

A Systems Modeling Approach to Assessing Carpet and Environmental Risk

Michael A. Berry, Ph.D.^{ab}

ABSTRACT

From an environmental science perspective, the indoor environment, like the outdoor environment, is a system of connected compartments through which matter and energy flow. Environmental analysis and modeling can help understand the effect carpet has on indoor environmental quality and the subsequent effect on humans. To the extent possible, basic environmental science principles and kinetic equations (zero and first order) are applied in this analysis. A model is constructed using STELLA by which to apply best estimate transfer rates under different low, moderate and high activity scenarios. A basic conclusion of this assessment is that carpet, if managed effectively, contributes to a healthy indoor environment.

INTRODUCTION

The purpose of this assessment is to examine carpet in a broad, systematic manner and to conduct a benefit-risk analysis for this widely used product. The main thrust of this assessment is directed at determining, applying and explaining transfer rates of various substances to and from carpet, other flooring, and major indoor compartments and assessing the various effects of indoor environmental quality.

From an environmental science perspective, the indoor environment, like the outdoor environment, is a system of connected compartments through which matter and energy flow. The following are the major compartments in the indoor system. These compartments are connected and influence each other. Depending how effectively each of these compartments is managed, they either achieve their intended purpose or create unintended environmental conditions (hazards). A basic assumption for this assessment is that carpet can, if managed effectively, contribute to a healthy indoor environment.

Major Compartments of the Indoor Environment

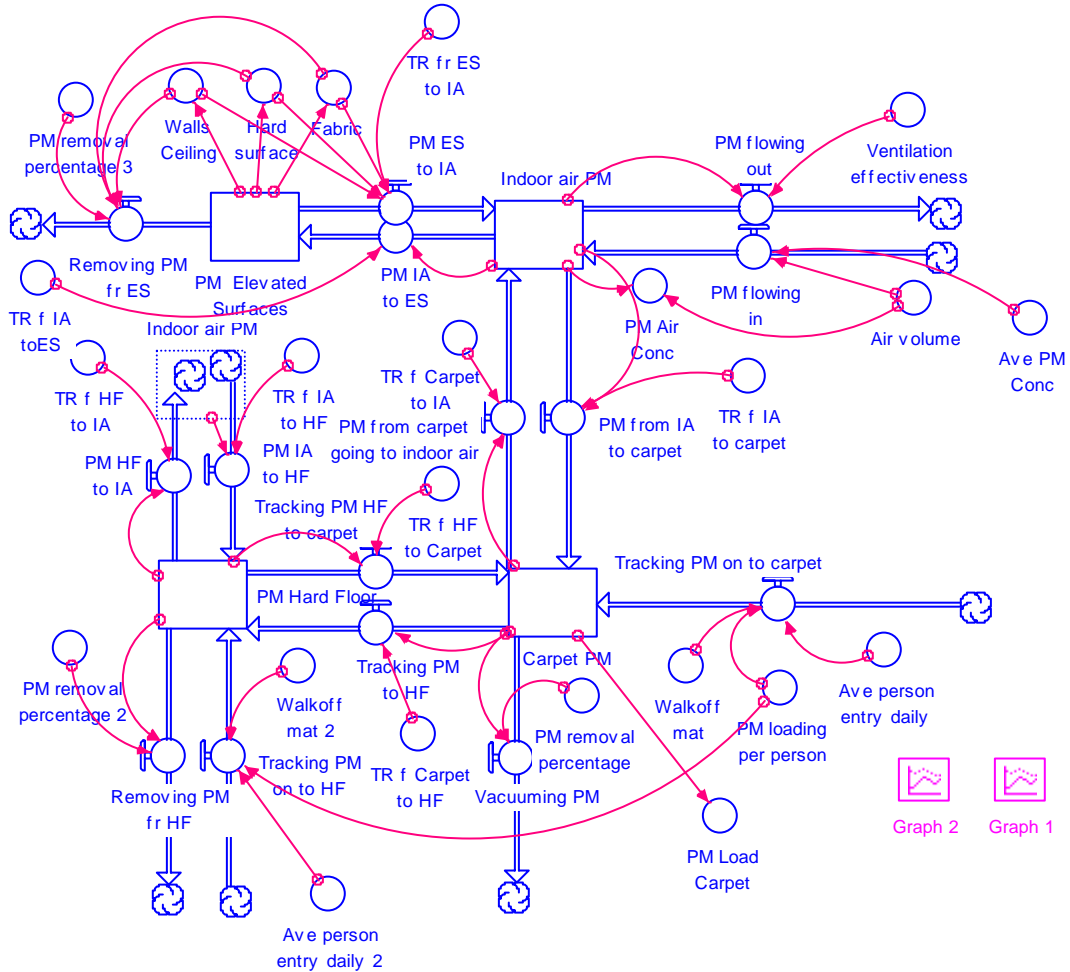
- Flooring
- Indoor Atmosphere (IAQ)
- Elevated Surfaces (Walls, Furniture, Ceilings)
- HVAC
- Extraction Systems (Cleaning, Vacuuming)

Understanding matter and energy transfer is important for assessing beneficial attributes, as well as exposure and risks associated with any single compartment. Humans respond in either a positive or a negative way to matter (substances) and energy (heat, light, vibration) that flow between compartments. Energy and matter flow can be either a benefit or a nuisance. For example, light is essential, but too much light energy can produce annoying glare, high albedo or light reflectance. Along the same lines, too much surface vibration or air displacement can create annoying noise levels.

^a Research Professor, Carolina Environmental Program, University of North Carolina at Chapel Hill.

^b Prepared August 2003.

Environmental analysis and modeling can help understand the effect carpet has on indoor environmental quality and the subsequent effect on humans. To the extent possible, basic environmental science principles and kinetic equations (zero and first order) are applied in this analysis. A model is constructed using STELLA by which to apply best estimate transfer rates under different low, moderate and high activity scenarios.



Transport

We can explain the dynamics of built environments by review of basic physics and environmental science. For example, matter is transported to and from environmental compartments four ways: gradational settling, buoyancy, carriage on currents, and diffusion.

The most basic physical attribute of every building is that gravity holds mass to the earth, e.g., dust on a shelf. (gradational settling). The denser the material, the greater the gravitational force holding it down. Matter is buoyant (floats in the air) when its density is less than the surrounding environment, for example indoor air.

Pressure and Flow

Air (fluid) flow is the result of pressure differences. Air exerts forces on matter (mass) with which it makes contact. As these forces build up inside or outside objects, they create and exert pressure. Air pressure is an important characteristic of a building that is often completely overlooked. It determines how much air (along with the matter it carries) flows in and out of a building and where it flows. Air always flows from regions of high pressure to regions of low pressure. The force of ambient air creates a positive pressure outside the building while the inside tends to be

under negative pressure. When there is negative pressure inside a building and positive pressure outside, a portion of outside air (along with the matter it carries) forces its way inside, often through cracks in the building envelope.

Under normal conditions, the lower interior region of a building is under negative pressure. As a general rule, the higher we go in a building, the more positive the inside air pressure becomes. Energy-efficient buildings are under more negative pressure than leaky buildings.

If the building is extremely tight, air has no way to flow out, unless forced out by a HVAC system. Air is contained inside along with the pollutants it carries. In most buildings, air flows into the lower region, crosses a pressure plane, and exits out the upper region. Because negative air pressure in lower floors allows pollutants to enter into the building, lower floors get a bigger dose of air pollution from the outside than upper floors would. Tight buildings also allow pollutants to build up or concentrate. Pollutants cannot flow out because of positive outside air pressure.

Zeroth and First Order Transfer

Matter transfers from an environmental compartment (carpet, shelves, indoor air, etc.) with or without dependence on the total amount of substance in the compartment at the instant of transfer. A “zeroth” order transfer is one where amount of substance leaving the compartment is not dependent on the amount of material in the compartment at the time of transfer. The amount of material in a compartment at time t is indicated by the differential equation: $dN(t)/dt = R_{in} - R_{out}$. The solution to this equation is $N(t) = N(0) + (R_{in} - R_{out}) t$ which indicates the amount of substance in the compartment at time t when the flow rate in and out of the compartment is known. This equation and solution are useful perhaps for describing cleaning effectiveness or foot traffic in and out of a building

On the other hand, a “first order” matter transfer is one where the amount of substance leaving a compartment at time t is in proportion to the amount of substance in that compartment at the time of transfer. This first order transfer is useful for describing matter deposition into carpet from indoor air and can be represented by the differential equation $dN(t)/dt = N(0) - \lambda N(t)$. The solution to this equation is $N(t) = N(0) e^{-\lambda t}$ where $\lambda = 0.693/T_{1/2}$, and $T_{1/2}$ is the half-life of the substance in the compartment. (λ is the “transfer rate constant” and is the fraction of material in the compartment that transfers during a specific time unit (second, day, year). The amount of specific material transferred to carpet from air at a particular moment is $N(t+1) - N(t)$.

Other first order equations such as $dN(t)/dt = R_{in} - \lambda N(t)$ with the solution $N(t) = R_{in} (1 - e^{-\lambda t})/\lambda$ where ($\lambda = 0.693/T_{1/2}$) are useful for describing the steady state matter retention of a substance deposited in carpet over time. This expression is sometimes called the “trickle in washout model.”

Healthy Building Objectives

There is a tendency in the contemporary discussion of carpet to focus on exaggerated risks. The benefits of carpet should not be lost in the discussion.

The purpose of every indoor environment is to provide for security, comfort, social interaction and productivity. A healthy indoor environment is one that achieves these three purposes and radiates a “sense of well-being” to inhabitants. An elevated sense of “well-being” is the basis for the human condition we call “healthy.”

Buildings are man-made barriers. Their envelope separates the inside from the outside. Indoor and outdoor environments differ primarily in that we cannot control the changing cycles outdoors. The primary reason we have buildings is so we can control the quality of what is going on inside.

Essential design elements for healthy indoor environments must at a minimum address the following:

- usable space that promotes social interaction and productivity;
- safety such as the prevention of slips and falls;
- aesthetics or a beautiful view;
- physical comfort (ergonomics);
- lighting, including the management of glare or light reflectance;
- acoustics and the management of annoying noise;

- climate control keeping the surrounding warm, cool, and dry;
- and maintaining a sanitary environment.

Carpet or Rug Contribution to a “Healthy” Environment

| Essential Environmental Design Factor | Home | Office | School | Health Care |
|---------------------------------------|---|--|--|---|
| Useful Space | Flexible, cost effective floor covers, seating and working area, additions, restored areas, basements | Auxiliary work space, flexible, rapid change cost effective, highly adaptive area enhancing. | Flexible, cost effective, primary work area, standing, sitting, laying | Enhances personal interaction compared to other floor covers |
| Safety | Stairways, nurseries, halls | Slippery, hard floor alternative | Slippery, hard floor alternative, impact reducer | Slippery, hard floor alternative especially in halls and common areas, impact reducer |
| Aesthetics | Color, patterns, decor | Corporate image | Color, inviting. Relaxing | Color soothing, energizing |
| Comfort | Softening | Softening, casual | Softening, secure | Softening, secure |
| Lighting | Low albedo | Low albedo | Low albedo especially in highly naturally lighted schools | Low albedo, stress reducing |
| Acoustics | Vibration control | Vibration controlled work environment | Noise control essential in school and not possible without carpet | Vibration control, annoyance reducing |
| Climate control | Insulator, heat sink, air resistant | Insulator, heat sink, air resistant | Insulator, heat sink, air resistant | Insulator, heat sink, air resistant |
| Maintaining Sanitation | Vacuuming | Vacuuming and Cost Effective HWE | Vacuuming and Cost Effective HWE | Vacuuming and Cost Effective HWE |

Much of a building's “healthy” psychology depends how it perceived, how it looks and feels which is mainly determined by how well it is maintained and ordered. Maintenance and cleaning cannot be separated from building design. If a building is not designed and constructed for easy and effectively maintenance, it will eventually deteriorate to a state that will oppress rather than enhance the quality of life.

Carpet is a product designed to enhance the quality of life indoors. From an environmental point of view, the desirable aspects of carpet are based on the fact that carpet is an energy absorber with a tendency to adsorb matter.

There are approximately 150 billion square feet currently installed in over 100 million buildings. About 1.2 billion square yards of carpet are installed every year. Research going back over 40 years, consistently shows (properly maintained) carpet to be a safe product as having desirable attributes. Foremost, carpet creates a sense of well-being in residences sensitive environments, such as nursing homes, hospitals and schools.

Carpet can be ranked on a scale of 1 to 10 in terms of its “essential-contribution” to key environmental design factors. The higher the ranking means that it less likely there are other cost-effective products that would do better than carpet in enhancing or contributing to or causing the essential environmental factor.

An Example of Carpet's Ranked Contribution to Environmental Factors in Different Built Environments

| Essential Environmental Factor | Home | Office | School | Health Care |
|--------------------------------|--------|--------|--------|-------------|
| Useful Space | (4-8) | (6-8) | (8-10) | (5-7) |
| Safety | (5-7) | (6-8) | (8-10) | (8-10) |
| Aesthetics | (7-10) | (6-10) | (6-8) | (7-9) |
| Comfort | (8-10) | (4-8) | (6-8) | (7-9) |
| Lighting | (6-8) | (6-8) | (8-10) | (6-8) |
| Acoustics | (5-7) | (6-10) | (8-10) | (8-10) |
| Climate control | (6-8) | (4-7) | (6-8) | (7-9) |
| Sanitation | (4-6) | (5-7) | (4-7) | (4-7) |

If clean or new carpet indoors were static, there would be a constant realization of quality of life benefits. However, carpet is a compartment in a dynamic system in which matter and energy is continuously transferred in and out. Many if not all the undesirable perceptions related to carpet originate from the fact that carpet has a strong tendency to adsorb and trap matter.

Matter and Indoor Compartments

Unwanted matter gets deposited indoors either by way of direct contact such as foot traffic or by air deposition, impact, or filtration. The source of these substances can be either inside or outside the building. All matter transfers into and out of compartments (carpet, hard floors, fabrics, HVAC) to some degree. Matter is transferred from one compartment to another by physical displacement, gradational settling, air currents (impaction, filtration), electro-attraction and direct contact (tracking).

The various substances we find moving around indoors have different shapes, sizes, chemical composition, densities, absorption, adsorption and adhesion characterizes. Heterogeneous mixtures of these solid substances (particles) are called dusts.

We measure the size of substances using the micron or micrometer unit. Micrometer (μm)=1/1,000,000 meter. A micron or micrometer size particle is about one hundred times smaller than a grain of salt. We normally lose sight of particles between 30-40 microns. We measure the mass of these substances as grams. Substances measured as concentrations in air are measured as micro-grams (millionth of a gram) per cubic meter of air ($\mu\text{g}/\text{m}^3$)

Particle counts are sometimes used to measure matter in an environmental compartment. This measure is for the most part irrelevant in that our interest is with the mass of substance and not the number of microscopic particles. In this regard, virtually all environmental health information is related to substance mass and not particle count.

Tracked Matter and Carpet

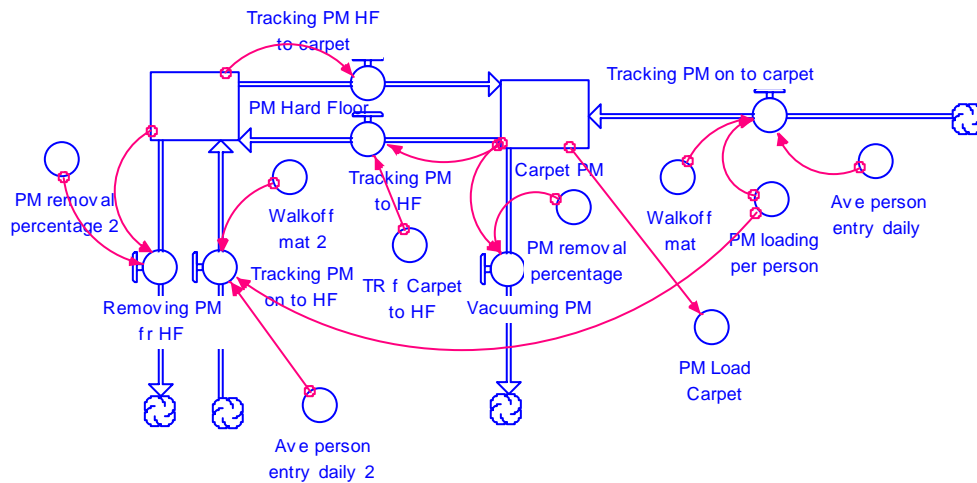
Large, dense substances such as clay, sand, oils, grass, leaves and a variety of biomass are, for the most part, tracked into a building through ground level entrances. Irregular or porous surfaces tend to collect foreign matter and hold them fast. Carpet has a large and irregular surface area and strong holding characteristics. By way of temporary containment, carpet can help control indoor pollutants. This can be referred to as the "trap effect."

Carpet dusts generally consists of 85-95% dry soil mainly tracked in from outside, which is in a size range which is for the most part $>20 \mu\text{m}$. These larger and denser particles are trapped by carpet close to entrances. Because of their large density, once in carpet they do not have a tendency to return to air.

The average surface area of a shoe=31 cm^2 so a single person as a shoe contact area of 62 cm^2 . Research has demonstrated that loading can occur in the range 500-3000 $\mu\text{g}/\text{cm}^2$ depending on matter availability. For the purpose of this analysis, three kinds of outside surfaces with different loading potentials are assumed.

| Outside Surface | Loading Potential | Person loading ug | Step 1 trans 10% ug | Step 2 cum trans 30% ug | Step 3 cum trans 50% ug | Step 4 cum trans 70% ug | Step 5 cum transfer 80% ug |
|-----------------|-------------------------|-------------------|---------------------|-------------------------|-------------------------|-------------------------|----------------------------|
| Pavement | 500 ug/cm ² | 31,000 | 3100 | 9300 | 15500 | 21700 | 24800 |
| Yard | 1000 ug/cm ² | 62,000 | 6200 | 18600 | 31000 | 43400 | 49600 |
| Bare soil | 3000 ug/cm ² | 186,000 | 18600 | 55800 | 93000 | 130200 | 148800 |

Lab studies show that 30% of loading is transferred after 2 steps and 80% of loading is transferred to carpet after 5 steps.

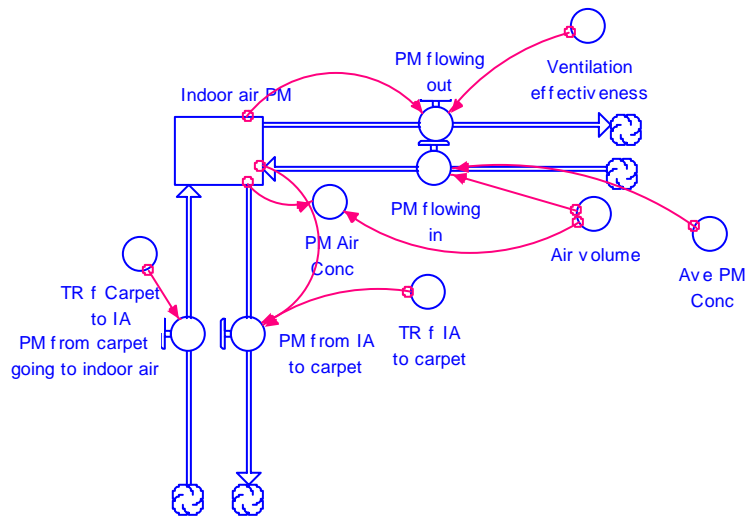


The above model segment allows us to get a sense of the particulate matter tracked into the indoor environment and tracked further onto other flooring surfaces. Walk off mats reduce the amount of matter entering flooring compartments. Cleaning systems and operations periodically remove matter from the flooring compartment.

Particulate Matter on Surfaces and in Air

Matter transferred from air to surfaces is best understood by our knowledge of particle physics and aerosol science. Primarily, particles transfer from air to surfaces through gradational settling, impaction, filtration and electrometric attraction. In general, large dense particles transfer from air to surfaces rapidly. Less dense matter transfers slowly. Matter from surface to air is primarily a function of attractive forces between the matter and surface where located. Matter with numerous contact points on a surface is more strongly attracted to the surface and require more force for displacement. The more dense matter is the less buoyant it is and more difficult to re-entrain into air.

In the absence of human activity, most indoor air matter is derived from outdoor sources. The typical background in a non-smoking indoor air environment rarely exceeds 10 micrograms per cubic meter for respirable suspended particulate matter (RSPM).



The above model segment represents the fact that IAQ is most heavily influenced by ambient air quality and ventilation effectiveness. The concentration of a substance in indoor air depends on the quantity mass of substance in a particular volume of air. IAQ is affected by carpet in proportion to the amount (mass) of transferable matter deposited in carpet at the time of transfer to air.

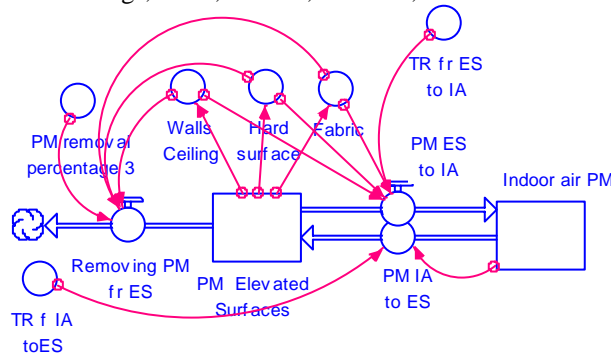
The larger and denser an airborne substance is, the faster it settles to the ground or floor through gravitational settling. For outdoor sources we tend to find larger size particles (>15 um) fall rapidly to the ground. Should they arrive indoors, they tend to become deposited in the outer regions of the building envelope such as on window sills, more than in the interior of the building.

Large size substances such as hair, skin scales and fibers generated by activities indoors tend to settle out rapidly and tend to be located in carpet near the activity area.

Outdoor atmospheric particles of size <15 um have the most influence on indoor air quality. These size particles are those that tend to be carried indoors on air currents. Small particles >1 um also eventually settle out, but less rapidly than more dense particles >15 um.

Very small particles in the <1 um range are a very large component of atmospheric dust. Should they become part of indoor air, they take a very long time to settle out, if they ever do. Should they settle or of be trapped (let us say on carpet), they are very difficult to remove and re-entrain.

Particles settle on and, depending on their shape and number of contact points, attach themselves with various attraction forces to surfaces such a ceilings, walls, shelves, air ducts, and floors .



A transfer model must recognize that flooring constitutes only about 16% of the surface area of an indoor environment. Elevated surfaces also influence IAQ but not the same large proportion as flooring. Flooring, especially carpet, holds more matter. Hard elevated surfaces such as table tops and shelves are not as strong a sink

as fabrics. Vertical surfaces tend to hold matter by means of electrostatic forces. This type of matter tends to be smaller in size and density. It takes about 10 times more energy to re-suspend matter from fabric as from a hard surface. Obviously, less matter is transferred from an elevated surface when cleaning is conducted on a regular basis.

Substance Characterization and Transfer Analysis

| Substances in Carpet | Common Origin(s) | Physical Size | Tracking transfer rate onto carpet | Air deposition rate into carpet | Transfer rate from carpet to indoor air | Transfer rate from carpet to humans/animals | Transfer rate from carpet to other compartments |
|---|--|---------------|------------------------------------|---------------------------------|---|---|---|
| Soils and PM | Litho & bio spheres | >20 um | High | Low | Low | Low | Moderate |
| Dusts | Ambient Air- Soils, plants, anthropogenic Indoor Air- Activities and breakage | 1-20 um | Moderate- High | High | Low- Moderate | Moderate | Moderate |
| Dust (fine) | Ambient Air - Natural and anthropogenic combustion Indoor Air- combustion processes (ETS) | <1 um | Low- Moderate | Low- Moderate | Low | Low | Low-Moderate |
| Toxic PM(e.g. heavy metals) | Soils/building materials | >10 um | Moderate | Low- Moderate | Low | Moderate | Moderate |
| Fibers (eg asbestos, MMMF) | Building materials | 3-20 um | Low | Low | | | |
| HC (oils) | Automotive, pavement, soils, home use products | liquid | High | N/A | N/A | Low-Moderate | Low-Moderate |
| Chemical/Pesticide | Soils outdoor and indoor applications | liquid/gas | Moderate to High | Low- Moderate | Low | Low-High | Low-Moderate |
| VOC (gas phase organic compounds) | products or services | gas | N/A | Low | Low | Low | N/A |
| Allergens | | | | | | | |
| Pollen | Outdoor plants | >15 um | Moderate- High | High | Low | Low | Moderate |
| Fungi | Decomposition indoor and outdoor | 10-30 um | Moderate- High | Moderate- High | Low- Moderate | Low | Moderate |
| (1,3 B Glucans) | Metabolites of fungi | | | | | | |
| Mite waste products | Excessive dander and moisture | 10-20 um | Low | Low | Low- Moderate | Low | Low-Moderate |
| Cockroach | Eating and | | Moderate | Low | Low- | Moderate | Moderate |

| | | | | | | | |
|--------------------------|------------------------------------|-----------|---------------|---------------|--------------|---------------|----------|
| | food disposal areas | | | | Moderate | | |
| Cat and Dog | Indoor pets | 1-10 um | Moderate-High | Moderate-High | Low-Moderate | Moderate | Moderate |
| Infectious Agents | | | | | | | |
| Bacteria | Decomposition | 0.4-10 um | High | Low | Low | Moderate-High | Moderate |
| (Endotoxin) | Products of gram negative bacteria | | | | | | |
| Viruses | Living hosts | <.0.3 um | Low | Low | Low | Low | Low |

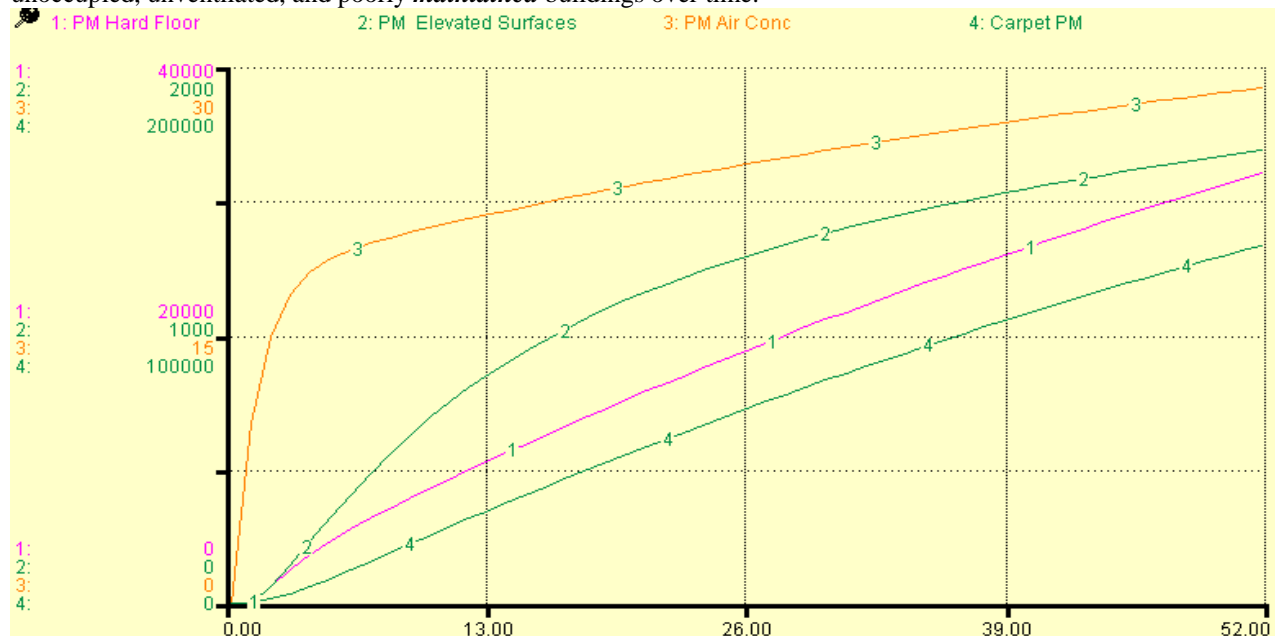
MODELING ANALYSIS

A modeling analysis of substances transferring into and out of a built environment that includes carpet suggest the following.

The quantity of matter in a compartment determines the quantity of matter transferred to another compartment, i.e., air. In any building, IAQ is influenced by outdoor air, ventilation effectiveness, and compartment (source) loading. Source loading occurs first through air deposition and subsequently by human activity in the form of tracking.

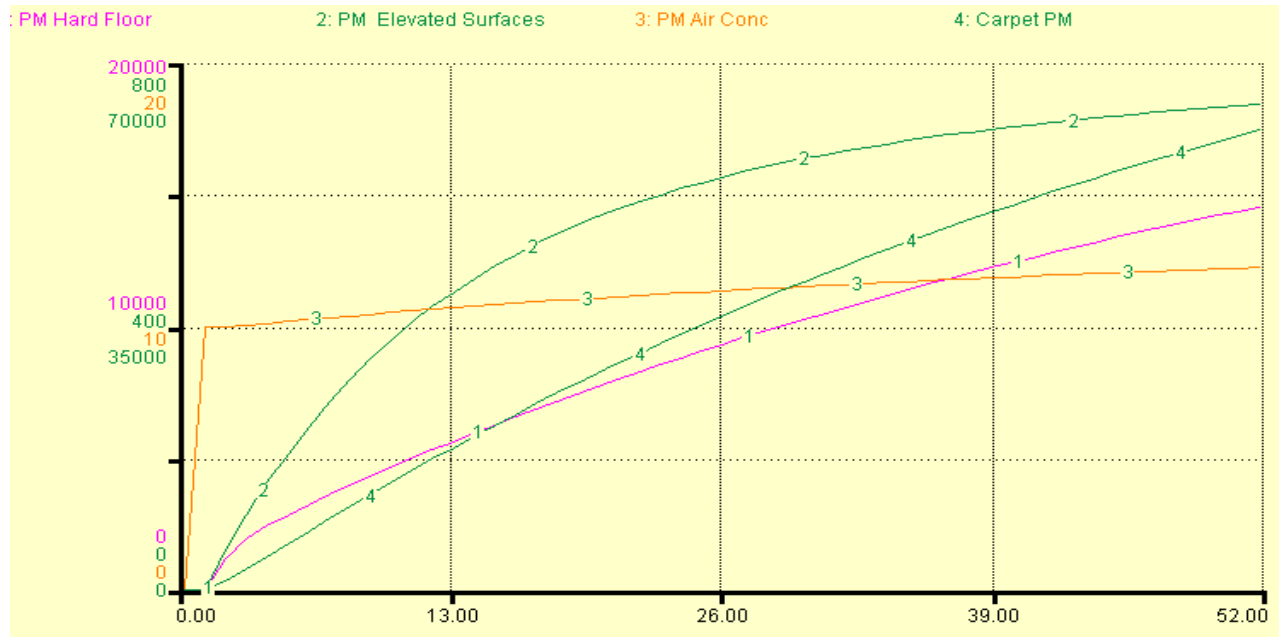
In the absence of human activity and ventilation, a condition of positive feedback exists. Sources (flooring, elevated surfaces) load with matter, and air concentrations constantly increase as matter is transferred from sources to air, depending on various transfer rates.

The graphs below show that over an extended time period (several weeks) in the absence of ventilation, particle mass continuously builds up on interior surfaces, transfers to air and degrades IAQ. Indeed, this is what happens in unoccupied, unventilated, and poorly *maintained* buildings over time.

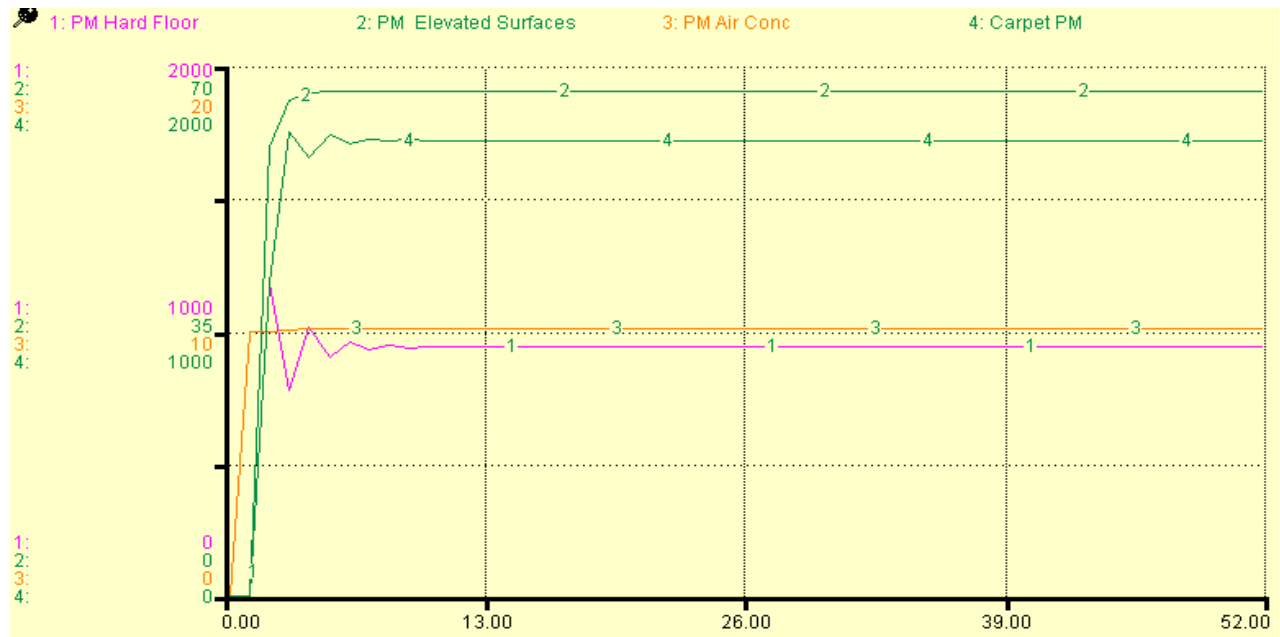


When ventilation exists, there is a tendency toward steady state air quality is achieved, even in the face of continuous compartment loading and the absence of periodic cleaning. The following graph shows that ventilation

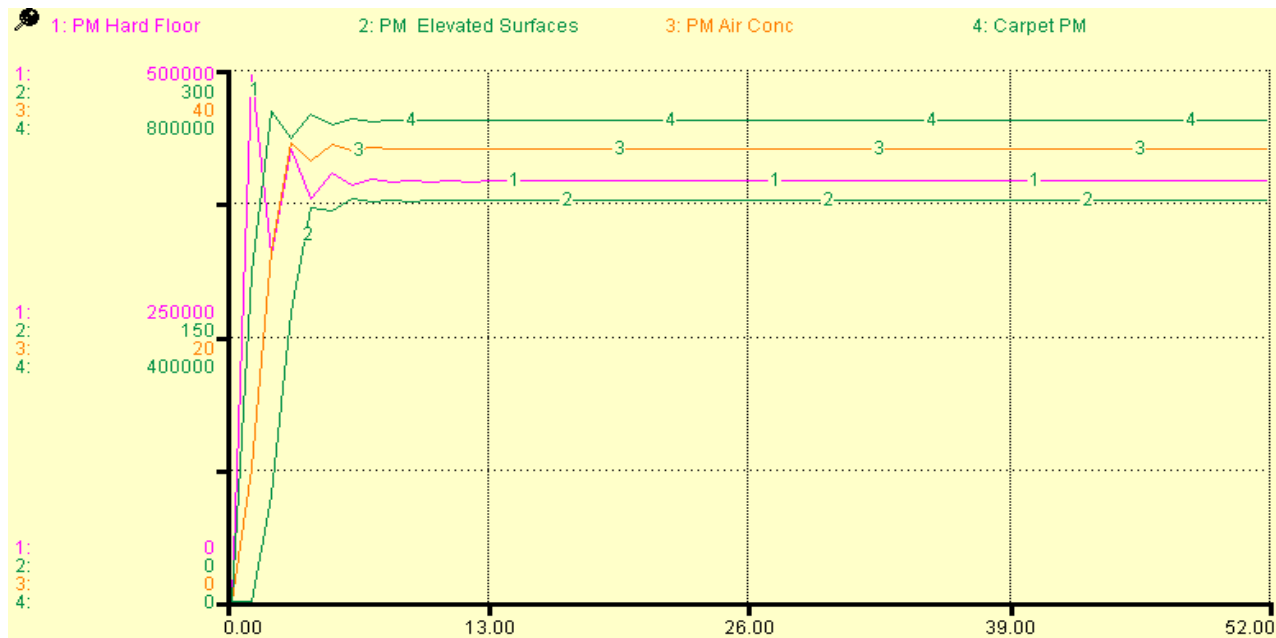
reduces the particle mass loading of compartments and surfaces and tends to keep IAQ concentrations near background levels.



Even in unoccupied buildings, a minimal amount of matter removal (cleaning) is required to bring source loading to a steady state condition. The following graph suggests that even a minimal (20%) removal of particle mass from compartments produces a steady state condition.



Carpet is a stronger receptor of matter than a transmitter of matter. When human tracking activity occurs in a building, carpet sources loading occurs to a much greater extent than with other compartments. Air quality is influenced/degraded depending on the amount of loading primarily in the carpet compartment.



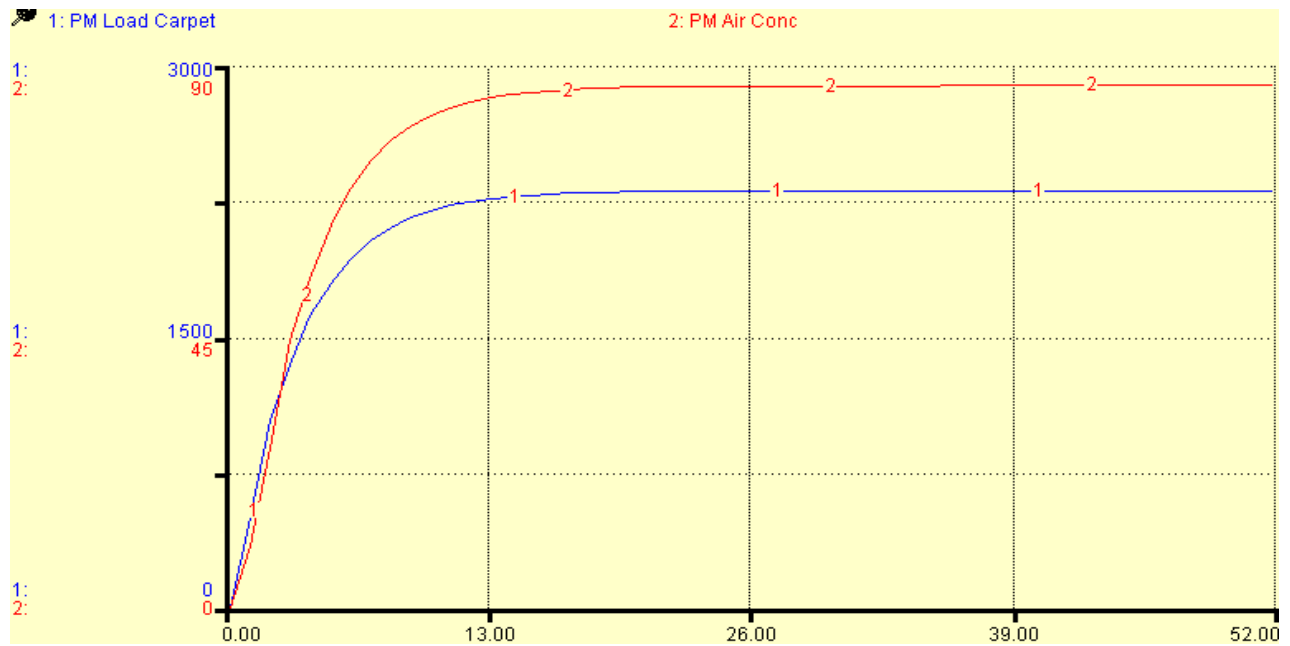
The most significant or likely air contaminants are particulate matter in the size range 1-10 μm that can be re-entrained into indoor air. Field data suggest that IAQ over carpet is adversely affected when there is high loading ($>2000 \text{ mg/m}^2$) of re-entrained matter.

Field Data Carpet Dust Loading and IAQ

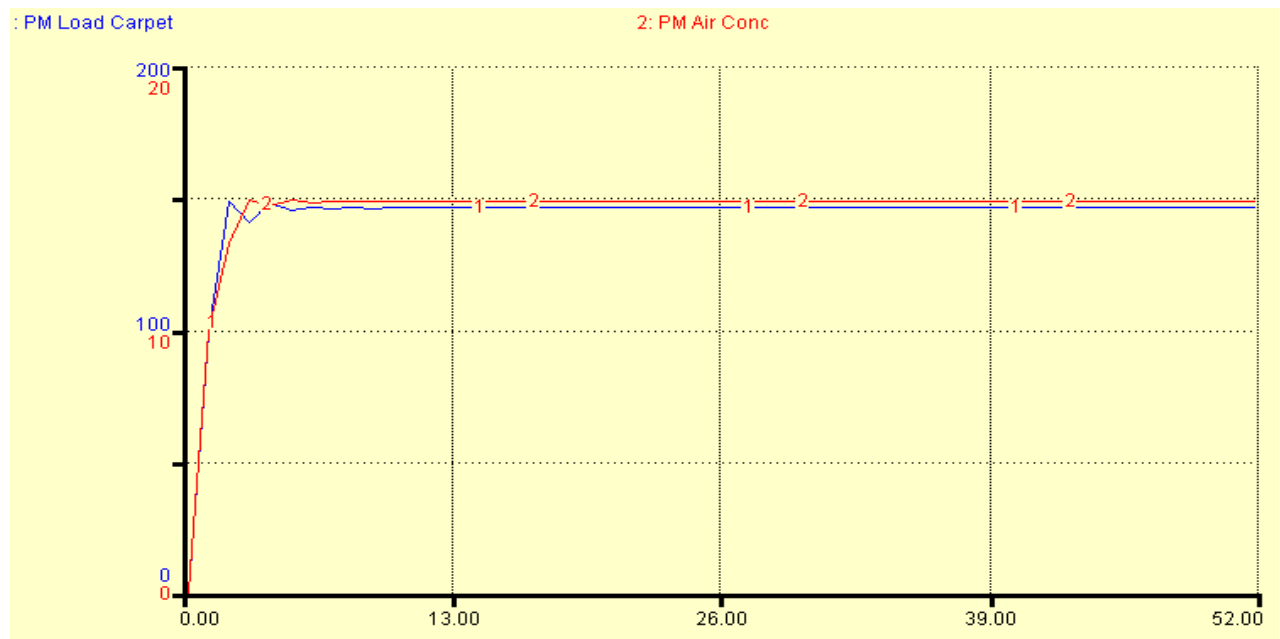
| RSPM | Outdoor AQ ug/m^3 | PM in Carpet mg/m^2 | RSP over Carpet ug/m^3 | PM on HS mg/m^2 | RSP over HS ug/m^3 |
|--------------|-------------------------------|------------------------------------|---------------------------------------|-----------------------------|-----------------------------------|
| CYS 98-99 | 35 | | 33 | | 64 |
| CYS 98-99 | 22 | | 15 | | 40 |
| CYS 98-99 | 29 | | 32 | | 40 |
| ACS 00-01 | 9.3 | 1000 mg/m^2 | 8 | | |
| ACS 01-02 | 13.2 | 400 mg/m^2 | 10.4 | | |
| DES 00-01 | 11.8 | | | 40 mg/m^2 | 13.9 |
| FPG 91-92(1) | | 1700 | 24.4 | | |
| (2) | | 2700 | 26.6 | | |
| (3) | | 200 | 6.9 | | |
| (4) | | 1600 | 3.8 | | |
| FPG 91-92(1) | | 2000 | 16.8 | | |
| (2) | | 2200 | 31.5 | | |
| (3) | | 200 | 9.9 | | |
| (4) | | 300 | 9 | | |

This observation is consistent with the first-order transfer principle (quantity of matter transfers from one compartment (carpet) to another (air) in proportion to amount of matter in the originating compartment. The

following graph indicates that a first order relation of carpet loading and IAQ suggests that excessively loaded carpet degrades IAQ well beyond background levels.



As cleaning effectiveness is applied to reduce source strength and as barriers (mitigation remedies such as activity management) are introduced, source strength is managed by way of steady state conditions and IAQ is brought into an acceptable control level.



Field demonstration research indicates that routine cost effective cleaning technologies can easily keep source strength of carpet and other surfaces at levels where IAQ will not be adversely affected. This will be discussed in following sections.

RISK ASSESSMENT

There is a perception that many of the substances found in carpet are transferred to air or directly to humans and that carpet is the *causal* source of adverse effect, for example, allergic reaction to include asthma attack. The benefits of carpet are forgotten or ignored in the face of perceived hazards.

Some common hazard perceptions include:

- “Allergen-ridden carpet triggers asthma.”
- “Carpet is a repository for carcinogens or poisons which can be inhaled or ingested by humans.”
- “Walking over carpet releases fine particles to the indoor atmosphere.”
- “VOC released from carpet triggers chemical sensitivities.”

The benefits of carpet are often abandoned by the removal of carpet based on the perception of risks and adverse effects. The following is an application of the risk assessment paradigm, using the previous discussion, to analyze possible human response to carpet in a dynamic built environment.

Risk is the probability of an adverse effect. The effect can be seen in response of a living (human, animal) receptor or damage to a valuable material. A discussion of risk from exposure to carpet must begin by assuming humans are exposed to heavily loaded carpet. A carpet free of matter poses zero risk to public health. Carpet with a loading of less than 1 gm/ m² is for all practical purposes “sanitary.” However, carpet with loading greater than 2 gm/m² is more likely to release matter to the surrounding environment, elevating exposure and risk.

As a primary source of risk, carpet has been assessed in terms of its VOC, man made mineral fiber (MMF) emissions. Carpet is also perceived as the primary habitat for living organisms: fungi, mites and bacteria.

Carpet stores a variety of hazardous substances that originate outside the carpet compartment. The primary risk concern is how much of the substance is transferred from carpet in a manner and quantity so as to adversely affect a human receptor. This suggests that carpet is primarily a “secondary” source of risk.

VOC, MMF, highly dense mineral or organic PM matter, oils (HC) and viruses do not become re-suspended (airborne) and have little probability of causing an adverse effect by way of dermal exposure. Ingestion of such substances has little potential to cause an adverse effect. Very fine particles (<1 um) do not have a tendency to become reentrained once in carpet. They are judged to be very low risk in term of carpet exposure.

There is some low to moderate risk of adverse response associated with the direct contact (dermal and subsequent ingestion) associated with useful poisons (pesticides), heavy metals, bacteria and mycotoxins (metabolites of fungi). These risks can be greatly reduced through the cleaning process.

Environmental Risk Assessment Framework—Heavily Loaded Carpet

| Substances in Heavily Loaded Carpet | Hazard Identification | Source and Transport Analysis | Exposure/Response Analysis | Human Risk Characterization (carpet exposure) |
|-------------------------------------|------------------------|---|----------------------------|---|
| Heavy soils and PM (>20 um) | Damage to materials | Tracking from outside | Minimal | N/A |
| Ambient Air Dusts (1-15 um) | Allergic response | Gravitational settling | Low-Moderate-High | Low-Moderate |
| Ambient Air Dust (fine <1 um) | Allergic response | Gravitational settling, impaction | Low | Low |
| Indoor Air Dusts (1-15 um <1 um) | Allergic response, SBS | Breakage | Low-Moderate- | Low-Moderate |
| Indoor Air Dusts (fine) | Allergic response | PIC | Low-Moderate- | Low |
| Toxic PM(e.g., heavy metals) | Cancer | Tracking from outside. Indoor settling | Ingestion-child | Low |
| Fibers (e.g., asbestos, MMMF) | Cancer | Indoor settling | Low | Low |
| HC (oils) | Damage to materials | Tracking from outside | Low-Moderate | N/A-Low |
| Chemical/Pesticide | Cancer, MCS | Tracking from outside. Indoor application | Low | Low |
| VOC (gas phase organic compounds) | SBS | Indoor emissions | Minimal | Minimal |
| Allergens | | | | |
| Pollen | Allergic reaction | Ambient air | Low | Low |
| Fungi | Allergic reaction | Ambient air | Low-Moderate | Low-Moderate |
| (1,3 B Glucans) | | Fungi marker | | |
| Mite | Allergic reaction | Indoor surfaces | Moderate | Low-Moderate |
| Cockroach | Allergic reaction | Indoor surfaces | Moderate | Low-Moderate |
| Cat and Dog | Allergic reaction | Indoor air | Moderate-High | Moderate-High |
| Infectious Agents | | | | |
| Bacteria | Infectious disease | Natural decomposition | Low-Moderate | Low-Moderate |
| (Endotoxin) | | Bacteria marker | | |
| Viruses | Infectious disease | Infected living host | Minimal | Minimal |

Some of the substances found in carpet are classified as allergens. This category of substances includes those that have the greatest potential to be reintrained to air. Entrainment potential as mentioned previously is a function of loading, i.e., the greater the loading, the more likely the entrainment.

Particles in the range >10 um are those that most cause allergic reactions. These large size particles irritate mucus membrane in the cranial cavity. The pulmonary system's natural defense mechanism usually clears the lungs of particles greater than 10 um.

The most common airborne allergens include *pollen* from trees, grasses, and weed; *molds and yeasts*, the two groups of organisms in the fungi family; *household dust* that contain a variety of spores, food particles, parts of plants and insects, dust mites and their waste products; *animal dander (saliva)* from household cats and dogs; *tobacco smoke*, and various *VOCs* (gas phase organic chemicals).

By and large these substances are allergens: fungi, mite, cockroach, cat and dog. Of these allergens, cat and dog pose the most common risk. (The good news here is that these primary sources can be kept outside)

An allergen is any substance that causes a hypersensitive reaction. In healthy humans, most allergic reactions are prevented by the immune system. However, after a significant exposure to a particular allergen, an individual who develops an allergy becomes sensitized to that allergen. Sensitization occurs when the antibody specific for the allergen attaches to the surface of the mast cells making the individual react to future exposures. Subsequent exposures cause the release of agents that interact with surrounding tissue.

The health literature indicates that respiratory allergies are triggered when an airborne allergen reaches the mucus membranes that line the inside of the cranial cavity (nose). People with allergies experience sneezing; nasal congestion; wheezing; coughing; post nasal drip; itching eyes, nose, and throat; dark circles under eyes; watering eyes; and conjunctivitis. (In very rare but severe case, allergic reactions can include feeling faint; rapid pulse; difficulty breathing; nausea and vomiting; stomach pain; hives; swelling of the lips tongue and throat; drowsiness, confusion, or loss of consciousness.)

These health effects are generally not life-threatening but detract from an overall sense of well-being and often interfere with human productivity, important in environments like offices and schools.

Most important to a proper understanding of health response to allergens is the principle, “It’s the dose that makes the poison.” We need a sufficiently high dose of allergen spores delivered to a human before we can have an effect. (Periodic vacuuming keeps concentrations of allergens at levels where they tend to not to cause reactions.)

Carpet and Environmental Risk Management

There is a widespread perception that carpet cannot be kept clean (sanitary) and that because of its inability to be kept clean, carpet contributes significantly to the deterioration of indoor environmental quality, especially unhealthy indoor air quality. This unnecessary misperception often leads to policy decisions for removing carpet from many environments such as schools, health care facilities and public agencies.

Often decisions to remove carpet as a response to ineffective cleaning deprive consumers and occupants of many desirable features provided by carpet, and simply transfers environmental problems related to cleaning breakdown to environments that do not have carpet.

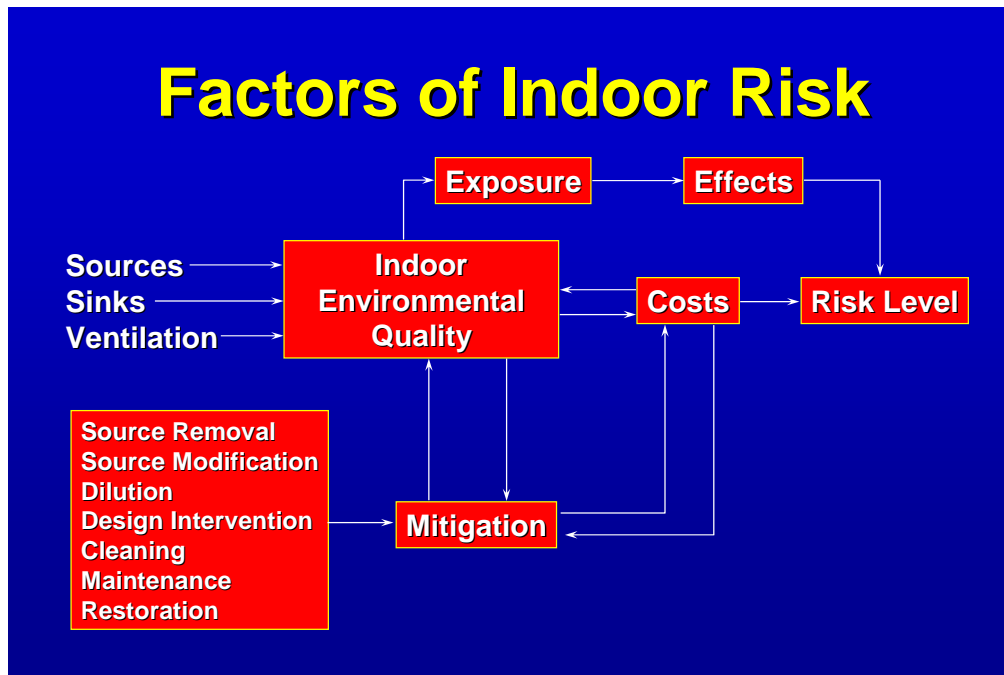
There are many reasons we clean any object, including carpet. The value of effective cleaning is magnified when we recognize cleaning accomplishes the following:

- Directly contributes to security, comfort and productivity
- Allows for the reuse of space and materials
- Maintains the value of property and reduces the rate of depreciation
- Creates a unique psychology that enhances quality of life
- Encourages topophilia (*love of place*)
- Elevates a sense of well-being which is the essence of good health
- Sends caring messages and image
- Promotes human dignity
- Accents aesthetics
- Manages waste and hazards and contributes to environmental protection
- Ensures sanitation—reduces adverse exposure levels
- Cleaning is a form of insurance that reduces risk and prevents crisis

As an environmental management tool, effective carpet cleaning must be focused on achieving specific objectives, especially those related to adverse exposure reduction, health protection and maintenance of valuable property.

Cleaning is a Management Process

Cleaning is the process of locating, identifying, containing, removing, and properly disposing of unwanted substances (mass) from a surface or environment. When cleaning occurs, exposure to unwanted substances is reduced. This in turn, reduces the probability of an unwanted effect (risk) from occurring. When the risk is acceptable, we call the environmental condition “sanitary.”



Cleaning is most protective of health when activity management, source control, design and ventilation all work together to keep concentrations of indoor pollutants -- gases, particles, and biopollutants -- at sanitary levels.

Applying the definition of cleaning in the interest of unwanted matter (mass) removal and exposure reduction, one must logically conclude that effective carpet cleaning is achieved through energy efficient processes that achieve maximum extraction and minimum residue of matter.

Carpet cleaning is a foremost a formally structured process of the following elements:

1. Unwanted substance awareness--knowing or locating unwanted substances in the carpet walk-off areas or high traffic areas, for example.
2. Identifying the nature of those substance so that the proper technology can be applied to removing them.
3. Effectively containing the unwanted substance so it can removed from the carpet and not transferred to some other indoor compartment.
4. Removing the greatest amount of unwanted mass with least amount of unwanted residue.
5. Properly disposing of that unwanted substance where it will not be a problem somewhere else.

Carpet Cleaning Effectiveness Analysis

| Substances in Carpet | Mitigation guidance | Vacuuming Effect | HW Extraction Effect |
|--------------------------|--|------------------|----------------------|
| Soils | Walk-off mat and frequent vacuuming | High | High |
| Atmospheric Dusts | Vacuuming Cleaning and Ventilation | Moderate to High | High |
| Toxic PM | Walk-off mat and frequent vacuuming | Moderate to High | High |
| Fibers | Containment | High | High |
| VOC | Ventilation | N/A | N/A |
| Chemical/Pesticide | Activity management | Low | High |
| Allergens | | | |
| Pollen | Walk-off mat and frequent vacuuming | High | High |
| Fungi | Dry, walk-off mat and frequent vacuuming | High | High |
| Mycotoxin | Dry, walk-off mat and frequent vacuuming | Moderate to High | High |
| Mite | Dry, frequent vacuuming | Moderate to High | Moderate to High |
| Cockroach | Dry, frequent vacuuming | Moderate to High | Moderate to High |
| Cat and Dog | Activity management | Moderate | Moderate to High |
| Infectious Agents | | | |
| Bacteria | Frequent cleaning | Low-Moderate | Moderate-High |
| Endotoxin | Frequent cleaning | Moderate to High | High |
| Viruses | Frequent cleaning | Low | High |

Overall, the health science literature suggests that carpet poses no risk to public health when it is clean. In addition we have a body of science over the past 15 years that help us better understand the impact of carpet and carpet cleaning activities on the quality of indoor environments, including air quality.

The Denver Study (1991)

The Denver study strongly suggests that carpet cleaning with the wet extraction method is the most effective process in reducing contaminant levels of biopollutants and particles. The "before" and "during" cleaning measurements of air pollutants show that the highest concentrations of airborne pollutants were associated with environments that were moderately to heavily soiled, cleaned infrequently, or were cleaned with methods that had excessive chemical or particle residue. This central finding in the Denver research suggests that an effective cleaning program is critical to improving or maintaining indoor air quality, even though the focus on the study was limited to carpet cleaning.

FPG Child Development Center Study (1993-1994)

The FPG data demonstrates that both indoor and ambient environment pollution are significantly controlled through an effectively managed indoor cleaning program. In the FPG study the building was nearly 70% carpeted. The study reinforces a key finding of the 1991 Denver Study that carpeted environments that are frequently vacuumed and cleaned applying the "maximum extraction and minimum residue" principle are not expected to be associated with indoor air problems.

Charles Young School Study (2001)

Maintenance of a high activity level, center city school emphasized effective vacuuming and scheduled extraction cleaning of all parts of the building including carpet. This cleaning program was found using of environmental measures to be highly effective in keeping the school building healthy. An investigation found there were no unsanitary conditions or health complaints related to the building in any way. There were no indications of IAQ problems or student or teacher health response to allergens. Data collected in the most health sensitive portions of the building found that indoor pollution levels tended to be higher over hard surfaces than over carpet.

The Anderson Creek School Study (2001-2002)

The results showed that there were significant improvements in the form of decreases in the pre- and post-cleaning levels of airborne of endotoxins (56%), β -1,3 glucan (48%), and cockroach antigen (66%). There was no difference in the airborne levels for the PM_{2.5} dust mass, dust mite and cat allergens, and culturable fungi, most probably indicating the holding strength of carpet. The extraction cleaning program resulted in reductions in the surface loading for all of the contaminants. Key to a successful cleaning program is effective extraction equipment, a system and schedule for cleaning, and the positive and proactive attitude of the custodial staff and leadership of the school and the school system.

The Air Quality Sciences Study of Carpet Cleaning (1999)

In this study, poorly maintained carpet from a high humidity/high temperature environment was cleaned and placed into a normal environment with humidity less than 65%. No mold re-growth was noted. After cleaning, test results from the previously contaminated carpet were comparable to those of a clean control carpet in terms of biocontaminants in the carpet and airborne particles.

HydroLabs Mold Study (2001)

The main conclusion of this research with respect to effective carpet cleaning is that hot water extraction method of cleaning is highly effective in reducing the likelihood of mold growth and that clean carpet does not support mold growth even at prolonged and elevated temperature and humidity levels. It was clearly demonstrated that vacuuming carpet surfaces is highly effective in reducing and managing the levels of culturable mold spore. It is conclusion for this project that for any organic material dirt plus water equals mold growth. The obvious management solution for mold indoors is to keep all carpet materials dry or at least clean.

SUMMARY AND CONCLUSIONS

Kinetic modeling is useful in understanding the influence various indoor compartments, including carpet have on one another, especially in the transfer of matter and the various concentrations of matter produced in a single compartment such as in indoor air.

Much of the challenge in assessing carpet in the context of environmental risk is to be found in developing a perspective that balances the many environmental benefits of carpet with hazards, should they be found to exist, and their effective management.

Kinetic modeling suggests that IAQ is most influenced by ventilation and cleaning practices. Models and first order relationships suggest that carpet can negatively influence IAQ when carpet is heavily loaded with matter. Tracking, not air deposition, is the primary means of loading carpet. Heavily loaded carpet has the potential to influence IAQ more than other elevated surfaces indoors because of the large amount of matter carpet is capable of holding, a small portion of which is eventually transferred to air.. So long as that matter deposited in carpet is not excessive or is managed, IAQ is not adversely affected.

Clean carpet poses no risk to public health. Carpet with a loading of less than 1 gm/ m² is for all practical purposes "sanitary." However, carpet with loading greater than 2 gm/m² is more likely to release matter to the surrounding environment and elevate exposure and risk.

For the most part, matter found in carpet poses minimal-to-low risk to humans. The size and density of matter in carpet determines exposure and risk by way of inhalation. Matter in the size range 1-15 um is the dusts most likely to re-suspend to air. These particles, some of which are allergens can be effectively managed through cleaning processes, source removal, and activity management. Toxic chemicals found in carpet can pose a slight risk through direct contact. These substances can be managed through proper usage and activity management.

Field demonstration research indicates that routine cost-effective cleaning technologies can easily keep source strength of carpet and other surfaces at levels where IAQ will not be adversely affected.

REFERENCES

1. Air Quality Sciences, Inc., Carpet Cleaning and Acceptable Indoor Air Quality: A General Review of Carpet Cleaning Effectiveness, June 1999.
2. Annual Book of ASTM Standards, "Strand Laboratory Method for Evaluation of Carpet-Embedded Dirt Removal Effectiveness of Household Vacuum Cleaners, Vol. 15.07, 1986, 376-390.
3. ASTM D 5438-94. Standard Practice for Collection of Dust from Carpeted Floors for Chemical Analyses. American Society of Testing and Materials.
4. Ayliffe GAJ, et. al, Cleaning and Disinfection of Hospital Floors, Brit Med Journal 1966, 2:442-445.
5. Berry, M.A. Assessment of Carpet in Sensitive Environments, May 2001.
6. Berry, M.A. Healthy School Environment and Enhanced Educational Performance: The Case of Charles Young Elementary School, Washington, DC, January 2002.
7. Berry, M.A. Final Report of the HydroLab Project 2001-Flooring, Humidity, and Mold Growth, March 2002.
8. Berry, M.A. The Contribution of Restoration and Effective Operation and Maintenance Programs on Indoor Environmental Quality and Educational Performance in Schools, Proceedings: Indoor Air 2002, Monterey California, July 2002.
9. Berry, Michael A. Protecting the Built Environment: Cleaning for Health for Health, Tricomm 21st Press, Chapel Hill, N.C. pg. 185. 1993.
10. Berry, Michael A., Carpet and High Performance Schools, January 2003.
11. Berry, Michael A., Dennis A. Rondinelli, *When Business and Government Clash: Crisis Management in The Carpet Industry*, Publication Series, Kenan Institute of Private Enterprise, University of North Carolina at Chapel Hill, 1998, Journal of Quality Management, Summer 2000.
12. Bishop, L. J. More Answers Than You Have Questions About Carpet Cleaning, Vols. 1 & 2. Dothan, AL: Clean Care Seminars, 1991.
13. Canadian Facility Management & Design, "When Clean is Not Green," April 2002.
14. Cole, E, et al. Indoor Air Quality Monitoring in Carpeted Environments. March 1992.
15. Foarde, K. Franke, D. RTI, Research Triangle Park, NC, Berry, Michael A., University of North Carolina at Chapel Hill, Cleaning Effectiveness Demonstration in a Carpet School, November 2002.
16. Foarde, Karin, M Berry, A Comparison of Biocontaminant Levels Associated with Hard vs. Carpet Floors in Non-problem Schools: Results of a Year Long Study, Proceedings: Indoor Air 2002, Monterey California, July 2002.
17. Food and Drug Administration, Center for Biologics Evaluation and Research. *Methods of the Allergenic Products Testing Laboratory*. [Docket No. 94N-0012]. Federal Register 1994; 59 (No. 225); 60362-3.
18. Franke, Deborah L., et. al., Cleaning for Improved Indoor Air Quality: An Initial Assessment of Effectiveness, Indoor Air, The International Society of Indoor Air Quality and Climate, Vol 7: 41-54, 1997.
19. Greene VW, Microbiological Contamination Control In Hospitals, Hospitals JAHA 1969, 43:78-88
20. Gschwandtner, Gerhard, Dennis Sanders, Michael A. Berry, Measurements of Indoor Particulate Pollution from Household Vacuum Cleaning, paper presented at the 82nd Annual Meeting of the Air and Waste Management Association, Anaheim California, June 25-30, 1989.
21. IICRC Carpet Cleaning Standard, S001-1991. Standard Reference Guide for Professional On Location Cleaning of Installed Textile Floor Covering Materials. Vancouver, WA: International Institute of Cleaning and Restoration Certification, 1991.
22. Indoor Air Quality Monitoring in Carped Environments, Environmental Criteria and Assessment Office, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1992.

23. Indoor Environment Characterization of a Non-Problem Building: Assessment of Cleaning Effectiveness, Environmental Criteria and Assessment Office, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1994.
24. Institute of Medicine, Indoor Allergens Assessing and Controlling Adverse Health Effects, National Academy Press, Washington D.C., 1993.
25. Lee R., The Advantages of Carpets In Mental Hospitals, Ment Hospital 1965, 16:324-325
26. Leese, K.E., Hall, R.M., Cole, E.C., Foarde, K.K., and Berry, M.A. 1993 Using a High-volume, Small Surface Sampler (HVS3) for the Microbiological Evaluation of Dust from Carpeted and Non-carpeted Surfaces. Proc. of the U.S. EPA/Air and Waste Management Association Measurement of Toxic and Related Air Pollutants Conference, Durham, NC 82-87.
27. Lefcoe, N.M. I.I. Incult, Archieve Environmental Health Vol 22, pages 230-238 (1971)
28. Lefcoe, N.M. I.I. Incult, Archieve Environmental Health Vol 30, pages 565-570 (1975)
29. Maki DG, Alvarado CJ, Hassemer CA, Zilz MA, Relation of The Inanimate Hospital Environment to Endemic Nosocomial Infection, N England J Medican 1982, #07:1562-1566.
30. Reist. P.C., Introduction to Aerosol Science, New York, NY, Macmillian Publishing Company, pafes 52-54.
31. Roberts, J.W., Budd, W.T., Ruby, M.G. Stamper, V. R., Camann, D. E., Fortman, R. C., Sheldon, L.S. and Lewis, R. G. A Small High Volume Surface Sampler HVS3 for Pesticides and Other Toxic Substances in House Dust. Paper No. 91-150.2. 84th Annual Meeting, Air and Waste Management Association, Vancouver British Colombbia June 16-21, 1991.
32. Shaffer J, Key I, The Microbiological Effects of Carpeting On the Hospital Environment, Hospitals JAHA 1966, 30:293-300.
33. Simmons D, et.al, Considering Carpets in Hospital Use, Dimensions 1982, June:18-21
34. Skoutelis AT, et. al, Hospital Carpeting and Epidemiology of *Clostridium difficile*, American Journal Infection Control 1993; 22:212-217.
35. Sly, R.M, S.H. Josephs, and D.M. Eby, Annuals of Alergy, Vol 54, pages 209-212, 1985.
36. Smith, D.D., R.P. Donovan, D.s. Ensor, and L.E. Sparks, Quantification of Particle Emission Rates from Vacuum Cleaners, The Fifth International Conference on Indoor Air Quality and Climate, Toronto, Canada, pp 647-652, 1990.
37. Spaulding EH, Role of Chemical Disinfection In the Prevention of Nosocomial Infections. In: Proceedings of the International Conference of Nosocomial Infections, 1970, Brachman PS, Eickoff TC, eds, Chicago, Il, American Hospital Association 1971; p. 247-254.
38. Spivak, Dr. Steven, University of Maryland - A Preliminary Assessment of Indoor Air Quality Issues Related to Textile Furnishing and their Professional Cleaning, literature review for USEPA, 1989
39. Turiel, Issac. Indoor Air Quality and Human Health. Stanford: Stanford UP, 1985.
40. U.S. Environmental Protection Agency, Indoor Environment Characterization of a Non-Problem Building: Assessment of Cleaning Effectiveness, 1994.