CONTROLLING VOLATILE ORGANIC COMPOUND EMISSIONS FROM BUILDING MATERIALS IMPROVES INDOOR AIR QUALITY

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ABSTRACT

Building materials are often sources of volatile organic compounds (VOCs) that pollute indoor air. Occupant exposure to these pollutants can result in eye, skin and throat irritation, headaches, nausea, and other symptoms of Sick Building Syndrome (SBS). Risk assessments suggest that exposure to VOCs commonly found in indoor air can present risks of cancer of the same magnitude as those posed by radon and environmental tobacco smoke. Many professionals and scientists are attempting to identify low-emitting building materials during building design. Others need to model indoor air quality (IAQ) for problem building investigations or for research. Manufacturers improve their products' performance using such modeling. These efforts focus on volatile organic compound (VOC) emissions from building materials. A step-wise procedure for the use of IAQ modeling may ultimately improve building performance. A procedure is described and its important steps are illustrated in this paper. Reasonably accurate estimates can be made based on careful use of available data. Barriers to reliable use of modeling include insufficient data characterizing emissions from many important indoor pollutant sources.

INTRODUCTION

Efforts to select low-emitting building materials during design or to model indoor air quality (IAQ) often focus on volatile organic compound (VOC) emissions from building materials and products (1-3). Methodologies involving modeling can be used to estimate air concentrations for design, investigations, or other applications (4). This paper outlines procedures to develop such estimates that perform reasonably well when compared to measured air concentrations. A systematic approach to evaluating the contributions of VOCs to total lifetime occupant exposure must consider the total mass and area of each material present, the emission characteristics of the embodied VOCs, its maintenance requirements, and its life cycle characteristics. Based on these considerations, some materials are far more important than others, with orders of magnitude more mass, surface area, or emission factors. Other materials will give rise to larger emissions from chemicals applied to clean, maintain, or renew their surfaces during their lifetimes (4).

METHODS

A step-wise procedure is used including the followed steps
1. Identify materials used in the building
2. Estimate quantities for area and mass of materials used

3. Determine prevalence and select modeling target materials
4. Determine materials' constituents and composition
5. Determine emission characteristics of materials
6. Determine time period to be modeled
7. Determine ventilation rates and scheduling for building, model
8. Select emission factors and decay rates
9. Select model equations and run model
10. Evaluate model performance

1. Identify materials to be modeled

Information is obtained from various sources including architects, engineers, contractors, and product manufacturers. Plans and specifications for the buildings are used to determine the type and quantities of materials used. There often are hundreds of products used including multiple types of many product classes. For example, it is not unusual to have from three to eight (or more) different types of paints used in a building and more than five adhesives.

2. Quantitative estimates of area and mass of materials

Quantity "take-offs" are made in the normal manner for construction materials list preparation or construction cost estimation. This involves measurements from plans and calculation of surface areas or lengths of materials. In some cases, where available, construction cost estimator's quantitative take-offs are used. Quantities of different materials used in buildings vary greatly. Floor, wall, and ceiling surfaces are the most dominant exposed surfaces inside the building. Furnishings such as open office systems furniture (work stations), drapery, seating, and bedding can also be important. Concealed surfaces exposed to circulating air must also be considered. These include spaces above suspended ceilings or inside structural assemblies like walls and floors. All surfaces exposed to circulating air should be included in area calculations.

3. Prevalence determinations and selection of model targets

Analysis of dominance can be useful in reducing the number of products modeled based on prevalence determinations. These determinations are made based on both area (m^2) and mass (g) of the materials, and they are compared as loading ratios to the volumes of the spaces in which they occur. Manufacturers' product data sheets are used to determine product density (mass per unit volume), application rates, installation procedures, drying or cure times, and other relevant characteristics necessary for estimating emissions. Areas or lengths and product densities are used to calculate mass per unit area (g/m^2) or length (g/m). These values are necessary for calculations of emission rates (mg/h) used in modeling concentrations resulting from a particular source. Experience indicates that there is a very wide range ($> 10^5$) of prevalence of materials in any building and that there are also large variations among buildings (5). After consideration of emission characteristics with respect to quantity and known human response (odor, irritation, toxicity), the number of materials to be modeled should be reduced to a few considered most important.

For both adhesives and wet surface coatings, there is a large potential variation in the quantities applied depending on the application tools chosen, the substrate surface characteristics, water activity or moisture at and near the surface of the substrate, and the installer's technique. Estimates solicited from knowledgeable individuals indicate large uncertainties accompany these numbers. These sources are important due to the large organic chemical solvent content of wet products (often 25 to 55%) and the large quantities of these materials used. Where organic solvents are used, there are also important indoor air quality implications. There is a trend currently toward reduced quantities of solvents in these products due to regulatory requirements and increasing manufacturer awareness.

4. Identify material constituents

Identification of material or product constituents is made from various sources. In the US, Material Safety Data Sheets (MSDSs) are prepared for each product under requirements of the Occupational Safety and Health Administration (OSHA) http://www.osha.gov. These sheets often list most of the major components although only regulated or listed hazardous materials are required to be shown. Constituents present at less than 1% of the total mass are not required to be listed and are often omitted. These may include biocides and other toxic chemicals. Additional information is requested from manufacturers' technical staff regarding detailed chemical contents of the products and estimated drying or cure times for "wet-applied" products. Cooperation by such individuals is highly variable but is improving as such information requests become more frequent.

5. Emission characteristics of materials

Products can be classified according to the rate at which their emissions decay (slow, fast) and the type of mass transfer processes governing emissions (diffusion- or evaporation-limited). The most difficult and one of the most critical steps in the process is quantification of the emission profiles of the materials. Tests have been conducted for only a small fraction of all products. Tests results are not necessarily comparable due to variations in test methods, conditions, and laboratory performance. Product formulations and manufacturing processes vary, both intentionally and otherwise, often without re-labeling products. Secondary emissions (sink effects) should be considered since they contribute significantly to indoor concentrations (6, 7).

6. Determine time period to be modeled

Often ignored, the timing (in the life of the material) of the emissions modeling (and of any emissions testing) is critical due to the emissions decay process (8). Explicit assumptions must be made about environmental conditions, exposure, and length of time from manufacture to time period of interest.

7. Determine ventilation rates and scheduling for building, model

Ventilation rates in buildings are highly variable among buildings and over time within buildings (9, 10). Therefore, it is important to determine accurately the ventilation rate of the building both while mechanical ventilation systems operate and when they are off. Buildings generally exchange air with the outdoors through leaks in the envelope, and outdoor weather affects the rate of this exchange (9).

8. Select emission factors and decay rates

Emission factors are based on measurements reported in the literature for similar products of similar age with corrections for environmental conditions as necessary (1,4). There are, among similar products, large variations in emissions, often up to an order of magnitude, occasionally up to two orders of magnitude (4, 8, 11) Therefore, it is important to carefully identify the product being modeled and the product(s) for which emissions test data are available, and to achieve as close a match as possible (12). Differences in nomenclature used within and among countries contribute to considerable confusion and mistaken assumptions of the appropriateness of reported test results. Where large uncertainty accompanies the available emission factors for products, assumptions must be made to enable estimation. These assumptions should include exponential emission decay rates within a mass-balance approach.

Large uncertainty accompanies emission factors for wet-applied products (13). This is important because wet-applied products are often dominant emission sources, at least early in the products' useful lifetimes. Some materials also continue emitting for very long periods of time (14). Important factors include product chemical composition, application thickness, substrate properties, and environmental conditions. Variations among these factors in actual building installations suggest that emissions test data must be interpreted carefully before emissions factors are chosen for use in modeling. As paints or adhesives dry, a skin-like layer may form over the outer surface producing a barrier to migration of vapors from the deeper layers into the adjacent air. Thus, a multi-stage process may occur. When wet products are applied to absorbent substrates such as concrete, wood, and gypsum board, significant absorption may occur onto the substrate creating yet another stage of delayed vapor transfer from the materials to the air. Paint film thickness was identified as an important factor capable of significantly affecting emission rates (13). Sealants applied to composite wood products inhibit formaldehyde emissions thereby showing the efficacy of barriers to emissions.

In the case of emissions from adhesives that are covered by another product shortly after application, emissions from the adhesive must travel through the covering material. The resistance to diffusion through the covering (flooring, wallpaper, etc.) will be an extremely important determinant of emissions once the covering is installed. Emissions occurring before installation of the covering will be large but may vary quite widely due to the factors identified above. In the case of adhesives, applications consist of fairly thick layers compared with paints or other architectural coatings. Several sub-layers may actually form in the adhesive as in the paints.

For paints, assumptions are made regarding the amount emitted during the initial burst (normal drying period), ~ 4 h to 168 h. The time was determined by discussions with manufacturers and other knowledgeable parties. A rough estimate of the mass emitted as a fraction of the volatile content can be obtained by assuming the initial burst to account for ~25% - 50% of total lifetime emissions. After the initial burst, it may be reasonably assumed that 90% of the available remaining volatile mass would be emitted in the next two hundred hours, after that, 90% of the remainder in the next two thousand hours, and so forth. While such estimates are not presumed to be precise, they are accurate within an order of magnitude or better after the initial drying occurs. Thus, unless it is necessary to estimate exposure during the initial drying period, estimates made this way may achieve acceptable accuracy.

9. Select model equations and run model

Emission factors are used together with information on test chamber and building environmental conditions to estimate quasi-steady state concentrations using equations in Reference (15). Several PC-based models are available with a range of complexity and sophistication (16-18) Or, a simple model can be developed from the equations in reference (15) and run in a spreadsheet program.

10. Evaluate model performance

Model results can be compared to concentration measurements in actual buildings to evaluate model performance. A detailed approach to evaluate the correspondence between predicted and measured values is described in reference (19).

STEP-BY-STEP PROCESS TO SELECT PRODUCTS BASED ON VOC EMISSIONS

Follow the steps outlined below to evaluate products and materials.

1. ***Obtain information on the chemical contents and emissions of IAQ Target Materials***
   - Request information from product manufacturers. Use products only from those manufacturers who provide the requested data.
   - Have product data sheets and volatile organic chemical (VOC) emissions tests been provided for dry products such as composite wood products?
   - Have chemical contents lists been requested of manufacturers of wet products?
   - Have all major "target" products been reviewed for their chemical contents and potential emissions?
   - Can any of the "wet" products be eliminated or their use reduced?
   - Can installation of necessary "wet" products occur with temporary or permanent ventilation system operation?
   - Will there be extensive use of composite wood products? If so, have low-emitting products been selected?

- Are composite wood products sealed, laminated, or otherwise isolated from indoor air?
- Is carpet specified? If so, is it required to meet the Carpet and Rug Institute's Green Label criteria? Can carpet be eliminated in any cases of its use?"

2. ***Obtain Information on Cleaning and Maintenance (C&M) Requirements:***
   - Request product manufacturers' instructions or guidelines on cleaning and maintenance of the major surface area materials (floors, walls, ceilings).
   - Identify chemical products required and obtain chemical composition of these products.
   - Include these C&M products in the assessment of emissions below.

3. ***Review chemical data for presence of strong odorants, irritants, acute toxins, and genetic toxins.***
   - Use standard references (examples include Sax, NIOSH RTECS, EPA IRIS, California OEHHA, ACGIH TLVs, OSHA PELs, etc.) to determine status of chemicals that will be emitted at significant rates (to be defined). Useful information is available from http://www.chemfinder.com/. There are listings on that site for a very large number of government and other databases and information sources on chemical properties including odor, irritation, and toxicity. Information on over 600 common chemicals is also available from EPA's Integrated Risk Information Service database (IRIS) on the web at http://www.epa.gov/ngispgm3/iris/.

4. ***Calculate Concentrations of Dominant Emissions:***
   - Use basic indoor air model to calculate emissions of worst case chemicals at 24 hours and 30 days. (Such a model is available at no cost from EPA's web site http://www.epa.gov/iaq/iaqinfo.html#IAQINFO or by contacting Sparks.Les@epa.gov.
   - Another IAQ model (CONTAM) is available from the National Institute for Standards and Technology (NIST). www.bfrl.nist.gov/863/contam.
   - Compare various sources and focus on those with the largest impact on IAQ.

5. ***Evaluate Calculated Concentrations and Total Potential Emissions Against Criteria:***
   - Use the following sources for criteria concentrations:
   - ❑ Odor – Devos et al, 1990 – Mutiply threshold by factor of 2.
   - ❑ Irritation – ACGIH TLVs for current year for irritants only; divide TLV by 40.
   - ❑ Cancer – Use latest lists from NTP, IARC, EPA, and CalOEHHA. Exclude known carcinogens, using concentration or total potential emissions criteria to be established by City of Oakland.
   - ❑ Toxicity – Use CalOEHHA, IRIS, and the Danish National Institute of Occupational Health VOCBase lists.
     http://www.oehha.ca.gov/air/chronic_rels/AllChrels.html
     http://www.epa.gov/iris/subst/index.html
     http://www.ami.dk/english/index.html

6 ***Assess total Potential Emissions:*** (Alternative to steps 4 and 5 above)

- Multiply mass present in the product times the vapor pressure for chemicals to get a dimensionless number. Multiply this number by the reciprocal of 1/40 TLV. Select from among the candidate products the one(s) with the lowest ratio. Note: this is an alternative method for comparing products when emissions data are unavailable, but it is not a true substitute for the detailed process outlined above.

Select Products and write installation specifications. For selected products, write specification for acquisition, storage, transport, handling, and installation.
Acquisition: This should include criteria used for selection in the specification
Storage: Ensure storage includes moisture and dust protection, adequate ventilation, absence of direct sunlight, moderate temperatures (freeze protection) and relative humidity.
Transport: should include same criteria as storage.
Handling: Protection against mechanical damage or chemical contamination.
Installation: Specify the installation of no greater quantity of wet products (paints, adhesives, caulks, sealants, surface preparation materials, etc.) than that required for the application and use of the product or material in question.
Ventilation: For all "wet" products and major floor covering products, specify no less than 3 air changes per hour during the installation and for 72 hours afterwards.

Determine indoor air implications of removal and replacement processes
Ultimately, surface materials will need to be replaced, and their removal and replacement can be a very large source of indoor air pollution. This should be evaluated when products are originally selected.

Specify construction practices
Temporary ventilation can reduce adsorption on surfaces and subsequent re-emission of contaminants from building products. Construction filters should be specified and changed before occupancy. Moisture protection for porous materials can reduce microbial growth when materials are installed. Moistened materials should be removed and replaced at the contractor's expense. Proper clean-up of exposed and concealed surfaces exposed to circulating air should be completed before initial occupancy. Indoor air quality can be improved by limiting fleecy and porous materials and by isolating them from high VOC concentrations and particles during construction. Specify finish construction installation practices including adequate ventilation (special temporary if necessary) to control concentrations and avoid excessive sink effects.

Construction Procedures

Review submittals to ensure conformance to IAQ performance specifications
No matter how careful the selection process, materials can be substituted during the construction process. It is necessary to monitor the submittals phase for substitutions that will result in IAQ problems.

Specify and observe construction site practices

It is essential to ensure that porous materials are protected from moisture. Wet or moist construction materials are a common source of microbial contamination once buildings are occupied. Specify and observe adequacy of ventilation conditions during installation of wet products. Specify and observe protection of fleecy and porous surfaces from dust, gases, and vapors. Ensure completion of HVAC Testing, Adjusting and Balancing, and of full HVAC commissioning before occupancy. Ensure ventilation and thermal control systems are operational and effective prior to move-in and initial occupancy. Recommend (if possible, specify) and monitor move-in and initial occupancy procedures to ensure indoor air quality and climate. Assemble the project manual to include full documentation of thermal and IAQ loads; HVAC system design criteria, assumption, and equipment; operational sequences and controls; warranties; record drawings and specifications; and, inspection, maintenance, and replacement requirements.

Maintenance and operation

Inspection, Cleaning, and Replacement.

Periodic inspection for IAQ with good record-keeping can create a preventive maintenance environment in which problems are less likely to occur. The records should be archived in an accessible location and protected from deterioration. This inspection should include but not be limited to HVAC systems. It should also be conducted to identify any new or modified indoor pollution sources.

Change of Use, Renovation, Adaptive Re-use, and De-mounting

Evaluate impacts of planned use changes on loads (thermal, IAQ) and determine system design capacities, distribution, etc. and the adequacy for planned changes. Treat renovation projects as new construction with respect to the items discussed above.

DISCUSSION

Modeling results depend on the adequacy of the model and the data used. There are large differences among buildings of different types and construction characteristics. Therefore, building specific analyses are required to properly prioritize materials that are to be addressed in the material selection process during design or in rigorous investigations of emission characteristics for modeling purposes. The results of exposure analysis from a life cycle perspective indicates that emissions from the materials themselves may not always dominate total occupant VOC exposure due to building material characteristics. Instead, maintenance and re-finishing requirements may be more important for some surface materials, particularly floor and wall-coverings (20). These requirements and the chemicals used should, therefore, be important considerations in material selection.

Among the most inscrutable emissions are those from "wet-applied" products, especially adhesives used for floor and wall coverings. Very little research has been conducted on this subject so that considerable uncertainty accompanies estimates of the behavior of emissions from this type of product in buildings. Further work is needed to improve the reliability of modeling involving these and other indoor air pollutant sources.

CONCLUSIONS

Modeling conducted in accordance with the procedure outline in this paper can achieve reasonably reliable and useful results for designers, manufacturers, building investigators, and scientists. Further emissions testing and research are necessary, and they can improve considerably the reliability and utility of modeling work, investigations, and materials selection.

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Architecture and IAQ

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Abstract
Good indoor air quality happens by design, not by accident. In fact it is simply one aspect of good design. Architects and other building designer professionals play a major role in determining indoor air quality (IAQ). Primary roles belong to the architect, ventilation system engineer, and interior designer. Major IAQ design concerns include project planning, pollutant sources identification and control, environmental control systems concepts, design and specification; construction administration; and commissioning. Leading architects now specify "low-emitting materials" including examination of the nature of the material's emissions over the entire life cycle. Good design optimizes indoor environmental quality for lifetime control of occupant exposure to contaminants. Only when the architect takes an aggressive position on IAQ is the achievement of good IAQ likely. Finally, a healthy building is one that is harmful neither to the occupants nor to the larger environment. Sustainable building practices will require substantial improvements in total building environmental performance. Tools now exist to evaluate building life cycle environmental performance and these tools are being used more commonly in projects with strong environmental objectives.

Introduction
Many building design, construction, and operational measures necessary to create good indoor air quality are well-established. Table 1 below provides an overview of the major measures required to create good IAQ in a commercial building. Following the table is an elaboration and discussion of each of the ten best practices. That is followed by consideration of how to integrate these with other sustainable design objectives in a rational and comprehensive fashion. More detailed guidance for indoor air quality can be found in several referenced publications (3-9).

Table 1. IAQ "best practice" concepts for building design

1. Understand relationships between exposure, dose, and occupant susceptibility that determine health effects:
2. Recognize relationships between indoor air pollution sources, ventilation, and concentrations.
3. Clear overall design concept for indoor air quality: cradle to grave.
4. Identify pollutant sources:
5. Consider source control options and strategies and select the most effective,
6. Carefully specify ventilation system design and operation,
7. Select and specify materials for good total life cycle IAQ,
8. Specify construction procedures to control short-term emission effects.
9. Identify and specify critical maintenance and operation requirements.
10. Consider IAQ in change of use, renovation, adaptive re-use, and de-mounting

Exposure, dose, and occupant susceptibility determine health effects:
Virtually everything can be toxic. If you drink too much water, you can harm or even kill yourself. Health effects are a matter of exposure, dose, and individual susceptibility. There are no "non-toxic" building products or chemicals, there are just more or less toxic or irritating ones. And their use or application and the occupants' exposures and susceptibility will determine the effects. Exposures may be either short-term, "peak" exposures, long-term, chronic exposures, or some combination or variation of the two. Consider the neuro-toxicity of alcohol. Drinking one beer an hour for 12 hours will result in inebriation above legal limits for operating a motor vehicle. But drinking 12 beers in one hour during a 12-hour period, you may be close to unconsciousness. Similarly, an odorous compound released at a sub-threshold detection level steadily for 12 hours will not result in its detection. Yet the same quantity of the compound released during a short time period is far more likely to result in detection of the odor.

Major indoor air pollutant classes and their effects:
The most commonly discussed indoor air pollutants are volatile organic compounds (VOCs), microbial contaminants (fungi, bacteria, viruses), non-viable particles, inorganic chemicals (nitrogen oxides, carbon monoxide, carbon dioxide, ozone), and semi-volatile organic compounds (SVOC - including pesticides and fire retardants). The VOCs and the microbial contaminants receive the most attention, and, perhaps, deservedly so. Common industrial solvents, adhesives, and other modern chemical products are abundant in most indoor air, although the concentrations are generally far lower than known thresholds for health effects. Nevertheless, the huge number of chemicals typically present in indoor air suggests that there may be effects due to additive or synergistic effects.

Major health effects:
Health effects can range from irritation and discomfort to disability or life threatening disease. Table 2 lists the major effects including health effects of exposure to indoor pollutants.

Table 2. Major Health Effects of Indoor Pollutants:

- Infectious disease: flu, cold, pneumonia (Legionnaires' Disease, Pontiac fever),
- Cancer, other genetic toxicity, teratogenicity - (Ecotoxicity)
- Asthma and allergy
- CNS, skin, GI, respiratory, circulatory, musculoskeletal, and other systemic effects
- SBS (Sick Building Syndrome)

SBS: causation hypothesis and interactions:
Sick building syndrome has received much attention as it has become more widespread in modern buildings. It is now generally recognized as a multi-factorial problem; that is, it is caused by a constellation of factors, not by a single building-related factor. It is probable that there are additive and even synergistic effects of some of the environmental factors, not just chemicals or microbes, but also the acoustic, thermal, illumination, and other aspects of the indoor environment that affect the incidence of SBS. It is also likely that work stress and other psychological and social or institutional factors play a role in the incidence of SBS ().

Relationships Between Indoor Air Pollution Sources, Ventilation, and Concentrations
Concentration = (source rate – removal rate) / ventilation rate.
There is a simple mathematical relationship that clearly expresses the most important relationships in indoor air quality. The concentration of a pollutant will be function of the sum of all the pollutant source contribution rates minus the sum of all the pollutant removal rates divided by the ventilation rate. The simplest form of this relationship states that concentration is a function of source strength divided by ventilation rate without accounting for outdoor sources nor for removal by sinks or indoor air chemistry. There are many types of contaminant removal mechanisms including filtration and air cleaning, deposition on surfaces, and chemical transformation. But the most important concepts are embodied in the simple relationship between source strength, ventilation, and concentration (7-9).

This relationship is expressed in equation 1:

$$\underset{(mg/m^3)}{\text{Concentration}} = (\underset{(mg/h)}{\text{Emission Rate - Removal Rate}}) / \underset{(m^3/h)}{\text{Ventilation Rate}} \qquad \text{Equation 1}$$

The emission rate is determined by the emission factor (mg/m^2 h) times the area of the source (m^2). The ventilation rate is the amount of uncontaminated air introduced into the space (or environmental test chamber) per hour.

In reality, the process is more complex than is suggested by this mathematical expression and should also include all the source terms and removal terms.

Source control is most effective.
The most effective strategy for achieving good indoor air quality is source control. Identification of pollutant sources is the first step. Then, elimination, reduction or isolation are the next three strategies that should be applied. For example, completely encapsulating a particleboard sheet material used in casework can reduce significantly the emission rates of formaldehyde and other volatile organic chemicals from the product (7-9). This is discussed further later in this paper.

Major sources:
The major sources of indoor pollutants include the outdoors, the building itself, the occupants, building equipment, appliances, and consumer products. The most important sources vary from project to project. Building materials are important, particularly when they are new and for weeks or months afterwards. Some, such as composite wood products, due to their thickness, density, and their pollutant content, can be sources for years after installation. Major pollutant sources and removal mechanisms are listed in Table 3.

Table 3. Determinants of indoor air quality

POLLUTANT SOURCES
- Outdoor Air, Soil, Water
- Building Envelope
- Building Equipment
- Finishes and Furnishings
- Machines and Appliances
- Occupants
- Occupant Activities
- Maintenance and Cleaning

POLLUTANT REMOVAL MECHANISMS
- Sinks
- Ventilation (dilution, exhaust)
- Air Cleaning and Filtration
- Chemical Transformation

Ventilation principles:
The most effective way to remove point or concentrated sources of pollutants is local exhaust. For distributed sources, dilution ventilation is used. An effective air supply strategy is displacement ventilation, usually involving introduction of air low in a space, then relying on thermal forces to transport low air upwards and create a strata of more polluted air just below the ceiling. There the polluted air is collected and removed for exhaust or cleaning and recirculation. It is essential to maintain overall ventilation system balance since it is pressure difference that result in air flows within and between spaces.

Other pollutant removal mechanisms:
Among the most common removal mechanisms are air cleaning and filtration, usually incorporated into a mechanical ventilation system, the process of particle or chemical deposition on surfaces, and chemical transformations. These are discussed further below.

Deposition on surfaces
Some pollutants are removed by the process of deposition on surfaces. Filters designed to remove particles function by "catching" the particles on their surfaces. The particles must be tightly bound to the filter media to eliminate re-entrainment in the air stream. Gases are removed by adsorption on charcoal or other media or by chemical transformation through contact with catalytic surface materials. Deposition of gases and particles also occurs on indoor surfaces. The rates vary with the nature of the gas or particle, the surfaces, the airborne concentrations, and the nature of the surfaces themselves. Fine particles deposit equally on horizontal and vertical surfaces while larger particles fall to the horizontal surfaces below them due to gravitational forces.

Sink effects
To various degrees, processes of removal are going on at all times for most pollutants by deposition on indoor surfaces. These processes, known as sink effects, are usually at least partially reversible. The sink effect serves to buffer very high concentrations by allowing chemicals to deposit on surfaces when concentrations are high. But the downside of this

buffering effect is the extension of the pollutant residence time in indoor air over much longer periods.

Different gas-phase chemicals and different surface materials produce different sink dynamics based on variable adsorption and desportion rates. Generally pesticides and other large or "heavy" molecules tend to be less volatile and, therefore, are found on surfaces more than in the air. As the air concentration diminishes, the chemical tends to leave the surface and re-enter the air. This works well to maintain a desired level of a pesticide in air but also results in some unwanted prolongation of the presence of pesticides and other toxic chemical substances such as PCBs, dioxins, and furans.

An excellent example of the sink effect is the deposition of particles and gases in environmental tobacco smoke (ETS) on surfaces. Non-smokers know that if they spend time in a smoke-filled environment, upon arrival at home they recognize the smell of ETS on their clothing. Some of the heavier molecules in ETS tend to be both the most toxic and the most difficult to eliminate.

Overall Design Concept to Achieve Good Indoor Air Quality: From Cradle to Grave
Much of what it takes to achieve good indoor air quality is simply common sense when all of the relevant factors are considered in the design, construction, and operation phases. Many indoor air quality problems occur simply because IAQ was not considered adequately during the process. By developing an overall project concept for IAQ and carrying it through from beginning to end, most common problems can be eliminated and the risk of unusual ones can be vastly reduced.

Planning through construction, commissioning
A major cause of indoor air quality problems is premature occupancy. Buildings are often occupied before construction is complete, either with respect to installation of finishes and furnishings, or with respect to the complete testing, adjusting, and balancing of the HVAC system. By considering the need for thorough curing of new products and complete verification of a properly functioning ventilation system, many IAQ problems can be avoided. This requires planning from the outset for adequate time between scheduled completion and initial occupancy.

Operation
Design and operation must be consistent. There is strong evidenced that the closer a building is operating to the design intent, the less likely occupants will report SBS symptoms. There are many steps from design to occupancy during which deviations from design intent can occur. Causes of failure include: lack of translation from design intent into clear, detailed design specifications; inadequate communication among contractors; deviation from specified materials and equipment by substitution or error; improper installation of materials and equipment; and failure to commission fully and properly, among others.

The design team must make appropriate assumptions about the use of the building, document their assumptions, and pass them along to the operators of the building. Operational schedules must be adequate not only to control thermal conditions but also to remove pollutants accumulated during off-hours. Early morning purging, especially after weekends and other extended unoccupied periods is essential. When maintenance or housekeeping activities involve the application of chemicals such as carpet shampoo, solvents, floor wax, or furniture polish, the accumulated emissions from these processes should be removed before re-occupancy.

Maintenance and housekeeping
Neglected or deferred maintenance is often the source of IAQ problems. Design should provide for access to all components of HVAC systems for inspection, repair, and cleaning. Cleaning of surfaces, especially periodic removal of accumulated dust from concealed surfaces above a suspended ceiling used as a return air plenum, is essential. Vertical fabric covered surfaces such as walls or office workstation panels should be vacuumed since small, inhalable particles deposit as easily on vertical as on horizontal surfaces.

Modification and Renovation or Adaptive re-use
During construction activities, construction dust, fumes, and vapors must be contained and not allowed to contaminate building surfaces or the air in occupied spaces. Temporary ventilation and isolation barriers should be employed. When the use of a space or building is significantly changed, it is essential to determine whether the building can support the new activities and occupancy loads. This can be done by reviewing record drawings and other documents. If such documents are not available, an engineering assessment should be conducted.

De-mounting and re-source or disposal
Ultimately, buildings or portions of buildings will be demounted and replaced. Care must be taken during demolition to avoid contamination of occupied spaces or of surfaces that will remain in use or be re-used.

Pollutant Source Identification
Control of indoor air quality requires adequate identification of pollution sources and development of strategies to address each source.

Outdoors
Sources outside the building include ambient air pollution, emissions from neighboring buildings or activities, contamination in soil adjacent to or under the building, A thorough review of the adjacent and other buildings in the immediate neighborhood of the project can often reveal obvious sources of pollution. Prominent among these are industrial and agricultural processes, dry cleaners, restaurants, gasoline service stations, parking garages, bus stations, heavy-use roadways, and a number of other common facilities. By avoiding sites where such obvious sources of pollutants are likely, far less stringent air cleaning and filtration will be required to achieve good quality indoor air.

Outdoor air quality exceeds the National Ambient Air Quality Standards (NAAQS) under the Clean Air Act in the communities where approximately 1/3 of all Americans live. Therefore, bringing in contaminated outdoor air is likely. Even where air may meet the NAAQS, it may still be desirable to remove some of the particles, ozone, carbon monoxide, or other contaminants before using it to dilute and replace polluted indoor air.

Building fabric
The building structure, envelope, and floor system are major components that must be considered, even though many of their surfaces will be covered by finish materials or will not be visible to the building occupants. Spray-on fireproofing or acoustic materials have very large surface areas and are often exposed to the circulating air within the building. Contaminants can adsorb on these surfaces and subsequently be re-released. Chemical reactions and emissions from the products themselves can occur due to changes in the humidity. Deterioration of aging

adhesives and binders or erosion by air currents can also result in breakdown of these materials and releases of pollutants into the building air.

Building finishes
As is the case with the building fabric, finishes can be sources and sinks for pollutants. Care in their selection is essential, and major surface areas and masses of materials should be identified and carefully considered as potential pollutant sources. While some materials can act as sinks that reduce airborne concentrations, they do not necessarily reduce exposure. An example would be carpet fibers that serve as sinks for airborne chemicals but where children play and receive exposure through skin contact or by breathing the air close to the carpet where the concentration may be higher.

Building equipment
HVAC systems are increasingly recognized as sources of pollutants. Microbial contamination of filters is a potential source of microbes and their metabolic by-products, microbial VOCs. Power, illumination, transport, communication, and security system components can also be significant sources.

Occupants and their activities
The most important source, and the one over which building designers and constructors have the least control is the building occupants themselves. The nature of the occupancy and use of the building is an important indicator of the type of contaminants that will originate from the occupants.

Load documentation and calculations
Thermal and pollutant loads should be documented and considered part of the design process as well as the building management process. By creating such documentation and including it with materials submitted to the building owner as part of the design approval process, designers ensure that there is a common understanding of the use of the building and its implications for pollutant sources.

Source Control Options and Strategies

Isolation from outdoors
For pollutants such as pesticides used to treat soil or for radon gas, complete isolation of the building from the outside is the most effective strategy. Moisture intrusion is a major contributor to microbial contamination, and, therefore, should be prevented. The integrity of joints in the construction, of coatings, seals, and other barriers is essential. It is also important to control pressure relationships across the envelope to prevent moisture accumulation on or behind surfaces. The placement of vapor barriers is determined by the indoor - outdoor humidity ratios and the local climate and should generally be placed on the side of greatest moisture content or generation to avoid migration through the envelope and condensation on the dew point plane. A drain plane should be provided to prevent the entry of rain water that enters the exterior wall through cracks or other gaps in the outer boundary.

Outdoor air cleaning and filtration
Rather than bringing polluted air into a building, air cleaning and filtration can be used to remove some gases and particles. Among the most common pollutant removal mechanisms is filtration, usually incorporated into a mechanical ventilation system. This involves circulation of

air through a filter where particles are removed primarily because they cannot pass through the openings in the media, usually made from cellulose or man-made mineral fibers. Recent advances in filter technology allows for much more effective filtration of smaller particles, those in the inhalable size range, without concomitant pressure drops that formerly required larger fan capacity and more energy consumption. In some cases air cleaning is done for gases by use of selective sorbent media.

Material Selection for good IAQ
Building materials can be sources of indoor air pollutants, especially in the early period of their lives or when they are requiring application of chemicals for their cleaning, waxing, polishing, surface renewal, or re-finishing. See the separate paper in these proceedings for a detailed description on the control of VOCs from building materials.

Surface cleaning
Frequent cleaning of surfaces can reduce the burden on ventilation and filtration or air cleaning and may be found cost effective in some applications. Where sink effects are a dominant removal mechanism, as for some pollutants in ETS, surface cleaning may be necessary for aesthetic reasons related to both appearance and odor. In any case, surfaces should be cleaned to control contaminant air concentrations of previously deposited particles and gases.

Indoor Air chemistry
Finally, chemical transformations can take place, as is the case when ozone brought in from outdoors or generated by photocopiers and laser printers reacts with certain organic chemicals, often forming more irritating compounds than were present before the ozone interaction. Ozone is often used to convert a "smoking" room to a "non-smoking" room in hotels. What is often inadequately understood or considered is the nature of the compounds formed by this process. While ozone may be effective in eliminating some or all of the odor associated with ETS and other pollutants, some of the reaction products formed may be more toxic than the chemicals from which they are derived.

Outdoor air ventilation rates and schedules
Adequate outdoor air supply involves assessing the quality of the outdoor air as well as the needs to remove pollutants from people and from materials or processes within the building. Starting up too late in the morning or not providing enough ventilation during housekeeping activities can cause unnecessary air quality problems.

Ventilation System Design and Operation
Local exhaust for point sources
The most effective way to control indoor air pollutants from sources within a building is to remove them at the source and not allow them to disperse to other portions of the space or building or to deposit on surfaces (sinks) from which they can be emitted later. Kitchen range hoods and bathroom exhaust fans are good examples. Smoking lounges with one-pass, direct-exhaust ventilation are another example.

Air distribution strategy and ventilation effectiveness
Consider air distribution and ventilation effectiveness before establishing outdoor air ventilation rates. Ventilation effectiveness indicates the portion of the supply air that reaches the occupants' breathing zone. To the extent that ventilation effectiveness is less than 100%, then additional

outdoor air needs to be provided to compensate for the shortfalls. The location of supply and return registers will affect air distribution and ventilation effectiveness under some conditions. Local supply directly into the breathing zone of the occupants may be the most effective strategy where feasible. In the long run, it can save energy and even first costs for mechanical ventilation and conditioning.

Outdoor air ventilation rate
It is necessary to ensure that there is adequate dilution for the people-related, activity-related, and the building-related sources. Traditionally ventilation rates have been based only on the number of people. This is not adequate since occupant density does not necessarily correlate with the source strengths of processes, building materials, and other potentially important sources.

Accessibility of all system components
This includes filters, coils, drain pans, ductwork, duct liners, plenums, valves, controllers, etc. They must be accessible for inspection, cleaning, maintenance, and repair. While this may seem obvious, it has frequently been neglected and caused serious IAQ problems.

Operator training
Operation of complex, modern HVAC systems requires competent, well-trained personnel. While operator training is often part of the construction contract, it is often skipped over because the operators are pre-occupied with getting a new building or system running at the time when the training is to occur.

Commissioning
Traditional testing, adjusting, and balancing is simply insufficient to ensure a properly function HVAC system. Increasingly in recent years, construction contracts call for complete HVAC system commissioning before final acceptance of the building. This is found to be both cost effective for the owner and beneficial for the contractor as well. Benefits include reduced call-backs, energy-saving during operation, and avoidance of many common IAQ problems in new buildings.

Thermal Control
There is substantial evidence linking elevated indoor air temperatures and humidity with occupant perception of stale, stuffy, or unacceptable indoor air quality. Therefore, it is only logical to attempt to design and operate buildings at the lowest practical temperature and humidity levels.

Material selection and specification
Quantify major materials and identify important sources
Based on mass and area ratios to space volume, the highest ratio products and materials should be selected as "target" products for careful review, specification, and installation. Some other products or pollutant sources will also be important although small in area or mass. These include many wet products such as paints, sealants, adhesives, caulks, and chemical additives.

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