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Dust and fibers as a cause of indoor environment problems

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In the absence of scientifically based guidelines for airborne dust concentrations, good practice calls for dust levels to be kept as low as practically achievable. To do so means reducing the sources. Once particles are introduced, there is only one way of removing them, through a combination of ventilation and surface cleaning. These removal processes, in combination with source emissions and material transport between indoor air and surface compartments, determine the net concentration of particles in the room air. Data on source emission and transport rates are presented in this paper. Such data provide useful background information for developing effective strategies for controlling particles in indoor air. Visually perceived cleanliness is one measure of indoor-air quality and is the subjective assessment of cleaning quality. Cleaning quality can be concisely defined and objectively assessed according to a Nordic standard on cleaning quality. An example of how to deal with complaints of irritation attributed to particles in the absence of concentration guidelines is presented for synthetic vitreous fibers.

Key terms cleaning; control; deposition; penetration; resuspension; review; source; synthetic vitreous fiber; track-in; transport.

The presence of dust and fibers in the indoor environment is a problem if occupants complain about visually perceived dustiness or have subjective or objective symptoms attributed or attributable to dust or fibers. Several species of particulate- or particle-borne chemicals for intended use, unintentional particle emissions, and particles of pet, pest or microbial origin are likely to cause health effects in nonindustrial indoor environments. For dust in general, a review of the literature up to August 2001 concluded that there was limited and inconclusive scientific evidence that mass or number concentrations are useful risk indicators for health effects in buildings. It follows that there was inadequate scientific evidence to establish health-based limits or guidelines for airborne particulate mass or number concentration (1). The study did not attempt to identify causative agents (ie, whether health effects were due to low levels of ubiquitous allergens, toxins, or irritants or specific major components). Recent chamber tests (2–4) involving human exposure to office dust without major reactive compounds (5) have provided limited additional evidence.

Control of concentration levels

In the absence of scientifically based guidelines for airborne dust concentrations, good practice would be to keep dust levels at benchmark levels attainable with the best available technology (6). To do so means that, first, the sources need to be reduced. Room air-cleaning devices are not very effective against strong intermittent sources, in particular if dust is generated or resuspended by the occupants themselves (ie, the source is close to the person) (7). When beds are made or vacuuming is done, for example, the concentration in the breathing zone could be up to a factor of 8.5 times the concentration measured at a stationary position over a 15-minute time period (8).

Once particles are introduced into the indoor environment, the only way of removing them is through a combination of ventilation air and surface cleaning. The need for this combination is supported by the study of Schneider et al (9), who compared the subjectively assessed quality of cleaning and the degree of ventilation with airborne concentrations of respirable and

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nonrespirable synthetic vitreous fibers. It was found that coarse (nonrespirable) fiber concentrations correlated significantly with cleaning only, and fine (respirable) fiber concentrations correlated with ventilation only.

Several studies have been made of the impact of cleaning on the concentration of particles in indoor air. Leese at al (10) measured airborne and surface dust levels in a nonproblem building during routine housekeeping and after professional cleaning had been performed once, followed by improved housekeeping. They found a reduction from 12 to 8 µg/m^3 in the mean levels of total airborne dust in the building. Kildesø et al (11) studied the effect of various cost-neutrally improved cleaning methods. Some of the improved cleaning methods could reduce surface dust levels, but the effect was less pronounced for airborne dust levels. A likely explanation of the limited reduction was that the dust levels in the studied building were relatively low and that the original cleaning method was effective already. In a very dusty building (200–300 µg respirable dust/m^3), in which normal cleaning practices were poor, cleaning intervention reduced the airborne respirable dust concentration by almost 80% on intervention floors relative to control floors (12).

A conceptual model

The *airborne concentration of particles* is the net result of source emissions, material transport between the indoor air and surface compartments, and removal from the compartments, as shown in figure 1, as modified from a paper by Schneider et al (13). *Emission* is the transport of particles into room air from all primary sources, such as office machines, room occupants, and the infiltration of contaminated outdoor air. *Track-in and spillage* involve the transport of particles and dirt into the system directly to surfaces. *Penetration* is the transport of outdoor particles in air infiltrating into the indoor air. Ventilation can either be included or considered a separate transport mechanism.

Deposition is the transport of particles from the air to surfaces. The deposition rate can be parameterized as the deposition velocity multiplied by the airborne concentration. *Resuspension* is the transport of deposited particles from surfaces to air. *Removal* is the transport out of the system through ventilation, air filtration, or surface cleaning.

Some quantitative data for source emissions and transport processes follows. Such data provide useful background information for the development of effective strategies for controlling particles in indoor air.

Source emissions

Occupants are significant particle generators. Yoon & Brimblecombe (14) agitated upper garments to simulate dust generation by a museum visitor. The particles deposited on the floor of the test chamber were sized, giving count median diameters (CMD) from 10 to 20 µm and very large geometric standard deviations (GSD), from 5 to 10. Mass collected by washing all surfaces in the test chamber gave an average of 4.9 mg for summer conditions and 7.6 mg for winter conditions.

The complete outer skin layer is shed within 1–2 days. This process can result in the release of several million skin scales per minute. A significant fraction can penetrate clothing and become airborne (15). Talking, coughing, and, in particular, sneezing generate large numbers of droplets that carry bacteria. One sneeze generates on the order of 100 000–1 000 000 droplets, many of which carry bacteria (16).

Scheff et al (17) used a mass balance approach to estimate emission factors for particles in a nonproblem school building. They did not distinguish between dust coming from primary sources and dust resuspended from surfaces by people's activities, and no information on

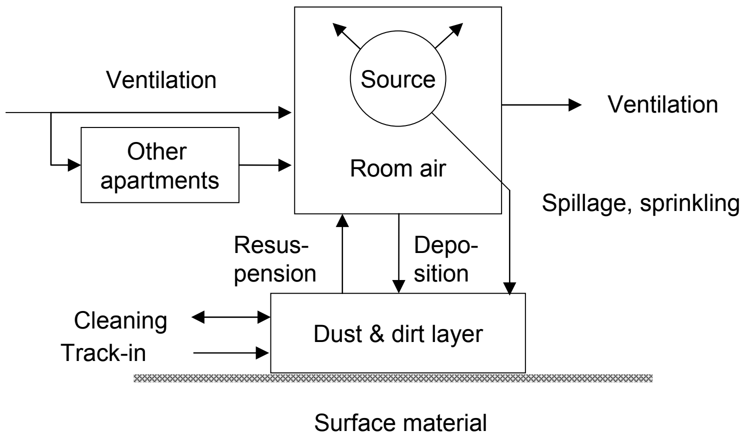

Figure 1. Conceptual model including source emissions and material transport between compartments (13).

the amount of carpeting was given. They found that one person "emitted" a total of 1.3 mg of particulate matter and 0.15 mg of respirable particulate matter per hour. The handling of new paper (recycled or not) was not a significant source of airborne dust (18).

From the particle total exposure assessment methodology (PTEAM) study, the following emission rates were obtained (19): 1.7 (SD 0.6) mg of $PM_{2.5}$/minute and 4.1 (SD 1.6) mg of PM_{10}/minute for cooking and 1.1 (SD 1.0) mg of $PM_{2.5}$/hour and 5.6 (SD 3.1) mg of PM_{10}/hour for other activities, excluding smoking [$PM_{2.5}$ and PM_{10} being particulate matter with an aerodynamic diameter of <2.5 µm and <10 µm, respectively].

Candles and oil lamps are significant sources of submicron particles. Furthermore, the flame height of oil lamps can have a large effect on emission (20). Emission was 6 mg of total particulate matter/hour when the flame height was normal and 115 mg of total particulate matter/hour when it was high.

Environmental tobacco smoke has been described well in the literature and will not be discussed. Suffice it to mention that particles of tobacco smoke are in the size range 0.1–0.7 µm and that a sizeable fraction of tobacco smoke will deposit on all room surfaces, even in well-ventilated rooms (21).

Table 1. Track-in of dust and dirt.

Process [a]	Mass transport
Track-in (22)	
Post office, rainy day	20 g/(day · m²)
Far from the entrance and low person traffic	0.02 g/(day · m²)
Net mass flux (27)	
Hall and lounge carpet	0.19 g/(day · m²)
Mass increase on uncleaned or vacuumed floors (23) [b]	
Carpet, upstairs	0.15 g/(day · m²)
Carpet, downstairs	0.31 g/(day · m²)
Linoleum downstairs	0.01 g/(day · m²)
Front doormat	6.2 g/(day · m²)
Mass increase on cleaned or vacuumed floors (23) [b]	
Carpet, upstairs	0.086 g/(day · m²)
Carpet, downstairs	0.083 g/(day · m²)
Linoleum downstairs	0.009 g/(day · m²)
Mass removed by vacuuming (24)	
Livingroom floor [c]	0.2–0.4 g/(day · m²)
Track-in of dirt on shoes into museums (25)	
Dry weather	0.13 g/person
Rainy weather	0.09 g/person
Wet weather	2.29 g/person

[a] Numbers in parentheses are the references from which the data were taken.
[b] Dust was sampled with the use of a micro-vacuum technique, and the results were corrected for sampling efficiency.
[c] Calculated on the basis of the amount collected by vacuuming, and the information given that floors were vacuumed by occupants every 1–2 days.

Track-in

The number of particles and dirt carried into the building on shoes depends on the outdoor climate, the design of the entrance with scrapers and mats, and the distance of the room from the entrance. The results of measured track-in are given in table 1. Studies of track-in from herbicides from a treated garden into the living spaces of homes (26) and of isotopes generated by the Tjernobyl accident (27) found that floor concentration gradients followed the traffic patterns from the entryway. Bare floors, in particular uncarpeted entries, may exacerbate migration into carpeted living areas (26).

In comparison, typical dust fall rates from room air in Finland (28–29) and in Germany (30) are much smaller, about 0.005 g/(day · m²).

Penetration from outdoors

Outdoor particles penetrate through openings and cracks into the indoor environment. Penetration through cracks depends on crack geometry and increases with increasing pressure differences. In general, penetration is largest in the diameter range of 0.1–1 µm, where it may approach 100% (31–32). Indoor sources thus will usually dominate ultrafine (<0.1 µm) and coarse (measured as the fraction in the size interval 2.5–10 µm) particles, as evidenced by a low indoor–outdoor correlation and a high indoor-to-outdoor ratio of particle concentrations for these size ranges (33). Particle concentration peaks in an apartment in an older multistorey building have been found to coincide with candle burning and smoking events in neighboring apartments, and they demonstrate that particles are transported between adjacent apartments (34).

Surface deposition rates

Airborne particles are removed from room air by ventilation and in competition with removal by deposition on a surface. The rate, N, by which ventilation exchanges contaminated air with clean air is measured as the air exchange rate per hour. The rate by which particles are removed from room air by deposition can likewise be characterized by an equivalent air exchange rate, N_e. The ratio $N_e/(N_e+N)$ is the fraction of airborne dust that is not removed by ventilation but is deposited on surfaces. Table 2 provides a summary of the data. Table 2 shows that very high ventilation rates are needed to prevent a large part of the particles generated (eg, by dusting) to redeposit. Such rates are achievable only by airing a room during the cleaning procedure, for example.

The time it takes for an originally clean surface to become visibly dusty is an important parameter for determining cleaning frequency. Soiling time has been defined as the time taken to deposit particles covering 0.2% of the area (40), which is the limit of the visual detection of black spots on a white surface (41). Typical soiling times, as predicted from a semi-empirical model range of 1 day to 1 week (horizontal shelf), 2 months to 2 years (smooth wall), and many years for ceilings (42). Measured soiling rates on hard horizontal furniture surfaces range from 1 to 3 days (43).

Deposition on upward-facing surfaces is dominated by the settling of large particles. Deposition on vertical and downward-facing surfaces increases with increasing surface roughness and increasing air turbulence. Textile surfaces collect more particles from the air than smooth surfaces due to the filtering effect of the protruding fibers (44). Porous ceiling boards act as coarse dust filters when air is forced through them due to local pressure differences. This action greatly increases the soiling rate of porous ceiling boards. Thermophoresis mainly causes submicron particles to drift towards a lower temperature in a thermal gradient. Thus increased amounts of submicron particles are deposited, for example, behind central heating pipes, where they form black stripes. Electric fields at surfaces enhance the deposition of charged and uncharged aerosols (42).

Table 2. Equivalent air-exchange rates (N_e). The last column is the theoretical fraction of airborne particles that will deposit on room surfaces. Ventilation air will remove the remaining fraction. It is assumed that the ventilation air-exchange rate is N=1 and that there is complete mixing. ($PM_{2.5}$ = particles <2.5 µm in aerodynamic diameter, PM_{10} = particles <10 µm in aerodynamic diameter)

Type of dust [a]	N_e, h^{-1}	$N_e/(N_e+N)$ for N=1/h (%)
Including resuspension by activities		
Homes, not standard size (35)		
$PM_{2.5}$	0.39	28
PM_{10}	0.65	39
Homes (36)		
$PM_{2.5}$		
Summer	0.55	35
Winter	0.30	23
No resuspension		
Office building [b] (37)		
Salts <2.5 µm	0.48	32
Salts >2.5 µm	3.0	75
Occupied house (28)		
House dust	5.5	85
Furnished experimental house (38)		
2 µm of aerosol	0.95	49
4 µm of aerosol	2.1	68
Experimental room, with or without carpet, bare or furnished (39); 4 speeds of a stirring fan		
0.55 µm	0.1–0.27	9–21
1 µm	0.1–0.38	9–28
3 µm	0.64–1.64	39–62
8.7 µm	4.9–12.6	83–93

[a] Numbers in parentheses are the references from which the data were taken.

[b] Values were calculated from deposition velocities on the assumption of a room size of 5.4 × 3.6 × 2.4 m.

Resuspension

Dust accumulating on surfaces is a secondary source of airborne particles if agitated. Harney et al (45) showed that air velocities of 15 cm/s and 37 cm/s did not resuspend particles (0.3–100 µm) of house dust "salted" on a horizontal surface of painted wood. However, when a mechanical disturbance simulating the typical 3-Hz mechanical disturbances in a building was used, particle release increased orders of magnitude in the size range 2–100 µm. Thus, normally, a mechanical disturbance is required to resuspend dust. However, once a large particle or textile fiber has been set in motion by air currents, it can dislodge smaller particles on its way (formation of dust bunnies).

Thatcher & Layton (23) determined the resuspension of dust caused by cleaning, walking, and normal activities in houses. They found that resuspension decreased with three orders of magnitude with particle size from >10 µm to practically insignificant levels for particles <1 µm. This occurrence explains, in part, the finding (46) that resupension affects PM_{10} but not $PM_{2.5}$. As could be expected, resuspension increases as the activity level increases (23, 47, 48).

In a livingroom, vigorous vacuuming and house cleaning can disperse more dust than continuous walking and sitting by one person for 2 minutes, which again can resuspend more dust than 5 minutes of normal activities by four people (23). Movement of the cleaning person could redisperse as much dust (number of particles larger than 3 µm) as cleaning with the use of a dust cloth (49). Long et al (33) measured dust concentrations during scripted activities in homes. The results are given in table 3. A study in a residence determined the total amount of dust resuspended per hour by one person. During sitting on furniture and vigorous walking, it was 15–30 mg PM_5/hour, and during dry dusting and vacuuming it was 40–60 PM_5/hour (8). Yakovleva et al (46) found that vacuuming in homes contributed to the 12-hour average PM_{10} concentration, but contributed to this concentration with less than 10%.

The convective plume around the body carries resuspended particles and particles shed from the person (skin scales, textile fibers, bacteria, etc) to the breathing zone (50). Thus a significant dust source may follow a person, introducing an ever-present concentration gradient. Therefore, the assumption of complete mixing does

Table 3. Maximum concentrations (5-minute periods) during activity, corrected for the background prior to the activity. Data taken from the report of Long et al (33). ($\mu m^3/m^3 = \mu g/m^3$ for a density of 1 g/cm^3). ($PM_{2.5}$ = mass of particles <2.5 µm in aerodynamic diameter, $PV_{(a-b)}$ = volume of particles with an aerodynamic diameter in the range of a to b µm)

Activity	Events (N)	$PM_{2.5}$ µg/m³		$PV_{(0.02-0.1)}$ µm³/m³ [a]		$PV_{(0.1-0.5)}$ µm³/m³		$PV_{(0.7-2.5)}$ µm³/m³		$PV_{(2.5-10)}$ µm³/m³	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Dusting	11	23	23	0.01	0.01	0.14	0.19	5.0	6.4	82	70
Vacuuming	10	5.6	3.9	0.06	0.08	0.43	0.49	1.8	1.4	6.7	3.7
Vigorous walking on carpets	15	12	9.1	0.04	0.13	0.19	0.27	6.7	5.0	29	19

not hold for particles generated by person-induced resuspension. This phenomenon has been termed a "personal cloud" (35). Concentrations measured by personal samplers during entire daytime periods in homes was about 50% above concurrent indoor concentrations measured by stationary samplers. This increase in particle concentration was dominated by particles above 2.5 µm in size (35, 51). The personal cloud factor is less pronounced for persons with impaired motion (chronic obstructive pulmonary disease), as could be expected. Wallace (52) analyzed six studies and found a personal PM_{10} cloud of about 30 (range 6.5–56) µg/m³ and a smaller $PM_{2.5}$ cloud (range 3.7–27 µg/m³). Experiments with controlled clothing exposure (53) found that clothing was a major contributor to personal clouds.

What is special about carpets?

Several studies have found larger amounts of dust accumulated on carpeted floors than on smooth floors (10, 23, 54). For a nylon carpet and flooring made of polyvinyl chloride (PVC), both soiled with the same amount of *Staphylococcus aureus* particles per area, airborne concentrations of colony-forming units during simulated walking were higher for the PVC flooring than for the carpet floor coverings (47). Opposite results showing that heavy and fast walking can resuspend more dust from carpets than from equally loaded hard floors have also been reported (48). In a study of homes in which floor dust loadings were not known (33), higher concentrations were found in rooms with carpets [8.0 (SD 6.6) µg $PM_{2.5}$] than in noncarpeted rooms [4.8 (SD 3.0) µg $PM_{2.5}$).

Factors that affect dust binding and the release process in carpets and thus the cleaning ability of vacuuming are basically the same as those that affect resuspension. Kivistö & Hakulinen (55) found that resuspension from carpets decreased at low (<20%) and at high (>83%) relative humidities and explained it as being due to static electricity and capillary condensation, respectively. Similarly, Wang et al (56) found that the efficiency of vacuuming a shag carpet decreased when the relative humidity decreased from 85% to below 50%. Kildesø et al (57) studied experimentally the resuspension of aluminum oxide test dust from bouclé, velour, and needle felt carpets using a specially designed instrument (STEPP tester) for simulating dust resuspension caused by walking. They found that the number of particles resuspended depended on both particle size and carpet type. In the size range 1–10 µm, three times as many particles were resuspended from the needle felt carpet than from the other two carpets, and in the size range 10–30 µm the corresponding difference was 5- to 10-fold. The differences were much smaller in a field study (58). This finding could support the hypothesis that, if there are differences in dust-holding capacities between carpet types, the differences in the actual amounts of resuspendable dust during use are leveled out because there is a balance between the ease of resuspension and the effectiveness of vacuum cleaning.

Lewis et al (59) measured dust retention by determining recovery as measured by a standardized vacuuming method. It was found that the total carpet surface (density of loops and height of cut pile) had a major effect on the recovery of mite allergen from house dust and of bulk dust—the larger the area the lower the recovery. They also found that Teflon coating increased recovery. Obviously, there is a trade-off in carpet design, since increased recovery (ie, ease of cleaning) also implies increased resuspension. The authors recommended that carpets with high recovery be used and that they be cleaned frequently. Kildesø et al (60) found that the resuspension of dust from carpets (as measured with a STEPP tester) in occupied buildings was higher in the morning than in the afternoon and suggested that this effect may have been due to walking having the effect of protecting dust from resuspension (eg, by closing the opened-up carpet surface).

Perception

Visibility, and thus the perception of particles and the resulting evaluation of the quality of cleaning by occupants, is dependent on the intensity and direction of illumination, the size of dust particles, surface roughness

Table 4. Actions to be taken, depending on the air or surface concentration of synthetic vitreous fibers (SVF) if complaints are made about upper-airway or skin irritation. Data taken from the report of Schneider (62).

Air (fibers/m^3)		Surface (fibers/cm^2)		Action
WHO [a]	Diameter >3 µm	Easily accessible	Infrequently cleaned	
<100		<0.2	<3	Search for causes other than SVF
>200				SVF sources have been active; include source control in building maintenance
			>10	Consider increased cleaning and/or improved cleaning methods
	>100			SVF is the likely cause; eliminate source followed by thorough cleaning

[a] Fibers having a diameter of <3 µm, a length of >5µm, and a length-to-diameter ratio of >3 (65).

and coloring, and the amount of dust, with dust in carpets as the extreme example. Under the most favorable conditions of visibility (black spots on white background), the contamination has to exceed 0.2% in order to be detectable by the naked eye, and contamination levels must differ more than 0.45% in order to be seen as different (41). The color and texture of surfaces can be designed specifically with the purpose of camouflaging spots and dust (61). As an example, yellow colors enhance the visibility of heel marks, and red and blue colors make dust more visible, while brown and brownish-green colors can camouflage spills of, for example, coffee and urine. Carpet fibers can be designed to refract light so as to reduce the visibility of dust entrained in carpets (59).

Synthetic vitreous fibers

The release of synthetic vitreous fibers (SVF) from recently installed materials for thermal and acoustic insulation is of no concern regarding lung cancer. SVF with diameters of >5 µm have some potential to cause transient skin irritation, and those with a diameter of >10 µm have a strong potential in this respect. Coarse fibers at high airborne concentrations may also irritate transient mucous membranes, but the diameter dependence is not known (62).

For SVF ceiling boards without surface treatment, it was found that boards bonded with water-soluble binder released more fibers than other types (9). A study from Germany (63) showed that there was no difference between old (>10 years) and new SVF materials, visible and covered products, and concentrations at background levels and during activities involving electricians drawing cables or mounting switches. An increase over the background level was found if a sandwich wall construction allowed a pumping effect. Schumm et al (64) only found SVF concentrations exceeding 100 WHO [2] fibers/m^3 if there was visible damage, a visibly leaking vapor barrier, material in physically poor condition, poor construction (such as ceiling tiles not mounted properly), or obvious penetration routes for SVF from the attic to living spaces.

Combining limited evidence for irritation effects with measured concentration benchmarks, Schneider (62) proposed a dual guideline based on airborne and surface concentrations of SVF (table 4). If an indoor-air problem has been reported for which occupant complaints about skin or upper-airway irritation are attributed to SVF, table 4 can be used as a decision tree for further action.

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