

Floor Coverings, Dust and Airborne Contaminants

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ABSTRACT

Floor coverings have been cited as both primary and secondary sources of contaminants. The former includes volatile organic compounds (VOC), whereas the latter could involve release of adsorbed VOC and dusts. Dusts, which are generically comprised of inorganic particles, cellulosic fibers, macromolecular organic debris, and allergens, have been at one time or another implicated in problem buildings.¹ Questions about floor coverings and VOC have been addressed elsewhere.^{2,3} Therefore, the intent of this review is to examine the published literature for information and trends with respect to the indoor environment, floor covering, dusts, and airborne exposures - more specifically, studies which address the composition of soils and dusts, surface loadings, surface loading rates, relationships to re-suspension of dust components, and airborne exposures.

INTRODUCTION

Over the last 15 years, the relationship between indoor environmental quality (IEQ) and floor coverings has been the subject of considerable discussion and debate. A deeper understanding of the respective roles of soft and hard floors has been difficult because of the complexities associated with assessment of exposure and risk for indoor environments. This can be attributed in large part to the myriad of contaminants found indoors, a wide range of physical properties associated with floor coverings, the IEQ contributions of building systems, the breadth of human susceptibilities, and a number of other confounding factors.

Soils and Dusts – General Composition and Sources

From a very general compositional standpoint, soils from various parts of the world were found to be of comparable make-up.^{4,5} Simple analysis for inorganic and organic matter of urban soils from six large metropolitan areas were relatively similar in work by Sanders and Lambert⁴ (see Table 1). Subsequently, Rivet (DuPont) reviewed internal and external studies of soils and has summarized the results, which are reproduced in Table 2.⁵ In essence, indoor soils were about 60% inorganic salts (silicates, phosphates, iron oxides, etc.), 20% fibrous (animal & cellulosic), ca. 15% macromolecular organics (resins, gums, etc.), and about 3-5 % lower molecular weight organics (non-volatile greases, fats, & oils). Particle size falls in the range of 1-1000 microns (majority < 100 um); however, a small fraction of particles <1 micron were found.⁵

^a Product Steward, Invista, Inc.

^b Prepared August 2003.

Table 1: Components of soil collected from six U.S. cities⁴

Component, %	Pittsburgh	Detroit	Cleveland	Buffalo	St. Louis	Boston
Water Soluble	15.4	13.5	15.9	11.4	14.9	15.4
Ether Soluble	10.8	4.9	7.1	6.5	12.8	7.7
Total Carbon	26.4	24.7	24.0	26.9	25.6	28.9
Ash	53.8	57.8	56.3	52.0	51.2	50.5
SiO ₂	25.6	25.5	26.4	24.0	24.1	21.4
Al ₂ O ₃	11.6	9.9	11.1	9.5	9.4	11.1
CaO (Total)	6.2	8.4	7.7	6.9	7.4	6.4
MgO (Total)	1.7	2.0	1.7	2.0	1.6	1.7
CaO (Water Soluble)	0.3	0.4	0.7	0.3	0.4	0.7
MgO (Water Soluble)	0.1	0.2	0.2	0.2	0.2	0.2
N	-	1.6	-	-	-	1.6
Carbon Black Equivalents	0.8	0.6	0.6	0.5	0.5	0.6

Table 2: General soil composition⁵

COMPONENT	%
Silica & silicates	30-40
Oxides, carbonates, & phosphates	6-24
Animal & cellulosic fibers	20-24
Resins & gums	6-10
Greases/fats	3-8
Moisture	3
Carbon	0-3

As a brief aside, it is useful to consider how soils actually accumulate in and on surfaces. For textiles, the accumulation of soils has been attributed to three mechanisms: 1) occlusion; 2) electrostatic forces; and 3) “oil binding”, in which the particle becomes imbedded in a soft organic matrix.⁶ The latter, when associated with the build-up of black carbon (soot), has historically been recognized as the principle contributor to visible soiling – i.e., the graying or darkening of surfaces and fibers.⁴

Most of the soil mass found on floor coverings appears due to foot traffic. Some older papers use the breakdown of 80% associated with foot traffic and 20% airborne.⁷ There was no data provided for this ratio in the paper most frequently referenced on this point. Intuitively, one would anticipate a relatively broad range with respect to soil accumulation from these two sources, which would depend on several internal and external factors. These will be addressed going forward.

Soils and Dusts – Trace Components and Sources

Although the general compositions of soils tend to be similar, it has been the trace components which seem to be of most interest. Not surprisingly, researchers around the world have identified a wide variety of low level contaminants in dusts collected from homes and buildings – organic, inorganic, and microbiological sourced.

Considerable attention has been drawn to semi-volatile organic compounds, especially pesticides, PCB’s, and PAH’s because of their persistence and toxicity.⁸ All have been identified often in indoor dusts. It would not be unexpected to find pesticides in rural house dusts;⁹ however, pesticides appear to be commonly encountered in virtually all residential settings – rural, urban, and suburban.^{10,11,12} Table 3 provides published pesticide results from a northeast rural setting by Lemley et al.¹²

Table 3: Selected Pesticide Residues (ug/m²) in Rural Carpet House Dust (Initial Visit)¹²

Pesticide	Freq	Min	Max	Mean	Std Error
Metolachlor	10	0.1	10.0	2.6	1.1
2,4-D (acid)	10	0.0	9.3	1.2	0.9
Picloram	10	0.1	3.4	0.7	0.4
Carbaryl	8	0.1	5.2	1.3	0.6
Atrazine	7	0.1	20.1	4.8	2.7
Mecoprop	7	0.0	0.6	0.1	0.1
Diazinon	6	0.2	27.4	6.4	4.3
Dicamba	6	0.0	2.7	0.8	0.4
2,4-D butyl ester	5	0.8	65.7	17.2	12.4
Methyl parathion	5	0.3	52.0	12.5	10.0
Alachlor	5	1.2	18.1	5.1	3.3
Tetramethrin	4	0.1	12.1	3.5	2.9
Resmethrin	4	1.7	7.0	4.5	1.4
Malathion	3	0.2	0.9	0.5	0.2
Chlorpyrifos	3	0.4	4.2	1.7	1.3
Pendimethalin	1	0.2	0.2	0.2	--
Methamidophos	0	ND	ND	ND	--
Trifluralin	0	ND	ND	ND	--

Because pesticides embody a diverse range of physical properties and have seen widespread application, a comprehensive coverage in this review was not practical. However, there were some representative studies that prove useful in understanding the dynamics around sources, accumulation, and exposure.

The analysis of carpet dusts may provide a picture of historical internal and external pesticide use. It has been offered that since pesticides (& other organic substances) embedded in the carpet have not been subjected to the degradation effects of light, heat, and moisture, they will be more persistent.^{9,11,13} This would explain, at least in part, the results from a pilot study of house dusts in which a significant number of metropolitan Washington, D.C. homes had detectable quantities of chlordane, DDT, and many common pesticides.¹⁰

Chlorpyrifos (Dursban®), synthetic pyrethroids (e.g., permethrin), and 2,4-D have been typically found in dusts collected indoors. The first two have been sprayed indoors on target surfaces or released as aerosols to manage pests such as roaches and fleas.^{14,15} As a result, both airborne and contact exposures have been of interest for humans. A few pesticides were sufficiently volatile to be quantified in the gas phase after application; however, most exist as either small particles or adsorbed onto small particles. These particles also provide an opportunity for human inhalation exposure. Most pyrethroids were particle bound.¹⁴ In a “test house” study, researchers detected Deltamethrin and Permethrin in the gas phase (2 ng/m³ and 13 ng/m³ respectively) only immediately after treatment (60 m³ rooms @ 230 mg/room Deltamethrin and 3-8 g/room Permethrin).¹⁴ The levels on suspended particles were 20 ng/m³ and 760 ng/m³ respectively after treatment. Both were found to diminish perceptibly over the first two days, but much more slowly over the following two years.¹⁴ One other observation of note in this study was that 76% of the permethrin mass was on particles ≤ 1 micron (see Table 4).¹⁴ This observation was also consistent with work by Lewis et al. who reported similar results on a broad spectrum of pesticides,¹⁶ and with Priess and coworkers.¹⁷ They also noted that slightly over 20% of the composite dust in their study was ≤ 25 microns.¹⁶

Table 4: Concentration of Permethrin on Particle Size Fractions¹⁴

Particle	ug/g
< 0.25	690
0.25 - 1.0	300
1.0 - 4.0	410
4.0 - 10.0	220
> 10.0	53

Lu et al. explored airborne and surface behavior of chlorpyrifos as a function of application methods (broadcast spray, fogger).¹⁵ After application of 21 mg/cm² (spray) and 2.8 mg/cm², they observed 118 ug/m³ and 82 ug/m³ respectively at 4 – 12 hours. These levels dropped rapidly over the next four days before leveling off at 1 ug/m³. Most of the Chlorpyrifos were not dislodgable from the carpet surface as determined by a wipe test. At one hour

after spray application, an average of 165 ng/cm² (0.78%) was observed. This dropped substantially lower within 9 h – to 22 ng/cm². Unfortunately the authors did not report wipe data for non-carpet hard surfaces, which would have been the result of non-target application with the fogger.

Nishioka et al. have determined 2,4-D to be mostly tracked into buildings, as would be anticipated based on intended use.^{18,19} They found carpet dust levels of 2,4-D to be highly correlated with outdoor dislodgeable turf residues. Although outdoor track-in was the principle source of 2,4-D, the actual amount determined to be turf dislodgeable was only 0.1 – 0.2% of the applied level, and approximately 3% of this transferred to carpet dust (0.1 to 5 ug/g dust).¹⁸ In later work, they garnered additional support for the predominance of track-in by collecting substantial data around building parameters, personal factors, and herbicide data from various home locations. This study also provided some very useful information around accumulations of dusts and contaminants on hard and soft surfaces (see Table 5). In this work, dust loadings on carpet were approximately ten times those on hard surfaces; however, they also estimated that only about 1% of the bulk carpet dust was available for dermal contact.¹⁸

Table 5: Dust and Pesticide Loadings in Comparable Columbus, Ohio Homes¹⁸

<u>Home B, carpeted</u>				<u>Home C, mixed flooring</u>			
Location	Flooring	2,4-D; ug/g	total dust; g/m ²	Location	2,4-D; ug/g	total dust; g/m ²	
Entry	carpet	67	1.1	Entry	vinyl	1.6	0.45
Kitchen	carpet	57	0.62	Hall	wood	1.2	2.6
Living Rm	carpet	28	0.48	Dining Rm	wood	1.7	0.98
Dining Rm	carpet	20	0.58	Living Rm	carpet	14	5
Bedroom	carpet	7.8	0.67	Bedroom	carpet	11	2.5

Polyaromatic hydrocarbons (PAH) appear to be common in house dust. Roberts found between 1 to 100 ug/g of PAH in house dust in an eight-home pilot study.²⁰ Chuang et al. found between 0.3 – 5500 ug/g in carpet dusts in Columbus, Ohio homes.²¹ Although geometric mean and median values are much closer to the lower end of the spectrum, Roberts offered that in some instances PAH levels in house and carpet dusts exceeded clean-up levels dictated for industrially contaminated sites.²²

Airborne levels of PAH's have been associated with combustion processes – tobacco smoke²³, cooking²³, kerosene heaters²⁴, and fireplaces.²⁵ However, the Chuang work concluded that much of the PAH found in dusts indoors was tracked in from outdoors.²¹ In essence, they found a consistent concentration gradient from high outdoor foot traffic areas to low foot traffic areas. Table 6 provides a summary of their findings.

Table 6: PAH Concentrations in Homes²¹

<u>Location*</u>	<u>PAH** Conc., ug/g dust</u>
Entry way track-in	58 - 5500
Indoor Pathway	.58 - 1200
House dust	16 - 580
Foundation Soil	0.63 - 63
* 8 home pilot study	
** 19 PAH monitored	

As was the case with pesticides, there appeared to be a significant relationship between concentration of PAH and particle size. The highest concentrations of PAH's were found by Lewis et al. on the smallest size particles (< 4 microns).¹⁶

The most important and most studied heavy metal found in the dusts of buildings and homes has been lead (Pb). **The underlying reasons for interest have been several; however, concerns over impacts on children's health appear overarching.** [surpassing, dominant, prevailing, overriding] For example, reductions in children's cognitive performance have been associated with elevated blood lead levels – in the range of 30 – 40 ug/dL.²⁶

Historically, the general population has been exposed to two primary sources of lead. The first was the result of the use of lead in gasoline, which spanned several decades.²⁷ The relationship between blood levels and leaded gasoline was striking – in the time period between 1976 and 1980 when leaded gasoline consumption dropped by 50%, average blood lead levels dropped by 30%.²⁸ Note, the use of these fuels has had the secondary effect of contaminating soils, especially in densely populated urban areas, which then have the potential for introduction into buildings via foot traffic.²⁹

With the phase-out in the 1970's of leaded fuels, the general consensus has been that the primary route of lead exposure for small children can be attributed to ingestion of dusts from deterioration of lead-based paint.²⁷ Even though lead based paints containing more than 0.06% lead by weight were banned in 1978, approximately 85% of housing units constructed prior to 1980 still contain some lead-based paint.³⁰ Farfel and coworkers in a Baltimore study, which compared lead dust deposition rates of older homes versus newer homes, observed lead geometric means to be over ten times higher in the older homes (130 ug/ft²/day vs. 9 ug/ft²/day).³¹ Note that this was attributable to lead concentration and not total dust levels.

It has been reported in a handful of studies that blood lead levels for small children correlate with lead levels in house and carpet dusts.³²⁻³⁴ For example, Clark et al. found a statistically significant correlation (r = 0.52; p = 0.01) between carpet surface dust lead levels and blood lead levels in young urban Cincinnati children.³⁴ Table 7 is a summary of the data from their 23 home study. It should be noted that reported associations were not indicative of cause and effect. The fact that carpet dusts explained only a relatively small percentage of the variance in the data suggests other factors had a role. Carpet dusts may serve as a marker for the lead burden of the environment as a whole. Research to date has indicated lead can be especially difficult to remove from carpet,^{35,36} attributable in part to lead residing with very fine particles (< 1 um). Therefore, lead in carpet dust may not be readily available for exposure.

Table 7: Summary of Surface Dust* Lead Loading and Blood Lead Levels in Cincinnati³⁴

Factor	GM	Range
Blood Lead (ug/dL)	7.1	1.8 - 20.8
Carpet Dust Lead (ug/g)	244	15.0 - 1030
Carpet Dust Lead (ug/m ²)	66.9	6.6 - 1733

* Surface dust was only that dust readily available – typically about 1% of the total.

Soils and Dusts – Allergens

Allergens have been of special interest with respect to the indoor environment due in large part to the dramatic increases in reported asthma symptoms over the last thirty years.³⁷ In addition, it has been determined that several common allergens can be associated with the development and the exacerbation of asthma symptoms.³⁸ Because the depth and breadth of published work on allergens has been enormous, this review will attempt to characterize consensus views and illustrate with relevant examples. Specific attention is paid to allergens from cat, dog, cockroach, and dust mite, and to mold spores.

In Denmark, Schneider et al. characterized vacuum cleaner dust recovered from office building floors for use in laboratory exposure studies.³⁹ Table 8 provides a summary of their findings. Also of note was the determination by the authors that this dust was estimated to have low toxicological potency.

Table 8: Characterization of Vacuum Cleaner Dusts from Danish Office Buildings³⁹

Contaminant	Observed Conc. Range
Microorganisms, cfu/g	130,000 - 160,000
Culturable Fungi, cfu/g	71,000 - 90,000
Endotoxin, EU/g	5 - 7.2
Dust Mite Allergen, ng/g	147 - 159
Dog Allergen, ng/g	395 - 746
Cat Allergen, ng/g	103 - 330

Cat allergen appears to be nearly ubiquitous. For example, it has been quantified in dusts from homes and schools where cats have never been present. Custis et al. observed from 1-112 ng/g dust of *Fel d 1* in homes without cats (see Table 9 and Table 10).^{40,41} Dybendal and Elsayed compared 40 classrooms for *Fel d 1* allergen – 20 with carpet and 20 with smooth floors.⁴² Accumulated dusts from vacuum cleaning once per day over five days were found to average 518 ng/m² and 151 ng/m² for carpet and smooth floors respectively. The difference was found to be statistically significant; however, this was more probably due to the fact this was a mass per unit area comparison. An earlier study indicated cat and other allergens were not significantly different in floor dust on a per gram basis.⁴³

Cat allergen has been associated with a rather broad particle size range - from < 1 um to > 10 microns. However, Luczynska and coworkers estimated 10% – 60% of cat allergen to be linked with particles < 2.5 microns, which provides the opportunity for deep lung exposure.⁴⁴

Table 9: Observed *Fel d 1* Levels in House Dust⁴⁰

<u>Home</u>	<u>Cat Present?</u>	<u>Floor <i>Fel d 1</i> (ug/g)</u>	<u>Airborne <i>Fel d 1</i> (ug)*</u>
1	Yes(1)	270.6	3.21
2	Yes(3)	514	20.4
3	Yes(1)	272	2.97
4	No	112	1.36
5	No	43.8	0.05
6	No	24.5	0.3
7	No	2.4	< 0.02
8	No	1.1	0.03

* Total accumulated allergen over 24 h; ca. 25 ft³/min; ca. 50% efficiency

Dogs have been reported to be in approximately 31% of U.S. homes,⁴⁵ which was a ratio similar to cats. However, dog allergy frequency in the human population was about half of that for cat allergy.⁴⁶ Dog allergen, like cat allergen, has also been reported in locations without dogs.^{47,48} In a study of 131 homes, Perry et al. reported dog allergen levels to be about twice as high in carpet dust samples than hard surface floors - 52 mg/g vs. 20 mg/g respectively for dog owners, and 0.81 vs. 0.42 for non-dog owners (geometric means).⁴⁷ Similar loadings were seen by Custovic et al. but there was no reference to floor covering in the dust sampling.⁴⁸ In a Swedish study dog allergen (*Can f 1*) was observed on school floors at 1.1 ug/g (GM; range <0.5-60), in homes with a dog at 79 ug/g (GM; range 13-625) and in homes without a dog 2.0 ug/g (GM; range <0.5-22).⁴⁹ Dog allergens have also been associated with particle sizes ranging from 10 – 90 microns.⁵⁰

Table 10: Concentration of house dust mite (*Der p 1*), cat (*Fel d 1*), and dog (*Can f 1*) allergens (ug/g; geometric means and 95% confidence intervals) in homes with and without pets⁴⁸

Allergen	With pets	Without pets
<i>Der p 1</i> LF	1.1 (0.63-1.31)	1.45 (0.93-2.27)
<i>Der p 1</i> S	0.96 (0.67-1.36)	1.39 (0.91-2.12)
	With dogs	Without dogs
<i>Can f 1</i> LF	181.34 (102.02-322.33)	1.56 (1.17-2.08)
<i>Can f 1</i> S	100.02 (42.01-238.07)	1.87 (1.37-2.57)
	With cats	Without cats
<i>Fel d 1</i> LF	204.5 (108.54-385.3)	0.8 (0.61-1.06)
<i>Fel d 1</i> S	208.89 (86.76-503.04)	1.36 (0.96-1.73)

LF: living room floor; S: sofa.

Cockroach allergens may be very important contaminants of indoor dusts.³⁸ For example, Rosenstreich et al. found in a study of 476 children with asthma 36.8% were allergic to cockroach allergen.⁵¹ This was apparently due in part to the widespread distribution of cockroach allergens throughout homes and public buildings.⁵² It has been offered that children who had been exposed to > 10 U/g of *Bla g I* and 5 U/g of *Bla g II* tended to have cockroach allergies.⁵³ In a study by Sarpong and coworkers, there also appeared to be a socioeconomic bias in exposure and sensitization.⁵³

Sarpong et al. (1997) concluded that significant exposures to Bla g I could occur in schools.⁵⁴ In a study of four Baltimore inner city schools, 69% of 147 dust samples had detectable levels of Bla g I - median levels were 0.8, 2.7, 3.0, & 5.2 U/g dust (range for all 147 samples was 0 – 591 U/g). The floor covering characteristics of the sampled classrooms were noted: three of the four schools had significant amounts of carpet (> 30% of the classrooms). No significant contributions associated with carpet were observed in the factor analysis of the data.⁵⁴ Physically, cockroach allergens have been described as amorphous and irregular shaped. Allergen has been primarily associated with particles > 10 um.⁵⁵

Dust mites (genus *Dermatophagoides*) have been widely viewed as the one of the most important sources of allergens in house dust.³⁸ Based on an extensive review of the scientific literature, the “Committee on the Assessment of Asthma and Indoor Air, Division of Health Promotion and Disease Prevention, Institute of Medicine” has concluded that there was sufficient evidence of a causal relationship between mite allergen exposure and exacerbation of asthma in mite allergen sensitive populations.³⁸ In addition, this same body found sufficient evidence of a causal relationship between dust mite allergen exposure and the development of asthma in susceptible children.³⁸ Platts-Mills and de Weck offered a threshold level of mite exposure of 2 ug/g dust of increased risk of sensitization for susceptible individuals.⁵⁶

The levels of dust mite allergen in homes can vary widely – non-detectable to greater than 100 ug/g dust.⁵⁷ Not surprisingly and consistent with earlier work, Munir et al. reported higher mite allergen concentrations in Scandinavian homes with higher humidity conditions.⁵⁸ They also included data which separated mite allergen loading in rooms with and without carpet (see Table 11). Bedrooms were significantly higher than living rooms (p < 0.01). Carpet was not significantly different from hard surfaces in allergen concentration per gram of dust.⁵⁸ In slight contrast, a study of schools by Zock and Brunekreef found mite allergen loadings to be highly variable; however, carpet did carry significantly higher loadings per gram of floor dust (see Table 12).⁵⁹

Table 11: Dust Mite Allergen Loading (Geometric Means) on Carpet and Smooth Floors⁵⁸

Factor	N	BR (ng/g dust)	LR (ng/g dust)
Carpet	21	168	157
No Carpet	105	147	98
Damp	67	199	165
Not Damp	59	109	64

Table 12: *Der p I* concentrations in the floor dusts of 49 schools⁵⁹

Floor Covering	GM Dust (g/m²), Range	<i>Der p I</i> (ng/g), Range	<i>Der p I</i> (ng/m²), Range
Smooth	0.284 (0.004 – 6.72)	22.5 (<5 – 193)	6.4 (<1 – 113)
Carpet	0.475 (0.044 – 9.30)	44.2 (<5 – 18662)	21 (<1 – 5794)

Overall, the consensus from the published data has been that mite allergen was predominantly associated with particles larger than 10 microns.⁶⁰ This conclusion has been largely supported by observations in the field of low ambient air concentrations in undisturbed or moderately disturbed environments, and a rapid concentration decrease after a significant disturbance of the space. The latter, of course, was consistent with the fall rate of a large particle.

Humans have been exposed to a wide variety of fungal spores, fungal debris, and metabolic by-products on a continual basis. Not surprisingly, allergens related to fungi have been related to indoor environmental quality problems.⁶⁰ The actual number of fungal species was estimated to be quite large > 1,000,000, and the characterization of allergenic activity continues to evolve. To date, only a handful of allergens from fungi have been isolated and identified (see Table 13).³⁸ Four key fungi from this small group (*Aspergillus*, *Alternaria*, *Cladosporium*, and *Penicillium*) have been frequently reported in data from dust and air samples in study locations worldwide.

Table 13*: Major Allergens Identified from Fungi³⁸

<i>Aspergillus fumigatus</i>	<i>Asp f I, Asp f III</i>
<i>Aspergillus oryzae</i>	
<i>Alternaria alternata</i>	<i>Alta a I, Alt a II</i>
<i>Cladosporium herbarum</i>	<i>Cla h I</i>
<i>Penicillium citrinum</i>	
<i>Penicillium chrysogenum</i>	
<i>Trichophyton Tonsurans</i>	<i>Tri t I</i>
<i>Malassezia fufur</i>	<i>Mal f I</i>
<i>Psilocybe cubensis</i>	<i>Psi c II</i>

*Extracted from Table 5-2 of the cited reference.

Reported dust burdens of viable fungal spores range widely. Typical loadings have run from a few thousand to a few million cfu/g dust. Skov et al. reported an average of 1100 cfu/g dust and a range of 200-6400 cfu/g dust in office settings.⁶¹ In a study of schools and offices, which also compared carpet and hard surface floor coverings, Gravesen and coworkers observed 1900 cfu/g and 900 cfu/g respectively in schools, and 1100 cfu/g and 600 cfu/g in offices.⁶² Hedge et al. reported a range of 128,000 to 522,000 cfu/g in carpet dust and 671,000 to 2,650,000 cfu/g in smooth floor dust from 42 residential settings in New York State.⁶³ In an EPA sponsored RTI study, fungi levels in carpet averaged 1,230,000 cfu/g in the initial sampling of a non-problem building. These dropped to 90,000 cfu/g with an improved cleaning regiment.^{64,65} Smooth surface floors were reported to average 230,000 cfu/g in this same study.

Fungal spores found in indoor dusts appear to be largely driven by outdoor species and levels.⁶⁶ However, in the presence of sufficient quantities of moisture, amplification can occur in the indoor environment. The species identified will be somewhat dependent on the nutrient sources available and ambient conditions in the building.⁶⁶

The relationship between fungi in house dust and airborne exposures appears complex. For example, Chew and coworkers found a few weak correlations between dust and airborne fungi; however, other factors appeared to be important as well (e.g., category of housing, presence of carpet).⁶⁷ The type building ventilation system also appears to play a role in airborne fungi exposure. In a study of UK office buildings, Harrison et al. found naturally ventilated buildings to be significantly higher than air conditioned or mechanically ventilated buildings (277 cfu/m³, 26 cfu/m³, and 36 cfu/m³ respectively).⁶⁸

The physical properties of fungal spores are highly varied. Dimensionally, they can be nearly spherical, rod or ribbon-like, or highly irregular. They also cover a wide size range – from slightly less than 2 micron to over 40 micron in aerodynamic diameter.⁶⁹ As such, their propensity to adhere to surfaces or to be released or re-suspended into the air will depend up these shapes and the character of the spore surface.⁷⁰ Many spores tend to have “sticky” surfaces or “appendages” which allow entanglement with target surfaces. In addition, adhesion mechanisms for some “dry” spores may involve electrostatic charge. Although this attribute has not been deeply studied, some evidence for an electrostatic charge role has been reported by Dart and Obendorf⁷¹ and by Buttner et al.⁷²

The particles, contaminants and allergens discussed in this section represent some of the more commonly studied indoor pollutants. However, they cover only a very small fraction of the vast array of contaminants to which humans can potentially be exposed. Owen, Ensor, and Sparks published an excellent review in 1992 outlining many of these substances.⁷³

Dust Accumulation and Accumulation Rates

Intuitively, one would anticipate that indoor accumulations of soils and dusts would be dependent on a variety of factors. For example, it would be expected that variables such as outdoor conditions (e.g., rain), preventative measures (e.g., walk-off mats), number of people, and interior location (e.g., higher vs. lower floors) could affect the amount of soil tracked into a space. With respect to elevated surfaces (e.g., desks and shelves), soil accumulations will depend on settled particles sourced from outdoor air, those generated from activities indoors (e.g., cooking), and those re-suspended from the floor. However, the overall scientific literature was relatively sparse in describing these relationships.

Not surprisingly, the published data indicates carpet had higher burdens per unit area of contaminants than hard surfaces. Although soil capacity for carpet was potentially quite high, it was not unusual for the reported differences in accumulated soils to be less than ten times that of smooth floors. One notable exception was the work by Shaughnessy et al. in southwest U.S. schools, in which the hard surface floor loadings and carpet loadings differed by 100 times or greater.⁷⁴ The smooth floor data was on average consistent with other studies, which implied the routine carpet maintenance for these schools was poor. Table 14 provides some relative comparisons between floor coverings.

Table 14: Comparison of Soil Loads between Carpet and Hard Surface Floor Covering in Schools⁷⁴

End Use	Floorcovering	Dust*, g/m ²	Reference
Entry	Vinyl	0.45	19
Hall	Wood	2.6	19
Dining Rm	Wood	0.98	19
Living Rm	Carpet	5	19
Bedroom	Carpet	2.5	19
School	Carpet	1.67	62
School	Hard Surface	0.58	62
Office	Carpet	0.42	62
Office	Hard Surface	0.12	62
School	Tile	0.015	74
School	Carpet	50	74
School	Concrete	0.21	74
School	Carpet	20	74
School	Tile	0.14	74
School	Carpet	17	74
School	Tile	0.096	74
School	Carpet	15	74
School	Tile	0.055	74
School	Carpet	99	74
Day Care, Offices	Carpet	1.8	64
Day Care, Offices	Tile	0.1	64

* Average Values

Data on rates of accumulation of dusts or soils was rare. Although many research groups looked at mass loadings, it was unusual to see any intentionally relating dust accumulations to time. There has been one study by Schaefer et al. occasionally cited in the literature, which assessed settled dust rates. In their work on dust accumulations associated with ambient air in U.S. homes, they observed an average dust accumulation rate of 0.02 g/m²/day based on 100 homes in five cities.⁷⁵

In some instances, it was possible to take accumulated soil data for carpet where the routine maintenance frequency was reported and calculate soil accumulation rates (see Table 13). In a handful of published work it was possible to estimate accumulations based on the information provided. Although rather limited, this exercise suggests that between 0.2 g/m²/week and 7.7 g/m²/week likely captures a majority of end uses. Of course, as was mentioned before, extraordinary events, conditions, or end uses could easily yield findings outside this range.

Table 15: Soil Accumulations in/on Flooring

Location	Surface	Dust Mass, g/m ²	Time Period	Reference
Residence	Carpet	0.45 - 5.0	1 week	19
Residence	Wood	0.98 - 2.6	1 week	19
Residence	Walk off mat	GM = 1.1	1 day	31
FPG "Day Care"	Carpet	0.2 - 5.8	Weekly	64
FPG Offices & Labs	Carpet	0.3 - 0.6	Weekly	64
School Adm. Office	Carpet	Mean = 0.15	Weekly	76
Office	Carpet	0.16 - 0.6	2/Weekly	77
Residence	Carpet*	2.2	Weekly	78
Residence	Carpet**	0.58	Weekly	78
Residence	Linoleum*	0.08	Weekly	78
Residence	Linoleum**	0.06	Weekly	78
Residence	Carpet***	1.08	Weekly	78
Residence	Carpet****	0.6	Weekly	78

*Traffic lane area ** Off traffic lane *** Upstairs Traffic lane **** Upstairs off traffic lane

Airborne Particles and Allergens

A fair amount of work has been completed over the last few years which has addressed sources of indoor airborne dusts. These covered indoor/outdoor ratios (I/O) of contaminants, infiltration of contaminants, and re-suspension of indoor soils. In general, indoor environments were influenced by outdoor conditions. However, there was a strong particle size dependency on contributions of outdoor air to indoor air. In essence, smaller particles (< 2.5 micron) in the absence of smoking were frequently dictated by outdoor air, whereas larger particles (> 10 micron) often appeared to have had an indoor source – via re-suspension.

On average indoor/outdoor ratios of particles tend to be less than one. Alzona and coworkers estimated an I/O of 0.3,⁷⁹ Spengler found ca. 1.0 in non-smoking homes,⁸⁰ and Colome et al. found a range of 0.4 to 1.5 for several California homes.⁸¹ For extremely sensitive environments such as hospitals, the I/O ratio could be as low as 0.03 for sub-micron particles and 0.01 for larger particles.⁸²

Typically, the challenge has been to distinguish between particles which enter with the outdoor air, those generated by internal activities (e.g., cooking), and those particles re-suspended from physical disturbances. In an effort to sort through infiltration, activity, and source factors in a residential setting, Long et al. quantified indoor and outdoor particle levels as a function of size at night when internal disturbances resulting in re-suspension were minimal (see Table 16).⁸³ The infiltration factors were much higher for the smaller particles (< 1 micron) versus the larger particles (> 2.5). Not surprisingly, deposition as a removal mechanism was more efficient for larger particles than smaller particles.

Table 16: Indoor / Outdoor Particle Levels as a Function of Size⁸³

Size	Indoor	Outdoor	Units
PM _{2.5}	7.06	10.11	ug/m ³
P(0.02-0.1)	0.31	0.46	um ³ /cm ³
P(0.1-0.5)	4.52	6.01	um ³ /cm ³
P(0.7-2.5)	1.34	2.64	um ³ /cm ³
P(2.5-10)	0.62	2.5	um ³ /cm ³

Ozkaynak et al. in an in-depth study of 175 Riverside, California residents, provided considerable insight into personal exposures to airborne particles.^{84, 85} Table 17 provides a brief summary of a few of their results. One of the major findings from this work was that personal exposures during the day exceeded concurrent background levels (indoor and outdoor) by about 50%.⁸⁵ The nature of the excess was not well understood; however, speculation was offered around the role of proximity to various activities such as cooking and cleaning. Both were

known to contribute significant levels of particles as illustrated in work published by Chao et al. who found that some cooking and cleaning efforts could contribute particle levels in excess of 5000 and 1500 ug/m³ respectively.⁸⁶

Table 17: Personal Exposure to Airborne Particles and Sources⁸⁵

<u>PM₁₀ concentrations, ug/m³</u>	<u>Personal PM₁₀</u>	<u>Indoors</u>	<u>Outdoors</u>
Day	150	95	95
Night	77	63	86
<u>In homes with smoking</u>			
	<u>PM_{2.5}</u>	<u>PM₁₀</u>	
N	61	61	
Outdoor air	60%	58%	
Smoking	30%	24%	
Other Indoor Sources	7%	17%	
Cooking	3%	3%	
<u>In homes with cooking</u>			
	<u>PM_{2.5}</u>	<u>PM₁₀</u>	
N	62	62	
Outdoor air	62%	56%	
Smoking	5%	4%	
Other Indoor Sources	8%	15%	
Cooking	25%	25%	

Attempts have been made to model particle sources and behaviors indoors.^{87,88} Nazaroff considered a variety of factors, which included the effects of filtration, ventilation, deposition, direct emission, and coagulation, all applied to cigarette smoke and found reasonable models.⁸⁷ Schneider and coworkers took this a step further and created models for particles in general. Although these models were fair, considerably more needed to be known about source dynamics, especially track-in and re-suspension to improve predictive exposure capabilities.⁸⁸

Interestingly, some of the better research to date has been done with libraries and museums. This has been driven to a large degree by concerns over the impact of soils and airborne contaminants on valuable works of art.⁸⁹ For example, Nazaroff and coworkers found deposition rates for particles carrying soot entering via outdoor air into three California museums to yield estimates of visible soiling rates which ranged from as little as one year to as long as 40 years.⁹⁰ They also observed a strong deposition dependence on particle size – i.e., < 0.5% of particles ca. 0.15 microns were deposited versus over 90% for particles larger than 2 microns.

Ligocki et al. studied five southern California museums in an effort to assess indoor sources of particles.⁹¹ They found indoor/outdoor ratios to range from 0.16 – 0.96 for fine particles and 0.06 – 0.53 for coarse particles. The indoor particle concentrations they reported ranged from a low of 10 ug/m³ to a high of 63 ug/m³. In sampling routines covering several days for each site, the fine particles tracked outdoor particles quite closely, albeit at lower concentrations. The coarse particles also tracked outdoor particles, although not nearly as precisely, and in a couple of locations the delta between indoor and outdoor particles was quite large (> 5x). They attributed the ranges to be a function of the ventilation systems employed at the respective sites.

Yoon and Brimblecombe took a somewhat different approach to soiling of museum artifacts, which included an assessment of the role of floor covering.⁹² They understood the importance of the soiling characteristics of soot (carbon), but they also recognized the role coarse particles and fibers played. These tended to accumulate to visible levels much faster, and because of their physical characteristics, could result in damage as a result of creating a need for frequent and/or overly aggressive cleaning. They examined soiling rates via a “% of coverage” metric (the method described involved collection of settled dust on “sticky tape” – in this study over 8 weeks, microscopic examination, and image analysis to determine % coverage).

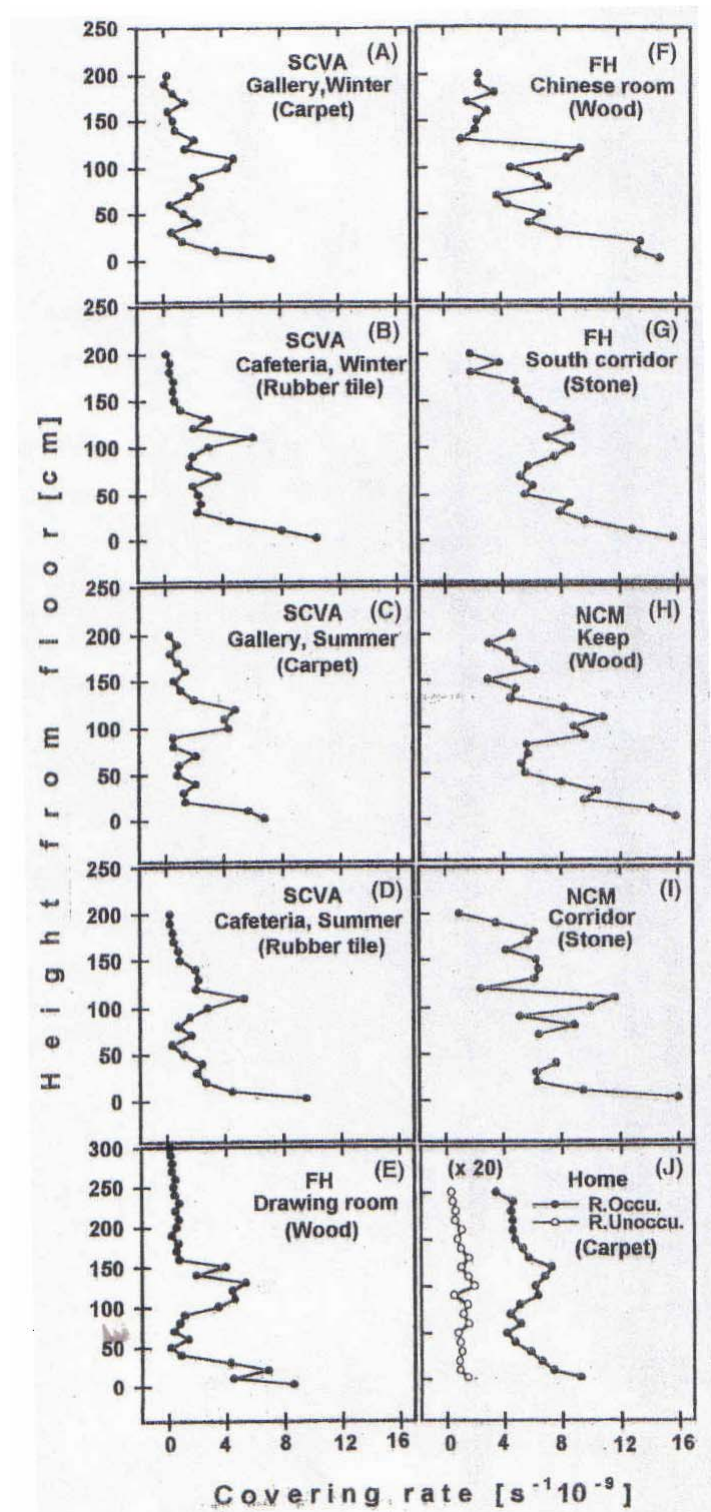
Some of the Yoon and Brimblecombe data has been reproduced in Table 18 and Figure 1.⁹² A handful of interesting observations stand out. Not surprisingly, the soiling rates were a strong function of human contributions and human proximity to the sampling location. With respect to the latter, dust coverage rates declined rapidly with increased

distance (> 0.5m) from the collector. Of special interest was the observation that a similar coverage rate versus height profile was observed at all sites; i.e., coverage rates were highest at 0 – 20 cm above the floor, diminished rapidly in the 25 – 100 cm height range, spiked again at 120 cm, and dropped off again by 150 cm. The explanation was that the spike at floor level was associated with foot traffic and very large particles (> 100 microns), which did not rise very high and dropped back to the floor rapidly. The second spike appeared to be sourced by clothing based on an analysis of the collected debris. Also of interest was the fact that carpeted floors had consistently lower dust coverage rates than wood and stone floors. The authors offered that it was likely the particles and fibers were more easily suspended from hard surface floors.

Table 18: Fibrous Dust Collected as a Function of Height in Active Museums⁹²

Site	2 - 30 cm	40 - 70 cm	80 - 150 cm	160 - 200 cm
A	57	40	54	27
B	69	46	58	32
C	71	50	63	35

Figure 1: Dust Collection Profiles as a Function of Height and Floorcovering⁹²



Another approach to assessment of soiling rates or accumulations was the use of a gelatin-coated foil first described by Schneider and coworkers.⁹³ The foil was pressed against a surface and soil particles were embedded. When a laser light was passed through the foil, the light was attenuated as a function of the amount of soil present on the foil tape. The system was calibrated to yield a percent dust coverage.

A few applications of this method have been published to date. Two studies provided some relative sense of soiling rates on elevated surfaces with this method and are summarized in Table 19.^{94,95} In the work by Kildeso, dust accumulations were monitored in office locations in both the U.S. and Europe.⁹⁴ In the three office settings highlighted in Table 19, soil accumulation rates ranged from 0.074%/day to 0.226%/day via this method. This compared to a range of 0.51%/day to 0.86%/day in the Dahl et al. study of schools.⁹⁵ The difference could intuitively be attributed to the different end uses. Dahl did note that there was no significant difference in the coverage rates between carpet and hard surface floors at any of the heights studied. A couple of other interesting observations came out of the Kildeso work. First, more dust was observed on infrequently disturbed surfaces. Second, there was a strong correlation between dust accumulations and the PM₁₀ fractions of airborne particles.

Table 19: Soiling Rates on Elevated Surfaces

End Use	Floorcovering	Average % coverage	Cleaning Freq.	Other Comments	Ref.
Office	Carpet	0.112	Daily		94
Office	Carpet	0.074	Daily		94
Office	Carpet	0.226	Daily		94
Height Above Floor					
School	Carpet	3	2x Week	50cm	95
School	Hard floors	2.7	2x Week	50cm	95
School	Carpet	2.6	2x Week	110cm	95
School	Hard floors	2.2	2x Week	110cm	95
School	Carpet	2	2x Week	200cm	95
School	Hard floors	1.8	2x Week	200cm	95

As earlier discussions suggest, indoor particles appear to have a significant size/source relationship. Thatcher and Layton in their studies of a California residence generally found particles smaller than 5 microns were not easily re-suspended, and particles smaller than 1 micron showed almost no potential for re-suspension, even with vigorous activity.⁷⁸ In essence, the smallest particles found indoors appeared to be driven by outdoor ambient air (in the absence of smoking and cooking). In their experiments, the largest increases in particle concentrations after a disturbance of an area (cleaning and walking) were observed for particles in the 15-25 micron range (about 4-fold over background) – see Figure 2. Table 20 includes particle “loss” rates as a function of size in a residence where the only factors affecting particle loss were air infiltration and deposition. Half-lives for the larger particles (> 10 microns) were < 30 minutes. Obviously if ventilation was introduced, the disappearance of some of these particles would be much more rapid.

Figure 2: Airborne Particle Concentrations as a Function of Size after a Vigorous Disturbance⁷⁸

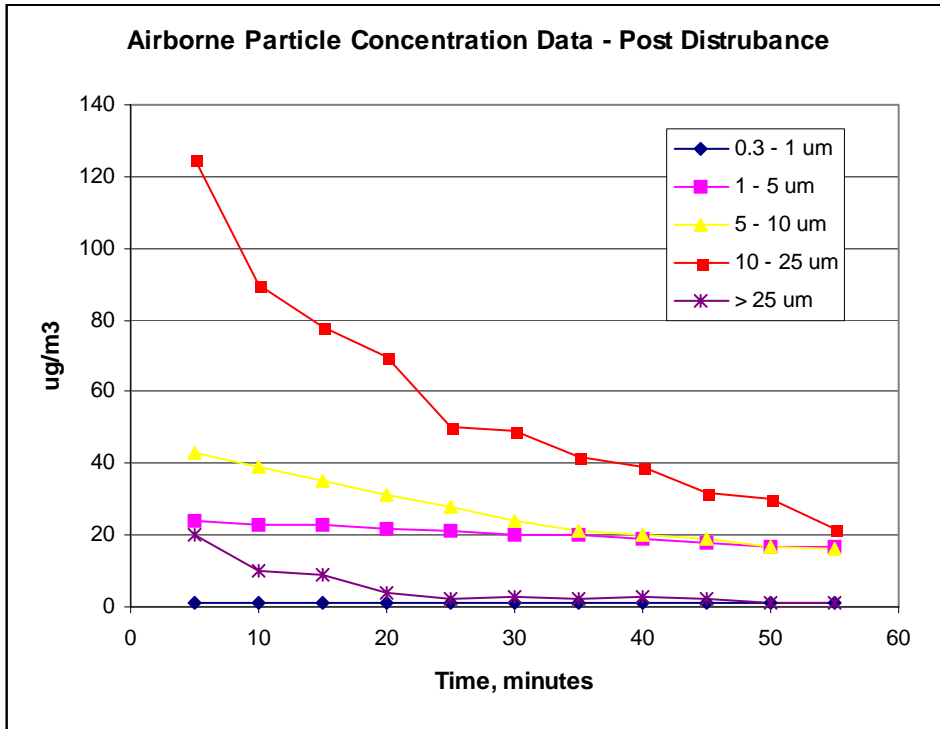


Table 20: Airborne Particle Loss Rates⁷⁸

Particle size,um	Particle Loss Rate, h-1	Half life, h
1 - 5 um	0.60	1.16
5 - 10 um	1.50	0.46
10 - 25 um	2.50	0.28
> 25 um	4.20	0.17

Thatcher and Layton also made an attempt to estimate re-suspension rates (results summarized in Table 21).⁷⁸ They found airborne particles in their study home tended to reach steady-state in 5 - 30 minutes with four persons engaged in “normal” activities. In addition, they had determined floor loadings of dust, particle infiltration, deposition velocities, and ambient air concentrations (all as a function of particle size), which allowed them to estimate the portion attributable to re-suspension. As covered earlier, particles in the range of 10 - 25 microns were easiest to suspend, whereas the small particles (< 1 micron) were not. They also observed that only a very small fraction of total dust load was re-suspended. It should be noted that the study house consisted of ca. 40% carpet and 60% hard surface flooring; therefore, it was not possible to identify the relative contributions of the flooring.

Table 21: Particle Re-suspension Rates in a Residential Setting during Normal Activities⁷⁸

Particle Size Range	[Indoor]	[Outdoor]	Deposition Rate	Infiltration Rate	Re-suspension Rate
<i>um</i>	<i>ug/m³</i>	<i>ug/m³</i>	<i>h-1</i>	<i>h-1</i>	<i>h-1</i>
0.3-0.5	1.2	0.3	0	0.3	9.90E-07
0.5-1	0.5	0.1	0	0.3	4.40E-07
1 – 5	6.8	3	0.5	0.3	1.80E-05
5 – 10	14.3	10.9	1.4	0.3	8.30E-05
10 - 25	38	21.7	2.4	0.3	3.80E-04
> 25	2	1.4	4.1	0.3	3.40E-05

There was only limited data on relationships between loadings of contaminants on floors and surfaces and the propensity of specific particles/contaminants for re-suspension.

Sansone had collected some information around “re-suspension factors”.⁹⁶ These were simply defined as the ratio of airborne concentration to surface concentration, which yields “units/m” (m^{-1}). Most of the Sansone factors were associated with movement of radioactive contaminated dusts. Nonetheless, his review provided insight into the release properties of select particles that would be anticipated to behave comparably to other inorganic particles. A few Sansone factors have been provided in Table 22. It was noted that most of the re-suspension factors (even those not included below) fell in the 10^{-3} to 10^{-6} range.

Table 22: Re-suspension Factors (K)⁹⁶

Contaminant	Disturbance	K (m^{-1})
Fluorescent powder	Walking	$0.8-120 \times 10^{-6}$
Alpha emitters	walking	$0.59 - 2.2 \times 10^{-4}$
Microorganisms	Walking	2.3×10^{-3}
CuO powder	light sweeping	7.1×10^{-4}
S. aureus	4 walkers, 30 min	3.5×10^{-3}
S. aureus	damp mop	2×10^{-4}

The work of Pauluhn with dust particles contaminated with pyrethroids was consistent with the body of work which indicated small particles were difficult to re-suspend.⁹⁷ He reported that continuous brushing of a contaminated carpet over 19 hours dislodged only 0.04%/m²h, and hence, presented no significant route to pesticide exposure (dermal or inhalation).

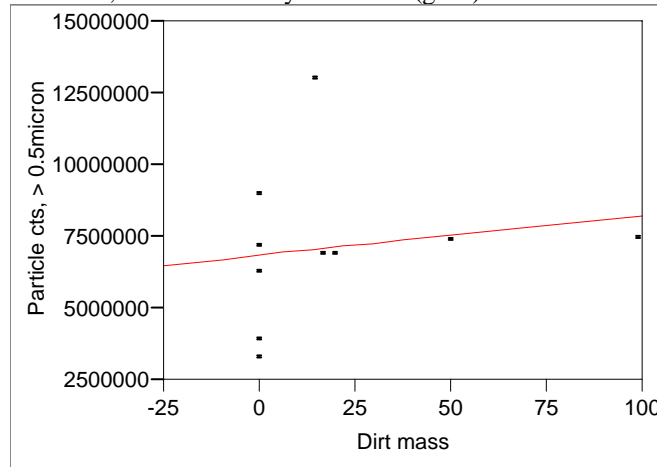
An early attempt to develop insight into surface contaminant loadings, airborne contaminants, and human health effects was by Skov and coworkers in the late 1980’s.^{61,98} Table 23 provides a few measures extracted from the “Danish Town Hall Study.” There were a few interesting observations extracted from the statistical analysis provided in the 1990 paper. Not surprisingly, because of the carrying capacity of textiles, fleece factor (fraction of textile surface) and organic dust load correlated well (0.90), and fleece factor and floor dust had a fair correlation (0.65).⁶¹ On the other hand, the correlation between airborne dust (> 10 micron) and floor dust loading was very poor (-0.02), and airborne dust (> 10 micron) and “fleece factor” did not correlate (-0.01).⁶¹

Table 23: Selected Indoor Environmental Measures from the “Danish Town Hall Study”⁹⁸

Factor	units	Mean	max	min
Airborne dust	mg/m ³	0.201	0.382	0.086
> 0.5 micron	per L	48000	119000	19000
> 2.0 micron	per L	2500	11600	800
Fungi	cfu/m ³	32	111	0
Bacteria	cfu/m ³	574	2100	120
Vacuum dust	g/12 m ²	3.67	11.56	0.32
Vacuum dust	g/12 m ²	6.14	17.04	0.66
Dust fungi	cfu/30 mg	33	90	11
Dust fungi	cfu/30 mg	32	192	6

More evidence that contaminant loadings and airborne contaminants do not typically correlate well can be seen in the work of Shaughnessy et al. with schools.⁷⁴ Although, the results were preliminary, the early indication was that the amount of soil in a carpet did not appear to translate to significantly higher airborne exposures. Figure 3 was a simple Y by X plot drawn from this data to illustrate the point.

Figure 3: Bivariate Fit of Particle cts, > 0.5 micron By Dirt mass (g/m²)^a



— Linear Fit

Data utilized from Shaughnessy et al.⁷⁴

Airborne fungi levels have been important considerations for indoor air quality. Reported exposures have been highly variable and ranged in concentration from a few cfu/m³ to several thousand. Airborne levels can be influenced by many factors. Geographic location and season appear to be major contributors.

By and large, indoor airborne fungi levels tracked outdoor levels; however, indoor concentrations were almost always lower than outdoor levels (absent an indoor source). I/O ratios for fungi were typically <0.5. By way of illustration, a survey of U.S. schools from diverse geographic settings by Levetin et al. saw wide ranges of airborne fungi levels as a function of location and season (see Table 24).⁹⁹

Table 24: Airborne Fungi Concentrations in Schools⁹⁹

School Location	Timing	Mean cfu/m ³	Range, cfu/m ³	Outdoor cfu/m ³	I/O Ratio
Kansas City, 1	Sept., 1991	494	152-1409	6267	0.08
Kansas City, 2	Sept., 1991	2100	136-4969	10196	0.21
Kansas City, 3	Sept., 1991	2087	1667-2712	5545	0.38
Kansas City, 4	Sept., 1991	1009	197-2166	8186	0.12
Spokane, 1	Dec., 1991	56	16-109	234	0.24
Spokane, 2	Dec., 1991	189	16-531	406	0.47
Spokane, 3	Dec., 1991	123	16-281	188	0.65
Santa Fe, 1	Feb., 1992	119	50-350	178	0.67
Santa Fe, 2	Feb., 1992	624	17-4134	83	7.52
Santa Fe, 3	Feb., 1992	419	150-1069	44	9.52
Santa Fe, 4	Feb., 1992	244	27-884	83	2.94
Orlando, 1	Apr., 1992	628	76-2970	3192	0.20
Orlando, 2	Apr., 1992	1756	515-6454	15761	0.11

Relatively few studies have attempted to directly compare airborne contaminants over carpet versus smooth floors. A few of these were conducted in hospital settings. For example, Bakker and Faoagali did not see significant differences of airborne bacteria between carpet and vinyl covered hospital corridors.¹⁰⁰ Anderson et al. found airborne levels of bacteria to be similar between carpet and smooth floor covered hospital rooms, despite the fact

that carpet was much more heavily contaminated per unit area.¹⁰¹ They did not see any differences in either “patient colonization” or levels of disease in the two rooms.¹⁰¹ Striefel and coworkers did report statistically significant differences in airborne fungi between carpet and non-carpet hospital wards.¹⁰² However, the differences were relatively small (see Table 25), and they reported that there were no significant differences in nosocomial fungal infections between the two wards.¹⁰²

Table 25: Hospital Study of Airborne Fungi Over Carpet Versus Smooth Floors¹⁰²

Year	N	Carpet* Ave. (std dev.)	Hard surface* Ave. (std dev.)	Ref. Hard Surface** Ave. (std dev.)	Outside Ave. (std dev.)
1995	13	14 (24)	14 (6)	73 (67)	1171 (1148)
1996	19	33 (38)	16 (19)	32 (45)	706 (986)
1997	13	43 (51)	18 (16)	22 (16)	408 (421)
1998	12	46 (27)	11 (8)	30 (24)	1131 (1293)

Although fungal spore burdens in carpet typically exceed those of hard surface floors by at least an order of magnitude, this difference does not apparently translate to increased airborne concentrations. For example, Gravensen et al. reported “higher” levels of fungi and bacteria over carpeted schools and offices; however, none of the differences was statistically significant ($p = 0.25$ and 0.09 for mold in schools and offices respectively; $p = 0.290$ and 0.155 for bacteria in schools and offices respectively).¹⁰³

In a study of offices, schools, and day-care centers considered non-problem environments by Stridh et al, the levels of particles did not appear to be a function of floor covering – day-care: $41 \pm 14 \text{ ug/m}^3$, office: $16 \pm 5 \text{ ug/m}^3$ (carpet 17, hard surface 16), and schools: $20 \pm 10 \text{ ug/m}^3$.¹⁰⁴

Norback, Torgen, and Edling in a 1990 study evaluated a variety of factors against “sick building symptoms” in six primary schools, which included two with carpet.¹⁰⁵ Unfortunately, they only reported the range of airborne respirable dust levels ($8 - 24 \text{ ug/m}^3$) and did not include data around floor loads. However, given the relative size of the range, one could infer there was no significant relationship between floor dust and airborne dust. In later work with primary schools, this organization provided slightly more data around dust and airborne contaminants.¹⁰⁶ Comparisons of data with those reported elsewhere was complicated by their choice of sampling technique, e.g., settled dust was collected from chairs and other elevated surfaces in each classroom (see Table 26).

Table 26: Contaminant Exposures in 28 school classrooms¹⁰⁶

Factor	Range
Respirable dust, ug/m^3	6 – 29
Settled dust, mg/classroom	18 – 107
Cat allergen, ng/g fine dust	<60 – 391
Dog allergen ng/g fine dust	<60 - 3990

In a recent work by Foarde and Berry, airborne contaminants over carpet in matched schools tended to be lower versus tile (see Table 27).¹⁰⁷ For $\text{PM}_{2.5}$, culturable fungi, and total spores, the differences were statistically significant. This study highlighted the value of a well executed routine building maintenance program – one that did not impose substantially higher costs on the school.

Table 27: Airborne Contaminants over Carpet and Tile Covered School Classrooms¹⁰⁷

Contaminant	Carpet [GM (GSD)]	Tile [GM (GSD)]
$\text{PM}_{2.5}$, ug/m^3 *	8.0 (1.9)	13.9 (1.4)
Dust mite antigen, ng/m^3	32.3 (2.3)	73.7 (4.4)
Cat antigen, ng/m^3	63.5 (5.4)	96.6 (6.1)
Cockroach antigen, ng/m^3	87.1 (4.2)	49.1 (3.0)
Fungi, cfu/m^3 *	50 (2.4)	160 (3.1)
Spores, spores/m^3 *	1200 (2.8)	2700 (2.1)
* $p < 0.5$		

An attempt was made in a laboratory setting by Buttner et al. to develop insight into the relationship between surface loading of a small mold spore (*Penicillium chrysogenum* – ca. 2 µm diameter) and airborne levels after a disturbance.⁷² In this work, mold spores were allowed to slowly settle on vinyl flooring, loop pile carpet, and cut pile carpet surfaces; and then each flooring was subjected to multiple one minute disturbances (brisk walk).⁷² Despite the fact the spores had settled in the upper portion of the pile, it required a loading of 80 million spores per square meter in order to see reliably quantifiable airborne levels. Interestingly, the loop carpet and the vinyl floor were very similar in release rate (ca. 0.004% of the spores aerosolized with the disturbance). Note that the vinyl was not sealed and as a result was very rough and porous at the microscopic level.⁷²

Luoma and Batterman conducted a study which explored relationships between office activities and airborne concentrations of particles, fungi, and bacteria.¹⁰⁸ They concluded occupant activities such as walking accounted for 24-55% of the variance in the 1-25µm size particle data. They further estimated that occupant activities contributed ca. 10 µg/m³ per person. Also, consistent with other work previously discussed, they saw no correlation between particles < 1 micron and indoor activities – particles in this size range did correlate well with outdoor particles. Bacteria and fungi did not vary significantly over time with regard to office activities. Unfortunately, the authors did not indicate the nature of the floor covering in this study.

As indicated earlier, loadings of dust mite allergen can range widely in dusts from carpet, upholstery, and bedding, but airborne levels do not appear to correlate. A lack of a correlation between the floor and the air was observed in work by Tovey⁵⁷, Price¹⁰⁹, and Sakaguci.^{110,111,112} In fact, about the only way mite allergen could be made airborne was via aggressive disturbances of bedding or the floor. Mite allergen was almost never detected in undisturbed rooms.⁵⁷ Even in these instances the airborne levels of mite allergen dropped quickly (a matter of minutes).^{57, 113} Although carpet has frequently been identified as a nest for dust mites, it does not appear that it plays a major role in airborne exposures. Tables 28 and 29 illustrate this point.

Table 28: Relationship Between Dust Mite Allergen Load and Airborne Allergen⁵⁷

Location	Air Undisturbed, ng (a)	Air Disturbed, ng (b)	Mean Dust Conc., ug/g
Bedroom	< 0.3 ng	7.3	45
Bedroom	< 0.3 ng	1.24	66
Bedroom	< 0.3 ng	4.7	7.5
Bedroom	< 0.3 ng	1.4	0.67
Bedroom	< 0.3 ng	30	59
Bedroom	< 0.3 ng	2.2	45
Bedroom	< 0.3 ng	8.6	7.5
Bedroom	< 0.3 ng	7.3	31
Bedroom	< 0.3 ng	9.3	41
Bedroom	< 0.3 ng	2.7	25
Bedroom	< 0.3 ng	23	19
Bedroom	< 0.3 ng	13	34
Bedroom	< 0.3 ng	0.15	0.4
Living room	< 0.3 ng	2.8	7.2
Living room	< 0.3 ng	1.9	6.8
Living room	< 0.3 ng	0.15	1.65
Living room	< 0.3 ng	0.8	21
Living room	< 0.3 ng	1.47	12

a) Sampled 2 h at 17 L/min
b) Sampled 45 min at 17 L/min

Table 29: Airborne Measurements of Dust Mite Allergen¹¹¹

Home**	Der I*, air (pg/m³)	Der I*, floor (ng/g dust)
A	49.9	651
B	104	1244
C	116	11600
D	7.6	4060
E	8.3	752
F	28.4	1450
G	19.4	2820
H	30.5	4610
I	9.7	789
J	85.1	2900

* Der I = sum Der p I, Der f I
 ** Living room measurements during normal routines

Zock and coworkers provided some additional insight into both dust and dust mite allergen loadings on carpet and hard surfaces in a Danish study (see Table 30).¹¹⁴ In essence, they concluded that carpet was not related to peak-flow variability in asthmatic children. Both the levels of recovered dust and the quantities of mite allergen were consistent with expectations.

Table 30: Comparison of Mite Allergen Levels as a Function of End Use¹¹⁴

Sample Location	ng/g	ng/m²	g/m² Dust
Living room, uncarpeted	161	9	0.056
Living room, carpeted	980	337	0.344
Bedroom, uncarpeted	154	5	0.032
Bedroom, carpeted	1663	423	0.254
Mattress	2753	594	0.216
Classroom, uncarpeted	21	3	0.143
Classroom, carpeted	35	19	0.543

In a review of several studies, which evaluated various housing factors against various respiratory symptoms, including allergy and asthma, Billings and Howard observed that increased dampness or moisture was found to correlate with increased symptom prevalence.¹¹⁵ It was suggested that the presence of water allowed amplification of dust mites, fungi, and bacteria, hence potentially increasing the allergen burden. This was also seen in a study of Canadian houses by Miller et al. in which they saw a correlation between “internal moisture strength” and health complaints.¹¹⁶ However, correlations of health effects to airborne particles or fungi did not materialize. The majority of the homes tested had particle levels of ca. 30 ug/m³ (< 15 um particles) and an average airborne fungi level of 345 cfu/m³. The most commonly encountered fungi were *Penicillium*, *Cladosporium*, and *Alternaria*. The complexities associated with the connection of health effects, airborne fungi, and dust fungi were further highlighted in a Finnish study by Hyvarinen et al.¹¹⁷ They compared 9 “mold problem buildings” with 9 “matched reference buildings” (see Table 31). They did observe airborne fungi differences between the two sets of buildings as a function of season (although some of this could have been driven by outdoor levels), but they saw no differences in the dust samples. Unfortunately, no reference was made to type floor coverings in the buildings. Similarly, Dotterud et al. found no significant differences in viable fungi in the homes (living rooms and bedrooms) of dust mite allergen sensitized children versus non-sensitized controls (58/45 – LR/BR and 31/31 – LR/BR respectively), although the homes of the sensitized population trended higher.¹¹⁸

Table 31: Comparison of Airborne Fungi in “Mold Problem” Buildings and Reference Buildings¹¹⁷

Viable fungi	Season	Problem Building	Outdoor	Reference Building	Outdoor
		GM, Range	GM, Range	GM, Range	GM, Range
Total	Fall	250, 19-7900	410, 37-11000	160, 40-580	190,37-630
<i>Penicillium</i>	Fall	31, 0-7900	14, 0-95	16, 0-72	12, 0-76
<i>Cladosproium</i>	Fall	18, 0-160	74, 11-430	20, 0-140	43, 15-160
<i>Aspergillus</i>	Fall	4, 0-76	1, 0-11	2, 0-20	2, 0-15
Total	Winter	120, 26-530	-	58, 15-220	-
<i>Penicillium</i>	Winter	38, 0-480	-	13, 0-220	-
<i>Cladosproium</i>	Winter	4, 0-28	-	5, 0-26	-
<i>Aspergillus</i>	Winter	3, 0-19	-	1, 0-5	-

Menzies et al. compared indoor environmental conditions of maximally and minimally symptomatic office workers in Montreal.¹¹⁹ They found no significant differences in airborne concentrations of mold spores or dust, and there was no significant difference between dust mite allergen loadings in the two populations. Table 32 provides a brief summary of the data.

Table 32: Comparison of Airborne and Dust Contaminants in Offices of Symptomatic Vs. Non-symptomatic Workers¹¹⁹

Contaminant	Max. Symptomatic, G.M.	Min. Symptomatic, G.M.	p Value
CFU/m ³	24.2	22.3	ns
<i>Der P I</i> , ug/g	0.86	0.89	ns
<i>Der F I</i> , ug/g	0.27	0.24	ns
Dust, ug/m ²	13.1	12.1	ns

Summary

Human exposures associated with indoor contaminants would be characterized as very complex. There were numerous factors that made this the case: a myriad of contaminants, a wide range of physical characteristics of contaminants, the influence of building systems, the impact of building occupants, the effects of occupant activities, the role of moisture, the effects of building care, and the influence of outdoor conditions.

The majority of the contaminants that accumulate on smooth floors, in carpet, and on other surfaces appear to be outdoor-sourced. Dusts and soils on flooring were mostly the result of foot traffic. The sources for dusts on elevated surfaces were more difficult to determine. However, settled dust from ambient air, particles from indoor activities, and re-suspension of dusts from floors and upholstery appeared to be able to explain much of these accumulations.

The composition of soils and dusts can be broken into two generic categories: bulk dust, which represents most of the total mass, and the trace contaminants. The bulk components of dust appear to be relatively similar worldwide: mixtures of inorganic particles, cellulosic fibers, animal dander, and high molecular weight organics (oils, resins, gums). The trace contaminants consist of potential allergens, low volatility organic compounds (pesticides, PCB's, etc.), and heavy metals. From a human health standpoint, the trace substances carry the most interest.

As expected, carpet almost always carried a higher burden of soils, dusts, and trace contaminants per unit area than smooth surfaces. For a large number of contaminants, the levels were similar on a per gram of dust basis. However, carpet dusts on average trended higher and in a few instances were statistically higher. One rationale offered was that organic substances and spores deep in the carpet pile were somewhat protected from the destructive properties of light. In a majority of the studies reviewed, the actual differences were not large and rarely exceeded a factor of two. In most cases the differences were a few percent.

Airborne was the primary route of human exposure for most contaminants of concern. Despite the fact that carpet typically carried higher burdens of contaminants than smooth surfaces, it was extremely rare to find a study that

reported a statistically significant contribution for carpet of contaminants to the air. In most of the work covered, indoor concentrations of contaminants were more frequently driven by outdoor conditions or by building occupant activities. There was no correlation between dust mite allergen loads in carpet and airborne concentrations. Cat allergen was the only allergen of interest which seemed to show a relationship between surface dust loadings (not just carpet) and air concentrations.

Most observations were not particularly surprising in light of a handful of physical considerations. For example, a couple of studies estimated that only about 1% of bulk carpet dust was available for dermal contact. Although speculative, it would not be unreasonable to expect that the contaminants re-suspended from a carpet would come from this fraction, and hence, a relatively low level source of airborne particles. There was a substantial amount of data that indicated small particles < 5 microns were not easily re-suspended. Note that this was likely a positive from the standpoint of exposure to lead (Pb), pesticides, PAH's, and PCBs, which were associated predominantly with sub-micron particles. Larger particles (> 25 microns) were not frequently observed in air because they tend to be removed more efficiently via deposition, do not become airborne easily, and settle quickly. Even though particle size fractions in the range where many allergens reside (10 to 25 microns) were more easily re-suspended than other size fractions, there were indications the percentage of available particles was still quite small. Overall, it appeared the ratio of airborne concentration of a contaminant to surface source loading ranged from 10^{-3} to 10^{-6} .

There were a few interrelated areas where additional work would be helpful in order to better understand and define the role of carpet and other floor coverings with respect to indoor exposures. The first would be to develop a more comprehensive understanding of the relationships between the physical properties of a surface and the propensity to release 10-25 micron particles with a disturbance. This would include an assessment of carpet construction variables as well. Another area of interest would be to develop a better understanding of the contaminant loading capacity of various carpets. Obviously carpets function as significant sinks for several key contaminants, so it would be very beneficial to know when the carpet begins to function as a significant source. In a somewhat related vein, a more comprehensive assessment of the "kinetics" associated with the movement of contaminants onto carpet, within carpet, and out of carpet would be anticipated to provide models, which could reliably predict human airborne exposures.

References

1. For example see "Clinical diagnosis and management of building-related illness and the sick-building syndrome" M.J. Hodgson, *Occup Med - State Of The Art Rev* 4 (4). 1989, 593; and "Building materials and indoor air quality" H. Levin, *Occup Med - State Of The Art Rev* 4 (4). 667. 1989.
2. "Evaluation of exposures to volatile organics offgassing from new carpets", R.G. Hetes, D.S. Womack, T.K. Pierson, D.F. Naugle, final report issued to EPA Environmental Criteria and Assessment Office, RTI Report Number 94U-4479-001/12-F, February, 1992.
3. "Toxicological considerations in evaluating indoor air quality and human health: impact of new carpet emissions", R.R. Dietert, A. Hedge, *Critical Reviews in Toxicology*, Vol. 26(6), 633. 1996.
4. "An approach to a more realistic cotton detergency test", H.L. Sanders, J. M. Lambert, *Journal of the American Oil Chemists Society*, vol 27, 153. 1950.
5. "Factors affecting soiling and soil hiding properties of carpets", E. Rivet, *Tufting Year Book*, 44. 1985.
6. "The soiling characteristics of textile fibers", A.S. Weatherburn, C.H. Bayley, *Textile Research Journal*, 1955, 549.
7. P.A. Floria, *Textile Research Journal*, July 641. 1955.
8. "Everyday exposure to toxic pollutants", W.R. Ott, J.W. Roberts, *Scientific American*, February, 86. 1998.
9. "Pesticides in household dust and soil: exposure pathways for children of agricultural families", N.J. Simcox, R.A. Fenske, S.A. Wolz, I.C. Lee, D.A. Kalman, *Environ. Health Perspectives*, Vol 103, 1126. 1995.

10. "Comparison of pesticides and other compounds in carpet dust samples collected from used vacuum cleaner bags and from a high-volume surface sampler," J.S. Colt, S.H. Zahn, D.E. Camann, P. Hartge, *Environmental Health Perspectives*, Vol 106, 721. 1998.
11. "Non-Occupational exposures to pesticides for residents in two cities," R.W. Whitmore, F.W. Immerman, D.E. Camann, A.E. Bond, R.G. Lewis, J.I. Schaum, *Arch. Environ. Contam. Toxicol.*, Vol 26, 47. 1994.
12. "Selected pesticide residues in house dust from farmers' homes in central new york state, USA", A.T. Lemley, A. Hedge, S.K. Obendorf, S. Hong, J. Kim, T.M. Muss, C.J. Varner, *Bull. Environ. Contam. Toxicol.*, Vol 69, 155–163, 2002.
13. "Carpet dust: an indicator of exposure at home to pesticides, PAH's, and tobacco smoke," D.E. Camann, J.D. Buckley, *Proceedings of the 6th conference of the International Society of Environmental Epidemiology and 4th Conference of the Society for Exposure Analysis*, Research Triangle Park, 1994.
14. "The behavior of pyrethroids indoors: a model study," E. Berger-Preiss, A. Preiss, K. Sielaff, M. Raabe, B. Ilgen, K. Levsen, *Indoor Air*, Vol 7, 248. 1997.
15. "Air and surface chlorpyrifos residues following residential broadcast and aerosol pesticide applications," C. Lu, R.A. Fenske, *Environmental Science & Technology*, Vol 32, 1386. 1998.
16. "Distribution of pesticides and polycyclic aromatic hydrocarbons in house dust as a function of particle size", R.G. Lewis, C.R. Fortune, R.D. Willis, D.E. Camann, J.T. Antley, *Environ Health Perspect.*, Vol 107, 721. 1999.
17. "Indoor pyrethroid exposure in homes with woolen textile floor coverings", E. Berger-Preiss, K. Levsen, G. Leng, H. Idel, D. Sugiri, U. Ranft, *International Journal of Hygiene and Environmental Health*, Vol 205, 459. 2002.
18. "Measuring Transport of lawn-applied herbicide from Turf to home: correlation of dislodgeable 2,4-D turf residues with carpet dust and carpet surface residues", M.G. Nishioka, H.M. Burkholder, M.C. Brinkman, S.M. Gordon, R.G. Lewis, *Environmental Science & Technology*, Vol 30, 3313. 1996.
19. "Distribution of 2,4-D in Floor Dust throughout Home Following Home Owner and Commercial Lawn Applications: Quantitative Effects of Children, Pets, & Shoes", M. Nishioka, H. Burkholder, M. Brinkman, R.G. Lewis, *Environmental Science & Technology*, Vol. 33, p. 1359. 1999.
20. "Chemical contaminants in house dust: occurrences and sources", J.W. Roberts, W.T. Budd, J. Chuang, R.G. Lewis, *Proceedings of Indoor Air '93*, Vol 2, 27. 1993.
21. "Monitoring methods for polycyclic aromatic hydrocarbons and their distribution in house dust and track-in soil", J.C. Chuang, P.J. Callahan, R.G. Menton, S.M. Gordon, R.G. Lewis, N.K. Wilson, *Environmental Science & Technology*, Vol 29, 494. 1995.
22. "Exposure of children to pollutants in house dust and indoor air", J.W. Roberts, P. Dickey, *Rev-Environ-Contam-Toxicol*, Vol 143, 59. 1995.
23. "Polycyclic aromatic hydrocarbons and their derivatives in indoor and outdoor air in an eight home study", J.C. Chuang, G.A. Mack, M.R. Kuhlman, N.K. Wilson, *Atmos Environ Part B Urban Atmos*, Vol 25, 369. 1991
24. "Selected organic pollutant emissions from unvented kerosene space heaters", G.W. Traynor, M.G. Apte, H.A. Sokol, J.C. Chuang, W.G. Tucker, J.L. Mumford, *Environ. Sci. Technol.*, Vol 24, 1265. 1990.

25. "Pattern of polynuclear aromatic hydrocarbons in indoor air exploratory principal component analysis", S. Mitra, N.K. Wilson, *Environ. Int.*, Vol 18, 477. 1992.
26. For example, see "Declining blood lead levels and cognitive changes in moderately lead-poisoned children", H.A. Ruff, P.E. Bijur, M. Markowitz, Y-C Ma, J.F. Rosen, *JAMA*, Vol 269, 1993, 1641; and "Environmental lead and children's intelligence. A systematic review of the epidemiological evidence." S.J. Pocock, M. Smith, P. Baghurst, *Brit. Med. J.*, Vol 309, 1189. 1994.
27. "Lead and Human Health", D.R. Juberg, C.F. Kleiman, S.C. Kwon, for the American Council on Science and Health, New York, December, 1997.
28. "Chronological trend in blood lead levels between 1976 and 1980", J.L. Annet, J.L. Pirkle, D. Makuc, J.W. Neese, D.D. Gayse, M.G. Kovar, *New Engl. J. Med.*, Vol 307, 1373. 1983.
29. "Urban lead exposures of children in Cincinnati, Ohio", S. Clark, R. Bornschein, S. Roda, B. Peace, *Chemical Speciation and Bioavailability*, Vol 3, 163. 1991.
30. "Report on the national survey of lead-based paint in housing: base report," U.S. Environmental Protection Agency, Rep. No. EPA 747-R95-003, Office of Pollution Prevention and Toxics, Washington, D.C. 1990.
31. "Comparison of two floor mat lead dust collection methods and their application in pre-1950 and new urban houses", M.R. Farfel, A.O. Orlova, P.S.J. Lees, C. Bowen, R. Elias, P.J. Ashley, J.J. Chisolm, *Environ. Sci. Technol*, Vol 35, 2078. 2001.
32. "Correlates of low-level lead exposure in urban children at 2 years of age", D. Bellinger, A. Leviton, M. Rabinowitz, H. Needleman, C. Waternaux, *Pediatrics*, Vol 77, 826. 1986.
33. "Relationship between blood lead and lead intake in two-year old urban children in the U.K.", D.J.A. Davies, I. Thorton, J.M. Watt, E.B. Culbard, P.G. Harvey, H.T. Delves, J.C. Sherlock, G.A. Smart, J.F.A. Thomas, M.J. Quinn, *Sci Total Environ*. Vol 90, 13. 1990
34. "The relationship between surface dust lead loadings on carpets and the blood lead of young children," S. Clark, S.L. Bornschein, W. Pan, W. Menrath, S. Roda, J. Grote, *Environmental Geochemistry and Health*, Vol 18, 143. 1996.
35. "Clean-up of lead in household carpet and floor dust", L. Ewers, S. Clark, W. Menrath, P. Succop, R. Bornschein, *American Industrial Hygiene Association Journal*, Vol 55, 650. 1994.
36. "Impact of home carpets on childhood lead intervention study", L-M. Yiin, P.J. Lioy, G.G. Rhoads, *Environmental Research*, Vol 92, 161. 2003.
37. "Centers for Disease Control and Prevention. Surveillance for Asthma Prevalence _ United States, 1960 – 1995", D.M. Mannino, D.M. Horna, C.A. Pertowski, A. Ashizawa, L.L. Nixon, C.A. Johnson, L.B. Ball, E. Jack, D.S. Kang, *Morbidity and Mortality Weekly Report*, Vol 47(SS-1), 1. 1998
38. "Clearing the Air: Asthma and Indoor Air Exposures", Committee on the Assessment of Asthma and Indoor Air, Division of Health Promotion and Disease Prevention, Institute of Medicine, National Academy Press, Washington, D.C., 2000.
39. "House dust in seven Danish offices", T. Schneider, S.K. Kjaergaard, L. Larsen, S. Norn, O. Jorgensen, *Atmospheric Environment*, Vol 34, 4767. 2000.
40. "Airborne allergen exposure: measurements with a novel ion charging device", N.J. Custis *, J.A. Woodfolk, J.W. Vaughan, T.A.E. Platts-Mills, *Proceedings: Indoor Air 2002*, Vol 1, 402. 2002.

41. "Prevalence of house dust mites, cat, and dog allergens in homes in one northeast American county", P. Ren, T.M. Jankun, B.P. Leaderer, *Proceedings: Indoor Air 2002*, Vol 4, 758. 2002.
42. "Dust from carpeted and smooth floors. V. cat (*Fel. d I*) and mite (*Der p I* and *Der f I*) allergen levels in school dust - demonstration of the basophil histamine release induced by dust from classrooms", T. Dybendal, S. Elsayed, *Clinical & Experimental Allergy*, vol. 22, p. 1100. 1992.
43. "Dust from carpeted and smooth floors. I. comparative measurements of antigenic and allergenic proteins in dust vacuumed from carpeted and non-carpeted classrooms in Norwegian schools", T. Dybendal, T. Hetland, H. Vik, J. Apold, S. Elsayed, *Clinical and Experimental Allergy*, Vol. 19, 217. 1989.
44. "Airborne concentrations and particle size distributions of allergens derived from domestic cats (*Felis domesticus*). Measurements using cascade impactor, liquid impinger and a two site monoclonal antibody assay for *Fel d I*." C.M Luczynska, Y. Li, M.D. Chapman, T. Platts-Mills, *American Review of Respiratory Disease*, Vol 141, 361. 1990.
45. "Defining allergens of mammalian origin." C. Schou, *Clinical and Experimental Allergy*, Vol 23(1), 7. 1993.
46. "Cat antigen in homes with and without cats may induce allergic symptoms." M.E. Bollinger, P.A. Eggleston, E. Flanagan, R.A. Wood, *Journal of Allergy and Clinical Immunology*, Vol 97, 907. 1996.
47. "Relationship of home characteristics to indoor allergen concentrations", TT Perry, Peyton A Eggleston, RA Wood, CS Rand, S Kanchanaraksa, B Merriman, 58th Annual Meeting of the American Academy of Allergy, Asthma and Immunology, 2002.
48. "Relationship between mite, cat, and dog allergens in reservoir dust and ambient air." A. Custovic, B. Simpson, A. Simpson, C. Hallam, M. Craven, A. Woodcock, *Allergy*, Vol 54, 612. 1999.
49. "Relevance of allergens from cats and dogs to asthma in the northern most province of Sweden: schools as a major site of exposure," M.S. Perzanowski, E. Ronmark, B. Nold, B. Lundback, T.A.E. Platts-Mills, *Journal of Allergy and Clinical Immunology*, Vol 103, 1018. 1999.
50. "The Particle Atlas", W.C. McCrone, J.G. Delly, Vol II, edition II, Ann Arbor Science, Ann Arbor, Michigan, 1973.
51. "The role of cockroach allergy and exposure to cockroach allergen in causing morbidity among inner city children", D.L. Rosenstreich, P. Eggleston, M. Kattan, D. Baker, R.G. Slavin, P. Gergen, H. Mitchell, K. McNiff-Mortimer, H. Lynn, D. Ownby, F. Malveaux, *The New England Journal of Medicine*, Vol 336, 1356. 1997.
52. For example see, "Short-term effect of extermination and cleaning on cockroach allergen Bla g II in settled dust," *Annals of Allergy Asthma and Immunology*, S.B. Sarpong, R. A. Wood, P.A. Eggleston, Vol 76, 257. 1996.
53. Socioeconomic status and race as risk factors for cockroach allergen exposure and sensitization in children with asthma", S.B. Sarpong, R.G. Hamilton, P.A. Eggleston, N.F. Adkinson Jr., *Journal of Allergy and Clinical Immunology*, Vol 97, 1393. 1996.
54. "Cockroach allergen (Bla g I) in school dust," S.B. Sarpong, R.A. Wood, T. Karrison, P.A. Eggleston, *Journal of Allergy and Clinical Immunology*, Vol 99, 486. 1997.
55. "Measurement and characterization of cockroach allergens detected during normal domestic activity," S.D. De Lucca, D.J.M. Taylor, T.J. O'Meara, A.S. Jones, E.R. Tovey; *Journal of Allergy and Clinical Immunology*, Vol 104, 672. 1999.

56. "Dust mite allergens and asthma. A world wide problem.", T.A.E. Platts-Mills, A.L. de Weck, *Journal of Allergy and Clinical Immunology*, Vol 83, 416. 1989.
57. "The distribution of dust mite allergen in the houses of patients with asthma.", E.R. Tovey, M.D. Chapman, C.W. wells, T.A.E. Platts-Mills, *American Review of Resp. Disease*, Vol 124, 630. 1991.
58. "Mite allergens in relation to home conditions and sensitization of asthmatic children from three climatic regions," A.K.M. Munir, B. Bjorksten, R. Einarsson, A. Ekstrand-Tobin, C. Moller, A. Warner, N.I.M. Kjellman, *Allergy*, Vol 50, 55. 1995.
59. "House dust mite allergen levels in dust from schools with smooth and carpeted classrooms", J.P. Zock, B. Brunekreef, *Clinical and Experimental Allergy*, Vol 25, 549. 1995.
60. See "Indoor Allergens: Assessing and Controlling Adverse Health Effects," A.M. Pope, R. Patterson, H. Burge, Editors; National Academy Press, Washington, D.C., 93, and references cited therein. 1993.
61. "Influence of indoor climate on the sick building syndrome in an office environment", P. Skov, O. Valbjorn, B.V. Pedersen, *Scand. J. Work Environ. Health*, Vol 16, 363. 1990.
62. "Demonstration of microorganisms and dust in schools and offices", S. Gravessen, L. Larsen, F. Gyntelberg, and P. Skov, *Allergy*, Vol 41, 520. 1986.
63. "Contaminants in residential floor dust," A. Hedge, A.A. Kline, A.T. Lemley, T. Dokuchayeva, V. Gaskins, S.K. Obendorf, *Proceedings: Indoor Air 2002*, Vol I, 998. 2002.
64. "Indoor environment characterization of a Non-problem building: assessment of cleaning effectiveness," E.C. Cole, D.L. Franke, K.E. Leese, P.D. Dulaney, K.K. Foarde, D.A. Green, R.M. Hall, RTI Report No. 95U-449-014, EPA Cooperative Agreement CR-815509-02-1, March 1994.
65. "Cleaning for improved indoor air quality: an initial assessment of the effectiveness", D.L. Franke, E.C. Cole, K.E. Leese, K.K. Foarde, M.A. Berry, *Indoor Air*, Vol 7, 41. 1997.
66. "Biologic Contaminants", Chapter by J. Seltzer in *Effects of the Indoor Environment, Occupational Medicine, State of the Art Reviews*, Vol. 10, 1; and references cited therein. 1997.
67. "Dustborne and airborne fungal propagules represent a different spectrum of fungi with differing relations to home characteristics", G.L. Chew, C. Rogers, H.A. Burge, M.L. Muilenberg, D.R. Gold, *Allergy*, Vol 58, 13. 2003.
68. "An investigation of the relationship between microbial and particulate indoor air pollution and the sick building syndrome", J. Harrison, C.A.C. Pickering, E.B. Faragher, P.K.C. Austwick, S.A. Little L. Lawton, *Respiratory Medicine*, Vol 86, 225. 1992.
69. "Aerobiology of the Indoor Environment," Chapter by H.A. Burge, in *Effects of the Indoor Environment, Occupational Medicine, State of the Art Reviews*, vol. 10, 27. 1995.
70. "Fungal Adhesion," E.B.G. Jones, *Mycological Research*, Vol 98, 961. 1992.
71. "Retention of *Aspergillus niger* spores on textiles.", B.L. Dart, and S.K. Obendorf, *Performance of Protective Clothing: Issues and Priorities for the 21st Century: Seventh Volume, ASTM STP 1386*, C.N. Nelson and N.W. Henry, Eds., American Society for Testing and Materials, West Conshohocken, PA, 251-268. 2000.
72. "Measurement of airborne fungal spore dispersal from three types of flooring materials," M.P. Buttner, P. Cruz Perez, L.D. Stetzenbach, P.G. Garrett, A.E. Luedtke, *Aerobiologia*, Vol 18, 1. 2002.

73. "Airborne particle sizes and sources found in indoor air", M.K Owen, D.S. Ensor, L.E. Sparks, *Atmospheric Environment*, Vol 26A, 2149. 1992.
74. "Preliminary study of flooring in school in the U.S.: airborne particulate exposures in carpeted vs. uncarpeted classrooms," R.J. Shaughnessy, B.Turk, S. Evans, F. Fowler, S. Casteel, S. Louie, *Proceedings: Indoor Air 2002*, Vol 1, 974. 2002.
75. Attributed to Schaefer et al., 1972 by J.W. Roberts in "Human exposure to pollutants in the floor dust of homes and offices", J.W. Roberts, W.T. Budd, M.G. Ruby, D.E. Camann, R.C. Fortmann, R.G. Lewis, L.A. Wallace, T.M. Spittler, *Journal of Exposure analysis and Environmental Epidemiology suppl.* Vol 1, 477. 1992.
76. "An intervention study of the effect of improved cleaning methods on the concentration and composition of dust", J. Kildeso, L. Tornvig, P. Skov, T. Schneider, *Indoor Air*, vol. 8, p. 12. 1998.
77. "Textile floor covering as part of indoor Environment", I.E.Dahl, S.B. Holøs, S.K. Nilsen, *Proceedings: Indoor Air 2002*, Vol I, 986. 2002.
78. "Deposition, re-suspension, and penetration of particles within a residence", T.L. Thatcher, D.W. Layton; *Atmospheric Environment*, Vol. 29, 1487. 1995.
79. "Indoor-outdoor relationships for airborne particulate matter of outdoor origin", J. Alzona, B.L. Cohen, H. Rudolph, H.N. Jow, J.O. Frohlinger, *Atmospheric Environment*, Vol 13, 55. 1979.
80. "Long-term measurements of respirable sulfates and particles inside and outside homes", J.D. Spengler, D.W. Dockery, W.A. Turner, J.M Wolfson, B.G. Ferris, Jr., *Atmospheric Environment*, Vol 15,, 23. 1981.
81. "Indoor-outdoor air pollution relations: particulate matter less than 10 um in aerodynamic diameter (PM10) in the homes of asthmatics", S.D. Colome, N.Y. Kado, P. Jaques, M. Kleinman, *Atmospheric Environment*, Vol 26A, 2173. 1992.
82. "Particulate matter in the hospital environment", L Morawska, M. Jamriska, P. Francis, *Indoor Air*, Vol 8, 285. 1998.
83. "Using time- and size-resolved particulate data to quantify indoor penetration and deposition behavior," C.M. Long, H.H. Sun, P.J. Catalano, P. Koutrakis, *Environmental Science & Technology*, Vol 35, 2089. 2001.
84. "Particle total exposure assessment methodology (PTEAM) 1990 study: method performance and data quality for personal, indoor, and outdoor monitoring", K.W. Thomas, E.D. Pellizzari, C.A. Clayton, D.A. Whitaker, R.C. Shores, J. Spengler, H. Ozkaynak, S.E. Froehlich, L.A. Wallace, *Journal of Exposure Analysis and Environmental Epidemiology*, Vol 3, 203. 1993.
85. "Personal exposure to airborne particles and metal: results from the particle team study in Riverside, California", H. Ozkaynak, J. Xue, J. Spengler, L. Wallace, E. Pellizzari, P. Jenkins, *Journal of Exposure Analysis and Environmental Epidemiology*, Vol 6, 57. 1996.
86. "Influence of different indoor activities on the indoor particulate levels in residential buildings", C. Chao, T. Tung, J. Burnett, *Indoor Built Environment*, vol. 7, 110. 1998.
87. "Mathematical modeling of indoor aerosol dynamics," W.W. Nazaroff, G.R. Cass, *Environmental Science & Technology*, Vol 23, 157. 1989.
88. "A two compartment model for determining the contribution of sources, surface deposition and re-suspension to air and surface dust concentrations levels in occupied rooms," T. Schneider, J. Kildesco, N.O. Breum, *Building and Environment*, Vol 34, 583. 1999.

89. "Indoor air pollution: effects on cultural and historic materials", N.S. Baer, P.N. Banks, *Int. J. Mus. Man. Curat.*, Vol 4, 9. 1985.
90. "Concentration and fate of airborne particles in museums," W.W. Nazaroff, L.G. Salmon, G.R. Cass, *Environmental Science & Technology*, Vol 24, 66. 1990.
91. "Characteristics of Airborne Particles Inside Southern California Museums", M. Ligocki, L. Salmon, T. Fall, M. Jones, W. Nazaroff, G. Cass, *Atmospheric Environment*, Vol. 27A, 697. 1993.
92. "The distribution of soiling by coarse particulate mater in the museum environment," Y.H. Yoon, P. Brimblecombe, *Indoor Air*, Vol 11, 232. 2001.
93. "Design and calibration of a simple instrument for measuring dust on surfaces in the indoor environment", T. Schneider, O.H. Petersen, J. Kildeso, N.B. Kloch, T. Lobner, *Indoor Air*, Vol 6, 204. 1996.
94. "Dust Build-up on Surfaces in the Indoor Environment", J. Kildeso, J. Vallarino, J. Spengler, H. Brightman, T. Schneider, *Atmospheric Environment*, vol. 33, p. 699. 1999.
95. "Textile floor covering as part of indoor environment", I.E. Dahl, S.B. Holøs, S.K. Nilsen, *Proceedings: Indoor Air 2002*, Vol I, 986. 2002.
96. "Redispersions of indoor surface contamination and its implications", E.B. Sansone in *Treatise on clean surface technology*, K.L. Mittal, editor, Plenum Publishing Corporation, 261. 1987.
97. "Risk assessment of pyrethroids following indoor use", J. Pauluhn, *Toxicology Letters*, Vol 88, 339. 1996.
98. "The sick building syndrome in the office environment: the Danish town hall study", P.Skov, O. Valbjorn, *DISG, Environment International*, Vol 13, 339. 1987.
99. "Indoor air quality in schools: exposure to fungal allergens", E. Levetin, R. Shaughnessy, E. Fisher, B. Ligman, J. Harrison, T. Brennan, *Aerobiologia*, Vol 11, 27. 1995.
100. "The effect of carpet on the number of microbes in the hospital environment", P.G. Bakker, J.L. Faoagali, *New Zealand Medical Journal*, Vol 85, 88. 1977.
101. "Carpeting in hospitals: an epidemiological evaluation", R.L. Anderson, D.C. Mackel, B.S. Stoler, G.F. Mallison, *Journal of Clinical Microbiology*, Vol 15, 408. 1982.
102. "Carpet as a source of airborne fungi in a university hospital", A.J. Streifel, M. Mazzarella, S. Kline, *Proceedings: Indoor Air 1999*, Vol 1, 285. 1999.
103. "Aerobiology of schools and public institutions - part of a study", S. Gravesen, L. Larsen, P. Skov, *Ecology of Disease*, Vol 2, 411. 1984.
104. "Total dust exposure and size distribution of air borne particles in day-care centres, schools and offices", G. Stridh, H. Andersson, B. Linder, J. Oscarsson, Ch. Sahlberg Bang, *Proceedings: Indoor Air 2002*, Vol II, 97. 2002.
105. "Volatile organic compounds, respirable dust, and personal factors related to prevalence and incidence of sick building syndrome in primary schools", D. Norback, M. Torgen, C. Edling, *British Journal of Industrial Medicine*, Vol 47, 733. 1990.
106. "Asthma among secondary schoolchildren in relation to the school environment", G. Smedje, D. Norback, C. Edling, *Clinical and Experimental Allergy*, Vol 27, 1270. 1997.

107. "A comparison of biocontaminant levels associated with hard vs. carpet floors in non-problem schools: Results of a year long study", K. Foarde, M. Berry, Proceedings: Indoor Air 2002, Vol 1, 980. 2002.
108. "Characterization of particulate emissions from occupant activities in offices", M. Luoma, S.A. Batterman, Indoor Air, Vol 11, 35. 2001.
109. "Measurements of airborne mite antigen in homes of asthmatic children", J. A. Price, I. Pollock, S.A. Little, J.L. Longbottom, J.O. Warner, Lancet Vol 336, 895. 1990.
110. "Concentrations of airborne mite allergens (*Der 1* and *Der II*) during sleep", M. Sakaguchi, S. Inouye, H. Yasueda, T. Shida, , Allergy, Vol 47, 55. 1992.
111. "Airborne cat (*Fel d I*), dog (*Can f I*), and mite (*Der I* and *Der II*) allergen levels in the homes of Japan", M. Sakaguchi, S. Inouye, T. Irie, H. Miyazawa, M. Watanabe, H. Yasueda, T. Shida, H. Nitta, M.D. Chapman, C. Schou, R.C. Aalberse, J. Allergy Clin Immunol., Vol 92, 797. 1993
112. "Measurement of allergens associated with dust mite allergy", M. Sakaguchi, S. Inouye, H. Yasueda, T. Irie, S. Yoshizawa, T. Shida, Int. Arch. Allergy Appl Immunol, Vol 90, 190. 1989.
113. "Airborne allergens associated with asthma: Particle sizes carrying dust mite and rate allergens measured with a cascade impactor", T.A.E. Platts-Mills, P.W. Heymann, J.L. Longbottom, S.R. Wilkins, Journal of Allergy and Clinical Immunology, Vol 7, 850. 1986.
114. "Peak-flow variability in asthmatic children is not related to wall-to-wall carpeting on classroom floors", P.D. Voute, J.P. Zock, B. Brunskreef, J.C. de Jongste, Allergy, Vol 49, 49. 1994.
115. "Damp housing and asthma", C.G. Billings, P. Howard, Monaldi Archives for Chest Disease, Vol 53, 43. 1998.
116. "Fungal and fungal products in some Canadian homes", J.D. Miller, A.M. Laflamme, Y. Sobal, P. Lafontaine, R. Greenhalgh, International Biodeterioration, Vol 24, 103. 1988.
117. "Characterizing mold problem buildings – concentrations and flora of viable fungi", A. Hyvarinen, T. Reponen, T. Husman, J. Ruuskanen, A. Nevalainen, Indoor Air, Vol 3, 337. 1993.
118. "Mould allergy in school children in relation to airborne fungi and residential characteristics", L.K. Dotterud, L.H. Vorland, E.S. Falk, Indoor Air, Vol 6, 71. 1996.
119. "Case-control study of microenvironmental exposures to aero-allergens as a cause of respiratory symptoms – part of the sick building syndrome (SBS) symptom complex", R. Menzies, C. Reed, F. Nunes, R. Tamblyn, J. Pasztor, P. Comtois, Y. St. Germaine, Proceedings of the ASHRAE IAQ '92 Conference, 201. 1992.