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INDOOR ENVIRONMENTAL QUALITY AND VENTILATION IN U.S. OFFICE BUILDINGS: A VIEW OF CURRENT ISSUES

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Indoor Environmental Quality and Ventilation in U.S. Office Buildings: A View of Current Issues

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ABSTRACT

Much of the current focus on indoor environmental quality and ventilation in U.S. office buildings is a response to sick building syndrome and occupant complaints about building-related health symptoms, poor indoor air quality, and thermal discomfort. We know that serious "sick-building" problems occur in a significant number of U.S. office buildings and that a significant proportion of the occupants in many normal (non-sick) buildings report building-related health symptoms. Concerns about the health effects of environmental tobacco smoke have also focused attention on the indoor environment. The major responses of industry and governments, underway at the present time, are to restrict smoking in offices, to attempt to reduce the emissions of indoor pollutants, and to improve the operation of heating, ventilating and air conditioning (HVAC) systems. Better air filtration, improved HVAC commissioning and maintenance, and increased provisions for individual control of HVAC are some of the improvements in HVAC that are currently being evaluated. In the future, the potential for improved productivity and reduced airborne transmission of infectious disease may become the major driving force for improved indoor environments.

1. THE DRIVING FORCES AFFECTING INDOOR ENVIRONMENTS

A number of important issues have been and continue to be a driving force for changes in building technologies, operating procedures, and rules or codes that affect indoor environmental quality in U.S. office buildings. Several of the major issues are introduced and discussed in this section.

1.1 Linkage between Energy Conservation, Indoor Air Quality, and Ventilation Rate

In recent years, energy conservation objectives have affected HVAC technologies and operational strategies more than the objective of improving indoor environmental conditions. Energy conservation results in quantifiable reductions in expenditures while the potentially larger financial benefits associated with improved indoor environments --reduced health care costs and increased productivity-- have not been well quantified.

Energy conservation and good indoor air quality (IAQ) are generally considered to be competing objectives. It is true that reducing the minimum rate of outside air ventilation simultaneously saves energy and increases indoor pollutant concentrations. However, if the HVAC system utilizes an economizer cycle[1], increasing outside air supply rates within the range of 2.5 L s^{-1} per person to 17.5 L s^{-1} per person, typically impacts HVAC energy costs in a large office building by less than 5% for a wide range of U.S. climates (Eto and Meyer 1988, Eto 1990). Total building energy use is even less affected by the minimum outside air ventilation rate. Larger percentage impacts on energy use occur for buildings with a high occupant density such as schools and restaurants (Steele and Brown 1990).

Outside air ventilation rates (which link energy use to IAQ) are also only a secondary determinant of indoor pollutant concentrations for many indoor air pollutants, especially those not generated directly by occupants. Indoor pollutant source strengths (emission rates) tend to be more variable between buildings than outside air ventilation rates; consequently, source strengths are the most important determinants of the indoor concentrations of many air pollutants. Because of the strong variability in source strengths, indoor pollutant concentrations appear to be unrelated to outside air ventilation rates in modest-size cross sectional surveys. For example, Figure 1a and 1b based on data from Turk et al. (1987a, 1987b) show indoor respirable particle concentrations and formaldehyde concentrations plotted versus ventilation rate from a study of commercial buildings located in the Pacific Northwest. In these figures, there are no evident trends relating concentrations with ventilation rate. Because source strengths are the most important determinants of the indoor concentrations of most pollutants, minimization of indoor pollutant source strengths should be a primary strategy employed by building operators and designers to achieve good indoor air quality.

1.2 Dissatisfaction with the Thermal Environment

Another driving force for changes in indoor environments is the substantial prevalence of complaints of thermal discomfort by workers in U.S. office buildings. In a large field study by Schiller et al. (1988), less than 25 % of the subjects were moderately satisfied or very satisfied with air temperature. Twenty two percent of the measured indoor thermal conditions during the winter were outside of the boundaries of the 1988 version of ASHRAE's winter thermal comfort zone (ASHRAE 1981). In the summer, almost 50% of the measured indoor thermal conditions were outside of the boundaries of ASHRAE's summer thermal comfort zone. The degree of dissatisfaction with the thermal environment in the office buildings exceeded the level of dissatisfaction expected based on the measured thermal conditions and the ASHRAE thermal comfort standard, suggesting that comfort standards based on laboratory research may overestimate comfort in actual office buildings.

1.3 Sick Building Symptoms

The phenomenon of sick building syndrome (SBS) is another major driving force for improved indoor environments. SBS is now widely recognized in the U.S. and elsewhere as a significant problem by public health officials, researchers, and building designers and operators. Incidents of SBS, within specific buildings (often office buildings), are characterized by an unusually high prevalence of health symptoms and health complaints among the buildings' occupants. The symptoms may include irritation of the eyes, nose or throat, dry or itchy skin, difficulty breathing, cough, headache and fatigue. These symptoms could have many potential causes; therefore, they do not generally indicate a specific disease or specific pollutant exposure. The occupants believe that their symptoms are caused by the indoor environment, generally air pollution within the building. They report that their symptoms improve when

[1] With an economizer cycle, outside air ventilation is increased above the minimum rate when the outdoor temperature makes it possible to use outside air for cooling.

they are not in the building, unlike the symptoms associated with typical infectious diseases. Severe cases of SBS prompt investigations by health officials and consultants and can lead to building evacuations.

During the past decade, researchers have started to use cross-sectional surveys conducted in multiple office buildings (chosen irrespective of the prevalence of occupant complaints) to evaluate the associations between the prevalences of health symptoms and characteristics of the individual, job, work space, building, and indoor environment. Questionnaires are used to determine the prevalences of health symptoms and to collect information on the individuals and their jobs and workspaces. Inspections and measurements are the basis for information on buildings and environmental conditions. In addition to these surveys, indoor environments have been intentionally modified in a few buildings (an experimental research approach) to assess the impact of the modification on health symptoms.

These surveys and experimental studies have shown that a substantial proportion of the occupants of "normal buildings", (i.e., buildings without identified sick-building problems) report that they have health symptoms that improve when they are away from the building. They report the same symptoms commonly associated with SBS. As an example, Figure 2 illustrates the substantial prevalences of symptoms reported by 880 occupants in 12 office buildings located near San Francisco (Fisk et al. 1993). Only one of the 12 office buildings had a prior history as a sick building. Forty percent of the occupants reported that they experienced eye, nose, or throat irritation often or always last year, and that the symptoms improved when they were away from the office building. For two other symptom groups, the prevalence in the entire population exceeded 20%. These data, plus comparable data from other studies suggest that a very large population of office workers is affected by SBS symptoms.

In a recent review of the literature, Mendell (1993) summarizes the current knowledge about the association of SBS symptoms to characteristics of buildings, jobs, and indoor environments. With substantial consistency, higher symptom prevalences have been associated with air conditioning (relative to natural ventilation), presence of carpets, increased number of workers in the study space, use of video display terminals, outside air ventilation rates below 10 L s^{-1} per person, and a high level of job stress or job dissatisfaction. Individual studies with particularly strong designs have found <u>decreased</u> symptoms to be associated with humidification, negative ionization, and improved office cleaning. The studies to date have identified no consistent associations between symptoms and measured concentrations of indoor air pollutants.

Higher air temperature has been associated with increased symptom prevalences in several studies (e.g., Skov et al. 1989, Jaakkola et al. 1991, Wyon 1992, Menzies et al. 1993). Laboratory studies in which temperature and concentrations of volatile organic compounds were varied have also demonstrated that air temperature can significantly affect ratings of air quality and subjective reports of several SBS symptoms (Molhave et al. 1993). Consequently, the indoor thermal environment appears to be linked to occupant health and to perceptions of IAQ.

1.4 <u>Environmental Tobacco Smoke</u>

The health effects of exposure to environmental tobacco smoke (ETS) are possibly the strongest driving force for changes in the indoor environments within U.S. office buildings. Recently, the U.S. Environmental Protection Agency has officially concluded that ETS is a human lung carcinogen (EPA 1992). In addition, ETS is commonly considered to be a major source of irritation and complaints.

2. RESPONSES TO THE DRIVING FORCES

In this section, some of the major responses to the driving forces are discussed. These responses include changes in HVAC and building technologies, changed practices for building construction and operation, and new or revised building-related rules or codes.

2.1 Changes in HVAC Technologies

Energy conservation objectives have been the stimulus for changes in several HVAC technologies that affect indoor environmental quality. Variable air volume (VAV) ventilation systems with a constant supply air temperature have been widely adopted to save energy. Several indoor environmental problems have been linked, largely anecdotally, to VAV systems. Maintaining the desired minimum outside air supply rates to all regions of a building is difficult with a VAV system. When the demand for cooling is small and the supply air temperature is fixed (e.g., at 13°C), air supply rates must be reduced or the space will become over-cooled. In some cases, the recommended minimum quantities of outside air can not be supplied without thermal discomfort. Increasing the supply temperature can reduce this problem. In addition, the variable rates of air flow in VAV systems can cause unintentional changes in the rates of outside air intake into air handling systems because the pressure drop across the outside air dampers can vary with system flow rates. Cohen (1994) introduces a simple method for obtaining a more constant rate of outside air intake with VAV systems.

Energy conservation objectives have also stimulated the use of economizer cycles which increase annual-average rates of outside air ventilation. This is a case where energy conservation usually improves IAQ. However, increased ventilation is not always entirely beneficial. The indoor concentrations of some outdoor pollutants such as ozone, increase with outside air ventilation (Weschler et al. 1989).

Task ventilation is another technology change. Recently, U.S. manufacturers have introduced task ventilation systems for use in office buildings. To date, they have only been installed in a few U.S. buildings. Similar systems are available in other countries. Task ventilation systems provide occupants with a greater degree of individual control of the environment near their workspace. With one system, the occupants can control the rate and direction of air supply from modules installed in the floor. Another system uses air supply nozzles installed on the desktop. The occupant is able to control the direction, flow rate, and temperature of the air supply, the output of a radiant heating panel, a task light, and a white noise generator. An occupancy sensor turns the system on and off. These systems can provide occupants with considerable flexibility to adjust their thermal environment to meet individual desires (Arens et al. 1991, Bauman et al. 1993). Because individual preferences vary with respect to the thermal environment, individual control is a logical approach for increasing the level of satisfaction with the thermal environment. In a recent field study, occupants of a building with task ventilation generally reported better thermal comfort with task ventilation compared to their comfort level in previous buildings with conventional ventilation systems (Bauman et al. 1994). However, low air supply temperatures also caused many occupants to block the floor-level air supply units, illustrating that proper automatic control of HVAC system parameters remain critical with task ventilation systems.

Another potential benefit of task ventilation is improved ventilation and indoor air quality in the occupant's breathing zone. Task ventilation systems can provide supply air (which is generally less polluted than room air) near the breathing zone, or direct supply air toward the breathing zone. However, laboratory studies indicate that the effective ventilation rate at an occupant's breathing zone is only marginally (i.e., 0% to 20%) higher when task ventilation systems are employed compared to a reference case with perfect mixing (Fisk et al. 1991, Faulkner et al. 1993)

Improved air filtration systems appears to be another technological change that is starting to be considered or adopted to improve IAQ. Most U.S. HVAC systems have air filters with a low efficiency in removal of the respirable particles, less than 2.5 μm in diameter, that are most important for human health. A primary purpose of the commonly-used filters is to protect HVAC equipment from excessive deposition of large particles. U.S. filter manufacturers are now heavily promoting more efficient air filters that have a moderate or high efficiency in removing submicron size particles. The General Services Administration, which owns or leases many buildings occupied by U.S. Government employees, has recently decided to upgrade filters to an ASHRAE dust spot rating of 80% to 85%. (Mills 1994).

2.2 Reduced Pollutant Emission Rates

Reductions in the pollutant emission rates from indoor sources is another response to improve indoor environments in office buildings. One of the most prominent examples is a voluntary effort undertaken by carpet and rug manufacturers that are members of the Carpet and Rug Institute (Carpet Policy Dialogue Group 1991). Manufactures periodically submit product samples for tests that measure emission rates of total volatile organic compounds, styrene, 4-phenylcyclohexene, and formaldehyde. If emission rates are below specified limits, the manufacturer is able to attach a label to the product indicating that it has been certified by the Institute.

For a small number of individual office buildings, consultants have assisted architects and building owners by implementing a program of pre-testing pollutant emission rates from candidate building materials and furnishings. Products with particularly high emission rates of total volatile organic compounds and products that emit significant amounts of highly toxic compounds are rejected. Levin and Hodgson (1994) discuss the protocols employed.

The State of Washington has established IAQ specifications for office buildings (Black et al. 1993) which include maximum acceptable concentrations of formaldehyde, total volatile organic compounds, and 4-phenylcyclohexene. For other pollutants, the maximum acceptable concentration is the concentration listed in the National Ambient Air Quality Standard published by the US Environmental Protection Agency or 10% of Threshold Limit Value published by the American Conference of Governmental Industrial Hygienists for industrial work places. The building designer or builder must select interior construction materials, furnishings, and finishing products so that these maximum acceptable pollutant concentrations are not exceeded. To comply with this IAQ program, manufacturers have been required to provide data on pollutant emission rates from their products.

Manufactures of office equipment, such as laserjet printers, have also made some product changes to reduce pollutant emission rates, particularly the emissions of ozone.

2.3 Changes in Building Operation, Maintenance, and Commissioning

In the 1980's, the desire to save energy led to restrictions on indoor temperatures in office buildings, causing indoor temperatures to be operated outside or near the boundaries of the thermal comfort zone. In particular, some government agencies limited both maximum temperatures when government-owned buildings are heated and minimum temperatures when buildings are cooled. To increase worker satisfaction, these restrictions are now being relaxed or eliminated. For example, the General Services Administration has decided to eliminate restrictions on indoor air temperatures (Mills 1994).

Anecdotal reports and case studies indicate that faulty HVAC equipment, and faulty design, installation, and operation of HVAC systems are very common in U.S. office buildings. A few examples include fans and dampers that do not operate or that operate backwards, disconnected ducts, inaccessible components, fully closed outside air dampers, poor balancing of air flows leading to improper distribution of supply air and outside air, and a variety of malfunctions associated with control systems. Many of these problems can adversely affect indoor thermal comfort and air quality and also waste energy. A discussion of the multiple and complex causes of these problems is beyond the scope of this paper. However, two responses, improved commissioning and improved maintenance, are discussed briefly.

ASHRAE (1989) has developed a guideline for a comprehensive process of commissioning of HVAC systems. The suggested commissioning process goes well beyond testing and balancing. The responsibilities of different parties are established, communication, documentation, and training are improved, and HVAC system performance is verified. The major barrier to comprehensive commissioning is the initial cost. However, commissioning may actually result in net cost savings. Seelen et al. (1993) describe a recent case study of comprehensive commissioning associated with installation of an HVAC system. The cost of commissioning was approximately 2.5% of the total project cost. Approximately 50% of the initial commissioning cost was recovered through savings during the first year. Improved indoor environmental quality is an anticipated benefit of better commissioning; however, data are not available that document or quantify the degree of improvement.

Better HVAC maintenance is also perceived as a method of reducing HVAC problems, thereby, improving indoor environmental quality, reducing SBS symptoms, and saving energy. HVAC maintenance is receiving increased attention in ASHRAE's technical meetings. Recently, the U.S. Occupational Safety and Health Administration (OSHA) has proposed an IAQ rule (Department of Labor 1994) for all non-industrial indoor work places, that mandates HVAC maintenance and keeping of maintenance records.

2.4 Changes in Codes and Rules

Many U.S. cities have passed legislation that restricts smoking in work places to separately-ventilated rooms designated for smoking. Restrictions on smoking have probably improved IAQ in office buildings more than any other factor. The IAQ rule proposed by OSHA (Department of Labor 1994) would expand these restrictions to all non-industrial work places.

The minimum outside air ventilation rates specified in standards and codes have fluctuated during the past decade as a consequence of competing energy conservation and IAQ objectives. In 1989, ASHRAE's recommended minimum ventilation rates for offices increased from 2.5 L s^{-1} per person to 7.5 L s^{-1} per person (ASHRAE 1989b). Local codes are often based on the ASHRAE recommendation. OSHA's proposed IAQ rule would limit carbon dioxide concentrations in work spaces to 800 parts per million, corresponding to an outside air ventilation rate of approximately 11.5 L s^{-1} per person. The trend is to increase the required minimum rates of outside air supply. It is the author's opinion that codes primarily affect the average minimum ventilation rates in the building stock built according to those codes. In individual buildings, minimum outside air ventilation rates are usually poorly controlled by the ventilation system, difficult to measure, casually adjusted by building operators (through manipulation of outside air dampers without actually measuring the outside air ventilation rate), and not well known by building operators. Hence, increases in the required minimum ventilation rates in codes, while likely to improve IAQ in the new building stock, are unlikely to eliminate buildings with low rates of outside air ventilation.

An important change in ASHRAE's Standard 62 (which contains recommended minimum ventilation rates) is under consideration. The change would link minimum ventilation rates to the strength of pollutant sources within the building. This change makes great sense from a scientific perspective. Due to the large influence of pollutant source strengths on IAQ, acceptable indoor air quality cannot be assured without controlling both minimum ventilation rates and maximum pollutant source strengths. However, development of a workable standard with this linkage is hampered by limited data on pollutant source strengths and a very imperfect understanding of the health affects associated with many pollutants.

3. DRIVING FORCES FOR FUTURE IMPROVEMENTS: PRODUCTIVITY AND DISEASE TRANSMISSION

The linkages among building technologies, indoor environmental quality, rates of infectious disease transmission, and productivity are receiving increased attention. In a unique and important study by the U.S. Army (Brundage et al. 1988), rates of acute respiratory disease with fever were 50% higher among recruits housed in barracks with closed windows, low rates of outside air supply, and extensive air recirculation compared to recruits in barracks with frequently open windows, more outside air, and less recirculation. Sick building symptoms and symptoms of allergies and asthma are also linked to indoor environmental quality and building technologies. All of these adverse health effects are expected to reduce productivity. A number of changes in building technologies and practices may be effective in reducing disease transmission and adverse health effects not associated with infectious disease. Examples of promising measures include improved air filtration, increased outside air ventilation, and better cleaning of indoor surfaces. Because salaries dominate the cost of operating an office building, there is a strong incentive to invest in technologies or practices that increase productivity even slightly. (For office buildings, Woods et al. (1989) show that salaries exceed energy costs by approximately a factor of 100.) If future research identifies methods to increase productivity, for example by decreasing absence due to illness, productivity may become the strongest driving force for better indoor environmental quality.

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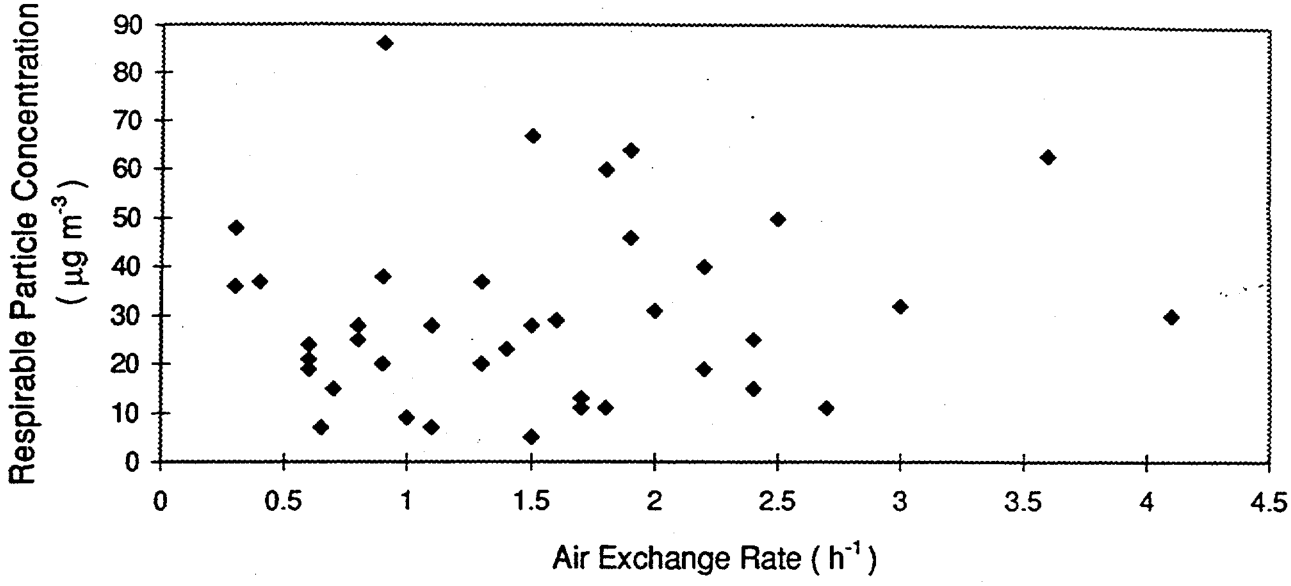

Figure 1A. Respirable particle concentration versus ventilation rate from measurements in 38 commercial buildings in the Pacific Northwest of the United States (Turk et al. 1987a, 1987b).

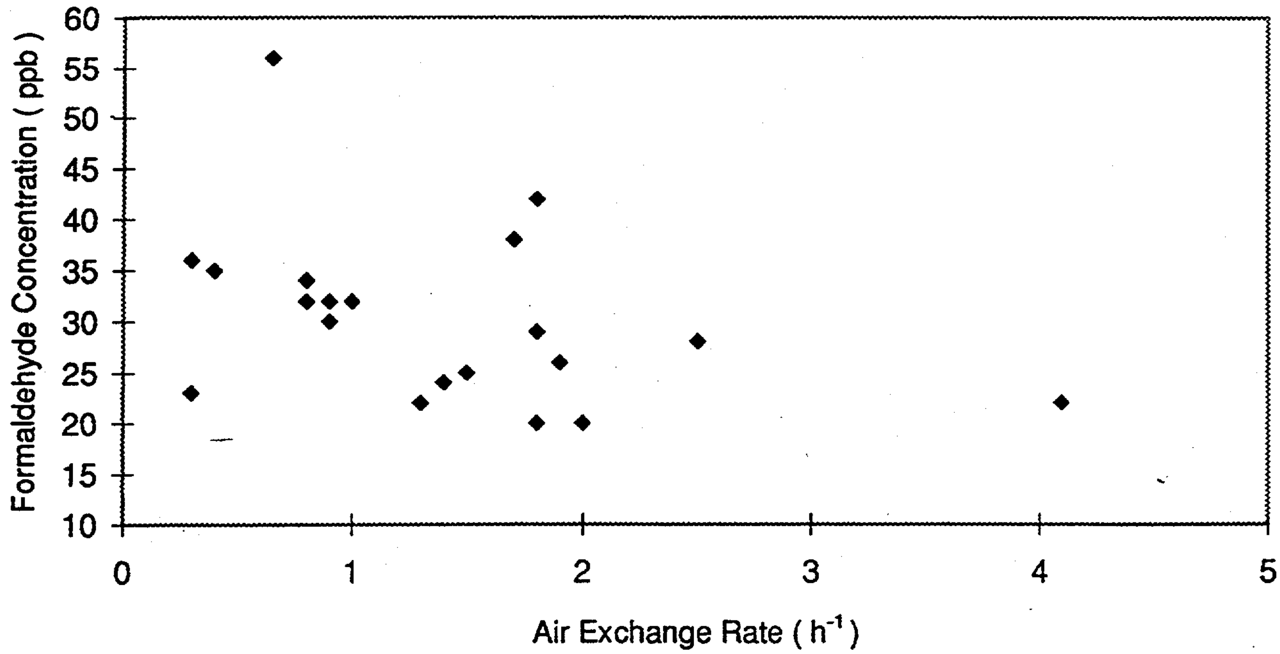

Figure 1B. Formaldehyde concentration versus ventilation rate from measurements in 20 commercial buildings in the Pacific Northwest of the United States (Turk et al. 1987a, 1987b).

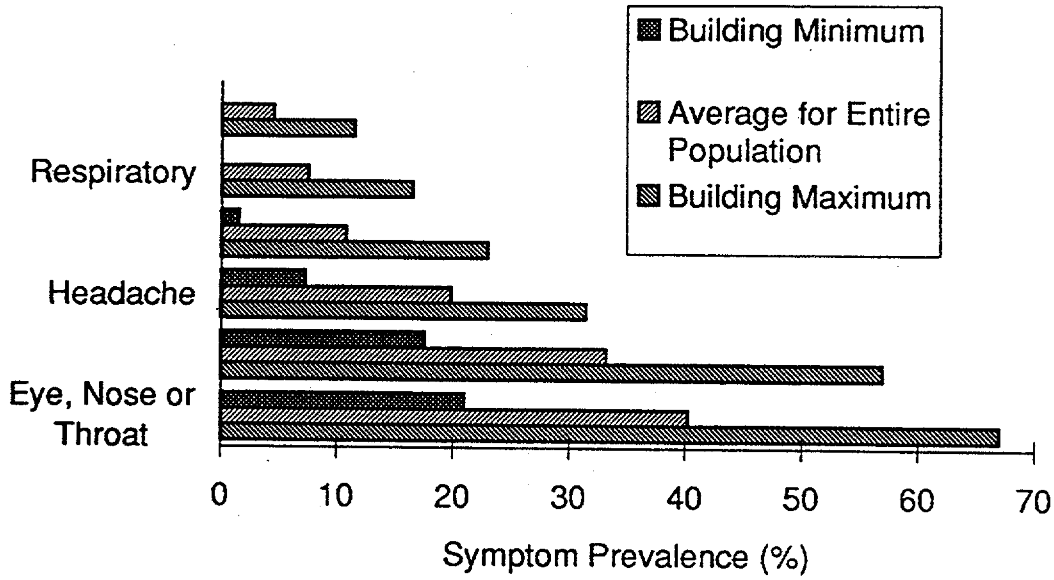

Figure 2. Prevalences of building related symptoms as reported on a questionnaire by 880 occupants of twelve office buildings in the San Francisco area. Occupants reported that these symptoms occurred often or always during the last year and improved when they were away from the building.