The 4th international Symposium on HVAC
Beijing, China, October 9~11, 2003

SUSTAINABLE BUILDINGS: THE LOW ENERGY PATH TO GOOD INDOOR AIR QUALITY

Hal Levin

Building Ecology Research Group, 2548 Empire Grade, Santa Cruz, California, USA 95060. hlevin@cruzio.com

ABSTRACT: As we attempt to improve the indoor climate (air, thermal, illumination, and acoustic quality) in buildings, we run up against the constraints of resource availability and the effects of their use. In particular, we are challenged to find ways to ventilate, heat, cool, illuminate buildings with minimal consumption of energy. We must find the low-energy pathways. Unfortunately, it is far too tempting to simply select advanced technologies based on their efficiencies and reliability rather than to consider more fundamental building design questions in the context of overall sustainability. When we consider the entire environmental context, both within and beyond the building enclosure, then we are compelled to seek the low-energy path to good indoor air quality. Fortunately, there are abundant opportunities to design comfortable, healthy, and productive indoor environments at less economic and environmental cost with currently available and proven technology including daylight-based illumination and passive ventilation and thermal control. However, to do so, we must re-examine some of our assumptions that have led us to the present crisis where only a small fraction of the world's population can afford the costs of energy services to provide building services exclusively through mechanical and electrical means. In the end, we need a comprehensive approach to buildings and the environment such as that described as “building ecology.” [1]

Keywords: Sustainable buildings, green buildings, ventilation, energy, comfort, health, productivity, building ecology

1. INTRODUCTION

Building technology available today can provide buildings that are more comfortable and healthier indoor environments that use only 10 to 25% of the average modern building energy use. Many of these technologies are less costly, less intrusive, and less susceptible to failure from improper construction, operation, or maintenance. They are more satisfying to their occupants, use fewer resources, and emit less pollution. The energy performance and satisfaction of occupants of buildings built with these technologies has been verified. Since buildings account for over 40% of total energy consumption, this 75% to 90% reduction in energy consumption amounts to a potential reduction of 25% to 35% of total national energy use in the United States and most industrialized countries.

Minimizing global climate change requires radically reduced greenhouse gas emissions and the energy consumption that relate to such emissions. Building and transportation energy consumption represent the two of the three major consumption sectors with the greatest potential for significant reductions due to their very large current inefficiencies. The inefficiency of the transportation system in general as well as the inefficiency of individual motor vehicles provides enormous opportunities for reductions. Today's more fuel-efficient automobiles get 18 to 25 km per liter of gasoline compared to the passenger vehicle "fleet" average, which is less than 40% of that value. Therefore, there exist today technologies that are capable of a two- to three-fold reduction in automobile fuel consumption. This alone could produce a 10 to 15% reduction in total overall energy consumption in industrialized economies. This is an excellent example for those of us who are scientists and building professionals.

So, just from applying demonstrated, currently available automobile and building technology, a 50% reduction in total current energy consumption is achievable. While this may seem improbable or unnecessary, keep in mind that as energy services become more widely distributed throughout the world, the number of installations will increase rapidly. Since less than a quarter of the world's population has access to these technologies now, as the number of people who gain access to them increases to 50% of the global population over the next 30 to 50 years, and as the global population simultaneous increases from the present 6×10^9 to the United Nations’ projection of 10×10^9 people by the year 2050, these potential 50% reductions will not even keep our energy consumption and greenhouse gas emissions rates where they are now. Clearly current levels of fuel consumption or greenhouse gas emissions and their effect on climate are clearly not sustainable. Therefore, far greater improvements must be made if much more of the world's population is to benefit from these technologies. Where will these improvements come from and how can we help accelerate their development and application?

1.1 The Challenge of Creating Sustainable Buildings

There is widespread, growing interest in protecting the environment, especially public buildings. But how is one to know what is "sustainable?" In general, the meaning is vague and inconsistent among so-called "green" buildings. Even the best of buildings built today fail to reduce resource consumption and pollution emissions to a sufficient degree compared to the scale of the reductions needed to create truly "sustainable" buildings. It is difficult (if not impossible) to find a building being built today that could be regarded as truly sustainable.

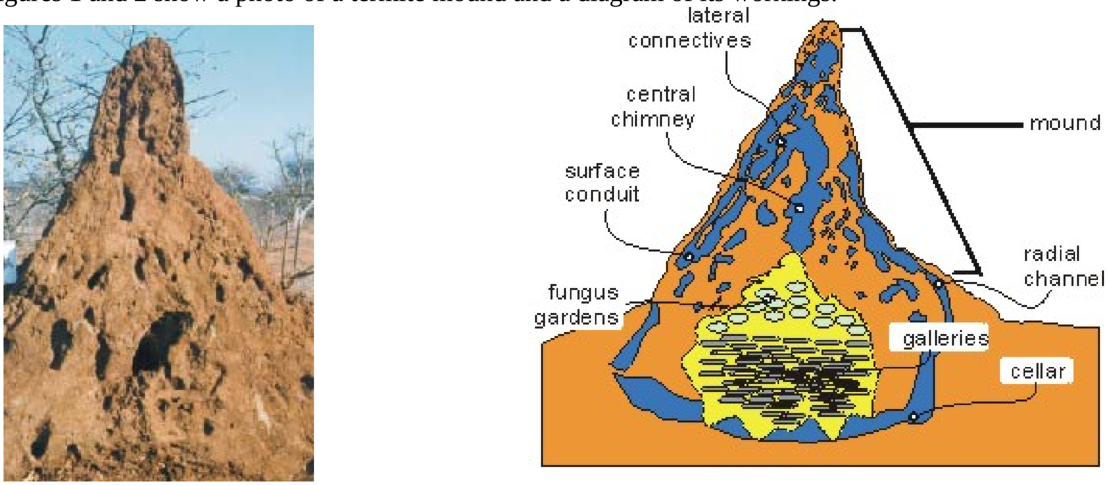
There are many barriers to sustainable buildings and a sustainable society. These include, among others, the excessive emphasis on short-term economic consideration; globalization of local, regional, national and continental economies, political realities, corporate criteria for profitability; and unbridled greed. The impacts and costs of these barriers to a sustainable society include a widespread and growing focus on consumption, not preservation of ecosystem productivity and environmental values. Environmental concerns include long-term considerations. A short-term focus increases long-term environmental costs. There is currently almost no understanding of the extent of environmental improvements required to achieve sustainable building practices, a sustainable economy, and sustainable societies.

"Sustainable building" is a construct without any inherent or consistent meaning. Everyone who uses the term has his/her own unique understanding its meaning. As with any such construct, it is not possible to measure just one characteristic of a building's environmental performance and then decide whether it is "sustainable." Many things have to be measured, and few of us would agree on what those many things are. Beyond that, we might disagree on the importance of various individual characteristics. Is air pollution more important than water pollution? What about global climate change or species extinction? These are matters of values, very personal matters. Yet implicit in the design decisions we make are choices to focus more or less on one or another environmental goal or concern.

1.2 A Natural Solution

"Imagine a very tall structure built with totally natural materials that is designed to maximize heat gain and storage in the winter, minimize heat gain in the summer, provide natural ventilation to maintain a near constant flow of fresh air and thermal stability for a whole community, including a "nursery" for babies and a farm. And when the structure reaches the end of its life and is abandoned, it goes back to the earth leaving the soil more fertile than before the structure was built and operated. Well, you don't have to imagine them, they exist and are designed and engineered and built by millions of tiny insects with even smaller brains. Of course if you took all the brains in a whole termite colony and clumped them together they might approximate the size of a human brain. What is most interesting is that mound building is an emergent property in termite colonies. Individual termites and smaller numbers of termites show no mound building capability or activity. Apparently it takes some critical mass of termites for this ability to emerge. Below that they just burrow and create more typical subterranean termite nests." [2]

“A startling example of complex and coordinated behavior emerging without leaders or plans is found in a species of termites. In Africa and Australia, certain termites build intricate towers 20 to 30 feet high; these are the largest structures on earth proportionate to the size of their builders. These towers are engineering marvels, filled with intricate chambers, tunnels, arches, and air-conditioning and humidifying capabilities. Termites accomplish this feat by following a bizarre job description. They wander at will, bump up against one another, and react. They observe what others are doing and coordinate their own activities with that information. Without blueprints or engineers, their arches meet in the middle.” [3] Figures 1 and 2 show a photo of a termite mound and a diagram of its workings.



Figures 1 and 2. Termite mound photo and diagram. [4]

1.3 In Search of Sustainable Buildings

The term "sustainability" has been defined frequently and used even more often. [5] When discussed in the context of the impacts of buildings on the environment, its meaning is ambiguous and often distorted. Buildings are not simply either "sustainable" or not. No buildings being built today are sustainable in the true sense of the word. While many guidelines exist for guiding design to improve building environmental performance, most of the available guidelines do not assess the total impact of a building on the environment. Instead, they tend to rate buildings on the basis of individual features considered "sustainable" by the designers. A more rigorous approach to assessing building sustainability is needed in practice. Such an approach evaluates a building by its total effect on the environment, not by the number of discrete "green" maneuvers it makes. The assessment of a building's impacts on the environment must be related to goals for meeting local, national, and global environmental needs. Such goals can be established and used as benchmarks for building performance. These procedures can be used with available design tools to create new buildings and to evaluate existing buildings on the basis of their projected total environmental performance. Some software tools exist that can support decision-making to design buildings based on rigorous analysis of the environmental impacts. Using such tools, we can learn enough to make wise decisions and create buildings that are more sustainable. [6]

1.4 Barriers to Sustainable Buildings

Environmental impacts often are hard to detect until they are extensive and difficult to mitigate or reverse. The appearance or detection of impacts is often delayed, sometimes by weeks, months, years, or even decades. The ozone hole wasn't discovered until it was quite extensive. There are only limited international agreements concerning the release of greenhouse gases, and the causal relationship to climate change is not adequately characterized. The problem is further exacerbated by the way we govern ourselves in democratic nations. Politicians run for re-election after very short intervals in office, so their focus tends to be short-term. Economic priorities similarly favor short-term thinking. Yet environmental health of our ecosystems is a long-term concern and necessity.

Their creators or users do not usually observe environmental impacts of an individual building; the affected population is often at a distance in time and space from the building itself. Energy used in a building is produced remotely. Acid deposition occurs downwind from the coal-fired power plants that release the acidic aerosols. Traces of highly toxic chemicals have been found at high altitudes in remote locations in the Andean Mountains of South America. Pesticides and fertilizers that drain into waterways (creeks, streams, and rivers) alter and usually harm aquatic environments downstream and in the lakes, seas and oceans into which they flow.

Buildings are very large contributors to environmental deterioration. Buildings account for 15% to 45% of the total U.S. environmental burden for each of the eight major Life Cycle Assessment inventory categories as shown in Table 1 [7,8]. Determining buildings' contributions allows prioritizing generic environmental protection goals (discussed later in this article). The portion of buildings' environmental impacts is generally consistent on a global scale.[9]

Table 1. Environmental Burdens of Buildings, 1993-5 U.S. data [7,8]

Resource use	***% of total***	***Pollution emission***	***% of total***
Raw materials	30	Atmospheric emissions	40
Energy use	42	Water effluents	20
Water use	25	Solid waste	25
Land (in SMSAs)	12	Other releases	13

1.5 The Dutch Concepts of "Ecocapacity" and "Ecospace"

A set of target values for environmental resource consumption and pollution can easily be derived. While such targets themselves are subject to human judgment, they can reflect the best available science, and if the methodology is transparent, as it should be, the targets can be revised as new information arrives. The Dutch government-commissioned a study to propose just such goals in order to move Dutch technology toward sustainability over a 50-year time frame [10]. The authors assumed that all humans are entitled to the same amount of environmental resources and to contribute an equal share of pollution -- that is, each inhabitant is entitled to the same "ecospace." They established some "ecocapacity" limits on basic resource consumption and pollution emissions, then calculated ecospace targets for 50 years in the future. The authors allocated environmental resources among nations and calculated the Dutch share. Then, working backwards, they calculated reductions ranging from 20 to 95% are necessary in current consumption and pollution to achieve sustainability.

The Dutch authors point out that there is a 30 to 1 disparity in resource consumption and pollution emissions shares between inhabitants of OECD (developed) nations and developing nations -- or between "north" and "south." The authors propose a goal of reducing the “ecospace” disparity to a ratio of 10 to 1 in the next 50 years. The Dutch estimate that their carbon dioxide emissions must be reduced by 80% in the next 50 years. Using their method to calculate reductions in per capita energy consumption in the United States necessary by the year 2050 for Americans to share equally with all the earth's projected 10 billion inhabitants, Americans must reduce current per capita greenhouse gas emissions by more than 95%. Reductions of 80 to 95% are necessary in several other categories.

2. DESIGNING SUSTAINABLE BUILDINGS

In trying to create a sustainable building - one that is healthy for its occupants and has minimal impacts on the environment -- we are dealing with a very complicated web of interactive problems, issues, goals, actors, and relationships. The relationship between sustainability, energy consumption, and good indoor air quality is complicated and inseparable. Reducing mass flows increases sustainability [11]. In buildings, this includes the mass of materials to construct, operate, and maintain a building and the energy and other resources consumed and the mass of pollutants emitted over a building's life cycle. It also includes preservation or restoration of natural habitats in order to minimize impacts on biodiversity and a healthy ecosystem. But there will be tradeoffs required, and these should be based on a clear set of environmental goals and priorities. Finally, to some degree, it includes enhancing human health and well-being, now and for the indefinite future. [5]

3. CREATING A HEALTHY INDOOR CLIMATE

A healthy indoor environment is an essential part of a sustainable building. It must address the ability of the indoor environment to support healthy, comfortable, and productive occupants. To do this, the focus on indoor environmental quality includes the whole indoor climate -- thermal, illumination, acoustic, and indoor air quality. The essential questions that must be answered are as follows:

- How to protect, facilitate, or enhance human comfort, health, and productivity?
- How to minimize the use of energy and other scarce and polluting resources to produce ventilation, heating, cooling and illumination?
- How to minimize pollution emissions and accumulation in sinks?
- How to protect ecosystems to preserve biodiversity and the services provided by natural systems?

3.1 What is good indoor air quality and how is it achieved?

Good indoor air quality requires source control and ventilation. Indoor air quality is a function of the quality of the air or the degree to which it is free from undesirable contaminants. The two major strategies for controlling indoor air quality are source control and ventilation. Ventilation required to dilute concentrations of contaminants and to exhaust them from indoor air can account for a significant fraction of energy consumption.

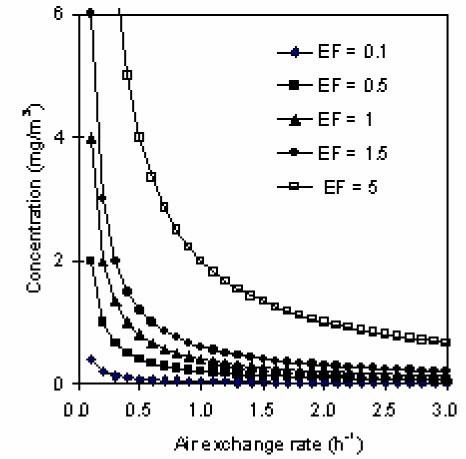


Figure 3. Pollutant concentration from various source strengths as a function of building ventilation rate. EF = emission factor (mg/m^2 h^{-1})

Source control is widely considered a more efficient means of providing good indoor air quality than ventilation, especially when the sources are related to building materials, furnishings, or other long-term sources since it continually reduces the need for ventilation in order to maintain a given level of air quality. Figure 3 shows that as the source strength increases, the amount of ventilation required to maintain a given concentration increases proportionally. Therefore, by selecting the lowest source strength materials, the amount of ventilation required will also be low. In some cases the selection of low-emitting building materials controls sources both from the materials themselves and from the products and materials required to maintain them over their useful lives. Many low-emitting sources are also more durable products, thus they may also impose less resource consumption burdens on the natural environment and result in fewer emissions over their lives. The useful lives of durable materials may be much longer thus making them inherently more sustainable.

Ventilation air is beneficial to the extent that it doesn't contain contaminants. In recent years it has been demonstrated that indoor air quality can be degraded considerable by ventilation air containing ozone, other oxidants, and fine particles. [12] The more buildings use ventilation (or other equipment - cooking, lighting, hot water heating, etc.) powered by combustion-based energy sources, the more polluted the outdoor air available for ventilation is likely to be. This sets up a “vicious circle” since polluted air requires air cleaning and filtration both of which increase pressure drop and require more fan power and energy consumption to deliver an equal amount of ventilation air.

3.2 Ventilation standards: 1973 to the present

> "Man strives for the point at which minimum expenditure of energy is needed to adjust himself to his environment. Conditions under which he succeeds in doing so can be defined as the "comfort zone," wherein most of his energy is freed for productivity." [13]
>
> "The use of massive air conditioning plants to correct an ill-conceived environment does not differ in principle from the use of a masonry façade to hide an unnecessarily ugly concrete structure." [14]
>
> "I am led to the conclusion, which I trust others will find persuasive, that we are becoming the servants in thought, as in action, of the machine we have created to serve us. [15]

Since the global energy crisis in 1973, energy conservation efforts have led to reduced levels of recommended or required ventilation in standards, codes, and regulations. In general these standards reflect both laboratory and field studies. Laboratory studies determine subjective responses to human body odor and to other pollution sources. Responses to odor have also been conducted in field settings. There have also been large-scale surveys of occupant sick building symptom response rates in relation to outdoor air ventilation rates per person. [16, 17] Table 4 shows that the amount of ventilation recommended by various authorities depends on the objectives and that a very wide range of ventilation rates have been recommended for various objectives.

Table 4. Various recommended and adopted ventilation rates (after Lindvall [18])

Ventilation Rate (L/s-p)[a]	Basis or recommending/adopting group and year
> 0.3	2% CO_2, (respiration)
> 0.5	1% $C0_2$ (performance)
> 1	0.5% CO_2, (TLV)
> 3.5	0.15% CO_2, (Pettenkofer Rule, 1858; body odor)
2.5	ASHRAE Standard 62-1981
3.5	Swedish Building Code 1980
4	Nordic Building Regulation Committee 1981
5 - 7-	Berglund et al. (body odor))
8	Fanger et al. (body odor
7.5	ASHRAE Standard 62-1989
5 - 10	Swedish Building Code 1988
10 – 30	Swedish Allergy Committee 1989
10, 20	Nordic Building Regulation Comm., preliminary 1989
16 – 20	Weber et al.; Cain et al. (Tobacco smoke, annoyance)
14 – 50	Fanger et al. (total odor)

[a] 1 liter per second ~ 2 cubic feet per minute

Of course any discussion about standards for outdoor air supply requirements, guidelines, standards, or codes implies that it is actually possible to measure and deliver the intended quantity of outdoor air ventilation and that buildings do indeed deliver the amount of outdoor air they are designed to provide. In fact, there is very little evidence that this is so. Field research reported in the peer-reviewed literature suggests that buildings generally provide somewhere between half and twice the outdoor air supply flows they are intended to provide. [19] It has become clearer from recent research that the measurement of outdoor air supply necessary to control it to a given air flow rate is difficult if not impossible. Only, perhaps, in unusual conditions is the amount of outdoor air be measured with reasonable reliability. In fact, such conditions rarely exist and even when they do, most systems used to measure outdoor air supply rates are not accurate or reliable. [20]

3.3 Natural vs. mechanical ventilation

Seppänen and Fisk [21] summarized results of studies on associations of ventilation system types in office buildings with sick building syndrome symptoms. "Most studies … indicate that relative to natural ventilation, air conditioning, with or without humidification, was consistently associated with a statistically significant increase in the prevalence of one or more SBS symptoms, by approximately 30% to 200%. In two of three analyses from a single study (assessments), symptom prevalences were also significantly higher in air conditioned buildings than in buildings with simple mechanical ventilation and no humidification."

The available data also suggest, with less consistency, an increase in risk of symptoms with simple mechanical ventilation relative to natural ventilation. The statistically significant associations of mechanical ventilation and air conditioning with SBS symptoms are much more frequent than expected from chance and also not likely to be a consequence of confounding by several potential personal, job, or building-related confounders. Multiple deficiencies in HVAC system design, construction, operation, or maintenance, including some of which cause pollutant emissions from HVAC systems, may contribute to the increases in symptom prevalences but other possible reasons remain unclear.

It is also important to note that the naturally ventilated buildings that have been studied usually have less outdoor air ventilation than the mechanically ventilated buildings. Thus, the notion that simply providing more outdoor air ventilation as a way to improve indoor air quality and occupant comfort, health, and productivity must be seriously questioned.

3.4 Thermal Comfort

Students from naturally ventilated and air-conditioned classrooms in Hawaii answered questions of comfort and satisfaction with the indoor environment on a variety of subjective scales. [22] On the ASHRAE seven-point thermal sensation scale, occupants of naturally ventilated classrooms with interior conditions well outside of the ASHRAE comfort zone responded that they were comfortable. Occupants in the air conditioned classrooms, felt cool with conditions that were on the cool side of the comfort zone-many conditions were well outside of the comfort zone.

3.5 Comfort in Office Buildings

Results from thermal comfort surveys in office buildings in Thailand were even more distinct because of higher humidity levels. [23, 24] All of the physical conditions in the naturally ventilated offices were well outside of the ASHRAE comfort zone, and occupants found conditions to be slightly warm. Comfort studies in Singapore [25] corroborated the Thai and Hawaii data. Adaptive behaviors observed in air-conditioned environments: office workers brought in sweaters to keep at their desks. In naturally ventilated offices, office workers used overhead fans, brought in cool drinks, and wore less clothing than their counterparts in air-conditioned offices.

Key opportunities, both adaptive and operational, can help reduce energy costs. As students move in and out of classes during the course of a typical school day, the movement from the hot outdoor environment into cool classrooms may enhance cool thermal sensations. These transient effects of comfort, combined with a significant number of occupants preferring warmer temperatures, offers the possibility of raising thermostat settings and classrooms need not be overcooled. Adaptive behaviors were observed related to clothing. Compared to offices, schools have relaxed fashion norms where students are often free to wear what they please. Measured CLO values were in some cases more than 1.0 CLO lower than other field studies. Cool sensation would be enhanced, particularly if students arrived from the warm outdoors. [26]

3.6 Thermal comfort standards

Thermal comfort requirements are increasingly limiting to designers, operators. Based primarily on laboratory studies of thermal comfort done with uniformly clad subjects in mechanically ventilated spaces, the results have been translated into rigid standards (and code) requirements. The environment was mechanically ventilated and carefully controlled in order to obtain good “scientific” data. Yet field studies show that buildings meeting these standards commonly fail to ensure thermal comfort for a large fraction or even the majority of occupants. The standards include many assumptions about acceptable thermal conditions and means to achieve them. They prescribe fixed, narrow temperature limit ranges (the “thermal comfort envelope”) from the laboratory study results. They ignore behavioral, physiological, and psychological adaptation to indoor and general climatic conditions. The result is that these requirements are energy wasteful and fail to deliver thermal comfort to the vast majority of building occupants.

More recent research, especially in field studies and including naturally ventilated as well as mechanically ventilated buildings, has shown that where subjects are free to choose their own clothes and where they expect fluctuations in thermal conditions, the range of acceptable conditions expands. This in itself can produce significant savings in energy consumption. Thus, past thermal comfort requirements based on laboratory research result in unnecessarily large energy requirements to condition and move ventilation air -- energy to power fans and to heat, cool, and adjust the moisture content of ventilation air.

Brager and deDear [27] reported the results of an extensive literature review on the topic of thermal adaptation in the built environment. They found that thermal perception in "real world" settings is influenced by the complexities of past thermal history and cultural and technical practices. The “adaptive” model of thermal comfort presumes that building occupants are not "passive" recipients of the thermal environment. Instead, the adaptive model sees occupants as active agents interacting with the person-environment system via multiple feedback loops. The literature attributes thermal adaptation to three different processes - behavioral adjustment, physiological acclimatization, and psychological habituation or expectation.

Evidence from climate chamber and field studies indicates that slower processes of acclimatization are not as relevant to thermal adaptation in the relatively moderate conditions found in buildings as behavioral adjustment and expectation which have a much greater influence. The evidence from field studies highlighted an important distinction between thermal comfort responses in air-conditioned versus naturally ventilated buildings. Brager and deDear opined that the difference most likely results from a combination of past thermal history in the buildings, and differences in levels of perceived control.

3.7 Environmental Lighting

Illumination standards are unnecessarily high and result in excessive energy consumption. Energy is used to produce the illumination and then to remove the waste heat in most temperate and warm climates. Illumination standards' criteria levels steadily increased, ultimately more than doubling during the period 1950 – 1975. After the 1973 Arab oil embargo, recommended lighting levels in offices were reduced from 700 lumens to 450 lumens. Prior to the 1960s they were set at 300 lumens. After the widespread introduction of personal computers into office work places during the 1980s, criteria for lighting levels were reduced even further as it was found that bright workplaces often resulted in glare on computer display (VDT) screens. The shift away from predominant form of general or overhead light sources to user controlled task lighting provides the opportunity for individual office workers to adjust the light level and to address its potential for glare. It is also up to 10 times more efficient to illuminate a surface from a distance of 0.5 m to 0.85 m than from a ceiling that may be 1.3 m to as much as 3 or 4 m above the work surface. Finally, it is more economical to replace lamps when the reach they end of their service life rather than replacing all the lamps in a ceiling at one time, usually after some have burnt out, some are flickering as they approach burn out, and many are still perfectly good. This rigid replacement routine and frequency of lamps in overhead illumination devices is usually done because of the cost of labor rather than to improve visibility, health, or productivity. Of course the task lamp also enables the user to control the angle and intensity of illumination and even to turn the device off when not needed or desired.

Standards for illumination in buildings are also based on laboratory studies and reflect visual acuity based on electrical illumination sources rather than daylight. The standards were based on research sponsored largely by the manufacturers of electrical illumination devices. The study subjects are generally accustomed to and adapted to prevailing lighting standards. Therefore the subjects are unlikely to adapt to lower illumination levels during the short exposure periods in the studies. It generally takes three weeks or more for people to adjust to significant changes in illumination levels, whether the changes are to lower or to higher levels of illumination. The studies also tend to ignore the influence of light source spectral distribution in establishing criteria for illumination requirements. Substantial research during the past 20 years at Lawrence Berkeley National Laboratory and the University of California, San Francisco, has shown that the composition of dominant electric fluorescent illumination sources historically was inefficient at providing visibility or visual material rendition while very good at producing perceived "brightness" and illumination levels.

Energy used for lighting adds additional heat in buildings. Where heating is necessary to attain thermally comfortable conditions, this does not cause much extra energy use. However, where cooling is required to attain thermal comfort, then waste heat from light sources results in the need for additional energy consumption to provide additional cooling. Therefore, it is obvious, that unnecessary use of electric lighting should be eliminated. Even daylight supplied through windows or skylights can increase the energy required to provide thermal comfort if windows are not properly sized, oriented, and shaded. Modern, high performance glass and window systems can reduce the entry of unwanted energy while still admitting sufficient visible light for illumination purposes. Similarly, high performance glass can reduce the loss of energy through window glass, thereby reducing energy requirements during the heating season.

During the day, where cooling is required, daylight can provide a significant fraction of the illumination requirements resulting in lower demands for cooling and mechanical ventilation energy. An additional advantage of daylight is that its frequency distribution with the electromagnetic spectrum is more like that experienced outdoors and found pleasant by most people. It is even necessary for people to have a full spectrum light for a portion of the day for better health. [28, 29] Finally, daylight modulates during the course of the day, thus allowing and stimulating human adaptation to the natural cycle.

3.8 The Importance of User Control

Several studies have shown that where occupants are in control of the environmental factors or conditions that most concern them, they are more satisfied and the rate of SBS symptoms reported is lower. Control over operable windows, lighting, temperature, or air movement are among the control options investigated. It is hypothesized that the psychological advantages of user control are able to counteract a certain amount of discomfort or inconvenience. Since not all people are alike, it is impossible to design an environment with a single, static set of environmental conditions that will be suitable, healthy and comfortable for all the occupants all or even most of the time. In fact, thermal comfort and ventilation standards only presume to “satisfy” 80% to 90% of occupants at their best. Figure 4 shows diagrammatically that the population is comprised of people who differ widely from each other; some are tall or short, thin or fat, young or old, healthy or sick, ambulatory or wheelchair-bound. To believe that we can design a single environment for all of them that will be most pleasing is pure fantasy. In order to satisfy a higher fraction of building occupants, some authorities believe it is necessary to provide occupants with a significant degree of control of their environment.

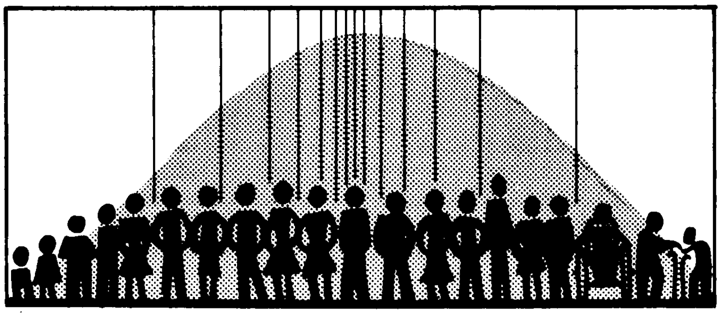


Figure 4. All people are not alike. [30]

3.9 Natural vs. mechanical environmental control systems

Current ventilation, thermal, and lighting requirements all create excessive energy requirements. The more outdoor air that needs to be supplied and to be conditioned and moved, the more energy for fan power, heating and cooling is required. That the requirements push toward mechanical environmental control is in no small part due to the fact that they were developed based on research in controlled laboratory conditions and often funded by industries whose products we have come to rely on to achieve environmental control in buildings. These conditions differ markedly from "real" building environments where occupants may determine and adjust their clothing, activity level, or even the environment itself depending on their response to the environment.

There is abundant evidence that naturally ventilated buildings create fewer occupant-reported SBS symptoms. [21]. Buildings without a/c create fewer occupant reported SBS symptoms. [21]. Mechanically ventilated buildings allow for a wider thermal comfort envelope, thus reducing required energy consumption for conditioning air. [27]. When one looks at the findings of Brager and deDear [27] as well as the evidence from Seppänen and Fisk [21], and Mendell [16], it clearly points toward the advantages of naturally ventilated buildings for health, comfort, and productivity of occupants. The benefits of daylight have been shown in schools and to many are self-evident. It appears that comfort, health and productivity can be achieved even better in naturally ventilated buildings at much lower economic, energy, and other resource costs than in mechanically conditioned buildings. It also draws our attention to the potential for significant reductions in energy and other resource consumption required to provide sealed, mechanically conditioned buildings.

4. THE DESIGN EXERCISE

We inevitably make many tradeoffs in we design -- where one goal or objective is sacrificed in order better to achieve another. There are costs to the environment not addressed directly in design, codes or standards. Yet all of us ultimately bear the costs of global climate change, loss of biodiversity, smog, acid deposition, depletion of resources – of environmental problems. Designers or economists do not take these environmental costs into account.

If we choose to build a building that is more energy efficient, it will cost less for the owner-operator and do less harm to the environment. What is the real choice here? Should we purposely choose to create buildings that are less energy efficient? There are some fundamental choices that we make that are like foundation stones for a building. They limit and significantly define what we can do after they are installed. The most important decisions are made at the very beginning. The further along the design process we go, the less impact our decisions have on the overall outcome. If we choose to ventilate and heat and cool mechanically rather than passively ("naturally"), then we lock ourselves in to a certain type of design and associated costs. If we choose to maximize passive environmental control (ventilation, light, temperature, and noise), then we minimize the requirements for mechanical ventilation and tempering of the air and the energy required to operate it. In the case of the energy efficient building, such choices include the overall shape, the major materials, the location and type of windows, the orientation on the site, and all of these in relationship to climate and sun. We make choices about how to ventilate, heat, cool, and illuminate our buildings, and these choices lock us into a limited set of feasible technical solutions.

What are the implications of these choices? Currently more than a third of the world’s population lacks the modern energy services enjoyed by industrial and post-industrialized economies. If all of the world's 6 billion (6×10^9) people were suddenly able to live in buildings that are mechanically ventilated, heated, and cooled the way they are today in North America and Europe, we would immediately increase the global per capita consumption of energy threefold. If current global automobile ownership is doubled - as it has been in China during the past five years - then that would increase global energy consumption to five times the current consumption. If the majority of the energy used to ventilate, heat and cool houses and to power motor vehicles continues to be fossil fuel based, then greenhouse gas emissions will increase proportionally. Even with all the efficiencies we know are possible now, we are talking about at least a doubling in current global greenhouse gas emissions. The resulting impacts on climate and sea level rises will probably alter living conditions for the majority of people on earth, most of whom live in the currently temperate climate zones. The resulting sea level will rise making many coastal communities, many of the world's largest and most important cities uninhabitable. The shifts in climate will modify conditions on most of the world's present agricultural lands, shifting the temperate zones in the northern hemisphere further north with necessary changes in crops grown and insects and other pests necessary to control. A similar northward shift in diseases is expected to accompany the change in climate. And hazardous weather events such as hurricanes, tornadoes, and other storms have already been observed to cause flooding and massive damage to buildings and communities.

The good news is that it will take a while for all of the six million inhabitants of the earth to acquire the technology and have the energy available to them to have completely mechanically ventilated, heated, and cooled buildings. So the problem won’t be 5 times worse next week. No, probably not for another 30 to 50 years; maybe even more. But here's the bad news. By the time the technologies are widely distributed to nearly all the earth's inhabitants, there will be 10 billion people on the earth. However, with improved efficiencies, the average per capita emissions of greenhouse gases may not go up at the same rate.

The task of moving and conditioning air can be accomplished to a far greater extent, by "passive" means. [13, 31] Passive means to heat, cool, and illuminate buildings have been employed historically with excellent results.[32] Today's buildings tend to involve an abundance of energy-consuming technologies while use of daylight, solar gain, stack effect, and other passive means of environmental control are neglected or ignored. Some of this has to do with real estate values, with short term, economic considerations, and with disregard for environmental considerations.

5. CONCLUSION: “STATE-OF-THE-SHELF”

Today's highly efficient buildings typically provide occupants more control over their personal or local thermal and lighting environment, provide better air quality, often cost less to build and to operate, and, use materials requiring far less consumption of non-renewable resources with far fewer apparent impacts on the environment. So why are there not more such buildings now? What is preventing wider application of healthy building practices, construction of buildings that are better for their occupants and for the earth's ecosystems? Even though some good efforts have been made, the best of buildings built today fail to reduce resource consumption and pollution emissions to a sufficient degree compared to the scale of the reductions needed to create truly "sustainable" buildings. It is difficult (if not impossible) to find a building being built today that could be regarded as truly sustainable.[11] So how do we balance all of the competing goals of creating healthy buildings -- buildings that are harmful neither to their occupants nor to the larger environment? [33] Can we go beyond healthy buildings to create buildings that actually produce healthy, comfortable, and productive human occupants? Can we do this without destroying the environment on which we depend?

REFERENCES

[1] Levin, H., "Building Ecology: An Architect's Perspective On Healthy Buildings" in Maroni, et al, (eds) *Proceedings of Healthy Buildings '95, Proceedings of the Fourth International Conference on Healthy Buildings*, Milan, Italy, September, 1995.

[2] Eisenberg, D. Personal communication. 2003.

[3] Wheatley M.J., and Kellner-Rogers, M., 1996. “The Irresistible Future of Organizing.”. July/August. http://www.margaretwheatley.com/articles/irresistiblefuture.html

[4] Turner, J.S., “The Structure of *Macrotermes* mounds.” 2003. http://www.esf.edu/efb/turner/research/moundstr.htm

[5] Dobson, A., 1996. “Environmental Sustainabilities: An Analysis and a Typology,” *Environmental Politics*, Vol. 5, No. 3, Fall 1966, 401-428.

[6] Levin, H., “What Counts as Green.” *arcCA*, vol. 2.4. 2002. http://www.aiacc.org/publications/arcCA/arcca.html

[7] Levin, H., Boerstra, A., and Ray, S. "Scoping U.S. Buildings Inventory Flows and Environmental Impacts in Life Cycle Assessment" Presented at Society for Environmental Toxicology and Chemistry (SETAC) World Congress, Vancouver, BC, November 1995.

[8] Levin, H., 1996. “Design for indoor air quality: addressing the global environmental context.” In *Indoor Air ’96, Proceedings of the Seventh International Conference on Indoor Air Quality and Climate, Volume 3* pp. 229-234

[9] Roodman and Lenssen, 1995. "A Building Revolution: How Ecology and Health Concerns are Transforming Construction" March, World Watch Institute, Washington, DC.

[10] Weterings, RAPM, JB Opschoor, 1992. "The Ecocapacity as a Challenge to Technological Development." Rijswijk, the Netherlands: Advisory Council for Research on Nature and Environment (RMNO). p. 25

[11] Kohler, N, Plenary Lecture, Presented at *Green Building Challenge '98*. October 1998, Vancouver.

[12] Weschler, C.J. Reactions Among Indoor Pollutants: What’s New. Paper # 291.*Proceedings of the Annual Meeting of the Air and Waste Management Association*, Orlando, FL June, 2001.

[13] Olgyay, V. 1963. Design with climate: Bioclimatic approach to architectural regionalism. Princeton, NJ:. Princeton University Press.

[14] Cowan, A.J., 1966. An historical outline of architectural science. Elsevier.

[15] Galbraith, J. K., *The New Industrial State*. New York: The New American Library, 1968.

[16] Mendell, M., Non-specific symptoms in office workers: a review and summary of the epidemiologic literature. *Indoor Air*, Vol. 3, No. 4, 227-236, 1993.

[17] 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.*

[18] 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.

[19] Persily A (1989) Ventilation rates in office buildings. *Proceedings of the IAQ'89 Conference The Human Equation: Health and Comfort*, pp. 128-136., ASHRAE, Atlanta.

[20] Fisk, William J, Faulkner, D, Sullivan, DP, and Delp, W, 2003. “Measuring Rates of Outdoor Airflow into HVAC Systems” (LBNL-51583 Revised with June 03 Modifications). Berkeley, CA: Lawrence Berkeley National Laboratory.

[21] Seppänen, O., and Fisk, W.J., “Relationship of SBS-symptoms and ventilation system type in office buildings.” *Proceedings of Indoor Air 2002, Ninth International Conference on Indoor Air Quality and Climate*, Monterey, CA, June 30-July5, 2002.

[22] Kwok, AG. 1998. Thermal comfort in tropical classrooms, *ASHRAE Transactions*. Vol. 104 (1B), pp 1031-1047.

[23] Busch, JF, 1990. “Thermal responses to the Thai office environment,” *ASHRAE Transactions*. Vol. 96 (1), pp 859-872.

[24] Busch, JF, 1992. “A tale of two populations: thermal comfort in air-conditioned and naturally ventilated office in Thailand,” *Energy and Building*, Vol. 18, pp 235-249.

[25] DeDear, RJ Leow, KG Foo, SC. 1991. “Thermal comfort in the humid tropics: Field experiments in air conditioned and naturally ventilated buildings in Singapore,” *International Journal of Biometeorology*, Vol. 35, pp 329-265.

[26] Kwok, AG, Personal communication, 2002.

[27] Brager, G. and deDear, R. “Thermal Adaptation in the Built Environment: A Literature Review.” *Energy and Buildings*. Vol. 27 (1). February 1998.

[28] Levin, H and Duhl, L, "Indoor Pollution: Lighting, Energy and Health". In Snyder, J (Ed.), *Architectural Research*, Van Nostrand Reinhold, New York, 1984.

[29] Levin, H., 1995, “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.

[30] Rubin, Arthur and Elder, Jacqueline, 1980. *Building for People: Behavioral Research Approaches and Directions* (SP474)). Gaithersburg, MD: National Bureau of Standards.

[31] Givoni, B. *Man, Climate and Architecture*. New York: Van Nostrand Reinhold Company. 1981.

[32] Banham, R. The Architecture of the Well-tempered Environment, Second Edition. Chicago: The University of Chicago Press. 1984.

[33] Levin, H. 2000. Design and Construction of Healthy and Sustainable Buildings. Healthy Buildings 2000, Helsinki, Finland.