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An Engineering Approach to Controlling Indoor Air Quality

by James E. Woods*

Evidence is accumulating that indicates air quality problems in residential and commerical buildings are nearly always associated with inadequacies in building design and methods of operation. Thus, the very systems depended on to control the indoor environment can become indirect sources of contamination if diligence is not exercised at each stage of a building's life: *a*) planning and design, *b*) construction and commissioning, *c*) operation, and *d*) demolition or renovation. In this paper, an engineering perspective is presented in which the existing building stock is characterized in terms of its environmental performance. Preliminary data indicate that 20 to 30% of the existing buildings have sufficient problems to manifest as sick-building syndrome or building-related illness, while another 10 to 20% may have undetected problems. Thus, only about 50 to 70% of the existing buildings qualify as healthy buildings.

Two methods and three mechanisms of control are described to achieve "acceptable" indoor air quality: source control and exposure control. If sources cannot be removed, some level of occupant exposure will result. To control exposures with acceptable values, the primary sensory receptors of the occupants (i.e., thermal, ocular, auditory, and olfactory) cannot be excessively stimulated. The three exposure control mechanisms are conduction, radiation, and convection. To achieve acceptable occupant responses, it is often practical to integrate the mechanisms of radiation and convection in heating, ventilating, and air conditioning systems that are designed to provide acceptable thermal, acoustic, and air quality conditions within occupied spaces. This paper concludes with a discussion of an engineering approach to indoor environmental diagnostic procedures that may be used to evaluate performances of buildings for acceptable environmental control as they evolve through the four stages of their lives.

Introduction

During the last 25 years, technical and socioeconomic changes have profoundly influenced the methods now used to plan, design, construct, and operate buildings. While new technologies have increased the potential for improving the overall environmental and economic performances of a building, they have also introduced new sources of contaminants and other physical stressors into occupied spaces, thus requiring increased sophistication in design and operation of the buildings and their systems. However, the realization of this potential has been impeded by several socioeconomic changes such as increased pressure for rapid returns on building investments, increased concern for professional liability, increased reliance on deferred maintenance strategies, and decreased commitment to provide technology transfer to operating personnel.

Characterization of the Existing Building Stock

One manifestation of these technical and socioeconomic changes is that 20 to 30% of the existing building stock may expose occupants to environmental conditions that result in occupant complaints and illness (*1,2*). As shown in Figure 1, this part of the building stock may be characterized as "problem buildings" and the remaining 70 to 80% of the population may be characterized as "buildings without known problems" (*3*).

Problem Buildings

The classification of "problem buildings" may be characterized by problem types, types of environmental stressors, and physical causes.

Problem Types. Two fundamental types of problem buildings have been described in the literature (*4–7*): building-related (or associated) illness (BRI) and sick (or tight) building syndrom (SBS). These types differ significantly. Building-related illness is suspected when exposure to indoor air pollutants results in disease or infirmity for two or more occupants. Examples include nosocomial infections, humidifier fever or hypersensitivity pneumonitis from exposure to bioaerosols (e.g., fungi, bacteria), fiberglass dermatitis 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 indoor air pollutants, and prolonged recovery times after leaving the building. An additional characteristic of BRI is that successful mitigation usually requires removal of the source of the indoor air pollutant.

Sick-building syndrome is suspected when occupant com-

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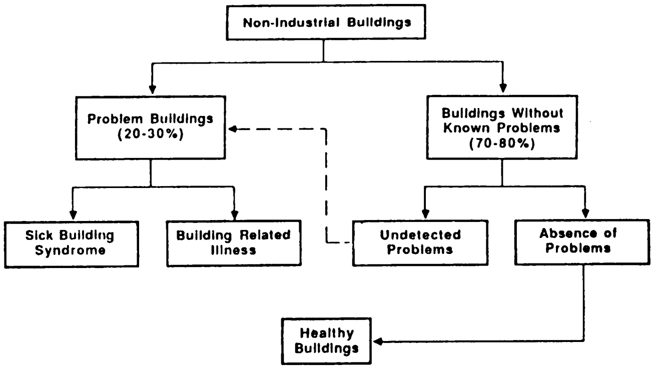

FIGURE 1. Two populations of nonindustrial buildings for environmental evaluations.

plains of certain symptoms associated with acute discomfort (e.g., headaches, fatigue, eye irritation, sore throat, nausea) persist for more than 2 weeks at frequencies significantly greater than 20% in an area of the building or in the entire building; 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 occurrence 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 (*5*).

An analysis of more than 30 problem buildings revealed that approximately 65% of the cases involved complaints and symptoms associated with SBS, and 35% involved symptoms and signs associated with a combination of SBS and BRI (*3*). Significantly, none of the investigations was in response to BRI alone.

Environmental Stressors. Four types of environmental stressors were predominant in the 30 cases analyzed by Woods (*3*): chemical and particulate contaminants in 75% of the cases (with odor discomfort present in 70% of the cases); thermal discomfort in 55% of the cases; microbiological contaminants in 45% of the cases; and nonthermal humidity problems (i.e., eye irritation and mold growth from low and high relative humidities, respectively) in 30% of the cases.

In another study, Robertson (*8*) reported chemical and particulate contaminants were found in 16% of 233 cases [i.e., in a recent analysis of these data, the frequency of occurrence for chemicals and particulates is apparently closer to 75% (G. Robertson, personal communication)]; and microbiological contaminants in 44% of the cases.

Other types of environmental stressors also occur, such as lighting and other electromagnetic radiation, noise, and vibration, but data are not yet available on the frequencies of occurrence of unacceptable exposures. Although the available data are preliminary and additional studies are needed to validate the expected frequencies of occurrences, they do indicate that stressors other than chemical must also be considered if risk assessments of exposures to unacceptable indoor environments are to be meaningful.

Physical Causes. Two categories of physical causes are associated with problem buildings: *a*) design inadequacies, which consist of system problems and equipment problems, and *b*) operational problems, which consist of inadequate maintenance, changes in thermal and contaminant loads imposed on the systems, and changes in control strategies. Frequencies of occurrence of these physical causes as reported by two investigative teams are shown in Table 1 (*3,8*).

Design inadequacies, characterized as system problems, may be described as:

- Inadequate outdoor air provided to the system because of an insufficient quantity outdoor air provided for ventilation, or an unacceptable quality of the outdoor air introduced as "ventilation air" (*9*).
- Inadequate air distribution for occupied spaces due to insufficient quantity and quality of air for thermal and ventilation control supplied to the occupied spaces; insufficient quantity of air returned or exhausted from the occupied spaces; or inappropriate air mixing within the occupied spaces. These characteristics are now being described as "ventilation effectiveness."

Design inadequacies, characterized as equipment problems, may be described as:

- Ineffective air cleaners used to remove particulates, much less gases and vapors, from the air distributed by supply air systems. In most systems, if air filters are provided, they are designed to remove large particulates from the air to protect the heating and cooling coils from fouling, rather than to protect the occupants.
- Inadequate drain pans and drain lines for cooling coils and humidifiers. If these do not function properly, they become significant amplification sites for microbiological contamination and associated bioeffluents including mycotoxins, endotoxins, and other odorous gases and vapors.
- Undersized or omitted access panels to components within the heating, ventilation, and air conditioning (HVAC) systems. If the components are not easily accessible, maintenance will likely be less than adequate and result in system malfunctions or contaminant accumulation.

Table 1. Frequencies of occurrence of physical causes of problem buildings reported by two independent investigative teams: Woods (*3*) and Robertson (*8*).

Problem category	Physical cause	Frequencies of occurrence	
		Woods	Robertson
Design	System problems		
	Inadequate outdoor air	75	64
	Inadequate air distribution to occupied spaces (supply and return device)	75	46
	Equipment problems		
	Inadequate filtration of supply air	65	57
	Inadequate drain lines and drain pans	60	63
	Contaminated ductwork or duct linings	45	38
	Malfunctioning humidifiers	20	16
Operations	Inappropriate control strategies	90	NA[a]
	Inadequate maintenance	75	NA
	Thermal and contaminant load charges	60	NA

[a] NA, not applicable.

- Inadequate contaminant protection of ductwork and duct linings. If care is not taken in design to minimize the accumulation of chemical or microbial contamination on these materials, especially near sources of moisture condensation, they are likely to become subsequent secondary sources of indoor air contaminants.
- Inadequate contaminant protection of humidifiers. Two basic types of humidifiers are used in buildings: water atomizing and steam injection or vaporizer humidifiers. Each type presents problems that must be considered in design to minimize occupant exposure to microbial and chemical contamination. Water atomizing humidifiers are more likely to become secondary sources of microbial contaminants if diligent maintenance is not employed; steam humidifiers are more likely to emit potentially toxic volatile amines from corrosion inhibitors contained in the steam generated from central plants (*10,11*).

Operational problems have been characterized in three categories (*3*):

- Inapropriate control strategies have been associated with nearly all problem buildings. Two basic problems with control systems have been reported: *a*) overcomplexity of control systems. Although the design engineer or 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 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. *b*) Aggressive 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 of the air supplied to and returned from occupied spaces, or reducing the air flow rates to occupied spaces. As a result, the systems no longer can perform as originally designed and increase the likelihood of occupant complaints and symptoms of SBS and BRI.
- Inadequate maintenance is also a major problem. Many of the problem buildings investigated had been occupied for more than 10 years. Thus, the mechanical systems in these buildings were more than 50% through their expected service lives. Maintenance problems in these buildings included dirty makeup 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. During the life-cycle of a building, changes from original design can occur in the thermal and contaminant loads that are imposed on the HVAC systems. The impact of these changes on the capacities of the existing systems is seldom evaluated. As a result, the building may undergo higher occupancy density, additional thermal loads (e.g., lighting, computers, office machines), and additional generation rates of contaminants (e.g., copy machines,printers, cleaning fluids, furniture, carpets) than the system was designed to handle. Two effects are common: *a*) the total system capacity becomes insufficient to meet the new demands, or *b*) although the total system capacity remains adequate, changes in the balance of loads throughout the building result in areas in which the zone capacity is no longer sufficient to the meet the new demands.

Buildings without Known Problems

As shown in Figure 1, "buildings without known problems" may be characterized as those in which problems exist but have not yet been detected and those in which problems are absent (i.e., healthy buildings) (*3*).

Undetected Problems. Incipient problems can exist without detection for indefinite periods. This category of buildings is characterized by a smaller percentage of occupants expressing discomfort and symptom prevalence than in problem buildings. Another characteristic of this population of buildings is that the performance of the systems and the level of maintenance may be just marginal. One way these incipient problems can be detected is by the rate of change in complaints and symptoms. Recognition and mitigation of these problems are important as this population of the building stock is the basis for a continuous source of problem buildings. The frequency of occurrence of buildings in this category has been postulated as 10 to 20% (*12*).

Healthy Buildings. No building has a complete absence of problems, but those that function with minimal occupant complaints and comply with acceptable criteria for occupant exposure, system performance, maintenance procedures, and economic objectives may be characterized as healthy buildings (*3*). Although data that quantify the frequency of occurrence for this category are not yet available, an initial postulate of 50 to 70% has been derived as the complement of the preceding categories (*12*).

Continuity of Degradation

These data, although preliminary, lead to a hypothesis that a continuum exists in the degradation of building performance, as shown in Figure 2 (*13*).

Approximately 50 to 70% of the existing building stock may qualify as healthy buildings. If this is true, it should be noted that the lower end of this range indicates that the probability of occupying a healthy building is no better than random chance. More-

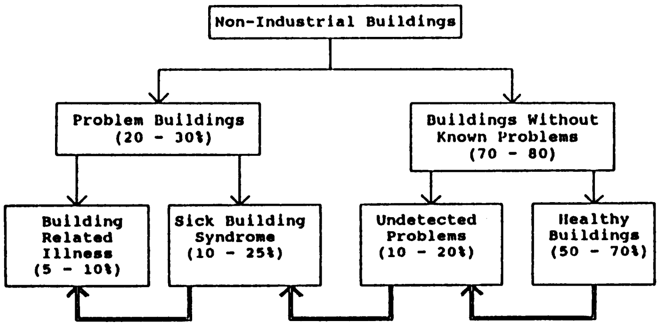

FIGURE 2. Continuous degradation of building performance in nonindustrial buildings.

over, the upper end of the range indicates that, although we probably have the knowledge and sometimes the motivation to design and operate buildings that provide healthy indoor environments over their lifetimes, significant improvements can be made.

The first level of degradation (i.e., undetected problems), which may represent 10 to 20% of the existing building stock, probably occurs whenever proactive assurance of building performance is not provided throughout the life cycle of the building. The second level of degradation (i.e., sick-building syndrome), which may represent 10 to 25% of the existing building stock, usually occurs when incipient problems are neglected until the prevalence of occupant complaints and symptoms forces action by those responsible for the building (e.g., building owners or managers). Mitigation of these complaints and symptoms is usually more expensive than at the undetected problem stage and may involve legal or sociopolitical interactions, but often does not require major building renovation.

The third level of degradation (i.e., building-related illness), which may represent 5 to 10% of the existing building stock, usually occurs when the symptoms associated with SBS are neglected. If environmental conditions are allowed to deteriorate to this level, the cost of mitigation is often substantial and can require major renovation or abandonment of the facility.

Probability of Total Exposure

There are approximately 4 million commercial (i.e, nonindustrial and nonresidential) buildings in the United States with an average floor area of 13,000 ft^2 (*14*). Assuming that typical occupancy densities in commercial buildings range from three to five persons per 1000 ft^2 of floor area [i.e., 50% of the design occupancies in ASHRAE Standard 62-1989 (*9*)], the percentage of the U.S. population exposed in commercial buildings ranges from 60 to 100% (i.e., 150–240 million people) (*12*). Thus, if 20 to 30% of the existing commercial buildings are problem buildings and another 10 to 20% are undetected problem buildings, the number of commercial buildings in the United States in these categories is expected to range from 1,200,000 to 2,000,000, and the number of exposed occupants is expected to range from 50 to 130 million.

In addition, approximately 84 million residential buildings in the United States house an estimated population of 240 million (*15*). Although the percentage of problem buildings in the residential sector is not known, the physical causes for the problems are not expected to be substantially different from those in the commercial sector. Thus, as an initial estimate, if 30 to 50% of the existing residential buildings are problem buildings or undetected problem buildings with a typical occupancy of 2.9 residents per residence, 70 to 120 million people may be expected to be exposed in the 25 to 40 million residences in these categories (*12*).

Unlike exposure to industrial environments, where relief of exposure is assumed when the worker leaves the workplace, relief from exposures in nonindustrial environments may not occur as the latter population may be exposed to similar contaminants and other environmental stressors in other commercial buildings and at home as they are in their place of employment (*16*). Nonindustrial occupant exposure is most likely to be dependent on total exposure within residential and commercial facilities (i.e., 90–95% of exposure time) and outdoors (5–10% of the time).

Table 2. Probabilities of indoor air exposures of U.S. population in sick and healthy buildings.

		Commercial building exposure	
		Sick[a]	Healthy
Residential building	Sick[a]	0.3^2–0.5^2 = 9–25% (15–60 million occupants)	(0.3–0.5) × (0.5–0.7) =15–35% (20–85 million)
Exposure	Healthy	(0.3–0.5) × (0.5–0.7) = 15–35% (20–85 million)	0.5^2–0.7^2 = 25–50% (40–120 million)

[a] For purposes of this preliminary estimate, buildings with undetected problems are assumed to be sick (i.e., not healthy).

Thus, as shown in Table 2, only 25 to 50% of the nonindustrial population (i.e., 40–120 million people in the United States) are probably exposed to both healthy homes and healthy commercial buildings. Conversely, 30 to 70% of the population (i.e., 40–170 million people in the United States) are likely to be exposed to either a sick home or sick commercial building, and 9 to 25% (i.e., 15–60 million people in the United States) are likely to be exposed to both sick residences and sick commercial buildings (*12*).

Methods of Control

To increase assurance that occupants are not exposed to environmental stressors that cause discomfort, illness, and lost productivity, technical and managerial efforts must be focused on improving environmental control throughout the planning and design, construction, operation, and renovation of these buildings.

Technical Considerations

Environmental control within occupied spaces relies upon three basic mechanisms to achieve acceptable human responses: conduction, radiation, and convection.

Conduction, which controls heat, noise, and vibration transmission through the physical elements of the building, is of only minor importance in the transfer of energy between the occupant and the indoor environment. Radiation of energy within the visible spectrum is the fundamental mechanism for control of lighting, and longwave radiation is the primary mechanism for control of acoustics within occupied spaces. Infrared radiation is also an important mechanism for control of sensible heat transfer to and from occupants who are located near surfaces with different temperatures than the air.

Convection is of equal importance as infrared radiation for control of sensible heat transfer within occupied spaces. Moreover, convection is totally relied upon to dissipate latent heat and bioeffluents from occupants, indoor processes, and building materials. When forced air systems are used for control of heat and mass transfer, convection also indirectly influences the acoustic environment, as noise is a byproduct of energy dissipated by the air transport.

A simple, steady-state mass balance of an occupied space indicates the importance of convection (i.e., air movement) to the control of thermal and air quality. Exposure to airborne contaminants and thermal exchange within occupied spaces can be controlled by two basic processes: source control, which can eliminate occupant exposure, and exposure control, which can eliminate occupant exposure, and exposure control, which can minimize but not eliminate occupant exposure. The relationship between these processes is shown schematically in Figure 3, and may be expressed as (*17*):

$$C_i - C_o = \frac{N - E}{V_o} \tag{1}$$

In this equation, $C_i - C_o$ represents the difference between concentrations in indoor and outdoor air, N is the term for source control, and E and V_o are two terms associated with exposure control.

For a mass balance, the concentrations C_i and C_o are expressed in terms of contaminant mass per unit volume or per unit mass of air (e.g., μg/m^3 or μg/kg).

The source control term, N, represents the difference between the emission and remission rates (i.e., net generation rate into the air) of the contaminant within occupied space; it is expressed in terms of contaminant mass per unit time (e.g., μg/hr). Note that for 100% effective source control, $N = 0$, the indoor concentration will always be equal to or less than the outdoor concentration. For source control less than 100% effective, the indoor concentration will always be equal to or greater than the outdoor concentration, if removal control is not used.

The exposure control term, E, in Eq. (1) represents the removal rate (i.e., removal control) of the contaminant from the occupied space and is expressed in terms of contaminant mass per unit time (μg/hr). Removal control is important because it allows control of the value of the indoor concentration below that of the outdoor concentration. This objective is achieved by selecting a process in which the removal rate, E, exceeds the net generation rate, N. The magnitude of the removal rate can be estimated as:

$$E = V_r e C_u \tag{2}$$

In this equation, e is the removal efficiency of the air cleaner evaluated in terms of the contaminant to be removed:

$$e = 1 - (C_d / C_u) \tag{3}$$

where C_d and C_u represent the concentrations of the contaminant downstream and upstream of the air cleaner, respectively, and are expressed in terms of mass of contaminant per unit volume or mass of air (e.g., μg/m^3, or μg/kg). V_r in Eq. (2) represents the air circulation rate through the air cleaner and is expressed in terms of air volume per unit time (e.g., m^3/hr).

Two important concepts can be demonstrated by Eq. (2): *a*) For a given upstream concentration, C_u, the removal rate, E, will vary directly as the removal factor, which is defined as the product of the air circulation rate, V_r, and the air cleaner efficiency, e. Therefore, a lower value air cleaner efficiency may be selected if the air circulation rate is increased by the same factor without affecting the removal rate: (i.e., $E = 2V_r \times e/2$). *b*) For a given removal factor, $V_r e$, the removal rate, E, will vary directly as the upstream concentration, C_u. Therefore, by placing the removal control device closer to the source (i.e., increasing the value of C_u), the removal rate will increase for the same value of the removal factor.

The other exposure control term, V_o, in Eq. (1) represents the rate of air exchange for dilution control and is expressed in terms of air volume or mass per unit time (e.g., m^3/hr or kg/hr). For source control less than 100% effective, the indoor concentration will always exceed the outdoor concentration by the ratio of N/V_o, if removal control is not used. Dilution control is important because it determines the effectiveness of transporting the contaminant to the point of control (e.g., either replacement with outdoor air or removal control).

For effective exposure control, not only is the quantity of air delivered to the room important, but the method in which this air is distributed within the occupied space is also critical to effective control. In other words, the method in which air is returned from a room may be as important to air quality control as the method of supplying air to the room is to thermal control. This concept has become known as ventilation effectiveness (*9*), and the integration of these processes for acceptable thermal and air quality control must be considered in both design and operation if healthy buildings are to be assured.

Building Diagnostics Procedures

A new discipline, known as building diagnostics, may be a management procedure needed to achieve healthy building assurance. This discipline is maturing within the professional building community and is now being introduced into building science curricula at the graduate level. It may also be useful in developing the control strategies to assure healthy buildings over their lifetimes and for providing a means of continuous accountability for those involved in the design, construction, and operations of buildings.

Building diagnostics is described as a "process in which a skilled expert draws on available knowledge, techniques, and instruments in order to predict a building's likely performance over a period of time" (*18*). This concept is similar to that of medical diagnostics, a mature discipline taught in medical schools, in that it contains the same four essential steps: knowledge of what to measure; availability of appropriate instrumentation; expertise

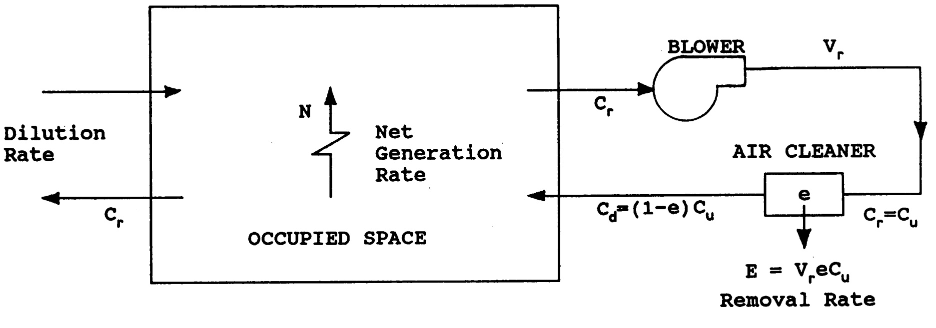

FIGURE 3. One-compartment, uniformly mixed, steady-state model for indoor air quality control.

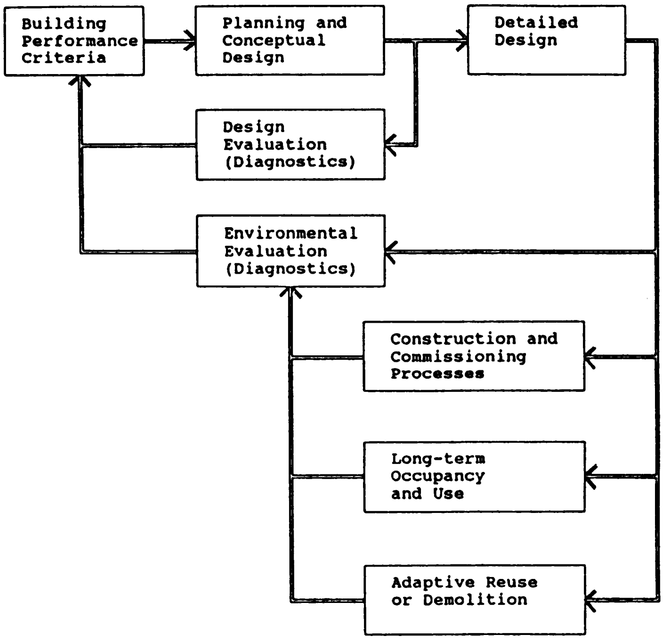

FIGURE 4. Building diagnostics flow chart for all stages of a building's life.

in interpreting results of measurements; and capability of predicting likely performance over time. From these steps, recommendations should follow that can improve system performance. This discipline is useful in diagnosing both sick and healthy buildings and, as shown in Figure 4, can be used in all stages of a building's life.

By incorporating these procedures into the design, construction, and operational phases, a "continuous accountability" process for assuring the performance of the building can be established. Some form of this concept is likely to be promulgated in the near future. One such concept is as follows (*13*):

1. During the planning and conceptual design phases, the building owner, financiers, and designers establish basic performance criteria that are consistent with codes, statutes, and regulations. These criteria should be measurable and should not be changed unless the function of the building changes during its lifetime.
2. During the detailing and construction phases, the performance criteria are translated into compatible prescriptive criteria. Those responsible for designing and constructing the facility are held accountable for compliance with the prescriptive criteria and for achieving consistency with the performance criteria.
3. During the commissioning phase, the performance of the building is evaluated before occupancy by an independent firm for compliance with the original performance criteria. Designers and builders are accountable for the successful commissioning of the building.
4. Periodically during the operational life of the building, and especially when modifications are anticipated, the performance of the building, including the anticipated changes, is evaluated by qualified professionals for compliance with the performance criteria. If changes in function or occupancy have occurred, they should be analyzed for impact on the system performance. Accountability at this stage returns to the building owner, who should provide assurance to the occupants that the building is performing satisfactorily in accordance with the characteristics of a healthy building.
5. During the intervals between inspections, accountability must also be shared between the managers of the occupied spaces and the occupants. If activities are allowed within the occupied space that exceed the capabilities of the system, or if tampering with the system is allowed, the probability of degrading system performance will increase.

Conclusions

Methodologies for assessing health risks from complex mixtures in indoor air must include an evaluation of the performance of the building, its systems, and its design and operations, if any degree of accuracy or precision is expected from these assessments.

As can be seen from the preliminary data presented in this paper, similar discomfort complaints and symptoms may result from several other important environmental stressors that must be controlled together with airborne chemical contaminants. One important consideration would be the synergisms that might occur because of the simultaneous exposures.

Technologies to provide healthy buildings are well known and, when used correctly, result in pleasant indoor exposures. However, when compromises are made in any of the four stages of a building's life, a process of continuous degradation probably begins. This process can be controlled by instituting a method of continuous accountability in which each of the participants in the conception, gestation, developing, and aging processes of a building interact.

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