# Building Ecology: An Architect's Perspective -- Plenary Lecture

**Conference Paper** · September 1995

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PREPARED FOR PRESENTATION AS A KEYNOTE LECTURE AT
“HEALTHY BUILDINGS ‘95,” MILAN, ITALY, SEPTEMBER 10-15, 1995

# BUILDING ECOLOGY: AN ARCHITECT’S PERSPECTIVE ON HEALTHY BUILDINGS

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## INTRODUCTION

A healthy building is one that adversely affects neither the health of its occupants nor the larger environment. Indoor air quality (IAQ) concerns are among many indoor environmental issues that must be addressed to avoid adverse impacts on occupants’ health and well being. Among the other indoor environmental factors that must be considered are the quality of thermal, light, acoustic, privacy, security, and functional suitability. In addition to concerns about indoor environmental quality and its affect on occupants, buildings must not adversely affect the larger environment. The construction, operation, use, and ultimate disposition of a building must have minimal adverse effects on the natural environment or ultimately it will adversely affect people whether indoors or out. Buildings are healthy only if their effects on their occupants and the larger environment are benign.

This paper addresses both indoor environment, especially indoor air quality concerns, as well as general environmental concerns. It discusses recent work evaluating the impacts of buildings on the larger environment. It also reviews data available to determine norms for important building parameters and analyzes major studies of building impacts on occupant health. The analysis presented here is intended to help buildings designers’ prioritize design alternatives that minimize harmful impacts on indoor and general environments.

Very little analysis has been done to form the basis of design of environmentally benign buildings. At best, designers have simply attempted to apply known design solutions to decrease the negative impacts buildings have on the environment. This paper discusses methodological approaches to establishing priorities for environmental problems that can be addressed by building design. In order to study buildings’ impacts on their occupants and the larger environment, building ecology has been proposed as an interdisciplinary, systematic approach (Levin, 1981, 1989, 1991).

The scope of “designing healthy buildings” is far too extensive for thorough treatment in the limited space available here. Therefore, this paper focuses on methodologies for developing design guidance rather than on the detailed guidance that can result. Previous publications (mentioned below) have addressed design issues related to indoor air quality and to “sustainable architecture.” However, these have generally not been established on a sound analytical basis. The emphasis here is to explore analytical methods and sources for developing sound design guidance for healthy buildings.

## Definition of "Healthy Building"

**Indoor Environmental Quality.** Indoor environmental quality refers to all aspects of the indoor environment that affect the health and well-being of occupants. This must include not only air quality but also light, thermal, acoustic, vibration, and other aspects of the indoor environment (Levin, 1995). With respect to the indoor environment, a healthy building is one that does not adversely affect the occupants. Some authors suggest that it should even enhance the occupants' productivity and sense of well-being to be considered healthy. Thus, it is not only the absence of harmful environmental characteristics but also the presence of beneficial ones that defines a healthy building. Thus, designers should begin by avoiding harmful elements and attempt to incorporate supportive, beneficial ones.

**General Environmental Quality.** The general environment (as used in this paper) refers to the environment of the entire planet Earth. This is obviously an enormously large and complex subject. Nevertheless, the concept of a healthy building must include concern for the impacts of the building on the total environment. Environmental degradation ultimately limits the healthiness of any building. Some environmental problems, although caused by local or regional pollution or resource consumption, result in impacts with important global implications. These include destruction of the ozone layer, global warming, loss of biodiversity, and destruction of unique habitats. Resource consumption and pollution emission result in important localiz impacts such as contamination of surface and groundwater, destruction or consumption of natural resources, photochemical smog, acidification, eutrophication, soil degradation and soil erosion. A healthy building is defined as one that has minimal impacts on the local and global environment.

## Criteria for Healthy Buildings

**Table 1**. Important factors for which 'Healthy Building' criteria should be established

| *Environmental focus* | *Criteria focus* |
|---|---|
| Indoor environmental quality | Thermal environmental quality |
| | Indoor air quality |
| | Illumination |
| | Acoustics |
| | Functional support |
| | Security |
| | Privacy |
| | Way-finding |
| General environmental quality | Mineral resource consumption |
| | Energy consumption |
| | Natural resource consumption |
| | Habitat destruction, Biodiversity loss |
| | Land use |
| | Atmospheric pollution |
| | Water pollution |
| | Soil pollution |

Determination of a building's healthfulness must be based on specific criteria that can be evaluated by measurement or by informed, structured judgment. Table 1 contains a list of factors for which such criteria should be established and used in the design of healthy buildings.

# DESIGNING HEALTHY BUILDINGS

The impacts of buildings on the quality of the indoor environment and the general environment are determined by numerous factors during design, construction, operation, maintenance, and ultimate disposal of a building. They are also determined by occupant behaviors and activities, sources introduced by cooking, cleaning, personal hygiene, office products, decoration, plants, and numerous other sources. Designers only control the intended construction; builders, users, managers, and others determine many building factors that determine indoor air quality. However, designers can improve the likelihood a building will be healthy with respect to indoor air quality by anticipating the use of the building and providing for it in their designs. Where building use cannot be anticipated, general principles can be applied and flexibile designs can provide for various potential uses.

The indoor air factors under the control of the designers are the materials and systems, the ventilation, the environmental control scheme, the layout, etc. All of these significantly affect indoor air quality and other environmental factors. However, any dysfunction in the indoor environment potentially affects occupant health and well-being. When buildings fail to do what they are intended to do, indoor environmental pollution in the form of indoor air pollution, noise, glare, etc. cause occupant discomfort, health problems, and poor performance. Space does not permit discussion of the whole range of design issues in the indoor environment; this paper focuses on indoor air quality. A healthy building is one that works well to provide for the intended users and activities.

## Building design and material selection for IAQ

The most important building design and material selection IAQ considerations have been discussed extensively (Levin, 1981, 1987, 1989a, 1991, 1992, 1994; Seppänen, 1993). A rational process for building design decisions on building-related environmental factors most critical to occupant health and comfort should be based on the following:

1. The most significant health and comfort outcomes (based on frequency and gravity);
2. The plausible causal environmental factors; and,
3. The building design elements that control those factors.

A scientific basis for building design and material selection to achieve good indoor air quality is still available only to those willing to draw inferences from their studies (Platt, 1964). Scientific studies of indoor air quality (IAQ) and occupant health and comfort usually identify only associations of risk factors but do not demonstrate causality. Logical analysis and examination of the dominant evidence can be used to hypothesize certain root or primary risk factors. Designers implicitly hypothesize causality in determining what factors are important and how to address them. Designers can best target their IAQ control efforts based on analysis of identified risk factors and logical plausibility. The process described here will help design efforts have maximum impact on primary or root building factors contributing to the prevalence of sick building syndrome (SBS) and building-related illness (BRI) (Levin, 1994).

## Identifying the Most Important IAQ Design Factors

Discussion of building design and material selection in the context of IAQ should be based on the best available knowledge. There are three fundamental approaches to identifying the most important factors and to establishing criteria for design. They are shown in Table 2.

**Table 2**. Three approaches to identify important IAQ design factors

| *Approach* | *Method/Comment* |
|---|---|
| Characterize factors important to indoor air | Review and analyze major building epidemiology studies and meta-studies of their results |
| Establish norms for design | Review and analyze major building indoor environmental factors characterization studies |
| Test hypotheses using intervention studies | Study effect of changing hypothesized critical variable on outcome of interest |

Using the first approach -- characterization of factors believed important to indoor air quality -- if elevated volatile organic compounds (VOC), are often associated with elevated SBS symptoms, then VOCs can be controlled by design. The first approach involves reviewing studies of occupant responses that determine their associations with the different environmental conditions. These may be building investigations, studies, or surveys. Then the second method -- establishing norms -- can be done for important volatile organic compounds and their relevant concentrations by reviewing data from comprehensive surveys that characterize VOCs most commonly found in buildings. . The third approach (not discussed here) uses intervention studies to test hypotheses developed using the first two approaches.

The second and third methods are relevant to determining control strategies -- evaluation of the common VOC control strategies including source control and ventilation. Normative values can be based on what has been observed in studies and surveys. The norms can be used as a basis for design or for evaluation of existing conditions. The methods and outputs of the first two approaches are very different, but both are valuable sources of data that can be used to assist designers determine values and criteria for their work. The results of the use of the first two approaches is discussed below.

## Analysis of Large Building Survey Results

The largest and most important SBS studies have been reviewed extensively by several authorities including Lindvall (1992), Mendell (1993), Norback (1990), Seppänen (1994), Stenberg (1994), and Sundell (1994). Their reviews and "meta-analyses" identify risk factors for occupant SBS symptoms. A logical analysis of SBS risk factors was performed and causation hypotheses formulated in a review of the highest risk factors in the Danish Town Hall Study (Skov, 1987) by Levin (1989). Potential synergisms among the factors were hypothesized. Finally, control measures were identified to minimize SBS risks (Levin, 1989b).

Later, a set of modified risk factors that can be addressed by building design and material selection decisions were presented based on the risk factors identified in the meta-analyses (Levin, 1994). The most frequent and logically-consistent building environment determinants of occupant responses should be the targets for building design and material selection decisions. Selected risk factors found frequently in the major studies, investigations and meta-analyses are shown in Table 3.

**Table 3**. SBS risk factors identified in major studies and reviews. (Levin, 1994)

| | |
|---|---|
| BUILDING FACTORS | |
| Low ventilation rates (< 10 L/s p) | (L, M, Se, Su) |
| Ventilation operations (<10 h/d) | (Su) |
| Insufficient materials control | (L, N) |
| Fleecy materials | (N, Sk) |
| Carpets | (M, N) |
| Air-conditioning | (M) |
| BUILDING ENVIRONMENTAL FACTORS | |
| High temperature | (M, Sk) |
| High humidity | (L) |
| Low relative humidity | (M) |
| Volatile hydrocarbons | (N) |
| Microbial VOC | (L) |
| Dust | (N) |
| BUILDING USE / OCCUPANCY FACTORS | |
| High occupant density | (M) |
| VDT use | (M, St, Su) |
| Photocopiers present | (St, Su) |
| OCCUPANT FACTORS | |
| Perception of “dry air” | (St, Su) |

**Notes:** Initials of lead authors of articles listed in the Reference section.

| | | | |
|---|---|---|---|
| L= Lindvall | M= Mendell | N= Norback | Sk=Skov |
| Se= Seppanen | Su=Sundell | St= Stenberg | |

## Prioritizing design concern for IAQ

Addressing those building factors that are primary or root factors from among the risk factors in Table 3 presumably will have the greatest impact on SBS symptom prevalence rates. “Root factors” are primary or basic; they can be controlled directly, and their outcomes can be secondary or indirect risk factors. Elevated temperature is a primary risk factor because it increases the rate of microbial growth and of VOC emissions from materials. It also affects occupant perception of air quality. Low relative humidity is a secondary factor relative to elevated temperature and air conditioning. VOCs (including formaldehyde) concentrations result from one or more factors including poor material selection, inadequate ventilation (low ventilation rate or insufficient operation) and elevated temperature. But elevated temperature may also be an outcome of other risk factors such as inadequate ventilation if outside air temperatures are lower than indoor air temperatures.

Table 4 shows an elaborated set of risk factors categorized as primary and secondary. In addition to the risk factors listed in Tables 3 and 4, certain factors logically pose important risks. These are the presence of carcinogens or other genotoxic substances, strong or noxious odorants, irritants, infectious agents, or allergens; extreme temperature or humidity; and, sources of micro-organisms and their amplification and dissemination. A design philosophy of “prudent avoidance” dictates that designers implement practical control measures that can reduce or eliminate these *a prior* risk factors. Designer and client judgment as well as regulatory authorities will determine the extent of such control efforts.

Because the etiology of many (if not most) indoor air related health and comfort problems is “multi-factorial;” it is necessary to understand the linkages among contributing factors. Designers must assess theselinkages, analyze their design implications, and determine their importance for building design and materials selection. Analysis of the linkages among contributing factors can direct designs to address primary factors rather than their secondary outcomes. Outside air ventilation rate, temperature, moisture intrusion, and strong sources of contaminants are root factors. Elevated airborne concentrations of contaminants result from some one or more of the above root factors.

**Table 4**. Primary and Secondary Risk Factors for SBS and Their Potential role in SBS or BRI Etiology (Levin, 1994)

| *Primary Risk Factors* | *Secondary Risk Factors* | *Exposure or Role in SBS/BRI Etiology* |
|---|---|---|
| LOW VENTILATION<br>Air exchange rate<br>Operational hours<br>Air distribution | Reduced dilution of contaminants | Increased exposures to chemical, physical, and biological contaminant |
| STRONG SOURCES<br>Building materials<br>Furnishings<br>Occupant activities<br>Consumer/office products<br>Housekeeping materials<br>Maintenance materials<br>Outside air or soil gas | VOC emissions | Increased exposures to odorants, irritants, toxins |
| TEMPERATURE (elevated) | Microorganism amplification | Increased exposure to fungi, bacteria, viruses |
| | Occupant discomfort<br>Perceived stuffy or stale air | Increased exposure to airborne VOC |
| MOISTURE INTRUSION OR ACCUMULATION<br>Leaky building exterior<br>Condensation on surfaces<br>Standing water | Material moistening - high water activity on surfaces<br>High indoor relative humidity | Microorganism growth, Increased occupant exposure to spores, MVOC<br>Odor from MVOC<br>Material deterioration and VOC, particle emissions<br>Increased VOC emissions and exposures |

To illustrate, the intrusion of moisture into exterior building walls does not itself cause health or comfort problems. But moisture intrusion results in mold growth and, most likely elevated air levels of VOCs including microbial VOCs (MVOC). Designers can specify mold resistant materials (e.g., mineral-based products such as stone or brick) or use fungicide-treated materials, but the root problem is the moisture penetration. High water activity at material surfaces supports fungal growth and competes with VOCs for adsorption sites. Preventing or controlling the moisture intrusion will control fungal growth, reduce airborne concentrations of VOCs, reduce indoor air relative humidity, and prolong the life of the building materials and contents. Many comfort and health problems and costly remediation measures can be avoided by directly controlling moisture intrusion.

Some key factors will have both direct and indirect effects on the building environment and the occupants. Many of these key factors appear more often in research on associations between occupant symptoms and environmental factors. A key primary factor is high indoor air temperature. Occupants are less comfortable at temperatures near the upper end of the thermal comfort envelope, and they are more likely to perceive the indoor air as stuffy or stale (Berglund and Cain, 1989; ASHRAE, 1993). Furthermore, increasing temperature will increase VOC emissions from building materials, furnishings, and other surfaces due to increased vapor pressures. This will increase occupant exposures to VOCs, and microbial growth and occupant exposure to bioaerosols and microbial VOCs will also increase.

### Trade-offs, Alternative Solutions

Ultimately, the designer and building owner or occupant determine which preventive or mitigation measures to employ in a newly designed or renovated building; Their decisions are based not only on the perceived importance of the measure to reduce the risks of health and comfort problems but also on the feasibility, practicality, and cost of implementing the measures. In most cases, trade-offs are made to achieve the desired outcome. For example, to reduce the concentration of a contaminant emitted from a particular material the decision may be 1) to select low-emitting products, 2) to condition or treat the product before installation in the building, or 3) to ventilate the building after installation prior to occupancy.

### Characterize Environmental Parameters

While the analysis presented above can provide guidance to the most important problems, designers need more specific guidelines for design. Following are excerpts from a review of several surveys of selected indoor environmental parameters intended to illustrate that guideline values or norms can be established on the basis of carefully selected data (Levin, 1995b). A valuable source of information is the collection of studies that have reported data based on a consistent measurement protocol. While only a small number of these exist, they are likely far more reliable than comparisons of results from studies based on different methods or studies of very diverse buildings. Among the most interesting of these surveys are those done at large scale using reasonably standardized measurement methods, at least within a single study. The most useful of these studies are several U.S. and European surveys, mostly reporting measurements of VOCs, formaldehyde, and, in some cases, ventilation rates.

### VOC Concentrations and Emissions Data

The concentrations found in occupied non-industrial buildings are often reported as total VOC (TVOC). Virtually every measurement method, even when used correctly, likely underestimates the true TVOC concentration due to method-specific limits on the compounds that can be collected and analyzed (Wallace, 1991). Compounds with very low or very high volatility are not measured by most of the methods in common use. Many authors reporting TVOC concentrations in fact are reporting the sum of the individual VOCs that they have identified and quantified. Therefore, these values are referred to here as the sum of the VOCs (SumVOC) rather than TVOC.

Values of SumVOC in indoor air reported using the various common methods tend to fall in a range from less than 0.1 milligrams per cubic meter (mg/m$^3$ ) to 1.0 mg/m$^3$. A few buildings have been reported to have concentrations above 1.0 mg/m$^3$, and even fewer above 2.0 or 3.0 mg/m$^3$. Occasionally a building is reported with 10.0 to 20.0 mg/m$^3$, and even more rarely, with concentrations of 20 to 100 mg/m$^3$. The higher concentrations are typically attributable to easily identified strong sources - either processes or products.

**Telephone Administrative Building Survey**. Shields reported long-term (~30-day) samples collected passively on charcoal at ten telephone company administrative offices throughout the United States (Shields, 1993). The results are shown in Figure 1. None of these offices was new at the time of the study, although minor construction activity was reported in some. Most buildings measured had SumVOC concentrations ranging from about 0.15 to 0.3 mg/m$^3$. None of the ten buildings had VOC concentrations that exceeded 1.0 mg/m$^3$. However, the reported limitations of the measurement method included loss of certain compounds and an inability to identify certain others. The high concentrations found in one building were associated with construction activity

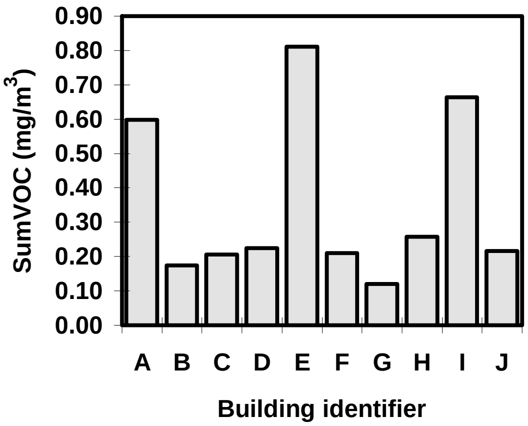

**Figure 1**. SumVOC concentrations from 10 telephone administrative offices.

**EPA Public Buildings Study.** Sheldon *et al* (1988) reported results from the two separate studies conducted for the EPA over a period of several years. The buildings included offices, nursing homes, elderly homes, and schools. In most of the buildings, the age of the building was reported. In some buildings, measurements were made on separate occasions several weeks or even months apart, thus allowing observation of the trend toward decaying emissions as building materials and furnishings age. The SumVOC values reported above 1.0 mg/m$^3$ were collected in buildings just 1 week after completion of construction.

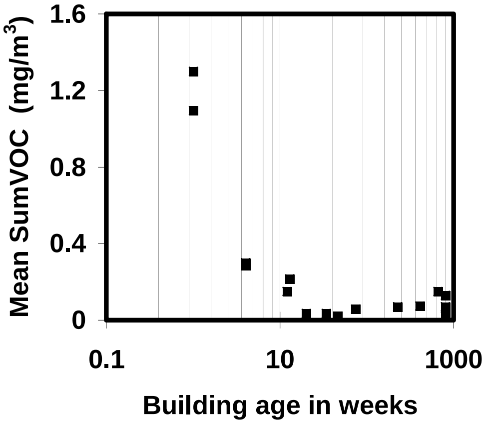

**Figure 2.** SumVOC from EPA Public Buildings Study by age of building

There is a clear overall trend in the data suggesting that the older a building may be, the lower the VOC concentrations. However, in one building, a hospital, the concentrations rose dramatically from the early to the later measurements. The specific compounds responsible for this increase were ingredients of common cleaning and maintenance materials.

**Preliminary European Audit Project Data**. Preliminary data were presented in posters by each participant country in the European Audit Project at Healthy Buildings '94 in Budapest. Data on VOCs in 38 buildings from six of the nine countries participating in the European Audit Project are shown in Figure 3. The data presented here were obtained by interpolation of bar charts presented at Healthy Buildings '94 and may not coincide exactly with the values obtained by the researchers. The six countries shown are France (F), United Kingdom (UK), Denmark (DK), Greece (GR), Switzerland (CH), and Finland (FI).

Figure 3 shows SumVOC concentrations by country for each building measured. The measurements were made using standardized sampling and analytical methods based on sample collection on Tenax, and analysis by GC/MS. (Note that these are preliminary data; Final data may differ and are expected to be reported by the overall project team in late 1995.)

The buildings were of various ages and were served by a variety of ventilation types. Many of the buildings were ventilated with mechanical systems. Smoking was permitted in some and not in others. There was a degree of variety in the buildings in each country but no strict mix formula appears to have been applied for building selection. Therefore, it may not be meaningful to plot the results together on a single chart. Similarly, even within each of the participating countries, the mix of buildings makes comparison of results among buildings difficult to interpret.

The data plotted in Figure 3 indicate that with only one exception, SumVOC concentrations in buildings were <1 mg/m$^3$, and, in most cases, they were <0.5 mg/m$^3$. There were significant variations among buildings in most of the countries reported here. Ventilation rates ranged from 0.4 air changes per hour (ach) to 10.5 ach. Country averages for air exchange rates were from a low of 0.9 ach (GB) to a high of 3.6 ach (GR). Studies reporting contaminant concentrations that also include ventilation rate measurements are particularly useful because they allow calculation of the source strengths associated with the concentrations.

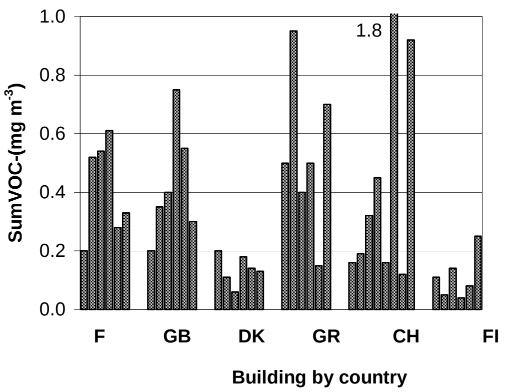

**Figure 3.** SumVOC for European Audit Project Preliminary Data

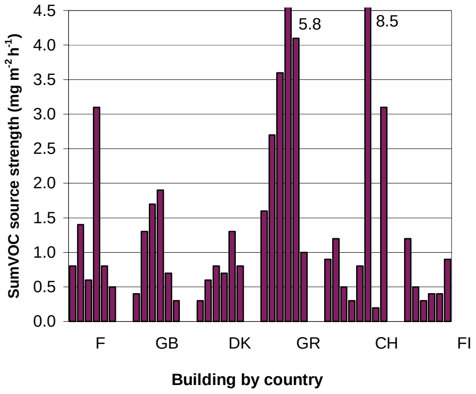

**Figure 4.** SumVOC source strengths calculated from European Audit Project preliminary data

Source strengths can be determined from measurements of concentrations and ventilation rates. For most buildings where these measurements have been made together, building-wide average source strengths tend to range from about 0.5 milligrams VOC per square meter per hour (mg m$^{-2}$ h$^{-1}$) to around 1.5 mg VOC m$^{-2}$ h$^{-1}$. In very low-VOC buildings, source strengths have been reported well below 0.5 mg VOC m$^{-2}$ h$^{-1}$, and in strong source buildings, source strengths of 2.0 to 10.0 mg m$^{-2}$ h$^{-1}$ have been found (Levin, 1995b).

Figure 4 shows average SumVOC source strengths by building for each country calculated from reported TVOC concentrations and ventilation rates. Note that the source strengths in Figure 4 are not consistent with those reported on the Healthy Buildings ‘94 posters. The source strengths reported on the posters appear implausible relative to the VOC and ventilation rate data. This may be due to lack of clarity in the project manual regarding calculation, measurment limitations, or some other cause. The final report may explain reasons for the discrepancies.

### Design Guidance for IAQ

It is clear that an analytical process can result in more systematic prioritization of design concerns to address IAQ problems. Existing data can be used to provide considerable guidance to designers considering IAQ issues. Further research will continue to clarify some of the issues, but existing research provides a considerable base of information for designing healthy buildings with respect to indoor air quality.

## GENERAL ENVIRONMENTAL IMPACT

Avoiding adverse building impacts on the larger environment may be more difficult than avoiding adverse affects on occupants. The purpose of buildings is to protect people and their possessions from the hazards and unfriendly forces of the natural environment. But to do this, the natural environment must be altered. Resources must be extracted and transformed to create and operate buildings. Water, land, living organisms, and mineral resources are used. Pollutants are emitted to the air, land, and water, and waste is produced that must be disposed if not re-used or recycled.

The major impacts of a building on the general environment are related to the materials and energy used for building construction, maintenance, and operation. Approximately 20% to 40% of all such resource consumption in the United States is related to buildings (Levin, 1995a). The impacts occur during the entire life cycle of the building as well as during the production of the building materials and products used to construct it. Life cycle analysis (LCA) methodologies are now being applied to evaluate the environmental impacts of buildings and advise designers regarding appropriate choices (AIA, 1995). These efforts are only now beginning, and much research and data gathering is necessary to fully evaluate building design decisions.

A recent trend toward increased concern about the impacts of buildings on the larger environment has led many building design professionals to design so-called “sustainable architecture” or “green buildings.” Their efforts are intended to reduce harmful environmental impacts of buildings. “Sustainable design” is usually defined as avoidance of environmental damage that will decrease the livability of the planet for future human generations. Some suggest also minimizing impacts on other living species. These are quite strongly interdependent, so treating them independently is dangerous. Regardless of which view one adopts, sustainable design remains an abstract goal not currently achieved by efforts in industrialized societies. The best that is being done now is to reduce the magnitude of the harmful environmental impacts imposed by most building activities.

Efforts to provide advice to designers abound. Among the most prominent are the BSRIA (1994), BEPAC (1993), and AIA Environmental Resource Guide (ERG) (1995). Each of these has been published - the AIA’s ERG being the most elaborate weighing in at more than 5 kg. But each of these publications and a rapidly growing number of others providing advice on “sustainable design” generally fail to provide any direction for prioritizing the various environmentally-conscious actions they recommend. Inevitably, designers must prioritize various design alternatives and recommend favored ones to their clients from among them. Design is always a matter of trade-offs, No building is likely to be completely harmless to the environment. The real question is how to boost efficiency in terms of energy and other resource use and in terms of reducing pollution while learning to build more sustainably.

The United States in particular must consider how to reduce significantly its consumption of resources and emission of pollutants by more closely balancing its environmental resource inflows and pollution outflows with the earth’s carrying capacity. Currently comprising only 4.6 percent of the global population, the U.S. accounts for about

25% of the worlds energy consumption, a little over 20% of its $CO_2$ emissions, and equally disproportionate shares of other other resource consumption and pollution emissions.

In California, more energy is used by the typical office worker commuting to work than is used in the offices where they work. Transportation and planning are critical factors. In Europe and elsewhere, efficient, convenient mass transport exists, and urbanization is generally far denser than in the United States, In most U.S. cities, and in some other parts of the world, most workers ride to work in automobiles, often one only occupant per car. The infrastructure does not exist for efficient commuting, and affordable and desirable neighborhoods are not always available close to one's workplace. The transportation sector accounts for more than one-quarter of all energy use in the United States, the industrial sector accounts for more than one-third, and commercial and residential building sectors account for more than one-third. Energy required to construct and operate buildings is estimated by various sources between 40 and 45% of all energy use in the United States (Darnay, 1994).

## Life Cycle Analysis

The :LCA process widely cited for building design has evolved from LCA methods used for consumer products. It has been codified by the Society for Environmental Toxicology and Chemistry (SETAC, 1991; 1993). It has also formed the basis for industrial ecology used to improve industrial processes and plant operations (Graedel and Allenby, 1995). The traditional use of LCA has been to evaluate consumer products. However, these evaluations have focused on inventory and impacts related to the production and disposal of consumer goods while largely ignoring the product's use phase. Building designers, operators and users must emphasize the use phase when they design, so a more meaningful "modified LCA process" includes the use phase. A building design-oriented adaptation of the LCA process is shown diagramatically below.

Inventory ⇒ Impact ⇒ Valuation/Ranking ⇒ Design ⇒ Implementation ⇒ Feedback

## Determining What's Important to Guide Design

To guide design to reduce buildings' environmental impacts, it is important to prioritize efforts according to the most critical environmental problems. For example, is global warming a more important problem than ozone depletion or biodiversity loss? Should design efforts to minimize one of these or other problems dominant or be submerged relative to other design alternatives? The problem of deciding what to do during design is unmanageable due to the large number and the inter-relatedness of the various environmental concerns. The necessary prioritization can be done by examining the total impact of buildings on the environment and by ranking the most important environmental problems. This will allow a hierarchy of design features related to environmental protection.

To assess buildings' contributions to LCA inventory flows and environmental impacts, estimates of building-related contributions were prepared from U.S. national data (Levin et al, 1995a). Building-related raw materials uses average about 40% of U.S. raw material consumption. For some materials such as PVC, timber, sand, and clay, it is >50%. Building operational energy use is >35% with an additional 5% or more of U.S. energy use embodied in building materials. Water use, including industrial and power plant operations attributable to building construction and operation, is ca. 20%. Building-related atmospheric emissions of $CO_2$ for building-related energy use and for producing building-related materials are >30% of U.S. totals. Between 25% and 35% of solid waste produced in the U.S. is building-related -- either direct (e.g., from construction, demolition) or indirect (e.g., mining resources for building materials and products).

Building-related "other releases" or emissions (including noise, thermal pollution, radiation, electromagnetic fields) represent significant fractions of such releases (Darnay, 1994; Brown, 1995).

These data indicate that building-related contributions to total inventory flows and environmental impacts normally assessed in LCAs are large and, therefore, important. The detailed analyses for these estimates are being used to scope ongoing modeling and to prioritize data gathering efforts aimed at developing guidance for building designers, product manufacturers, and others trying to create "sustainable" buildings or "green" building products.

By examining building-related environmental impacts, it is possible to identify those of greatest concern. By assessing inventories in relation to prioritized impacts of concern, design, manufacturing, construction and building operation activities can be focused on those most likely to produce buildings that are least harmful to environmental end points of concern. Work in progress is improving the reliability of the inventory estimates. Work is also being undertaken to articulate the network or chain of impacts in order to categorize the end-points of concern and identify inventory-impact vectors of greatest significance.

## Identifying the most important problems

To identify the most important environmental problems, it is necessary to apply consistent criteria. The Science Advisory Board (SAB) of the U.S. EPA developed a set of criteria for their report, "Reducing Risks" (EPA, 1992) Table 5 shows the four criteria used by the EPA's SAB plus two more appropriate for building design considerations.

**Table 5.** Criteria for priority ranking of building-related environmental problems

1. THE SPATIAL SCALE OF THE IMPACT
   Global, regional, local (large scale being worse than small)
2. THE SEVERITY OF THE HAZARD
   More toxic substances being of more concern than less toxic substances
   Irreversible changes - e.g., death or species extinction -- is more severe than reversible damage
3. THE DEGREE OF EXPOSURE
   Well-sequestered substances being of less concern than readily mobilized substances
4. THE PENALTY FOR BEING WRONG
   Longer remediation times being of more concern than shorter times
5. THE STATUS OF THE AFFECTED SINKS
   An already overburdened sink is more critical than a less-burdened-one
   (Sinks = receptors, environmental compartments)
6. THE RELATIVE CONTRIBUTION OF BUILDINGS
   Large share of building-related in- or out-flows being worse than a small share

Using these criteria, environmental problems are classified or ranked. The U. S. EPA Science Advisory Board (SAB) used the first four criteria shown in Table 5 and ranked risks as top, medium, or low priority. The two additional criteria added to the SAB list are intended to improve the applicability of the criteria for application to building problems and design. The resulting rankings are shown in Table 6.

**Table 6 .** Priority ranking of environmental problems; (source: EPA Science Advisory Board, 1990).

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Relatively High Risk Ecological Problems:

- Habitat alteration and destruction
- Species extinction and overall loss of biological diversity
- Stratospheric ozone depletion
- Global climate change

Relatively Medium-Risk Ecological Problems:

- Herbicides/pesticides
- Toxics, nutrients, biochemical oxygen demand, and turbidity in surface waters
- Acid deposition
- Airborne toxics, including smog related constituents

Relatively Low-Risk Ecological Problems:

- Oil spills
- Groundwater pollution
- Radionuclides
- Acid runoff to surface waters
- Thermal pollution

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A separate list of health problems was also prepared, although not with any ranking. These appear in Table 7.

**Table 7**. High risk health problems (source: EPA Science Advisory Board, 1990).

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High Risk Health Problems:

- Indoor Air Pollution
- Outdoor Air Pollution
- Worker exposure to industrial or farm chemicals
- Pollutants in drinking water
- Pesticide residues in food
- Toxic chemicals in consumer products

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Using the lists in Tables 6 and 7 to prioritize actions intended to avoid or minimize environmental damage focuses design efforts on the most critical problems. Thus, solution of the problems listed as high risk should not be compromised substantially to address problems ranked lower. A difficulty occurs when attempting to make trade-offs between ecological risks and health risks. Nevertheless, this ranking allows prioritization of the various “environmentally conscious” design activities and actions related to the highest risk environmental problems. Table 8 shows an example of several environmental problems and the design issues related to them. By focusing on the highest priority problems, designers can be more confident that their solutions have appropriately addressed environmental issues of greatest importance. An example is shown in Table 8 using five ecological and health risks prioritized according to the criteria in Table 5 as top, medium, or low, priority. In the right hand column, building design issues are identified related to the ecological or health problem in the left hand column.

**Table 8.** Example of five environmental (ecological and health) impacts listed by priority with their main contributors in buildings.

| *Ecological or health problem* | *Priority group* | *Contributors in buildings (that can be influenced during design or by changing the building)* |
|---|---|---|
| TOP PRIORITY | | |
| Ozone depletion | TP | Refrigerants<br>Foams for insulation<br>Excess energy consumption requiring refrigeration |
| MEDIUM PRIORITY | | |
| Acid deposition | HP1 | Electricity use (coal/oil generated) for lighting, heating<br>Some building related industries |
| Groundwater resource depletion | HP2 | Water used for washing/bathing, toilet flushing<br>Water used for cooling in power plants<br>Water used when making building materials |
| LOW PRIORITY | | |
| Indoor air pollution -- non-radon | MP 1 | Building materials, ventilation systems<br>Operation and maintenance<br>Operations malfunction<br>Finish renewal, renovation |
| Chemicals in the workplace | MP2 | Copper in electrical wires<br>Roofing materials<br>Plastics in pipes/on roofs, etc.<br>Aluminum window frames, etc. |

A more sophisticated approach requires estimation of the resources consumed and environmental emissions of each alternative. Then the emission or resource consumption must be related to the environmental problem of concern and the magnitude of the environmental impact estimated for each environmental problem. Next, the emissions must be multiplied by a weighting factor representing the seriousness of the problem as ranked by criteria shown in Table 5. One difficulty in assigning a weighting factor is determining the economic and other basis for valuing various environmental and health risks. Different people will value them differently according to their viewpoint and interestss. Many useful approaches to valuation have been described that can incorporate the value of natural resources such as significant views, resources, species, or other elements of the natural world that are not necessarily valued by traditional economic analyses (Pearce, 1993).

The ranking or score or other information can be derived to guide design decisions will ultimately be limited by data availability, scientific knowledge of environmental impacts, and projections of future population, resource limitations, and environmental consequences. Nevertheless, a score or ranking system can call attention to critical problems and produce more informed design decisions. It can also help prioritize the actions of building products manufacturers, of researchers, and of policy-makers. Finally, it can call attention to data and research needs to improve the process of determining critical environmental factors.

## DECIDING WHAT’S IMPORTANT IN DESIGN

A simple illustration of the application of criteria that might be developed for healthy material selection considering the indoor air quality, indoor environment, and the general environment is shown in Table 9. The importance of each factor for each environment is indicated by the number of marks in the matrix. This exercise shows that there is considerable overlap among the criteria for different environmental compartments.

**Table 9**. Sample Matrix of Criteria for Healthy Materials Selection

| *Material Selcetion Criteria* | *IAQ* | *Indoor Env't* | *General Env't* |
|---|---|---|---|
| Resource conservation | X | | XXX |
| Durability | XX | X | XXX |
| Low emissions/pollution production | | | XXX |
| Low emissions/pollution finished | XXX | | XX |
| Maintenance chemical requirements | XXX | X | XX |
| Replacement frequency | XX | X | XXX |
| Hard surface (IAQ vs. acoustics) | XX | XXX | |
| Smooth surface | XXX | XX | X |
| Energy consumption | X | XX | XXX |

## Design Guidance

Following is preliminary design guidance that attempts to integrate both indoor and general environmental considerations.

**Resource conservation.** Selecting building materials and products that are extremely durable and can be expected to perform well over an extended useful life will generally result in a better environmental choice than one that must be replaced twice or even ten times during the same time period. This is evident from the approximately ten-fold greater relative additional resource extraction/consumption, manufacturing, transport, installation, and disposal. A roof used in many European applications may last between one and three hundred years while in the United States typical roofs last ten to thirty years. It is obvious that the environmental impacts of U.S. roofs are roughly ten times that of the European roofs regarding the extraction and disposal of materials. Long-lived products are an inherently preferred solution for resource conservation and environmental protection.

Re-using materials and products that have reached the end of their useful lives is the next most effective way to avoid withdrawal of additional resources and creation of environmental pollution associated with the extraction, transport, processing, manufacturing. and installation. A longer-lasting material is inherently more desirable (Goldbeck and Goldbeck, 1995).

Durable materials tend to have low emissions. Therefore, the tend to be better for indoor air quality than less durable ones. They may also require less frequent application of maintenance and surface renewal chemicals and use of less harmful chemicals. There is a sort of multiplier effect from the use of durable materials..

Designs that assume frequent changes in interior partitions should provide for re-mounting durable ones rather than demolition/disposal and new construction.

**Pollutant source control.** Controlling pollution at the source is generally four times as cost effective as removing pollution from air, water, or soil. This applies both to indoor air as well as ambient air. It also applies to both surface and groundwater water. It is widely accepted that the most effective strategies for indoor air quality involve reducing indoor air pollutant sources and their source strengths or toxicities by one of the following measures: elimination, reduction, substitution, or source isolation. Important considerations for material selection and indoor environmental quality include functional requirements, surface characteristics, total mass, chemical composition and emissions, durability - longevity, and cleaning, maintenance and renovation requirements. Selecting low-emitting materials, especially for those products that will be present in large quantities by mass or exposed surface area, is also important to reduce emissions to the general environment. Typically, low-emitting products will have resulted from production processes involving lower exposures of the manufacturing workers.

Design for effective moisture protection is important to prevent intrusion of water from outdoors through cracks, openings, or semi-permeable membranes and eliminate potential for standing water or condensate inside the building from chilled water systems. This will prevent the growth of microorganisms. This will also prolong the life of the building and its components resulting in resource conservation.

**Energy conservation.** The first step toward reducing energy consumption is conservation. This includes effective building envelope insulation, tightly-sealed openings, and control of air movement and thermal transport mechanisms between the building and the outside and, in some cases between spaces within the building. This does not mean minimal ventilation; it mean reducing the requirements for conditioning ventilation air by avoiding unintentional thermal losses. Energy conservation will produce more comfortable indoor environments. Energy conservation is extremely important in reducing potential emissions of greenhouse gases at power plants, and acid-forming gases that cause acid deposition. This will also reduce the need for refrigeration involving ozone-depleting compounds.

**Energy efficiency.** Where energy-consuming devices are required (such as fans, pumps, motors, appliances, etc.) it is essential to select efficient appliances. The ratio between the best and worst in a class of products may easily be 2-to-1 or even 3-to-1, so it does make a great deal of difference which product is selected.

**Ventilation.** Ensure adequate ventilation to control pollutants that reach the indoor air by reducing and removing them through dilution, exhaust (local, general), filtration, and air cleaning. Occupant-controlled ventilation can produce energy savings while reducing occupant stress and building sickness symptoms.

**Overall design.** Design for the whole person: The human body and mind integrate all the factors in the physical, chemical, biological, and psychosocial environment. Full integration of environmental considerations in design will include not only indoor air quality but also thermal comfort, lighting, acoustics, and spatial relationships. Such designs will be inherently healthier. A building that meets the needs of its users (occupants, operators, others) will endure longer and not require demolition, replacement, or other resource- and pollution-intensive actions. The more satisfied building users are, the longer the building will remain in service, avoiding the need for additional construction.

Building design and indoor environmental quality issues must be considered throughout the process of planning, design, construction, use, and disposal/re-use/recycling buildings. The major design phases include site selection, project feasibility, budgeting, building configuration, building envelope, environmental control scheme, energy considerations, and environmental impact analysis.

## DISCUSSION and CONCLUSION

This paper has emphasized a “building ecology” view of buildings as dynamic, interdependent systems (Levin, 1981). This view argues for planning during the design phase for varying cycles of building performance and use or requirements during the building’s lifetime. The more specific the analysis, the more relevant its application to any given building design. Generic analyses are helpful but suffer from the potential to miss important characteristics of a particular situation.

Examining sample decisions, it becomes apparent that in many instances, the design alternative best for indoor environmental quality is also best for general environmental quality. For example, durable materials will be less likely to emit contaminants into the indoor air, will require lower quantities and less toxic chemicals for the maintenance and refurbishing, and, by definition, will be longer lasting. Service life is an extremely important determinant of overall impact on the general environment since each replacement cycle requires the use of additional resources with the concomitant pollutant emissions.

Designers must be aware of the impacts of the building on the larger environment. These will include impacts on biodiversity, global warming, ozone depletion, on the soil, air, and water, on resource depletion, on waste generation, and on energy consumption,. Some of these will ultimately, although perhaps imperceptibly, affect the building itself and its users. Therefore, each building must be planned and designed as though it were being replicated a million times over so that we take seriously the consequences of its impacts on the global environment and, in a very real sense, its own environment.

## ACKNOWLEDGMENTS

The preparation of this paper was based in part on work prepared by Atze Boerstra, Shela Ray, and Eugena Bendy.

## REFERENCES

Aizlewood, C. and R. Walker, and D. Dickson, 1994. The European audit project to optimize indoor air quality and energy consumption in office buildings; national preliminary results: UK. Poster presentation at Healthy Buildings ‘94, Budapest.

AIA, 1995. “Environmental Resource Guide.” Washington, D.C.: American Institute of Architects.

ASHRAE, 1993.. *Standard 55-1993, Thermal comfort for human occupancy.* American Society of Heating, Refrigerating, and Air-conditioning Engineers, Inc., Atlanta:

BEPAC, 1993. *Building Environmental Performance Assessment Criteria; Version 1, Office Buildings, British Columbia.* Vancouver: University of British Columbia School of Architecture..

Berglund, L. and W. S. Cain 1989.. Perceived air quality and the thermal environment. *Proceedings of IAQ ‘89* American Society of Heating, Refrigerating, and Air-conditioning Engineers, Inc., Atlanta:

Black, M.S., W.J. Pearson, L.M. Work. 1991. A methodology for determining VOC emissions from new SBR latex-backed carpet, adhesives, cushions, and installed systems and predicting their impact on indoor air quality. in *IAQ '91 - Healthy Buildings*, Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., pp. 267-272. 1991.

Brown, L. et al, 1995. *State of the World, 1995*. New York: W. W. Norton & Company, Inc. 255 pp.

Brown, S., M. Sim, M. J. Abrahamson, C. N. Gray, 1992. Progress towards national indoor air quality goals for volatile organic compounds, report to the Air Quality Panel of the National Health and Medical Research Council (Australia).

BSRIA, 1994. *Environmental Code of Practice for Buildings and Their Services*. Bracknell, Berkshire, UK: The Building Services Research and Information Association. 130 pp.

Cochet, C., S. Kirchener, and J. Ribéron, 1994. The European audit project to optimize indoor air quality and energy consumption in office buildings; national preliminary results: France. Poster presentation at Healthy Buildings ‘94, Budapest. 1994.

Darnay, Arsen J., (ed.) 1994. *Statistical Record of the Environment, Second Edition*. Detroit: Gale Research Inc.

EPA Science Advisory Board1990. “Reducing risks: Setting priorities and strategies for environmental protection”. Report SAB-EC-90-021 and 021a. Washington DC: United States Environmental Protection Agency.

Friends of the Earth, Netherlands 1992. “Action Plan ‘Sustainable Netherlands.’” The Netherlands.

Goldbeck, Nikki and Goldbeck, David, 1995. *Choose to Reuse*. Woodstock, New York: Ceres Press. 452 pp.

Graedel, Thomas, and Allenby, B. R. 1995. *Industrial Ecology*. Englewood Cliffs, New Jersey: Prentice Hall. 412 pp.

Groes, L., G. Clausen, J. Peitersen, and P. O. Fanger, 1994. The European audit project to optimize indoor air quality and energy consumption in office buildings; national preliminary results: Denmark. Poster presentation at Healthy Buildings ‘94, Budapest. 1994.

Lazoudi, F., D. Asimakopoulos, M. Santamouris, 1994. The European audit project to optimize indoor air quality and energy consumption in office buildings; national preliminary results: Greece. Poster presentation at Healthy Buildings ‘94, Budapest. 1994.

Levin, H. 1981 Building ecology. *Progressive Architecture*. Vol. 62, No. 4, (April) 173-175.

Levin, H. 1987. Protocols to improve indoor environmental quality in new construction, in *Proceedings of IAQ ‘87.* American Society of Heating, Refrigerating, and Air-conditioning Engineers, Inc., Atlanta.

Levin, H. 1989a. Building materials and indoor air quality, in, Hodgson, M. and Cone, J., (eds.), *State of the Art Reviews in Occupational Medicine*, Vol. 4, No. 4.

Levin, H. 1989b. Edifice complex, anatomy of sick building syndrome and exploration of causation hypotheses. *Proceedings of IAQ ‘89.* American Society of Heating, Refrigerating, and Air-conditioning Engineers, Inc., Atlanta.

Levin, H. 1991. Critical building design factors for indoor air quality and climate: current status and predicted trends. *Indoor Air* 1, 79-92.

Levin, H. 1992. "Controlling sources of indoor air pollution" in H. Knöppel and P. Wolkoff (Eds.) *Chemical, Microbiological, Health and Comfort Aspects of Indoor Air Quality -- State of the Art in SBS*. Kluwer Academic Publishers. 321-342.

Levin, H., 1994. “Building Design and Material Selection.” Keynote lecture in *Proceedings of Indoor Air; An Integrated Approach*. (Symposium held in Queensland, Australia, November 1994). in press.

Levin, H., A. Boerstra, and S. Ray, 1995a, “Scoping U.S. Buildings Inventory Flows and Environmental Impacts in Life Cycle Assessment” Presented at Society for Environmental Toxicology and Chemistry (SETAC), Impacts assessment work group meeting, Alexandria, VA, April 19.

Levin, H. 1995b. “Emissions Testing Data and Indoor Air Quality.” in, Haghighat, F. (ed.), *Indoor Air Quality, Ventilation, and Energy Conservation in Buildings, Proceedings of the Second International Conference, Volume 1*, 465-482.

Lindvall, T. 1992, The sick building syndrome - overview and frontiers. in H. Knöppel, and P. Wolkoff, (eds.) *Chemical, Microbiological, Health and Comfort Aspects of Indoor Air Quality - State of the Art in SBS.* Kluwer Academic Publishers, Dordecht.

Mendell, M..J. 1993. Non-specific symptoms in office workers: A review and summary of the epidemiologic literature. *Indoor Air* 3, 227-236.

Norbäck, D. 1990. Environmental exposures and personal factors related to sick building syndrome, Thesis, Uppsala University, Uppsala, Sweden.

Pearce, David W. 1993, Economic values and the Natural World. Cambridge, Massachusetts; MIT Press. 129 pp.

Persily, Andrew, 1989, *Proceedings of ASHRAE IAQ '89*. Atlanta: American Society of Heating, Refrigerating, and Air-conditioning Engineers, Inc.

Platt, John R., 1964. "Strong inference." *Science* Vol. 146 (3642): 347-353.

Roulet, C.-A., F. Foradiri, C.-A. Bernhard, L.Carlucci, 1994. The European audit project to optimize indoor air quality and energy consumption in office buildings; national preliminary results: Switzerland. Poster presentation at Healthy Buildings '94, Budapest.

Seppänen, O. 1994. *Indoor Air '93; Summary report*. Finish Society of Indoor Air Quality and Climate (FiSIAQ), Helsinki.

SETAC, 1991. *A Technical Framework for Life-Cycle Assessment* Washington, DC: SETAC. 134 pp.

SETAC, 1993. *A Conceptual Framework for Life-Cycle Impact Assessment.* Pensacola, Florida: SETAC. 160 pp.

Sheldon, L., R. W. Handy, T. D. Hartwell, R. W. Whitmore, H. S. Zelon, and E .D Pellizzari, and L. Wallace, Indoor air quality in public buildings. Volumes II and II. EPA Report EPA/600/6-88/009a and EPA/600/6-88/009b. 1988.

Shields, H.D. and. M. Fleischer, 1993. VOC survey: sixty-eight telecommunication facilities, *Proceedings of the 6th International Conference on Indoor Air Quality an Climate*, Vol. 2, 93-98.

Skov P, Valbjorn O, and the Danish Indoor Study Group: 1987. The sick-building syndrome in the office environment: the Danish Town Hall Study. *Environ Internat* 13:339-349.

Stenberg, B 1994. Office illness; The worker, the work and the workplace. Umeå University Medical Dissertations, New Series No 399. Umeå , Sweden.

Sundell, J. 1994. On the association between building ventilation characteristics, some indoor environmental exposures, some allergic manifestations and subjective symptom reports. *Indoor Air, Supplement No. 2/94.*

Wallace, L., E. Pellizzari, and C. Wendel, 1991. Total volatile organic concentrations in 2 700 person, indoor, and outdoor air samples collected in the US EPA Team studies, *Indoor Air*, Vol. 1, 465-477.

Woods, J.E. 1987. Testimony presented before the Subcommittee on Environmental Protection of the Committee on Environment and Public Works, United States Senate. November 20.