gas can be very high, typically from less than 10 000 to 100 000 Bq/m^3. Entry of this radon-bearing air into living spaces is the main reason for elevated indoor radon concentrations. Mineral building materials also emit radon. Radon that enters enclosed spaces, such as buildings, can reach relatively high concentrations in some circumstances.

When radon decays it forms tiny radioactive particles called radon daughters which may be breathed into the lungs. If formed in air, these particles may be inhaled and some will be deposited in the lungs. The radiation emitted by them as they decay can give a high dose to lung tissues and damage them. Being exposed to radon and its decay products increases the risk of developing lung cancer. In addition, smoking and exposure to radon are known to work together to greatly increase the risk of developing lung cancer. It is important however to confirm that whilst radon causes lung cancer the majority of lung cancer risk is caused by smoking.

In addition to the risk from radon in air it is now recognised that some private water supplies contain levels of radon which should also be controlled. However, it is important to recognise that radon in water presents a far smaller health hazard than radon in air, both in term of the numbers of people exposed to high levels, and in terms of the risks to the most exposed individuals. Tap water supplied by public utilities is usually treated and poses no risk to the user. However it is advisable to have water from private bore holes in radon affected areas tested, and if necessary treated.

Radon is classified by International Agency for the Research on Cancer as known human carcinogen (IARC Group 1). The unit risk estimate for radon is $3\text{-}6*10^{-5}$ Bq/m^3 (Pershagen et al. 1994). Radon is second only to tobacco smoking as a cause of lung cancer, and radon in the indoor air accounts for about 9% of the deaths from lung cancer and about 2% of all deaths from cancer in Europe. (Darby *et al.* 2005) Radon is not known to cause any other health effects besides lung cancer.

3.5.2. Results

Table 3.5.2.1. Radon concentrations in dwellings determined in indoor surveys (Compiled from National Summary Reports at http://radonmapping.jrc.ec.europa.eu/ and UNSCEAR 2000)

COUNTRY AND POPULATION	NO. OF DWELLINGS SAMPLED	PERIOD AND APPROX DURATION OF MEASUREMENT	MEAN VALUE BQ/M^3	GEOM. MEAN BQ/M^3	GSD	PERCENT. >200 BQ/M^3	PERCENT. >400 BQ/M^3	MAX. OBSERVED BQ/M^3
Albania (3.4×10^6)	NA	NA	120	105	2.0			270
Austria (8.2×10^6)	16 000	1991-2002 3 months	97	61		12	4	8 325
Belgium (10.4×10^6)	10 447	1995-present 3 months	69	76	2.0	2.4	0.5	4 500
Bulgaria (8.45×10^6)	NA	NA		22				250
Croatia (4.5×10^6)	782	2003-05 1 year	68			7.2	1.8	751
Cyprus (0.76×10^6)	NA	NA	7	7	2.6			78
Czech Republic (10.2×10^6)	>150 000	1984-present 1 year	140	110		12-18	2-3	25 000
Denmark (5.5×10^6)	3 120	1995-96 1 year	53	64	2.2	2.9	0.2	590
Estonia (1.5×10^6)	NA	NA	120	92				1 390
Finland (5.2×10^6)	3 074	1990-91 1 year	120	84	2.1	12.3	3.6	33 000
France (62.2×10^6)	12 261	1980-2003 3 months	89	53	2.7	8.5	2	4 964
Germany (82.4×10^6)	>50 000	1978-2003 1 year	50	40	1.9	3	< 1	>10 000
Greece (10.8×10^6)	1 277	1994-98 1 year	55	44		3.1	1.1	1 700
Hungary (10.1×10^6)	NA	NA	107	82	2.7			1 990
Ireland (4.2×10^6)	11 319	1992-99 1 year	89	57		7.5	1.5	1 924
Italy (58×10^6)	5 361	1989-1998 1 year	70	52	2.0	4.1	0.9	1 036
Lithuania (3.7×10^6)	NA	NA	55	22				1 860
Luxembourg (0.49×10^6)	2 619	1993-2002 3 months	115		2.0		3	2 776
Netherlands (16.6×10^6)	952	1995-96 1 year	30	25	1.6	0.3	<0.0001	382
Norway (4.6×10^6)	37 400	1990-99 2 months	89			9	3	50 000
Poland (38.5×10^6)	2 886	1992-94 3 months	49		2.0	2	0.4	3 261
Portugal (10.7×10^6)	3 317	1988-91 2.5 months	86	39	2.2			3 558
Romania (22.7×10^6)	NA	NA	45					1 025
Slovakia (5.4×10^6)	NA	NA	87					3 750
Slovenia (2×10^6)	892	1993-95 3 months	87			7.7	2	1 890
Spain (40.5×10^6)	5 600	1990-2005 3 months	90	45	3.7	6	2	15 400

Sweden (9×10^6)	1 360	1991-92 3 months	108	56		9-13	3-4	3 904 (85 000)
Switzerland (7.6×10^6)	55 000	1980-2005 3 months	77			17	7	29 705
UK (61×10^6)	450 000	1980-2005 3-12 months	20			0.5	0.1	17 000

3.5.3. Environmental and Occupational Guidelines & Standards

Radon concentrations in the ambient air vary significantly in time and space, typically around the order of magnitude of 10 Bq/m^3. Similar levels would be desirable but are not achievable in the indoor air. WHO Air Quality Guidelines (2000) does not recommend any guideline value for radon, but suggests that remedial measures should be considered for buildings where the radon progeny concentrations exceed 100 Bq/m^3 as an annual average.

National indoor air radon guidelines are rather similar across Europe. The guideline values and respectively the preventive actions have gradually become stricter over the past decades. Differences, therefore, depend mainly on the year when the guideline came into effect. The Finnish regulation here is give as an example: Current national radon guideline value (action value) for older buildings is 400 Bq/m^3 and design criterion for all new buildings is 200 Bq/m^3. 400 Bq/m^3 is also set as an action value for all workplaces and as a limit value for all schools and day care centres.

* Radiation Act (592/1991) chapter 12 Natural radiation, section 45-49 latest amendment 22.12.2005
* Radiation Decree (1512/1991) chapter 7 Natural radiation, section 26-28 (pursuant to the Radiation Act); latest amendment 29.12.2005/1264
* Ministry for Social Affairs and Health Order on the Upper Limits for Radon Concentration in Places of Residence (944/1992) (pursuant to Radiation Act section 48 and Radiation Decree)

3.5.4. Discussion

Of all indoor air contaminants radon is the most unpredictable. Even at extremely high concentrations it is not detectable by the senses, it is of natural origin and penetrates into the building from the ground underneath. In spite of these obstacles, and thanks to large randomised surveys and harmonised monitoring methods, the levels of radon as well as its large (country averages) and small (building statistics) scale distributions are probably better known and more reliably comparable between the different regions of Europe than those of any other indoor air contaminant. Table 3.5.1.1 demonstrates that there are fivefold differences between the country averages and that the maximum levels may exceed country median values by more than three orders of magnitude. Distribution of the exposure to and risk of radon within the population is the most skewed of all common indoor air contaminants.

Because the radon level in any existing or new building is still quite difficult to estimate without actual measurement, most of the buildings with radon levels that exceed the guideline values are still unknown to the owners, occupants and national authorities, and, thus, outside of any remedial programmes. Pointing out all buildings which do not meet the guideline values would require monitoring of almost every building, renovating all detected non-compliance buildings would require convincing millions of building owners and occupants of the necessity of the work and costs, and finally, actually accomplishing these tasks would still

reduce the lung cancer risks of radon only marginally, because most of the radon induced lung cancers are caused by indoor air radon concentrations which do meet the current guidelines.

These facts clearly point out that the most effective radon mitigation policies will focus on new buildings and buildings undergoing major renovations, and would aim at reducing all indoor radon levels, also those that are otherwise well below, e.g., 200 or even 100 Bq/m^3.

3.6. Dampness / mould

3.6.1. Introduction

Extensive reviews have summarized findings demonstrating associations between dampness, moisture / mould and adverse health effects among building occupants (IOM, 2004; Bornehag *et al.* 2001, 2004, Jaakkola and Jaakkola 2004, Fisk *et al.* 2007). These health effects include onset of new asthma, prevalence of asthma and exacerbation of symptoms of pre-existing asthma in both children and adults.

Although an association between exposure to dampness/mould in buildings and adverse health effects has been demonstrated, the causal agents and the pathophysiological mechanisms are still largely unknown. It is plausible that the exposure leading to harmful effects consists of many parallel agents of both microbial and chemical origin. At present, there are no comprehensive data on such combined exposures, but a useful surrogate for the multifactorial exposures is “dampness”, or observations of excess moisture (such as mould, condensation, and water damage) in indoor environment. Population exposure of dampness mould is therefore estimated from prevalence of dampness/mould in buildings.

Survey based prevalence estimates of dampness/mould in residential buildings have varied widely, approximately from 2 to 85%, depending on the study design, climate, and definition used (Bornehag *et al.* 2001). It is likely that the prevalence of dampness/mould in the housing stock changes over time depending on economical situation and/or degree of housing deprivation and changes in the environment for several reasons. Therefore, the estimates of exposure should rely on relatively recent studies, taking into account differences in the study design, methodology, and definitions.

The main difference in the methodology of exposure assessment is whether the estimates are based on occupant self-reporting or home inspections made by trained staff. Trained inspectors are likely to provide more objective results than occupants’ self-reporting. Comprehensive data utilizing on-site home visits come from WHO LARES survey, and in addition there are some national surveys complementing information. In all, such data are available from nine countries.

3.6.2. Results

LARES survey was undertaken in eight European cities in 2002 and 2003, consisting of data on roughly 400 dwellings from each city (WHO 2007), and it relied on on-site home visits. According to the dwelling inspections conducted by trained surveyors, visible mould growth was detected in at least one room of almost 25% of all visited dwellings. Country specific data were not reported in the preliminary overview of LARES findings. Findings related to

other dampness/moisture related variables (including smell of dampness and signs of condensation) were not included in the report.

Brasche *et al.* 2003 reported signs of damp / mould in 21.9% of a 5530 studied dwellings in Germany. Specifically 9.3% of the dwellings had visible mould. In addition a study from Finland (Chelelgo *et al.* 2001) reported overall prevalence values for major or minor mould or water damage at 26-38% in Finland (depending on dwelling type). A more recent Finnish study (Pekkanen *et al.* 2007) reported moisture damage in the main living area at 20% (minor) and 10.5% (major), and visible mould in the main living area at 9.4%. However, the study by Pekkanen *et al.* was a case-control study of asthmatic (N=121) and non-asthmatic children (N=241), so the estimates may not be used for general population estimates.

Table 3.6.2.1. Prevalence of dampness/mould in European countries based on on-site inspections by trained staff.

Reference	**Definition of exposure**	**Prevalence %**	**Cities/Countries involved; comments**
WHO 2007 8 European cities surveyed in 2002-2003	Visible mould in at least one room - Visible mould in the bathroom - Visible mould in the kitchen	25% 14% 10%	Vilnius/Lithuania; Geneva/Switzerland; Forli/Italy; Ferreira/Portugal; Budapest/Hungary; Bratislava/Slovakia; Bonn/Germany; Angers/France; country specific values not reported
Brasche *et al.* 2003	Signs of damp/mould - Visible mould	22% 9%	Germany
Chelelgo *et al.* 2001	Moisture damage - Houses - Apartments	 38% 26%	Finland; Observations included signs of water leaks, condensation, and moisture damaged materials

3.6.3. Discussion

Studies based on on-site home inspections indicate that the overall prevalence of dampness/mould problems may vary between 20 to 30%. Larger variation with lower mean estimates has been reported based on occupant self-reporting. For example, The European community respiratory health survey (ECRHS) investigated self-reported dampness and mould in 38 study centres in 18 countries (Zock *et al.* 2000). During the year prior to the interview water damage was observed in 12.4% (range 4-32%), and mould or mildew in 22.1% (5-56%) of the dwellings. In general, the prevalence estimates bear uncertainty due to relatively small number of studies and/or variation in exposure definitions used in different studies, however, it appears that objective reports of indoor dampness based on on-site home visits provide more accurate estimates than occupant self-reporting.

4. Indoor air exposure modelling

4.1. Predictive models for indoor air exposures

The pollutant concentration in an indoor space depends, besides the quality of the ambient air, on the rate of pollutant emission and the rate at which the space is ventilated. These concentrations and the occupant time activity together drive the exposure patterns. Therefore the first component of predictive models for indoor exposures is a concentration model accounting for the behaviour of emissions from indoor sources. The current text reviews first modelling principles available in this area and then evaluates a number of actual models built on them.

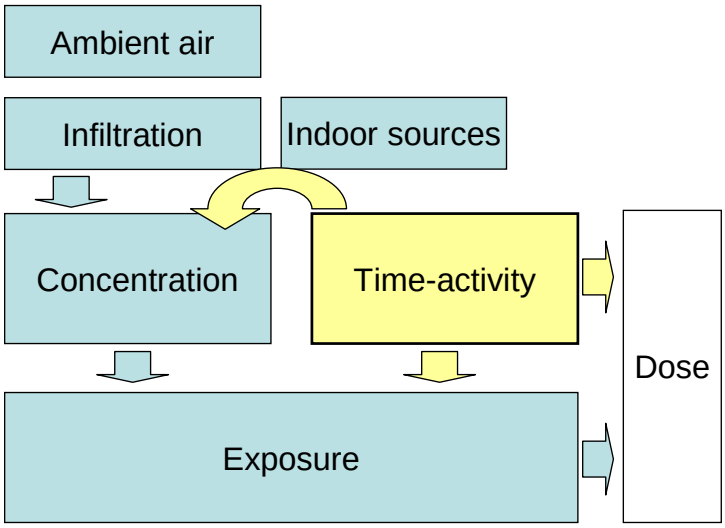


Figure 4.1.1. Diagram of the factors affecting exposure assessment and modelling in indoor environments.

Models for concentrations and exposures caused by indoor sources are evaluated in this chapter. Modelling the contribution and associated potential for protection from ambient air for the exposures are presented in the next subchapter.

4.2. Deterministic and probabilistic approaches

The main element in exposure modelling is the understanding of the physical principles affecting the investigated processes. Traditional deterministic models have been built on concise physical interpretation of the factors affecting exposures, which were determined prior to the development of a particular model. Such models must be used for estimates in a particular situation, but they have difficulties in capturing the full variability the variables. In addition, uncertainty in the values of the parameters used to make the estimates is not included. To overcome these limitations, probabilistic, or stochastic, numerical techniques

have been applied making it possible to present concentrations and population exposures as distributions rather than point estimates.

Probabilistic approaches are suitable for both empirical as well as physical approaches. The simplest example of the former is to present the distribution of observed concentrations instead of the average value. The second approach estimates indoor air concentration distributions based on distributional information for mass balance parameters such as indoor source emission rates, building volumes, and air exchange rates. The complexity and computational heaviness of computational fluid dynamic (CFD) equations restricts their use in the deterministic mode. Nevertheless, the outputs from a series of CFD model outputs can be described probabilistically and use to generate such inputs for further probabilistic assessment of exposures.

4.3. Indoor exposure modelling principles

4.3.1. Concentration models

Physical indoor air quality models are based on the principle of conservation of mass. The contaminant accumulation is equal to the difference between the mass released within or entering a particular space and the mass leaving that space. Pollutant concentrations are increased by emissions within a defined volume and by transport from other air spaces, including obviously the outdoors often as a major source of pollutants indoors. Concentrations are decreased, except by transport exiting the air space, by removal to chemical and physical sinks indoors, or by conversion of the contaminant to other forms which may be more or less harmful.

The two main methods for predicting indoor air flows and contaminant distribution are microscopic and macroscopic models. Microscopic models use computational fluid dynamics (CFD) to calculate the values of all relevant parameters, at closely-spaced points in all parts of the flow field, with a high degree of resolution. The major difficulties with CFD, especially when it is necessary to use three dimensional analysis, are that setting up the model, and identifying and specifying appropriate boundary conditions, is difficult and time consuming.

Relationships are in the form of one or more differential equations representing the rate of accumulation and the contaminant gain and loss.

4.3.2. Time-activity

Models to quantify human inhalation exposure to contaminants need to consider air quality in various microenvironments such as residences, workplaces, and outdoors. Because most people spend a large fraction of their time indoors, inclusion of an indoor air quality model is an important component of total or 24-h exposure modelling. Another important component of exposure modelling is consideration of human activity patterns, that is, where and how people spend their time during the conduct of their daily activities. In the past, simplifying assumptions have been made in modelling, such as a constant source rate over time, a negligible sink rate, steady-state conditions, or an isothermal air mass. In addition, activity patterns have not been considered or have been treated with simplistic assumptions. These may be appropriate assumptions under some limited circumstances but, to obtain greater

generalizability and to better understand the behaviour of indoor contaminants or the factors that affect exposures, it is important to examine situations in a more realistic manner.

Momentary concentrations exhibit substantial variability and steep gradients that can be captured only by computational fluid dynamics models – and even by them only when the momentary factors, e.g. fluctuations in the emission rates and effects of heat sources, occupant movements and wind are properly reflected in the model inputs. However, the occupant activities themselves are often tightly associated with improved mixing of the indoor air, e.g. in case of opening the windows, vivid activities, like cleaning, and even in steep gradients the mobility of the occupants decreases their importance by mixing the exposure between areas of different concentrations. Therefore the applicability of averaging indoor air quality models may be acceptable for exposures even in the case of non-complete mixing.

4.3.3. Model validation

Indoor air quality models often have to use non-validated components for example for sink and source terms. Guo (1993) listed five major problems areas:
(1) elusive model parameters, that results from attempts to model complex reality with a simple model, so that some adjustable parameters are necessary;
(2) confusion in parameter estimation methods, specifically uncertainty in selecting appropriate regression models to accurately fit various portions of emissions decay;
(3) uncertainty in scale-up and misleading scaling factors, for example, the commonly used ratio of air exchange rate to the chamber loading factor is incorrect unless the source is constant at steady state;
(4) unspecified valid range, particularly the limited time over which a model is valid and the limited degree of air turbulence for which a model is valid; and
(5) weakness in quantitative comparisons between models and observations, that is caused by an almost exclusive dependence upon graphic comparisons and a failure to use statistical methods.

Several of the listed items are related to the fact that model parameters estimated form a set of measurements using e.g. regression techniques or averages do not carry the variability to the model and while are suitable for screening models targeting population averages, actually should not be used in models attempting to capture a specific situation.

Evaluating a model for population exposure assessment it is more important to minimize bias while preferring methods maintaining and describing the variability than to attempt to use the most detailed physical approaches with missing or poorly estimated input data.

4.3.4. Model Characterisation

Several authoritative publications have been prepared about the appropriate exposure model characterization and documentation procedures. WHO International Programme on Chemical Safety (IPCS; WHO 2005) model harmonisation report also suggests a list of 10 questions about any exposure model, for which the model documentation should provide answers. These questions cover the following (Kephalopoulos *et al.*, 2007):

- General model description ((1) description of the model purpose and its components, (2) individual or population level analysis (level of aggregation), (3) modelled time resolution, and (4) applicability to diverse exposure scenarios);
- Model inputs ((5) description of data inputs);

- Model processes ((6) modelling tool methodology, (7) model code and platform, and (8) model performance and evaluation summaries);
- Model outputs ((9) description of model outputs and (10) model sensitivity and uncertainty).

4.3.5. Ventilation systems

The mass-balance equation based models are based on assumed complete mixing within each zone. When the ventilation rate is low and the indoor space has many activities and/or heat sources than induce air mixing, the complete mixing assumption is reasonable. However, in some cases high concentration gradients are created by non-complete mixing, potentially affecting exposure assessment, and some ventilation systems are particularly designed to prevent pollution spread. Some of the most typical cases are discussed shortly below.

Displacement ventilation system introduces fresh air to the floor level with optimally good spreading. The fresh air is slightly cooler than the room temperature and thus the thermal gradient makes the fresh air spread horizontally instead of mixing. Excess air is removed from the roof level. When working optimally, the thermal lift surrounding occupants produces a upward air flow, replacing the air surrounding the occupant from below from the fresh air and moving CO2 and any other odours and emissions of the occupant to the upper layer from where they are removed before complete mixing is taking place. Therefore the displacement ventilation minimizes the mixing of many emissions and produces optimal air quality with minimal air exchange rate.

Mixing ventilation on the other hand is designed to maximally mix the fresh air with the indoor air. In mixing ventilation buildings the assumption of complete mixing generally works well.

Mixing in natural ventilation varies depending on the temperature differences between indoor and outdoor air, outdoor wind velocity, the openings available for ventilation, and the general tightness of the building envelope. In cases when the air intake is evenly distributed between all rooms and ventilation rate is relatively low, the complete mixing assumption may hold quite well. On the other hand, when windows are opened, the flow pattern between rooms may become quite uneven.

Some mechanical ventilation systems use air recirculation, in which substantial part of the ventilation air is actually taken from the outflow air. This allows for removal of indoor air generated pollutants by filtering the air and improves the mixing, therefore making the conditions suitable for complete mixing assumption.

4.4. Critical review of indoor air quality modelling techniques

There are two general types of computer simulation techniques for studying airflow and contaminant transport in buildings – multi-zone modelling and room airflow modelling. Multi-zone modelling takes a macroscopic view of indoor air quality (LAQ) by evaluating average pollutant concentrations in the different zones of a building as contaminants are transported through the building and its HVAC system.

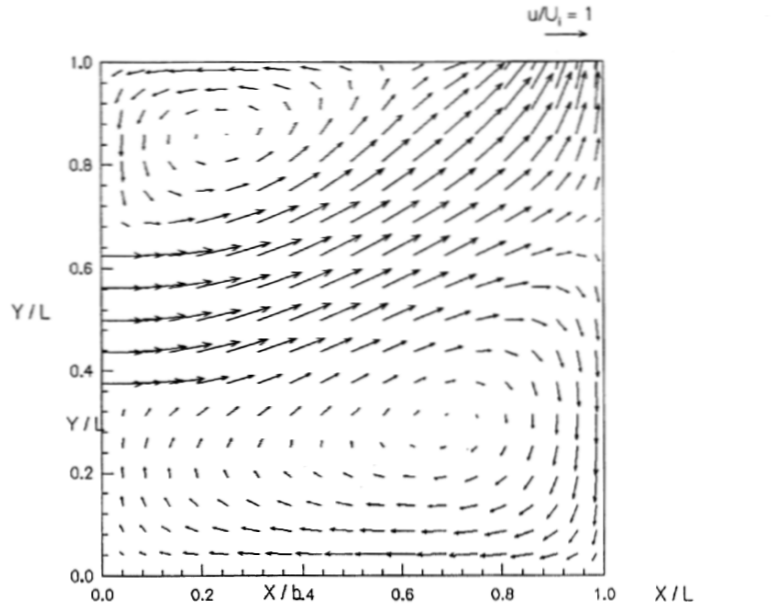
4.4.1. Fluid dynamics (CFD): airflow modelling

Room airflow modelling takes a microscopic view of IAQ by applying a computational fluid dynamics (CFD) program to examine the detailed flow fields and pollutant concentration distributions within a room or rooms. Each approach has strengths and limitations for studying different building ventilation and IAQ problems (Emmerich, 1997).

One of the most important recent efforts was International Energy Agency (IEA) Annex 20 "Air Flow Patterns within Buildings" (Moser 1991). The objective of the Annex was to evaluate the performance of both CFD and multi-zone airflow simulation techniques and to establish their viability as design tools. Research under the Annex included simulation and measurement in the following areas: air supply device, room flow field, simplified methods, and evaluation. Moser's conclusions include:
-CFD simulations are useful when values of difficult-to-measure variables are needed in all points of the flow field.
-Simulations are useful to study trends (sensitivity of flow patterns to small changes).
-Simulations are useful to predict airflow patterns for critical projects, i.e. when neither similar experience nor measured data exist (such as large spaces, unconventional ventilating systems, and strong buoyancy effects).

Topics discussed in the literature include room airflow case studies involving calculation of airflow patterns, temperatures, ventilation system performance and thermal comfort for various ventilation systems, strategies and room configurations; flow from diffusers; modelling occupants; exhaust ventilation system performance; wind pressure distribution for flow around buildings; thermal and airflow performance in large enclosures; pollutant transport including particles and moisture; air curtains; pressure loss in ducts; coupling of CFD programs with multi-zone airflow models and/or building energy simulation models.

An example of the output from a CFD model is shown below (Ayad, 1999). The model describes instantaneous air movements within the space in a given moment.



Vector plot for room flow with openings at windward wall center and far end adjacent wall

A schematic presentation of the inputs needed for CFD modelling is depicted in the figure below (Allocca et al, 2003). Important variables are the physical dimensions of the space as well as objects affecting the air flow, all heat sources (and in some cases sinks too), and the momentum of air intake. Heat sources may exhibit delays due to their mass and thermal insulation that affect the speed at which the changes in the electrical power consumption are reflected to the heat input to the air flow system.

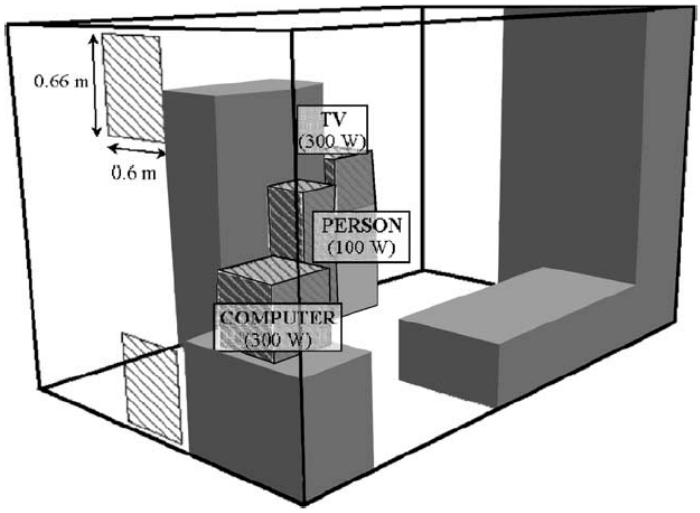


Fig. 2. Indoor stack model for single-sided ventilation study in CFD.

4.4.2. Zonal models (from Stewart 2007)

Macroscopic models mainly include multi-zone and zonal models.

Multi-zone models require the user to identify and describe all the zones (rooms) of interest and the links (e.g. flow paths) between those zones (and with the outside air). They generally take into account mechanical ventilation, tightness of buildings, terrain, shielding and climate conditions. The outputs of these models include air flow rates across the envelopes, between the rooms and through the mechanical ventilation system. (Li, 1993).

The network of links is described by a series of flow equations which are solved simultaneously to provide air flow rates between rooms. Assuming that air flow patterns are unaffected by any contaminant present, a mass balance calculation in each zone at each time step can be included in a multi-zone model to predict the variation of concentrations with time. Multi-zone models use average or representative values for the parameters describing the conditions in a single zone (pressure, temperature, etc.). While they may be used to predict air flows into and out of a room and the mean pollutant concentration within a room, they cannot resolve air flow patterns or variations in temperature or pollutant concentration within a room. If knowledge of such variations is important, then multi-zone models will not be suitable. Examples of this type of model which are in widespread use are COMIS (Feustel and Raynor Hoosen, 1990, Feustel 1999) and CONTAM (Walton 1997).

Zonal models may be used where it is required to model variations within a single zone. A room is divided into a small number (tens to hundreds) of zones, each of which has single representative values for pressure, temperature and pollutant concentrations. Zonal models can be used to predict airflow and temperature variations within a room providing it is feasible to predict the main driving flows, which may be air jets from fans or ventilators or

thermal plumes from heaters or other warm surfaces. Published details of current zonal models suggest they have only been applied to single rooms with a limited set of driving forces. Details have been published of their use to predict airflows and temperature distribution within rooms (Inard *et al.* 1996) and, more recently, to predict indoor air pollutant distributions (Musy *et al.* 1999).

Combined models: Combining the capabilities of low and higher resolution models offers the potential to use higher resolution when appropriate and low resolution for the rest of a building. For example, some researchers have succeeded in coupling multi-zone models with CFD (Schaelin *et al.* 1002, Clarke *et al.* 1995), but the combined models still suffer from the inherent difficulties of the CFD approach.

4.4.3. Some sample models

4.4.3.1. Existing indoor exposure models

CONSEXPO 4
AIRPEX
BEAT
CALENDEX
E-FAST
EUSES
EXPOLIS Simulation model
LIFELINE
MCCEM
NOTITIA/CARES
PROMISE
SHEDs
SPEED
TRIPM
WPEM

Consider also:
ComET
First Principle Emission Models
EUROPOEM
SWIMODEL

http://www.epa.gov/oppt/exposure/pubs/screen.htm Screening Level Tools include:

- Chemical Screening Tool for Exposures and Environmental Releases (ChemSTEER),
- Estimation Program Interface Suite (EPI Suite), Exposure and Fate Assessment Screening Tool (E-FAST),
- Pesticide Inert Risk Assessment Tool (PIRAT), and
- ReachScan.

http://www.epa.gov/oppt/exposure/pubs/higher-tiers.htm The Higher Tier Tools include:

- Internet Geographical Exposure Modelling System (IGEMS),
- Wall Paints Exposure Model (WPEM), and
- Multi-Chamber Concentration Exposure Model (MCCEM).

http://www.epa.gov/iaq/schools/ Technical tools:

- Healthy School Environments Assessment Tool (HealthySEAT)
- Indoor Air Quality Building Education and Assessment Model (I-BEAM)
- School Advanced Ventilation Engineering Software (SAVES)

I-BEAM is a computer software package for use by building professionals and others interested in indoor air quality in commercial buildings. However, much of the information will also be useful to those interested in indoor air quality in schools. I-BEAM contains text, animation/visual, and interactive/calculation components that can be used to perform several tasks including: conducting an indoor air quality (IAQ) building audit; diagnosing and resolving IAQ related health problems; establishing an IAQ management and maintenance program to reduce IAQ risks; planning IAQ compatible energy projects; protecting occupants from exposures to construction/renovation contaminants; and calculating the cost, revenue, and productivity impacts of planned IAQ activities.

Mass balance models/ www.exposurescience.org:
A Total Human Exposure Model (THEM)
Multi-Chamber Indoor Air Quality Model (MIAQ)
Human Exposure Research Package (heR)

5. Building as shelter from outdoor air pollution

Atmospheric outdoor air particles are associated with approximately 350000 premature deaths annually in the EU countries (EU25) (Watkiss *et al.*, 2005). The European Community Thematic Strategy on air pollution aims by 2020 to cut these deaths by almost 40% from the 2000 level (Commission press release IP/05/1170 21/09/2005), which implies a corresponding reduction in population exposures. In additions to ambient air PM also ozone has been unequivocally associated with significantly increased mortality and morbidity.

While the focus of ambient air quality management is in efficient reduction of primary PM emissions and gaseous emissions contributing to secondary PM and ozone formation in the atmosphere, the large health effects and associated costs and the straightforward challenges in solving the problem by emission reductions makes the further development of building envelopes and ventilation systems towards improved protection of the occupants from outdoor air pollution very attractive.

For the reactive ozone, the sealed envelope of a modern building, its balanced two way mechanical ventilation system and internal building surfaces are, by themselves already effective absorbents, which reduce the indoor ozone levels to a fraction of the outdoor air level. The same components provide also efficient protection against the coarse (> 2.5 µm by particle mass) and ultrafine (< 0.1 µm by particle count) ambient air particulate matter fractions. The highest mortality impact, however, has been associated with the $PM_{2.5}$ mass fraction, which penetrates effectively into most naturally ventilated indoor environments, in particular, when windows are kept open.

In balanced mechanical ventilation systems mechanical or sometimes electrostatic filters are used extensively in to remove particles from incoming outdoor air and from recirculated indoor air. Historically, filters were installed to reduce the accumulation of deposited particles on heating, ventilating and air conditioning (HVAC) equipment which diminished airflow rates and impeded heat transfer. Within the last two decades, the potential benefits to health have been increasingly recognized as a primary purpose of filtration. Janssen *et al.* (2002) showed that association of respiratory and cardiovascular incidences with ambient air PM_{10} is significantly reduced in communities with a high frequency of air conditioned homes vs. communities, where summertime cooling is achieved by open windows. Hänninen *et al.* (2004b and 2005) have shown that in Helsinki the reduced infiltration of ambient air $PM_{2.5}$ into buildings built after 1990 vs. buildings built before 1990 reduced the occupants' exposure to urban ambient air $PM_{2.5}$ as much as eliminating all traffic sources from the Helsinki Metropolitan area.

Other potential benefits of filtration include reducing unsightly soiling of indoor surfaces and reducing the deposition and accumulation of organic matter on surfaces such as HVAC ducts where it can become odorous or provide a substrate for microbiological colonization. (Fisk *et al.*, 2002)

6. General Conclusions

It is important to realise, when reading and comparing these data, that although the comparability within one study may be good, there is no justification for comparing the data between the studies. This is not so much due to the differences in air sampling and chemical analyses – these may compare quite well – as it is due to the differences in the study time, objectives and designs. It is fair to say that comprehensive indoor air quality data are not available from any European country, nationally representative indoor air quality data for many indoor air contaminants is available from only Germany and France (time series from only Germany; GerES I – IV, 1986 – 2006), and comparable representative data from across Europe only for radon.

The poor representativeness, heterogeneity and the sheer absence of indoor air pollution data from most of the European countries presents huge obstacles for indoor air epidemiology (which is available at satisfactory levels for only environmental tobacco smoke, nitrogen dioxide and radon), risk assessment and policy development. These, however, are challenges for the EnVIE WP4 report.

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