

## INDOOR AIRBORNE PARTICULATES - A REVIEW

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### INTRODUCTION

Airborne particulate matter is an important constituent of the indoor air. The particles are often classified according to their origin. They can also be divided into natural and man-made particles. Examples of natural particles that affect the *indoor air environment* are:

- *Pollen* or other kinds of *seeds* with sizes of 20-100  $\mu\text{m}$ , which sometimes cause asthmatic reactions, see McCartney (1990) and Cromton (1990) the latter regarding pollen causing hay fever.
- *Moulds*, see Staib (1982); the review of Comtois (1990) for indoor moulds in various types of rooms and environments; and Kunkel et al. (1982) for a review of the problems with moulds (and other spores in the indoor air).
- *Dust mites*, see Fain et al. (1980), Hoffman (1982), and Spiekma (1990) to mention just a few. Mites can also cause asthmatic reactions.

Some of the *man-made* particles in the indoor air are:

- Particles from *smoking* and *cooking* (or other domestic processes).
- Particles from vacuum cleaning, dusting and other activities, see Lioy et al. (1990) and Kamens et al. (1991).

Man-made particles are mainly produced from *combustion* (domestic or industrial) for heating, incineration, and internal combustion in engines. Such particles are mostly (but not always) emitted to the outdoor air but find their way into houses by airing, through the ventilation system or simply during traffic in and out of the house.

Indoor dust can also originate from processes or activities going on indoors, as mentioned. This occurs in many industrial plants, in offices (e.g. fibres and flakes of paper) and in dwellings, where dust comes from clothes and skin, see Fig. 1, or from the floor, see Fig. 2.

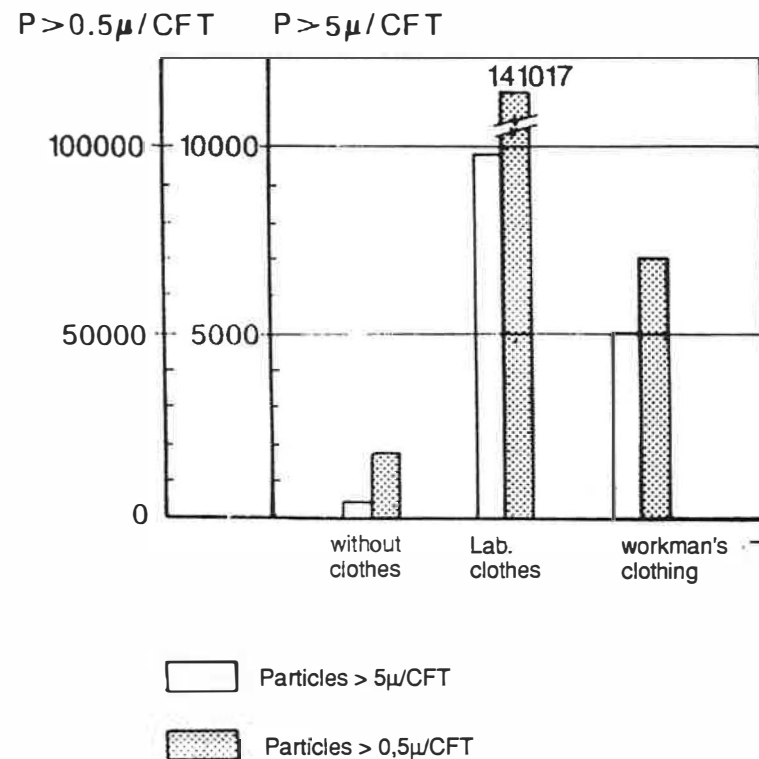


Fig. 1. Particle formation from various clothing types.

The small particles are of particular interest in sick buildings. Very small particles follow air streams almost like gases, they react very quickly and they are deposited in the alveoli and deeper parts of the respiratory system.

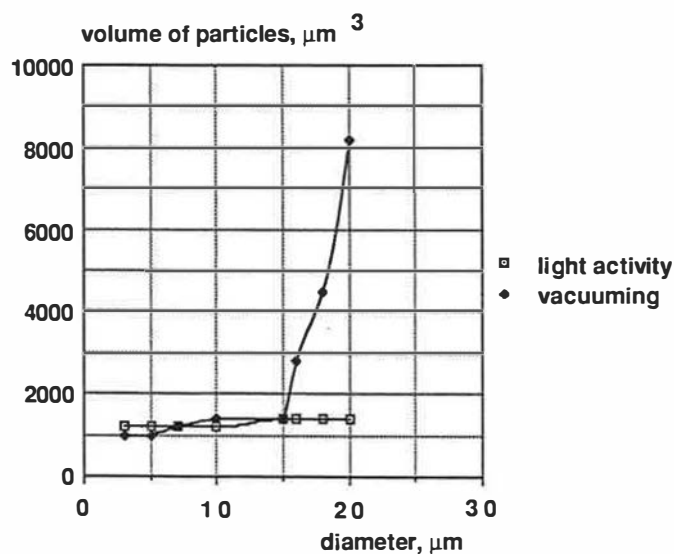


Fig. 2. Particles originating from the floor.

## OUTDOOR PARTICULATES

As mentioned, particles outdoors can easily be transported into houses. So a reasonable place to start this investigation is with a study of outdoor particulates - their size, composition, concentration etc.

### Origin of outdoor particles

Outdoor particles of natural origin are quite large. They include sand, particles from evaporated drops and particles from forest fires. Only those from forest fires are also sufficiently small to be of interest here, i.e. small enough to pass through man-made or natural filters and enter houses.

Some of the outdoor emissions form secondary particles, see Table 1.

Most man-made particles come from either stationary *combustion* sources, i.e. production of heat in factories for processes and the incineration of waste, or from mobile sources such as cars, lorries and busses, (Table 1).

Table 1. Tropospheric aerosol production rates, from van Vate and ten Brink (1986).

Source	Production rate, tons/day	weight-%
<b>Natural</b>		
<i>Primary</i>		
dust, sand etc.	$2 \cdot 10^4 - 10^6$	5,6
sea spray	$3 \cdot 10^6$	33,4
volcanic	$10^4$	0,1
forest fires	$4 \cdot 10^6$	4,5
<i>Secondary</i>		
vegetation	$5 \cdot 10^3 - 3 \cdot 10^6$	22,2
sulphur cycle	$10^5 - 10^6$	5,6
nitrogen cycle	$2 \cdot 10^6$	22,2
volcanic	$10^3$	0,01
Subtotal, natural	$6 \cdot 10^6 - 10^7$ (93,6%)	
<b>Man-made</b>		
<i>Primary</i>		
combustion and industry dust	$10^5 - 3 \cdot 10^5$	2,2
cultivation	$10^2 - 10^3$	0,005
<i>Secondary</i>		
hydrocarbons	$7 \cdot 10^3$	0,08
sulphates	$3 \cdot 10^5$	3,3
nitrates	$6 \cdot 10^4$	0,7
ammonia	$3 \cdot 10^3$	0,03
Subtotal, man-made	$5 \cdot 10^5 - 7 \cdot 10^5$ (6,4%)	
Total	$6 \cdot 10^6 - 11 \cdot 10^6$	

The table shows that secondary particles, particularly sulphates, make up a significant portion of the man-made particles.

Primary particles are formed by the process itself. Secondary particles are formed in the air by several mechanisms: condensation, see McMurry and Wilson (1982); nucleation, see Twomey (1977); coagulation, see Hofschreuder (1981); and by various chemical reactions. In 1990 van Houdt suggested that more than 50% of the submicron particles in the atmosphere are secondary particles. Particles formed from combustion are mostly rather small, see McGarry and Gregory (1972) and Peterson (1972). But particles from heavy oil burners tend to be larger, see Peterson (1972). The emissions show a multimodal distribution, see Fig. 3.

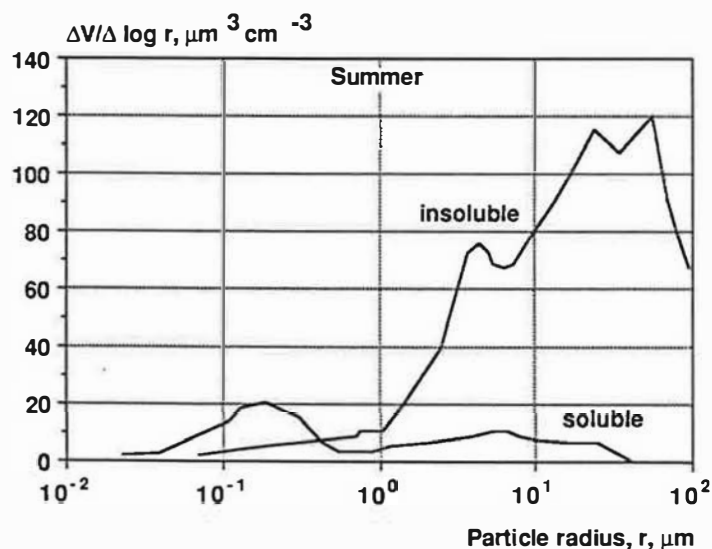


Fig. 3. Emission of particles from an oil burner.

The emissions from wood combustion are relatively well known, see Mavroudis (1979, 1980, and 1982) and Rydberg (1983). The emissions from wood pellets are less well studied. Tests with three kinds of pellets, made from waste, have been carried out in an attempt to improve the current level of knowledge.

#### Particle size

The particle size is maybe the most important characteristic of the particle. It can be expressed in many ways, e.g. aerodynamic and

projected diameters. The residence time of a particle in the air is mainly dependent on its aerodynamic size. Airborne particles with a larger aerodynamic diameter than 10-20  $\mu\text{m}$  are less likely to occur both outdoors and indoors, except where high air velocities are involved.

The residence time for particles outdoors is normally short. Particles with an aerodynamic diameter smaller than 0,01  $\mu\text{m}$  have a short residence time because of *coagulation* (due to Brownian motion). For the larger particles (10-20  $\mu\text{m}$ ) the settling velocities are high, Fig. 4, giving rise to so called *dry deposition*, see Sehmel (1980). The intermediate particles either act as condensation nuclei or they are washed down by rain, see Gatz (1976), Gillette (1981) and Tanaka et al. (1980). Either way, intermediate particles are removed by *wet deposition*.

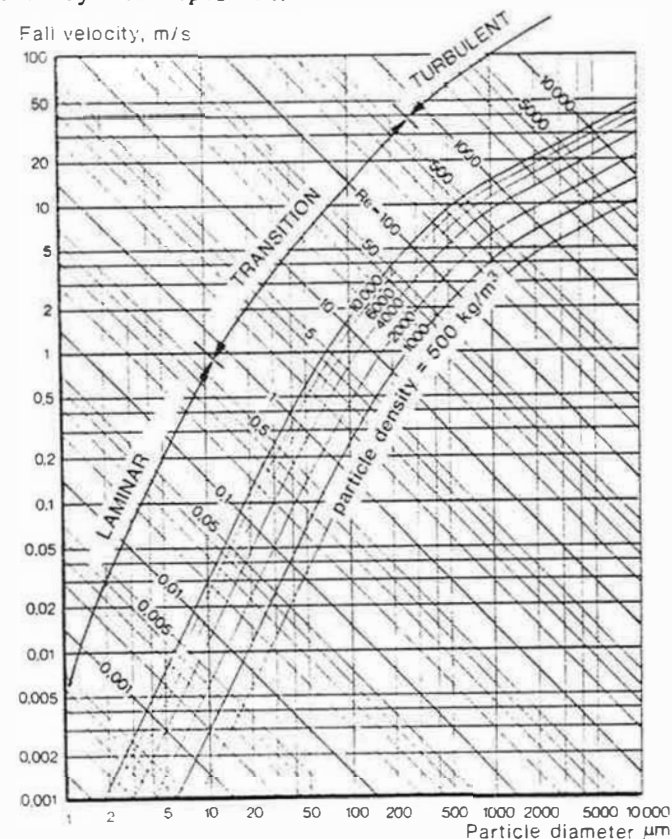


Fig. 4. Fall velocity for spherical particles in air at 20°C.

Particles can be transported by winds to be deposited thousands of kilometers from their source, see Berg (1981). The relationship between particle size, transported distance and residence time is given by Husar and Pattersson (1980), Fig. 5.

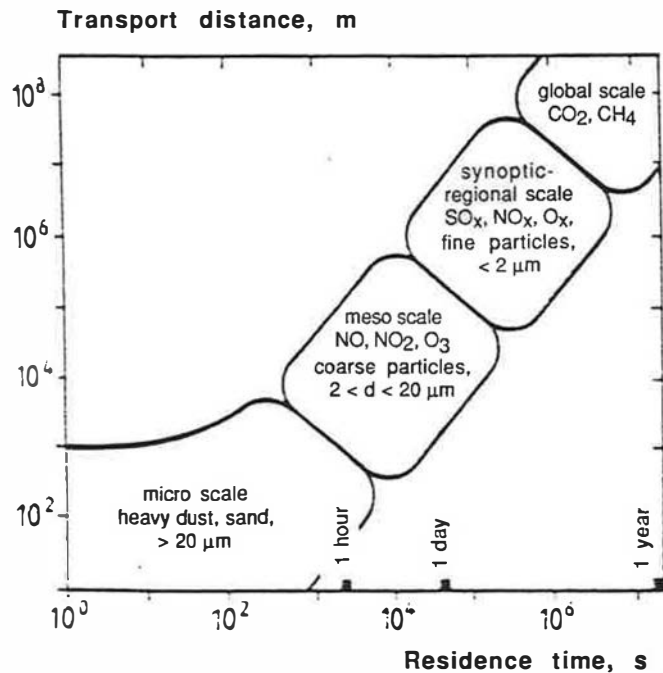


Fig. 5. Indications of transport distances of particles as a function of residence times.

### Size distribution

The size distribution of outdoor particles depends on their origin. Particles from internal combustion engines are small except for a minor fraction, see Little and Wiffen (1978). Particles from the combustion of fuel droplets are small if they are formed in the gas phase of the flame, but large if formed as a residue from the droplet. The particle distribution from one source can be approximated by the so-called log-normal distribution. Normally there is more than one mechanism producing particles, even from a single source, so the emissions are multimodal. Fig. 6 shows how the emissions from a boiler can be divided into three parts.

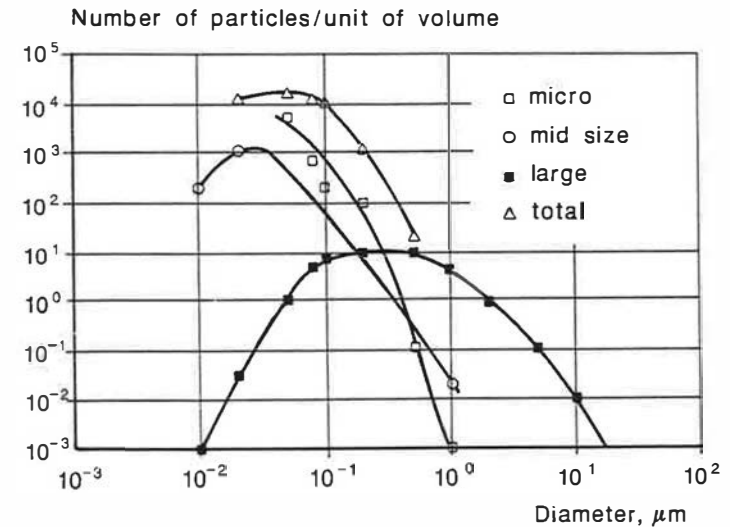


Fig. 6. Emission of particles from an oil-fired boiler.

The total distribution can be shown as a graph of  $dN/d(\ln r)$  against  $\ln r$ , where  $dN$  is the number of particles in the range and  $r$  (and  $dr$ ) the aerodynamic radius of the particles. The distribution can often be described with a straight line and a curved line, see Fig. 7 from Junge (1955). The various curved parts are for the smallest particles. The many curves are due to the changes by coagulation. Coagulation and clogging (from ionisation) make it very difficult to give a precise distribution for particles with a smaller radius than  $0,05 \mu\text{m}$ .

The distribution curve for particles with a larger radius than  $0,05 \mu\text{m}$  can be described by the so-called Junge distribution:

$$dN/d(\ln r) = A r^{-n} \quad (1)$$

For the exponent,  $n$ , many investigators have found a value around 3 for outdoor air. The same value can be used for flue gases, even though the particulates are of different origin.

The distribution for particles smaller than  $0,05 \mu\text{m}$  radius is different and no general distribution curve can be given. However, an investigation of three situations, as in Fig. 8, shows that the total mass is almost the same.

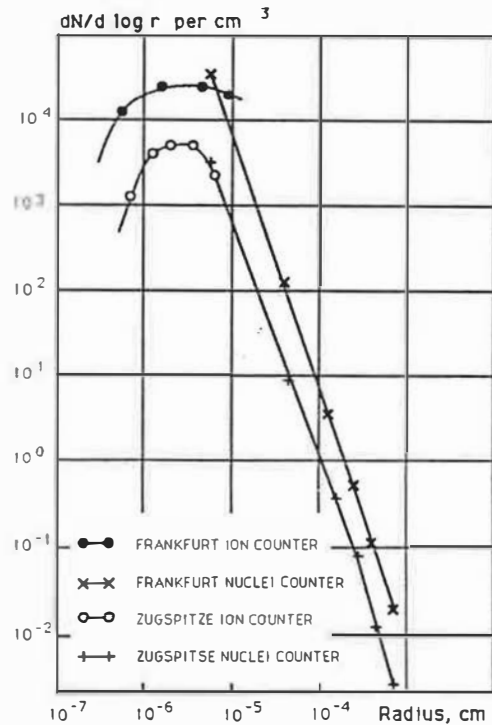


Fig. 7. Size distributions of emitted particles.

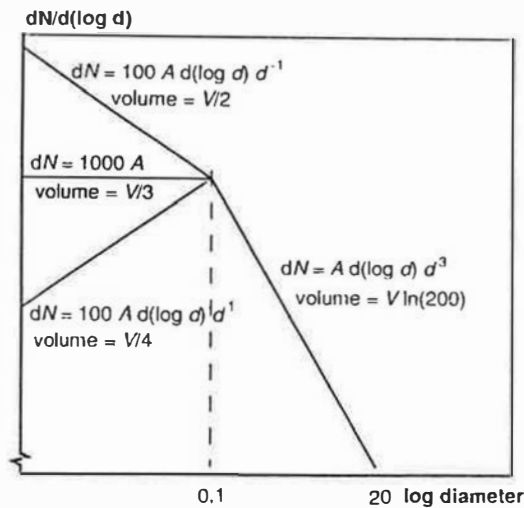


Fig. 8. Distribution of small particles.

The values in Fig. 8 have been obtained by assuming that equation (1) (Junge's equation) can be approximated for particles  $> 0,1 \mu\text{m}$  for three other conditions assumed for smaller particles:

$$dN/d(\log r) = A/r \quad (2)$$

$$dN/d(\log r) = A_2 \quad (3)$$

$$dN/d(\log r) = A_3 r \quad (4)$$

These assumptions give the total particle distribution of Fig. 8. Note that the small particles hardly contribute to the total volume.

### Concentrations

The problem of high particle concentrations outdoors was already well known in the Middle Ages. In London, coal was the main fuel then. In the Swedish town Birca, the main fuel at the same time was wood. Both produced plenty of particles.

The situation is not much changed now. Towns with a large population and a relatively small area are still suffering from smoke problems. Particulates may be even higher, now that they also come from cars and factories. The problem may be exacerbated by the location of the town, (e.g. in a valley) or by local regulations (e.g. the amount of traffic allowed in the inner city), see Lyons et al. (1990) or Viras et al. (1990).

Measurements of dust concentration in the outdoor air have been performed for a long time. In 1914 "deposit gauges" were used in London to collect impurities by sedimentation. The number of particles in the air was measured by "dust counters", first by the British Meteorological Institute and later by the Department of Scientific and Industrial Research. Reports were given every year and so it is possible to follow the changes in "air quality" over a long period, see Auliciems and Burton (1973).

Since the early 1930s the German Institute Preussische Landesanstalt für Boden- Wasser- und Lufthigiene has carried out similar measurements in several towns.

In Asia, similar studies were undertaken by the "Hygienic Laboratory of Osaka", starting in 1922, and in America the "Mellon Institute" in Pittsburgh was one of many stations involved in such measurements.

In Northern Europe, the quality of the outdoor air was studied by Tuxen (1890) who examined wet depositions. Andreassen and Gravesen (1949) reported on the atmospheric pollution of Copenhagen, Fig. 9.

The measurements in the various countries gave similar results, which were used to draw maps of the air quality. These maps were a guide for the authorities in controlling the traffic, implementing pollution control and in town planning. Some air-quality maps for Copenhagen are shown in Fig. 9-11. The particles were soot, unburned hydrocarbons and other chemicals that can give rise to odours, oxidation and health effects, even at small concentrations.

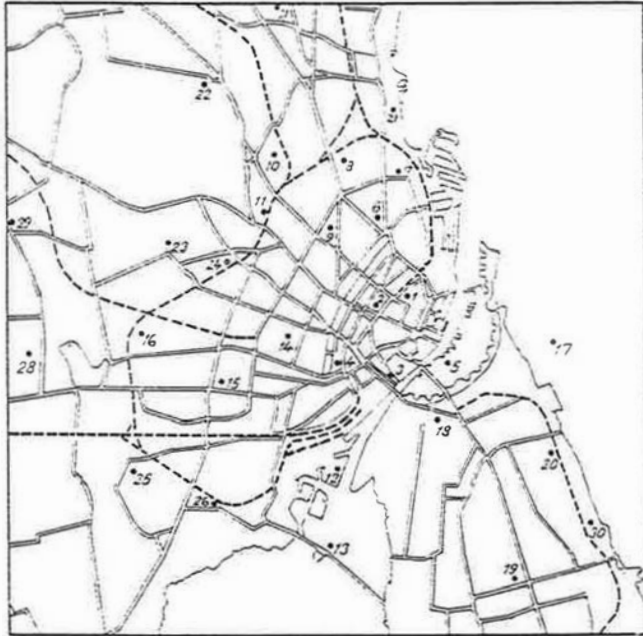


Fig. 9. Measuring stations in Copenhagen for air particles (1949).

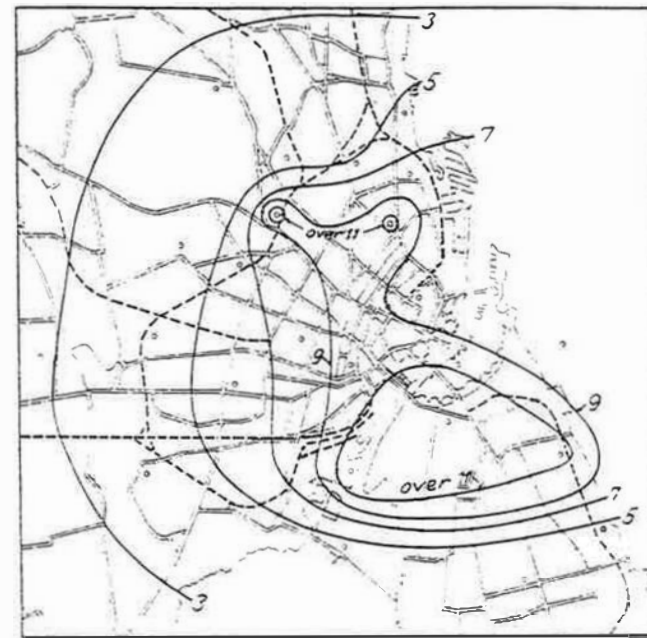


Fig. 10. Map of insoluble matter in the air in Copenhagen (1949).

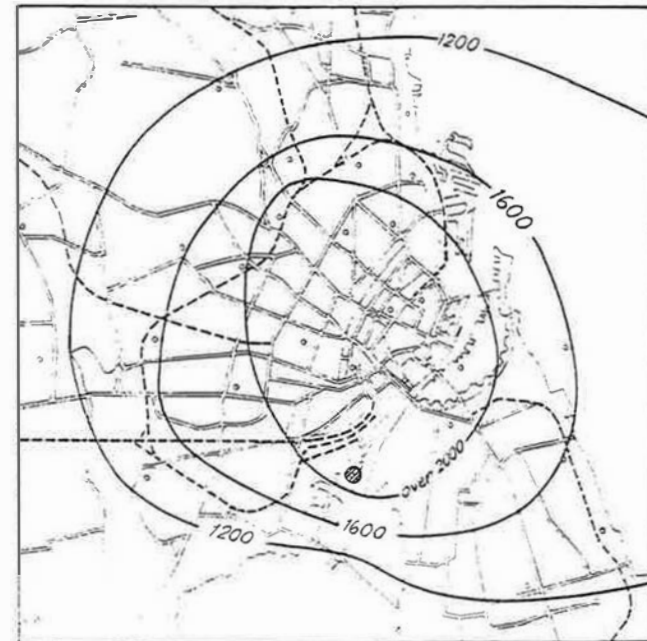


Fig. 11. Map of sulphates in the air in Copenhagen (1949).

More recent investigations show that *the situation has not improved very much*. Many measures are taken nowadays to decrease the emission of particles from vehicles and industry, but industrialization and the growth in transportation have been so large and rapid that the situation now is often worse than before!

The height of an emission site and the width of a street affect the concentration of car emissions. The emissions can be expressed as the concentration or fallout of the total organic carbon (TOC). In Sweden, the average fallout is about  $160 \text{ mgC/m}^2$  per month, see Neumann et al. (1959) and Boström et al. (1982). In Tokyo, values up to  $500 \text{ mgC/m}^2$  per month have been found, see Matsumoto and Hanya (1980). The average is  $360 \text{ mgC/m}^2$  per month with a 90% confidence interval of  $160 \text{ mgC/m}^2$  per month. The differences are due to differences in traffic, urban structure etc.

Another example of pollution from traffic is given in a recent paper by Lyons et al. (1990). They studied the influence of urban structure on vehicle air pollution and its relation to different variables. One of the variables was the vehicle speed. The cars emitted CO and  $\text{NO}_x$  as shown in Fig. 12. The results are similar to those found by Iverach et al. (1976) for the US and for other places and situations. The figure contains data on traffic density and types of fuel that are helpful for simulating air pollution situations, see Govenius and Norén (1973) and Hallbäck (1979).

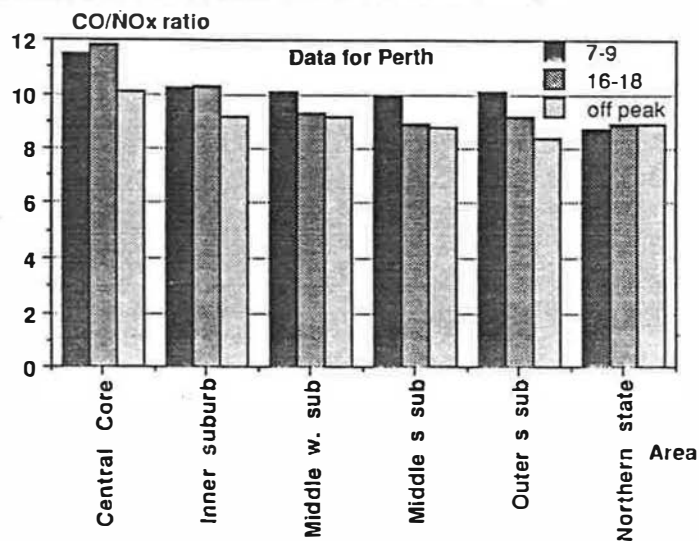


Fig. 12. Concentration of exhaust emission from cars in various parts of a large city.

The levels of individual pollutants are also closely correlated, see Fig. 13. So measuring just *one* of them gives an idea of the others. This can be useful when one wants to separate emission values in a complex situation with various pollutant sources. Particles from cars can be estimated, as can the hydrocarbons attached to the particles. Fig. 14 gives some results from an investigation on the short-term levels of suspended particulates in New York City.

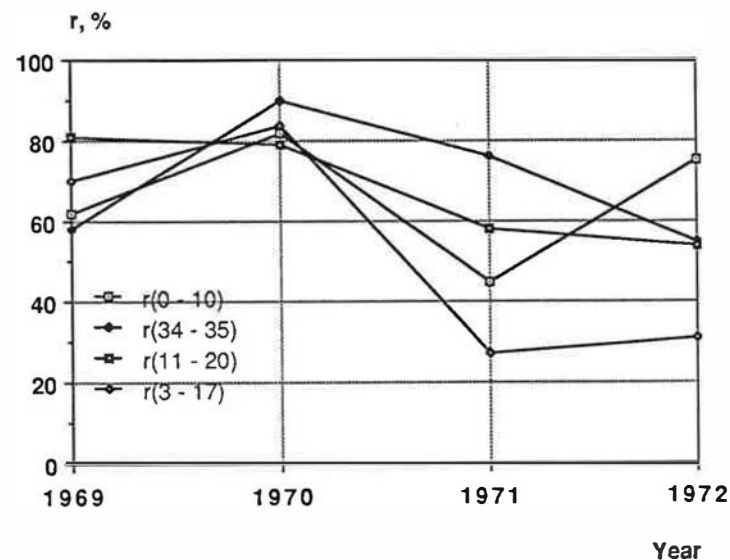


Fig. 13. The correlation coefficient  $r$  for the relationship between the level of air pollutants at some stations in New York City. The location of the stations is shown in Fig. 14.

Fig. 13 shows that the levels of pollutants are fairly similar at the various stations. So the number of measuring points needed in a city is not large, and could be reduced in New York, for example. Note that the correlation is still fairly good in spite of changes in traffic density, new constructions etc. Fig. 14 gives the data in more detail.

Table 1. Correlation coefficients\* by season for all pairs of stations giving a correlation coefficient of greater than 0.80 for the period December 1969-February 1970 (particulate dioxide)

Corr. Station No.	1969		1969		1969		1970		1970		1971		1971		1972	
	W	SPR	S	F	W	SPR	S	F	W	SPR	S	F	W	SPR	S	F
0-10	64	35	29	60	82	86	53	71	45	74	58	50	74			
0-15	49	70	34	64	82	82	65	6	56	57	4	50	60			
0-17	-13	65	35	70	84	71	11	0	32	62	-4	37	42			
0-33	18	48	28	64	84	62	51	61	49	39	-5	36	57			
1-37	-	-	24	54	81	45	40	75	14	37	47	33	50			
3-10	11	35	32	42	81	65	76	75	70	58	68	67	60			
3-16	-39	5	24	52	81	77	65	62	61	71	38	55	77			
3-17	68	14	17	30	81	39	57	36	2	62	-16	-43	27			
6-8	27	18	13	31	81	70	54	43	71	62	46	1	75			
6-10	58	16	13	48	81	71	42	68	65	77	46	72	72			
6-17	8	47	25	59	80	79	55	32	61	71	9	41	48			
8-11	35	18	26	41	80	69	46	51	74	52	37	30	30			
8-15	22	46	19	39	80	69	46	51	74	52	81	-8	39			
8-16	24	2	29	23	82	65	45	106	48	64	30	40	21			
9-15	9	51	25	63	82	66	2	4	53	45	45	86	41			
10-15	43	18	17	52	83	62	34	60	60	60	48	30	41			
11-12	-	52	44	69	84	68	80	59	76	52	60	84	55			
11-14	23	70	56	79	84	79	71	69	58	48	60	84	55			
11-20	82	65	58	60	83	78	80	60	79	71	79	71	54			
12-15	41	31	61	83	69	47	72	60	79	72	81	54	55			
12-16	-	37	-	7	83	62	63	53	56	73	33	29	77			
12-20	-	15	-	54	82	82	80	68	75	64	48	20	45			
13-15	62	77	43	65	82	71	46	75	70	83	38	81	81			
14-15	61	83	57	83	82	71	55	71	70	84	77	75	82			
14-16	41	41	23	43	82	55	71	58	47	84	61	61	65			
14-20	8	63	37	35	83	81	64	61	47	51	79	75	68			
15-16	47	51	10	52	80	67	57	57	38	82	82	39	65			
15-23	61	28	42	38	80	67	59	65	31	79	75	68	68			
16-20	-	56	7	36	80	55	62	65	55	58	52	56	41			
17-37	-	31	65	33	47	87	32	28	55	3	8	39	16			
19-26	-	-	-	43	81	69	70	55	17	23	53	68	77			
24-25	-	-	-	40	81	82	78	19	80	76	23	39	41			
24-28	-	-	-	41	83	37	22	11	57	36	11	10	43			
24-31	-	-	-	38	86	85	64	65	31	67	45	64	54			
24-34	-	-	-	36	87	70	64	23	81	43	12	77	53			
25-37	-	-	-	17	84	42	56	109	38	38	38	53	8			
26-27	-	-	-	2	82	21	11	58	30	12	21	14	14			
26-32	-	-	-	40	72	85	73	36	54	60	56	19	60			
27-32	-	-	-	48	26	30	83	76	57	61	45	21	67			
31-34	-	-	-	13	30	55	85	76	51	48	45	41	28			
31-35	-	-	-	44	59	47	83	69	67	68	71	58	37			
33-34	-	-	-	39	56	63	82	72	71	60	62	63	55			
34-35	-	-	-	60	47	49	68	90	61	69	79	76	53			
34-37	-	-	-	60	47	49	68	90	61	69	79	76	53			
35-36	-	-	-	66	39	71	82	30	46	53	17	57	35			
Avg. Cor.	31.3	45.9	28.2	52.9	83.0	65.3	52.8	51.6	60.4	60.4	40.9	47.8	51.4			
S.D. of Cor.	29.0	22.6	19.1	14.5	2.3	13.5	16.5	17.1	16.0	21.8	23.9	24.4	19.8			
No. of Cor.	33	39	48	48	48	48	48	48	48	48	48	48	48			

\* Divide each entry of the table by 100. W = winter, S = summer, SPR = spring, F = fall.  
† Average correlation coefficient

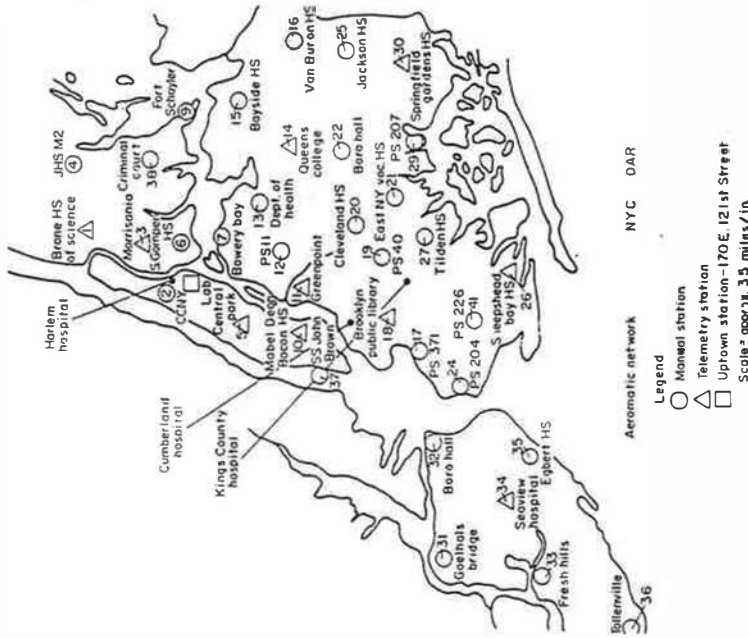


Fig. 14. Levels of suspended particulates in New York City.

How does the composition of outdoor air affect the indoor air? Fig. 15 from von Ubisch and Westerlund (1970) shows that the carbon monoxide level probably reflects the traffic intensity in the city (although data for the actual traffic intensity was not obtained here). So air intakes should be located with this in mind, and should not be placed downwind and facing a busy street, for example.

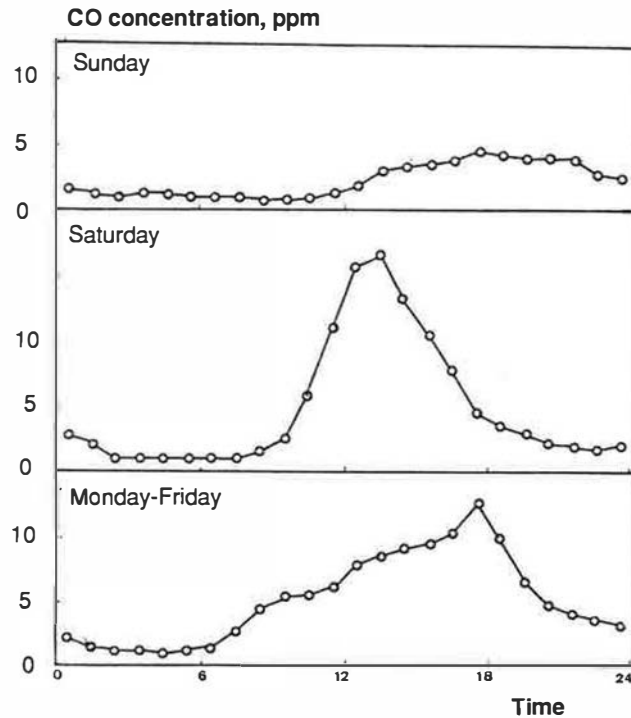


Fig. 15. Hourly mean values of carbon monoxide concentration in air from a conference room measured over one month, from von Ubisch and Westerlund (1970).

The concentrations of particles and carbon monoxide decrease with increasing height, see Fig. 16 from Lindblad and Peterson (1966). The change in concentration with height indicates the importance of locating the air-intakes as high as possible on the façade or, better still, on the roof. The intakes should not be downwind from the exhaust vents and other chimney plumes, or particles may contaminate the supply air, see Peterson (1972).



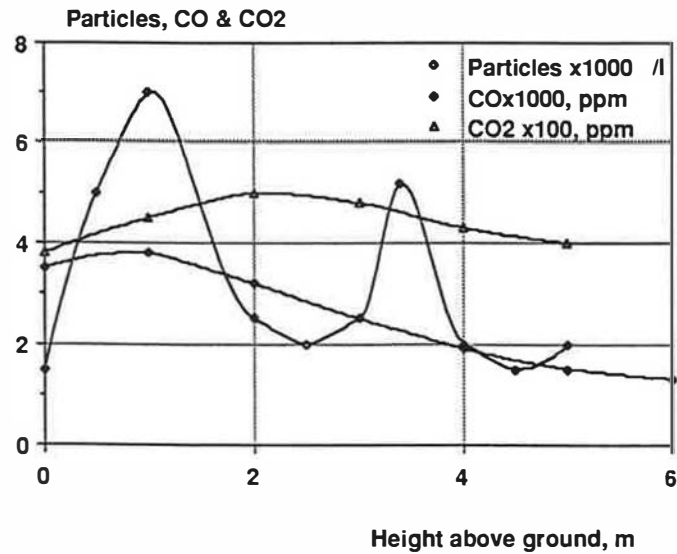


Fig. 16. Variation of particle concentration with height above a street in Stockholm, from Lindblad and Peterson (1966).

### Composition

Some results from the investigation in Copenhagen done in 1949 are shown in Fig. 17-19. The measurements shown are:

- *insoluble and soluble matter*, e.g. total solids due to deposition
- the amount of *sulphates, chlorides and nitrates* in the deposition
- the *pH value* of the wet deposition.

The values from this old investigation show some of the influences particulate matter had at that time.

When air is drawn through ventilation slots in the walls or when a room is aired, the ions in dust have a severe fouling effect on the room surfaces. Dusts also directly soil walls and furnishings, see Saucier and Sansone (1972).

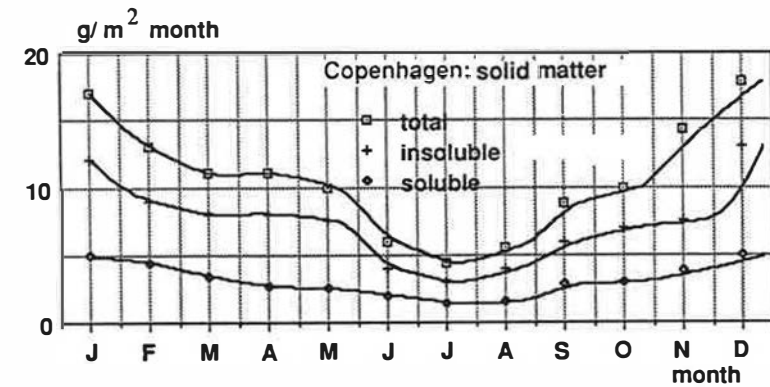


Fig. 17. Levels of solid matter in Copenhagen.

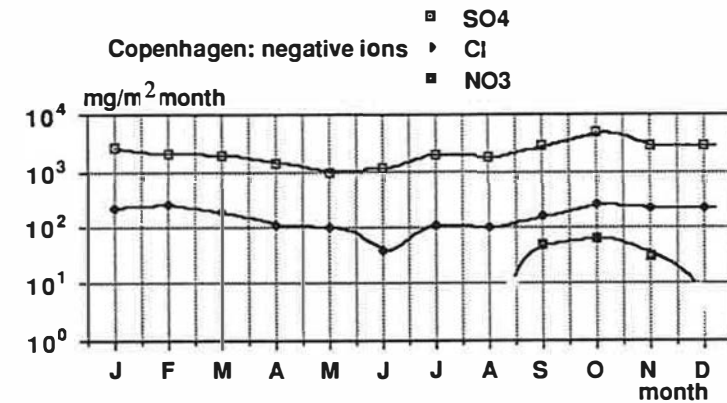


Fig. 18. Levels of negative ions in Copenhagen.

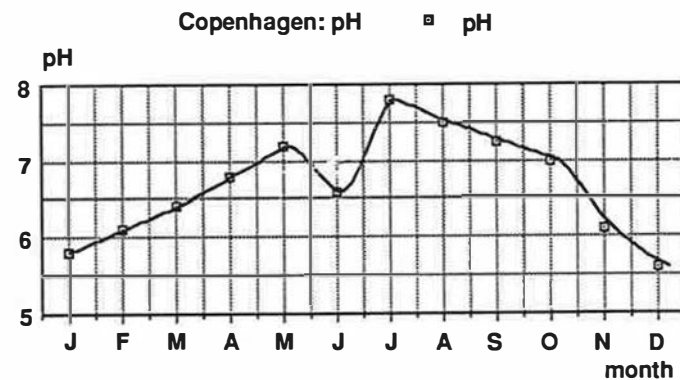


Fig. 19. pH Levels in Copenhagen.

Sulphur from the combustion of coal occurs as sulphur dioxide in the air. It corrodes structures, damages plants and is harmful to health, see Kagawa (1984). Particles of tar and soot also occur in air pollutants and are deposited in the lungs, where they can have a carcinogenic effect.

More recent investigations of similar types have been reported by the hundred, if not thousand. A few results will be given here.

Organic constituents in atmospheric fallout in Tokyo were reported by Matsumoto and Hanya (1980), who compared the situation in Tokyo with measurements from other cities. Such organic matter has also been reported from combustion sources by Schmitt (1982), van Vaeck et al. (1980, 1984), van Houdt (1990) and many more.

Viras et al. (1990) reported on the mutagenic activities of airborne particulates in Athens. The particulates include polycyclic aromatic hydrocarbons (PAH) some of which have been identified as carcinogens, see IARC (1973). These particles also have a mutagenic activity, as shown by Hughes et al. (1980) and many more. The mutagenicity was shown to be as high as  $8 \text{ rev/m}^3$  with an average of  $1.5\text{-}2.5 \text{ rev/m}^3$ . Together with a high concentration of other air pollutants, see Cvitas et al. (1985), the situation has become worse than before.

## OUTDOOR AIR FOR VENTILATION

### Introduction

The transport of particles from outdoor air into houses occurs through open windows, open doors, ventilation ducts (if any) and other openings for supply air.

When airing a room, transport occurs without any filtering. However, some dust is usually taken up by filters and ductwork. This can easily be seen when inspecting a duct used for some time, see Fig. 20. The duct in question had been used to ventilate a kitchen for one year. The inlet in Fig. 21 was used for several years without cleaning. Such deposits pose a fire risk, see Peterson (1989) and reduce the ventilation flow rate, see Peterson (1991). There are now regulations in Sweden for inspecting the ventilation plants of all houses.

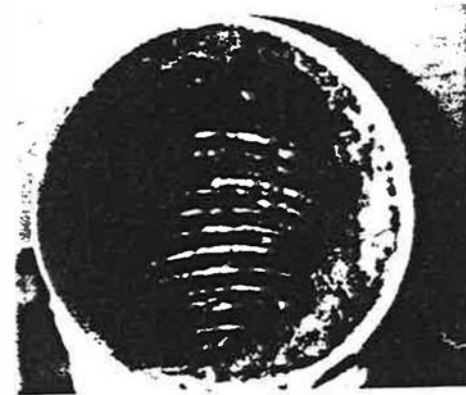


Fig. 20. Fouling in an extraction duct from a kitchen.



Fig. 21. Deposits on a grill over an air intake.

In Fig. 20 and 21 the amount of dust due to deposition on the duct walls and the decay in air velocity is far from negligible. The decrease in particle content can be roughly estimated from the curves in Fig. 22 from Davies (1973). The longer the ductwork the greater the deposition, up to the maximum shown.

However, Fig. 23 shows that the smallest particles are not collected very efficiently. They pass through the ductwork and most filters and enter the rooms. It is therefore necessary to find out if very small particles are more dangerous than the larger ones.

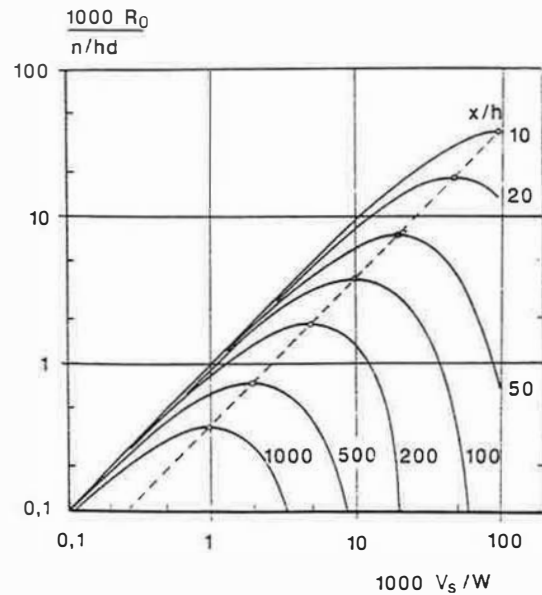


Fig. 22. Deposition in ventilation ducts.

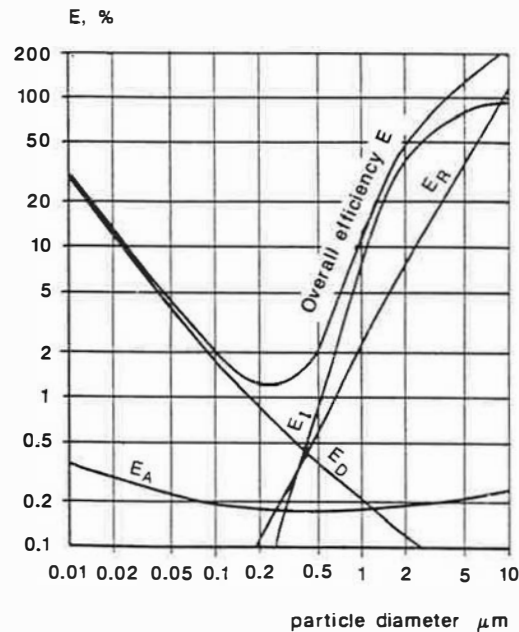


Fig. 23. Collection efficiency of filters, from Cai (1986).

## Transport of particles

Even if the concentration indoors is seldom the same as outdoors, there is a close relation between the two. This is because many of the particles in indoor air have been transported into the houses by airing and ventilation. When outdoor air is used for ventilation without any filtration, the concentration of particles in the ventilation air is the same as that in the outdoor air. To reduce the concentration, modern buildings are equipped with ventilation plants in which there is some kind of device for filtering the air. The concentration of particles indoors is then less than it was outdoors. The same applies even if there is no filter but complicated ductwork. Deposition on the walls in rooms also reduces the concentration.

Deposition in the ductwork or diffusion to the walls of the ductwork and other parts of the ventilation supply system removes about 50% of the dust particles in the air before it enters a room. Inside the room the dust levels fall further owing to diffusion and electrical forces.

## Indoor Particles

The indoor particles come from the outdoor air or from indoor sources. The particles from outdoor air will be examined first.

The particles transported into houses are probably the smallest ones. This was found by DeMarcus and Thomas (1952), Thomas (1955) and Lee and Gieseke (1980), who gave a simplified way of calculating the penetration of particles through channels and ducts. The somewhat lower concentrations indoors are due to the deposition of heavier and larger particles in the duct system. The calculations show that the number of small particles that pass through the system into the room is rather high. This is quite a crucial point, as most of the hydrocarbons are carried by the fine dust, not by the large particles, see Fig. 24 from Little and Wiffen (1978). This means that the air flow transported through the duct system into the houses carries most of the harmful particles, which pose a health risk owing to mutagenic components. However, as pointed out by Cohen and Cohen (1980), the health risks from air are generally less indoors than they are outdoors.

A revealing experiment was carried out by Alzona et al. (1979). A room in a house was cleaned from particulate matter. Samples were taken from both the room air and the outside air. X-rays were used

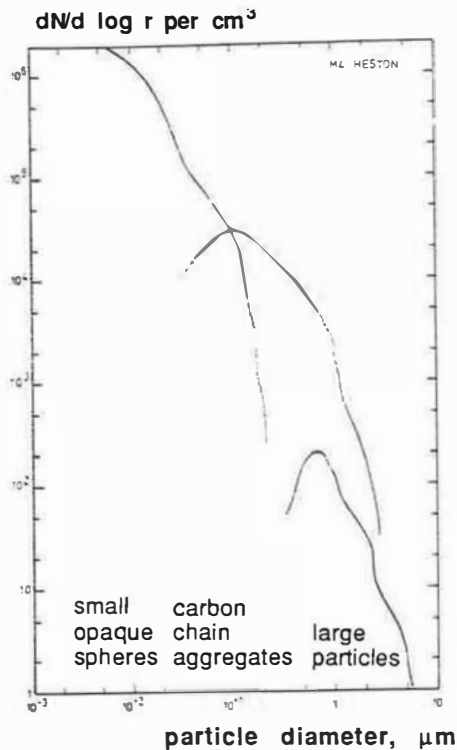


Fig. 24. Three classes of particles emitted from vehicles, from Little and Wiffen (1978).

to examine the particles for elements that were known to be of outdoor origin, such as lead and bromine (from car exhausts), iron and zinc (from nearby factories) and so on. Fig. 25 shows some of the results. The amounts of lead (Pb) and bromine (Br) will be considered as an example. It is known that the particles containing these elements probably come from internal combustion engines. The figure shows that they occur in conjunction with heavy traffic, and that they reach high concentrations outdoors and indoors at the same time. This can be seen even more clearly from the ratio of particle concentrations, (Fig. 25).

#### Fallout on surfaces

The fallout of particles on the indoor surfaces results from sedimentation for the larger particles, and other processes like ionisation and turbulence for the smaller particles. The influence of some of the most important parameters is given in Fig. 26, from Schmel (1980).

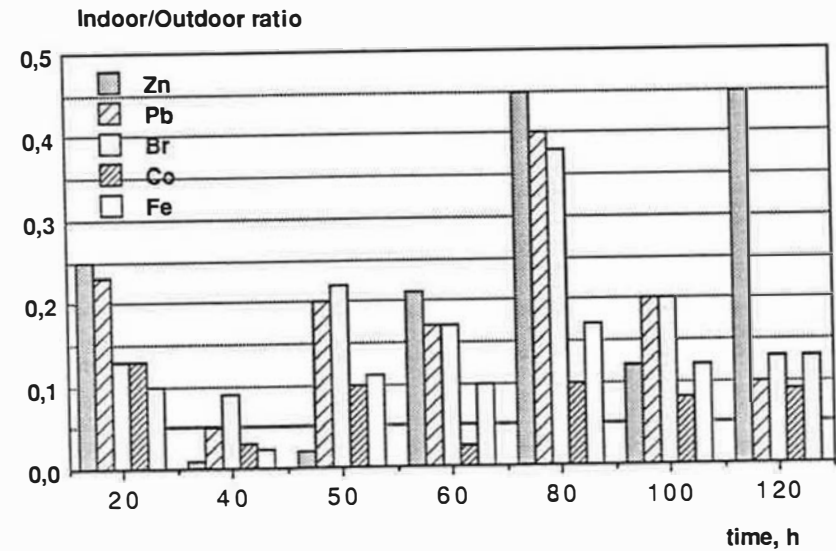


Fig. 25. Levels of particulates of outdoor origin.

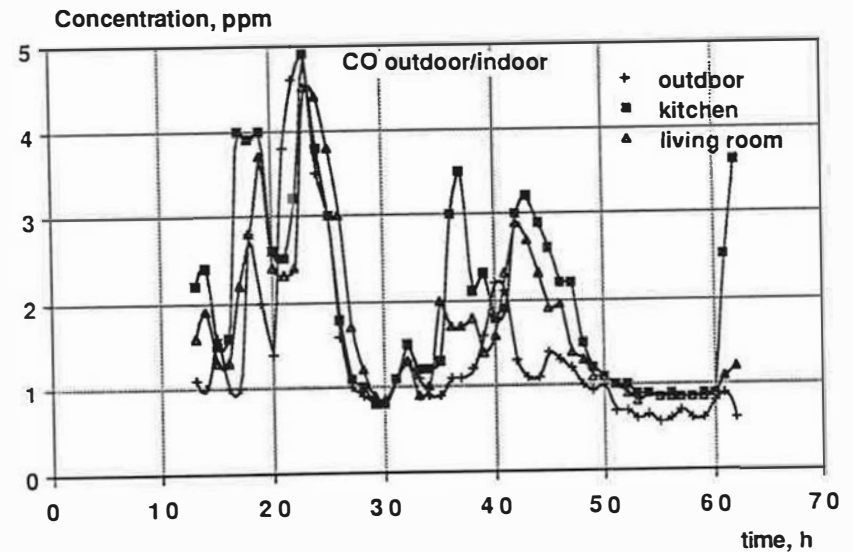


Fig. 26. Reduction of pollutants indoors due to fallout.

### Indoor/outdoor concentrations

Bierstecker et al. (1965) compared indoor and outdoor particulates. They found a close correlation between the concentration of impurities in the two environments. This has been shown in many other investigations, see Fig. 27 from Yocom et al. (1971). The figure shows the carbon monoxide content outdoors and indoors for a single-family house in the USA. Regarding particles, some of the largest are captured in the ventilation ductwork, but small particles can pass through the ducts. So the indoor dust concentration tends to change according to the outdoor concentration, and adds to the particles created from indoor activities. This is shown in Fig. 28. The concentrations follow each other during daytime and nighttime, and in summer and winter.

These figures are not the only ones that suggest that indoor particles are at least partly of outdoor origin. Similar results were obtained by Derhem et al. (1974), Alzona et al. (1978) and Thompson et al. (1973), just to mention a few, and a review of the indoor/outdoor ratio for various substances is given by Seifert (1982).

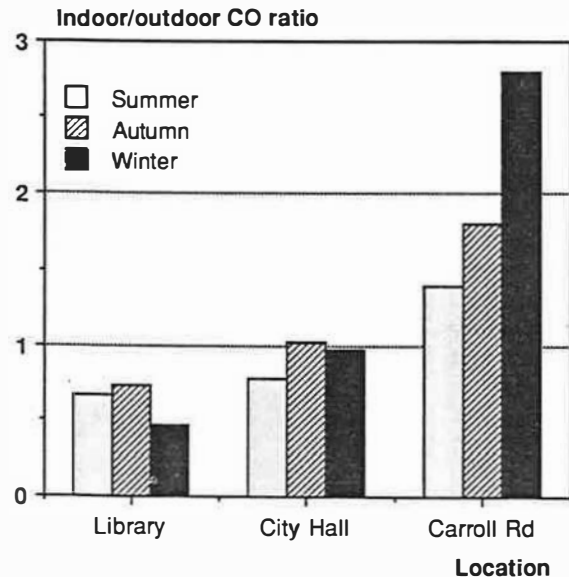


Fig. 27. Carbon monoxide for a single-family dwelling.

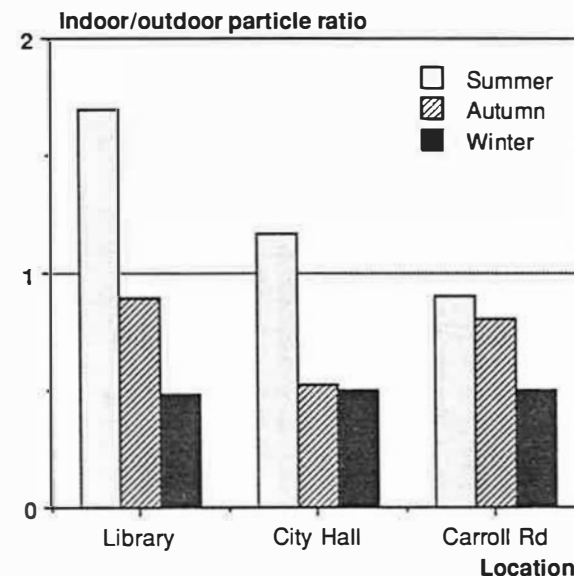


Fig. 28. Particles for a single-family dwelling.

### Transported particles

Fig. 27 and 28 show that the ratio between the indoor and outdoor concentrations is usually less than one. Even if the outdoor air is bad, the filtration by the ventilation ducts or supply slits in the structure at least bring the concentration down to average levels. The worst situations probably occur with mechanical ventilation (which supplies a large amount of outdoor air), with no filtration, or when there is a large amount of impurities during some part of the day. Such impurities can accumulate on the walls etc., as seen from many investigations.

Lioy et al. (1990) measured particles of PM-10 ( $d_{50} = 10 \mu\text{m}$ ) in some houses, see Fig. 29. This particle type was chosen because it is collected in the upper or tracheobronchial section of the respiratory system, and to some extent in the alveoli. Two results are shown in Fig. 30 and 31.

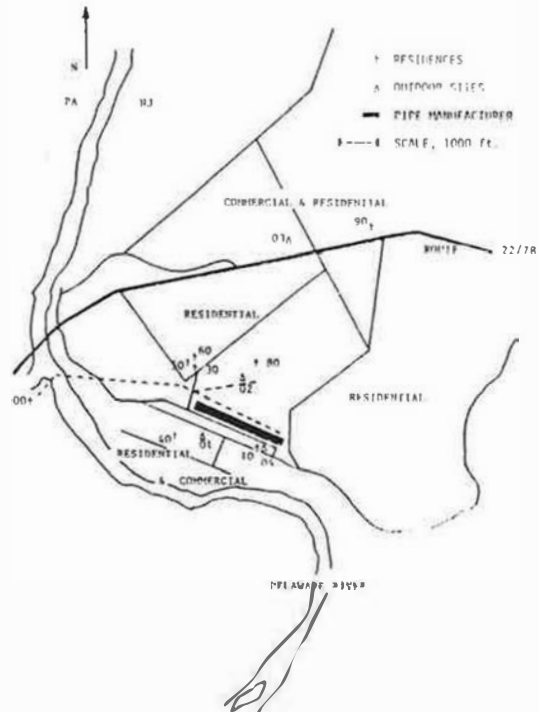


Fig. 29. Measurements sites for the concentrations of PM-10 in winter, from Lioy et al. (1990).

Fig. 30 gives the results for a house with electrical oven, a micro oven and with oil heating. The indoor concentrations are compared with those at a site about 500 m from the house. Two retired persons live in the house. They are both over 70 years of age and the dust from indoor activities is probably small. The indoor concentration of airborne dust fairly closely follows the outdoor level. This is also true for the other house, Fig. 31, inhabited by two people aged 41 and 43. They have oil-heating and a coal space-heater. In the kitchen they use a kerosine heater. The indoor concentrations are compared with those at the same site as with the first house. The indoor air in the second house has a slightly higher dust content than in the first house, mainly because of the higher activity level and the emissions from cooking and combustion.

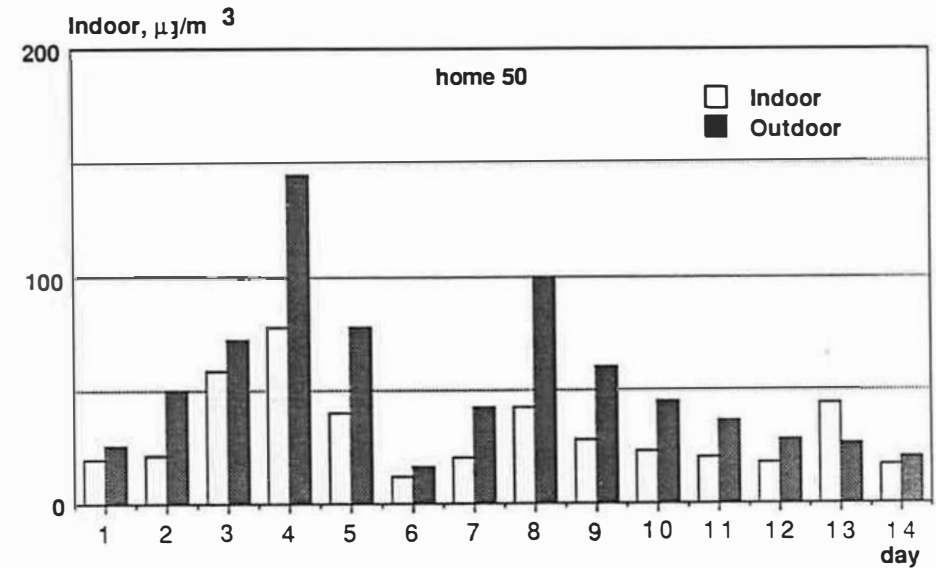


Fig. 30. Concentrations of PM-10 in winter for home No. 50, from Lioy et al. (1990).

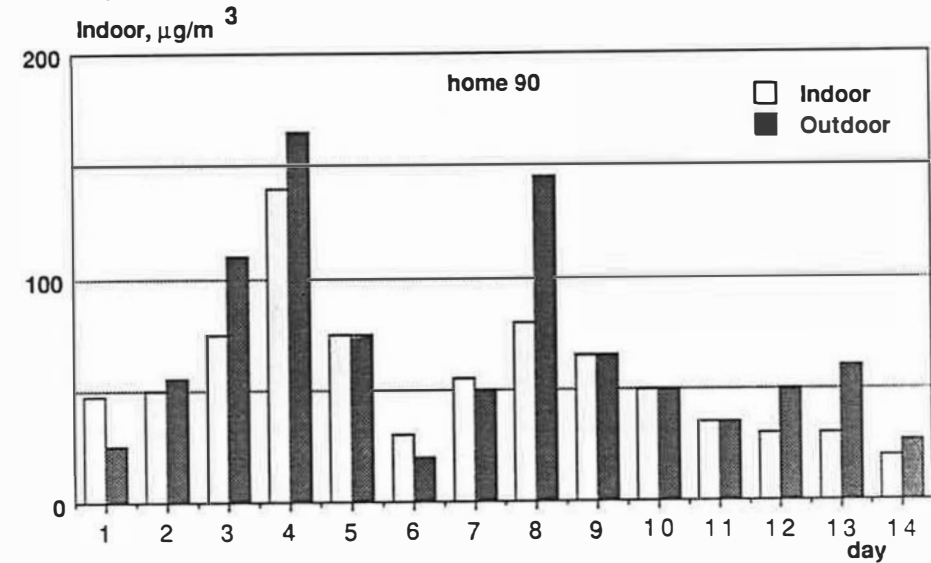


Fig. 31. Concentrations of PM-10 in winter for home No. 90, from Lioy et al. (1990).

## Composition of the particles

If the deposition of particles in the ventilation system is known, then it is possible to find which particles indoors have come from outside. If the outdoor concentrations are known, it should be possible to at least estimate the size distribution of the particles brought into the building. The question now is whether these particles pose any health risks.

Natural particles carry many volatile organic substances into houses. The substances involved sometimes have little effect on health, see Altshüller (1981), although they can reach high concentrations indoors. However, they may react with ozone,  $\text{NO}_x$  etc. in the air and give secondary particles or fumes with possible adverse health effects. With man-made particles the health risks are much higher, see the extensive references in Houdt (1990).

As mentioned, the particles from car exhausts contain lead (Pb) and bromine (Br). Particles 1-10  $\mu\text{m}$  in diameter can be carried from the roads and settle hundreds of metres away. The highest concentration is near the roadside, where they can contaminate the plants growing there. The smaller particles may be transported into houses. An investigation in Germany by Ketelsen and Knöchel (1985) showed high concentrations of many metals for small particles, see Fig. 32 and 33. With metals like copper (Cu), nickel (Ni), manganese (Mn) and zinc (Zn), the large particles ( $d = 5-10 \mu\text{m}$ ) also contained high amounts. But for elements like lead (Pb), arsenic (As), vanadium (Vn) and selenium (Se), with a pronounced impact on organisms, the highest contents were found in the small particles.

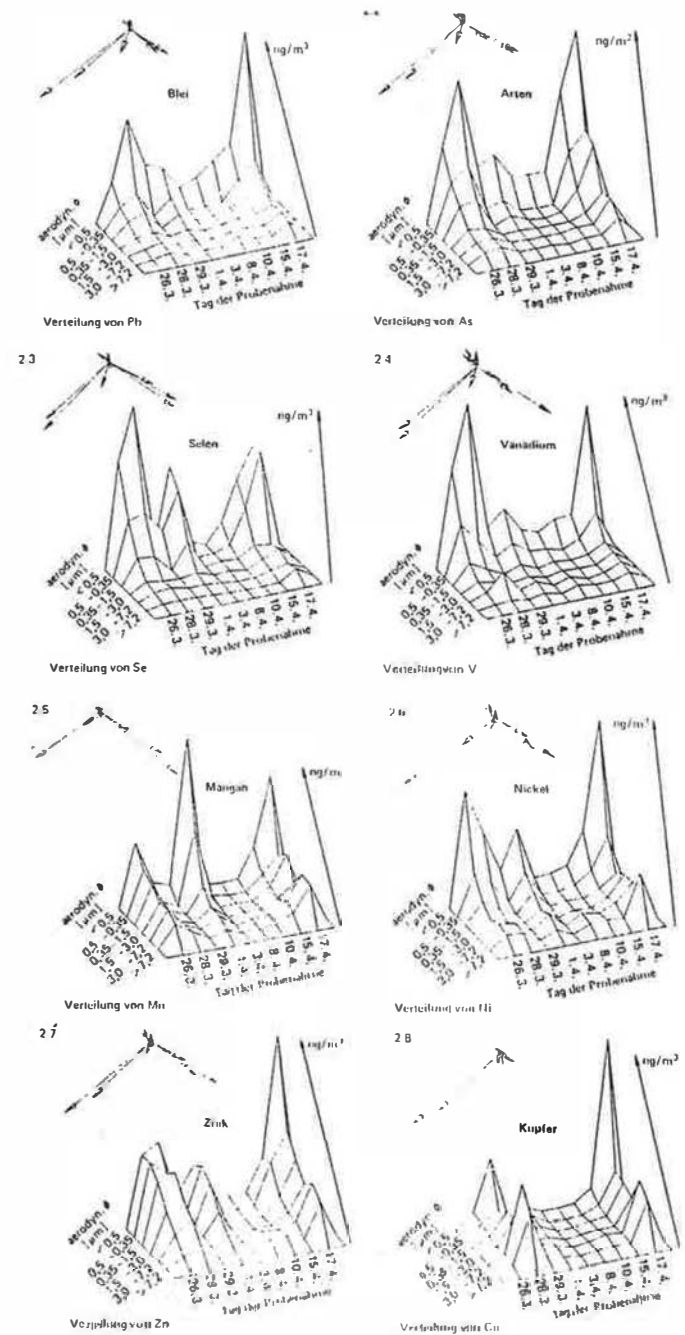


Fig. 32. Levels of lead, arsenic, selenium, vanadium, manganese, nickel, zinc and copper in the Hamburg area.

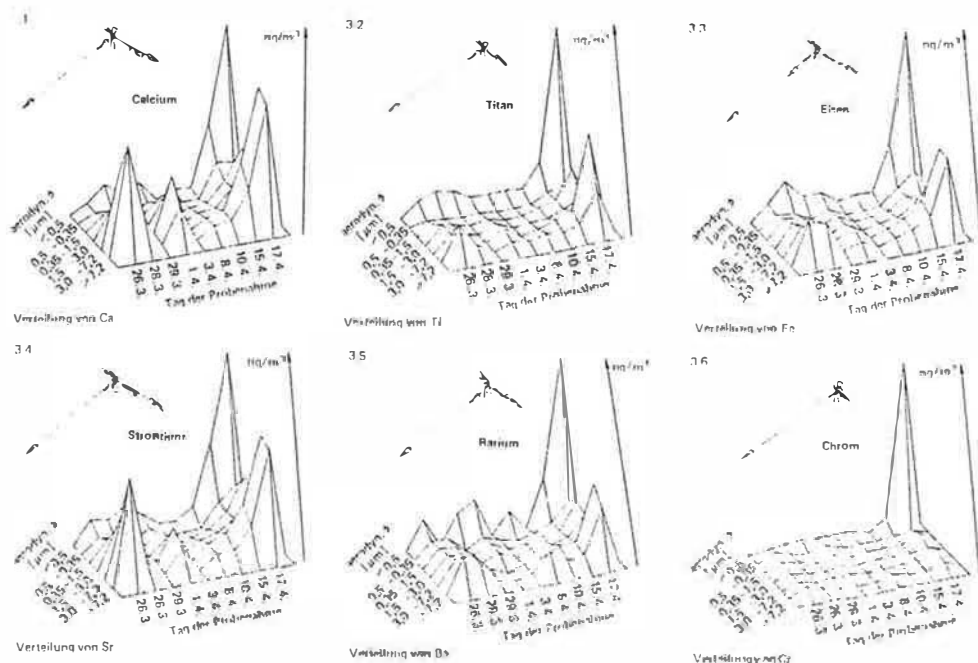


Fig. 33. Levels of calcium, titanium, iron strontium barium and chromium in the Hamburg area.

With the polycyclic aromatic hydrocarbons (PAH) mentioned earlier, a similar result was found by Pflock et al. (1983) and Israël and Friese (1985). Some of the results from Pflock et al. (1983) are given in Fig. 34-36. Four different PAH components are distributed according to particle size; the PAH components are found in the small particles ( $d < 2 \mu\text{m}$ ). Similar results have been found by several other researchers, e.g. Cautreels and Cauwenbergh (1978), König et al. (1981), Krstulovic et al. (1980), and Herlau and Mayer (1978).

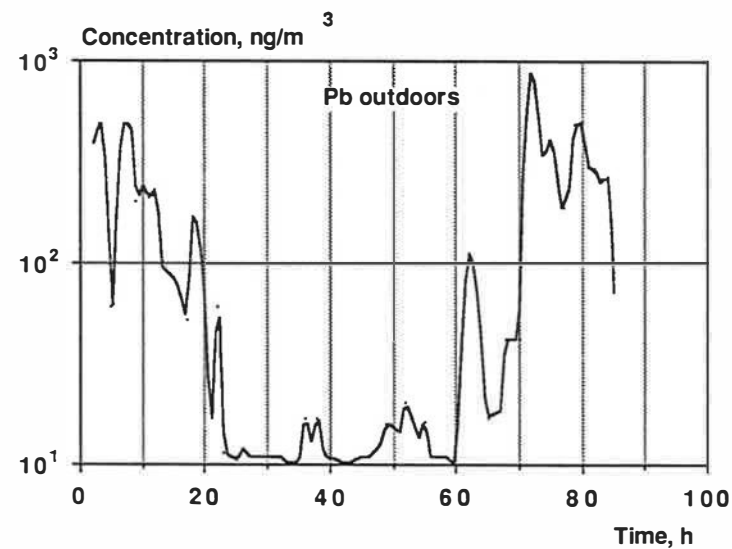


Fig. 34a. Concentration of lead outdoors.

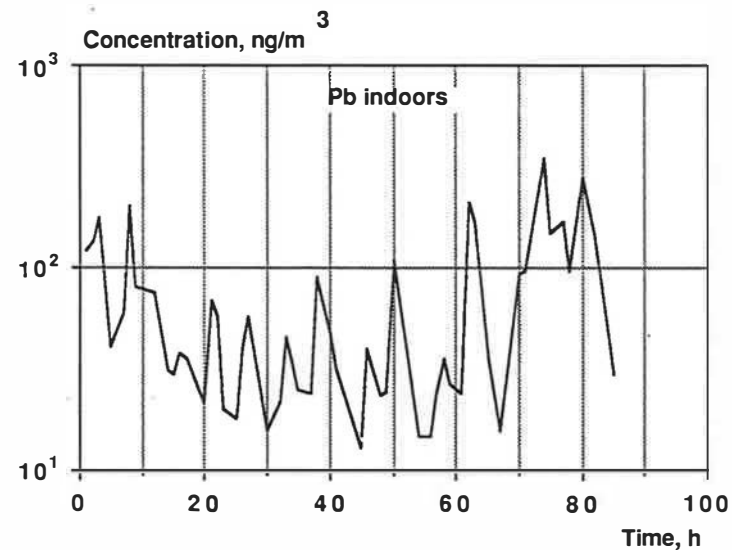


Fig. 34b. Concentration of lead indoors.



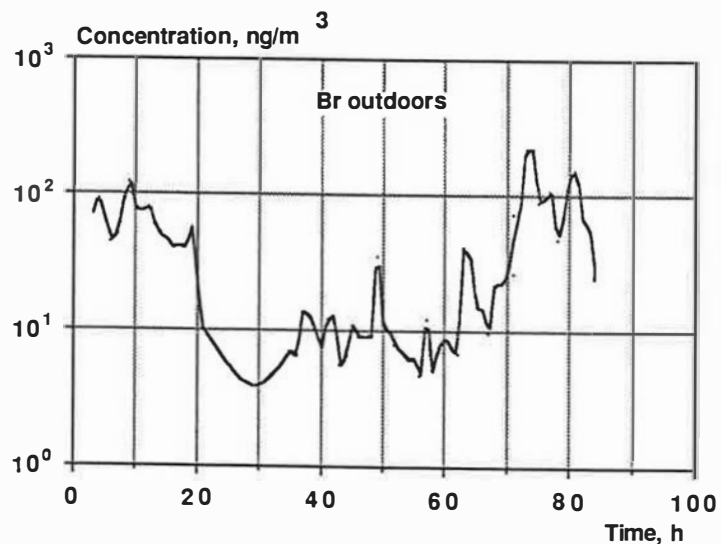


Fig. 35a. Concentration of bromine outdoors.

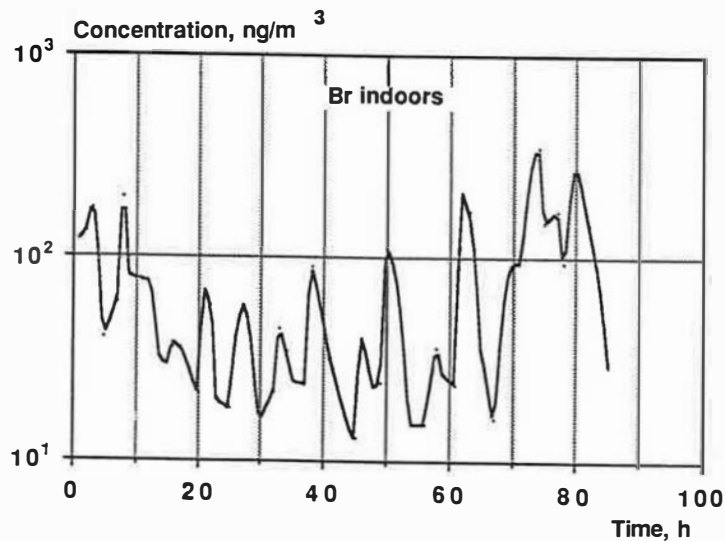


Fig. 35b. Concentration of bromine indoors.

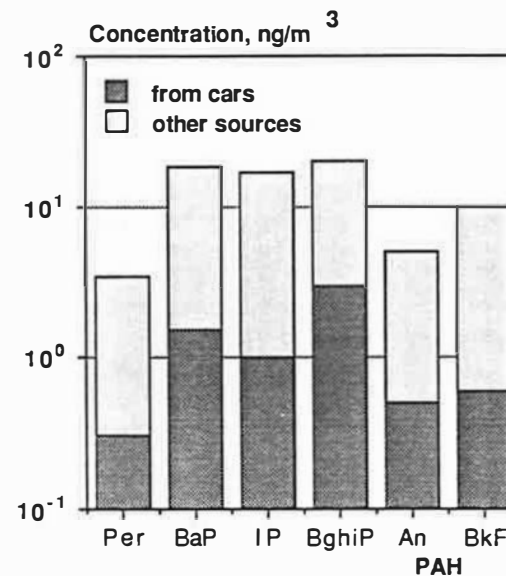


Fig. 36. Concentration of polyaromatic hydrocarbons (PAH).

#### Indoor sources

There are several indoor sources for airborne dust:

- textiles (linen, clothes), see Peterson (1991)
- building materials, such as mineral fibres from insulation or dust particles from floor materials, see Jaffrey (1990)
- indoor activities, see Leaderer (1984)
- animals, insects and spores, see Staib (1982) and Hoffman (1982)
- reentrainment of particles in the air when cleaning and during other activities, as shown by Dybendal et al. (1989).

#### Particles from building materials

The most dangerous particles from building materials are mineral fibres from insulation and fibres from asbestos. The size distribution of such fibres has been studied by Jaffrey (1990), who was interested in the amount of fibres after installing insulation.

The particles seem to have a log-normal distribution for both their diameters and length, see Fig. 37 and 38 respectively. However, the results show very few such particles, and insulation materials seem to pose a negligible health risk. Asbestos fibres on the other hand are known to be dangerous in small amounts, causing asbestosis. As long as an item made of asbestos is not moved, there seems to be little risk. But if it is moved or broken it will release fibres. The particle concentration remains raised for a fairly long time.

In general, a disturbance of the materials gives rise to higher levels of particles in the air, see also Jaffrey et al. (1990).

### Carpets and floors

The cleaning of rooms is another activity that increases particle contents in rooms. Dust from carpets and floors has been investigated by Dybendal et al. (1989a, 1989b and 1990). They studied the particles in dusts obtained by vacuum cleaning in Norwegian schools, and suggested various cleaning solutions for removing allergenic particles.

Kamens et al. (1991) showed that when somebody dusts a room, the average diameter of the airborne dust particles increases from 0,03 to 0,05  $\mu\text{m}$ . Similar results occur when using vacuum cleaners. The particles settle during periods with small air movements or when nobody disturbs the settling process.

### Clothes

The number and size of particles given off from clothes depend on the type of fabric and the activity of the person, see Fig. 39 and 40 from Cohen and Cohen (1980). The style of cloth also matters, as can be seen from the differences due to gender, see Fig. 41.

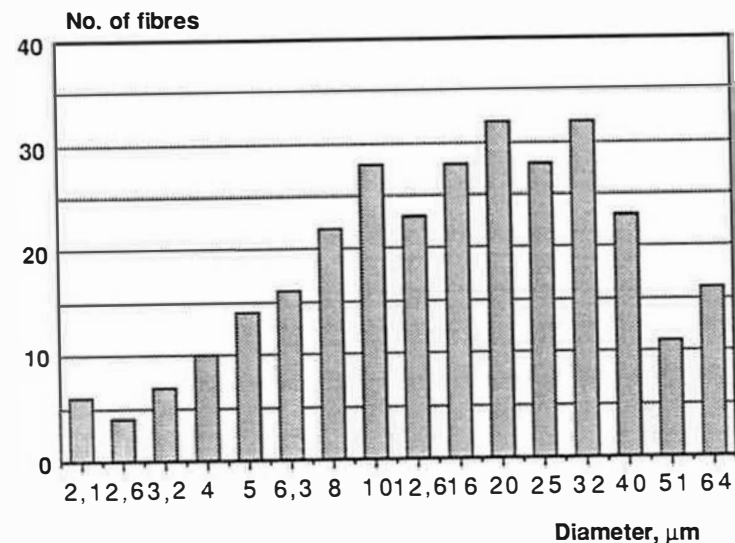


Fig. 37. Distribution of the diameters of fibres emitted after installing insulation.

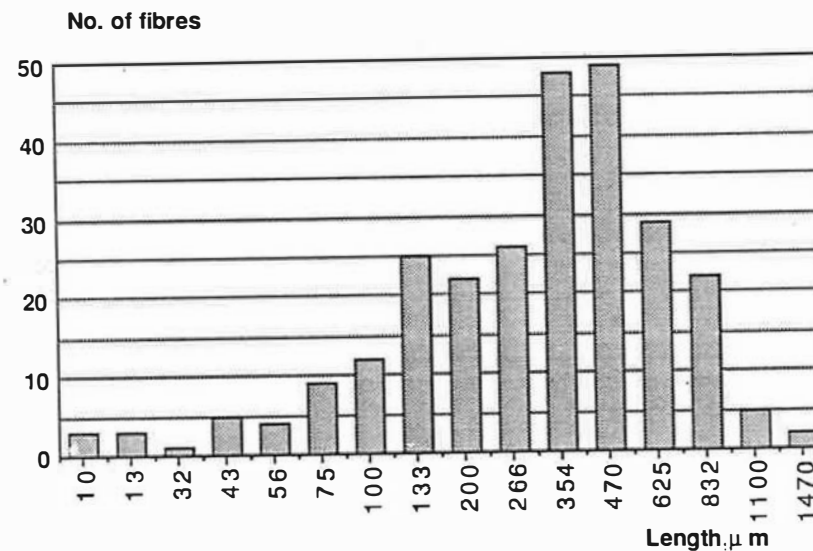


Fig. 38. Distribution of the length of fibres emitted after installing insulation.

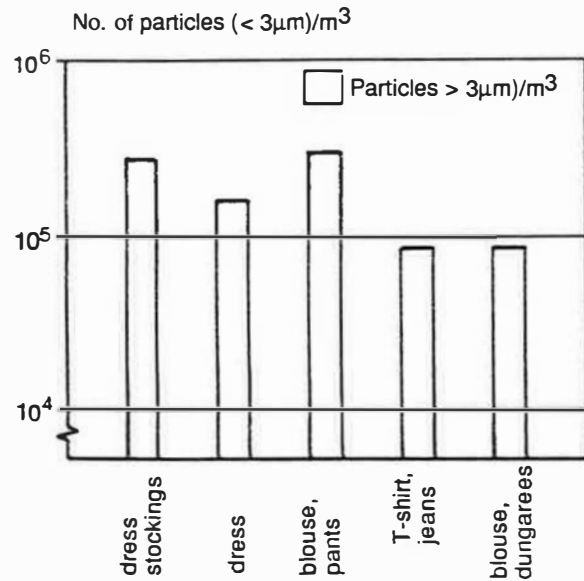


Fig. 39. Number of particles produced by various types of clothing.

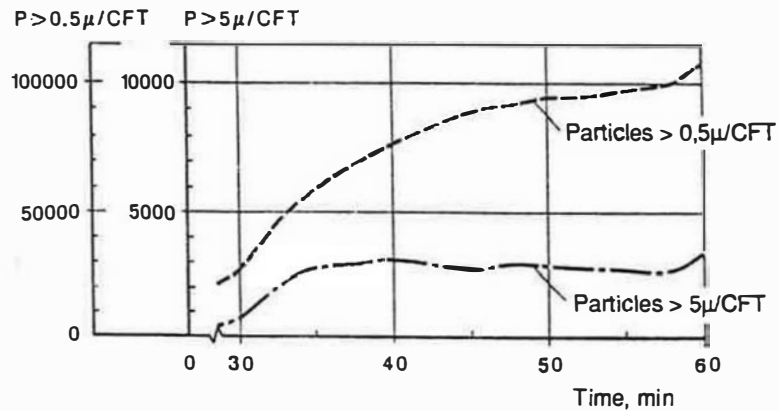


Fig. 40. Number of particles produced during various working periods.

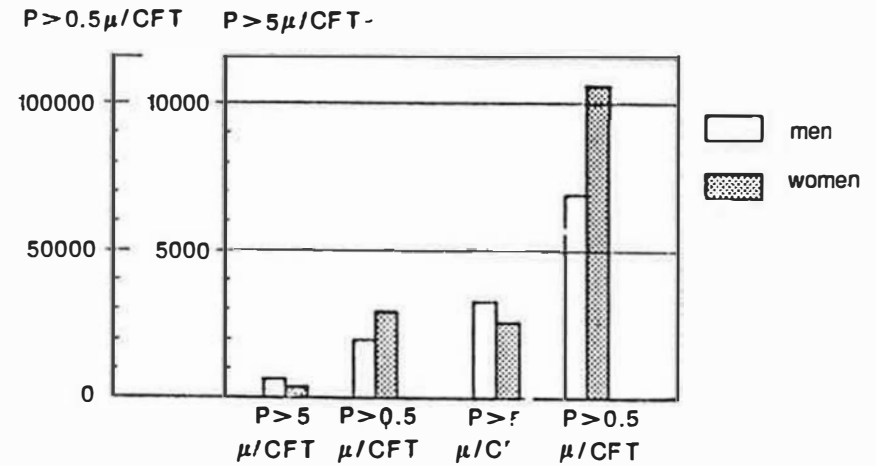


Fig. 41. Particles produced from men's and women's clothing.

### Smoking

The influence of small particles such as those from smoking is important, as they are the carrier for at least some of the PAH, see above. The number of particles produced is high, about  $4 \times 10^{11}$  particles larger than  $0.03 \mu\text{m}$  from one cigarette. However, they do not contribute much to the total dust concentration in rooms, see Fig. 42. The size distribution of such particles is shown in Fig. 43 and 44. Once again, for particles smaller than  $0.1 \mu\text{m}$  in diameter the Junge distribution is not valid.

The total amount of particulates from smoking is shown in Fig. 45 with various ventilation flow rates. This is due to the extremely small particle sizes in the smoke, see Fig. 40-44.

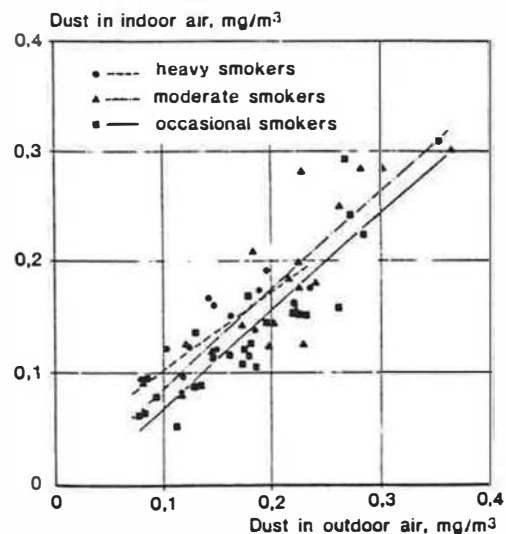


Fig. 42. Concentration of particles produced by cigarettes.

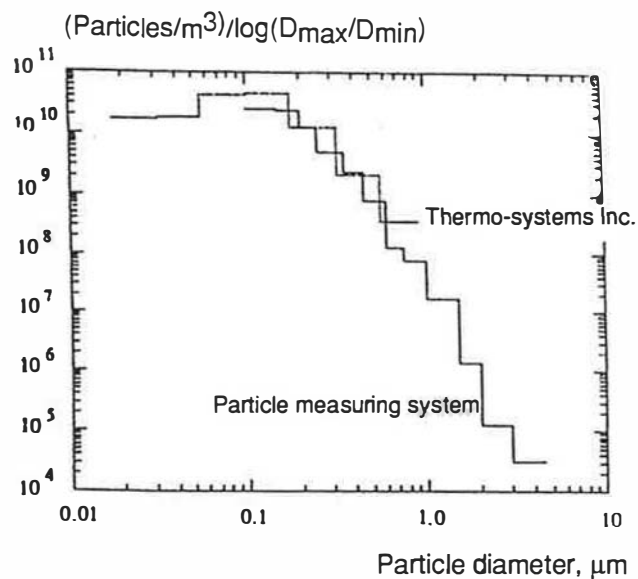


Fig. 43. Number distribution of the particles in the side-stream smoke from one cigarette in a closed room of  $100 \text{ m}^2$ .

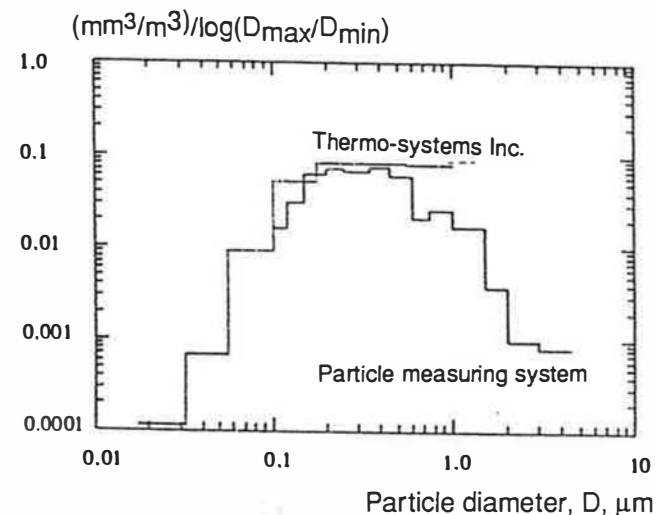


Fig. 44. Volume distribution of the particles in the side-stream smoke from one cigarette in a closed room of  $100 \text{ m}^2$ .

#### Combustion sources in households

Kerosine heaters, like all combustion sources, release particles of various shape and size. In addition, they emit  $\text{NO}_x$ . Both affect the air quality adversely, see Ryan et al. (1983). Fig. 46 is from an investigation by Kamens et al. (1991) of the air quality in non-smoking households. The figure shows the particles produced by cooking. At noon, a lunch is prepared and the amount of particles rapidly increases. Note that the amount is given in the same units as used for the Junge distribution.

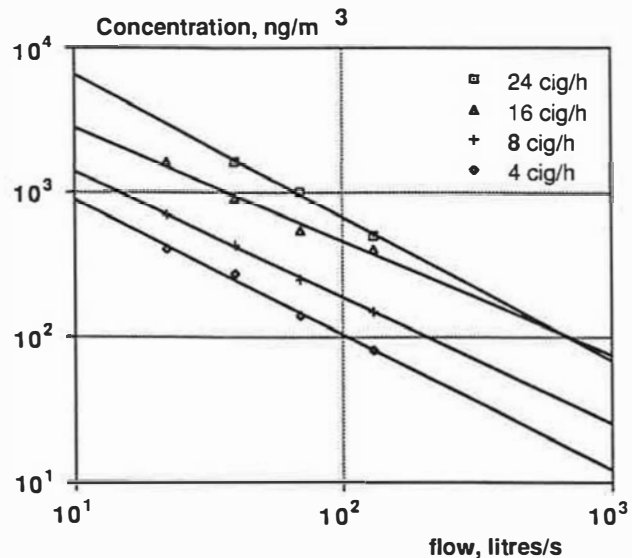


Fig. 45. Total amount of particulates from smoking.

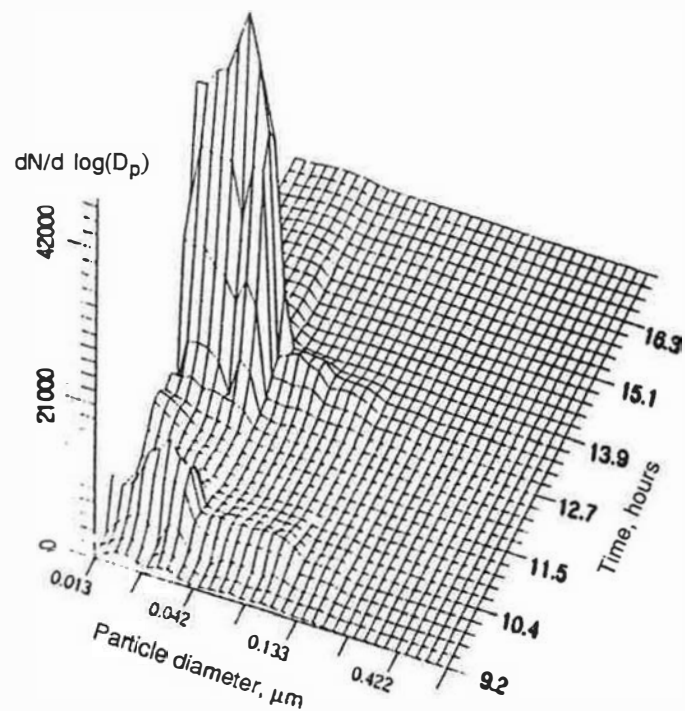


Fig. 46. Particles produced by cooking in a non-smoking household.

## Organic compounds

The organic compounds of particulate matter have already been examined for the outdoor particles. The indoor particulates can be measured by gas chromatography, e.g. Fig. 47. Some constituents in the outdoor air are removed during the passage into the building. The air also picks up some constituents when travelling into the building. More constituents are added by various indoor activities such as cooking. Overall, there is a *higher* level of hydrocarbons in the indoor air than in the outdoor air. This holds true whether the dwelling is inhabited or uninhabited. Whether such levels of hydrocarbons pose a health risk is not certain, but they are certainly associated with an *odour problem*.

Typical results for different types of food preparation are shown in Table 2.

Table 2. Particles from food preparation.

Food	geometric mean diameter, $\mu\text{m}$	geometric standard deviation, $\mu\text{m}$
stir-fried vegetables	0, 021	1, 55
fried eggs	0, 028	1, 73
grilling cheese	0, 052	1, 44

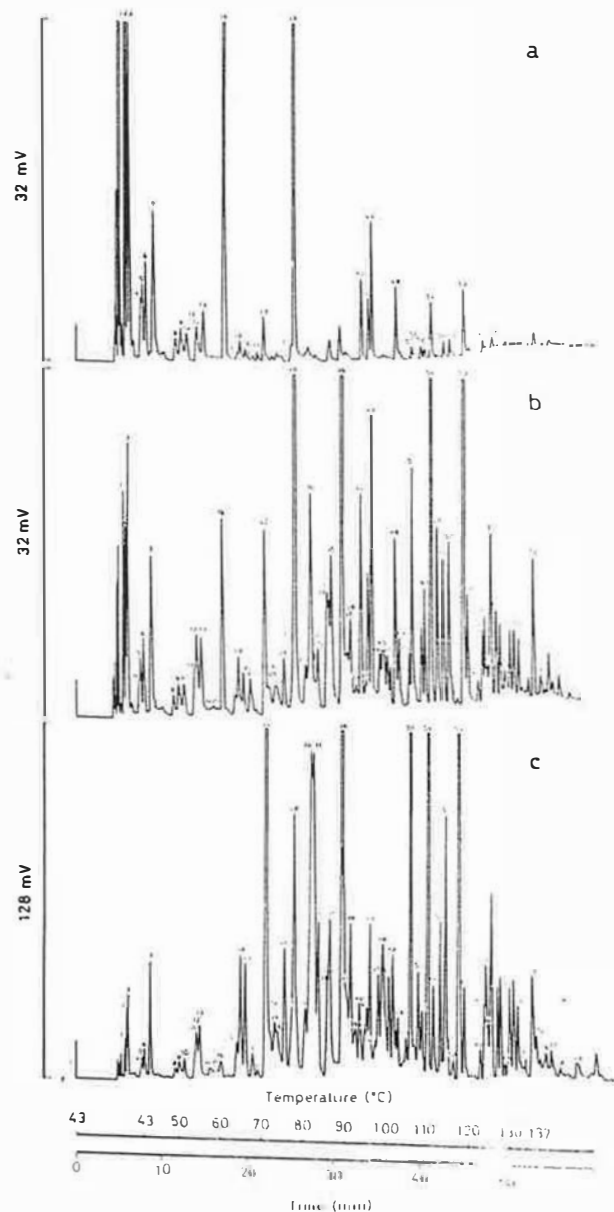


Fig. 47. Gas chromatograms of samples taken in (a) the outdoor air, (b) an unoccupied schoolroom and (c) an occupied schoolroom.

Fig. 48 shows some changes during food preparation. There is a sharp increase in particle content for all sizes during cooking.

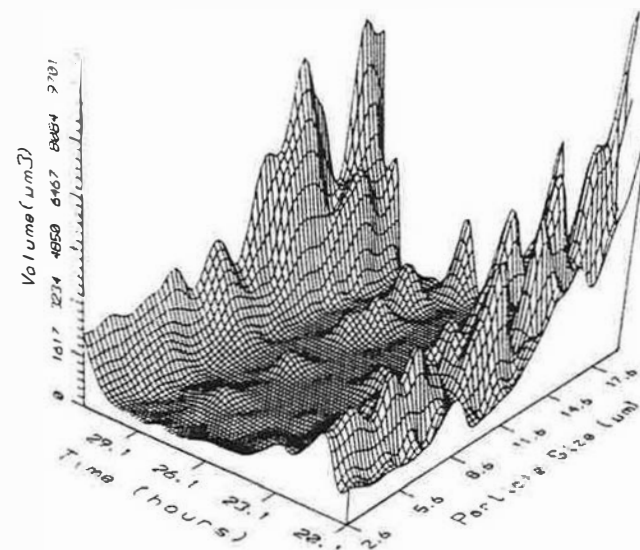


Fig. 48. Change in volume particle size distribution in the late evening and early morning hours in a house (only relatively large particles are represented).

#### Cleaning of rooms

The particles stirred up by cleaning floors are mainly mineral particles. For indoor conditions these particles have geometric diameters of about  $3 \mu\text{m}$  (with a geometric standard deviation of 1-2  $\mu\text{m}$ ). Tobacco particles have a quite a small diameter ( $< 0.01 \mu\text{m}$ ), see Leader et al. (1984) and so does soot ( $< 0.1 \mu\text{m}$ ). Some floor particles may come from outdoor air, and so may contain lead. The resultant increase in blood lead levels is significant. The same applies to other heavy metals like cadmium. Fig. 49 shows some results from two vacuum cleaning methods.

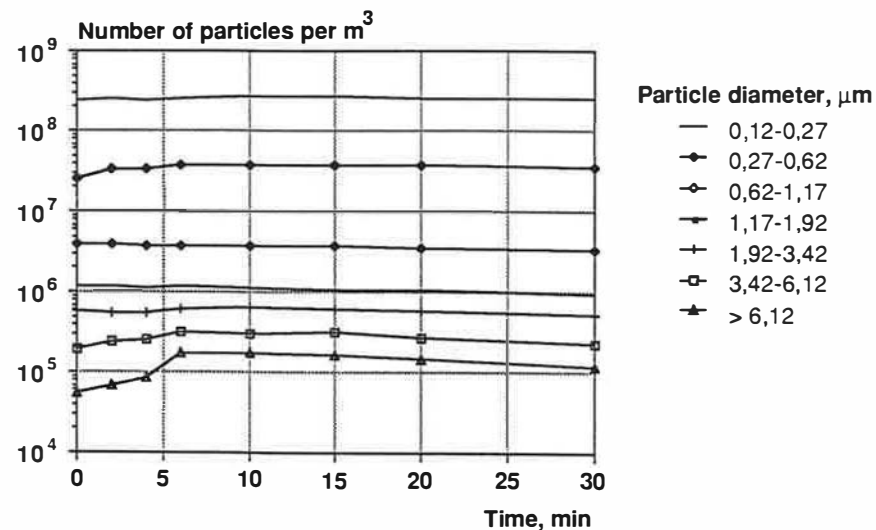


Fig. 49a. Distribution of particles in the air while using a conventional vacuum cleaner.

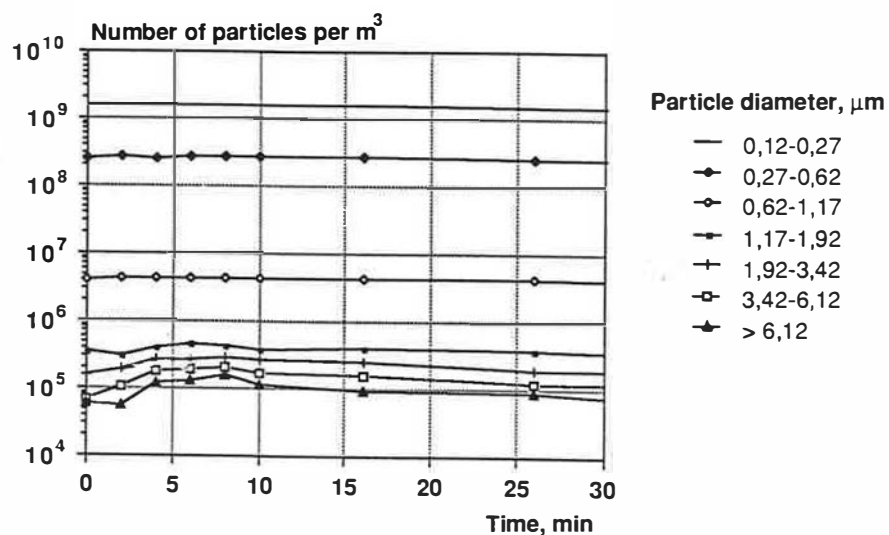


Fig. 49a. Distribution of particles in the air while using a central vacuum cleaner.

## Living compounds

Viruses, bacteria and mites have quite defined sizes. So do pollens and seeds. They can all contain allergens, see the review given by Dybendal et al. (1990). Faeces from house dust mites have a fall velocity of around 0,00002 m/s, and so they are easily held suspended in the air at normal indoor air velocities.

## Other substances

A review like this can only be a summary. Many substance have not been treated in any detail, even though their effects can be significant. Wright (1969) measured the transport of natural particles into houses. The transport of man-made particles appears to follow the same pattern.

Many papers have been written on the organic compounds released from people and from building materials. Johansson (1978) gave a list of 15 different substances that can attach to particles and affect their composition. The influence of indoor fireplaces and the influence of carpets, see Meckel (1982) and Dybendal et al. (1990), are important.

## Size distributions for indoor particles

The size distribution for particles in the *indoor air* have been investigated by Sun (1989), Peterson (1989, 1991) and others. The analyses showed that the particle size distributions of airborne matter in indoor air can be simplified by the Junge distribution, equation (1). Sun gave  $n = 5$  and Peterson gave  $n = 3$ . Other values have been given in the literature. Some examples are given in Fig. 50.

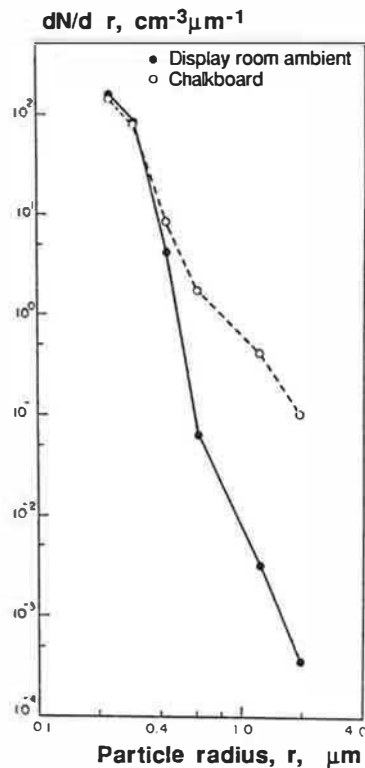


Fig. 50. Aerosol size spectra in display room prior to and during proximate chalkboard activity.

By using the equation of Junge, equation (1), the amount of fine and coarse dusts can be found for  $r < 1,5 \mu\text{m}$ ,  $0,1 < r < 1,5 \mu\text{m}$  and  $r > 1,5 \mu\text{m}$  (0,7%, 35,5% and 64% of the total mass respectively), see Fig. 51.

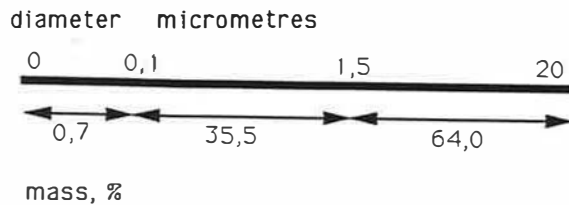


Fig. 51. Proportion of fine and coarse dusts obtained from Junge's equation.

The particles from smoking and some of the particles with outdoor origin are much smaller than  $1 \mu\text{m}$ , and their content of PAH is quite high. Because the particles are formed in several ways, they have different distributions. This is why the Junge distribution can be used again to give a general size distribution. However, the volume of the particles given off is small, as is their area. So there is usually little fouling of the walls.

### Summary

The particulates in indoor air come partly from outside and partly from indoor activities. So when the indoor situation is examined, the size and distribution of outdoor particles must be considered.

The smallest particles from outdoors are transported into houses via ventilation systems, open doors etc. The smallest particles are the ones most effectively transported; larger particles are caught in filters or are deposited in the ventilation system.

As the small particles are the carriers of such components as ions, heavy metals and PAH, there is a parallel transport of such harmful substances into the rooms. So outdoor airborne particles are of great importance for the inhabitants.

The particles formed inside a house by cooking, smoking, and other activities are added to particles of natural origin like mould spores and pollen. Together they form a suspension which can be harmful and give rise to so-called sick buildings. The exact process is not clear, but it can at least be said that particulate matter in the indoor air plays a large role in the sick building syndrome.



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