2004

Quality Indoor Environments and Sustainable Buildings -- Can We Have Them Both?

Hal Levin
Building Ecology Research Group, Santa Cruz, California, USA

Abstract
The quality of the indoor environment and the impact of the built environment on sustainability have been discussed increasingly in recent years, yet little has changed in the fundamental relationships between Post Occupancy Evaluation (POE), assessment of indoor environmental quality (IEQ), and sustainability. POEs have focused very little on indoor air quality (IAQ), one of the most important factors in IEQ and arguably a major component of sustainability. Buildings' impacts on occupant comfort, health and well-being have not become significant factors in assessment of building sustainability. Two major components of IEQ -- indoor air quality (IAQ) and thermal conditions – are strongly dependent on outdoor air quality, weather, and ventilation. The impacts and implications of the increased concern about sustainability are not sufficiently connected in practice. Finally, some comments are made regarding development of more robust assessment of IAQ and sustainability that might be useful in POEs.

Keywords: Indoor air quality, Sustainable buildings, Post-occupancy evaluation, Commissioning, Building Ecology

Introduction
The building community has shown rapidly increasing interest in sustainability and in the quality of the indoor environment in recent years. However, these two aspects of buildings have not been adequately linked in practice. It is evident from ecosystems studies that there not only are connections between environmental compartments but that there is a *dynamic interdependency* among them that requires a more comprehensive approach to the study of the of the built environment's impacts on building occupants and on the larger environment. In 1981, well before the recent surge in interest in the sustainability of the built environment, we proposed such an approach and called it "building ecology" (Levin, 1981). Later, a "healthy building" was defined as one that adversely affects neither its occupants nor the larger environment (Levin, 1995a).

POE has been advocated and utilized to improve understanding of buildings' impacts on their occupants. This is a necessary but insufficient component of a building ecology approach. Some Post Occupancy Evaluations (POEs) have addressed energy consumption as have building (or HVAC) commissioning endeavors. There have been very few efforts to assess rigorously the relationships between indoor environmental quality (IEQ), and sustainability. POEs assess indoor air quality (IAQ), one of the most important factors in IEQ. However, indoor air quality measurements in POEs are usually quite insufficient and rely primarily on occupant perception of IAQ. Yet many harmful common indoor air contaminants are not detected subjectively. The cost of measuring indoor air is offered as an explanation for not making more specific and useful IAQ indicators. While cost is a significant barrier to thorough evaluation of IAQ, it is also important to recognize fully the limitations of both physical and non-physical measurements of indoor air in the assessment of indoor air quality. POEs have been characterized generally by a paucity of physical measurements. One might ask whether POEs have gone too far in emphasizing (depending on) occupant perceptions of the indoor environment and its impacts on them in order to redress the widespread absence of concern about such impacts and perceptions in mainstream building design, construction, and operation.

This paper provides a preliminary discussion of the links between the subjects of Indoor Air Quality (and indoor environmental quality in general), Post-Occupancy Evaluation, and sustainability. The paper discusses the lack of serious attention to sustainability issues at any level with a focus on the building community. It considers the use of assessment and evaluation methods and tools for Post Occupancy Evaluations and Building Commissioning, especially the methods used for evaluating indoor air quality and other indoor environmental quality factors. It presents sample results from the assessment of IAQ in a recently completed "green" building for the State of California emphasizing the important linkages between ventilation, pollutant source strength, and airborne pollutant concentrations. It is hoped that by showing the significant gap in current practice and suggesting some approaches to bridge the gaps, more effective and useful building assessments can be performed.

SUSTAINABILITY

There has been practically no rigorous scientific assessment of sustainability issues. This is true not only related to the built environment but more broadly to social, economic and environmental policy and planning at governmental and academic levels. An exception is the work in the early 1990s of Weterings and Opschoor for the Dutch government, "Ecocapacity as a challenge to technological development" (1992). Opschoor and van der Straaten later described the implications in development policy (1993). The "ecocapacity" approach requires assessment of each nation's share of global resource consumption, pollution emission, and land encroachment under assumptions of the earth's carrying capacity – *i.e.*, the amount of resource consumption, pollution, and habitat loss that can be sustained over the long term. The work used a 50-year time frame to estimate global and Dutch targets for sustainability considering issues of equity among peoples of all nations and assuming that each inhabitant of the Earth is ultimately entitled to the same quantity of "ecospace." The results are a startling picture of the dramatic reductions required to move toward sustainable societies. The methodology is transparent and susceptible to revision of the assumptions and the data used to make the calculations. But neither the Dutch government nor any other government has followed this model in estimating sustainable targets and to use them to plan for a sustainable society. Of greater concern is that currently there is no serious dialogue at a national or international level regarding the establishment of ecocapacity-based targets.

Current use of the term "sustainability" is commonly focused more on the sustainability of human economic activity than on the sustainability of ecosystems on which life depends. It is usually dominated by a short-term focus and a lack of any rigorous analysis of the actual or potential environmental impacts of any building or development on the long-term sustainability of the ecosystems on which human and other life depend. Virtually all of the hundreds of definitions of sustainability are simply too vague to be useful in evaluating the impacts of human activities living systems. Current use of the term "Sustainable buildings" (or its frequently presumed or implied surrogate "green buildings") is in conflict with the meaning of the word "sustainable" as the ability to continue indefinitely.

Frameworks for Assessing Sustainability

Andrew Dobson of Keele University in the UK (1996) proposed that a meaningful definition of the sustainability of a project, product, or other object [including buildings] is determined by the way it responds to the following questions:

- What to sustain?
- Why to sustain it?
- What are the "objects of concern?" This means, for whom is anything being sustained? Is it for both human and non-human species? Is it for present and future generations? Does it address only human needs or does it also address human wants (desires)?

Table 1 presents Dobson's framework.

Table 1. Andrew Dobson's framework for assessing sustainability

	A	B	C	D
What to sustain?	total capital (human-made and natural)	critical natural capital: *e.g.*, 'ecological processes'	irreversible natural capital	'units of significance'
Why?	human welfare (material)	human welfare (material and aesthetic)	human welfare (material and aesthetic) and obligations to nature	obligations to nature
Objects of concern:				
primary:	1,3,2,4	1,2,3,4	(1,5) (2,6)	(5,1), (6,2)
secondary:		5,6	3,4	3,4
substitutability between human-made and natural capital	considerable	not between human-made capital and critical natural capital	not between human-made capital and irreversible natural capital	eschews the substitutability debate

Key to numbers:

1 = present generation human needs
2 = future generation human needs
3 = present generation human wants
4 = future generation human wants
5 = present generation non-human needs
6 = future generation non-human needs

Dobson frames the "objects of concern" questions as follows:

- Questions of social justice: these involve differences among populations according to genders, races, nations, socio-economic status, etc.
- Questions of genetic justice: differences of species, both animal and plant species might be included
- Questions of generational justice: the importance of the living or the next generation versus later generations yet to follow

By examining the implicit way a project or product responds with respect to those questions in Table 1, Dobson proposes that the sustainability of any project or activity is determined.

"SocioEcological-Indicators of Sustainability"

Azar, Holmberg, *et al* (1996) suggested that predicting environmental impacts is too difficult due to the large uncertainties involved. Therefore, they have proposed to compare critical resource consumption to various benchmarks considered useful indicators of sustainability. Their framework has been translated into the so-called "Natural Step" approach and widely disseminated. However, it still has not found much use in the assessment of building designs or operations.

Life Cycle Assessments (LCA)

So-called "cradle-to-grave" assessments of the resources consumed and pollution emitted are done under methods known as life cycle assessments. Software programs for LCA developed in the Netherlands for housing designs and in Germany for larger building designs have been available for several years now (Kortman *et al*, 1998; Kohler *et al*, 1998). Various other software tools have developed and can be accessed through the LCA Hotlist website at http://www.doka.ch/lca.htm, the HUD user website at http://www.huduser.org/publications/destech/lifecycle.html, and the U.S. EPA's LCA website at http://www.epa.gov/ORD/NRMRL/lcaccess/resources.htm.

POE, IEQ AND SUSTAINABILITY

Until recently, concern for the quality of the indoor environment and its impact on the occupants has been expressed with little attention to the impact of buildings on the long-term sustainability of the built and the natural environment. While sustainability has become an important concern in recent years, too few assessments of factors important for sustainability are conducted during design, commissioning, or post occupancy evaluations. An important but all-too-rare exception is the occasional concern regarding energy consumption and its impact on greenhouse gas emissions.

Most discussions of sustainable buildings have focused on the individual building level. However, the location of a building in a community and the design of communities themselves can have very large impacts on both the indoor and the larger environment. For example, commuting by automobile can typically require more energy consumption than is used in the building to which commuters drive. Yet the high mobility of the American workforce argues against relocation for purposes of convenient access from home to the workplace. Such problems have received far too little attention but they illustrate the interconnectedness of various aspects of the built environment and the broader societal organization and trends.

Two major components of IEQ -- indoor air quality (IAQ) and thermal conditions – depend strongly on outdoor air quality, ventilation, and the impacts their interdependent characteristics have on energy consumption. While energy consumption is widely accepted as important to sustainability, air quality and occupant satisfaction have not been so widely recognized as major sustainability factors. So far, buildings' impacts on occupant comfort, health and well-being have not been treated as significant factors in assessment of building sustainability. The means of controlling indoor environment quality impacts both occupant satisfaction as well as building environmental performance.

Completed buildings have often been occupied before all of their systems have been fully tested and adjusted to meet design intent. Complaints from occupants or post-occupancy evaluations have been used as sources of information regarding the failure of buildings to perform according to standards, guidelines, or design intent. More recently a more formal process of verifying building performance, "building commissioning," has been used to avoid problems of occupant dissatisfaction or health effects while also ensuring energy consumption met expectations and was not unnecessarily excessive. Meanwhile, at least in some quarters, POEs have been performed that served a similar purpose by identifying major problems in building design or operation that could be corrected after occupancy.

Closing the loop between design intent and actual building involves confirmation not only of the building's performance according to the design assumptions, but confirmation of the design assumptions themselves. Often the intended use at the start of design has been modified during the construction phase or later. But closing the loop has another meaning that is relevant today. It has to do with the loop between the building, the occupants, and the larger environment – with "building ecology." The dynamic interdependence of the building, its occupants, and the larger environment must not be ignored if we are to create truly sustainable buildings. The expression "cradle to grave" has been used and now, even, "cradle to cradle" implying that we must eliminate the concept of waste and re-use or recycle everything. Since, as Barry Commoner pointed out, everything must go somewhere, in a sustainable world, we will plan for the ultimate disposal of the waste products associated with the building life cycle. But in a more immediate way, relevant to the POE domain, we must look at the on-going processes of ventilation and the off-gassing of chemicals from materials and the metabolic by-products of human occupants. We must account for their "management" so that exposures to them are not unpleasant, harmful or noxious.

The concerns for the performance of environments within buildings with particular reference to occupant well-being and achievement of individual and institutional/organizational goals are closely linked to the achievement of sustainability in two fundamental ways:

- First, human health must be considered an essential component of sustainability, at least "sustainability" as defined by humans. However, to date, so-called "green building" designers have paid far too little attention to buildings' actual and potential impacts on their occupants' health. Indoor air pollution and its impacts on human health is arguably one of the most important and most readily-assessed indicators of sustainability. Yet POE and commissioning have generally failed to address IAQ in any systematic or detailed way. POE and commissioning have relied on very incomplete or indirect and often loosely-related data for drawing conclusions about IAQ and its actual and potential impact on occupants.

- Secondly, building performance -- in particular, the ability of buildings to meet the needs of their owners, their occupants', and the broader public -- is indispensable for the long-term "survivability" of a building. The potential for a very long service life is a major determinant of the sustainability of buildings because constructing new buildings is necessarily resource-intensive and, in most cases, results in the production of waste. The recognition of a building's value by its users and its owners is a necessary but not sufficient condition for a sustainable building. It also must be maintainable as its economic viability depends partly on the operation and maintenance costs which, over the life of a building (or a major building component) is generally many times the original cost of the building or building component. This applies to building services (mechanical systems, lighting, vertical transportation systems, etc.) as well as to surface coverings and installations.

POE and IAQ/IEQ and A Building Life Cycle Perspective
The time at which a POE, commissioning, or IAQ/IEQ assessment takes place is critical to the outcome. POE or commissioning can occur at various time points, and there is no standardized system for addressing the need to evaluate the changes in building performance over time. In fact, the problems that can be expected in a new building are often worked out during the early occupancy period. Some of them are difficult to discover before occupancy occurs. But changes continue to occur in the building environment, some of them as a result of efforts to address problems discovered previously. Therefore, to some extent, commissioning or POE should occur on a continuous or periodic basis throughout the life of a building.

IAQ is a function of the conditions at any particular point in time, especially the indoor and outdoor sources of contaminants and the ventilation system performance including but not limited to outdoor air ventilation rate. It can vary greatly over time depending on source strengths and ventilation rates. This implies the need for multiple data collection times involving the full range of building operating conditions or, at least, sufficient data to model building environmental performance over the full range of reasonably expected conditions.

Outdoor air change rates (outdoor air ventilation rates) are important primarily for dilution and removal of indoor source contaminants and secondarily for their potential introduction of outdoor source contaminants. Dilution of contaminants generated indoors by ventilation with outdoor air is the most common approach to control indoor air quality followed by source control, although most authorities stress that source control is the most effective approach. The capital and energy cost penalties for excess outdoor air ventilation include both their economic and their environmental costs.

Interactions between common indoor source contaminants and outdoor source contaminants have been shown to produce chemical reactions that result in formation of new chemicals that can be far more odorous or injurious to health than the original chemicals from which they are formed. An important example is the case of ozone and other oxidants commonly found in outdoor air reacting with terpenes such as citrus- and pine-based solvents that have become popular recently as "green" substitutes for traditional industrial solvents. These reactions result in the formation of formaldehyde and other, higher-molecular-weight aldehydes as well as acidic aerosols and ultra-fine particles that pose potentially significant threats to human health (Weschler, 2000).

Ventilation is required in proportion to the sources whose emissions it is intended to control, but it must be designed and managed with adequate consideration of its implications for energy and other resource consumption as well as its potential to introduce contaminants from outdoors. Furthermore, it is extremely difficult to control accurately the delivery of outdoor ventilation air in most buildings, and research has shown repeatedly that building ventilation rates usually vary substantially from their design values, code requirements, and operator assumptions (Persily, 1989). This is partly due to the fact that it is difficult and expensive to measure the quantity of outdoor air actually supplied or the total quantity of outdoor air ventilation including both mechanical system outdoor air supply rate and infiltration rate.

Most efforts to standardize, regulate and evaluate outdoor air supply are based on the relationship between total outdoor air supply and occupant metabolism with carbon dioxide used as a surrogate for metabolism and the difference between indoor and outdoor CO_2 concentrations is the basis for assessing the outdoor air delivery performance of the ventilation system. However, this approach neglects the importance of ventilation for non-human sources of contaminants and the impact of outdoor air pollution on indoor air quality.

Commissioning

Commissioning is extremely important to confirm the performance of ventilation systems including the delivery of adequate outdoor air. Yet the variability of building ventilation system operation including the rate of outdoor air supply as a function of thermal conditioning requirements and climate mandates commissioning activities under the full range of possible operating conditions.

Occupant populations may vary greatly

Occupant populations may vary greatly and typically do. Efforts to standardize design conditions and to control buildings within a narrow range of conditions are doomed to failure for at least some if not many or even most building occupants due to the difficulty of controlling building environmental conditions and, even more importantly, the unlikelihood that any given set of conditions will please or even satisfy a large majority of occupants. In fact, efforts to establish and to achieve targets for uniform conditions of indoor environmental parameters necessarily leave a significant fraction of occupants dissatisfied due to individual variability.

Indoor environment design parameters are based on field or laboratory research with groups of subjects, usually as large as the research funding permits. Ultimately, design values or targets are established based on distributed population responses and some assumptions about the "acceptability" of conditions and the fraction of the population that "should" be "satisfied." Yet the effects of thermal conditions and indoor air quality are dominated by comfort and health endpoints while illumination and acoustic environmental conditions are focused on task performance. Recently there has been more work examining the performance impacts of indoor air quality and thermal conditions, and there certainly are well-established comfort and health impacts of illumination systems (Levin, 1995b).

Individuals vary in terms of their needs and preferences for illumination, acoustic conditions, thermal conditions, and air quality. Yet modern buildings are designed according to standards and guidelines generally intended to meet comfort and functional requirements of a majority of building occupants. Variations in individual human physiological characteristics result in different needs and preferences for indoor environmental conditions. Designers, especially in spaces that are centrally controlled or open space environments such as offices, tend to adopt a single set of target values for environmental parameters and to design control of the environment within a narrow range. This approach often fails to deliver what is designed, and even when it does, it usually fails to achieve optimal conditions for the vast majority of occupants. It is unnecessarily costly and energy wasteful, and it deprives individuals of the opportunity to adjust their environment according to their own needs and preferences. A user controlled approach could often be used more economically and achieve a high fraction of satisfied and comfortable occupants.

In each category, we list below the reasons why uniform conditions will not best satisfy or support the activities of the majority of building occupants.

Differences in inter-individual responses to light
- Differences in "natural" visual acuity
- Deterioration of vision with age
- Color perception differences
- Light sensitivity/tolerance
- Different habits and preferences
- Needs for task performance

Differences in individual responses to acoustic conditions
- Different tasks require varying background noise levels
- Conversation requires signal 3 dbA > background
- Some tasks require background noise for masking to preserve privacy
- Concentration/mental task requirements vary greatly between individuals

Human response to thermal conditions
- Variations in human metabolic rates
- Variations in clothing
- Variations in thermal comfort preferences
- Variations in optimal thermal conditions for distinct task performance (*e.g.*, digital vs. mental tasks)
- Adaptation (psychological and physiological)

In any group of occupants, a range of thermal comfort preferences is found. Buildings are generally designed to provide comfortable thermal conditions under extreme or near-extreme thermal and pollutant loading conditions, yet they usually operate for the vast majority of the time under far less severe conditions. Thus, thermal and ventilation provision is usually under partial load conditions. However, rarely are buildings fully commissioned under both typical and worst case (extreme weather and highest and lowest occupancy). To do this would require extending the commissioning period over the full range of seasons and the full range of occupancy scenarios.

Human response to Indoor Air Quality

- Individual odor sensitivity varies by factors of 10^3 to 10^7 among individuals.
- Susceptibility to effects of pollutants (particles, gases, bioaerosols) varies greatly in the population.
- Chemicals (VOCs, SVOCs, MVOCs, PAHs, etc.) in indoor air can cause nausea or even severe illness in one person and have no effect on another.
- By design, outdoor air ventilation rates can vary over a range of a factor of five or tenfold changes in air change rates.
- Ventilation rates can vary even more in outdoor air supply per occupant.

VOC Sources, Concentrations, and Ventilation

While many datasets are available that report the concentrations of volatile organic chemicals in offices, schools, and residences, (Hodgson and Levin, 2003a), very little is understood about the sources of these chemicals and especially about the relative contributions of various sources to the airborne concentrations. Even less is known about the potential human impacts of chemicals found in indoor air on human occupants. Hodgson and Levin (2003b) have compared airborne VOC concentration data from a large number of building surveys to recognized exposure guidelines and standards to determine which commonly-measured VOCs have been found at concentrations that could be of concern for odor, irritation, or non-cancer health effects from chronic exposure. This analysis provides some important insights as to which chemicals should be monitored and should be considered most worthy of source control efforts.

Very few field studies have been conducted that could identify separately the sources of indoor air contaminants found in most buildings in use. The major sources may vary depending on the type and age of the building structure and surface materials and the type of building use. Focusing primarily on residences, schools, offices, commercial establishments, and health care facilities encompasses indoor environments where the vast majority of people spend the vast majority of their time – perhaps upwards of 90% in most cases. It is well known that contaminant concentrations indoors are generally as high or higher, even significantly higher than those found in outdoor air. Therefore, exposures to air indoors comprise the major exposures to air pollution experienced by most people. Furthermore, unless unusually effective air cleaning and filtration technologies are used, most contaminants in outdoor air entering buildings for ventilation remains largely unmodified by the building itself so that occupants are exposed to contaminants in outdoor air even when indoors.

It is necessary to simultaneously measure both concentrations and ventilation rates to determine the source strengths of contaminants found in indoor air. Very few surveys of concentrations include ventilation rate measurements. Therefore, very few data are available on the source strengths of chemicals commonly found in buildings.

State of California "IAQ Commissioning" Project
In California, a set of new State office buildings were built with achievement of good indoor air quality as an important goal. In the first of these buildings, VOCs and outdoor air ventilation rates were measured at various stages of construction and through almost a year of occupancy. The results allow rough calculation of source strengths. Examination of the changes in source strengths over time yields valuable information that can be used to identify the relative contributions of various sources at various times in a building's life. Figures 1-3 show concentration measurement results monitoring. and calculated source strengths from the first of the "green" State of California office buildings. When these are compared, it is apparent that measuring concentrations alone can be misleading regarding the potential concentrations under different ventilation conditions. This is due to the very strong inverse relationship between ventilation and concentrations when source strength is constant.

Volatile organic compound
VOCs were collected on multisorbent tubes and analyzed by thermal desorption-gas chromatography/mass spectroscopy (GC/MS). More than 50 individual VOCs were quantified. Total VOC (TVOC) was determined by GC/MS total ion current response Formaldehyde and acetaldehyde were collected using DNPH impregnated cartridges and analyzed by High Pressure Liquid Chromatography (HPLC) with an ultraviolet (UV) detector. Ventilation rates were determined by the tracer gas decay method using sulfur hexafluoride (SF_6) as the tracer gas with analysis by portable gas chromatograph using electron capture detector for quantification. VOC source strengths based on VOC and ventilation rate measurements made as part of the "IAQ commissioning" process in a new "green" State of California office building are reported (Levin, 2003).

Quasi-steady state source strengths were calculated by multiplying the indoor minus the outdoor concentration by the product of the air change rate and the ceiling height. Source strengths are sometimes referred to as emission factors or area specific emission rates. Although samples were collected on five of the six floors during the project, only the 6^{th} floor concentrations were measured immediately before and after furniture installation and only selected 6^{th} floor source strengths are presented here in Table 2 and Figures 1-3.

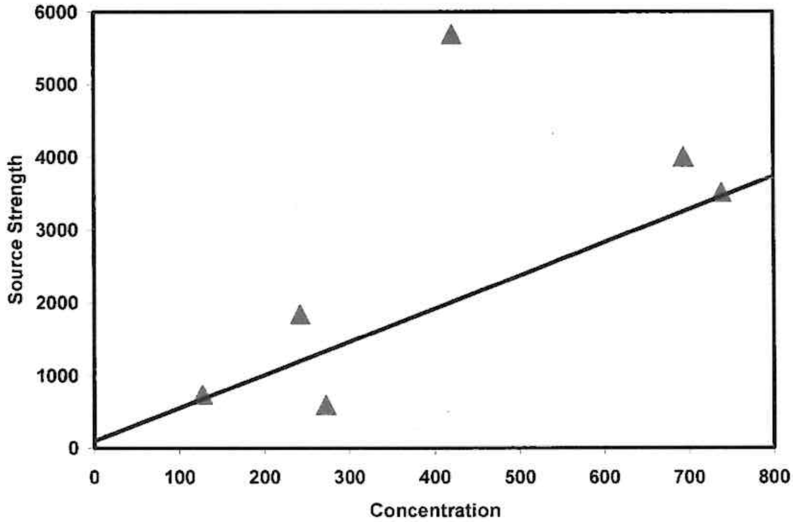
Table 2. Total VOC Concentrations and Source Strengths During IAQ Commissioning at a New California State Office Building

Date	*Concentration*	*Source strength*	*Air Changes per Hour*
2/26/02	242	1839	4.3
4/2/02	127	739	3.6
5/28/02	739	3515	4.3
6/25/02	421	5689	3.6
6/28/02	694	4007	1.4
10/29/02	272	595	0.7

It can be seen from Table 2 and Figure 1 that concentration and source strength do not co-vary, Ventilation rate plays an important role, as illustrated in Figure 2. Therefore, any concentration measurement must be accompanied by ventilation rate measurements in order to interpret correctly the potential concentrations at other times under different ventilation scenarios. Of course sources can change radically, as they do when cleaning and other building operations take place or even during normal use patterns. Therefore, the timing of POE, IAQ, and commissioning measurements is critical, and single time point measurements are insufficient to characterize adequately building performance. Table 4 lists some major times or events that can significantly affect source strengths, concentrations, or ventilation rates.

Table 3. Life cycle changes in building use important to indoor air quality
Installation of building materials,
Initiation of ventilation system operation,
Installation of furnishings, and equipment,
Move-in (initial occupancy) by building occupants
On-going use, Cleaning, and maintenance of the building.
Refinishing or replacement of surface materials, Renovation
Changes of type of occupancy or schedules of use

Figure 1. Comparison of Total VOC concentrations and source strengths at Block 225, Capital Area East End Complex, Sacramento, California.



Source Strengths vary considerably with time. Different individual VOCs' emissions decay at highly varying rates. The higher the vapour pressure (generally the lower the molecular weight), the more rapidly VOCs are emitted from materials. New materials generally emit strongly when first exposed to the environment after manufacture or installation. Surface coatings applied in thin layers generally decay by evaporation although a "skin" can be formed resulting in a second, slower phase governed by diffusion rate through the "skin." Thicker materials such as composite wood products have an initial burst of emissions from substances adsorbed on their surfaces but then their emissions are governed by diffusion through the material. This diffusion process depends on both the chemical being emitted and the surface through which it must diffuse. Secondary emissions occur as a result of adsorption of VOCs on surfaces and subsequent re-emission.

Indoor air quality typically changes on several time scales. The major changes relate to a number of major phases in a building's life cycle as shown in Table 3.

Figure 2. Source strength, concentration, and ventilation rate.

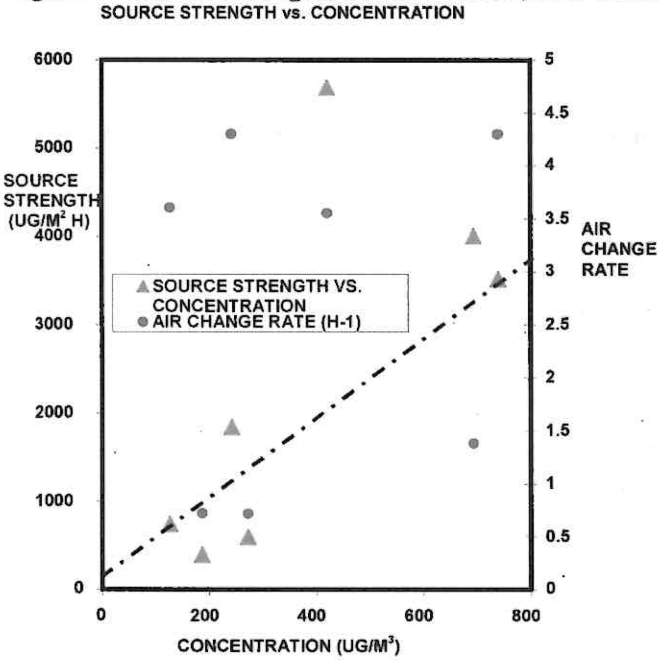
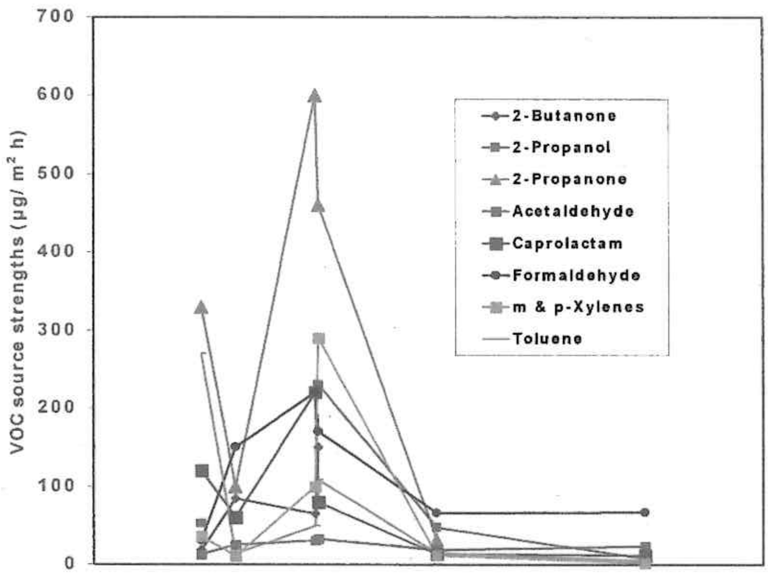


Figure 3. Selected VOC Source Strengths During IAQ Commissioning at a New California State Office Building



Discussion

It can be clearly seen from the data reported for the California State office building, that the concentration is highly dependent on the source strength and the ventilation rate. Therefore, characterization of indoor air quality at any point in time can only be used to generalize when the full range of potential ventilation rates and source strengths are known. Ventilation in a building can easily vary by factors of five to ten under normal operations. Source strengths can vary even more, particularly after application of wet products including paints, waxes, cleaning products, and personal hygiene products, among others. Care should be taken in the selection of materials that are applied immediately prior to or during occupied periods. Evaluations of IAQ should consider carefully the recent history of such applications and installations.

Concluding remarks

While IAQ measurements can be costly and can not adequately ensure good IAQ under conditions other than those prevailing when measurements are made, detailed IAQ measurements are the only means to determine whether harmful contaminants may be present at concentrations that pose a threat to human occupants. The work by Hodgson and Levin discussed above showed that few indoor pollutants reach concentrations of concern for chronic, non-cancer effects. However, a score or more of the chemicals measured in large surveys since 1990 do appear to warrant further concern and, perhaps, efforts to reduce their concentrations through source control and ventilation.

More broadly, sustainable buildings must adequately protect building occupants from exposure to harmful chemicals. Post-occupancy evaluations and building commissioning must consider the time-related changes in building environments and resulting occupant exposures. At the same time, sustainability assessments or efforts to design more sustainable buildings must more carefully and thoroughly assess the total environmental impact of the building on both the occupants and the larger environment. Only when more integrated assessments become more practical and, perhaps, more common, can we claim that we have designed healthy, sustainable buildings. A building ecology approach can lead us to such integrated assessments and help us identify the connections among the various aspects of the built environment.

References:

Azar, Christian, John Holmberg, and Kristian Lindgren, 1996. Socio-ecological indicators for sustainability. Ecological Economics 18: 89-112.

Kohler, Niklaus, and Thomas Lützkendorf, 1998. "Evaluation Methods of Environmental Impact and Resource Consupmtion." Green Building Challenge '98. Vancouver, British Columbia. October, 1998.

Kortman, Jaap , H. Van Ewijk, , J. Mak, D, Anink, M.Knapen, 1998. "Presentation of the Outcomes of Tests by Architects of the LCA-based Computer Tool Eco-Quantum Domestic." Green Building Challenge '98. Vancouver, British Columbia. October, 1998.

Hodgson and Levin, 2003a. Volatile Organic Compounds in Indoor Air: A Review of Concentrations Reported Since 1990. LBNL report #51715. Berkeley: Lawrence Berkeley National Laboratory. April 21, 2003.

Hodgson and Levin, 2003b. Classification of Measured Indoor Volatile Organic Compounds Based on Noncancer Health and Comfort Considerations. LBNL report #53308. Berkeley: Lawrence Berkeley National Laboratory. September 2003.

Levin, H. 1981. "Building Ecology," *Progressive Architecture*, April, 1981.

Levin, H. (1995a). "Healthy Buildings; An Architect's Perspective." Healthy Buildings '95, Milan, Italy, 10-14 September 1995.

Levin, H, (1995b). Physical Factors in the Indoor Environment," in, Seltzer, J. (ed.) *Effects of the Indoor Environment on Health*, Occupational Medicine: State of the Art Reviews, Vol. 10, No. 1, January-March, 1995. Philadelphia: Hanley & Belfus, Inc.

Levin, H (2003), VOC Source strengths in pre- and post-occupancy periods of a new California state office building, ISEA 2003: 13th Annual Conference of bthe International Society of Exposure Assessment, Stresa, Italy, 21-25 September, 2003.

Opschoor, Hans, and Jan van der Straaten, (1993) "Sustainable Development: An Institutional Approach." *Ecological Economics*. Vol. 7, pp. 203-222.

Persily, Andrew (1989) "Ventilation Rates in Office Buildings." In *IAQ 89 - The Human Equation: Health and Comfort*. pp. 128-136.

Weschler, Charles, 2000. "Ozone in Indoor Environments; Concentration and Chemistry." *Indoor Air*. Volume 10: 269-288.

Weterings, R.A.P.M., J.B. Opschoor (1992). "The Ecocapacity as a Challenge to Technological Development." Rijswijk, the Netherlands: Advisory Council for Research on Nature and Environment (RMNO).