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Monolayer and Multilayer Particle Deposits on Hard Surfaces: Literature Review and Implications for Particle Resuspension in the Indoor Environment

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Particle deposits on indoor surfaces can be as complex and diverse as the indoor environments in which they exist. Dust loading can range over several orders of magnitude, suggesting the existence of different types of particle deposits. These deposits can be broadly classified as either a monolayer, in which particles are sparsely deposited on a surface, or a multilayer, in which particles are deposited on top of one another and there is particle-to-particle adhesion and interaction. Particles within these diverse structures of settled indoor dust can become airborne through a process known as resuspension, which can occur due to airflow in ventilation ducts or human activity indoors. The dust loading and deposit structure on an indoor surface may have important implications for resuspension in the indoor environment. This literature review provides a summary of dust loads found on indoor surfaces in field studies and classifies each dust load as either a monolayer or multilayer particle deposit. The article highlights the unique attributes associated with resuspension from both types of particle deposits by summarizing key findings of the experimental resuspension literature. The fundamental differences in the resuspension process between monolayer and multilayer deposits suggest that resuspension may vary considerably among the broad spectrum of dust loads found on indoor surfaces.

INTRODUCTION

Resuspension has been identified as an important secondary source of particles in the indoor environment. Resuspension from indoor particle deposits can occur due to airflow in ventilation ducts (Krauter and Biermann 2007; Wang et al. 2012) and human activities indoors (Thatcher and Layton 1995; Ferro et al. 2004; Qian and Ferro 2008; Tian et al. 2011; Shaughnessy and Vu 2012). Additionally, resuspension can be an exposure pathway to the multitude of pollutants that are commonly found in settled indoor dust, such as: allergens (O'Meara and Tovey 2000), lead, pesticides, phthalates, and flame retardants (Roberts et al. 2009).

Particle deposits in the indoor environment can be very complex and indoor dust loads can vary across several orders of magnitude. On the surfaces of ventilation ducts, dust loads can range from less than 1 g/m^2 to loads in excess of 100 g/m^2 (Nielson et al. 1990; Laatikainen et al. 1991; Pasanen et al. 1992; EPA 1996; Fortmann et al. 1997; Möritz et al. 2001; Kolari et al. 2005; Lavoie et al. 2011). On hard flooring, such as vinyl, linoleum, and hardwood, dust loading is typically in the range of 0.1–1 g/m^2, although lighter and heavier dust loads are commonly reported (Adgate et al. 1995; Rao et al. 2005; Johnson et al. 2009; Hoh et al. 2012). The wide range of dust loads suggests that there can exist different types of particle deposits on indoor surfaces, including both monolayer and multilayer deposits (Tovey and Ferro 2012). A monolayer deposit is one in which particles are sparsely deposited on a surface and there is minimal to no contact between them. A multilayer deposit is a porous structure of particles deposited on top of one another, forming multiple layers.

The diversity of dust loads and particle deposits may have important implications for particle resuspension from indoor surfaces. The resuspension literature has highlighted unique characteristics associated with resuspension from monolayer and multilayer particle deposits. For monolayer deposits, we are primarily interested in particle-to-surface attractive forces. Monolayer resuspension is strongly influenced by particle size and air velocity (Corn and Stein 1965; Wu et al. 1992; Nicholson 1993; Braaten 1994; Ibrahim et al. 2003; Jiang et al. 2008; Mukai et al. 2009; Goldasteh et al. in press), surface material and roughness (Wu et al. 1992; Nicholson 1993; Gomes et al.

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2007; Jiang et al. 2008; Mukai et al. 2009; Goldasteh et al. in press; Kassab et al. 2013); particle composition (Wu et al. 1992; Braaten 1994; Ibrahim et al. 2003; Goldasteh et al. 2012); characteristics of the airflow, such as acceleration (Wu et al. 1992; Nicholson 1993; Ibrahim et al. 2003), turbulence (Ibrahim et al. 2004; Mukai et al. 2009), exposure time (Ibrahim et al. 2003); and relative humidity and residence time (Ibrahim et al. 2004).

As we transition from a sparse monolayer to a complex multilayer deposit, additional parameters begin to influence resuspension, most notably particle-to-particle adhesion (Lazaridis and Drossinos 1998); layer location (Lazaridis and Drossinos 1998; Friess and Yadigaroglu 2001); aggregate formation and deaggregation (Matsusaka and Masuda 1996; Kurkela et al. 2006; Gac et al. 2008; Gotoh et al. 2011); possible saltation effects (Bagnold 1941; Shao et al. 1993; Kok et al. 2012); dust loading (Fromentin 1989; Nitschke and Schmidt 2010); and the deposit's structure and porosity (Friess and Yadigaroglu 2002).

The primary aim of this literature review is to demonstrate the important role of the type of particle deposit on resuspension from indoor surfaces. The article begins with a comprehensive overview of dust loads reported in field studies in the literature and presents a simple scaling analysis to classify each dust load as either a monolayer or multilayer deposit. The article then transitions to a discussion of the unique attributes of resuspension from both types of deposits based on findings in the experimental resuspension literature. The article concludes with a discussion about the implications of different dust loads and particle deposits on resuspension from ventilation ducts and hard flooring.

INDOOR PARTICLE DEPOSIT CHARACTERIZATION

Numerous field studies have measured dust loads on a variety of surfaces in indoor environments. These studies are often aimed at investigating particle deposition, transport dynamics, and identifying pollutants in deposited dust. Table 1 presents a summary of dust loads from selected field studies ($n = 29$). In addition to field studies, Table 1 also presents dust loads from both wind tunnel ($n = 29$) and full-scale ($n = 11$) resuspension studies.

Particle Deposit Classification

For this literature review, a simplified, approximate method was developed to describe dust loads on hard, flat surfaces, including ventilation ducts and hard flooring (complex surfaces such as carpet are not considered here), for the field studies presented in Table 1. This scaling method applies the particle deposit structural analysis presented in Friess and Yadigaroglu (2002). They proposed a quantity called the layer number, λ, to distinguish between monolayer and multilayer deposits. λ represents the average number of particles intersected on a line perpendicular to the wall, and is based on several physical parameters of the deposit:

$$\lambda = \frac{6m_0}{\pi\rho D} \qquad [1]$$

where m_0 is the dust load (g/m^2), ρ is the particle density (kg/m^3), and D is the mass median diameter of deposited particles (μm).

Particle deposits are porous, and can also be defined by their porosities, ε, which represents the fraction of a deposit not occupied by particles. The structure, and therefore the porosity, of a deposit are determined by the deposition mechanism. Dense deposits formed by inertial impaction can be considered "cake-like" deposits, whereas those formed by gravitational settling result in "fluffy" deposits (as illustrated in Figure 1 of Friess and Yadigaroglu 2002). By combining λ and ε, this investigation proposes an approximation for the height, δ, of the particle deposit:

$$\delta \sim \frac{\lambda}{(1-\varepsilon)} D \sim \frac{6m_0}{\pi\rho\,(1-\varepsilon)}. \qquad [2]$$

The height of the deposit increases with porosity, suggesting fluffy deposits formed by gravitational settling will be taller than those formed by impaction. δ can be used as a basis to classify a particle deposit given its dust load.

To determine an approximate δ for a dust load in the literature, the following assumptions were made when applying Equation (2): homogenous porosity within the deposit; the particles are of unit particle density, 1000 kg/m^3; deposits in ventilation ducts are formed by a combination of gravitational settling and inertial impaction due to convective airflow and turbulence; and deposits on indoor flooring are formed primarily by gravitational settling (for coarse particles in both cases). Based on the analysis presented in Friess and Yadigaroglu (2002), deposits in ventilation ducts are assumed to have porosities of approximately 0.50, and those on flooring are assumed to be approximately 0.75.

There is relatively little information on the size distribution of settled dust in different indoor environments. Furthermore, the distribution of a reported dust load can be influenced by the dust collection and sieving methods employed in a field study. Thus, it is difficult to estimate the mass median diameter for each dust load in Table 1. However, several studies offer some insight into the polydisperse size distribution, in the form of mass fractions and mass median diameter of settled indoor dust. Que Hee et al. (1985) found 18% of particles in dust to be <44 μm, 58% in the fraction 44–149 μm, and 24% >149 μm. Seifert (1998) found a wide range of 0.3–24% for the fraction <30 μm and a range of 6–35% for the fraction 30–63 μm. Edwards et al. (1998) analyzed settled dust on deposition plates near the floor and found 99% of the particles to be <50 μm. Lewis et al. (1999) found the mass median diameter of settled dust to be ~100 μm, with 25% of the mass less than 25 μm, Rodes et al. (2001) found the mass median diameter to be ~60 μm, Wei

TABLE 1
Dust loads and particle deposit classification in selected field, wind tunnel, and full-scale laboratory studies

Study	Description	Dust load m_0 (g/m^2)	Particle deposit classification for given range of dust loads[2]: Reference $D = 10\ \mu$m	Reference $D = 100\ \mu$m	Surface(s)
		Field Studies: Ventilation ducts & hard flooring			
Nielsen et al. (1990)	Measured dust loading in office and school ventilation systems	Mean: 6.8, range: 1.1–50.9	Mono., Inter., & Multi.[3]	Mono. & Inter.[3]	Ventilation duct
Laatikainen et al. (1991)	Measured dust loading in office, school, and residential ventilation systems	Mean: 18.2, range: 3.6–140.8	Inter. & Multi.[3]	Mono., Inter., & Multi.[3]	Ventilation duct
Pasanen et al. (1992)	Examined the composition and location of settled dust in ventilation systems of public buildings	Mean: 10.6, range: 1.2–58.3	Mono., Inter., & Multi.[3]	Mono., Inter., & Multi.[3]	Ventilation duct
Auger (1994)	Measured dust loading in residential ventilation systems	Mean: 0.2, range: < detection limit (DL)-2.7	Mono. & Inter.[3]	Monolayer[3]	Ventilation duct
Kalliokoski et al. (1995)	Explored the impact of cleaning residential ventilation systems	Mean: 1.2, range: 0.2–3.9	Mono. & Inter.[3]	Monolayer[3]	Ventilation duct
Fransson et al. (1995)	Measured dust loading in supply ducts	Mean: 2.6, range: 1.9–3.0	Mono. & Inter.[3]	Monolayer[3]	Ventilation duct
Pasanen et al. (1995)	Measured dust loading in office ventilation systems	Mean: 13.2, range: 1.2–158	Mono., Inter., & Multi.[3]	Mono., Inter., & Multi.[3]	Ventilation duct
Adgate et al. (1995)	Measured lead in house dust in 216 homes	Bare floor mean: 0.42, range: 0.05–7	Mono., Inter., & Multi.[3]	Monolayer[3]	Flooring: bare floor
Thatcher and Layton (1995)	Characterization of indoor particle dynamics in a residence	Tracked area of linoleum: 0.58	Monolayer[3]	Monolayer[3]	Flooring: linoleum
EPA (1996)	Measured lead concentrations in settled dust	Ventilation duct mean: 3.03, range: 0.054–1,385 Uncarpeted floor mean: 1.94, range: 0.005–155	Duct: Mono., Inter. & Multi.[3] Flooring: Duct: Mono., Inter., & Multi.[3]	Duct: Mono., Inter., & Multi.[3] Flooring: Duct: Mono., Inter., & Multi.[3]	Ventilation duct and uncarpeted flooring
Ito et al. (1996)	Studied particle deposition in ventilation systems	Mean: 7.5	Mono., Inter., & Multi.[3]	Monolayer[3]	Ventilation duct
Fortmann et al. (1997)	Measured dust loading in residential ventilation systems	Mean: 6.4, range: 1.5–26	Mono., Inter., & Multi.[3]	Monolayer[3]	Ventilation duct
Franke et al. (1997)	Assessed the effects of surface cleaning on indoor air quality	Routine and improved housekeeping mean: 0.08	Monolayer[3]	Monolayer[3]	Flooring: vinyl
Edwards et al. (1998)	Measured seasonal differences in dust loading rates in a home	Loading rates at 0.3 m above floor (per day): Summer mean: 0.0042, winter mean: 0.0028 Assumed loading for 1 month: Summer mean: 0.126, winter mean: 0.084	Monolayer[3]	Monolayer[3]	Deposition plate: Glass

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TABLE 1
Dust loads and particle deposit classification in selected field, wind tunnel, and full-scale laboratory studies *(Continued)*

Study	Description	Dust load m_0 (g/m^2)	Particle deposit classification for given range of dust loads[2] Reference $D = 10\ \mu$m	Reference $D = 100\ \mu$m	Surface(s)
Küchen (1998)	Measured dust loading in ventilation systems of public buildings	Collection method 1 mean: 18.8, range: 4.0–131 Collection method 2 mean: 7.0, range: 0.2–82 Collection method 3 mean: 1.9, range: <DL-21	Mono., Inter., & Multi.[3]	Mono., Inter., & Multi.[3]	Ventilation duct
Rich et al. (1999)	Measured dust and lead loading in residences	Floor (preclean) mean: 6.45 Floor (postclean) mean: 4.64	Mono., Inter., & Multi.[3]	Monolayer[3]	Flooring: linoleum, wood, stone, and tile
Möritz et al. (2001)	Measured dust loading using different collection methods	Collection method 1 mean: 13.8, range: 3.1–52.7 Collection method 2 mean: 8.6, range: 1.1–50.1 Collection method 3 mean: 5.6, range: 0.6–22.6 Collection method 4 mean: 6.9, range: 0.8–36.5 Collection method 5 mean: 2.1, range: 0.3–10.9	Mono., Inter., & Multi.[3]	Mono., Inter., & Multi.[3]	Ventilation duct
Holopainen et al. (2002)	Measured dust loading in recently installed ventilation systems	Cleanliness category 1 mean: 0.9, range: 0.4–2.9 Cleanliness category 2 mean: 2.3, range: 1.2–4.9	Mono. & Inter.[3]	Monolayer[3]	Ventilation duct
Kolari et al. (2005)	Measured dust loading in office ventilation systems	Before duct cleaning mean: 8.8, range: ∼2–19	Mono., Inter., & Multi.[3]	Monolayer[3]	Ventilation duct
Rao et al. (2005)	Measured dust loading and bioaerosols in hospitals	Mean: 1.0, range: 0.2–8.9	Mono., Inter., & Multi.[3]	Monolayer[3]	Flooring: Vinyl
Lewis et al. (2006)	Measured dust and lead loading on indoor surfaces	Vinyl mean: 4 Wood mean: 3	Mono., Inter., & Multi.[3]	Monolayer[3]	Flooring: Vinyl and wood
Johnson et al. (2009)	Measured dust loading in 488 homes	Mean: 0.325, range: 0.04–13.860	Mono., Inter., & Multi.[3]	Mono. & Inter.[3]	Flooring: smooth/hard
Layton and Beamer (2009)	Modeled transport of contaminated soil and airborne particles	Mean: 0.28, range: 0.04–6 (values referenced from NHEXAS study, Midwest residences)	Mono., Inter., & Multi.[3]	Monolayer[3]	Flooring: Flat, variety
Salares et al. (2009)	Studied the impact of cleaning on dust loading and levels of pollutants in dust	Small dust fraction ($<150\ \mu$m) range across cleaning intervals: 0.055–0.326	Monolayer[3]	Monolayer[3]	Flooring: Hard

Khoder et al. (2010)	Measured dust loading rate in nonsmoking and smoking residences	Loading rates (per week): Mean: 1.45, range: 0.49–3.77 Assumed loading for 1 month: Mean: 6.3, range: 2.1–16.4	Mono., Inter., & Multi.[3]	Mono. & Inter.[3]	Deposition plate: Glass
Raja et al. (2010)	Measured the resuspension of allergens from settled dust	Living room mean: 0.952, range: ∼0.4–1.6 Bedroom mean: 0.418, range: ∼0.1–1.9 School classroom mean: 0.245, range: ∼0.1–1.5	Mono. & Inter.[3]	Monolayer[3]	Flooring: Not specified
Lavoie et al. (2011)	Evaluated a criteria for the initiation of duct cleaning in nonindustrial ventilation systems	Collection method 1 mean: 2.51, range: 0.012–28.14 Collection method 2 mean: 4.3, range: 0.014–33.38 Collection method 3 mean: 1.18, range: 0.002–15.58	Mono., Inter., & Multi.[3]	Mono. & Inter.[3]	Ventilation duct
Zuraimi et al. (2012)	Developed a protocol to access duct cleaning impact in office buildings	Case study B1 preduct cleaning: 0.28 Case study B1 postduct cleaning: 6.6	Mono., Inter., & Multi.[3]	Monolayer[3]	Ventilation duct
Hoh et al. (2012)	Analyzed pollutants in household dust of smokers and nonsmokers	Hard flooring median in homes of smokers and nonsmokers: 1.07, range: ∼0.1–10	Mono., Inter., & Multi.[3]	Monolayer[3]	Flooring: Wood, tile, and linoleum
		Wind tunnel studies: Various hard surfaces			
Corn and Stein (1965)	Fundamental resuspension study	Mean seeding density[1]: ∼0.14 particles/mm^2 5.3 μm glass beads: 2.7×10^{-5} 10.6 μm glass beads: 2.1×10^{-4}	Monolayer[4]		Deposition plate: Steel and glass
Fairchild and Tillery (1982)	Impact of saltating particles on resuspension	Not reported, monolayer mentioned explicitly	Monolayer[4]		Deposition plate: Steel
Wen and Kasper (1989)	Resuspension model and experimental data for validation	Mean seeding density[1]: ∼1000 particles/mm^2 0.412 μm latex particles: 4×10^{-5} 0.509 μm latex particles: 7×10^{-5} 1.019 μm latex particles: 6×10^{-4}	Monolayer[4]		Deposition plate: Stainless steel
Fromentin (1989)	Time dependence of multilayer resuspension	Range: 100–1000	Multilayer[4]		Deposition plate: Stainless steel
Braaten et al. (1990)	Fundamental resuspension study and model validation	Not reported, monolayer mentioned explicitly	Monolayer[4]		Deposition plate: Glass
John et al. (1991)	Resuspension by impacting particles	Seeding density[1] range: 800–1200 8.6 μm ammonium fluorescein particles: 0.36–0.54 Note: Authors mention 8–16% of particles were touching one another	Monolayer[4]		Deposition plate: Polyvinyl fluoride

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TABLE 1
Dust loads and particle deposit classification in selected field, wind tunnel, and full-scale laboratory studies *(Continued)*

Study	Description	Dust load m_0 (g/m^2)	Particle deposit classification for given range of dust loads[2]: Reference $D = 10\ \mu$m	Reference $D = 100\ \mu$m	Surface(s)
Wu et al. (1992)	Examined particle bounceoff and resuspension mechanisms	50–100 particles/microscope field of view, monolayer mentioned explicitly	Monolayer[4]		Deposition plate: Glass, plexiglas, and white oak leaves
Taheri and Bragg (1992)	Resuspension by turbulent flow	Not reported, monolayer deposit implied	Monolayer[5]		Deposition plate: Glass
Nicholson (1993)	Resuspension from concrete and grass surfaces	Not reported, monolayer mentioned explicitly	Monolayer[4]		Deposition plate: Concrete and grass
Braaten (1994)	Resuspension characteristics of particles 18–34 μm in diameter	Mean seeding density[1]: ~5 particles/mm^2 28 μm lycopodium spores: 0.07 34 μm timothy pollen: 0.11 30 μm microballoons: 0.08 20 μm glass spheres: 0.05 18 μm nickel spheres: 0.14	Monolayer[4]		Deposition plate: Glass
Otani et al. (1995)	Resuspension by impinging jets	Not reported, monolayer deposit implied	Monolayer[5]		Deposition plate: Glass and silicon
Matsusaka and Masuda (1996)	Aggregate resuspension from a fine powder layer	Not reported, multilayer mentioned explicitly	Multilayer[4]		Dust bed
Smedley et al. (1999)	Resuspension by impinging jets	Seeding density[1]: 300 particles/mm^2 8.3 μm polystyrene particles: 0.10	Monolayer[4]		Deposition plate: Glass
Loosmore and Hunt (2000)	Resuspension from a dust bed without saltation	Not reported, multilayer deposit implied	Multilayer[6]		Dust bed: Acrylic
Adhiwidjaja et al. (2000)	Simultaneous deposition and resuspension of particles	Loading when deposition and resuspension are at an equilibrium state: 4.7 μm alumina powder: 22 5.6 μm alumina powder: 18	Multilayer[3]	Inter.[3]	Deposition plate: Brass, copper, aluminum, and stainless steel
Reeks and Hall (2001)	Fundamental particle adhesion and resuspension study	Not reported, monolayer mentioned explicitly	Monolayer[4]		Deposition plate: Stainless steel
Chiou and Tsai (2001)	Resuspension of road dust	Not reported, multilayer deposit implied	Multilayer[6]		Dust bed: Aluminum
Ziskind et al. (2002)	Resuspension by pulsed air jets	Seeding density[1] range: ~2800–4500 particles/mm^2 2–5 μm alumina silicate particles: ~0.3–0.5	Monolayer[4]		Deposition plate: Glass and silicon
Ibrahim et al. (2003); Ibrahim et al. (2004); Ibrahim and Dunn (2006); Ibrahim et al. (2008)	Impact of airflow and particle deposition characteristics on resuspension	Mean seeding density[1]: ~0.5 particles/mm^2 30 μm lycopodium spores: 0.01 52 μm glass particles: 0.09 64 μm stainless steel spheres: 0.55 72 μm glass particles: 0.24 76 μm stainless steel spheres: 0.92 90 μm glass particles: 0.46 111 μm glass particles: 0.86	Monolayer[4]		Deposition plate: Glass

Huang et al. (2005)	Reduction in road dust resuspension using a porous fence	18–29.1 μm: 1095 10–18 μm: 210 5.6–10 μm: 35 3.2 to 5.6 μm: 27 1.8–3.2 μm: 25	Multilayer[3]		Deposition plate: Aluminum cell
Miguel et al. (2005)	Deposition and resuspension from indoor surfaces	Not reported, monolayer deposit implied	Monolayer[5]		Flooring: Metal plates coated with paper
Gomes et al. (2007)	Resuspension of allergens from a variety of indoor surfaces	Quartz particles on linoleum: 0.5 and 6.2 Roach dust particles on linoleum: 6.2	Monolayer[7] & Multilayer[7] Multilayer[7]		Flooring: Linoleum
Jiang et al. (2008)	Impact of surface roughness on resuspension	Not reported, monolayer mentioned explicitly	Monolayer[4]		Deposition plate: Stainless steel
Nitschke and Schmidt (2010)	Development of an experimental methodology to create reproducible particle layers	Range: 6.5–14	Multilayer[3]	Mono. & Inter.[3]	Deposition plate: PMMA and steel
Goldasteh et al. (in press)	Experimental modeling study of resuspension from flooring	Not reported, monolayer mentioned explicitly	Monolayer[4]		Flooring: Hardwood and vinyl
Kassab et al. (2013)	Experimental study of particle motion during resuspension	26.41 μm glass particles: 0.10 36.24 μm glass particles: 0.22 45.31 μm glass particles: 0.24	Monolayer[4]		Deposition plate: Hardwood, ceramic, and glass
		Full-scale laboratory studies: Ventilation ducts & hard flooring			
Karlsson et al. (1999)	Human-induced resuspension study	Seeding density[2] ~100 particles/mm^2 12 μm *Bacillus Subtilis* spore clusters: 0.13	Monolayer[4]		Flooring: Vinyl
Foarde and Menetrez (2002)	Impact of dust loading on antifungal sealants	Moderately soiled: 10 Heavily soiled: 100	Multilayer[3]	Mono., Inter., & Multi.[3]	Ventilation duct
Hu et al. (2008)	Electrostatic detachment of particles from indoor surfaces	Alumina particles, mean: 30 *Bacillus Thuringiensis* spores, mean: 10 Note: authors mention formation of particle aggregates	Inter. & Multi.[4]		Flooring: rubber and vinyl
Qian and Ferro (2008)	Walking-induced resuspension study	Mean: 20	Multilayer[3]	Inter.[3]	Flooring: Vinyl
Kubota et al. (2009)	Walking-induced resuspension study	Mean: 56	Multilayer[3]	Multilayer[3]	Deposition plate: Plexiglas
Tian et al. (2011)	Walking-induced resuspension study	House dust: 2 and 8	Inter. & Multi.[3]	Monolayer[3]	Flooring: Wood and vinyl
Gotoh et al. (2011)	Resuspension induced by an ascending flat object	Not reported, multilayer mentioned explicitly Note: Authors mention formation of 2 and 8 mm thick powder layers of 26 μm silica particles	Multilayer[4]		Deposition plate: Flat disk
Shaughnessy and Vu (2012)	Walking-induced resuspension study	Test dust from occupied school classrooms: Mean: 18	Multilayer[3]	Inter.[3]	Flooring: vinyl

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TABLE 1
Dust loads and particle deposit classification in selected field, wind tunnel, and full-scale laboratory studies *(Continued)*

Study	Description	Dust load m_0 (g/m^2)	Particle deposit classification for given range of dust loads[2]: Reference $D = 10\ \mu$m	Reference $D = 100\ \mu$m	Surface(s)
Wang et al. (2012)	Short-term resuspension in full-scale ventilation ducts	Polydisperse 0.25–10 μm calcium salt particles, range: 18.34–21.06 Note: Authors mention formation of multiple layers	Multilayer[3,4]		Ventilation duct
Hubbard et al. (2012)	Resuspension due to mechanical impulses	Not reported, monolayer mentioned explicitly Note: Authors mention surface coverage of particles was 5–10%.	Monolayer[4]		Deposition plate: Titanium dioxide and silicon dioxide wafers
Kubota and Higuchi (2013)	Walking-induced resuspension study	Mean: 56	Multilayer[3]	Multilayer[3]	Deposition plate: Smooth and hard surface
		Additional studies: Ventilation ducts			
Waring and Siegel (2008)	Modeled dust loading rates on various surfaces in ventilation systems	Residential supply duct median: 0.0051 g/month, range: ∼0.0001–0.1 g/month Commercial supply duct median: 1.00 g/month, range: ∼0.001–10 g/month Commercial return duct median: 0.262 g/month, range: ∼0.001–1 g/month Note: Authors did not normalize dust loading on duct surfaces by area	N/A		Ventilation duct
Zhou et al. (2011) (and references therein)	Modeling of resuspension in ventilations systems before and after duct cleaning. Provides a list of dust load limit values in ventilation ducts in different countries.	Limit values for after & prior to duct cleaning: China: after: 1, prior: 20 Japan: after: 1, prior: – U.S.: after: 0.075, prior: – Finland: after: 1–2.5, prior: – Great Britain: after: 0.1, prior: 1–6	Mono., Inter., & Multi.[3]	Monolayer[3]	Ventilation duct

[1]Seeding density is defined as the number of particles deposited in a given area. The dust loading is calculated as the product of the seeding density and particle mass.

[2]If a mass median diameter is mentioned explicitly in a reference, it was used in the deposit classification, as opposed to the reference diameters of 10 and 100 μm.

[3]Approximate classification of deposit based upon particle classification method presented in our investigation. Dust loads on surfaces such as deposition plates are assumed to have porosities of 0.75, due to gravitational settling mechanisms (same as hard flooring surfaces).

[4]Type of deposit mentioned explicitly in study.

[5]Monolayer deposit implied in article due to the use of microscope particle counting methods to determine an absolute resuspension fraction.

[6]Multilayer deposit implied in article due to the presence of a thick dust bed or powder layer.

[7]Approximate classification of deposit based upon mass median diameter and density of particles used in study.

et al. (2009) found the mass median diameter to be ~75 μm, and Southey et al. (2011) found the mass median diameter to be ~90 μm. However, as discussed in Lewis et al. (1999) and Rodes et al. (2001), size distributions likely shift toward larger particles due to the agglomeration of smaller particles during the dust collection process and loss of particles <10 μm in diameter due to adherence to vacuum collection bags. Given the variability in size distributions among these studies, and the potential for particle agglomeration during dust collection, two reference diameters were selected for the particle deposit classification: 10 and 100 μm.

After determining δ for a given dust load, it can be compared with the reference diameters to approximate the type of particle deposit. The classification criteria is as follows:

- if $\delta \leq D$: the deposit is a monolayer,
- if $D < \delta < 2D$: the deposit is an intermediate between a monolayer and multilayer,
- if $\delta \geq 2D$: the deposit is a multilayer.

There is inherent uncertainty in the assumptions used to estimate δ and to describe each dust load in Table 1; however, the assumptions provide a good basis for classifying particle deposits given the limited data available on the structure and size distribution of deposits in different indoor environments. δ, and thus the deposit classification, could change if ρ, ε, and/or D were different from the values listed in the assumptions.

Monolayer and Multilayer Deposits: Field Studies

The results of the classification analysis are presented in Table 1 for each field study. If a range of dust loads is reported, the possible range of particle deposits is presented. It is evident that monolayer, intermediate, and multilayer deposits can exist on the surfaces of ventilation ducts and hard flooring. As expected, the presence of an intermediate or multilayer deposit is more likely for a reference D of 10 μm compared to 100 μm. Regardless of the size distribution of a reported dust load, it is very likely we may see significant particle-to-particle contact in the heavier dust loads (>5 or 10 g/m^2), in which the resuspension mechanisms would be more closely aligned with that of multilayer deposits, as compared to monolayer deposits, in which there is no particle-to-particle contact.

Ventilation Ducts

As shown in Table 1, dust loading on the surfaces of ventilation ducts is highly variable, and dust loads greater than 10 g/m^2 are common. Studies by Nielsen et al. (1990), Laatikainen et al. (1991), Pasanen et al. (1992), Pasanen et al. (1995), EPA (1996), Ito et al. (1996), Fortmann et al. (1997), Küchen (1998), Kolari et al. (2005), Lavoie et al. (2011), and Zuraimi et al. (2012) have reported heavy dust loads representative of multilayer deposits, whereas studies by Auger (1994), Kalliokoski et al. (1995), Fransson et al. (1995), and Holopainen et al. (2002) have reported lighter dust loads suggestive of monolayer deposits. Dust loading in ventilation ducts can be influenced by many factors, such as characteristics of the building and its ventilation system, indoor particle sources, in-duct filtration, deposition mechanisms, and frequency of duct cleaning. Therefore, based on the field studies as presented in Table 1, it would be expected that dust loading would vary considerably from any one building to the next, suggesting that deposits ranging from sparse monolayers to heavy multilayers are likely to exist.

Hard Flooring

On hard flooring, such as linoleum, wood, and vinyl, lighter dust loads representative of monolayer deposits are frequently observed. Dust loads reported by Thatcher and Layton (1995), Franke et al. (1997), Salares et al. (2009), and Raja et al. (2010) were classified as monolayer deposits. Field studies by Adgate et al. (1995), Rich et al. (1999), Rao et al. (2005), Lewis et al. (2006), Johnson et al. (2009), Layton and Beamer (2009), and Hoh et al. (2012) reported ranges of dust loads that likely include both monolayer and multilayer deposits. The range of dust loads can be attributed to the frequency of floor cleaning or the number of particle sources indoors, among other factors.

For both reference particle diameters of 10 and 100 μm, the classification analysis identified a greater prevalence of multilayer deposits in ventilation ducts than on hard flooring. However, the potential for both types of deposits on ventilation duct surfaces and hard flooring emphasizes the need to consider the role of the deposit characteristics when studying particle resuspension and transport in the indoor environment.

Monolayer and Multilayer Deposits: Wind Tunnel and Full-Scale Laboratory Studies

Table 1 also presents the results of the classification analysis for selected wind tunnel and full-scale resuspension studies. Wind tunnel studies commonly report a seeding density. To convert to a dust load in g/m^2, the seeding density (particles/m^2) was multiplied by the particle's mass (g/particle). For some resuspension studies reported in Table 1, the type of deposit was mentioned explicitly in the article.

Wind Tunnel Studies

Although we see the existence of both monolayer and multilayer deposits indoors, the bulk of experimental wind tunnel studies have primarily focused on the former in order to develop a more fundamental understanding of the resuspension process and particle-to-deposition surface interactions and adhesion. Monolayer deposits were examined in studies on the aerodynamic resuspension of particles by Corn and Stein (1965), Wen and Kasper (1989), Braaten et al. (1990), John et al. (1991), Wu et al. (1992), Taheri and Bragg (1992), Nicholson (1993), Braaten (1994), Otani et al. (1995), Smedley et al. (1999), Reeks and Hall (2001), Ziskind et al. (2002), Ibrahim et al. (2003), Ibrahim et al. (2004), Miguel et al. (2005), Ibrahim and Dunn (2006), Ibrahim et al. (2008), Jiang et al. (2008), Goldasteh et al. (in press), and Kassab et al. (2013). For these studies, dust loads are on the order of 10^{-5} to 1 g/m^2.

Only a few experimental wind tunnel studies have explored resuspension from multilayer deposits, including those by Fromentin (1989), Matsusaka and Masuda (1996), Loosmore and Hunt (2000), Adhiwidjaja et al. (2000), Chiou and Tsai (2001), Huang et al. (2005), Gomes et al. (2007), and Nitschke and Schmidt (2010). As shown in Table 1, only a few of these studies evaluated the impact of dust loading on resuspension, and none have systematically studied resuspension from both monolayer and multilayer deposits on indoor surfaces.

Full-Scale Laboratory Studies

Dust loads for full-scale resuspension studies, e.g., studies not conducted in small-scale wind tunnels, are also reported in Table 1. These studies are primarily aimed at exploring human-induced resuspension due to walking, resuspension in full-scale ventilation systems, or resuspension due to application of electrostatic or mechanical forces. Dust loads were found to be more representative of those found in the indoor environment. For example, Foarde and Menetrez (2002), Hu et al. (2008), Qian and Ferro (2008), Kubota et al. (2009), Shaughnessy and Vu (2012), Wang et al. (2012), and Kubota and Higuchi (2013) studied dust loads in excess of 10 g/m^2, which were classified as multilayer deposits.

In summary, Table 1 provides a comprehensive overview of dust loads and particle deposits on the surfaces of ventilation ducts and hard flooring, along with the types of deposits examined in various resuspension studies. Collectively, these resuspension studies highlight important fundamental differences in the resuspension process between monolayer and multilayer deposits. It is important to understand these distinctions when studying particle resuspension and transport in the indoor environment, where a wide range of deposit structures can be found.

MONOLAYER DEPOSITS

The majority of experimental wind tunnel resuspension studies have focused on monolayer deposits. These studies, including many of those presented in Table 1, offer valuable insight into the key variables influencing aerodynamic resuspension from monolayer deposits, such as particle size and air velocity; surface material and roughness; shape and composition of the deposited particles; characteristics of the airflow, such as exposure time, acceleration, and turbulence; and relative humidity and residence time. These variables are likely to influence resuspension from the monolayer deposits that were identified in the indoor environmental field studies of Table 1.

Particle Size and Air Velocity

As previously discussed, settled indoor dust can have wide particle size distribution, with particles <10 μm to >100 μm in diameter. Additionally, air velocities over indoor surfaces may vary considerably, from air bursts associated with human movement to airflow in ventilation systems. Wind tunnel resuspension studies, such as those by Corn and Stein (1965), Wu et al. (1992), Nicholson (1993), Braaten (1994), Ibrahim et al. (2003, 2004, 2008), Jiang et al. (2008), and Mukai et al. (2009), among others, have demonstrated the important role of particle size and air velocity on resuspension from monolayer deposits. Generally, the amount of particles that resuspend from a surface increases with increasing particle size and air velocity.

Of particular interest in the indoor environment is the resuspension of particles 2.5–10 μm in diameter (coarse particles). Many monolayer studies have examined particles >10 μm in diameter, e.g., Braaten (1994) and Ibrahim et al. (2003, 2004, 2008), which more easily resuspend compared to their smaller counterparts, and only a few studies, e.g., Corn and Stein (1965), Jiang et al. (2008), and Goldasteh et al. (in press), have examined particles near 10 μm in diameter. The results of the latter demonstrate that very high velocities, unrealistic of what would be found in the indoor environment, are required to resuspend significant quantities of coarse particles. Corn and Stein (1965) did not observe resuspension for 10.6 μm glass particles at 30, 60, and 90 m/s, and it was not until a velocity of 117 m/s that resuspension was reported, and Jiang et al. (2008) found that velocities greater than 50 m/s were necessary to resuspend 11 μm poly(methyl methacrylate) (PMMA) particles. Additionally, a recent wind tunnel investigation by Goldasteh et al. (in press) observed minimal resuspension for 1–10 μm dust particles from linoleum flooring for velocities below 18 m/s (resuspension fraction remained below 0.10). It is apparent that phenomenally high velocities, often in excess of 25 m/s, are required to resuspend significant fractions of coarse particles from monolayer deposits due solely to the application of aerodynamic removal forces, e.g., lift and drag, via convective airflow in wind tunnels.

Surface Material and Roughness

Given the diversity of surfaces that can be found indoors, from metal ventilation ducts to vinyl flooring, it is important to understand the impact of the deposition surface when studying resuspension from monolayer deposits. Various characteristics of the deposition surface material have been found to influence resuspension, such as the Hamaker constant between the particle and surface, surface electrostatic charge, and surface roughness. Many monolayer wind tunnel resuspension experiments have been conducted using glass deposition plates (Table 1) and there are limited studies that have systematically investigated resuspension from different surfaces.

Wu et al. (1992) found that resuspension of lycopodium spores (30 μm) was significantly greater from glass compared to plexiglass due to the enhanced electrostatic adhesion of the plexiglass. Mukai et al. (2009) investigated resuspension of potassium chloride particles (1 to 20 μm) from two flat indoor surfaces, galvanized sheet metal and linoleum, and reported greater relative resuspension fractions for linoleum compared to sheet metal. Goldasteh et al. (in press) found greater resuspension of dust particles to occur from vinyl flooring compared to hardwood flooring due to the greater contact area, and thus adhesion force, between the particles with hardwood. Jiang et al. (2008) investigated resuspension from stainless steel of varying surface roughness and found resuspension to increase with increasing submicrometer-scale surface roughness (from 0.01 to 0.3 μm), although micrometer-scale surface roughness (0.3–1.64 μm) had minimal impact. Lastly, Kassab et al. (2013) found surface material and roughness to influence particle motion and trajectories during the resuspension process, with more rapid liftoff and minimal rolling/bouncing motion for surfaces with greater roughness, e.g., hardwood compared to glass.

Particle Composition and Shape

In the indoor environment, there can exist a broad spectrum of particles, which vary in composition, surface features, shape, and density. The impact of particle composition has also been explored in monolayer wind tunnel resuspension studies. Wu et al. (1992) explored resuspension of uranine particles, polystyrene/divinylbenzene particles, lycopodium spores, and two types of pollen. Low resuspension was found for uranine and polystyrene/divinylbenzene particles. The wind tunnel experiments were performed at relative humidities in the range of 58–78%, and polystyrene particles have been found to plastically deform at relative humidities above 65%, resulting in enhanced adhesion and reduced resuspension (Cleaver and Looi 2007). Lycopodium spores were found to resuspend in significant fractions at very low velocities (4–8 m/s). Ibrahim et al. (2003) reported a similar trend, with threshold velocities for 30 μm lycopodium spores roughly half of those as found for 32 μm glass microspheres. Lycopodium spores are spheres with small bars along their surface, which significantly reduce their contact area and adhesion force with a surface (Nitschke and Schmidt 2009). Braaten (1994) also found the threshold velocity of 28 μm lycopodium spores (8.73 m/s) to be slightly less than that for 34 μm timothy pollen (12.57 m/s) and 30 μm glass microballoons (9.72 m/s). Ibrahim et al. (2003) found resuspension of stainless steel microspheres to be greater than that of glass microspheres due to the reduced adhesion between stainless steel and the glass deposition surface. Lastly, Goldasteh et al. (2012) highlighted the impact of particle surface roughness and irregularity on resuspension in their monolayer modeling study.

Airflow Characteristics: Exposure Time, Acceleration, and Turbulence

Monolayer wind tunnel studies have highlighted the important role of various characteristics of the airflow on resuspension. The time a deposit is exposed to a controlled airflow in a wind tunnel is particularly important. Wu et al. (1992) confirmed the findings of Hall and Reed (1989) and found that two distinct temporal regimes exist during the resuspension process: a short period of less than 1 min with very high resuspension, and an extended period of minimal resuspension. Nicholson (1993) investigated resuspension for exposure times of 10–3600 s, and found that almost half of the resuspended particles were removed in the first 10 s, with the resuspension rate decreasing by three orders of magnitude over 3600 s of exposure.

The acceleration of the airflow during the initial period of exposure is likely responsible for the enhanced resuspension. Ibrahim et al. (2003) also found that two distinct temporal regimes exist, a period of high resuspension during the acceleration of the airflow to the steady-state velocity, and a period of low resuspension during steady-state airflow. As discussed in Tadmor and Zur (1981), an additional aerodynamic removal force, known as the Basset force, can arise as the airflow is accelerated. Ibrahim et al. (2003) found that the resuspension rate during the acceleration period (4.6 s^{-1}) is roughly 600 times greater than during the steady-state period (0.0075 s^{-1}).

Mukai et al. (2009) examined the role of turbulence and found threshold velocities to decrease with increasing turbulence intensity of the airflow. The increased penetration of turbulent bursts into the viscous sublayer is likely responsible for enhanced particle resuspension at higher levels of turbulence (Cleaver and Yates 1973). Turbulent airflow is often associated with flow across joints in ventilation systems and air bursts generated by human movements such as walking, and is therefore an important variable to consider when studying particle resuspension.

Relative Humidity and Residence Time

Relative humidity has been found to influence the adhesion force between a particle and a deposition surface (Corn and Stein 1965; Hinds 1999; Paajanen et al. 2006; Cleaver and Looi 2007; You and Wan 2012). Thus, it is an important variable to consider when studying resuspension from monolayer deposits in the indoor environment. As demonstrated in Ibrahim et al. (2004), increasing both the relative humidity and the residence time over which a particle is deposited on a surface increased the velocity required to resuspend a particle. At 30% relative humidity, and a very short residence time (several hours), the threshold velocity for stainless steel microspheres (64–76 μm) was 4.2 m/s. For the same residence time, but at 61% relative humidity, the threshold velocity increased to 10.7 m/s. By increasing the residence time to 24 h, the threshold velocities were found to increase considerably. This suggests that the impact of relative humidity on the adhesion force, and therefore resuspension, is a time-dependent process. Some of the wind tunnel studies presented in Table 1 exposed samples to the test flow conditions a short time after the particles were deposited (residence of several minutes to hours) (Nicholson 1993; Ibrahim et al. 2003). Based on the findings of Ibrahim et al. (2004), it is likely that the resuspension rates and fractions presented in these studies would decrease for longer residence times.

MULTILAYER DEPOSITS

As shown in Table 1, the majority of fundamental wind tunnel resuspension studies have focused on monolayer deposits. As such, the bulk of our knowledge on the resuspension process is derived from these studies, including the impact of the numerous parameters that were addressed in the preceding section. However, multilayer experimental and modeling studies have elucidated a few unique attributes of resuspension from multilayer deposits, including: the impact of the layer location, particle-to-particle adhesion, resuspension in the form of particle aggregates, impact of saltation, the relevance of the dust loading on a deposition surface, varying deposit porosity resulting from different deposition mechanisms, and time dependency of the resuspension flux.

Layer Location and Particle-to-Particle Adhesion

An important variable for resuspension from multilayer deposits is the layer location. A multilayer modeling study by Lazaridis and Drossinos (1998) considered a two-layer deposit of spherical particles and found particles from the canopy layer to resuspend at lower velocities compared to particles along the surface layer. Additionally, a model proposed by Friess and Yadigaroglu (2001) found the resuspension flux at a given exposure time to increase with the layer number. For example, for 1 s of exposure, resuspension from the 100th layer was found to be approximately two orders of magnitude greater than resuspension from the surface layer.

The enhanced resuspension associated with the outermost layers, relative to the surface layer, may be explained by considering the varying magnitudes of adhesion forces within a deposit. Lazaridis and Drossinos (1998) demonstrated that the adhesion force between two spherical particles is less than that between a spherical particle and a flat surface. Similarly, they found the interaction potential between two 10 μm aluminum oxide particles to be approximately one-half of that between a particle and a flat, stainless steel deposition surface. Additionally, Zhu et al. (2012) highlighted the importance of considering the reduced adhesion forces between particles in multilayer deposits. They modified their adhesion force equation to account for the reduced Van der Waals forces between particles, compared to that between particles and a flat deposition surface. By accounting for particle-to-particle adhesion in their revised model, they found the velocity required to induce resuspension to decrease. For multilayer deposits of many layers, the reduced particle-to-particle adhesion forces may result in greater resuspension relative to monolayer deposits, where there is only deposition surface adhesion. Lastly, given the elevated resuspension along the outermost layers relative to the surface layer, it would be expected that the characteristics of the underlying deposition surface might have less of an impact on resuspension from multilayer deposits compared to monolayer deposits, where only the surface layer of particles interact with the airflow.

Aggregate Resuspension

One unique characteristic of multilayer deposits is resuspension in the form of larger particle aggregates. Matsusaka and Masuda (1996) studied the resuspension of particle aggregates from multilayer deposits. They deposited a multilayer of 3 μm fly ash particles and found resuspension to typically occur in small aggregates, with diameters ranging from 10 to 30 μm. Additionally, a multilayer study by Gotoh et al. (2011) on the resuspension induced by an ascending circular plate found silica particles to resuspend in aggregates of similar size, regardless of their initial size. These experimental studies confirm the modeling study of Friess and Yadigaroglu (2002), who found the resuspended aggregates to be larger than the deposited particles and discussed that the tendency for particles to resuspend in aggregates is likely due to the lower aerodynamic removal forces that are necessary to resuspend a larger aggregate compared to smaller, individual particles.

Due to the large size of the resuspended aggregates, it may be expected that the particle aggregate will simply deposit back to the deposition surface from which it detached. However, as discussed in Gac et al. (2008), resuspended particle aggregates are often broken apart due to stresses imparted to the aggregate by turbulent eddies. By increasing turbulence in their wind tunnel, Gac et al. (2008) noticed a decrease in the size of the resuspended particles, suggesting enhanced deaggregation of the resuspended aggregates due to higher levels of turbulence. Kurkela et al. (2006) also found particle deaggregation to increase with increasing Reynolds number of the airflow. Therefore, once broken up, the smaller particles are more likely to be carried away with the airflow, rather than settle back to the surface. The deaggregation process is an important consideration when studying particle resuspension and transport from multilayer deposits on indoor surfaces.

Saltation

For multilayer deposits on indoor surfaces, which can contain particles on the order of 100 μm in diameter (as discussed in the Classification Analysis section), saltation may play a role in resuspending smaller particles. Large particles or aggregates, $\sim$100 μm in diameter, can be lifted away from a deposit by aerodynamic stresses. These particles are too large to remain airborne, so they return to the deposit and begin to hop along the surface and impact settled particles in a process known as saltation. Thus, a large saltating particle or aggregate can be responsible for the resuspension of smaller particles. Shao et al. (1993) demonstrated that impacts by saltating particles, as opposed to direct aerodynamic resuspension, are the primary mechanism of resuspension for smaller particles from outdoor sand and dust. Additionally, Fairchild and Tillery (1982) found the resuspension flux of <10 μm aluminum spheres to increase by factors of 1.33 and 2.3 when 100 and 200 μm saltating particles, respectively, were injected in the upstream airflow. Lastly, resuspension may occur due to the fragmenting of saltating particle aggregates, that is, the breaking apart of the aggregate into smaller fragments as the aggregate impacts the surface (Kok et al. 2012).

Dust Loading and Air Velocity

Given the wide range of dust loads found in the field studies of Table 1, it is important to consider the impact of dust loading on resuspension from multilayer deposits. Gomes et al. (2007) studied resuspension from dust loads of 0.5 and 2.5 g/m^2 and observed more particles to resuspend at the higher dust loading. A wind tunnel study by Nitschke and Schmidt (2010) found resuspension to generally increase with dust loading. Between an exposure time of 3 and 8 s, the resuspension fraction increased as the dust load increased from 6.5 to 14 g/m^2 for both steel and PMMA deposition surfaces. Additionally, as with monolayer deposits, resuspension from multilayer deposits has been found to increase with increasing air velocity. Fromentin (1989) found a similar trend for heavy multilayer deposits of 100–1000 g/m^2 and observed a significant increase in the resuspension flux by increasing the bulk air velocity from 8.5 to 20 m/s. Huang et al. (2005) and Matsusaka and Masuda (1996) observed similar trends in their respective wind tunnel studies.

Deposit Porosity

Particles may form very complex structures in multilayer deposits (Friess and Yadigaroglu 2002; Henry et al. 2012). One parameter relating to the deposit structure that can influence resuspension is the porosity. As discussed in the deposit classification analysis, porosity is an important variable in approximating the height of a deposit, and is linked to the deposition mechanism. Based on the work of Friess and Yadigaroglu (2002), porosity might have a significant impact on resuspension. The authors found the resuspension fraction for a given exposure time to be nearly an order of magnitude greater for a multilayer deposit with a porosity of 0.76 (at 30 min, resuspension fraction of ∼0.97) compared to one with a porosity of 0.45 (at 30 min, resuspension fraction of ∼0.03). The “fluffy” nature of more porous deposits formed by gravitational settling likely results in enhanced resuspension compared to the compact nature of “cake-like” deposits formed by mechanisms such as inertial impaction. In denser deposits, particles are in contact with more particles, thereby increasing the total adhesion force acting on a particle.

Time Dependence

As with monolayer deposits, resuspension from multilayer deposits is a time-dependent phenomenon. Fromentin (1989) explored the time dependency of multilayer resuspension, finding that resuspension decreases with time at a rate of approximately 1/time. The decay in resuspension from multilayer deposits may be explained by considering the enhanced resuspension along the outermost layers relative to the surface layer. Studies by Chiou and Tsai (2001), Mortazavi (2005), and Wang et al. (2012) have observed that loosely adhered particles along the outermost layers would resuspend initially, sometimes in the form of a large puff of dust, leaving behind the strongly adhered particles along the surface. This phenomenon was also observed in the STORM experiments analyzed by Friess and Yadigaroglu (2002). The authors discussed that a large amount of “loose, fragile material” will resuspend initially, leaving behind a more “robust” particle deposit, from which resuspension does not occur at such a high rate. Lastly, Loosmore and Hunt (2000) found the resuspension from a multilayer deposit to approach a long-term, steady-state flux after some peak initial period.

IMPLICATIONS FOR RESUSPENSION IN THE INDOOR ENVIRONMENT

Dust Loading on Indoor Surfaces

A wide range of dust loads representing both monolayer and multilayer deposits can be found on indoor surfaces (Table 1). The resuspension literature has offered valuable insight into the fundamental differences associated with resuspension from both types of particle deposits. As such, it is expected that the source strength of resuspension, in the form of a resuspension fraction or rate, may vary considerably across the diverse dust loads found in the indoor environment. Given the enhanced resuspension that may occur from multilayer deposits due to the impact of particle-to-particle adhesion, aggregate resuspension, and possible saltation effects, we may expect to see a greater number of particles resuspend from heavier dust loads in excess of 5 or 10 g/m^2, as compared to very light loadings representing sparse monolayers. Based on the findings of several multilayer resuspension studies, we would also expect resuspension to increase with increasing dust load as more and more particles accumulate on an indoor surface. Additionally, for a given multilayer dust load, resuspension may vary due to differences in deposit structure and particle size distribution. Lastly, there may be considerable variability among monolayer deposits indoors. These deposits can contain a variety of particles of different sizes and composition and can exist on a variety of different surfaces at different environmental conditions. As discussed in the preceding sections, all of these parameters have been shown to influence resuspension from monolayer deposits.

Ventilation Ducts

Resuspension from the surfaces of ventilation ducts is primarily associated with aerodynamic removal forces (Krauter and Biermann 2007; Wang et al. 2012). For most residential and commercial building applications, velocities in ventilation ducts are generally below 10 m/s. Wang et al. 2012 reported resuspension in a full-scale ventilation duct from multilayer dust loads in the range of 18–21 g/m^2 at velocities in the range of 3.8–8.8 m/s and Krauter and Biermann 2007 detected significant resuspension of spores (dust load not reported as a mass basis) in a full-scale ventilation system operating at a flow rate of 2.83 m^3/min. In both studies, resuspension rates were found to reach peak values during transient operation of the ventilation system, e.g., initial period of airflow acceleration or periodic pulsations, and then decayed with time. This further demonstrates the strong time dependence of resuspension from both monolayer (Wu et al. 1992; Nicholson 1993) and multilayer (Fromentin 1989; Loosmore and Hunt 2000) deposits. Additionally, turbulent flow and complex flow regimes may develop over duct surfaces, such as irregularly shaped flex-duct, and in duct bends, which may play an important factor in particle resuspension (Mukai et al. 2009).

As shown in Table 1, dust loading on ventilation ducts is highly variable, and loading rates can range from ∼0.0001 to 10 g/month (Waring and Siegel 2008). Given the possibility for greater resuspension from multilayer deposits compared to monolayer deposits, it may be desirable to prevent the accumulation of heavy dust loads in ventilation systems. Dust loading can be significantly reduced in ventilation ducts through proper duct cleaning techniques (Kolari et al. 2005; Zuraimi 2010), however, the process of duct cleaning itself may cause elevations in particle concentrations due to resuspension of the settled dust (Auger 1994; Zuraimi 2010) and dust loading may actually increase after ducts are cleaned (Zuraimi et al. 2012).

Zhou et al. (2011) reported limit values for dust loads in ducts in different countries, which are reference values for the maximum acceptable dust loading permitted on the duct surface (Table 1). Many of these countries have limit values near 1 g/m^2, which, based on the preceding particle classification analysis, would ensure the existence of a monolayer deposit. With annual dust loading rates in the range of less than 1 to as high as 5 g/m^{2}year (Zuraimi 2010), ducts should be cleaned at least once a year to prevent the formation of multilayer deposits. Zhou et al. (2011) considered the exposure implications for resuspension in ventilation ducts with varying dust loads. Cleaning a duct to reduce the dust load from 20 g/m^2 (multilayer) to 0.075 g/m^2 (monolayer) was found to significantly reduce particle inhalation exposure in a room by a factor of 267. This can be explained by the enhanced resuspension associated with multilayer deposits.

Hard Flooring

Resuspension from hard flooring has been primarily associated with human walking. Full-scale walking-induced resuspension studies have reported resuspension from both monolayer (Karlsson et al. 1999; Tian et al. 2011) and multilayer deposits (Qian and Ferro 2008; Kubota et al. 2009; Tian et al. 2011; Shaughnessy and Vu 2012, Kubota and Higuchi 2013) on hard flooring. Gomes et al. (2007) found aerodynamic removal forces associated with airflow disturbances generated by human walking to be the primary mechanism for particle resuspension from flooring, although surface vibrations, mechanical abrasion, and electrostatic forces can contribute to resuspension (Gomes et al. 2007; Hu et al. 2008; Qian and Ferro 2008; Hubbard et al. 2012). Several studies investigated the airflow generated by foot motions. Kubota et al. (2009) and Kubota and Higuchi (2013) reported jet velocities of approximately 2–3 m/s associated with the downward foot motion, Gomes et al. (2007) reported peak air velocities of 1.5–2 m/s associated with walking-related airflow near the floor, and a modeling study by Zhang et al. (2008) found a maximum radial velocity of 18.3 m/s beneath the foot. Additionally, the airflows are likely very impulsive with high acceleration (Khalifa and Elhadidi 2007), and an important factor affecting resuspension (Ibrahim et al. 2003).

As shown in the field studies of Table 1, light dust loads, and thus monolayer deposits, are found to be more common on hard flooring compared to ventilation ducts. However, in cases where an occupant does not frequently clean their flooring, multilayer deposits may form, as may be the case for some of the higher dust loads reported in Table 1, including values reported by EPA (1996), Rich et al. (1999), Rao et al. (2005), Lewis et al. (2006), Johnson et al. (2009), and Hoh et al. (2012). As discussed in Franke et al. (1997), routine housekeeping and floor cleaning can prevent the accumulation of particles on hard flooring, maintaining dust loads below levels of 0.08 g/m^2. Rich et al. (1999) also found floor cleaning to reduce dust loading. Given the elevated resuspension that may occur from multilayer deposits, it may be desirable to prevent the formation of heavy multilayer deposits on flooring.

Along with hard flooring, carpet is a common indoor flooring material, although it was not considered in this review and deposit classification analysis as the focus was on flat indoor surfaces. Higher dust loads are often reported for carpet compared to hard flooring, e.g., Chuang et al. (1995) (7.43–8.48 g/m^2), Adgate et al. (1995) (0.3–99 g/m^2), and Roberts et al. (2004) (0.7–21.1 g/m^2, surface dust). However, higher dust loads may not necessarily lead to the formation of multilayer deposits, as the total surface area is much greater for carpet and particles may be distributed across the entire surface area of a fiber (Rosati et al. 2008). Qian and Ferro (2008) compared walking-induced resuspension between carpet and hard flooring (vinyl) and found resuspension to be greater for carpet. Additionally, Mukai et al. (2009) observed greater levels of resuspension for carpet when compared to linoleum flooring.

CONCLUSION

This literature review provided a comprehensive summary of dust loads on the surfaces of ventilation ducts and hard flooring reported in indoor environmental field studies and classified each dust load as either a monolayer or multilayer deposit. Dust loads on indoor surfaces were found to range over several orders of magnitude, representing both monolayer and multilayer deposits. Key findings from the experimental resuspension literature were summarized to highlight important differences in the resuspension mechanisms associated with both types of particle deposits. Resuspension from monolayer deposits can be influenced by numerous variables of relevance to the indoor environment, including characteristics of the deposited particles and deposition surface, airflow dynamics, and environmental conditions. The literature suggests that resuspension from multilayer deposits can be considerably different, and possibly be enhanced, compared to monolayer deposits. This is due to the effects of parameters unique to multilayer deposits, such as particle-to-particle adhesion forces, aggregate resuspension, saltating particles, deposit structure and porosity, and dust loading. Therefore, the type of particle deposit may have important implications for the resuspension and transport of particles from indoor surfaces, where a diversity of dust loads and particle deposits can be found. Future research efforts should aim at better characterizing the structure and size distribution of settled indoor dust, along with developing a more comprehensive understanding of resuspension from real indoor particle deposits, with consideration for multilayer deposits on indoor surfaces, for which there are limited experimental data in the literature.

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