#4232

SICK BUILDING SYNDROME: REVIEW AND EXPLORATION OF CAUSATION HYPOTHESES AND CONTROL METHODS

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ABSTRACT

Control and abatement of indoor air quality (IAQ) problems are dependent upon reliable investigation and diagnosis. Sick building syndrome (SBS), building-related illness (BRI), and other health and comfort problems are selectively reviewed and discussed. Psychological and social as well as physical, chemical, and biological factors that affect occupant physiological and health responses are identified.

Confusion exists regarding definitions and attributes of problem buildings. Timely, comprehensive, systematic investigations are rare, expensive, and difficult. Systematic and other biases result in inadequate investigations and incomplete or incorrect diagnoses. Building ecology and building diagnostics are described as a comprehensive framework for understanding and investigating indoor air quality problems.

Hypothesized causes of SBS are identified based on published SBS and BRI investigation reports and review articles. Methods to control SBS, BRI, and other building-associated illnesses are presented and discussed. Preventive measures to control IAQ-related health and comfort problems and recommendations for further research are given.

INTRODUCTION

Sick building syndrome (SBS) may affect as many as 20% of the office workers in the United States. In a survey of U.S. office workers, symptoms associated by respondents with poor air quality included a tired, sleepy feeling (56%); a congested nose (45%); eye irritations (41%); difficulty in breathing (40%); and headaches (39%) (Woods 1987). Efforts to control and abate the causes of SBS in buildings are potentially important to the economy and to public health. The present paper is a review of selected published reports related to SBS and a discussion of some of the problems limiting our understanding of it.

The complexity of modern buildings presents significant unmet challenges to designers, operators, and investigators. Problems other than air quality can cause or exacerbate the symptoms of sick building syndrome. Psychological and social as well as physical and biological factors interact to create occupant physiological and health responses to building environments. Yet detailed, comprehensive investigations of building-associated outbreaks are infrequent due to the resources and personnel required to conduct them.

Control and abatement of SBS is dependent upon knowledge developed through reliable investigations and diagnoses. Understanding the potential causes of SBS is essential to such investigations and diagnoses. No clear understanding of SBS and no consistent definition of SBS is used. Authorities in the field use differing definitions or confusing terms which impede progress in understanding the phenomenon. In fact,

TABLE 1

Common Features of Symptoms Reported in Cases of Sick Building Syndrome (WHO 1983).

Eye, Nose and Throat Irritation
Sensation of Dry Mucous Membranes and Skin
Erythema
Mental Fatigue
Headaches, High Frequency of Airway Infections and Cough
Hoarseness, Wheezing, Itching and Unspecific Hypersensitivity
Nausea, Dizziness

TABLE 2

Mølhave's classification scheme for symptoms related to sick building syndrome and examples of each (Molhave 1987).

1. Sensoric irritation in eye, nose or throat
   - dryness
   - stinging, smarting, irritating sensation
   - hoarseness, changed voice
2. Skin irritation
   - reddening of skin
   - stinging, smarting, itching sensation
   - dry skin
3. Neurotoxic symptoms
   - mental fatigue
   - reduced memory
   - lethargy, drowsiness
   - reduced power of concentration
   - reduced memory
   - headache
   - dizziness, intoxication
   - nausea
   - tiredness
4. Unspecific hyperreactions
   - running nose and eyes
   - asthma-like symptoms in non asthmatic persons
   - respiratory sounds
5. Odor and taste complaints
   - changed sensitivity
   - unpleasant odor or taste

TABLE 3

WHO classification scheme for symptoms found in sick buildings (WHO 1986).

1. Sensory irritation of skin and upper airways, along with headache and abnormal taste
2. Odor
3. General symptoms such as fatigue, dizziness and nausea
4. Lower airway and gastrointestinal symptoms (*)

(*)Not generally found in sick building syndrome the most widely accepted definition of SBS requires the absence of identified causes, but even those who present this definition fail to use it consistently.

Knowledge and understanding of SBS is obtained through four primary means: (1) *investigations* of problem or complaint buildings, with or without non-complaint control buildings; (2) multiple building *studies,* which may or may not include complaint buildings; (3) controlled *experiments* in buildings or laboratories where environmental factors are manipulated and the responses of occupants are surveyed; and (4) *literature reviews* where data or findings from various investigations or studies or both are collected and analyzed. The investigations are usually commissioned by building owners, operators, or occupants while the studies and research are usually funded by public or private research or by governmental agencies. Reviews (including the present paper) are usually initiated by interested authors.

DEFINITIONS OF SBS AND OTHER BUILDING-ASSOCIATED ILLNESSES

SBS is variously defined by its symptoms, by its hypothesized causes, or by the demonstration of a statistically valid association of SBS symptoms with a particular building.

Symptoms

SBS is frequently defined by the occurrence of reported symptoms from a group of symptoms listed in several authoritative publications. Most of these definitions declare that the symptoms abate upon leaving the building and worsen upon re-entry (NAS 1981; WHO 1983; Stolwijk 1984; Fanger 1987; Finnegan et al. 1984; Mølhave 1987; Woods 1987). A widely cited World Health Organization report (WHO 1983) lists a broad spectrum of symptoms reported primarily in Scandinavia and the United States. Those symptoms have many features in common and are listed in Table 1.

Mølhave (1987) has proposed a classification scheme for the major symptoms of SBS (Table 2). A World Health Organization Working Group on Indoor Air Quality Research (WHO 1986) has proposed a classification scheme for "sick" buildings (Table 3). These two authorities have presented conflicting schemes. Their lists are inconsistent, and Molhave has classified SBS symptoms while the WHO has classified "symptoms found in sick buildings." The WHO list includes symptoms which it states are not found in sick building syndrome, so a sick building is not equated exactly but overlaps with one in which sick building syndrome occurs.

Causal Factors

Commonly, several broad classes of factors are considered potentially related to an elevated incidence of reported symptoms when a problem is termed SBS (Skov and Valbjorn 1987; Mølhave 1987). These factors include chemical (Mølhave et al. 1984), physical (Alsbirk 1983), biological (Morey 1984), and psychosocial factors (Colligan 1981; Alexander and Fedoruk 1986).

Many authors state that most investigations of SBS have not resulted in definitive identification of causal factors. In fact, most definitions of SBS require that the reported symptoms not be associated with specific environmental or other causal agents. Other definitions of SBS expressly require that the causal agent(s) not be clearly identified or demonstrated by the investigation. Generally, where a causal agent is identified, the symptoms are no longer considered "sick building syndrome"; rather, the building problem is specified as contamination by the causative agent and the illness is termed building-related illness (see discussion below). But confusion exists because many investigators still apply the term SBS to cases where symptom etiology is clearly identified.

Elevated Rate of Symptom Reports

Some definitions of SBS require the demonstrated presence of excess reported symptoms in the complaint building compared with a control building or some other comparable baseline. This involves surveys of building occupants, usually using epidemiologic techniques. However, the measurements made in most reported studies are insufficient to enable identification of the pollutant concentrations and their associations with symptoms. There are usually too few measurements of environmental factors. Large occupant populations are studied through questionnaire surveys, either self-administered or administered by the investigators. The large expense of comprehensive pollutant measurements in each distinct environmental niche within a study building results in few samples of few pollutants in nearly all investigations. Large spatial and temporal variability of indoor air pollutant concentrations within a single building or even spaces within the building (for CO_2, RSP, and VOC, for example) reduce the likelihood that one or a small number of measurements will provide adequate information to identify associations between exposures and symptoms. The "limitations of investigations" are explored later in this paper.

Under the elevated symptom prevalence definition, one or even a small percentage of a building's occupants cannot suffer from sick building syndrome regardless of the symptoms or the building-relatedness of their onset and recurrence.

Sources of Confusion About Terminology

There are two sources for much of the confusion. One involves definitional differences; the other involves inconsistent use of terms. Where the etiology of symptoms and complaints is identified, most investigators do not label the symptoms or complaints SBS or the building "sick" (WHO 1983; Mølhave 1987; Woods 1987). Rather, they define the symptoms as manifestations of illness and classify it as building-related illness (BRI) to distinguish it from SBS. BRI includes such medical conditions as hypersensitivity pneumonitis, Pontiac fever, and allergic dermatitis (Hodgson 1986; Woods 1987). Building-related illnesses are attributed to a broad range of pollutants including infectious microorganisms, allergens, chemicals, moisture, temperature, noise, vibration, and poor illumination.

Building-Associated Epidemics

Kreiss and Hodgson have used the term "building-associated epidemics" to include both SBS and BRI (Kreiss and Hodgson 1984).

Other authors have used BRI as the all-inclusive term covering two categories of episodes: "those characterized by a generally uniform clinical picture for which a specific etiology can often be identified, and those in which affected workers report nonspecific symptoms temporally related to work" (Samet et al. 1988).

While asserting that SBS does not involve identified etiology, some authors still label cases as SBS which include bacterial diseases (such as Legionnaire's disease and Pontiac fever), thermal discomfort, and irritation caused by chemicals, and they call such buildings examples of "sick" buildings

(WHO 1986; Berglund and Lindvall 1987). Thus, confusion is caused by the overlapping but different use of the terms "sick building" and "SBS."

Some authorities argue that buildings cannot be "sick," they may only be contaminated. The term "sick building syndrome" may just inappropriately medicalize an engineering, architectural, or maintenance problem (Hodgson 1989).

Sick Buildings

In listing types of "sick buildings," Berglund and Lindvall (1986) include buildings contaminated with radon, molds, contagious agents, and formaldehyde, and they add to the list "buildings in which the occupants show reactions and symptoms similar to those known to be caused by formaldehyde (Andersen et al. 1975) but in which the concentrations of formaldehyde are well below known reaction thresholds." Berglund and Lindvall appear to focus on defining "sick" buildings rather than the symptoms of the occupants, as in SBS. Recently, Berglund and Lindvall have promoted the use of the term "healthy buildings" through the convening of an international symposium on the subject (Berglund and Lindvall 1988).

Alexander and Fedoruk (1986) have categorized the particular type of problem building added by Berglund and Lindvall as "epidemic psychogenic illness" or "mass hysteria." According to Alexander and Fedoruk, the terms are interchangeable but the first is preferred due to the tendency to misunderstand the second. Like many investigations of sick building syndrome, the diagnosis of mass psychogenic illness is difficult to document and strongly resisted by the affected building occupants (Alexander and Fedoruk 1986).

An example of mislabeling is a recently reported investigation of "tight building syndrome," or "closed building problem," and "new building problem." The authors described the case as fitting the WHO (1983) SBS definition including the usual symptoms and the failure to identify the causative agent(s) (Whorton et al. 1987). When an extended summary of the Whorton article was prepared by others later, the case was termed an investigation of an outbreak of "building-related illness" (HESIS 1987).

Building-Related Illness

Many authors explicitly distinguish SBS from building-related illness (BRI), which includes allergic respiratory disease (sinusitis, tracheobronchitis, asthma, hypersensitivity pneumonitis, and humidifier fever), skin diseases (irritant, allergic, and photodermatitis), irritant syndromes (carpet shampoo, formaldehyde), and infections (Legionnaire's disease, Pontiac fever, Q fever) (Kreiss and Hodgson 1984; Hodgson and Kreiss 1986; Stolwijk 1984; Woods 1987; Mølhave 1987).

Building Sickness

The term "building sickness" was proposed in 1984. Lars Mølhave of Denmark suggested the term "building sickness" to characterize reported symptoms in a building in which "the occupants report comfort or health problems which they assign to the indoor atmospheric environment." Mølhave would limit the use of the term "sick building" to cases in which the problem is identified as multifactorial and in which no measured factor exceeds generally accepted thresholds or recommendations (Mølhave 1987). This is similar to most definitions of SBS without the criterion that there be a statistically significant excess of reported SBS complaints and symptoms.

It is possible that the term "building sickness" has not received more use due to the alternate meanings of the initials BS—British Smoke, which is used in epidemiologic studies involving particulate matter, and a vulgar American slang expression.

TABLE 4

Proposed classification scheme for occupant condition in problem buildings (after Woods 1988).

1. Unresolved.
   Symptoms reported or complaint rates deemed unacceptable by owners, operators or occupants but do not meet standard statistical tests to confirm their association with occupancy of the building. This can occur where contamination or complaints are limited to a small area of a building or occur among the general building population but at rates similar to those found in buildings in general.
2. Building-associated illness.
   Complaint or symptom rates are elevated compared to control buildings or numbers derived from large population studies. Investigation confirms that the complaints are related to occupancy of the building.
   a) Sick building syndrome (SBS) or building sickness (BS). Symptoms are similar to those identified in Tables 1 and 2, but no specific cause of the complaints can be demonstrated by the investigators.
   b) Building-related illness (BRI).
   The disease entity is medically identified and verified. Contamination problems determined as directly associated with the disease(s) involve a wide range of agents and factors including infectious microorganisms, allergens, chemicals, moisture, temperature, noise, vibration and illumination.
   c) Unclassified building associated illness.
3. Undetected problem buildings.

TABLE 5

Causal factors identified in investigations of SBS (after Wallace 1988).

MULTIFACTORIAL
- Sex
- Hay fever
- Migraine
- Smoking
- Home-related illness
- Carbonless copy paper use
- Xeroxing > 25 sheets/d
- VDT use > 1 h/d
- Unsatisfied with job

PHYSICAL FACTORS
- Ventilation
- Ions
- Other physical causes

CHEMICAL FACTORS
- Formaldehyde
- Other volatile organic chemicals
- Semivolatile organic chemicals

BIOLOGICAL FACTORS
- Molds
- Bacteria
- Allergens

Etiology of Confusion

Mølhave suggests that the different or inconsistent use of terminology results from the involvement of different groups of "indoor climate experts." For example, the term "irritation" is used by medical experts as a synonym for toxic skin damages known from occupational exposures; by technical and engineering experts to describe acceptability or unacceptability of the indoor environment; and by the occupants to describe subjective feelings of reduced comfort due to dry nose, dry eyes, and dryness or stuffiness of the air (Mølhave 1987). Thus, the backgrounds of the investigators may significantly impact the diagnoses.

Working Assumptions

In the remainder of this paper, the definitions and concepts articulated by the WHO Working Group (WHO 1983), Stolwijk (1984), Mølhave (1987), and Woods (1987) are relied upon as the basis for the discussion. These exclude building-related illness and emphasize multifactorial sick building syndrome.

Classification of the occupants' conditions in problem buildings will be classified according to a scheme adapted from that proposed by Woods as follows: 1) unresolved building-related complaints or symptoms; and 2) building-associated illness including a) building sickness, b) building-related illness, and c) unclassified building-associated illness. Woods has also added the category "undetected problem buildings" which will not be discussed further here (Woods 1988). See Table 4 for definitions of each of these categories.

FINDINGS FROM MAJOR STUDIES

Potential Etiologic Agents of SBS from Recent Studies

Wallace has reviewed the recent literature on SBS (1988). The review covers published reports from 1984 through 1987. The results of his review are presented in Table 5. Five causal factor categories were developed: physical, chemical, biological, psychological, and multifactorial. Wallace did not review research on psychological factors.

The causal factors hypothesized cover a wide range and the study methods also were diverse. Wallace drew no conclusions from the literature, but his presentation is interesting for the range of factors considered and the amount of interest in SBS represented by the reviewed work.

Several major multi-building, multi-disciplinary studies have been reported, four in Great Britain (Finnegan et al. 1984; Pickering et al. 1985; Harrison et al. 1987; Hedge et al. 1987) and one in Denmark (Skov and Valbjorn 1987). They have developed conflicting conclusions about SBS causal factors.

Two British studies found higher symptom prevalence rates in mechanically ventilated buildings than in naturally ventilated ones (Finnegan 1984; Harrison 1987). Among the mechanically ventilated buildings in the later study, those with humidification had the highest symptom rates. However, among 11 naturally ventilated buildings were two in which symptom prevalence rates were typical of the 16 sealed buildings in the study (Harrison et al. 1987).

Finnegan reported a threefold excess of SBS symptom prevalence rates in five mechanically ventilated buildings (15%–45%) compared with three naturally ventilated buildings (5%–15%) (Finnegan and Pickering 1987). There was a noticeably wide range of building-specific symptom prevalence rates (5%–45%) in buildings characterized by the authors as non-complaint buildings. Incomplete evaluation of building system performance or operation through either inspection, analysis, or environmental measurements has been reported by these authors. No reported measurements have been published.

Another large-scale British study of 30 buildings found "few differences in symptom prevalence" between naturally and mechanically ventilated buildings. (The definition of mechanical ventilation here was "a ducted system but with no plant for heating and cooling.") Higher symptom prevalence rates were found for all symptoms in air-conditioned than in non-air-conditioned buildings and for females than for males. A higher prevalence was found for all symptoms and all ventilation system types in the public sector than in private-sector buildings (Hedge 1987). The published report does not detail the inter-building variations in prevalence rates.

The Danish investigators found no correlation between complaints and building ventilation type. They found a number of factors associated with elevated symptom prevalence including age of building, sex of occupant, job category, type of work, temperature, number of occupants, amount of open shelving, and what they called the amount of "fleecy material" (Skov and Valbjorn 1987). These findings are discussed in greater detail below.

"Multifactorial Sick Building Syndrome"

Several investigators have suggested that the etiologic agents in SBS were multiple factors, none of which alone causes increased symptoms and complaints (Turiel et al. 1983; Mølhave 1987; Woods 1988; Valbjorn and Skov 1987). In fact, measurement of a broad spectrum of environmental parameters usually fails to isolate particular agents as etiologic. Multifactorial analysis identifies clusters of factors associated with higher rates of reported symptoms (Valbjorn and Skov 1987).

The Danish Town Hall Study

The most comprehensive SBS study reported to date is a multifactorial investigation known as the Danish Town Hall Study (DTHS). Covering a total of 27 buildings that were not known problem buildings, the DTHS involved measurements of indoor climate and other environmental parameters in 14 town halls. A questionnaire and clinical study of 4369 employees in the town halls and 13 affiliated buildings was also conducted. While reported symptom levels were high for mucosal irritation (28%) and for general symptoms in the form of headache, abnormal fatigue, or malaise (36%), the measurements of environmental parameters did not result in elucidation of the epidemiology.

However, the differences in the prevalence of symptoms among buildings was significant and was correlated with building factors as well as occupant factors. Building factors that could explain the difference in the prevalence of symptoms included the total weight and potentially allergenic fraction of floor dust, the area of "fleecy" material per cubic meter of air, the length of open shelves per cubic meter of air, the number of work stations, and the air temperature. Occupant factors included sex, type of work, and job category. See Table 6 for the results of the environmental measurements (Valbjorn and Skov 1987).

Among the findings were the following:

1. Elevated rates of reported mucosal irritation were associated with the size of the allergenic fraction of floor dust, the length of open shelves per cubic meter of air, the area of fleecy material per cubic meter of air, the number of work stations, and air temperature.

TABLE 6

Indoor climate measurements in 14 Danish town halls (Valbjorn and Skov 1987).

	Units	Mean	Range Low	Range High
Mean external temperature	(24 hours)(°C)	2.4	−1.2	11.4
Average daily sunshine	(hours)	2.3	0	6.4
Air temperature	(°C)	22.7	20.5	24.1
Person-weighted air temperature	(°C)	23.0	22.0	24.4
Temperature rise during a work day	(°C)	2.5	1.0	8.0
Vertical temperature gradient	(°C/m)	0.9	0.4	2.0
Air velocity	(m/s)	0.15	<0.15	0.20
Relative humidity	(%)	32	25	40
CO_2	(%)	0.08	0.05	0.13
Formaldehyde	mg/m³	0.04	0	0.08
Static Electricity: Observer	(kv)	1.4	0	4.8
Occupants max.	(kv)	1.7	0	4.0
Airborne dust	(mg/m³)	0.201	0.086	0.382
Dust particles: > 0.5 um	(l^{-1})	48×10^3	19×10^3	119×10^3
> 2.0 um	(l^{-1})	25×10^2	8×10^2	116×10^2
Airborne microfungi	(col/m³)	32	0	111
Airborne bacteria	(col/m³)	574	120	2100
Airborne actinomycetes	(col/m³)	4	0	15
Vacuum cleaned dust[a]	(g/12m²)	3.67	0.32	11.56
Vacuum cleaned dust[b]	(g/12m²)	6.14	0.66	17.04
Macromolecular content in the dust	(mg/g)	1.53	0	5.24
Macrofungi in the dust[a]	(col/30mg)	33	11	90
Macrofungi in the dust[b]	(col/30mg)	32	6	192
Bacteria in the dust[a]	(col/30mg)	199	41	380
Bacteria in the dust[b]	(col/30mg)	296	160	680
Man-made mineral fibers in air MMMF	(f/m³)	5	0	60
Not MMMF (< 3 um) in the air	(f × 10³/m³)[c]	33.2	18.5	59.1
Not MMMF (> 3 um) in the air	(f × 10³/m³)[d]	3.1	0.7	5.0
Volatile Organic Compounds (charcoal)	(mg/m³)	1.56	0.43	2.63
Volatile Organic Compounds (Tenax)	(mg/m³)	0.5	0.1	1.2
A-weighted equivalent background noise, $L_{a,eq}$	(dB)	56.7	51.3	60.3
A-weighted equivalent background noise, L_{95}	(dB)	36.2	28.2	44.1
Reverberation time	(s)	0.41	0.28	1.05

[a] = In the office where all the measurements were performed
[b] = In an office with a considerable loading of clients during the day.
[c] = Mean readings in 6 buildings
[d] = Mean readings in 13 buildings, in one building measured 32 mg/m³

2. Symptoms correlated strongly with job category. The symptom prevalence varied highly with job category, and the highest prevalence was found in the subordinate job categories. Jobs involving photoprinting, working at video display terminals, and handling carbonless paper correlated with the reported frequency of mucosal irritation and of general symptoms; the number of weekly working hours of women also correlated with reports of these two symptom categories, although less markedly.
3. As in several other studies, women had a higher symptom prevalence rate than men and complained more frequently about indoor climate.
4. Symptom prevalence rates varied significantly among buildings, supporting the notion that the symptoms are building-related. Individual town halls correlated significantly with reported mucosal irritation and general symptoms. The lowest prevalence of symptoms was found in the oldest town halls (buildings were mostly newer than 30 years of age, with one almost 50 and another 80 years old).
5. The difference between mechanically and naturally ventilated buildings was not significant for this study. This is in sharp contrast to the findings on the large-scale British study (Finnegan et al. 1984; Robertson et al. 1985).

The DTHS strongly supports the findings of many investigations that extensive measurement of environmental variables, including air quality, may not reveal "the cause" of the complaints. It appears more likely that a constellation of factors including some combination of those identified above as well as chemical or biological contamination and improper ventilation system design, construction, maintenance, or operation will be found in problem buildings.

POTENTIAL ETIOLOGIC AGENTS IN SBS FROM THE DTHS

We have hypothesized etiologic relations of some potential causal agents/factors identified in the Danish Town Hall Study (see Table 7). In Table 8 we have attempted to identify potentially additive or synergistic co-variables. The following discussion is based on those two tables. The discussion focuses on some environmental and institutional factors frequently associated with increased symptom or complaint rates in problem buildings (Turiel 1983; Mølhave 1987; Valbjorn and Skov 1987; Woods 1987).

VOC as Potential Sources of Complaints

Reporting on an earlier study, Mølhave (1982) identified 42 commonly used building materials and measured their volatile organic compound (VOC) emissions. A total of 52 compounds were identified. An average of 22 compounds was identified from each material, and the range of emission rates

TABLE 7

Building and occupant factors (Valbjorn and Skov 1987) and their possible connection to the etiology of building sickness.

FACTORS IDENTIFIED IN DANISH TOWN HALL STUDY	ENVIRONMENTAL AND OCCUPANT EFFECTS: CO-FACTOR	ENVIRONMENTAL AND OCCUPANT EFFECTS: HYPOTHESIZED FACTOR IN SBS ETIOLOGY
1. TEMPERATURE (elevated)	Microorganism proliferation	Bioaerosol increase
	Higher VOC emissions/air levels	VOC increase
	Reduced airflow	Contaminant increase
	Reduced ventilation	Increased contaminant levels
2. FLEECY MATERIAL	More VOC sources	Increased VOC levels
	More VOC adsorption surface area	Increased VOC levels
	More fiber sources	Increased airborne fibers
	Difficult housekeeping	Increased airborne dust
3. OPEN SHELVES	More adsorption sites	Increased VOC
	Fine particle deposition sites	Increased airborne particles
	More difficult housekeeping	Increased particles, VOC, bioaerosols
	More source surface area	
4. NEWER BUILDINGS < 30 years	More fleecy surfaces	VOC, particles, aerosols
	Fewer private offices	Noise, crowding, contaminant levels
	Higher occupant density	Increased exposure to contaminants
	Less occupant control	Decreased resistance to illness
5. JOB CATEGORY	Less mobility during day	Increases exposure to contaminants
	Less control over time/work	Personal stress, reduced resistance
	Lower status	Higher exposure, less ventilation
	Less control over work area	Increased stress, reduced resistance
6. TYPE OF WORK	More exposure to toxins	More physiological stress
	More exposure to irritants	More physical and mental stress
	Stressful work posture	More physical stress
7. OCCUPANT DENSITY	Lack of privacy	Psychological stress
	Inadequate ventilation	Increased contaminant levels, exposure
	More local pollutant sources	Increased contaminant levels, exposure
8. #/WORK STATIONS	Anonymity, impersonal environment	Psychological stress
	Lack of privacy, control	Psychological stress
	More local pollutant sources	Increased exposure

was extremely large. The arithmetic average emission rate was 9.5 mg/m^{2}h. Three model rooms constructed from the materials were found to contain between 23 and 32 of the compounds at concentrations from 1.6 to 23.6 mg/m^3. When the cancer risks and health effects (Mølhave classifies irritation as a health effect) of each of the 52 compounds were reviewed, 82% were known or suspected mucous membrane irritants and 25% were suspected or known animal carcinogens.

A very high percentage of common VOC emitted from building materials are known or suspected mucous membrane irritants; therefore, it is reasonable to expect significant numbers of building occupants to experience mucous membrane symptoms in newly constructed, remodeled, or furnished buildings. Turiel et al. (1981) suggested that a number of contaminants acting synergistically may have been responsible for the higher symptom incidence in a comprehensively investigated problem building.

Hollowell (1981) suggested that the reason building occupants complained about what they ought not to be able to perceive (VOC) at the very low measured airborne concentrations was that the composite effect might give rise to the reported health effects. Others have supported that theory (Mølhave 1982; Stolwijk 1984).

Noma et al. (1988) have found correlations between VOC profiles and their distribution patterns in one "sick" and one "healthy" Swedish preschool of identical design. Using sophisticated statistical analyses, they examined the patterns of VOC distribution in various locations in the two buildings. They concluded that the distribution of VOC was more uniform in the healthy than in the sick preschool.

Thermal Factors

Elevated temperature in a building can have many effects on the building environment and directly or indirectly on the occupants. Not the least among them is discomfort from the temperature itself. This discomfort can reduce tolerance to other factors, many of which may be exaggerated by the elevated temperature. Additionally, microorganism growth may be enhanced, VOC emissions from materials will increase, and ventilation airflow will normally decrease.

Microorganism Contamination. Biological aerosol concentrations might increase due to increased growth and proliferation of microorganisms associated with higher temperatures, reduced outside airflow, and increased demand on air-conditioning equipment. Some organisms may proliferate outdoors or on building equipment surfaces in warmer weather. An important example are the Legionella bacteria responsible for Pontiac fever, which has been reported as occurring almost exclusively in spring and summer (Friedman et al. 1987). Many of the reported outbreaks of Legionnaire's disease have also occurred in spring or summer.

VOC Emissions. VOC emissions will increase as a result of the temperature-based increase in vapor pressure. Girman (1987) has calculated that a 13°C rise in temperature will result

TABLE 8

Identification of Possible Synergistic Risk Factors for SBS Based on Risk Factors in Danish Town Hall Study

1. TEMPERATURE + FLEECY MATERIAL + OPEN SHELVES
   More organic sources, emissions
   More microbiological activity
2. JOB CATEGORY + TYPE OF WORK
   Low status = loss of control, mobility, job satisfaction
   Reduced proximity to windows − light, views, outside air
   Combined stressors of work posture, toxins, irritants
3. NUMBER OF WORK STATIONS + AGE OF BUILDING
   Higher density in open office plan, newer buildings
   More local sources
   Less privacy, control, space
4. SEX + JOB CATEGORY
   Females in subordinate (clerical) positions
   Type of work (see #2 above)

in a 200% increase in typical VOC vapor pressure. The increase in emissions will be greatest from materials with large surface areas in the airstream and from materials where the emission process is dominated by evaporation from the surface rather than diffusion from within the material. Some of the materials with large exposed surface areas are freestanding partitions, bottoms of ceiling tiles facing the interior, tops of ceiling panels facing concealed spaces serving as return air plenums, fibrous linings of air ducts, and textiles or fabrics covering walls, furnishings, or floors.

Ventilation Airflow. Many mechanical ventilation systems will reduce airflow and outside air supply to the interior when temperatures rise toward the upper end of the comfort range. This is particularly true of variable-air-volume (VAV) systems. When temperatures are elevated, increased ventilation is most necessary to remove contaminants resulting from higher emission rates and increased airflow is required to provide evaporative cooling of occupants' exposed skin surfaces. Yet, under most ventilation system control designs, airflow or ventilation or both may be reduced.

High Surface Area Interiors

"Fleecy material" and "open shelves" were identified as risk factors in the Danish Town Hall Study. "Fleecy" refers to materials such as fabrics and carpets which have rough, textured surfaces. The association with elevated symptoms might result from the extremely large effective surface areas facing the interior space on fleecy materials or open shelving systems. "Effective" surface area refers to the actual surface area available for adsorption and re-emission sites for VOC or deposition of small particles. Recent advances in mathematics (fractal math) have shown that the actual surface area available for particle deposition or molecular adsorption is many times larger than the two-dimensional (plane geometry) measured surface area. Small particles, which penetrate deepest in the respiratory system, deposit equally efficiently on horizontal and on vertical surfaces (Weschler 1988).

Carpets, textiles used for wall coverings and furnishings, and insulation materials facing the interior or the airstream in mechanical ventilation systems are high-surface-area materials that provide more adsorption sites for VOC and more deposition sites for small particles. Fibrous materials also provide readily available source material for airborne particles through surface erosion, abrasion, or deterioration of the binding forces. Housekeeping tasks including cleaning, vacuuming, and dusting are made more difficult by rough surfaces and the larger surface areas, thereby resulting in the presence of a greater reservoir of unattached particles which may become airborne when disturbed by human activity or ventilation airflow.

VOC Emissions. VOC emitted from building materials have been shown to distribute themselves on exposed materials throughout enclosed spaces and then are re-emitted for several weeks or more (Berglund et al. 1987). Many "fleecy" materials (such as carpets, upholstered furnishings, fabric wall coverings, fiberglass insulation, and air ducts) are known sources of VOC. Many carpets and wall coverings are fastened to the floors and walls, respectively, with adhesives that are known sources of VOC. It is apparent that buildings with large surface areas (from both fleecy materials and open shelves) will likely be associated with elevated VOC air concentrations. It is also likely that VOC concentrations in such buildings will decrease more slowly than in buildings with hard or smooth surfaces and less surface exposed to the interior.

Age of Building

A clear association was found in the Danish Town Hall Study between age of building and complaint or symptom rate, with the oldest buildings having the lowest rates. Newer offices are often constructed from softer, less durable materials on the major surfaces—floors, walls, and ceilings. This could result in higher airborne particle concentrations from deterioration of the surfaces or finishes and polishes applied to them. Newer offices are usually planned with some or all "open office planning" rather than predominantly enclosed or private office spaces typical of older offices.

Densities of workers (per unit of area) in open offices are usually higher than in private offices. This results in many environmental problems, including noise; chemical, physical, and biological contamination of air; lack of visual privacy; lack of audial privacy; and lack of control over personal workspace.

Architects usually control open office acoustic problems by using high-surface-area materials and components (open shelves, freestanding partitions) and by utilizing fleecy materials (carpets, fibrous glass ceiling panels or insulation, fabric-covered partitions). This reduces reverberation time and breaks direct paths of sound transmission. The partitions, where used, also provide some visual privacy and a feeling of occupant control (at least over the immediate work station area). However, they do substantially increase surface area and impede space air distribution.

Job Category and Type of Work

Lower status jobs were associated with higher complaint and symptom rates in the DTHS. Subordinate workers, such as clerical and drafting personnel, tend to spend more time at the work stations than their supervisors, who often move about the building or leave it to attend meetings. Lower status workers also tend to have less space and to be located near the interior of the building.

Outside air supply to the interior is usually less than at the perimeter. Some buildings deliver primarily or only recirculated air to the interior spaces. Thus, interior spaces may have stagnant or stale air. The combination of higher density, more activity, and less ventilation would result in higher concentrations of airborne contaminants. Perimeter offices would be more likely to have views out of windows, providing the worker with visual and psychological relief.

Type of Work. Certain jobs involve exposure to chemical and physical agents known to cause irritation, nervous system effects, and other health outcomes. Equipment and materials used in duplicating, printing, mailing, and clerical activities in general are all associated with various chemical and physical agents which may contaminate indoor air. It is also likely that individuals performing such work will be in subordinate positions and therefore at risk as discussed above.

Occupant Density and Number of Work Stations

It is not clear whether the DTHS found high occupant density associated with higher symptom report rates because of the density or the possible correlation of high density with job category and type of work, as described above. Lower status workers are likely to have less assigned personal work area, i.e., higher occupant density. At higher densities, the occupant-generated air contaminants (metabolic- and activity-based) will be more concentrated prior to dilution or removal by ventilation.

A higher number of work stations might be associated with increased anonymity, a lack of personal privacy and control, and a higher rate of contaminant generation. All of these could affect occupant stress and comfort levels.

Woods (1988) has found a high proportion of buildings with high occupant densities that exceed the design capacities of the ventilation system. Occupants are added without modification to the ventilation system, resulting in inadequate air supply, interruptions of design airflows, and excessive loads on cooling and heating equipment.

LIMITATIONS OF INVESTIGATIONS

There are numerous limitations on investigations of problem buildings which suggest explanations for the frequent failure to identify etiologic agents or contributory building factors. Among these limitations are cost, timeliness, investigatory methods, building complexity, building dynamics, institutional constraints, and insufficient guidance to investigators.

Unsystematic and incomplete investigations result in inadequate diagnoses and unsuccessful remedial efforts. Yet complete, systematic investigations are rare. Expert investigators are usually selected by the occupants or building owner according to the owner's perceptions of the problem etiology. Expertise is usually confined to one or a limited number of fields, resulting in incomplete investigations and narrowly focused findings in many (Mølhave 1987; Kreiss and Hodgson 1984).

The perseverance of the investigators and the availability of methods can determine whether chemical and biological agents can be eliminated as etiologies of building-associated outbreaks (Kreiss and Hodgson 1984). In many instances, ventilation system problems are identified early in the investigation. Modifications to the system equipment, operating schedule, or operational modes (airflow, temperature) will result in a significant reduction of complaints and symptoms, and the investigation will be terminated before problem causes are defined.

Timely investigations rarely occur due to institutional constraints. Frequently, when complaints or symptoms are initially reported, there is hesitation by management to give importance to them. It is often only when complaints become very numerous, when upper-level management personnel are affected, or when workers initiate organized or formal action that management commissions investigators.

Comprehensive and systematic investigations are expensive, difficult, and more time-consuming than building operators or users can normally tolerate. In many cases it is not considered necessary and it is not economically feasible to identify causes if remedial measures can effectively reduce complaints and symptoms, as in the case of ventilation system modifications. Thorough characterization of environmental factors, including detailed chemical and biological contaminant measurements, can be prohibitively expensive and is only undertaken in the most severe or persistent of cases.

Protocols to guide investigations of problem buildings have not been widely tested, validated, or promulgated by any standards development organization. While some generalized protocols have been prepared, significant differences among problem building cases require individualization of protocols and measurement methods (Levin 1987c; NAS 1985; NIOSH 1987; Sterling et al. 1987; Woods et al. 1988). A standard guide for investigation of problem buildings is currently being prepared by the ASTM (Levin 1988).

Standardized sampling and analytical methods for indoor air are limited and those that exist are not uniformly applied or widely used. Efforts to address these shortcomings are under way by the ASTM (Levin 1988). However, interbuilding variations limit standardization of investigations and comparability of results (Levin 1987c).

Comprehensive monitoring for airborne contaminants is extremely expensive and rarely definitive in problem building investigations. Monitoring for airborne VOC is expensive and there is a lack of general agreement regarding appropriate monitoring methods. Characterization of total VOC is not as expensive as identification and quantification of specific compounds, although the methodological problems are significant.

Even where extensive environmental monitoring is conducted, interpretation of results is limited by the absence of guidelines and standards. Interpretation is often based upon standards or guidelines developed in and for different contexts, such as the industrial workplace and ambient air. Comparison of measurements to such guidelines or standards can lead to incorrect assumptions about the effect of the measured parameter on occupant health and comfort (Eisinger 1988).

Limitations Imposed by the Problem Context

Buildings are dynamic, responding to changes in the external environment, internal loads, and the building itself. Internal loads may be generated by user activities, building equipment, or occupants' appliances and equipment. Building loads vary as a result of normal operation of building equipment, principally lighting, ventilation, heating, and cooling. Malfunctions in building equipment, interventions by occupants, manipulation by building operators, and signals from building systems controls constantly effect changes in equipment operation, resulting in load changes and load handling.

Environmental variations among locations within a single building can be enormous. Small distances between locations can involve large differences in some environmental variables including critical air quality factors. Significant variations in environmental factors occur hourly, daily, and seasonally. Therefore, monitoring of environmental factors, including but not limited to the sampling and analysis of indoor air, can produce misleading results unless an adequate number of representative samples is collected over extended or adequately representative time periods and locations. This may be an especially important factor in the failure of many large building or multi-building studies where associations between reported symptoms and environmental variables are not found at statistically significant levels. Single-area measurements or one measurement per floor or per ventilation system for many occupants will simply average precisely the variations that the study seeks to elucidate.

Designer, operator, and occupant perceptions frequently differ from each other and from actual building conditions. Investigator interviews with some but not all of these parties can result in biased assumptions or hypotheses followed by incomplete or poorly focused investigations.

DISCUSSION OF SICK BUILDING DIAGNOSES AND FINDINGS

By definition, an SBS diagnosis requires confirmation that an elevated complaint or symptom rate is associated with occupancy of a particular building, that no known etiology accounts for the symptoms, and that clinical evidence of building-related illness is absent.

SBS can be hypothesized but not diagnosed or defined based solely on clinical evidence unless sufficient numbers of occupants are examined in the case building and compared to occupants of a control building or to a valid baseline for symptom prevalence. Clinical identification of symptoms associated with occupancy of a particular building can result in an SBS hypothesis. Only an epidemiologic or clinical investigation can define the occurrence of SBS. Even where epidemiologic evidence supports an SBS hypothesis, BRI may be present in some or all of the occupants manifesting SBS symptoms.

SBS may involve diverse reactions among building occupants. This may be a function of varying conditions within the building, varying individual responses to environmental factors, or both. Where this is the case, it will reduce statistical associations between reported symptoms and measured environmental conditions, and may lead to incorrect interpretations of even the most complete and careful investigations.

Therefore, as defined and discussed in this paper and elsewhere, SBS may not be a useful term in that it refers to symptom sets which are manifestations of various distinct illnesses or diseases. Aggregating these distinct medical conditions may be the greatest barrier to discovery of the causes of sick building syndrome.

Building Diagnostics

"Building diagnostics" is the name given to a set of practices used to assess the current performance and capability of a building and to predict its likely performance in the future (NAS 1985). While building diagnostics can be valuable at many stages in the life of a building, it may be most useful in investigations of problem buildings. Four elements are essential to building diagnostics, according to the NAS report; they are as follows:

(1) knowledge of what to measure,
(2) availability of appropriate instruments and other measurement tools,
(3) expertise in interpreting the measurements, and
(4) capability of predicting the future condition of the building based on that interpretation.

Several authors have proposed phased investigations of problem buildings or in other applications of building diagnostics (NAS 1985; Sterling et al. 1987; NIOSH 1987; Woods et al. 1988). Woods et al. (1988) have divided the phases as described below.

1. Consultation—scope of the investigation is defined and observations of the building and its systems are made (walkthrough survey). Few or no instrumented measurements are made.

Most advocates of phased diagnostic investigations of problem buildings urge extremely limited use of airborne monitoring during the initial phase. They assert that the majority of building problems can be solved or resolved without extensive monitoring. Furthermore, it is argued that monitoring is of limited effectiveness until it can be focused on hypothesized causal agents or factors.

2. Qualitative diagnostics—hypotheses are formulated through engineering analysis; system performance analysis is initiated with limited measurements (such as airflow and pressure differences). Medical evaluation identifies suspect pollutants and air or bulk samples will be collected for these substances.

3. Quantitative diagnostics—if further investigation is needed to test hypotheses, samples will be collected and analyzed and other environmental measurements will be made.

BUILDING ECOLOGY

Indoor air quality is beginning to receive recognition as an important indoor environmental factor as lighting, acoustics, privacy, security, thermal comfort, and aesthetics have received historically. An approach to understanding buildings and human health based on a systematic, comprehensive framework is badly needed. We recommended an ecological approach—a methodology utilizing knowledge and analytical methods like those used by biological scientists in the study of living organisms in relationship to their environment. We have borrowed from the core of the definition of ecology to coin the term "building ecology," which we define as the study of buildings and their relationship to the natural and built environment around them and to humans who use or are otherwise affected by them (Levin 1981).

We suggest that the concepts of dynamic, interdependent flows used in studying ecosystems exemplify methods that can be adapted to the study of indoor air and human health. An example is a mass balance and mass flow analysis of a contaminant or of moisture into, through, and out of a building. Models for such mass balances and flows have shown that changes in one factor can shift the rate of the processes and the overall distribution of contaminants. Chaos theory in physics has shown that a small perturbation can initiate major deviations from a steady state or regular periodic behavior. Building environmental control systems designed to address these perturbations are themselves subject to changes resulting in small perturbations. There are time constants or lags for each of these changes as well. Thus, the system is an ever-shifting collection of interconnected entities—in the case of the building, both living and inanimate; in the case of the ecosystems, each organism and its environment.

PREVENTING AND REMEDIATING PROBLEM BUILDINGS

Based on the causal factors identified in the Danish Town Hall Study and other investigations, we have identified some potential preventive or remedial measures to minimize SBS. These measures, which are listed in Table 9, have not been systematically evaluated, but there is considerable evidence to support their potential efficacy in reducing the occurrence of sick building syndrome.

CONCLUSION

Buildings are complex. Their effects on humans are extensive and are poorly understood. Attitudes toward and un-

TABLE 9

Potential Control Measures for Multifactorial SBS

HARD SURFACES
- Reduce surface area of materials exposed to interior,
- Use building form, layout, and surface treatment for acoustic control.

LOWEST COMFORTABLE AIR TEMPERATURE
- Especially when building or furnishings are new or after floor and furniture polishing, waxing.

MINIMIZE OPEN STORAGE SHELVING
- Use enclosed shelves where possible.
- Locate shelves in separate space with exhaust ventilation, no recirculation.

LOW OCCUPANT DENSITY
- Utilize total building space for roughly equal area per occupant. Avoid crowding. Confirm HVAC capacity for additional occupants.

MAXIMIZE OUTDOOR AIR SUPPLY
- Extend hours and days of operation; increase percent outside air. Start-up earlier after days of vacancy.

INCREASE WORKER CONTROL, PRIVACY
- Provide local and individual control over lighting, ventilation, heating, cooling, acoustic environment.

FLEXIBLE WORK HOURS
- Allow individual schedule, where feasible.

MINIMIZE EXPOSURE IN STRESSFUL JOBS
- Rotate jobs, mandatory rest (fresh air?) breaks.

derstandings of buildings' effects on occupant health and comfort are not generally shared.

Sick building syndrome is inadequately understood at this time, in part due to confusion in definitions and terminology, in part due to inadequate efforts to study comprehensively its occurrence and causes. Potential causes have been identified and discussed, but the definition of SBS may itself preclude elucidation of its causes due to the limitations on investigations. There are great difficulties inherent in conducting comprehensive investigations or studies that are sufficiently sensitive to detect relevant associations.

Causes of SBS require further investigation. An approach for conceptualizing and conducting problem building investigations has been outlined. We recommend that further efforts to develop and refine models for application in diagnosing problem buildings be developed. Field studies, laboratory studies, and modeling efforts need to be performed to further elucidate the causes and nature of sick building syndrome.

Potential control measures have been identified. Evaluation of the efficacy of potential control measures is warranted due to the large costs involved in their implementation and the risks attendant to their failure.

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