Environment International, Vol. 8, pp. 117-127, 1982

0160-4120/82/070117-11$03.00/0

INDOOR AIR POLLUTION DUE TO ORGANIC GASES AND VAPOURS OF SOLVENTS IN BUILDING MATERIALS

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The emission of organic gases and vapours of solvent type from 42 commonly used building materials was measured under standard atmospheric conditions. An average of 22 compounds was found in the air around each building material, and the total concentration of gases and vapours was from 0.01 to 1410 mg/m^3. The average arithmetic emission rate was 9.5 mg/m^2 h, and 52 different compounds were identified. A mathematical model was established for the indoor air concentrations of pollutants originating from building materials. The model was tested on three model rooms constructed from the materials investigated. The calculated total air concentrations of gases and vapours in the three rooms ranged from 1.6 to 23.6 mg/m^3, and the number of compounds in the air from 23 to 32. These concentrations and number of compounds did not differ from those found in actual rooms similar in size and construction to the model rooms. The risks of health effects due to the compounds identified from the building materials were investigated, and criteria for future air quality standards are discussed. It is concluded that the possibility of negative health effects cannot be neglected, especially not for the more sensitive minority of the general population.

Introduction

For several years both moderate and severe complaints about indoor climate have been registered among occupants of modern buildings. Formaldehyde in the air or malfunctioning ventilation and climate systems are in most cases found to be the main reason for the complaints. Some complaints are, however, reported from rooms in which these and other technical explanations can be excluded.

The symptoms reported by the occupants are often similar to those resulting from exposure to low concentrations of irritating gases and vapours, e.g., solvent type organic compounds, and the symptoms are often found in new buildings or renovated older buildings using construction materials with unknown effects on the indoor climate. If the complaints are related to exposure to low concentrations of gases and vapours originating from such materials, their impact could be increased through the general effort to decrease domestic energy consumption by reduction of ventilation rates and through the introduction of huge volumes of new types of construction and installation materials.

The occurrence of organic gases and vapours of the solvent type in indoor air was demonstrated by measurements of their concentrations in seven new houses and 39 older dwellings (Mølhave, 1978a, 1979). The emission of the same compounds from common building materials was later measured in our laboratory. Some preliminary results of examinations of the first 32 building materials have been reported (Mølhave, 1978b).

The present paper summarises the investigation of all 42 building materials, and describes a mathematical model for the relation between emission rates of gases and vapours from building materials and the air concentrations of the same compounds. Furthermore, the influence of organic gases and vapours on the indoor climate is discussed. The investigation was performed in cooperation with the Danish Institute of Building Research (SBI), and funded by the National Health Foundation.

Materials and Methods

The measurements of gas and vapour emissions from construction materials have previously been described in detail (Mølhave, 1978b). In short, the concentration of gases and vapours was measured in the air around 0.25

m^2 of test material in a 1-m^3 stainless steel tank supplied with 0.69 l fresh air per min [1.0 air change per 24 h at 21.1°C (SD: 1.7°C)] and 35%–40% relative humidity. The exhaust air from the box was analysed by combined gas chromatography–mass spectrometry (GC–MS) for the content of gases and vapours of solvent type.

Industrial gas detection tubes were applied for aldehydes, especially formaldehyde, and for amines. The odour intensity and the air quality was judged by a trained panel. The odour quality scale used by the panel was from −1 (totally unacceptable), zero (neutral, indeterminable character) to +1 (totally acceptable). The intensity was measured on a scale from zero (no odour) to one (overwhelming, strong odour). The emission of Ra-222 from each material was measured by N. Jonassen, The Danish Technical University. The detection limit was 0.05 atoms Ra-222/kg/sec.

The statistical distribution of the results could be approximated by either normal or log-normal distributions. In consequence, either arithmetic (AM) or geometric (GM) means were used. The corresponding standard deviations were designated as SD or GSD. Linear regression analysis was used for the examination of correlations.

The 42 building materials investigated were selected by SBI according to an international classification system (CIB, 1972). Only materials produced for use as construction materials were included. The 42 materials are shown in Table 1. Surface materials such as carpets, wallpaper, paints, and so on, constituted 67% of the 42 materials. Tightening, sealing, or puttying materials

Table 1. The 42 materials studied and the classification of their normal use.

No.	Type of Material	Description	Group Classification[a]
1	Particle board	Urea-formaldehyde glued	3
2	Particle board	Urea-formaldehyde glued	3
3	Plaster board	12 mm, paper-coated	3
4	Calcium silicate board	22.8-mm board	3
5	Sealing agent	Plastic, compound	5
6	Sealing agent	Plastic, silicone compound	5
7	Sealing agent	Putty, strips 5 × 7 mm^2	5
8	Insulation batch	Mineral wool	3
9	Particle board	Urea-formaldehyde glued	3
10	Plywood lining	Teak	3
11	Woodfiber board	12-mm board	3
12	Tightening fillet	Neoprene/polyethylene	5
13	Tightening fillet	Plasticized PVC/polyethylene	5
14	Felt carpet	Synthetic fibers/plastic backing	1
15	Felt carpet	Synthetic fibers	1
16	Wall paper	Vinyl and paper	3
17	Wall paper	Vinyl and glass fibers	3
18	Wall paper	Printed paper	3
19	Floor covering	Linoleum	1
20	Wall and floor glue	Water-based EVA	3
21	Texture glue	Water-based PVA	1
22	Filler	PVA glue/cement	3
23	Filler	Sand, cement, water-based hardener	3
24	Wall covering	Hessian	3
25	Floor covering	Synthetic fibers/PVC	1
26	Floor covering	Rubber	1
27	Wall paper	PVC foam	3
28	Tightening fillet	Heat expanding neoprene	5
29	Fiber board	Glass fiber reinforced polyester	4
30	Paint	Acryllatex	3
31	Floor varnish	Epoxy, clear	1
32	Floor varnish	2-component, isocyanate	1
33	Floor varnish	Acid hardener	1
34	Wall covering	PVC	3
35	Laminated board	Plastic	4
36	Floor covering	Soft plastic	1
37	Insulation foam	Polystyrene	3
38	Insulation foam	Polyurethane	3
39	Floor covering	Homogeneous PVC	1
40	Floor and wall covering	Textile	3
41	Floor and wall covering	Textile	3
42	Cement flag	Concrete	3

[a] Group classification as in Table 6.

Table 2. The results of analysis of the air around 42 building materials. Type of material: C = used inside the construction; S = used on surface; P = putty or sealing compound. Other compounds: • not examined; – no reaction; + trace amounts.

No.	Type	Concentration (mg/m³)	Specific Emission (mg/m²h)	Number of Compounds: Detected	Number of Compounds: Identified	Other Compounds: Formaldehyde	Other Compounds: Amine (ppm)	Other Compounds: Ra 222 atoms/kg • s	Odour: Intensity	Odour: Quality	Number: Expected Carcinogens	Number: Airway Irritants	Number: Odorous Compounds
1	C	1.56	0.12	29	10	•	•	–	0.50	+0.30	5	7	2
2	C	1.73	0.13	28	11	•	•	–	0.42	+0.08	6	7	3
3	S	0.66	0.026	17	3	•	•	0.22	0.46	–0.13	3	3	1
4	S	1.69	0.064	20	5	•	•	–	0.38	–0.03	4	3	3
5	P	169	72	35	19	•	•	–	0.82	–0.38	3	7	4
6	P	77.9	26	23	4	•	•	–	0.46	–0.69	1	1	2
7	P	1.38	0.34	20	0	•	•	–	0.06	–0.07	0	0	0
8	C	0.38	0.012	13	1	+	–	2.0	0.54	–0.16	1	1	1
9	C	3.56	0.14	24	7	–	–	–	0.88	–0.21	5	6	4
10	S	1.07	0.044	16	0	–	–	–	0.65	–0.43	0	0	0
11	S	2.96	0.12	23	7	–	–	–	0.74	–0.40	4	5	3
12	P	0.81	0.16	19	9	–	–	–	0.50	–0.06	4	4	3
13	P	1.05	0.056	18	0	–	3	–	0.78	–0.45	0	0	0
14	S	3.15	0.11	24	11	–	–	–	0.41	–0.23	3	5	1
15	S	1.95	0.080	28	8	+	–	–	0.41	–0.22	3	5	1
16	S	0.95	0.040	21	5	–	–	–	0.60	–0.32	2	3	2
17	S	7.18	0.30	32	12	–	–	–	0.64	–0.18	3	7	3
18	S	0.74	0.031	12	2	–	–	–	0.46	–0.27	1	1	0
19	S	5.19	0.22	21	6	–	–	–	0.80	–0.37	1	3	2
20	P	1410.0	271.0	34	11	–	–	–	0.72	–0.27	3	2	3
21	P	9.81	2.1	29	18	–	–	–	0.72	–0.15	4	10	3
22	P	57.8	10.2	9	2	–	–	8.0	0.85	–0.72	1	1	0
23	P	3.95	0.73	31	15	–	–	2.0	0.88	–0.22	5	9	4
24	S	0.09	0.0054	7	1	–	–	–	0.65	–0.15	1	0	0
25	S	1.62	0.12	12	6	–	–	–	0.39	–0.35	3	2	2
26	S	28.4	1.4	30	7	–	–	–	1.00	–0.37	2	3	0
27	S	5.50	0.23	25	12	–	–	–	0.75	–0.33	1	6	1
28	P	0.35	0.016	12	2	–	–	–	0.63	–0.30	1	1	0
29	C	0.40	0.017	6	3	–	–	–	0.68	–0.59	2	3	0
30	S	2.00	0.43	23	5	–	–	–	0.86	+0.28	2	3	2
31	S	5.45	1.3	42	10	–	–	–	0.81	–0.37	3	8	2
32	S	28.9	4.7	10	8	–	–	–	0.80	+0.06	2	4	3
33	S	3.50	0.83	10	3	–	–	–	0.55	+0.09	0	3	0
34	S	2.43	0.10	19	5	–	–	–	0.40	+0.22	2	4	1
35	C	<0.01	<0.0004	0	0	+	–	–	0.54	–0.07	0	0	0
36	S	3.84	0.59	5	1	–	–	–	0.63	–0.33	1	0	0
37	C	40.5	1.4	15	5	–	–	–	0.61	–0.42	2	4	2
38	C	3.59	0.12	5	2	–	–	–	0.50	+0.03	1	1	0
39	S	54.8	2.3	62	27	–	–	–	0.85	–0.33	5	15	6
40	S	39.6	1.6	61	23	–	–	–	0.85	–0.33	5	17	7
41	S	1.98	0.083	28	15	–	–	–	0.50	–0.52	4	9	3
42	C	1.45	0.073	12	9	–	–	21	0.67	–0.68	4	7	3

represented 14%, and 19% were materials normally hidden within the house construction, e.g., concrete and insulation materials.

The materials, which were all delivered directly from production or factory stock, were cut in standard A2-format (420 × 594 mm²) by the producer and wrapped in heavy polyvinylidenchloride foil to prevent contamination. Liquid or soft materials were sent in original containers. These materials were applied to cleaned aluminum boards in our laboratory and were allowed to dry in a hood for 24 h before being tested. The average (AM) weight of each sample was 1.7 kg ranging from 0.02 to 8.6 kg. The average (AM) surface of the samples (including saw cut) was 7260 cm², ranging from 1690 to 13,620 cm².

Results

The general results of examination of the first 32 materials as described in the preliminary report (Mølhave, 1978b) was only slightly modified by the examination of 10 more materials. Table 2 comprises the results of the measurements.

The average concentration of organic gases and vapours of solvent type in the air around the 42 materials was 3.2 mg/m³ (GM). The range was 0.01–1410 mg/m³, and modus between 1.0 and 3.2 mg/m³. Figure 1 shows the distribution of emission rates in mg/m²h for all 42 materials. The average emission rate (GM) was 0.25 mg/m²h (GSD: 11.7) ranging from more than 270 to less than 10^{-3} mg/m²h with modus between 0.1 and 0.5 mg/m²h.

The average number (AM) of compounds detected in the air around each of the 42 materials was 22, and on the average (AM) 10 of these were chemically identified. On average, this corresponds to an identification of 73% of the total amount of compounds in each sample. The 52 different compounds that were chemically completely identified are shown in Table 3. Alifatic and aromatic hydrocarbons comprised 17 and 18 of the 52 compounds, respectively. Table 4A shows the 10 compounds most frequently identified, and in Table 4B the 10 compounds found to have highest average air concentration are listed. Only toluene, 2-xylene, and 3-xylene are found in both tables.

The formaldehyde gas detection tubes reacted positively to air from three materials, and the amine gas detection tubes reacted to the air around two materials (Table 2). Radon emission could be measured from five materials, but only the emission from concrete flag (No. 42) exceeded 10 atoms/kg/sec.

The distribution of the odour acceptability of the 42 air samples as voted by the panel is shown in Fig. 2. The average acceptablity was −0.23 (SD: 0.24), corresponding to moderately unacceptable odour. Only seven air samples of 42 (17%) were rated positive. The average (AM) odour intensity (Fig. 3) of the air around the 42 building materials was 0.61 (SD: 0.20) on a scale from 0 (no odour) to 1 (strong odour). The distribution of the intensities is shown in Fig. 3. Only for two (5%) of the 42 materials did the background odour of the equipment exceed the odour intensity of the material.

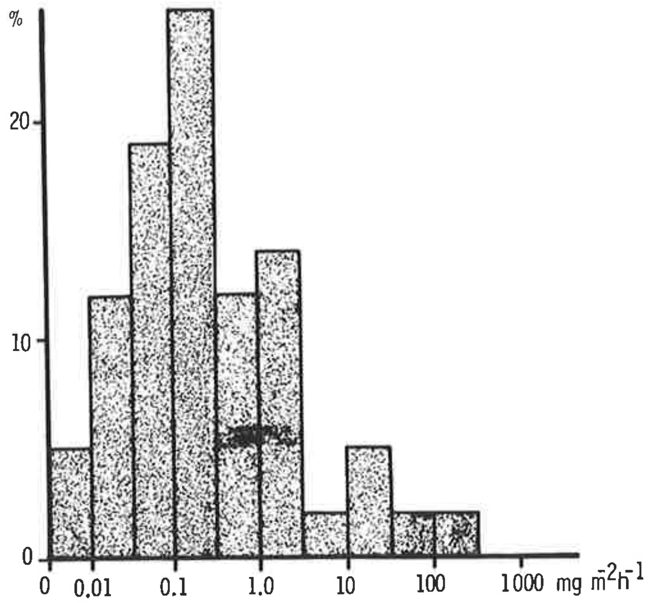

Fig. 1. The distribution (%) of emission rates (mg/m² h) of solvent type organic gases and vapours from 42 building materials. The average emission (GM) rate was 0.25 mg/m²h.

Discussion

Gases and vapours from building materials

Organic solvents are widely used to bring other compounds into a solution in which they can be handled and applied in industrial processes. Most industrial products have been in contact with solvents, and human ingenuity is always increasing the number of different solvents and the ways they can be brought into homes. The physical-chemical spectrum of compounds to be expected in the indoor air is therefore very broad, and not all of these compounds could be detected in the present investigation. In general, only nonpolar or slightly polar compounds with boiling points between 25 and 250 °C could be detected, and within that range the detection limit was high for reactive, acetic, or basic compounds. The presence of formaldehyde and triethylamin, which are potential strong irritants, was therefore indicated with gas detection tubes.

The total concentration of organics reported here is the sum of the concentrations of all individual compounds detected by the GC–MS method. This total is not expressed in methane equivalents, as is the case when total hydrocarbon concentrations are measured with integrating FID-detectors, which do not separate individual compounds. Due to the low response factor for methane on a FID-detector, higher total concentra-

Table 3. Preliminary toxicological evaluation of 52 compounds identified in the air around 42 common building materials.

Compound	Danish MAC value[a] (mg/m³)[f]	Suspected Biological Effect: Carcinogenicity[b,c,f]	Mucous Membrane Irritation[d,f]	Estimated Odour Threshold[e] (mg/m³)[f]
Alkanes				
n-Hexane	360	–	–	550
n-Heptane	1600	–	(+)	480
n-Octane	1450	–	(+)	(100)
iso-Octane	(1450)	–	+	(100)
n-Nonane	1050	–	(+)	60
n-Decane	–	AZ 77500[g]	(+)	11
n-Undecane	–	AZ 77500[g]	(+)	23
n-Dodecane	–	AZ 77500[g]	(+)	37
3-Methylheptane	(1450)	–	–	(100)
Alkenes				
1-Heptene	–	–	–	(5)
1-Octene	–	–	?	5
1-Nonene	–	–	(+)	(5)
1-Decene	–	–	(+)	(5)
Terpenes				
α-Pinene	–	WZ 63500[g]	+	0.016[k]
Δ-3 Carene	–	WZ 63500[g]	(+)	(0.01)[k]
Limonene	–	WZ 63500[g]	(+)	0.01[k]
Cyclohexanes				
Ethyl methyl cyclohexane	–	–	+	(100)
Aromatic compounds				
Toluene	375	XS 52500[g]	–	44.3
2-Xylene	435	–	–	4.6
3-Xylene	435	–	–	0.83[k]
4-Xylene	435	–	–	3.1
ethylbenzene	435	DA 07000[g]	+	0.4 [k]
1,2,4-Trimethylbenzene	120	–	(+)	0.45[k]
1,3,5-Trimethylbenzene	120	–	(+)	4.5
1,2-Ethylmethylbenzene	(120)	–	(+)	(1)
1,3-Ethylmethylbenzene	(120)	–	(+)	(1)
1,4-Ethylmethylbenzene	(120)	–	(+)	(1)[k]
n-Propylbenzene	(245)	–	(+)	(0.1)
iso-Propylbenzene	245	–	+	0.12 [k]
1,2,3,4-Tetramethylbenzene	–	–	+	0.087
1,3-Diethylbenzene	–	–	(+)	(0.1) [k]
n-Pentylbenzene	–	–	(+)	(0.1) [k]
Benzaldehyde	–	–	+	3.7
Styrene	210	WL 36750[g,h,i,]	+	2.1
Methyl styrene	480	–	+	0.18[k]
Ketones				
2-Propanone	600	AL 31500[g,h]	–	212
2-Butanone	440	EL 64750[g]	+	84
3 Methyl 2 buthanone	(700)	–	(+)	(10)
4 Methyl 2 pentanone	(230)	–	(+)	11
2 Pentanone	(700)	–	+	(10)
Alcohols				
Ethanol	1900	–	–	207
n-Propanol	500	UH 82250	+	122
n-Butanol	150	–	+	329
n-Pentanol	–	–	+	(50)
n-Hexanol	–	–	+	17
Esters				
Ethylacetate	1100	–	+	358
n-Butylacetate	710	–	+	38
tert.Butylacetate	710	–	(+)	(40)
tert.Butylformiate	–	–	(+)	(40)
Ethoxyethylacetate	540	–	+	0.3[k]

Table 3. (Continued)

Compound	Danish MAC value[a] (mg/m³)	Suspected Biological Effect		
		Carcinoge-nicity[b,c]	Mucous Membrane Irritation[d]	Estimated Odour Threshold[e] (mg/m³)
Aldehydes				
n-Pentanal	–	–	+	0.072
n-Hexanal	–	–	+	0.039[k]
Halogenated Alkanes				
1.2 Dichloroethylene	20	KI 05250[g,h,j]	+	473

[a] Arbejdstilsynet 1981
[b] NIOSH 1976a (Althouse *et al.* 1979; OSHA 1980)
[c] Numbers are filenumbers in ref. (NIOSH 1976).
[d] Patty, 1962; Verscheren, 1977; Sax, 1975; NIOSH, 1977; NIOSH, 1976; NIOSH, 1980.
[e] Gemert *et al.*, 1977; Stahl, 1973.
[f] Parentheses indicates values resulting from conclusion by analogy to chemical similar compounds.
[g] EPA selected for priority attention as point source water effluent discharge toxic pollutant;
[h] currently (1976) tested by NCI for carcinogenicity by standard Bioassay protocol;
[i] IARC classified as potential human carcinogen ref. (Althouse *et al.* 1979).
[j] OSHA classified as potential human carcinogen ref. (OSHA 1980).
[k] average concentration of the compound exceeded odour threshold.

tions would have been reported if such a detector had been used in this investigation.

52 different compounds were chemically fully identified during the measurements. Another 10 could be partly identified with regard to chemical group. Table 5 shows how the 52 chemicals are distributed according to chemical groups. The distribution is not different from that found in dwellings and houses (Mølhave, 1978a; 1978b; Mølhave *et al.*, 1979), and indicates that building materials may be the main source of organic vapours and gases in the indoor air.

Table 4. (A) The 10 compounds most frequently identified in the air around 42 building materials; (B) the 10 compounds with highest average (AM) equilibrium concentration in the air around 42 building materials.

Compound	Average Concentration µg/m³	Frequency
A		
Toluene	39.7	22
n-Decane	1.49	20
1,2,4-Trimethyl benzene	0.56	18
n-Undecane	1.00	17
3-Xylene	23.0	16
2-Xylene	3.81	14
n-Propyl benzene	0.20	13
Ethyl benzene	1.79	12
n-Nonane	1.05	11
1,3,5-Trimethyl benzene	0.36	11
B		
Toluene	39.7	22
3-Xylene	23.0	16
$C_{10}H_{16}$ (Terpene)	20.8	6
n-Butylacetate	15.2	1
n-Butanol	9.4	5
n-Hexane	8.8	5
4-Xylene	7.3	8
Ethoxyethylacetate	5.9	1
n-Heptane	5.0	2
2-Xylene	3.8	14

A mathematical model

To estimate the importance of each building material for the indoor climate, both the amount of each material used in normal rooms and the potential toxic effects

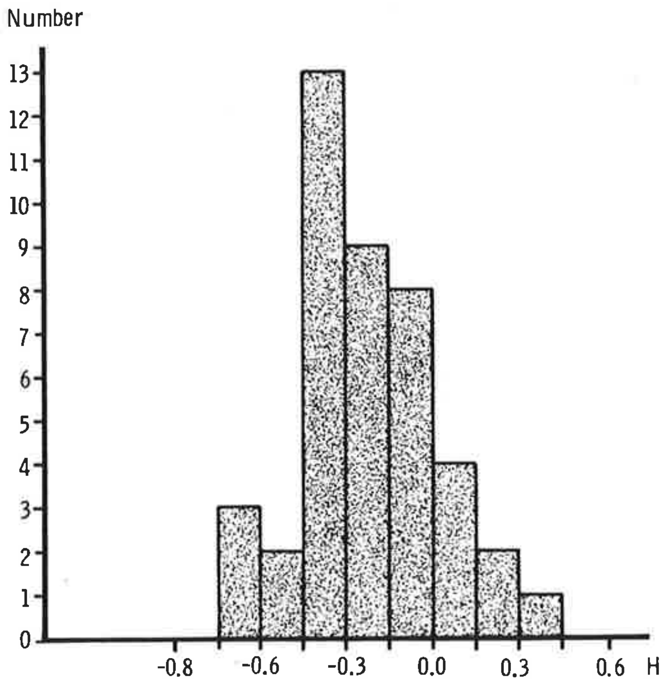

Fig. 2. The distribution of acceptability (*H*) of the air around 42 building materials (−1 = unacceptable, 0 = neutral, +1 = acceptable). Intervals are downwards open.

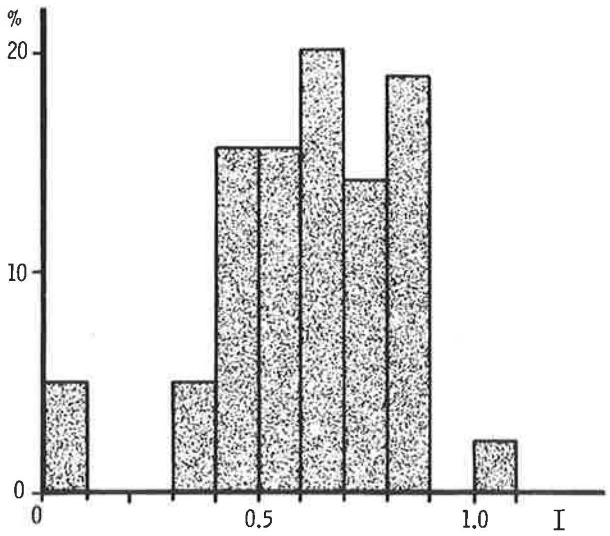

Fig. 3. The distribution (%) of odour intensity (I) of the air around 42 building materials (0 = no odour, 1 = very strong odour). Intervals are downwards open.

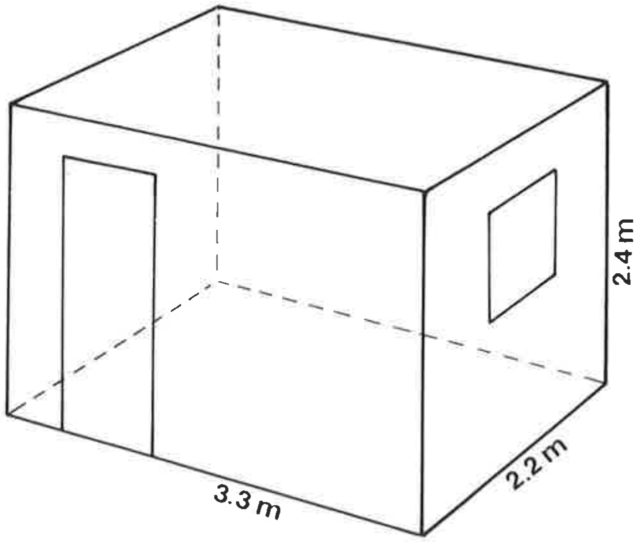

Fig. 4. The standard room. Dimensions: Total inner surface 40 m^2, volume 17 m^3. Floor 2.2 × 3.3 m^2 = 7.0 m^2; door 0.9 × 2.1 m^2 = 2.0 m^2; window = 0.7 m^2; walls (total area) = 24.0 m^2. Indoor climate: 0.25 air change per hour, 23°C, 45% RH.

of the chemicals must be considered. A mathematical model was therefore developed for the relation between indoor air concentrations of organic gases and vapours, and the amount used of each type of material. The mathematical model relates emission rates as measured in these experiments to indoor air concentrations in rooms. The model was based on a standard room dimensioned according to Danish and Swedish building laws (Boligministeriet, 1977). The dimensions are typical for childrens' bedrooms in modern Danish single-family houses and flats. The main dimensions of the rooms are as follows (see Fig. 4): the floor is 7 m^2, the volume 17 m^3, and the total inner surface is 40 m^2. The standard indoor climate is 23 °C and 45% RH, representing the average Danish indoor climate throughout a year. The ventilation is 0.25 air changes per hour (ach) with clean outdoor air. This minimum ventilation is to be expected in rooms in modern Danish houses built according to the proposed new Nordic ventilation norm (NKB, 1980): a maximum of 0.5 ach for the entire building. Taking into account ineffective airmixing and the need for high ventilation in kitchens and bathrooms, an effective ventilation of 0.25 ach may be expected in rooms such as bedrooms, which are generally considered to be subordinate rooms.

Table 5. The distribution on chemical main groups of 52 compounds detected in the air around 42 building materials.

Group		Frequency		%	
Alifatic		17		33	
Alkanes	(C6–12)		9		17
Alkanes	(C7–10)		4		8
Terpenes	($C_{10}H_{16}$)		3		6
Cyclohexanes	(C9)		1		2
Aromatic		18		35	
Alkylbenzenes	(C6–11)		15		29
Other	(C7–8)		3		6
Ketones	(C3–6)		5		10
Alcohols	(C2–6)		5		10
Esters	(C4–6)		4		8
Aldehydes	(C5–6)		2		4
Halogenated alcanes	(C2)		1		2
Total			52		102

Excluding 0.7 m^2 window, the standard room is constructed of five types of building materials (Table 6). All building materials may be classified as belonging to one of these five groups. The amount of each group of material to be used in the standard room is shown in Table 6. These surface-to-volume ratios should be used in future tests instead of the standard A2 samples used in the present study. In this way a better estimate of the importance of each material for the indoor climate is obtained.

To classify the 42 materials according to their impact on indoor climate it is assumed that the specific emission rate of each material is independent of ventilation rate and of the area-to-volume ratio (such effects are known, however, e.g., for formaldehyde emission from particle boards, Andersen *et al.*, 1976).

The mathematical model takes the following form:

Table 6. The five principal types of building materials considered in the mathematical mode and the ratio between material area (m^2) to standard room volume (m^3).

Group	Use	m^2/m^3
1	Floor only	0.41
2	Floor and Ceiling	0.82
3	Walls	1.41
4	Casing, frames, sills	0.24
5	Sealings, putty, etc.	0.012

Suppose A_i (m²) of material (i) is installed in a room V (m³) ventilated n times per hour. The material emits N identified compounds (j) with a rate of E_{ij} (mg/m²h). The emission rate of unidentified compounds is E_{iu} (mg/m²h). The equilibrium concentration of each of the compounds is

$$C_{ij} = \frac{E_{ij}A_i}{V \cdot n} \text{ mg/m}^3, \qquad (1a)$$

$$C_{iu} = \frac{A_i E_{iu}}{V \cdot n} \text{ mg/m}^3, \qquad (1b)$$

and the total concentration of gases and vapours originating from material (i) is

$$C_i = \frac{A_i}{V \cdot n} \left\{ \sum_{j=1}^{n} E_{ij} + E_{iu} \right\} = \frac{A_i E_i}{V \cdot n}, \qquad (2)$$

where E_i is the total emission rate of the material measured in the present experiment. In the standard room V and n are 17 × 0.25 m³/h = 4.25 m³/h. A_i and E_i are found in Tables 1, 2, and 6.

The 10 materials that, according to the mathematical model are contributing the most to the total concentration of solvent gases and vapours in a standard room, are found in Table 7. The table confirms that the main sources for organic gases and vapours are products with a high content of solvents. The main sources are related to the floor (filler, glue, and carpet) while painting and sealing agents seem to be of minor importance.

If several materials are used at the same time in the room the equilibrium concentrations C_{Tj} of each compound (j) is

$$C_{Tj} = \frac{1}{V \cdot n} \sum_i E_{ij} \cdot A_i, \qquad (3a)$$

$$C_T = \frac{1}{V \cdot n} \sum_i (C_{Tj} + C_{iu})$$

$$= \frac{1}{V \cdot n} \sum_i \sum_j (E_{ij} + E_{iu}) A_i. \qquad (3b)$$

To test this hypothesis, three model rooms were constructed as shown in Table 8. The total concentration of organic gases and vapours in each room was estimated for Room 3, as shown in Table 9. The total emission rate in the room is 65 mg/h. Of that amount, 62% originates from glue and 16% from the sealing compounds. With time these materials may dry out as sources for organic compounds and the long-term equilibrium concentration therefore may end up as about 25% of the initial value, that is, 3.9 mg/m³.

Table 10 shows the calculated initial (short-term) concentrations in the three model rooms. Measurements in similar rooms in seven single-family houses (Mølhave

Table 7. The 10 most and 10 least important sources for organic gases and vapours of solvent type in the indoor environment and the estimated contribution of each material to the total equilibrium concentrations in a standard room.

Material		Concentration (mg/m³)	
No.	Type	Corrected	Uncorrected
10 least important sources			
15	Synthetic fiber carpet	0.13	2.0
11	Wood fiber board	0.11	3.0
8	Mineral wool	0.068	0.38
24	Hessian wall covering	0.031	0.09
29	Glass fiber board	0.016	0.40
7	Putty	0.016	1.4
12	Neoprene fillet	0.0075	0.81
13	PCV fillet	0.0026	1.1
28	Neoprene fillet	0.0008	0.35
35	Laminated board	<0.0004	<0.01
10 most important sources			
20	Eva glue	1530	1410
22	PVA filler	58	58
21	PVA glue	34	9.8
40	Floor textile	9.0	40
37	Polystyrene foam	7.9	41
32	Isocyanate varnish	7.7	30
39	PVC floor covering	3.8	55
5	Sealing agent	3.4	169
30	Acryllatex paint	2.4	2.0
26	Rubber floor covering	2.3	28.4

et al., 1979) showed concentrations ranging from 0.48 to 18.7 mg/m³, as compared with the range of 1.6 to 23.5 calculated here. If fast emitting materials such as paint and glue, etc., are omitted from the calculation, a long-term equilibration concentration may be estimated as shown in Table 10. This concentration, which is ranging from 0.42 to 0.77 mg/m³ with an average of 0.63 mg/m³, may be compared to the results obtained in 39 old occupied rooms (Mølhave, 1978a), where the average concentration (AM) was 1.3 mg/m³ (SD: 3.3).

The model deals with equilibrium concentrations which very seldom occur in homes, etc. Moreover, no corrections were made for differences in indoor climate and room construction between real houses and the model. The agreement between model and practice is therefore acceptable; in fact, it is supporting the use of the combined analytical procedure and mathematical model to classify building materials according to their emission of organic gases and vapours of the solvent type.

Toxicological evaluation

No satisfactory toxicological information on the potential health effects of most of the compounds identified in this investigation is available. A preliminary toxicological evaluation of each of the 52 compounds is shown in Table 3.

No compound was measured in concentrations exceeding their Danish threshold level values (TLV),

Table 8. Three model rooms used in the tests of the mathematical model.

Area		Materials	m²/m³
Room 1			
Floor	1	Particle board	0.41
	14	Felt carpet	0.41
Wall	3	Plaster board	1.4
	18	Wall paper	1.4
Ceiling	42	Concrete	0.41
	30	Paint	0.41
Door	10	Plywood lining	0.24
	33	Varnish	0.24
Room 2			
Floor	42	Concrete	0.41
	22	Filler	0.41
	41	Textile covering	0.41
Wall	42	Concrete	1.4
	21	Texture glue	1.4
	24	Hessian	1.4
Ceiling	42	Concrete	0.41
	30	Paint	0.41
Door	10	Plywood lining	0.24
	33	Varnish	0.24
Room 3			
Floor	2	Particle board	0.41
	33	Varnish	0.41
Wall	9	Particle board	1.4
	21	Texture glue	1.4
	24	Hessian	1.4
Ceiling	9	Particle board	0.41
	30	Paint	0.41
Door	10	Plywood	0.24
	33	Varnish	0.24
Seams	5	Sealing agent	0.01

Table 9. Calculation of the contribution of each material in Room 3 to the total concentration of organic gases and vapours.

Material			Amount	Total Emission	
Area	Type	No.	(m²)	(mg/h)	(%)
Floor	Particle board	2	6.93	0.49	(0.8)
	Floor varnish	33	6.93	5.64	(9)
Walls	Particle board	9	23.66	2.28	(4)
	Texture glue	21	23.66	40.27	(62)
	Hessian	24	6.93	0.057	(0.1)
Ceiling	Particle board	9	6.93	0.67	(1)
	Paint	30	6.93	1.77	(3)
Door	Plywood	10	4.06	0.–	(0)
	Floor varnish	33	4.06	3.30	(5)
Seams	Sealing compound	5	0.17	10.56	(16)
				65.04	(100)

Volume = 16.9 m³; ventilation 0.25 h^{-1}.

$$\text{Equilibrium concentration} = \frac{65.04}{16.9 \times 0.25} = 15.4 \text{ mg/m}^3$$

Table 10. Calculated equilibrium concentrations of organic gases and vapours of solvent type in 3 rooms.

Room no.	Equilibrium Concentration (mg/m³) Short Term	Long Term	No. of Compounds	The Five Compounds with Highest Concentrations
1	1.6	0.42	23	*n*-butanole, toluene, *n*-decane, limonene, C4-benzene
2	23.5	0.71	26	*n*-butanole, *n*-decane, *n*-nonane, C3-benzene, toluene
3	15.4	0.77	32	*n*-decane, *n*-butanole, *n*-nonane, C3-benzene, toluene

which are similar to American TLVs. The concentration of gases and vapours in Table 7 for material no. 20 (Eva glue) is, however, so high that this material should only be applied when special attention is paid to room ventilation or personal protection aid.

Table 11 shows the 13 suspected or known human carcinogens identified in the air around the 42 building materials. The occurrence of styrene and 1.2 dichloroethane may cause special concern.

Average odour thresholds of the compounds as found in the literature are shown in Table 3; Fig. 5 shows the distribution of known or estimated odour thresholds for the 52 compounds. The range was from 0.01 to 550 mg/m³, and the geometric mean value was 24 mg/m³. Table 12 shows the compounds for which the average concentration was higher than their odour threshold. The most prominent type of odorous compounds seems to be the terpenes. It should be noted that many compounds have threshold far below their ana-

Table 11. Suspected or known human carcinogens in the air around 42 building materials.

	L	W	T	O	A
n-Decane	x	–	–	–	–
n-Undecane	x	–	–	–	–
n-Dodecane	x	–	–	–	–
α-Pinene	x	x	–	–	–
Δ 3-Carene	x	x	–	–	–
Limonene	x	x	–	–	–
Toluene	x	x	–	–	–
Ethyl benzene	x	–	–	–	–
Styrene	x	x	x	–	x
2-Propanone	x	x	x	–	–
2-Butanone	x	x	–	–	–
n-Propanol	x	–	–	–	–
1,2-Dichlorethane	x	x	x	x	–

W = EPA high priority (NIOSH, 1976).
T = currently tested (1976) (NIOSH, 1976).
A = IARC classification (Althouse *et al.*, 1979).
O = OSHA classification (OSHA, 1980).
L = listed in NIOSH (1976).

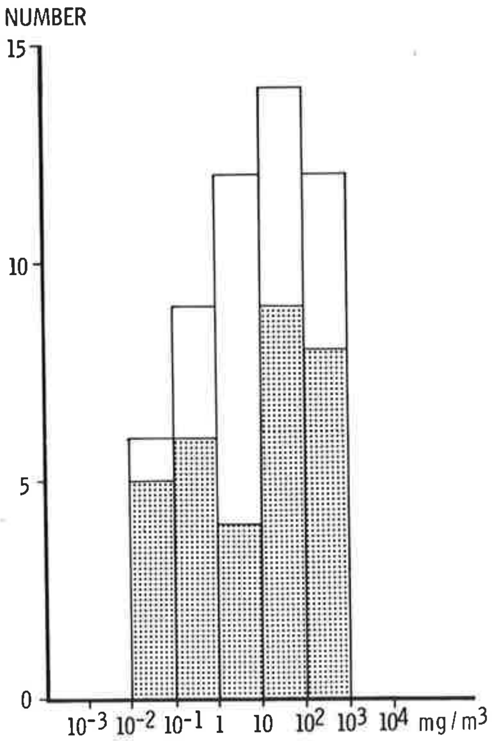

Fig. 5. The distribution of known or estimated odour thresholds mg/m³ for 52 compounds identified in the air around 42 building materials (Gemert *et al.*, 1977; Stahl, 1973). Shaded areas show the values found in literature; unshaded areas show the values estimated by analogy to similar compounds.

lytical detection limit in this investigation. In consequence, the compounds mentioned in Table 12 are not necessarily the most odorous compounds emitted from the materials.

The effects on indoor climate of the 52 compounds identified in the air around the 42 building materials examined can only be roughly estimated due to scarce toxicological information. Until more detailed information is available, it is suggested that the evaluation is based on the three effects: irritation of eyes, throat, etc.; carcinogenicity; and odour intensity. The preliminary toxicological evaluation of the 52 compounds (Table 13) accordingly concludes that 82% of the compounds are known or suspected irritating compounds, 25% are suspected carcinogens (two compounds

Table 12. 16 odorous compounds among 52 identified in the air around 42 building materials.

Odorous Compounds	Average conc. / Odour thresh.
Limonene	4500
α-Pinene	153
n-Hexanal	37
3-Xylene	28
Ethoxyethylacetate	20
n-Pentyl benzene	11
Δ 3-Carene	9
Methyl styrene	5.1

Table 13. Preliminary toxicological evaluation of 52 compounds identified in the air around 42 building materials.

Effect	Mucous Membrane Irritation	Suspected Carcinogen	Odorous Compound[b]
Unknown	2	75 (Unknown + None)	60 (Unknown + None)
None	17		
Suspected	42	25[a] (Suspected + Known)	30 (Suspected + Known)
Known	40		
Total (%)	101	100	100

[a]Two compounds suspected human carcinogens.
[b]Average concentration exceeds estimated or known odour threshold.

are suspected human carcinogens), and 30% have known or suspected odour threshold below the average concentration measured in the present investigation.

Conclusion

The measurements of the emission of organic gases and vapours of solvent type from building materials show that building materials may be the main source of such compounds in the indoor home environment, and that the testing facilities are suitable for classification of building materials according to their emission of such gases and vapours.

A mathematical model was established with which indoor air concentrations of pollutants originating from building materials can be calculated. The model was tested on three model rooms constructed from the investigated materials. The calculated air concentrations of gases and vapours ranged from 1.6 to 23.6 mg/m^{-3}, and the number of compounds in the air ranged from 23 to 32. These numbers are similar to those obtained in actual rooms.

The risks of health effects due to the compounds identified from the building materials were investigated, and criteria for future air quality standards discussed. It was concluded that the possibility of negative health effects cannot be neglected, especially not for the more sensitive minority of the general population.

References

Althouse, R., Tomatis, L., Huff, J., and Wolbourn, I. (1979) Chemicals and industrial processes associated with cancer in humans. IARC Monographs, Vol. 1-20, Report of meeting 15-17/January, 1979, Lyon.

Andersen, I., Lundqvist, G. R., and Mølhave, L. (1975) Indoor air pollution due to chipboard used as a construction material, *Atmos. Environ.* **9**, 1121-1127.

Arbejdstilsynet (1981) Occupational threshold limit values. Publication No. 62, Arbejdstilsynet, Copenhagen.

Boligministeriet (1977) Danish Building regulation 1977. Boligministeriet, Copenhagen.

International Council for Building Research (1972) CIB master list for materials. CIB Report No. 18, CIB, Brussels.

Gemert, L. J. and Netterbreijer, A. H. (1977) Compilation of odour taste threshold values data. Central Institute for Nutrition and food research, TNO, Holland.

Linder, Curt (1979) Suggested principle for standard setting of formaldehyde emission from building materials (Byggnadsteknikbyron, Statens planverk 31/05 1979. Stockholm.

Mølhave, L. (1978a). The atmospheric environment in modern Danish dwellings—measurements in 39 flats. Proceedings of the First International Indoor Climate Symposium, Copenhagen, Aug. 30th–Sept. 1st, P. O. Fanger and O. Valbjorn, eds., pp. 171–186.

Mølhave, L. (1978b) Indoor air pollution due to building materials. Proceedings of the First International Indoor Climate Symposium, Copenhagen, Aug. 31–Sept. 1st. P. O. Fanger and O. Valbjørn, eds., pp. 83–110.

Mølhave, L., Møller, J., and Andersen, I. (1979) Air concentrations of gases, vapours and dust in new houses. *Ugeskr.f. læger* **141,** 956–961.

National Institute of Occupational Safety and Health (1967a) Suspected carcinogens, 2nd Ed. HEW Publication No. 77-149. NIOSH, Cincinnati, OH.

National Institute of Occupational Safety and Health (1976b) Criteria for a recommended standard occupational exposure to ethylene dichloride (1,2-dichloroethane) DHEW (NIOSH) No. 76-139. NIOSH, Cincinnati, OH.

National Institute of Occupational Safety and Health (1977) Criteria for a recommended standard occupational exposure to alkanes (C5–C8). DHEW (NIOSH) No. 77-151. NIOSH, Cincinnati, OH.

National Institute of Occupational Safety and Health (1980) Pocket guide to chemical hazards. NIOSH/DHEW No. 78-120. NIOSH, Cincinnati, OH.

The Nordic Committee on Building Regulations (1980) Suggested Nordic principles for air quality and thermic indoor climate. NKB TS 28, Byggestyrelsen Sag 719-2. Statens planverk, Stockholm.

Occupational Safety and Health Administration (1980) OSHA candidate list: Variety of target. CZEN, Aug. 25, p. 23. U.S. Department of Labor, Washington, DC.

Patty, F. A. (1962) *Industrial Hygiene and Toxicology.* 2nd rev. ed. John Wiley and Sons, New York.

Sax, N. I. (1975) *Dangerous Properties of Industrial Materials.* 4th ed. Van Nostrand Reinhold Co., New York.

Stahl, W. H. (1973). Compilation of odour threshold values in air and water. ASTM DS 48, American Society for Testing and Materials, Philadelphia, PA.

Verschueren, K. (1977) *Handbook of Environmental Data on Organic Chemicals.* Van Nostrand Reinhold Co., New York.