D R A F T

BUILDING ECOLOGY:
AN INTERDISCIPLINARY HANDBOOK FOR INDOOR AIR QUALITY CONTROL

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FOREWORD

The purpose of this handbook is to provide useful information on improving indoor air quality to those involved in the design, construction, and operation of buildings: architects, engineers, interior designers, facility managers, and others whose professional and institutional roles enable them to affect the quality of indoor air.

The field of indoor air quality control has evolved as a specialized and focused activity for people from a wide range of backgrounds and interests. Scientists, design professionals, health professionals, safety professionals, building owners, building operators, and tenant representatives are among the many diverse individuals who are concerned about IAQ as a result of many cases of indoor air pollution. Some of these cases involved temporary or permanent evacuation of entire buildings. Others involved removal of one or more individuals whose health and well-being had been severely affected. All of them involved substantial losses of time and expenditures of resources to deal with negative health effects and decreased productivity.

Ever since the Arab oil embargo of 1973, efforts to improve the energy efficiency of buildings has resulted in conservation efforts which often decreased ventilation air exchange rates. Although this practice lowered costs, it increased occupants' complaints about health and comfort. However, the reduced ventilation associated with energy conservation is not, in itself, the cause of indoor air quality problems. The sources of contaminants have proliferated. Changes associated with energy cost increases have contributed to many problematic changes in building design, construction, operation, and maintenance. Also, new products and processes have brought more sources of contaminants into modern buildings.

Indoor pollution dates at least as far back as the first use of fire by cave dwellers. Modern industrial changes have shifted population from rural to urban locations and jobs from agriculture and industry to service-oriented functions. People spend far more time indoors than before, and buildings are larger, closer together, and more cut off from the out-of-doors. Modern conveniences often involve the use of products which emit harmful substances into the air. Using these products in enclosed, poorly ventilated spaces results in significant increases in airborne pollutant concentrations. Human exposure to indoor air pollutants is greater from the higher concentrations of chemicals and the longer amount of time spent in closed environments.

Longer life expectancy increases the concern for cancer and other illnesses which involve long latency periods between exposure and disease. Asbestos diseases, tobacco smoke related cancers, and chronic respiratory system debilitation are examples. As a result, we have become increasingly aware of the significance of indoor air quality. During the past 15 years, scientists have begun to understand much more about its occurrence, its effects, and its control.

Applying the lessons of science to the design, construction, and operation of buildings is a difficult and lengthy process. Many people are involved: people with diverse backgrounds and interests in the process and the results. This handbook is written to try to provide guidance to those responsible for decisions which affect indoor air quality. It is by no means a definitive manual of practice. Rather, it is a handbook with some basic information which allows any interested professional to begin facing the challenge of maximizing indoor air quality.

PREFACE

This handbook is designed to familiarize architects, engineers, interior designers, and other design professionals with two topics: the concept of good indoor air quality and the way to design for it.

The first five chapters of this handbook provide an overview of indoor air quality issues. These chapters establish a rationale for the practical, task-oriented chapters that follow. Several appendices provide detailed reference sources for subjects covered in the chapters.

The handbook is organized as follows:

Chapter 1 Introduction

This chapter introduces the concept of indoor air quality and discusses the implications of problem buildings.

Chapter 2 Pollutants and Their Sources in Commercial Buildings

This chapter describes the pollutants commonly found in commercial buildings and their most-likely sources.

Chapter 3 Health Effects of Indoor Air Pollutants

This chapter describes the adverse health effects of a number of pollutants found in indoor air.

Chapter 4 Indoor Air Quality Control Strategies

This chapter describes methods of controlling pollutants that adversely affect indoor air quality. Both source and ventilation control strategies are discussed.

Chapter 5 IAQ Criteria and Standards

This chapter describes criteria and standards necessary for good indoor air. Outside air standards, pollutant control criteria, HVAC system standards, and documentation standards are discussed.

Chapter 6 Design

This chapter describes in detail how to plan for good indoor air quality when designing a building. All phases of the building design are covered, from project planning to initial occupancy and on-going operations.

Chapter 7 Evaluating Materials and Building Components

This chapter describes how to evaluate building materials for indoor air pollutants. It also lists common building components and explains their impact on indoor air quality.

Chapter 8 Building Diagnostics

This chapter describes the use of building diagnostics to ensure good indoor air quality. Practical diagnostic methodologies are also explained.

Appendix A Medical aspects of the health effects of indoor air pollutants

Appendix B

Appendix C

Appendix D

1.0

Introduction

1.1. How a Building is Similar to a Space Capsule.

A space capsule must maintain the following activities to keep its occupants healthy. One, it must supply oxygen to the breathing zone of the capsule occupants. Two, it must remove the pollutants generated by the occupants, the activities, and/or the materials inside the capsule by filtration or other techniques. Three, it must control temperature and humidity levels. And four, it must minimize or eliminate the impact of undesirable outside conditions (e.g., vacuum in space). If these activities are taken to ensure a comfortable and healthy indoor environment, then the space capsule occupants will be able to productively carry out their work without harming their health.

The analogy between a space capsule and a building is very real and direct. One, a building must provide fresh oxygen-containing air to the interior breathing zone of the building. Two, a building must remove indoor-generated pollutants such as carbon dioxide and body odors from people. Three, it must keep temperature and humidity levels within tolerable or acceptable limits. And four, it must minimize or eliminate the impact of undesirable outdoor air conditions (e.g., high outdoor temperature or pollution levels). The interior air quality in a building, as in a space capsule, is characterized by the following parameters: indoor temperature, humidity, oxygen, and pollutant levels inside the breathing space. The following factors determine these parameters: ventilation/filtration systems, outdoor air quality, and indoor sources of air pollution. In a space capsule, if these factors are not harmoniously designed and implemented, a disaster that could threaten the lives of the occupants could occur. In a building, the impact of poorly designed factors or systems is not, in general, as disastrous; however, the consequences can be very costly to the occupants' health and productivity and to the building owner's or operator's pocketbook. The disastrous results of poor air quality in a building have been termed the "sick building syndrome" or "building-related illness." Whatever you want to call it, a building with poor air quality (we will call such a building a "problem building") should be avoided and, more importantly, the design of the building should incorporate features that will minimize or eliminate the chance of having a costly problem building.

1.2. What is a "problem building" and why should I be concerned?

Imagine that you are a building owner and that you have just moved your staff from old, rented headquarters. Two days after occupancy, your staff starts complaining of poor air quality. You get your ventilation person into the building to make sure the heating, ventilation, and air conditioning (HVAC) system is working. He/she says everything is fine and sends you a bill. You then hire an air balancing company to rebalance the HVAC system. After the system has been rebalanced, and you have been rebilled, the occupant complaints persist. Next, you go through the phonebook to find an environmental analysis firm to test the air quality in your building. They send an industrial hygienist to your building to take a large number of air quality samples that need expensive analysis by gas chromatography. Several months later, you get a report that states all measured pollutant levels were below the Occupational Safety and Health Administration's (OSHA's) air quality guidelines. The employee complaints continue. Your staff has now formed a coalition and filed complaints with various state agencies and has hired a law firm. You double check with your HVAC person and find out that you are getting the amount of fresh, outdoor air that the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) recommends. Frustrated, you consider demolishing your brand-new building.

Finally, you find a qualified indoor air quality specialist who discovers that fumes from the smoking room are recirculating throughout the building, solvent fumes from the specialized printing room are also circulating throughout the building, and that the carpet installers used twice as much carpet glue as was needed. Furthermore, the fresh air intake is located between a bus stop and your loading dock, sewer gases back-vent into the bathrooms, and the particulate filters in the HVAC are dirty and inefficient. You then get the estimate for remodeling and renovating your new building; you again consider demolition. Meanwhile, one of your employees has a miscarriage and blames the building air quality. It may have had nothing to do with the miscarriage, but her lawyer has no one else to sue.

Some readers may think that the above story is an extreme example. It may be somewhat extreme, but stories similar to the above are not uncommon. (An extreme example is the Legionella episode which will be discussed later.) Other readers will think that the story sounds all too familiar. Most indoor air pollutants that cause a problem building can be tracked down and identified by a qualified indoor air quality expert. However, good planning and intelligent building design by the architect and the builder can help prevent these problems from occurring in the first place. The old adage that an "ounce of prevention is worth a pound of cure" definitely applies in the area of building air quality.

1.3. Factors That Affect a Building's Air Quality

The primary parameters that constitute a building's air quality are temperature, humidity, oxygen level, and pollutant level. Numerous books contain technical discussions on temperature and humidity control (REFS.) and their discussion will be limited here. Also, except for space capsules, if you control the concentration of indoor pollutants, especially carbon dioxide, you will not have a problem with indoor oxygen levels. Therefore, if you control your indoor pollutant concentration to acceptable levels (which, by the way, are not well-defined for most indoor air pollutants), then you will avoid the dreaded "problem building." Figure 1 schematically represents the factors that ultimately lead to indoor pollutant concentrations in a building: especially a commercial building.

[INSERT FIGURE 1-1

There are two major sources of indoor air pollution: the outdoor air and indoor-generated pollutants. There are three pollutant removal processes: ventilation, filtration, and indoor pollutant reactivity. Although ventilation and filtration may be familiar to most readers, the notion that pollutants are removed by a "reactivity" process may not be. Several pollutants, such as ozone and nitrogen dioxide, can physically or chemically "react" with indoor surfaces and, through this process, are removed from the indoor air. A simplified mathematical representation of the factors that determine indoor air pollution levels follows:

$$\text{Indoor Air Pollution Concentration} = \frac{\text{Sources of Indoor Pollutants}}{\text{Removal of Indoor Pollutants}}$$

The above equation shows that a combination of sources and removal mechanisms determines indoor air pollutant levels. Buildings may have high indoor pollutant levels because of either large amounts of pollutants or because of inadequate ventilation. The opposite is also true. Buildings may have low indoor air pollution levels because of low-emitting sources or because of high-ventilation rates. The overall philosophy in "optimizing" indoor sources and ventilation is to first minimize the number and pollutant emission rates of indoor sources and then to adequately ventilate the sources that remain. Of course, indoor air pollutant sources cannot be eliminated altogether because humans themselves emit carbon dioxide and odorous compounds.

1.4. How many buildings have indoor air quality problems?

The effects of problem buildings affect a large proportion of office workers in the United States. In a survey of U.S. office workers, 56% complained of having a tired, sleepy feeling, 45% had a congested nose, 41% had eye irritation, 40% had difficulty breathing, 39% had headaches, and 20% reported that their performance was hampered by poor office air quality (Woods, 1987). Although sick or polluted buildings are only one possible cause of the above symptoms, the survey results indicate that the problem of sick, unhealthy buildings may be much more widespread than was previously thought.

1.5. What are the disadvantages of owning or operating a problem building?

Avoiding lawsuits is probably the number one reason that building owners and operators are worried about the indoor air quality of their buildings. Unfortunately, it took the potential for lawsuits to bring about an increased awareness of indoor air quality in commercial buildings. However, that this increased awareness has occurred at all is fortunate no matter what the reason is. Good, healthy working environments have many more advantages that just avoiding lawsuits. These other advantages include reduced absenteeism, increased worker productivity, increased morale and job satisfaction, and reduced employee turnover rates. Also, long-term benefits such as reduced health and liability insurance premiums are possible.

(FIGURE 1-2 A BOX AND ARROW DIAGRAM TO HIGHLIGHT THE ADVANTAGES OF A HEALTHY INDOOR ENVIRONMENT. OR MAYBE SHOW A CARTOON TYPE PICTURE WITH TWO BOXES -- ONE OF A WORKER WHO IS IN A POLLUTED ENVIRONMENT, LOOKS SICK AND TIRED, DESK IS MESSY, FUMES ALL AROUND HIM AND ANOTHER OF A WORKER IN A HEALTHY ENVIRONMENT WHO IS HAPPY, PRODUCTIVE, and HAS A NEAT DESK.)

1.6. What are the health symptoms associated with a problem building?

Problem buildings cause at least some occupants to experience a variety of irritation-type symptoms. These health symptoms are called acute symptoms because they are experienced over a short time period. Other health symptoms, such as cancer, are called chronic because they occur over a very long time period. Table 1-1 lists the acute symptoms experienced by occupants of a problem building. They range from headaches and mental fatigue to eye irritation and physical tiredness.

Table 1-1. Acute symptoms reported by occupants of problem buildings (Molhave 1987).

1. Irritation in eyes, nose, and throat
    - dryness
    - stinging, smarting, irritating sensation
    - hoarseness, changed voice
    - dry mucous membranes
    - wheezing, throat itching
    - frequent airway infections and coughing
2. Skin irritation
    - reddening of the skin
    - stinging, smarting, itching sensation
    - dry skin
    - erythema
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
    - respiratory sounds
5. Odor and taste complaints
    - changed sensitivity
    - unpleasant odor or taste

Poor building air quality may cause or exacerbate other more serious health ailments. Occupants can bring in a wide variety of infections; the HVAC system can disperse these throughout the building. A building can cause hypersensitivity pneumonitis, humidifier fever, asthma allergic rhinitis, and other similar health problems if standing water has allowed molds, fungi, or bacteria such as Legionella to thrive. Finally, a wide variety of cancer-causing chemicals may be elevated in buildings. Chemicals or pollutants such as radon, asbestos, environmental tobacco smoke (ETS), polychlorinated biphenyls (PCBs), volatile organic compounds (VOCs), combustion products, and pesticides can all cause cancer over a long period of exposure to relatively high concentrations. See Appendix xxx for more detailed information on the health effects attributed to problem buildings.

1.7. What are the major causes of a problem building?

Research to date by one firm shows interesting trends on what types of problems cause problem buildings (Woods, 1987??). Some type of chemical contamination was found in 75% of the buildings investigated, 55% had thermal problems, 30% had humidity problems, and 45% had microbial contamination.

Analyses of the data showed 75% of the buildings had inadequate outside air supplied to the building and 65% had inadequate supply air distribution. In addition, 45% had contaminated ducts, 20% had contaminated humidifiers, 60% had inoperable or inadequate drain pans and drain lines, 60% had inadequate access panels to service or inspect equipment, and 65% had inadequate filtration.

1.8. What are the strategies to control indoor air pollution levels?

The first step in maintaining a healthy building is to minimize the amount of indoor-generated pollutants. This is done in two ways: eliminating the source altogether or ventilating it separately without allowing the pollutants to recirculate throughout the building. The second step is to adequately filter outside air to each zone in the building. The third step is to maintain the equipment and filters to prevent failures. This book contains information throughout on how to design for a healthy building.

1.9. How to Build Ventilation Standards

ASHRAE is the prime organization that sets ventilation standards for office buildings. Their current ventilation standard for general office space is 20 cubic feet per minute (cfm) per person (ASHRAE Standard 62-89). However, not all buildings have the same indoor pollutant sources. The ASHRAE committee that developed the standard had to make many assumptions about the sources in an average or typical building. In reality, buildings with very few indoor pollutant sources can ventilate less and buildings with many potent indoor sources need to ventilate more. Therefore, just ensuring that your building meets the ASHRAE outside ventilation guideline does not prevent your building from having an indoor air quality problem. Statements such as "my building meets the ASHRAE requirements for outside air; therefore, my employee's complaints are unfounded and may be a result of hysteria" are usually not appropriate. Experience has shown that most air quality complaints have a very real basis. And, in some cases, outside air is the problem since it may be contaminated before it enters the building. The building air quality results from numerous factors - not just the amount of outside air provided to the building.

1.10. Does recirculating air improve or degrade air quality?

Air is often recirculated in buildings in order to heat or cool them less expensively. Recirculated air is already close to the desired room temperature. Also, filtered and recirculated air has fewer airborne particles and thus has a better quality. If a building has a sufficient amount of fresh-filtered outdoor air, then recirculating a portion of the ventilation air will not usually cause an indoor air pollution problem. The primary exception is if the air recirculates from a "contaminated" room such as a smoking room or a print room containing high concentrations of evaporated solvents. Such contaminated rooms should be separately exhausted and their air should not recirculate.

1.11. Case Studies of Problem Buildings

Literally thousands of case studies demonstrate how poor indoor air quality in commercial buildings has caused problems from high rates of absenteeism to high rates of fatalities. Many fatalities have been associated with elevated levels of carbon monoxide from faulty combustion appliances. Other fatalities were a result of bacteria (e.g., Legionella). Some case studies have investigated worker perceptions in presumed healthy buildings. Case studies involving two of these subjects follow.

1.11.1. The Legionella Outbreak

The most famous case of a problem building occurred at the Bellevue-Stratford Hotel in 1976 (Broome ?). The hotel was hosting a Legionnaire convention. A bacterium, later named Legionella, had infected the hotel's cooling tower and was dispersed throughout the hotel via the HVAC system. In all, there were 182 cases of legionellosis. Death occurred in 29 cases. This is only the most extreme of thousands of cases where bacteria have infected a building and caused numerous ailments in the building's occupants.

1.11.2. The Danish Town Hall Study

This study was significant because it investigated 27 buildings that did not have known indoor air quality problems (Valbjorn and Skov, 1987). The study involved 14 town halls, 13 affiliated buildings, and over 4,000 employees. It included measurements of indoor climate parameters and employees' health and perceptions. Employees reported the primary symptoms to be mucosal irritation (28%) and general symptoms such as headaches, fatigue, or malaise (36%). Selected findings included the following:

* Elevated rates of mucosal irritation were associated with allergenic floor dust, length of open shelves, area of "fleecy" material, the number of work stations, and the indoor air temperature.

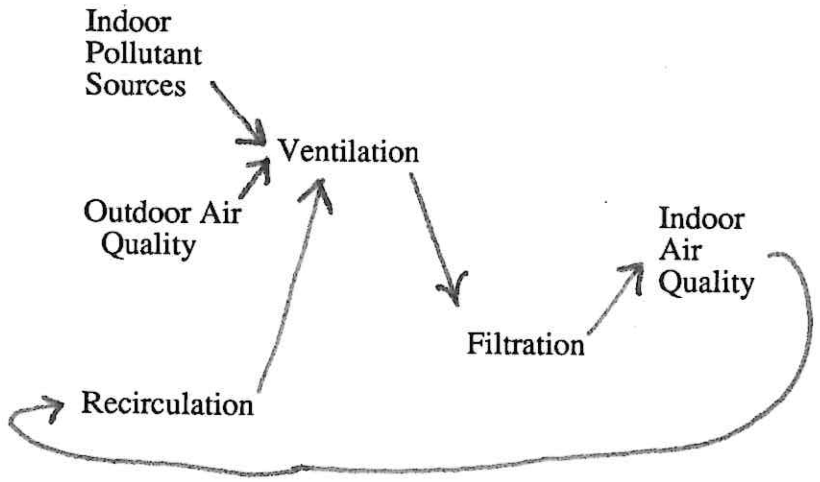
* Symptoms were correlated to job category with the most symptoms reported by employees in subordinate job categories. In addition, jobs involving photoprinting, video display work, and carbonless paper handling had increased reporting of mucosal and general irritation.

* Women reported more symptoms and complained more about the indoor climate than men.

* The prevalence of symptoms correlated significantly from building to building supporting the notion that the symptoms are building related. The lowest prevalence of symptoms was found in the older buildings.

The major conclusion of the DTHS was that presumed "normal" buildings had some indoor air quality problems; although, the exact natures of the problems were only indirectly addressed. In these normal buildings, there was the potential to improve indoor air quality, employees' health, productivity, and happiness.

Figure 1



[FIGURE 1 WILL CONSIST OF A BOX AND ARROW DIAGRAM SHOWING HOW SOURCES, OUTDOOR AIR, VENTILATION RATES, VENTILATION, RECIRCULATION AND FILTRATION COMBINE TO DETERMINE INDOOR AIR POLLUTANT CONCENTRATIONS.]