Prepared for presentation at:
CIB Conference "Healthy Buildings '88"
Stockholm, Sweden
September 5-8, 1988

RECENT DEVELOPMENTS FOR HEATING, COOLING, AND VENTILATING BUILDINGS: Trends for Assuring Healthy Buildings

James E. Woods, Ph.D., P.E.
Honeywell, Golden Valley MN, USA

Abstract

Recent investigations suggest the existence of two populations of buildings for environmental evaluations: 1) problem buildings (20-30%) and 2) buildings without known problems (70-80%) including those with undected problems and those with an "absence of problems" (i.e, Healthy Buildings). Data are presented that indicate most problem buildings are associated with inadequate performance of heating, ventilating, and air conditioning systems. Performance criteria are suggested for evaluation of these systems. These data and criteria lead to propositions that indoor air quality control is evolving from the principles of psychrometrics, and that ventilation efficiency may be a critical concept for cost-effective control. Finally Healthy Buildings are characterized in terms of human response, system performance, and service factors that can be employed to assure acceptable building performance.

Introduction

The fundamental objective of environmental control is to not only prevent the existence of deleterious or unpleasant conditions, but to provide for the comfort and well-being of the occupants. However, another important objective is to provide these conditions cost effectively. Because of cost (and sometimes energy) constraints, the design and operation of buildings and their systems have occasionaly been compromised. When this occurs, environmental quality is usually degraded, sometimes to deleterious conditions.

According to the World Health Organization: "Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (5). Within this context, the sense of well-being may be characterized in terms of comfort. Occupant responses of comfort or discomfort require sensory perceptions of environmental stressors. Some of these stressors cause physiological strains while others, such as job-related stress, predispose the physiological strains. If these stressors, which stimulate the four basic types of sensory receptors (i.e., thermoreceptors, olfactory receptors, auditory receptors, and visual receptors), are controlled within certain limits, resultant physiological strains (e.g., vasomotor control) can be pleasant or comfortable to the occupant. However, if acceptable limits are exceeded, if the perceived stressors are not recognized (e.g., strange odors), or if psycho-social stressors are significant, complaints of discomfort will usually result. Symptoms associated with unacceptable stressors include headaches, nausea, and fatigue from heat, glare, noise, and odors; eye irritation from low humidity, glare, and odorous compounds; throat and respiratory irritations from cold drafts, low humidity, and odorous compounds. Thus, to provide comfort, simultaneous control of the four basic environmental stressors is required.

The objectives of this paper are to: 1) Present findings from investigations of existing buildings that assess the role of heating, ventilating, and air conditioning (HVAC) systems in providing for acceptable occupant responses; 2) Identify performance criteria for these systems; and 3) Characterize Healthy Buildings in terms of these criteria.

Findings from Existing Buildings

Two Populations of Buildings

A committee of the World Health Organization has estimated that as many as 30% of the buildings in the developed world may have problems that can lead to occupant complaints and illnesses (1). In another study, a stratified random sample of 600 U.S. office workers surveyed at home by telephone, indicated that a significant percentage of respondents (24%) were dissatisfied with the air quality at the office (10). Moreover, 20% of the 600 perceived their performance to be hampered by the air quality. This 20% of the sample also reported "serious" or "very serious" concern with five symptoms associated with Sick Building Syndrome at frequencies more than twice those expected from normal populations (i.e., a tired-sleepy feeling, 56%; a congested nose, 45%; eye irritations, 41%; difficulty in breathing, 40%; and headaches, 39%). From these data the following hypothesis was proposed: "It is possible that 20% of the office workers in the United States are exposed to environmental conditions that are manifested as the Sick Building Syndrome".

For the purpose of evaluating environmental quality in buildings, it is proposed, here, that two building populations may exist, as indicated in Fig. 1: 20 - 30% of non-industrial buildings which may be considered as "Problem Buildings"; and 70 - 80% which may be considered as "Buildings Without Known Problems".

Problem Buildings. Two types of building problems have been described in the literature (4, 9, 14): "Sick (or Tight) Building Syndrome" (SBS), and "Building Related Illness" (BRI). These differ significantly:

When exposure to indoor contaminants results in disease or infirmity, the occurrence has been referred to as Building Related Illness. Examples of BRI include: nosocomial infections, humidifier fever or hypersensitivity pneumonitis from exposure to bioaerosols (e.g, fungi, bacteria), fiberglass dermitis from exposure to fibers from materials such as duct liners, legionellosis from exposure to bacteria, and toxicity from exposure to chemical or biological substances (e.g., carbon monoxide, radon, mycotoxins). BRI is usually characterized by clinical signs (e.g., blood serology, fever, infection, tissue deterioration), identifiable pollutants, and prolonged recovery times after leaving the building. An additional characteristic of BRI is that successful mitigation usually requires removal of the source rather that increased ventilation. The attack rate on occupants is often low (e.g., two or more cases is often used as an indicator of potential BRI).

Sick Building Syndrome is suspected when occupant complaints of certain symptoms associated with acute discomfort (e.g., headaches, fatigue, eye irritation, sore throat, nausea) persist for more than two weeks at frequencies significantly greater than 20%; the cause or causes of the complaints are not recognizable; and a substantial percentage of the complainants report almost immediate relief upon exiting the building. In most cases, a physical basis for the occurance of the SBS can be found: lack of proper maintenance; changes in thermal or contaminant loads imposed during the building's life; changes in control strategies to meet new objectives (e.g., energy conservation); or inadequate design.

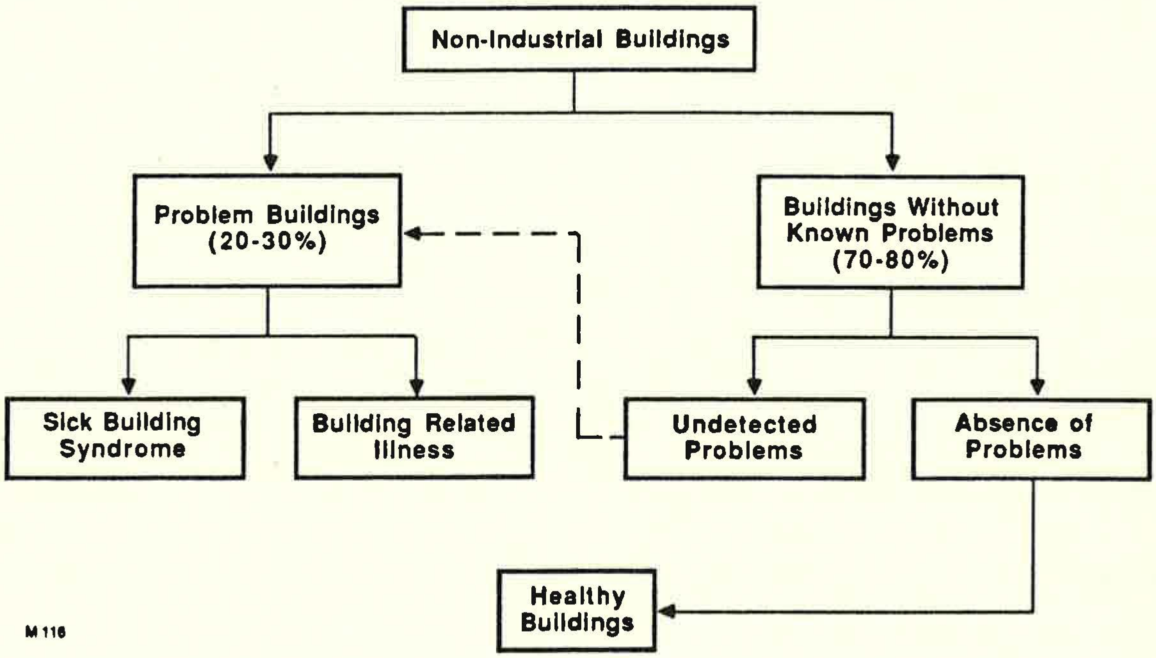

Fig. 1. Two populations of non-industrial buildings for environmental evaluations.

Buildings Without Known Problems. As shown in Fig. 1, this population of buildings can be categorized as those in which problems exist but have yet to be detected and those in which problems are absent.

Incipient problems, such as those that are "not perceived but cause physiological strains" (4), can exist without detection for indefinite periods of time. This category of buildings is important to recognize as it is the basis for a continuous source of problem buildings. Although incipient problems are more difficult to identify, they can be minimized through preventive maintenance and diagnostics programs.

Buildings that function with minimal occupant complaints and within acceptable performance and economic criteria meet the objectives of environmental control and may be defined as Healthy Buildings.

Summary of Recent Cases

In the past two years, we have received more than 300 inquiries about problem buildings. Of these we have investigated more than 30. These cases have been characterized by two types of problems, four types of contaminants, and two types of physical causes.

Types of Problems. About 65% of these investigations were in response to symptoms associated with SBS, and 35% in response to symptoms associated with a combination of BRI and SBS; none were in response to BRI, alone.

Types of Contaminants. Symptoms were associated with thermal problems in 55% of the cases; humidity problems other than thermal (e.g., eye irritation, allergies) in 30% of the cases; chemical contaminants in 75%; and microbiological contaminants in 45%. Of the chemical contaminants, odors were detected in 70% of the cases; particulate concentrations above 50 ug/m^3 in 5%; and other chemicals (e.g., PCBs) in 5%.

Physical Causes. These can be considered in two categories: design inadequacies, which consist of system problems and equipment problems; and operational problems, which consist of inadequate maintenance, changes in loads imposed on the systems, and changes in control strategies.

- Inadequate Design.
  - System Problems. The most commonly found problems were inadequate outdoor air in 75% of the cases, inadequate supply air to occupied spaces in 65% of the cases, and inadequate return/exhaust air from occupied spaces in 70% of the cases.
  - Equipment problems. The most commonly found problems were inadequate filtration in 65% of the cases, malfunctioning condensate drain pans and drain lines in 60% of the cases, inadequate access panels to HVAC components in 60% of the cases, contaminanted duct linings in 45% of the cases, and malfunctioning humidifiers in 20% of the cases.
- Operational Problems.
  - Maintenance. Many of the buildings investigated have been

occupied for more than 10 or 15 years. In 75% of the cases, inadequate maintenance procedures have been found. These included: dirty make-up air intakes, missing or dirty filters, fouled and contaminated heating and cooling coils, contaminated supply and return air ducts, disconnected damper linkages, disconnected exhaust fans, and abandoned automatic control systems.

- Load Changes. In 60% of these cases, the thermal or contaminant loads imposed on the systems had changed from original design. When these changes occur, the impact on the capacities of the existing systems is usually not evaluated. As a result, the building may undergo higher occupancy density, additional thermal loads (e.g., lighting, computers), and new sources of contaminants (e.g., copy machines, printers, cleaning fluids) than the system was designed to handle. Two effects are common: 1) the total system capacity becomes insufficient to meet the new demands; or 2) while the total system load remains adequate, the balance in loads throughout the building changes resulting in areas of the building not being supplied enough air to meet the demands.

- Control Strategies. In 90% of the cases, we found control systems had been modified since original design. Two basic problems exist:

  1) Overcomplexity of control systems. Although the design engineer and the original owner/operator of the building may have had adequate documentation and may have understood the logic of the control systems, subsequent owners or operators failed to receive appropriate training, or economic pressures caused less qualified personnel to be placed in responsible charge of the systems. Often, the original system is subsequently modified to meet the level of understanding of the current operating personnel, resulting in system malfunction or inadequate performance.

  2) Energy Management. To reduce energy costs, many existing control systems have been modified by reducing the amount of outdoor air that could be supplied to an occupied space, reducing the temperature or enthalpy differentials between supply and return air systems, or reducing air flow rates to occupied spaces.

Performance Criteria

The need for standards which can be used to specify, control, and evaluate indoor environmental conditions has been recognized for many decades (14). During this time, two basic types of sandards have evolved: prescriptive criteria, which typically describe acceptable system throughput (i.e., ventilation rates or heat transfer rates), and performance criteria, which typically describe acceptable conditions within occupied spaces (i.e., contaminant concentrations or temperature and humidity conditions). Both types of criteria are useful and in most cases, it should be possible to rationalize between them (11). Prescriptive criteria, which are often derived by consensus processes, are primarily used for design (i.e., for selection of system capacity), whereas performance criteria, which are more often based on scientific findings, are primarily used for system evaluation and control (i.e., for system operation).

Environmental Criteria

For purposes of indoor air quality diagnosis, we currently recommend three sets of performance criteria for evaluation of acceptable indoor air quality and HVAC systems:

- Thermal criteria should comply with ASHRAE Standard 55-1981 (2).

- Six air contaminants are recommended as measurable variables for evaluating office spaces as shown in Table 1 (13). These can each be used as surrogate indicators of both the intensity of human activity and the adequacy by which a ventilation system dilutes contaminants from human activity in occupied spaces. For special environments, such as hospitals, additional criteria should also be considered (12).

- Standards for risk associated with exposure to saprophytic bioaerosols have not yet been published. We therefore recommend assessment of this exposure by current guidelines of the American Conference of Govermental Industrial Hygienists (3): compare samples with those taken in a non-problem (i.e., control) area and in the outdoor air. Concentrations should not exceed one-third of the those outdoors and the rank order of the taxa should be similar.

Energy and Economic Criteria

An important secondary objective of environmental control is to provide cost-effective system performance (15). Criteria by which this objective can be evaluated are also needed. These are usually developed on an on-site basis, as they are dependent on the environmental criteria chosen and the physical constraints of the systems. We recommend the following criteria to evaluate system performance:

- Energy Requirements (MJ/m^2 floor area) of the HVAC system to comply with the chosen environmental criteria.

- Energy Consumption (MJ/m^2) by the HVAC system to provide energy requirements.

- Energy Costs ($\$/m^2$) for the building.

- Maintenance Costs ($\$/m^2$) for the building.

o Operational Costs ($\$/m^2$) for housekeeping, repair, and other incidential expenses for the building.

Table 1. Honeywell IAQD recommended guidelines for six airborne contaminants in office spaces (13).

Agent	Occupational Exposure Limit	Odor Recognition Threshold	Recommended Guidelines	Protection Factor
Butyric acid	N.A.	0.001 ppm	0.002 ppm (C)	N.A.
Carbon dioxide	5000 ppm	N.A.	1000 ppm (C)	5
Total suspended particulates	10,000 ug/m^3	N.A.	50 ug/m^3(Y)	200
Pyridine	5 ppm	0.02 ppm	0.05 ppm (C)	100
Furfural	2 ppm	0.002 ppm	0.004 ppm (C)	500
Toluene	100 ppm	2 ppm	4 ppm (C)	25

N.A. = Not applicable; C = Ceiling concentration; Y = Yearly average

Trends in HVAC Control Criteria

Psychrometrics. Because of the strong interactions between occupant responses to thermal and air quality parameters, and because the most common methods of providing for occupant comfort involve HVAC systems, control criteria for common factors are desirable. Moreover, investigations of problem buildings indicate strong relationships between reported SBS symptoms, thermal control problems, humidity control problems, and energy management strategies. It is therefore reasonable to assume that acceptable indoor air quality is evolving from a strong foundation in the specialized field of thermodynamics known as psychrometrics.

In this context, the characterization of indoor air is beginning to focus on the interactions between airborne contaminants and moist air. As shown in Fig. 2, the impact of simultaneously requiring acceptable air quality and thermal acceptability is to constrain the psychrometric criteria now specified in ASHRAE Standard 55-1981 (2). For example, our investigations indicate that relative humidities above 60% are conducive to microbial growth and odors in HVAC systems and in occupied spaces, whereas relative humidities below 30% tend to elicit complaints of eye and respiratory irritation.

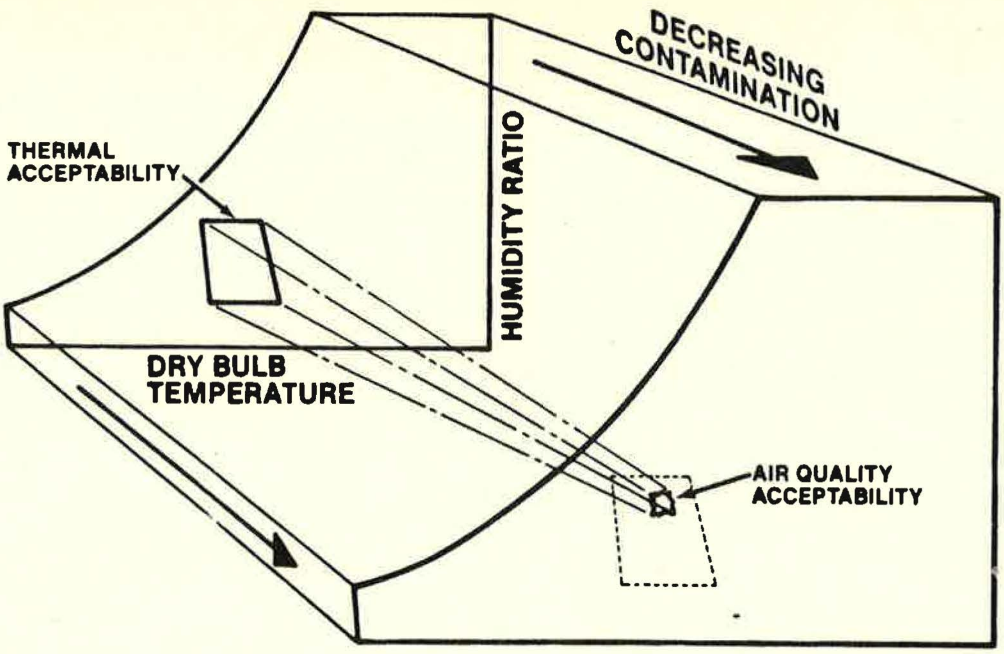

Fig. 2. Conceptual impact of improved air quality (i.e., decreasing contamination) on the phychrometric profile of thermal acceptabality specified in ASHRAE Standard 55-1981 (2).

Ventilation Efficiency. Air movement (i.e., convection) is an important method of sensible heat control in occupied spaces. Moreover, it is the only practical method available today for control of latent heat and airborne contaminants within occupied spaces. Traditionally, air movement control in non-industrial buildings has focused on methods of supplying air to rooms (7). However, only recently has the distribution of supplying air to personal spaces within the room or the effectiveness of removing this air from the personal spaces been seriously considered for non-industrial applications. To address the overall ventilation performance of HVAC systems for thermal and air quality acceptability, concepts of ventilation efficiency have been introduced and are being evaluated for standardization by ASHRAE (6, 8). Our investigations of problem buildings have resulted in measurements of ventilation efficiencies (i.e., the fraction of outdoor provided by the system that ventilates the personal space) as low as 33%. Values this low indicate either inadequate ventilation for acceptable air quality or significant energy waste in providing acceptable conditions. We recommend that ventilation efficiencies be maintained above 80% to comply with both environmental and economic criteria.

Characterization of Healthy Buildings

As indicated in Fig. 1, Healthy Buildings should have an absence of problems as evaluated by a building diagnosis. From a practical perspective, it is recognized that any occupied facility cannot exist without some problems. It is therefore suggested that a Healthy Building be characterized with three sets of criteria: human responses, system performance, and service factors.

Human Responses

To be characterized as a Healthy Building:

- No known clinical signs of BRI should exist among any of the occupants, and
- The frequency of reported SBS symptoms and discomfort complaints should be significantly below 20%.

System Performance

The building and its systems should meet the following criteria:

- Compliance with environmental criteria.
- Ventilation efficiencies for each space should exceed 80%.
- Energy management strategies should not compromise environmental acceptability.
- Outdoor air for ventilation should not be contaminated by exogenous or indogenous sources (e.g., combustion products or cross-contamination for exhaust air).
- Supply and return air ductwork should not be conducive to contaminant accumulation.
- Exhaust air systems should be balanced with make-up air systems to assure acceptable ventilation in all occupied spaces.
- Systems should be designed for ease of maintenance.

Service Factors

The continued acceptable performance of the building should be assured by the following:

- Records should be established to document occupant complaints and symptoms.
- A structured preventive maintenance program should be instituted to include:

- Periodic inspections and routine procedures for all components comprising the HVAC systems.
- Scheduled filter changing or cleaning.
- Scheduled control calibration.
- Scheduled air and hydronic balancing of systems.

(7) Nevins, R.G. and Miller, P.L. Analysis, evaluation and comparison of room air distribution performance - a summary. ASHRAE Trans. 1972, 78(2), 235-242.

(8) Sandberg, M. and Sjoberg, M. The use of moments for assessing air quality in ventilated rooms. Building and Environment, 1983, 18, 181-197.

(9) Stolwijk, J.A.J. The "sick building" syndrome. Proceedings of the Third International Conference on Indoor Air Quality and Climate. Berglund, B. et al (Eds). Swedish Council for Building Research, 1984, Vol 1, pp. 23-29.

(10) Woods, J.E., Drewry, G.M., and Morey, P.R. Office worker perceptions of indoor air quality effects on discomfort and performance. Proceedings of the Fourth International Conference on Indoor Air Quality and Climate. Seifert, B. et al (Eds). Institute for Water, Soil and Air Hygiene, 1987, Vol. 2, pp. 464-468.

(11) Woods, J.E., Janssen, J.E., and Krafthefer, B.C. Rationalization of equivalence between the "ventilation rate" and "air quality" procedures in ASHRAE Standard 62. In Managing Indoor Air for Health and Energy Conservation. Janssen, J.E. (Editor). ASHRAE, Atlanta GA, 1986, pp. 181-191.

(12) Woods, J.E., Ficht, M.A., and Albrecht, R.J. Criteria and methods of controlling indoor air quality. CLIMA 2000. P.O. Fanger (Editor). VVS Kongres, Copenhagen, 1985, Vol. 4, pp. 291-299.

(13) Woods, J.E., Morey, P.R., and Rask, D.R. Indoor air quality diagnostics: qualitative and quantitative procedures to improve enviornmental conditions. Proceedings on Design and Protocol for Monitoring Indoor Air Quality. N. Nadga (Editor). American Society for Testing and Materials, Philadelphia PA (In Press).

(14) Woods, J.E., Morey, P.R., and Stolwijk, J.A.J. Indoor air quality and the sick building syndrome: a view from the United States. Advances in Air Conditioning. The Chartered Institution of Building Services Engineers, London, 1987, pp. 15-25.

(15) Woods, J.E., Teichman, K.Y., Seppanen, O.A., and Suter, P. Relationships between building energy management and indoor air quality: perceptions of conflict and opportunity in the United States and Europe. Proceedings of the Third International Congress on Building Energy Management, Presses Polytechniques Romanades, Lausanne Switzerland, 1987, Vol. 1, pp. 49-70.