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How Building Systems Affect Worker Wellness

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The Army has a significant financial investment in its facilities, especially in the construction, modification, and maintenance of buildings used as workplaces. Just as the physical environment of the workplace affects work productivity, there is a fundamental relationship between the quality of its facilities and how well the Army can perform its mission. Despite high building costs and limited financial resources, the Army must cost-effectively improve its facilities for better productivity.

Many factors combine to determine how well a facility can function as a workplace. This study examined how the facility performance attributes of thermal comfort, indoor air quality, lighting performance, and spatial configuration affect the individual worker. This study will help establish a body of knowledge that can exploit the links between definable physical environments and optimal human health, job performance, and satisfaction.

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The Army has a significant financial investment in its facilities, especially in the construction, modification, and maintenance of buildings used as workplaces. Just as the physical environment of the workplace affects work productivity, there is a fundamental relationship between the quality of its facilities and how well the Army can perform its mission. Despite high building costs and limited financial resources, the Army must cost-effectively improve its facilities for better productivity.

Many factors combine to determine how well a facility can function as a workplace. This study examined how the facility performance attributes of thermal comfort, indoor air quality, lighting performance, and spatial configuration affect the individual worker. This study will help establish a body of knowledge that can exploit the links between definable physical environments and optimal human health, job performance, and satisfaction.

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EXECUTIVE SUMMARY

Good facility design and planning must produce facilities that satisfy several fundamental objectives at once; they must maintain appropriate air quality, thermal comfort, and lighting for building inhabitants, while minimizing energy consumption and maintaining system flexibility.

Designing an effective spatial configuration for an office involves matching the office space to the needs of the organization that houses the structure, and the individuals who occupy it; an office must be suited to both the work and the workers. Traditional offices were divided between closed offices for supervisors, and open ("bullpen") offices for workers. Larger modern organizations have incorporated "cuoicles," or free-standing partitions that allow a desirable amount of privacy to individuals or small groups of workers. Partitioned workplaces are seen as flexible alternatives to the traditionally structured offices that allow work areas to accommodate economic and ergonomic factors, and "cognitive personalities." As in all aspects of building design, designing for spatial configuration must strike a balance between the objective needs of the organization and the more subjective human ingredient. Good building design is a holistic integration of all these factors, regardless of whether it involves new building design or a redesign of existing facilities. (Chapter 2)

The use of lighting in the office workplace involves issues of both function and aesthetics. Functional issues involve objective and measurable attributes of physical comfort, quantity, and efficiency. User-aesthetic issues involve less measurable attributes of psychological comfort, and lighting quality and effectiveness. In fact, occupants' assessments of lighting are based on a mixture of objective and subjective characteristics. The same objectively measured "glare" produced by a standard office luminaire, for instance, may not be seen as "glare" when it is produced by chandelier or window light. Those functional evaluations of lighting based solely on mathematical approaches to lighting and mechanical design that promote uniformity are based on many weak assumptions and do not produce accurate or consistent results. Generally, uniform overhead lighting provides poor illumination that wastes energy and imposes an oppressive and mundane atmosphere. A combination of ambient and task lighting of the office provide the basic ingredient to a good office environment. (Chapter 3)

Thermal comfort is influenced by a range of environmental and personal parameters. Environmental parameters that influence thermal comfort are (1) air temperature, (2) mean radiant temperature, (3) humidity, and (4) air motion. Two quantifiable personal parameters used in calculating thermal comfort are activity level and clothing insulation. Several mathematical algorithms combine these parameters to predict the comfort range within a given space. However, objective measurement of thermal comfort is hard to achieve. Like any calculations, these algorithms depend on the accuracy of their measured input, even though thermal characteristics can fluctuate from point to point in a given area. Moreover, thermal comfort is a highly subjective quantity that may better lend itself to survey or questionnaire measurement on a broad "comfort scale." (Chapter 4)

The effects of indoor air pollution are broad and far-reaching. Economic costs involve: (1) materials and equipment damage, (2) direct medical costs, and (3) lost worker productivity. Other costs less readily quantifiable are: (1) welfare loss associated with pain and suffering associated with health effects not fully alleviated by medical treatment, (2) the value of unpaid time spent, in the home, caring for those whose health has been affected, and (3) losses due to the reduced enjoyment of recreational or nonproductive activities affected by indoor air pollution. (pp 49-65)

A good facility design will bring several factors to bear to maintain good air quality in the office workplace. Tobacco smoke is a common source of indoor air pollution that can be minimized by creating or establishing designated nonsmoking areas. Workplaces unavoidably close to smoking areas and smoking areas themselves should be designed with adequate extra ventilation, or should be equipped with air-cleaning mechanisms. (pp 49-51)

Often building materials themselves are the sources of indoor air pollutants. Materials containing volatile organic compounds or formaldehyde should be avoided where possible. If such materials cannot be avoided, several strategies can help guarantee good quality indoor air. The risks of using such materials can often be minimized by aging the materials in a warehouse before using them for construction. Once installed, some VOCs can be "baked out" of construction materials before the building is occupied. Increased ventilation and use of air cleaners can also improve air quality. Formaldehyde-containing materials may be sealed to prevent or reduce the escape of vapors. (pp 51-54)

Radon is an important external source of indoor air pollution. New facilities may best be located to avoid radon-containing soil, or, in some cases, radon-containing soil may be removed before construction begins. In existing facilities, the danger of radon can be minimized by sealing off possible radon entryways or by providing good subfloor ventilation. (pp 54-55)

In all climates, the ability to provide adequate thermal comfort levels, and thus to enhance productivity, is an important consideration for the designer. Thermal comfort demands require the building to meet users' functional needs, and to respond to stresses of the changing climate. In its broadest sense, building design for thermal comfort involves a balance between the building's orientation, its windowing scheme, the use of thermal mass, and the use of mechanical systems to maintain interior temperature and ventilation.

FOREWORD

This study was conducted for the U.S. Army Construction Engineering Research Laboratories (USACERL) under Project 4A161102AT23, "Basic Research in Military Construction"; Work Unit SA-X02, "Human-Facility Interior Interaction."

This research was an interdivisional effort of the Energy and Utility Systems Division (FE) and the Facility Systems Division (FF) of the Infrastructure Laboratory (FL), and the Environmental Laboratory (EL), USACERL. David Joncich is Chief, CECER-FE, and Alan Moore is Acting Chief, CECER-FF. Dr. Michael J. O'Connor is Chief, CECER-FL, and William Goran is Chief, CECER-EL. The USACERL technical editor was William J. Wolfe, Information Management Office.

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CONTENTS

FIGURES

TABLES

HOW BUILDING SYSTEMS AFFECT WORKER WELLNESS

1 INTRODUCTION

Background

The Army has a significant financial investment in its facilities, especially in the construction, modification, and maintenance of buildings used as workplaces. Many factors work together to determine how well a building can function as a workplace. It must be flexible enough to respond to organizational changes, must be able to meet changing technological requirements, and most importantly, must create an interior environment that serves the needs of its inhabitants.

Several trends have combined to emphasize the importance of the fundamental relationship between the Army's ability to fulfill its mission, and its facilities. Costs of owning and operating buildings continue to increase; financial resources have diminished; and user productivity has remained unchanged or declined. This study investigated the physical and psychological relationship between the individual and the facility, emphasizing how an individual worker's "wellness" can be affected by the physical attributes of the environment. In this context, wellness is defined as the health, performance, and satisfaction of the individual worker. Some physical attributes of a facility that affect wellness are thermal comfort, indoor air quality, lighting, and spatial configuration. A comparison of how a worker's wellness responds to a differing facility physical attributes can provide the basis for a system to measure, evaluate, and recommend changes to improve facility quality.

Objective

The overall objective of this study is to outline how to design and implement facility support systems to optimize worker wellness. Information gained from this preliminary study will contribute to further research to develop a comprehensive methodology for relating interior building performance attributes to human wellness.

Approach

A team of experts in the area of building performance attributes was formed. The group met regularly to discuss and to develop strategies to relate interior building performance attributes to occupants' wellness. A literature search was performed to examine the characteristics of each interior attribute in detail, and to identify areas that a designer should consider in developing or evaluating physical space. Researchers identified and investigated four areas that should be considered to effectively evaluate physical spaces. To facilitate this research, it was imperative to narrow the discussion to issues related to an office or administrative type of function. It is presumed, however, that the proposed general principles and methods can be used in a broad variety of work environments.

Mode of Technology Transfer

The results of this research will be forwarded to Corps of Engineers offices and installation Directorate of Public Works (DPW) personnel for use as a reference guide to designers and facility managers. This research will also be incorporated into the Corps of Engineers PROSPECT courses "Interior Design I and II." This work will also contribute to further research in issues concerning quality of life, facility delivery process, interior design, and facility management, which will be used to produce advanced products, systems, and methodologies to further support the designers or facility managers' function.

2 SPATIAL CONFIGURATION

Introduction

One of the most difficult problems associated with office workers productivity, is being able to identify and quantify what it is they are expected to do. In effect, white collar employees are paid for their ability to apply their knowledge to work. In most cases they are not asked to produce "10 widgets per hour," but rather to solve a given problem using their knowledge and other resources. Office workers are in control of their own "rate of productivity." The question is, does the function and needs of the worker drive the space (office) or does the space (office) define worker needs based on other issues? For example, what is the effect on the worker if the organization reduces individual office space due to the high cost of rent? What impact do organizational standards have on workers? If standards do exist, why do they exist, how are they used, and how are they implemented?

Steelcase Inc. (Lathrop, 1991) has adopted the philosophy that if the physical space drives the users, the net result is a negative impact to the workers effectiveness. If, however, the organizational needs, all the way down to the individual performing a given task, shape their space needs, the net result is a positive impact on the workers effectiveness. They go on further to imply that this thinking uses "Effectiveness" versus "Efficiency" as its driver and often means providing more space for their workers. Again the net result is a gain for the organization and the workers because even a small increase in overall productivity of the workers far outweighs extra expense on furniture, construction, or rent.

The following is a simplified illustration of how much productivity costs.

In a 100,000 sq ft administrative building (1 sq ft = 0.093 m^2), assume an occupancy of 400 persons.

- Assume an average salary of $20,000 per person. Annual payroll = $8 million.
- At full capacity, $8 million worth of productivity results.
- If something has an impact on employee productivity, say 1 percent, the cost or gain in productivity is $80,000. ($8 million x 1 percent = $80,000).

Organizations must identify what it is they are to impact–basically, answer the question why they are in business. For example, a company that produces widgets wants to be able to produce a quality widget in the most time efficient method. In an office, the product is generally a misnomer; what the organization must do is support the workers to allow them to be most effective. Once the organization identifies their "product," then they can better evaluate their ability to influence that "product." The goal of this research is to recognize costs associated with providing the "product" involved (the workplace), look at it over time by some life cycle analysis/measure, and determine the impacting variables.

History of the Office

Offices in the past were quite different than those we are familiar with today. Different needs, office procedures and technology meant a simpler office with little or no privacy–a bullpen office. This type of office consists of a large space with desks arranged closely together without vertical separation between them. Bullpen offices often facilitated work flow between workers and encouraged informal communication between employees. The bullpen office was typically combined with enclosed offices for supervisors. The enclosed offices were an expression of rank, reward, and leadership.

The bullpen office is still used today but has become less popular as people tend to view some amount of enclosure as important. Also, new technologies have affected the office, requiring one to use the vertical space around workstations as well as to reduce the footprint of each workstation. This need helped the development of systems furniture that uses panels to support the workstation components.

Technology tools like the telephone, typewriter, computer, and photocopier have had a major influence on the interior office environment as well. External communication (correspondence) led to the generation of paper, which was stored in pigeon-holes on desks, flat, in boxes or in drawers. The introduction of vertical filing helped revolutionize the office by making filing easier and in fact led to generation of even more paper. More internal correspondence, standardized formats and varying theories of indexing or methods of filing pushed for the development of increased ease in storage of paper. This increase and change in paper generating activities impacted the office in several ways. One way, personal filing at each desk became, and still remains, critical to the effective performance of one's job.

The need for some enclosure and requirements to use the vertical space introduced landscaped partitioning by the Herman Miller Company. This initiated some form of privacy to the user as well as different worksurfaces, storage units, and miscellaneous accessories like task lights, paper handling devices, etc. Landscaped partitioning was the start of "cubicle, semi-private workstations," much of which still exists today. These first cubicles incorporated free-standing furniture (conventional desks, bookcases, file cabinets, etc.) with free-standing partitions. Enclosed offices still existed for supervisors or conference areas in most conditions.

The first generation of systems furniture developed and contributed to the workplace environment by removing storage units from the floor and having the panel support them, forming a system. Simply, the first generation of systems furniture have panels of varying heights that offer an enclosure that is strong enough to support storage units thereby saving space (workstation square footage). The second generation of systems furniture incorporates these same features but introduces cable management capability. It also incorporates ergonomically sensitive design features such as workstation height/angle and keyboard adjustability. Finally, a third generation of systems furniture employs horizontal and vertical panel modularity and allows users to stack the panel enclosures. This system also integrates the capability of environmental responsiveness through their functional modularity. The systems resemble building blocks where each panel block can be dictated by function: fans for circulating air and exhausting heat, filters for cleaning air, acoustical panels for sound privacy, glazed panels for visual access with acoustical privacy, etc.

The use of systems furniture has helped to reduce the square footage requirements of each workstation (use of vertical space), generally giving the users some level of privacy (visual and acoustical), and functionally and aesthetically improving the interior work environment. Research, industry analysis, and surveys have begun to show a change in using exclusively systems furniture. Workers are requesting more open, "team areas" versus smaller, more private workstations. As stated earlier in this section, Steelcase strives to provide Effective vs Efficient workstations in reference to the square footage of spaces. Consequently, while systems furniture saves valuable real estate, the cost of not providing an Effective workstation as it impacts a user's productivity must still be considered.

The Changing Office

Change in office configuration came about for a variety of reasons, including: the size and make-up of the workforce (demographics), the attitudes, satisfaction, and knowledge level of the workers, and an increase in office automation and technology.

The Workforce

The number of white-collar workers in the workforce has increased from less than 29 million in 1960 to over 67 million in 1990, requiring organizations to look for an economical means to provide office space for the larger workforce. The aging workforce, handicapped accessibility requirements, and the increase in women in the workforce are a large proportion of the workforce, requiring more considerations in all aspects of the office space.

Worker Attitude and Satisfaction

Office workers are increasingly dissatisfied with their work. According to a 1991 Steelcase report, only 43 percent of office workers are "very satisfied" with their work. Most of the job satisfaction has been reported by clerical, secretarial, and union workers. The reasons for the dissatisfaction vary by person, place, and organization. Office workers are more knowledgeable today, have more formal education, and are much more aware of office-related issues. As a result, office workers demand more from their work and their work environment. Research studies have shown that job satisfaction depends on worker satisfaction with both the individual workspaces and the whole office environment. This illustrates the integration required of building attributes and human characteristics to produce a truly good quality, synergistic design.

Health and safety in the workplace are concerns of office workers. Problems like eyestrain, backaches, carpal tunnel syndrome, and hazards like radiation from computer terminals, poor air quality and exposure to hazardous materials have become major issues to office workers. Stress, which is virtually impossible to quantify, impacts office workers also.

Office Automation and Technology

Technology requires a supporting infrastructure of power, cabling, lighting, and thermal control. In most cases, the current infrastructure cannot meet all of the requirements for the various technology tools. Office technology is noted as a major cause of problems in today's office. Computers are becoming more widely used and while technology is changing quickly, the office environment is slow to change to meet the new needs. In the 1991 Steelcase report, 85 percent of office workers reported using a computer, 33 percent more than 5 hours per day.

Computers require space and different types of furniture to avoid health problems in workers. Predictions of the "paperless office" never came to fruition and most offices generate more paper than before. Along with the visual and postural health problems are the psychological effects of office technology. Automation in the office can lead to rigid work procedures, repetitive and routine jobs, and less mobility, all of which may lead to potential health disorders. In addition, electronic mail has led to a feeling of isolation in many office workers and a distinct lessening in informal communication, which is important to worker satisfaction.

Factors in Spatial Configuration

The most common office spatial configurations used today (open, enclosed, and bullpen offices) are faced with all the problems stated above. An improved quality of worklife and a humanized work environment are psychological incentives that can increase productivity. Worker specific incentives can be categorized as either psychosocial or psychophysical. These factors, along with three more (organizational factors, economic factors, and ergonomic factors) must be addressed to produce the most effective and productive workplace.

Psychosocial Factors

Psychosocial factors are those that affect the worker's psychological state through the social environment or interaction with others, encompassing such aspects as job design, motivation, training, supervision, expectations, group work flow, status, and social interaction.

Psychophysical Factors

Psychophysical factors are those that affect the worker psychologically through the physical environment. Often, the way management views the importance of the workforce is evident in the decisions made regarding the physical interior environment. These factors include: privacy, communication with other employees, and the public, personalization and display, aesthetics, and traffic flow, both horizontally (doors and hallways) and vertically (stairways and elevators).

Organizational Factors

Organizational factors are those that influence workstation design and workers through the standards of the organization. These factors usually include company structure, long range goals, and corporate culture. Many organizations have been moving from a departmental-based structure toward a project- or group-based structure. In a departmental structure, employees are placed in close proximity to those that perform similar functions even though they are often working on separate projects.

In a project structure, employees who perform different functions are working together on a project and are in adjacent office spaces. Unlike a departmental structure, as one project is finished and new ones begun, project teams will shift according to the needs of the new work; this requires a physical movement to allow new teams to be in the same area. This creates a need for flexible work environments.

Growth is an organizational factor which involves flexibility. When first deciding on the spatial configuration of an office, it is important for the organization to somehow predict the future growth and needs of the office and to prepare for it accordingly. If an organization expects to grow in the near future, the office design chosen must allow for office space for the increasing employee population and avoid major office changes in the future that may lead to high costs. Use of modular design and workstation components in space-saving layouts is a cost-saving way to plan office changes.

The organizational culture will control such things as the size of a person's office based on rank, the amount of privacy afforded in that space, the office's location, whether or not there is a window, and even the quality of the furnishings. Again, like psychophysical factors, the interior physical environment can tell the observer how important management feels their workforce is to the organization based on its attention given to the work environment.

Economic Factors

Economic factors will directly affect an organization's organizational policy. These factors include such things as increasing office rents, and the need to maximize the use of office space and minimize costs–get the greatest number of people in the least amount of space without negatively affecting productivity. Economic factors also cover the increasing need for flexibility. In most organizations, the "churn rate," or the percentage of occupants relocated within the same facilities during a year, has been steadily increasing; flexibility has become a major consideration. As the annual churn rate nears 50 percent there is a need to compare the costs of relocating offices with the costs of reconfiguring the space (Lindo 1991).

Worker absenteeism is a large economic cost to organizations. Absenteeism occurs when workers become ill or injured in the workplace due to postural problems, illness due to indoor air contaminants, eyestrain and headaches because of improper lighting, and injuries because of an inadequate office configuration. For example, exposed cables cause people to trip; and back strain may result when employees try to reach needed items placed out of reach because there is no room to store things properly. It has been reported that a 1984 estimate by the American Academy of Orthopedic Surgeons cited lost earnings and medical-related expenses of more than $27 billion annually, and that some businesses spend $9000 per day treating such disorders in their employees. Absenteeism will also occur when workers are unhappy in their work due to a variety of psychosocial and psychophysical factors; people will just stay home.

Ergonomic Factors

The term "Ergonomics" is derived from the Greek term "ergo," meaning work, and "nomos," meaning natural laws, and refers to the study of the relationship between the worker and the work environment. The increased use of computers in the office has made ergonomics a major issue in promoting health and safety, and in increasing productivity in the office. The important aspects of ergonomics include chair adjustability, work surface height, electronic equipment and office layout especially in terms of accessibility.

Office chairs should be adjustable for height and angle of the backrest, should have lumbar support, and (depending on the individual task) arm rests, and should swivel, preferably on a five-point base for stability.

Worksurfaces should be vertically adjustable to accommodate a wide range of user sizes. They should also allow sufficient room for the user's knees, and worksurface legs should not interfere with the movements of the user. Worksurfaces should have rounded edges and corners to prevent injuries. Computer users should have keyboard trays with adequate wrist support to allow for the proper posture while typing to prevent back fatigue.

The office layout or spatial configuration should provide accessibility to all equipment and flexibility to perform various tasks. It should also provide sufficient space to allow for maximum productivity, proper job execution, and safety in the workplace.

Cognitive Personalities

One study suggested that an office environment should contribute to a person's ease of communicating, choosing, or evaluating information (Williams, Armstrong, and Malcolm 1985). An office can further the work of an individual and an organization only if its members understand the structure of that organization, and if that structure is reflected in the office design. Note that the office is the tool for the white collar worker; office design must reflect the psychological aspects and work style of the individual and the task to be done.

Individual work styles are developed from intellectual processes known as cognitive styles. Swiss psychologist Carl Jung has postulated that there are four innate personal characteristics that can offer observable differences in the way individuals perceive the workplace:

1. Sensing: Becoming aware of things directly through the five senses and concentrating on the actual facts and details to be verified by seeing, hearing, touching, weighing, and measuring.

2. Intuition: Becoming aware of things indirectly by incorporating ideas and associations from the unconscious with data provided through the senses.

3. Thinking: Coming to a conclusion by a logical process aimed at an impersonal finding.

4. Feeling: Coming to a conclusion by appreciating the personal, subjective values assigned to things, people, and events.

Combinations of these characteristics in an individual result in a particular pattern of needs, behavior, values, and interests resulting in four cognitive styles. These four styles suggest different requirements for how office space is used, and how workstations are designed. Generally, a personality type will associate with similar types, creating a corporate culture both in personalities and in spatial layout.

Visionaries: These individuals have the personal characteristics of thinking and intuition. They collect theoretical possibilities, tend to base decisions on impersonal information and take a broad view of things. They want to appear competent and use a few general rules to gather data and gear it towards making decisions quickly. They need an office that was designed for large quantities of reference materials, plenty of shelving and storage, preferably little interruption, and room to expand workstation layouts (Figure 1).

Catalysts: These individuals have the personal characteristics of feeling and intuition. They also collect data, but act on it differently, tend to base decisions on the personal values of all those involved rather than some abstract future. They generate possibilities, hunches, and alternatives and look at events as a part of a dynamic process towards decisionmaking. An office with room for personal items to reflect their more personal approach to decisionmaking, a mixture of memorabilia and work objects best reflects their needs. (Figure 2).

Stabilizers: These individuals have the personal characteristics of thinking and sensing. They collect hard data and make decisions based on logic aimed at creating stability and order. They strive for procedures, rules, and regulations to maintain the organization logically and systematically. Their needs require an environment geared toward action and space to display relevant data (Figure 3).

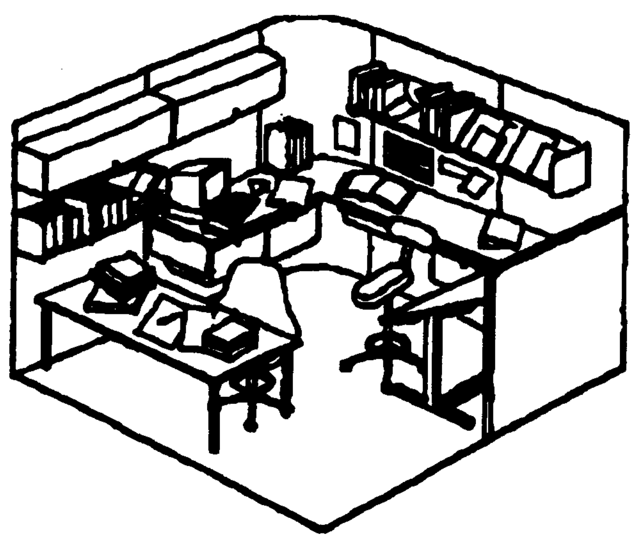


Figure 1. Spatial Layout for a "Visionary's" Office.

<u>Cooperators</u>: These individuals have the personal characteristics of feeling and sensing. They collect facts and experiences and make decisions in light of their own personal values or others affected by these facts. They have a live-and-let-live approach and are receptive to change. They often try to harmonize any differences that emerge. They need contact with others to work efficiently, and require an office that allows accessibility to co-workers. Privacy is a nonissue. (Figure 4).

Figure 2. Spatial Layout for a "Catalyst's" Office.

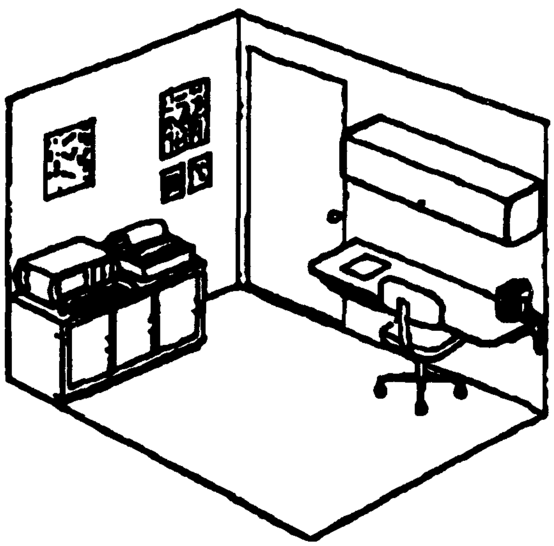


Figure 3. Spatial Layout for a "Stabilizer's" Office.

Figure 4. Spatial Layout for a "Cooperator's" Office.

Concepts in Spatial Configuration

Because of the many changes happening in offices today, organizations are always looking for more effective office environments to promote worker satisfaction and productivity. The best office environments would address the concerns of the user through effective spatial configuration techniques as described in the following section.

Office Types

Bullpen Offices. Bullpen offices (described earlier) became inefficient and dysfunctional to tasks to be performed as organizations grew larger. The need for privacy became of primary importance and workers have become more conscious of and discriminating in what they thought was a satisfying workplace. Bullpen offices do offer some benefits. They encourage informal communication, make work flow easy to follow, and maximize flexibility and economy. Many organizations decided the problems of lack of privacy and noise outweighed the benefits and attempted to find another office type that better fit their needs. Bullpen offices have been appropriately used for pooling people who need visual and physical proximity.

Enclosed Offices. On the opposite end of the spectrum from bullpen offices, are enclosed offices (Figure 5). Enclosed offices offer privacy, personalization, status, and an inexpensive original cost, but are nonflexible and expensive in materials and downtime to reconfigure. Enclosed offices do not encourage communication and often foster isolation. They also require more floor area than open office plans, and workers may complain of feeling claustrophobic. Supervisors or executives generally need enclosed offices due to the level of privacy needed to perform their job. Enclosed offices often are on exterior walls and can therefore capitalize on windows.

Open Plan Offices. The general concept of open plan offices is to gain visual privacy using a pre-manufactured panel system (Figure 5). Panel systems are flexible; it is easier and cheaper to reconfigure panel-system offices than enclosed offices. (This depends on whether the workstations were designed on a module, and how easily the panels can be moved.) Included in moving panels is the cost of moving HVAC and electrical outlets along with telecommunications wiring. However, panel systems can interrupt

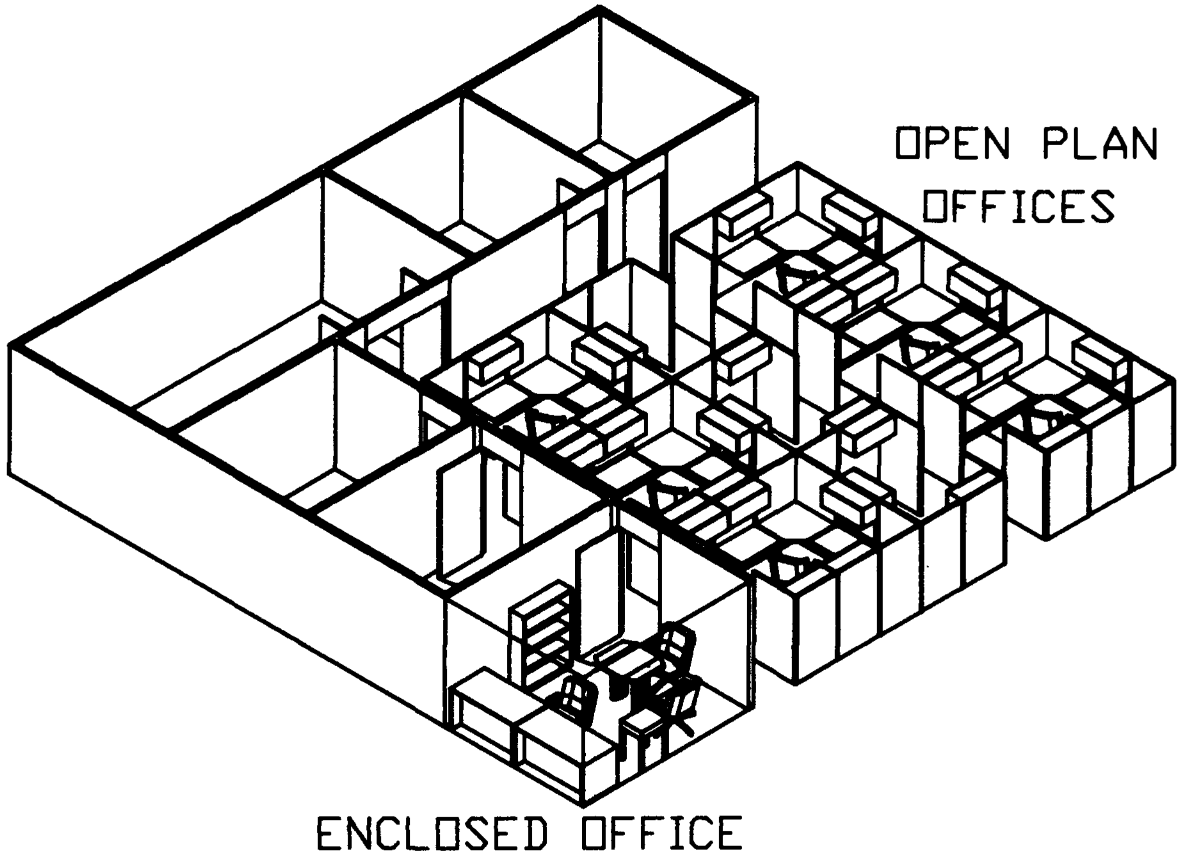


Figure 5. Use of Panel Systems To Structure Open Plan Offices.

office air flow and block ambient room lighting (Figure 6). A panel system requires coordinated HVAC system placement to avoid drafts and stagnant air in the office. Open offices require less floor area per office to achieve the same amount of worksurface and storage area of an enclosed office due to active use of vertical storage.

Office Design Issues

Multiple Task Environments. Individuals are often required to perform tasks that require different office settings. Some tasks such as reading, thinking, or meeting generally require privacy. Other tasks such as group projects require communication and participation among workers. Conflicts between privacy versus participation can arise. Independence versus inclusion are also areas of potential conflict.

In the past, landscaped partitioning (panel systems) have attempted to create flexibility and eliminate conflicts by allowing the user to modify the configuration relatively easy. However, many designers feel that landscaped partitioning represents an inadequate solution as the design may actually impose nonaccommodating standards. A facility manager will find it virtually impossible to appropriately manage a space if no standards are in place. A standard manufacturer, common module footprint for both open and enclosed environments, and similar colors are just a few of the opportunities that designers have the ability to influence.

Stone and Luchetti (1985) developed a concept based on the idea that one workstation is usually not sufficient for all of a worker's needs and tasks (Figure 7). The concept shows a variety of specialized

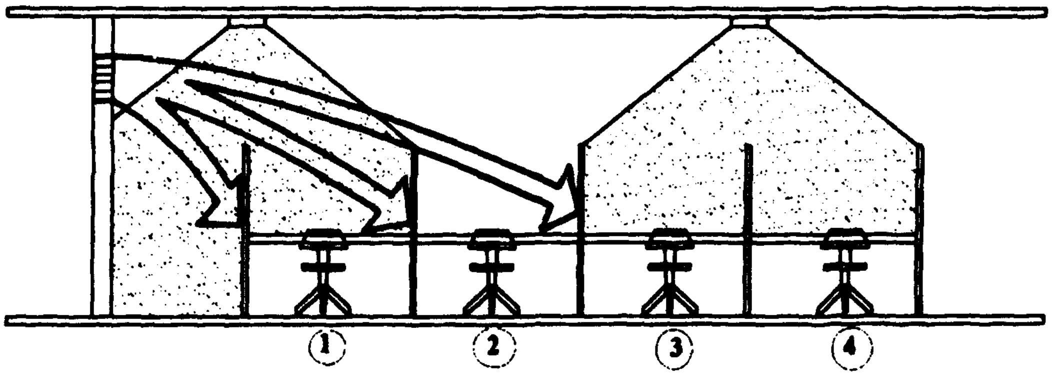


Figure 6. Light and Air Blockage Caused by Panel Placement.

workstations that workers can move between depending on the task to be completed. Each person still retains a small, permanent "home-base" unit. This concept allows the workplace to change to meet different work related tasks daily. It can also accommodate a project team (or several project teams) concurrently.

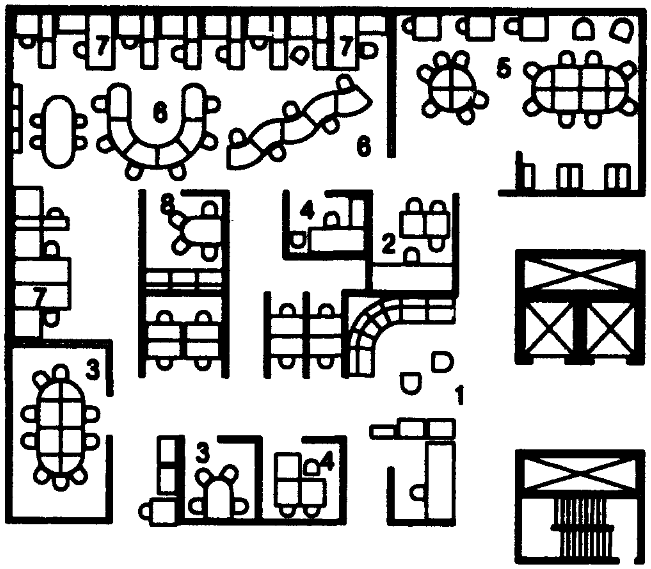
A concept similar to Stone and Luchetti's (Figure 8) allows worksettings to be linked electronically so that an individual is no longer tied to one workstation. Frank Becker's "loosely-coupled settings" divide the office into two major zones (that can be easily modified if desired):

- the edge, which consists of small, permanent workstations near natural light and views
- the core, which contains flexible group areas that could be deliberately located away from team members to increase contact between workers as they move from one space to another.

Group Identity. Corporations are often organized into a matrix structure where the major emphasis is placed on groups of individuals working together towards a common goal. Matrix structures are continually reorganizing teams as projects are completed and new ones are begun. Physical enclosure can contribute to a teams sense of cohesion because:

- Physical boundaries provide a symbolic edge indicating a unit.
- Barriers around a group encourage conversation within it, assuming that people will choose the most convenient partner in conversation.
- The physical enclosure of a group may allow privacy for the group. Privacy may permit an autonomy or identity more supportive of group objectives.

An example of group identity is the Herman Miller Headquarters: Building B. This building is based on a concept involving city planning guides in Kevin Lynch's, Image of a City (Figure 9). Major corridors became "streets," individual departments became "neighborhoods" and public areas (conference rooms, copy area, break areas) became "parks." Architectural elements were used to define fixed characteristics such as permanent walls to define the edges between areas. Systems furniture was used to define individual workstations.



1. Reception
2. Meeting Room
3. Conference Room
4. Special Equipment Room
5. Library
6. Open House
7. Home Base
8. Management

Figure 7. Stone and Luchetti's Office Concept.

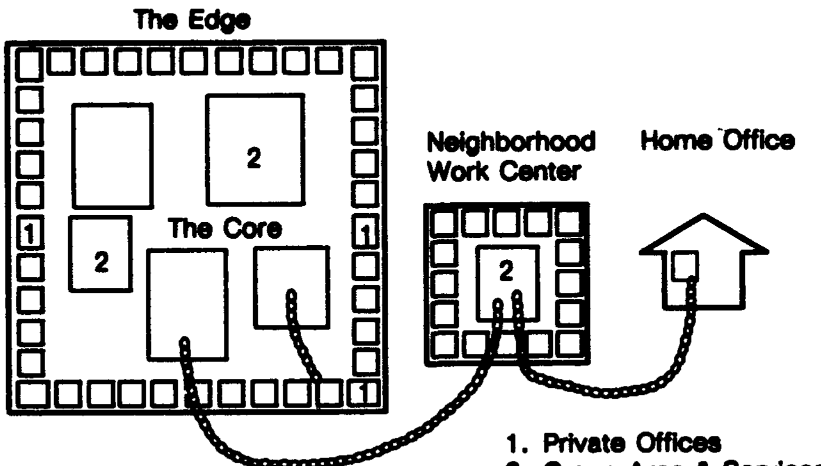
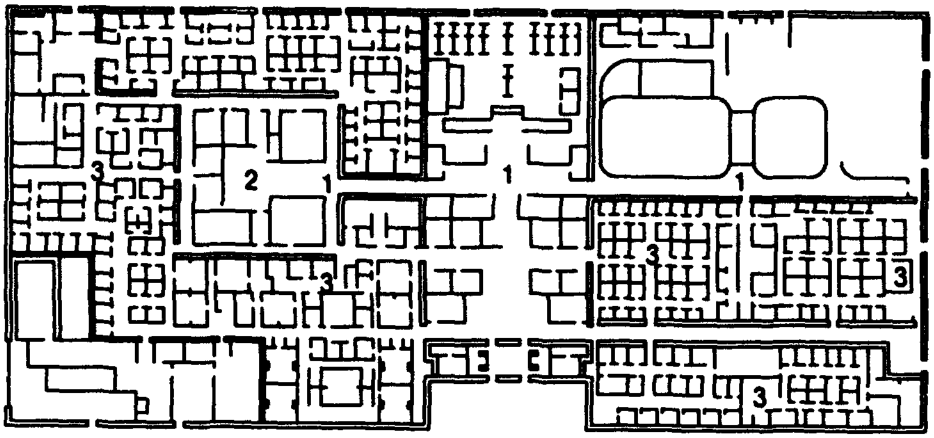


Figure 8. Frank Becker's Office Concept.

La Rinascente Headquarters in Milan, Italy is also a group identity building, based on a concept that links together a series of courts, each representing a different department (Figure 10). Each court contains approximately 40 workstations organized around a central zone. Each zone contains files, samples, and displays of that team's work, and contains the main circulation for the floor. By forcing the main circulation to go through the zones, workers are exposed to the work other groups are involved in and lines of communication between groups are maintained.



1. Streets: Corridors
2. Parks: Conference Rooms, Copy Rooms, Break Areas
3. Neighborhoods: Departments

Figure 9. Herman Miller Headquarters, Grand Rapids, MI.

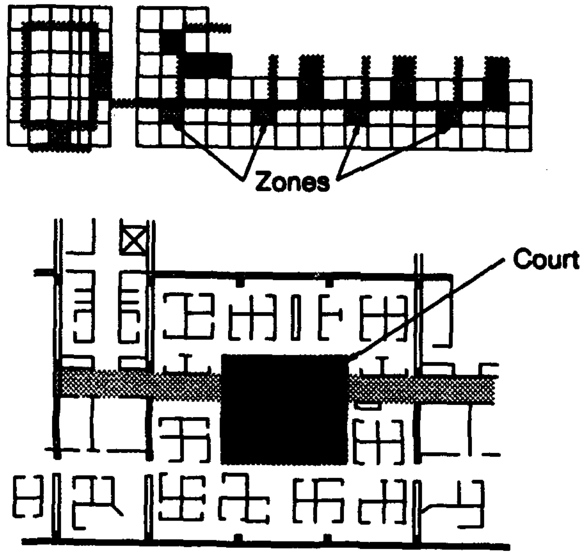


Figure 10. La Rinascente Headquarters, Milan, Italy.

Task-Related Design. A task-related concept of office design has three major areas of concentration, to: (1) facilitate the performance of specific activities, (2) minimize the building-related problems associated with office work, and (3) provide sufficient space for the person and the materials needed to perform the work effectively.

To achieve these goals, a task-related design would redirect the traditional approach of organizational and architects/interior designers imposing decisions and viewpoints on employees. Instead, this concept recommends a bottom-up approach in which those who would be using the workstations are involved in the design process.

The procedure used in this concept first assesses the general or macro goals of the organization that involve function, flexibility, required tools, and planned future growth. Next, is to obtain user information about their tasks, needs, and preferences. At this point, generic job categories are established e.g., executive, managerial, professional, technical, secretarial, and clerical. Each category is assigned normal task activities, and each activity is ranked by time spent and level of importance. From this it is possible to identify space allocation and furniture needs, and to establish functional, standard workstations.

Determining a standard workstation for each job category requires a certain flexibility. The designer should relate the workstation footprint to a building module to optimize the entire design. A modular design can allow users to adjust and personalize their space based on their individual cognitive personalities. Often this module will be a subset of some larger building element like the structural grid, which influence the smaller building and furniture-related elements like the individual workstations. A complete facility design must meet the individual functional goals along with the goals of common areas, mechanical areas, support areas, and corridors.

For planning purposes, the Army has established guidelines to estimate gross office facility spatial requirements based on personnel only (AR 405-70 1991, *AEI*). Note that these guidelines do not account adequately for nonpersonnel specific spaces like toilets, corridors, storage areas, conference rooms, etc. Regulations and organization-specific policies often use a net-to-gross square footage conversion to provide space for these nonpersonnel areas. Designers should augment these recommended square footages, to plan the facility holistically in determining their overall square footage requirements. Most times, the structure of a building and its various systems limit the actual footprint of an office. Consequently, the designer is often tasked to meet the users needs with programmed spaces that are based on quantities lower than user's actual requirements.

3 LIGHTING PERFORMANCE AND QUALITY

Introduction

Office lighting is important to the comfort and satisfaction of the people who work there. A Harris poll showed that 92 percent of those questioned believed that "proper lighting" was "very important" to the quality of the workplace (Harris 1989). Another survey showed that, of eight different office environmental features, only good heating and ventilation ranked more importantly than good lighting. Of the attributes that describe an interior environment (lighting, air quality, thermal comfort, and acoustical quality), lighting facilitates the work process most directly by affecting the ability to see and perform physical tasks. Eyesight or vision is the most influential sense for gathering information and creating knowledge–the two primary functions in today's office work environments.

Also, office workers visually evaluate the physical appearance of their work environment. Human beings naturally consider things holistically, as a combination of all environmental features and their interaction. No single feature–including lighting–is perceived or evaluated in isolation. A particular lighting scheme will appeal to the user for both its functional capability and the resulting appearance of the room. Therefore, a successful approach to lighting will go beyond optimizing specific performance attributes or expressing an abstract concept for decorative potential. Good lighting should help create a functional whole, a building that harmonizes with and supports the intended mission. A holistic view of lighting considers qualitative and aesthetic issues to be as important as the quantitative and functional issues. It strives to create visual order without sacrificing function. Lighting quality is the result of skillful and thoughtful application of lighting quantity, color and distribution.

Flynn, a pioneer in the field of lighting and behavior, argued that the evaluation of lighting in purely functional terms is too mechanistic and doesn't adequately account for the humanistic concerns in our value system (Flynn 1973). The design of lighting should not ignore the sensitivities and psychological needs of users, and must consider more than just task, utility, and manual performance to be truly "functional." Conversely, creating adequate visibility for the task at hand is the foremost purpose of almost any lighting system. Any approach must decide the quantity, kind, and directionality of light that is required for any particular task. The Illuminating Engineering Society of North America (IES), through the publication of research and the establishment of standards, has put architectural lighting on a rational and scientific base in full cognizance of its artistic potential. IES has recognized the validity of a holistic approach.

User Issues

A holistic approach to lighting concerns itself with two basic types of issues: user-functional and user-aesthetic. User-functional issues involve objective and measurable attributes in the context of physical comfort, lighting quantity, and efficiency. User-aesthetic issues consider subjective and sometimes immeasurable results in the context of psychological comfort, lighting quality, and effectiveness. The balance of this chapter presents information on office lighting as a phenomenon that physically and mentally affects the satisfaction and productivity of the white collar worker.

User-Functional Issues: Quantity and Efficiency

Several objective characteristics of light affect the way office personnel can and do work: illuminance, contrast, and glare control.

Illuminance. Illuminance refers to the quantity of transmitted light that reaches a surface, defined specifically as the density of luminous power expressed in lumens per square foot; it is measured in footcandles (1 foot-candle = 1.08 lux). The lumen is a measure of photometric power or the power of light as perceived by the human eye. It accounts for the sensitivity of the eye to the energy levels of different frequencies of visible light. Illuminance is affected by color of light and its distance from the light source.

Illuminance is the key measure of the general visibility of a task. In an office environment, the level of illuminance can affect reading rates, error rates, and quality control. In terms of user satisfaction, however, increasing illuminance levels follows a pattern of diminishing returns. Satisfaction of the user with the lighting increases with illuminance to a point and then decreases. While most workers generally favor high levels, excessive lighting levels create discomfort from glare.

The IES has introduced standardized illuminance levels and categories based on the type of activity, age of the observer, speed or accuracy demanded by the activity, and presence of a particularly low or high background reflectance. In an office setting, useful places for measuring lighting are at the floor for ambient illumination, and at the work surface for task illumination.

The preliminary findings of a post-occupancy evaluation of 1000 occupied workstations in 13 buildings in the United States indicate that perceived lighting acceptability is strongly associated with the degree of perceived brightness. Of the workers who described their workstations as bright, 80 percent were satisfied with the lighting conditions available to them. Conversely, of the workers who described their workstations as dim, only 15 percent were satisfied with the lighting conditions available to them (Marans 1987).

Color. The color scheme of a uniformly illuminated office greatly affects its appearance. The perception of color is influenced by the spectral content of the light source, the spectral reflectance of the surface, and the level of adaption of the observer. In an office environment, the most important of these is the spectral reflectance of the surfaces, unless fine color discrimination is needed. It is more the color of the surface than the color of the light that influences our judgement of acceptability.

The color of a light source is evaluated by a measure called the "Color Rendering Index," which is defined as the degree to which the perceived colors of objects illuminated by a test source conform to the colors of the same objects illuminated by daylight at the same color temperature as the test source.* An index of 100 indicates equivalence to daylight at that color temperature. A light source with good color rendering generally produces greater saturation in surface colors than those with poor color-rendering properties. Color saturation describes the way the color of a surface corresponds to the color of incident light. Warmer surface colors, such as reds and browns, will better saturate warmer light sources such as an incandescent. Cooler surface colors, such as blues and grays will achieve better saturation with cooler light sources such a fluorescent. Better color saturation will produce colors that are more true and vivid. Generally, higher illuminance increases color saturation.

Uniformity. Most lighting designs assume that illuminance is uniform throughout the desired area. However, an undesirable range of illuminances does occur occasionally because of improper spacing of fixtures or underestimated light loss factors. Some zones may appear "gloomy" or "depressing," and may affect user satisfaction. A design may use the "uniformity ratio," or the ratio of minimum illuminance in a zone to average illuminance of the larger area, to help prevent those situations. A quotient of 0.8 is the guiding standard in current practice.

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* "Color temperature" describes the chromaticity of the light source. Two light sources cannot be compared for color unless they have matching or close to matching color temperatures. A higher color temperature means the light is more white.

Extremely nonuniform illuminance levels can cause eye strain, especially in older personnel. The eyes normally go through a period of visual adjustment in moving from light to dark or vice versa, but to do this on a regular basis in an office routine will result in irritation of the eyes for some workers.

Luminance Ratios. Just as illuminance is a measure of light from a given source, luminance is a measure of light reflected from a surface. As such, luminance is the product of source illuminance and surface reflectance. It is the aspect of lighting often referred to as "brightness."

The ratio of two luminances is termed "contrast," which has no units of measurement, but is gauged on a scale between zero and one, zero being no contrast and 1 being maximum contrast. Contrast is essential to visual performance. Since the most basic visual tasks are detail discrimination and detection of low contrast, the luminance of the task in relation to the luminance of the background becomes critical. For example, reading type on a page is helped by the low luminance black print that contrasts to the high luminance white paper. Above a certain minimum value, contrast does not depend on illuminance. For example, one can read by moonlight as well as sunlight.

Luminance ratios are not precisely held measures for all situations, but can be a range of values applied to a specific condition. For example, one can read at the same speed a black type printed on various shades of gray paper. It is only when the contrast approaches zero that the performance of a given task is affected. Luminance ratios can become a problem in the contemporary office where personal computers exist in conjunction with paper-based activities. The illuminance required for paper functions is considerably higher than the optimal level for video display terminal (VDT) operation. Such situations require adjustable task lighting that will not interfere with use of the computer.

Control of Glare. Glare is a result of a very high luminance in an otherwise low luminance field; it is a condition of very excessive contrast. Glare is generally categorized into disability glare and discomfort glare. Disability glare impairs vision through direct dazzle of the eye from a light source and may immobilize the viewer. It rarely occurs in an office environment because light sources are usually mounted away from the line of sight and luminance differences are relatively small across the space. Discomfort glare arises from a continual excessive contrast between bright and dim surfaces. It may distract the viewer and cause eye strain. Strictly, disability glare refers to a severe reduction in the visibility of objects, and "discomfort glare" refers only to the sense of discomfort produced (Boyce 1981, p 305). In the office environment, discomfort glare is the more common of the two.

Discomfort glare (as well as disability glare) may be perceived directly from the luminance source or indirectly from a high reflectance or spectral surface. The sensation and discomfort of direct glare are based on four principle factors (Boyce 1981, p 306):

1. Luminance of the glare source
2. Luminance of the background
3. Angular subtense of the glare source at the eye
4. Deviation of the glare source from the line of sight.

The four are related in that it is rare to vary one factor independently. For example, a more powerful light source will increase the luminance of the glare source, but will also increase background luminance, so that the effects may cancel each other. The luminance of the glare source is affected by the size and number of the source(s). The effect of glare is cumulative; an increase in size, number or luminance of the source(s) will increase the level of glare. As above, background luminance will usually vary with the luminance of the source, and can serve to moderate perceived glare with the use of higher reflectance, diffuse finishes.

The American measure of direct glare in an interior space is called Visual Comfort Probability (VCP), which is based on a statistical manipulation of the four factors above with units defined as the percentage of users who would feel comfortable in the measured environment. A VCP index of 70 or more with a source luminance ratio (maximum to average) not exceeding 5:1 at various angles from the source constitutes an acceptable environment.

Indirect glare is the presence of a high luminance source reflected from a surface and into the visual field of the observer. Veiling reflections on the screens of computer monitors are a significant example. They are caused by a mirroring of the light source in the task surface. The visual definition of the object, or the ability to see the task itself, is due to the degree of task surface diffusion. A perfectly diffuse surface reflects only a small portion of incident light into the eye, whereas an undiffused or specular surface will reflect incident light much the same as a mirror. The principle effect is a sharp reduction of contrast between the task and its background, thus severely decreasing its visibility.

Veiling reflections are often a function of the geometry between observer, task, and light source. The physical arrangement of a light source, task, and observer should position the task forward of the light source so incident light comes from behind the observer. To minimize objectionable brightness, make the task illuminance larger to overcome the detrimental veiling and use adjustable supplementary task lighting. In designing the light source, reduce the overall luminance of the luminaire or reduce the luminance at the critical offending angles of 25 to 40 degrees. The task quality can be changed by reducing the specularity of the task and using matt or low gloss paper and felt tip pens. The use of tiltable worksurfaces can also be considered.

Glare can only be accurately evaluated in context. The particular circumstance in which glare occurs can have an important effect on an occupant's assessment of comfort or discomfort. For example, a standard office luminaire is generally uninteresting to look at and the attention they attract because of their high luminance is regarded as unfavorable. A crystal chandelier however, because of its beauty will be regarded more favorably even though the luminance is higher than the office luminaire. Likewise, an office window may produce luminance values comparable to a luminaire regarded as high in glare, but the occupant will be less sensitive toward it. Since the window is valued for its association with the view as well as the incoming light, occupants judge it by a different standard (Boyce 1981, p 314).

The assessment of glare also depends on the presence of a task. One study showed that users evaluated two identical lighting conditions differently depending solely on the presence or absence of a task to perform. The presence of a task produced a different boundary between comfort and discomfort (Guth 1951, p 65).

User-Aesthetic Issues: Quality and Effectiveness

User-aesthetic issues are those that do not affect the physical comfort of the user or visibility of the task but nevertheless appear significant to the user's evaluation of lighting; they are issues of "lighting quality." Subjective issues as appearance and aesthetics, psychological comfort and impression, and personal control are important because they appeal to our inner values as human beings and play a role in the symbolic communication between organization and worker. Unfortunately, it is difficult to measure and even harder to form guidelines about user-aesthetic concerns. The correlation method of relating subjective judgements of lighting to physical descriptors of lighting, which many researchers use, produces limited information on a single variable. However, some lighting criteria based on results from the method have proved sound in practice.

Appearance. A lighting plan principally affects the appearance of a space by distributing light to create contrasts between lighter and darker areas. Users usually find small or moderate contrasts to be pleasing and interesting, whereas those that are large and excessive can create interiors that are gloomy and forbidding (Hawkes, Loe, and Rowlands 1977).

The general appearance of the space also influences the user's evaluation of the lighting design (Hawkes, Loe, and Rowlands 1977). Poor aesthetic quality of the space will inevitably influence the user's assessment of the lighting's objective capability (Ellis 1986, p 243). The subjective consequences of a lighting scheme have as much to do with its success in the eyes of the user as its objective characteristics.

It is difficult, however, to specify aesthetic preferences since they are always subject to particular social and cultural situations. Human reaction to the environment is variable and inconsistent; few rules or patterns are identifiable. It is apparent that the interaction of people to environmental stimuli is influenced by their perception of the associated social situation in which they find themselves (Ellis 1986, p 227). Often user's attitudes toward work and the organization manifest themselves in the assessment of physical conditions. Novelty in the lighting design may meet with user approval more readily in a less regimented, more spontaneous workplace. Conventional schemes are more likely to find acceptance in offices where definition and security are valued. It is the unconscious link between unpredictable social interaction to an associated environment that makes regimentation of one aesthetic treatment for all environments so unacceptable. No universal aesthetic preference exists.

Daylight in the Office Environment

Many office buildings use daylight to some extent to meet their lighting needs. Where there are windows, there is potential daylight to illuminate the interior. In general, people strongly prefer daylight as a primary source of illumination (Heerwagen and Heerwagen 1986, p 47), and overwhelmingly prefer working in windowed buildings over nonwindowed ones (Heerwagen and Oriands 1986, p 624). Workers in windowless offices are less positive about their jobs and their working conditions than those who work in windowed spaces (Finnegan and Solomon 1981). These studies all underscore the fact that people highly value the opportunities for view and daylight in their work environment.

Yet it is obvious that an office relying solely on daylight to meet all of its illumination needs at times would be severely dysfunctional and inadequate. Concepts to combine daylight and electrically-generated light have existed for more than 40 years. The British concept of Permanent Supplementary Artificial Lighting of Interiors (PSALI) has been the most prevalent model. In contrast to many contemporary lighting schemes, it views electrical light as supplementary to daylight, not vice versa. Its focus is not primarily on how to provide daylight, but how to do so in a manner that minimizes the attendant effects of glare, shadow, and heat gain. It is contingent on a thorough daylight analysis including maximum, minimum, and average sky luminance values, typical cloud conditions, and fenestration. The recent concern for energy efficiency and the immediate topic of office productivity suggests that the integration of daylight and electric light is quite important.

User-Functional Issues

Lighting plans that disregard the effect of daylight have an impact on how the illuminance is considered. It is still considered as the most prominent attribute, but with less rigidity. Nondaylighting schemes regard the continuous attainment of recommended illuminance levels as mandatory. Schemes that integrate daylight assume that a variation of the interior daylight illuminance levels during the course of the day will not affect visual performance, even when actual levels fall below accepted recommendations. Illuminance levels that are recommended by the IES are still the target, but since daylight changes slowly, the eye can adapt to the altered level and see basically the same scene. The eye appreciates lightness or brightness not only by actual luminance of the object being viewed but also by contrast with the surrounding area. The concept regards visual performance as more closely related to contrast discrimination than to the actual daylight illuminance range.

As daylight enters a building, its illuminance values fade quickly as the distance from the window increases. A goal of integration is to keep an acceptable uniformity ratio across the space while erasing the distinction between the electrically and naturally illuminated. A simple way to achieve this is to place more light fixtures in the vicinity of the building core and fewer at the perimeter. Uniform placement of fixtures is redundant and unnecessary in a daylit building.

Essential to the cost effectiveness and uniformity of daylighting is the automatic dimming of the electric lighting. Dimming compensates to some degree for the inherent variation in daylight, and can be accomplished by two different approaches. A system that uses full-range dimming with electronic ballasts is preferable to one that makes use of partial dimming with conventional ballasts and a stepped switching scheme. The stepped switching action can disturb occupants.

The proper establishment of zones is critical for a daylight compensation system. The size of a zone is established by determining the maximum room depth that receives at least half of its illuminance from daylight for several hours each day. Exact delineation depends upon latitude, climate, orientation, fenestration and cost of electric energy. The most likely scenario is perimeter and interior zones.

The proper use of lighting controls can reduce energy use by 60 percent, depending on the type of space as well as occupancy usage and patterns. Controls can extend lamp and ballast life, reduce cooling costs, and lower maintenance costs. Investment payback for lighting controls can be very short if the application is properly selected and electrical energy rates are favorable.

The color of daylight coming into the interior workspace is composed of all wavelengths across the visible spectrum. It varies in its primary makeup across the day and across the seasons. It has been shown that people prefer the color of daylight and use it as a reference to judge the quality of artificial light. Most fluorescent light sources achieve color compatibility with daylight. Since most offices are illuminated with fluorescent sources, occupants rarely complain of lighting color. Care must be taken, however, with the use of high- and low-pressure sodium sources in daylit offices since they generate a golden color light from a narrow band of the visible spectrum that will contrast excessively with daylight.

Daylight glare is caused by direct sunlight and/or excessively bright sky as seen through a window or glazed surface. Generally, glare is usually not a problem on the north face of a building unless the circumstances of the site reflect direct sunlight through the glazed areas.

The control of direct glare from windows on all other elevations is essential. Several architectural solutions to the problem are common. The use of low emissivity glass reduces glare and heat gain. Certain chemical coatings on the glass will reflect some incoming light and reduce the daylight transmission to the interior, also producing a somewhat muted view of the exterior. Architectural sun shading and control devices can also reduce glare and help project light deeper into the interior. A light shelf will shade the window below and act as a reflector to direct light inward. Another exterior measure used in lowrise office buildings is placement of exterior plantings near the building perimeter. Large trees can directly shade glazed areas, and low shrubbery can diffuse incident light. Both measures can enhance the view from the building.

The use of lighter color finishes on a building's interior will help reduce contrast and the visual effect of direct glare. If the glare factor is too high, occupants will close blinds and curtains, eliminating the benefits of daylighting. To occupants, the minimization of eyestrain and discomfort is more important than the perceived benefits of daylight.

User-Aesthetic Issues

It is not clear why people prefer to work in daylight. One theory suggests that daylight may be perceived as inherently psychologically soothing because its changing illuminance suggests the passage of time and the peacefulness of shelter. Electric lighting is more diffuse than daylight, which lends a more meaningful aesthetic quality to the space by its inherent flow and directional quality. Also, the body's biological process of producing vitamin D3 by absorbing ultraviolet light may produce a feeling of well-being (Greer 1984, p 66). Occupants behind glass windows cannot achieve this benefit since glass absorbs most of the UV spectrum.

The window itself may be part of the reason for the preference of daylight. Research suggests that occupants desire daylight independent of its contributions to task visibility (Ne'eman and Vine 1984, p 160). Daylight entering through a window gives a psychological benefit; it allows a view to the outdoors, which gives a periodic, temporary relief from the day's work by allowing outside visual contact and escape from the sense of enclosure. That contact also enhances break times by giving a sense of removal from the work environment. However, windows alone are not enough; there must be "something to look at" (with psychologically significant content or information) for the windows to be perceived as more than just sources of daylight. Research has shown that distant and mid-distant views are more desirable than close views to office workers, and views of nature are preferred over those lacking natural elements (Markus 1967). Several studies have shown that occupants prefer views of the natural environment over urban scenes (Heerwagen and Orians 1986, p 625). It appears that the opportunity for natural views is associated with social well-being and health. A study of housing project residents found that the more large trees and woods people were able to see from their windows, the more friendly, supportive, and attractive they rated their neighborhood (Kaplin 1983, pp 127-162). Medical research has shown that patients in intensive care units recover faster and have fewer setbacks in facilities with windows than in those without. The windows contributed to the shorter recovery period by providing a sense of stimulation and arousal in addition to such basic information as the weather, time of day, and seasonal changes (Wilson 1972, pp 225-226).

It reasonably follows that, if a windowless building is required, the office areas should be designed as larger spaces to promote greater activity and social interaction. Outside views and natural light should especially be considered if workers are isolated or restricted in their activities. Deprivation of contact with other human beings and the outdoors will result in passivity, listlessness, and depression.

The optimal daylighting of a building is an issue that has been thoroughly researched and discussed but rarely implemented. The problems involved in utilizing "free" light in the context of an actual building project are many and complex. Requirements for user well-being and performance, functional planning, energy savings, and lowest long-term cost often cannot be optimized simultaneously. A climatically sensitive and ideally daylit building dictates a particular massing, site orientation, and physical dimensioning that may not always be congruent with the other components of a complete building program.

The principal concept in the daylighting of interiors is that of penetration. Since most workers are located away from the building's perimeter, daylighting design attempts to distribute a greater amount of light to a greater number of people. The success of daylight penetration depends on a combination of a building based on a narrow plan form, high floor-to-ceiling heights, and/or skylights. A narrow building oriented east and west with large glazed areas to the south optimizes the use of daylight. The narrow plan however may not always accommodate an organization's special needs or fit the conditions of the site. Greater floor to ceiling height will increase the daylight penetration and create a sense of spaciousness within the interior. An area of glass 10 ft above the floor will let in twice as much light as the same area of glass 5 ft above the floor (Daryanani 1984, p 111). However, greater ceiling height will increase the initial cost of the building by increasing the materials and labor required for construction. The inherently larger glazed areas may also put a larger load on the mechanical system, which would increase its size and cost. Skylights can provide great quantities of natural light, but are limited in most cases to one-story applications.

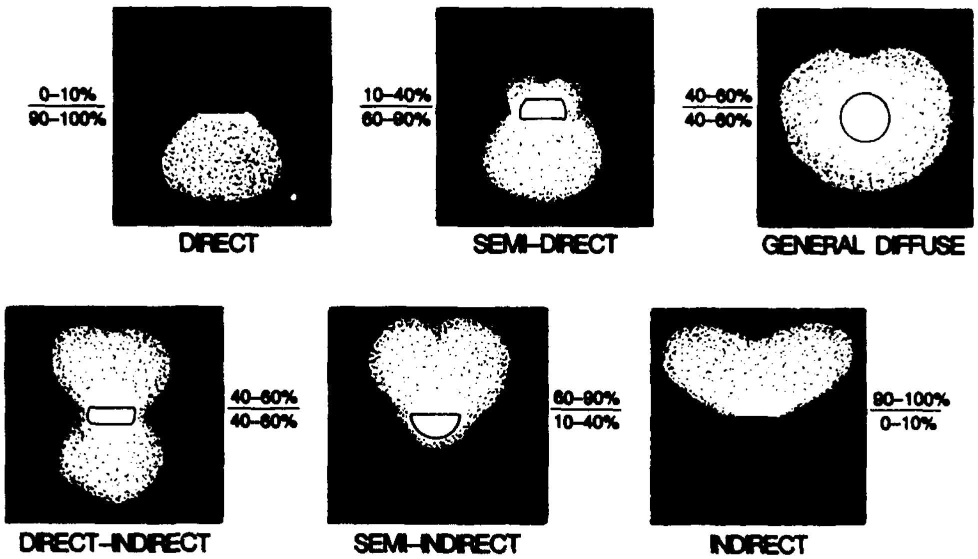
In hard functional terms, integrated daylighting schemes are disfavored for their complexity and cost. Some decisions made in a specific project concerning the role of daylight may adversely impact other building systems. Research has shown that drawbacks of the concept are not economically compensated by increased satisfaction and productivity of the user. Although a sample of 33 people indicated they strongly preferred daylight to electric light for a range of psychological and physical needs, "having daylight in ones work area" ranked 19th out of 20 office variables in terms of importance for a comfortable work environment (Heerwagen and Heerwagen 1986, p 48). The same study also showed that those with windowed offices consistently valued daylight less than those stationed in core spaces. Daylight as a psychological asset apparently becomes more pronounced for those who are deprived of it.

Ambient and Task Lighting Systems

Ambient lighting systems are those that provide the general space illumination. Task lighting provides illumination for specific activities within a space. Until the energy crisis of the 1970s, the functions of both were always performed by one general overhead system. Stark uniformity in the placement of fixtures and in illuminance levels was the result. This came about from a scientific approach to design based more on rigorous mathematical modeling than intuitive acknowledgement of human values. The level of ambient light in a space was determined by the most visually demanding task. Uniform illuminance levels on the order of 100 foot-candles at the worksurface were not uncommon. In addition to wasting energy, the excessive brightness caused glare problems and eyestrain for many office workers, and it was also criticized as oppressive and uninteresting (Ellis 1986, p 225). The general overhead system, however, is still very common today.

The premise of task/ambient lighting is that the amount of light delivered is based solely on the function to be performed. The concept separates the lighting of the task from the lighting of the surroundings. A whole space need not be illuminated to the degree required for a visually demanding but locally performed task. In the office environment, work is performed in predetermined areas such as a desk, a workstation, or a conference table. These areas are locally illuminated to a level in accordance with the visual difficulty of the task. At the task level, the primary consideration is given to performance through mathematical modeling. Beyond work areas, the need is only for general orientation within the overall space. This requires much lower illuminance levels. Ambient light controls contrast with the task lighting within the room.

Ambient lighting systems can be categorized based on way the light is delivered into the space by direct and indirect systems; other systems may display characteristics of each (Figure 11). A direct lighting system is usually mounted in or close to the ceiling and focuses concentrated or spread light downward. The spread type is the most common for offices and most aptly represented by the recessed 2 x 4 ft fluorescent fixture called a trouffer. Direct lighting gives very little vertical surface illumination, and so requires perimeter lighting for blackboards or other presentation surfaces. Often the perimeter lighting consists of recessed incandescent downlights.



Luminaires for general lighting are classified by the CIE in accordance with the percentages of total luminaire output emitted above and below horizontal. The light distribution curves may take many forms within the limits of upward and downward distribution, depending on the type of light source and the design of the luminaire.

Figure 11. **CIE (International Commission on Illumination) Classification System.** (Source: Illuminating Engineering Society of North America. Used with permission.)

Indirect lighting reflects off the ceiling plane and upper wall surfaces to the worksurfaces so that the ceiling plane and upper wall surfaces become the light source. It follows that these surfaces should have a high reflectance value. Positive qualities of an indirect system include a resultant illumination that is quite diffuse or shadowless, generally uniform, and low in direct and reflected glare. This type is of particular advantage in spaces with specular visual tasks, such as computer work.

Task lighting is nearly always localized direct light. Fixtures may be mounted under overhead cabinets in an office arrangement that uses systems furniture. Adjustable arm models may also be used and are recommended to control veiling reflections and to focus light into specific areas around the workstation. A fluorescent source has the advantage over an incandescent because of lower local heat gain. A diffusing lens over the source will prevent shadows over the work surface and promote uniformity.

User-Functional Issues

Illuminance from ambient lighting systems is measured as an average maintained across the space. The lumen (flux) method is used most often for determining illuminance. It is based on a coefficient of utilization and various factors of light loss that occur through time.

The coefficient of utilization gauges the overall luminous efficiency of a particular unit in a particular space. It is the ratio of the lumens reaching the horizontal working plane, to the lumens generated by the source. Zonal cavities are determined by the proportions of the room, mounting height, and surface reflectance; these combined with the specific fixture efficiency and distribution, yield the coefficient. Light loss factors account for anything that contributes to the decrease in initial source lumens, including decreased voltage, colder temperatures, lamp and ballast age, and dirt depreciation of room and lamp surfaces. The coefficient and the loss factors are combined to predict the average illuminance across the space.

Orfield raises some questions concerning the usefulness of the lumen method and the validity of the mathematical approach to lighting. The calculation of coefficient of utilization requires a number of assumptions that impede its effectiveness, including:

1. The layout of luminaires must be symmetric.
2. Reflectance is assumed to be constant on relevant surfaces.
3. The space is free of barriers such as partial height partitions.

Failure of the lumen method to accurately determine the illuminance is predictable when applied to the open office environment. The method overstates the lighting level by about four times what actually reaches the worksurface (Orfield 1987, p 19). A predicted 50 foot-candles is actually 12.5 foot-candles.

The problem with mathematical models are twofold. First, they implicitly promote the proposition that office space must be very simple, uniform, and symmetric for the calculations to be reasonably solvable. The calculation of valid averages requires a good degree of uniformity. Second, even with simple, uniform spaces, the assumptions required to use the formulae do not consider the activity in the area, air flow, or acoustical values.

Luminance ratios at the workstation should be moderate. Lighter color finishes and fabrics improve the ratio. The task light should not be extraordinarily bright, but should provide about the same luminance as the ambient system. However, the greater portion of light must be on the task. The ambient light performs a secondary role of controlling contrast. It is safe to say that, in office environments, moderate levels of illumination in task and ambient light will almost always meet the comfort needs of the user without sacrificing the function to be performed. The current recommendation is that the local background illuminance produced by the ambient system should not be less than one-third of the task illuminance (Boyce 1980, p 301).

Direct glare in an ambient direct system is most often controlled through the design of the fixture itself. Prismatic lenses, baffles, and reflectors within the luminaire manage the diffusion of light. Fixtures with parabolic reflectors have been successfully introduced to control direct glare. The parabolic shape directs light downwards while allowing only very little to scatter at high incident angles. From typical viewing positions, the fixture appears to be a part of the ceiling and tends not to be a glare source.

Indirect systems generally reduce or remove glare from the ambient source. The creation of a luminous ceiling plane will reduce the potential for gloominess. The general color of the ceiling plane is of great importance as it affects the color of the reflected light.

Whatever the benefits of indirect lighting, a large survey showed that 75 percent of building occupants working under direct recessed fluorescent lighting fixtures with louvers were satisfied with their workstation lighting, and only 14 percent were dissatisfied. Occupants having indirect, furniture-mounted systems had lower levels of satisfaction (56 percent expressed satisfaction and 36 percent expressed dissatisfaction). Also workstations with supplemental task lighting were consistently rated less favorably than those which received their light from the ambient system only (Marans 1987, p 36).

Direct glare and veiling reflections can be controlled easily with adjustable or movable task lighting. This is essential with the use of computers, where the spectral surface of the screen is prone to veiling reflections. By positioning the screen and controlling surrounding contrast, screen glare can be minimized. Direct glare from the fixture itself must be handled through design and manufacture.

User-Aesthetic Issues

The aesthetic purpose of ambient lighting is to create moderate visual contrast. In the office environment, there are many creative opportunities to use different light types and delivery systems. Fluorescent and incandescent systems can be enhanced with metal halide or high pressure sodium accents. A direct diffuse system can be supported with spotlights to enliven the space. The profusion of new hardware in the last few years provides greater opportunities to create visual contrast inexpensively. All lighting problems can become creative opportunities.

Combining perimeter incandescent downlighting with an indirect or direct fluorescent system for general space illumination can successfully integrate function and aesthetic. General ambient light downplays wall surface, whereas perimeter downlighting illuminates the content or texture of the surface with a wash of warm light. The warm, concentrated incandescent light differs from the cool, dispersed fluorescent to create a simple, pleasurable contrast.

Moderate lighting contrast can work to create hierarchy and differentiation in the visual elements of the office. Lighting contrast may promote a sense of order and accomplishment, whereas uniformity suggests regimentation. Lighting that supports visual hierarchy and differentiation may contribute psychologically to improved employee morale toward the task and pride in the work place. Perceptually, it breaks down the greater physical reality into elements more of human scale. As large organizations are composed of groups, subgroups and individuals, the luminous environment can be delineated through a physical hierarchy of area, zone, and workstation.

Different areas within the larger facility can be illuminated to accommodate its function. The degree to which the area is exposed to the public will have an impact on its lighting scheme. The zones within an area can be differentiated by their specific function within the overall operation. For example the needs for an executive area are different than those of a clerical area. At the workstation, the individual is prominent. A task light contributes to an individual's sense of importance by allowing personal control in its placement and usage. The organization hierarchy can be highlighted through proper lighting design.

4 THERMAL COMFORT

Introduction

Since a correlation exists between occupant comfort and productivity, there is much current interest in building occupant comfort. In addition, legal and economic liabilities associated with occupant discomfort may be at issue.

The ability to provide adequate thermal comfort levels, and thus facilitate productivity, is an important consideration for a building designer. A well designed building allows for the integration of the facility's envelope, mechanical systems, and interior layout to provide the best thermal environment. This may be done by isolating the interior space from the outside, or by incorporating desirable outside conditions. Interior conditions conducive to human occupancy and worker productivity rely on many environmental parameters. This chapter discusses thermal comfort-related issues addressed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

Background

ASHRAE Standard 55-81R, "Thermal Environmental Conditions for Human Occupancy," specifies the combinations of space and personal factors that will produce comfort conditions acceptable to 80 percent or more of the occupants in a given space. The environmental parameters that Standard 55-81R addresses are temperature, thermal radiation, humidity, and air speed; the personal parameters are those of activity and clothing.

It should be explicitly stated that one's perception of the physical environment is a response to several interrelated factors. The environmental factors that ASHRAE examines to determine occupant comfort are measurable, quantifiable, and rationally derived environmental parameters. Other personal (subjective) parameters also affect how individuals perceive an environment. It is these personal factors that keep thermal comfort evaluation of an environment bound to statistical predictions rather than empirical techniques.

The definitions for thermal comfort and thermal sensation indicate that subjective parameters can also influence thermal comfort. Personal likes and dislikes along with the potential influence of nonthermal parameters such as air quality, lighting, and acoustics complicate the use of the measurable, physical parameters. Furthermore, a person's metabolic heat production (primarily a function of activity level), its transfer to the environment, and the resulting physiological adjustments and body temperature, influence individual perception of the thermal environment. Environmental parameters affect this heat transfer process as do clothing insulation properties.

A few of the important terms (ASHRAE, 1981) presented in Standard 55-81R include:

1. *Acceptable Thermal Environment*: An environment that at least 80 percent of the occupants would find thermally acceptable.

2. *Occupied Zone*: The region within a space, between planes 3 and 72 in. (75 and 1800 mm) above the floor, and more than 2 ft (600 mm) from the walls or fixed air-conditioning equipment (ASHRAE Terminology of Heating, Ventilating, Air Conditioning and Refrigeration).

3. *Thermal Comfort*: That condition of mind that expresses satisfaction with the thermal environment.

4. *Thermal Environment*: Those characteristics of the environment that affect a person's heat loss or gain.

5. *Thermal Sensation*: A conscious feeling commonly graded into the categories of cold, cool, slightly cool, neutral, slightly warm, warm, and hot.

Design For Thermal Comfort

Providing comfortable thermal conditions for building occupants should be a fundamental goal of building designers. Many environmental and personal factors influence a person's perception of the environment, and design can strongly influence environmental parameters. Studies in this field have established environmental boundaries to predict a certain percentage of people who will perceive given conditions as comfortable. Designers should plan buildings to stay within these boundaries.

Optimizing thermal comfort through building design is a difficult and complex process that requires the designer to assimilate many interrelated design aspects into an optimal configuration. Issues and elements of building design impact the thermal comfort component of facility design. Global parameters such as a buildings' function and its environment combine with building specifics to affect thermal comfort.

Building Function/Occupancy

A building's function will usually influence occupancy loads and schedules, and sometimes the selection of building materials, all of which can affect a building's thermal properties. Optimal thermal conditions are not unilateral; they depend on the tasks individuals perform in the building, and thus vary considerably. Optimum thermal conditions in an office building will differ from those in a building where heavy manual labor is the primary task. A building's use will therefore dictate the acceptable comfort range for the tasks to be performed there. The higher the rate of physical work (i.e., the metabolic rate), the lower the thermal requirements, and vice versa. Both occupancy loads and schedules need to be examined and evaluated for their effects on thermal loads, and their relationship with climatic loads.

Climate

Military building energy usage is principally determined by the building "envelope," the point of demarcation between interior and exterior that moderates between exterior climatic conditions and controlled interior conditions. Before designing the envelope, a designer should investigate the climatic conditions that will affect the building. Many environments involve a diversity of possible weather conditions. Building designs typically compensate for temperature extremes only, ignoring climatic parameters that can have a significant influence on a building's energy consumption such as solar and wind effects.

The Corps of Engineers *Architect Engineer Instruction (AEI)* (1991) dictate ranges for interior and exterior design temperatures for assorted building types and also prescribe whether or not a particular location qualifies for mechanical air-conditioning or humidity control. Design criteria do not address how other environmental elements can or will affect building design. Although the addressed parameters may have a significant effect on interior thermal comfort, future building designers will have to respond to all the variables that affect interior climate design rather than just a select few.

Except in rare instances, climate and thermal comfort are inseparable design companions. Envelope and mechanical design solutions are simply responses to interior design prerequisites, and exterior conditions.

Building Design

A building's design should respond to programmatic (functional) needs and the climate. However, buildings are often not integrated with their environment. Mechanical systems often compensate for design deficiencies. For example, a chiller may counterbalance large expanses of glass exposed to the sun where solar shading or a redesign of the facade would have been more efficient. Rising fuel prices and concerns about chlorofluorocarbons (CFCs) have increased interest in efficient mechanical systems and intelligent building design.

Intelligent building design involves many inter-related building design parameters. The following sections briefly explore the larger issues involved with building design that affect thermal comfort, and the nature and degree of their interrelationships.

Building Site. Building placement can profoundly influence how the local microclimate and climate in general will impact the building. Factors that can affect building orientation are existing infrastructure (road and utility networks) and the surrounding context (buildings and terrain). Often the original layout of roads, utilities, and buildings is conducted without thought of their future impact on optimized building orientation. This forces the building designer to work within parameters that limit an optimized solution.

Issues involved with siting a building that can affect thermal comfort include solar exposure, exposure to winds, and relation to the surrounding landscape elements (both natural and manmade). Properly accounting for these environmental parameters can help create a thermally comfortable building while also affecting its energy consumption characteristics.

Fenestration. Fenestration, the design and placement of windows in a building, can significantly influence thermal comfort and energy consumption. Orientation, size, type of glazing, shading, exterior surroundings, interior finishes, and type of task being performed on the interior can all affect the quantitative and qualitative aspects of a particular fenestration scheme. It is possible to quantitatively determine the heat gain or loss through windows, and (although somewhat more difficult), the quantity and distribution of daylight. Qualitative analysis of a fenestration scheme can be difficult since the qualitative aspects of the light being admitted change throughout the day and different types of tasks require different types and quantities of light. A change in building function can render an existing fenestration scheme ineffective.

Fenestration can also affect other directly and indirectly related building systems such as the lighting and the heating, ventilation, and air-conditioning (HVAC) system. Good daylighting design can reduce the lighting load, which in turn can reduce the cooling or increase the heating load, depending on the season. Changing any one aspect of a fenestration scheme can result in a chain reaction that affects many other elements of a buildings' design.

Thermal Mass. The use of thermal mass to modulate interior conditions is a concept that has been used for a long time. Mass can be used to absorb, retain, and release thermal energy. Although building mass can be linked to thermal comfort, optimal levels of thermal mass are rarely calculated. Thermal mass is usually a simple function of the structural system and interior furnishings. The potential for thermal mass to become an integral component of the thermal environmental control system is considerable and its thermal comfort implications and energy conservation potential should not be underestimated. Building mass, similar to fenestration, also affects many other aspects of building design, directly and indirectly. Startup loads, peak loads, exposure to solar radiation, etc. are all related to building mass and other associated building systems.

Mechanical Systems. One of the fundamental purposes of a mechanical system is to maintain interior temperatures and ventilation rates within an acceptable range. Design of the mechanical system primarily depends on the size of the building's envelope, exterior conditions, interior needs, functions, and equipment. Due to all of the variables that can impact HVAC system design, optimizing a design is not a simple task.

HVAC system design is of great importance due to the impact it has on the occupants and the amount of energy that it typically consumes. A properly designed system will maintain comfortable interior conditions while minimizing energy consumption. This can be a relatively straightforward process in the design of a new facility. However, determining the effects of changing building functions, demands, and the adequacy of the existing systems to meet these changes can be difficult.

The mechanical system also plays a key role in providing proper and adequate indoor air quality. Thermal comfort involves both occupant comfort and safety. It is important to achieve energy savings while providing proper temperature humidity. On the other hand, poor indoor air quality can have long-term physical effects that impact the user far beyond matters of comfort. Also note that energy savings on the mechanical system are more than mechanical design; savings must continue through the life and operation of the system, including its maintenance and upkeep. The following section deals specifically with indoor air quality issues and their impact on users.

Environmental Parameters

An individual reacts thermally with the environment in several ways. Evaporative heat losses occur through the evaporation of body fluids, and dry heat exchange can occur through convection or radiation. The physical parameters of the environment work together to affect these processes. The four environmental parameters that influence the thermal comfort of a space are: (1) Air Temperature, (2) Mean Radiant Temperature, (3) Humidity, and (4) Air Speed.

Air Temperature

Air Temperature (t_a) is the most elementary environmental parameter to be measured. It is a measure of the sensible heat of air and is significant in judging comfort, particularly in cold environments. Figure 12 shows the environmental parameters that affect heat exchange between a person's body and the surroundings. In warmer environments, humidity can have a significant effect on the body's temperature regulation through sweating, thus limiting the importance of air temperature in the determination of thermal comfort. Convective heat exchange with the environment is thus influenced by air temperature, humidity, and velocity. As the difference in temperature between the body and the surrounding air increases, so does the rate of convection.

Air temperature can be measured using a standard liquid in glass thermometer, resistance thermometer, thermocouple, or bimetallic thermometer. For an accurate air temperature reading, the measurement device should be shielded from direct radiation while not restricting air motion around the device.

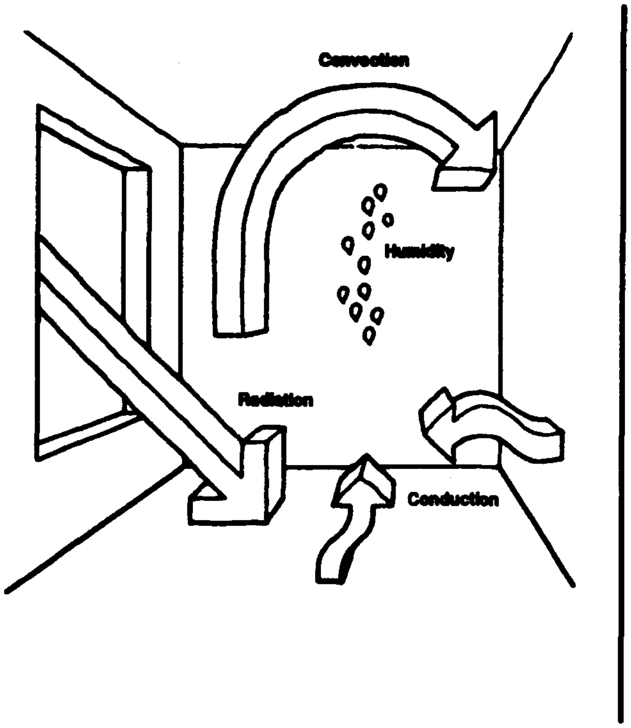


Figure 12. How Thermal Comfort Parameters Operate.

Mean Radiant Temperature

Mean Radiant Temperature (MRT or t_r) is defined as the uniform surface temperature of a radiantly black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual nonuniform space. Radiative heat transfer is governed by the surface temperatures of the individual and the surrounding environment. Physical properties such as emissivity and absorptivity of each surface, as well as its angle factor to the individual, affect the amount of radiation exchange.

MRT can be calculated with reasonable accuracy by summing the products of the various surface temperatures and their respective angle factors to the person. In many cases, the air temperature and MRT are equal; however, in certain instances the convective and radiant heat exchange in a given environment may differ significantly.

A simple example can show the importance of radiant heat. Imagine standing outside on a calm, clear, sunny day, in the middle of the winter. Although the air temperature may be below freezing, it is possible to feel comfortable, even warm, by staying in the radiant heat of the sun. Conversely, one may feel cold in a room that has reasonable air temperatures but also contains a large cold surface such as an exterior glass wall. In both instances, the air temperature alone does not finally determine comfort. This should be an important consideration of the designer whenever a potential radiant heat source or sink may be present.

Usually the mean radiant temperature tends to stabilize at room air temperature. However, exterior walls with large glass surfaces or without insulation may introduce considerably lower surface temperatures during the heating season than other interior surfaces, thereby lowering the mean radiant temperature of a space. The effect of this reduced mean radiant temperature can be significant; a 1-degree change in the mean radiant temperature is assumed to have about a 40 percent greater effect (on comfort) than a 1-degree change in air temperature. Therefore, it is usual to reduce the air temperature 1.4 °F for every 1 °F that the mean radiant temperature exceeds the air temperature, and to increase the air temperature 1.4 °F for a decrease of 1 °F in mean radiant temperature (1 °F = [°C x 1.8] + 32). Figure 13 shows the necessary mean radiant temperature and corresponding air temperature to maintain a thermal sensation of 70 °F.

Thermal radiation is measured using either a globe thermometer or a two-sphere radiometer. The rationalization for describing the thermal radiation inside a space by specifying its mean radiant temperature is to reduce numerous values (i.e., the radiation from various directions) into a single figure for calculation.

Humidity

Comfort is directly affected by humidity since moisture in the air affects evaporative heat losses. Evaporative heat loss is influenced by humidity and air temperature. When temperatures and humidity levels are high, it becomes difficult for the body to cool by perspiration because the air is unable to accept additional moisture, thus restricting latent heat loss from the individual. Evaporative losses are particularly important at higher air temperatures as convective and radiant heat loss decreases as the environmental temperatures approach, or surpass, the body temperature.

At lower temperatures, i.e., approximately 60 °F and below, the convective and radiant heat loss from a human body are approximately seven times greater than evaporative losses (from perspiration and respiration). At temperatures above normal body temperatures (98.6 °F), convective and radiative heat loss from a human body will be zero; thus the only means for cooling is through evaporation from either perspiration, or respiration. Figure 14 shows the relationship between the various modes of body heat loss and ambient room temperatures.

Humidity can be determined by measuring either dew point, relative humidity, wet bulb, or vapor pressure, and converting from one measure to another. Instruments used to determine these quantities are psychrometers, dew point hygrometers, or electrical conductivity or capacity hygrometers.

Air Speed

Induction of air motion within a space is important for many reasons, all of which affect human comfort. Supply of fresh air, removal of accumulated heat and moisture next to the body, and mixing of air to avoid thermal stratification, all contribute to perceived comfort. Air velocities of approximately 10 to 50 ft per minute (fpm) are considered adequate to produce favorable conditions, with an upper limit of 160 fpm. The summer comfort zone (on the psychrometric chart) can be extended with higher air velocities up to a maximum of 200 fpm (Figure 15).

Figure 14 also illustrates why air motion can be such an important component of thermal comfort at higher temperatures. Notice that, as the room temperatures approach or surpass 80 °F, the primary means of heat removal from the body is through evaporation. Air motion can profoundly influence the rate of evaporation. Still air can cause discomfort, while moving air can help create tolerable conditions by promoting evaporation. Convective heat exchange can be enhanced by increased air velocity across the body, e.g., by using a fan. The use of the wind chill factor as a measure of cold also shows the strong effect air speed has on convective heat transfer.

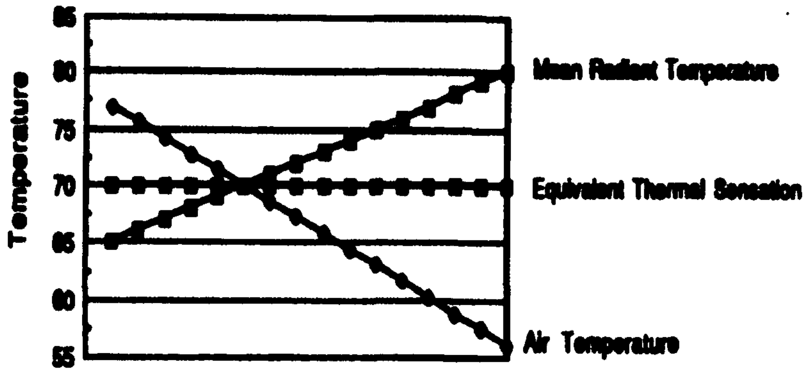


Figure 13. Mean Radiant Temperature and Air Temperature for and Equivalent Thermal Sensation of 70 °F.

Air speed can be measured with a variety of instruments, including hot-wire, heated sphere, or heated resistance anemometers. The most important aspect of a measurement device is that it be omnidirectional and capable of detecting air movement fluctuations.

Heat Generated, Btuh	400	400	400	400	400
Heat lost by:					
Radiation & Convection	350	300	200	100	0
Evaporation	50	100	200	300	400
Total Btuh	400	400	400	400	400

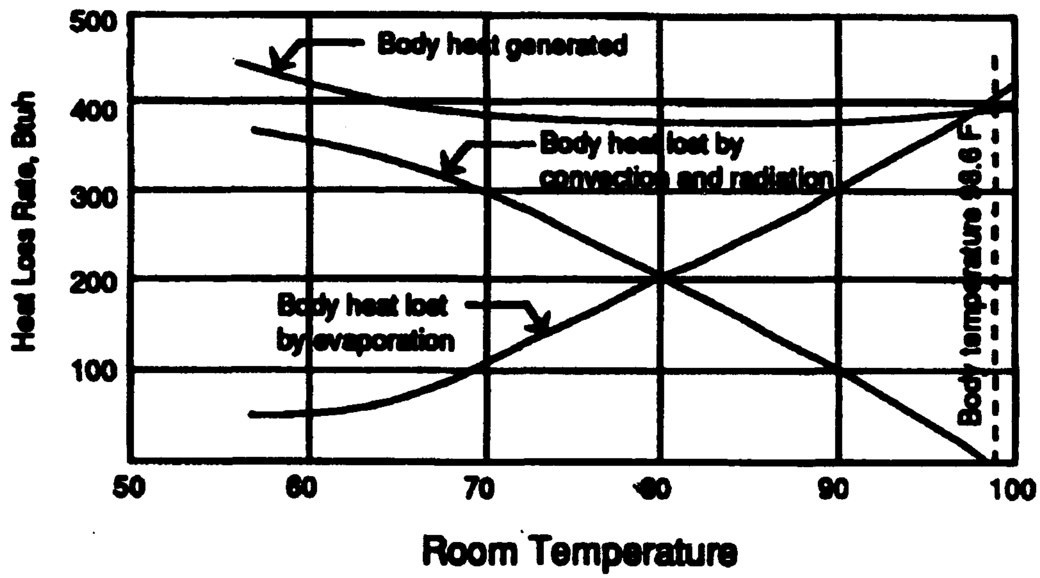


Figure 14. Approximate Heat Generated and Lost by a Person at Rest.

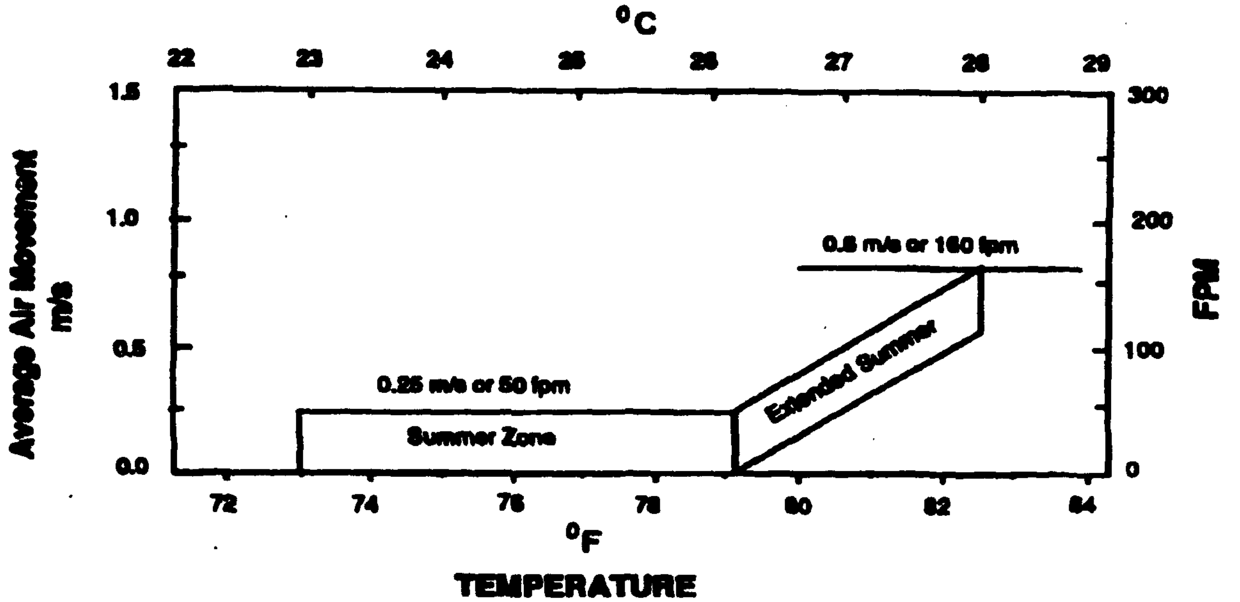


Figure 15. Extension of Summer Comfort Zone.

Combined Environmental Parameters

Operative Temperature

Operative temperature (t_o) relates the combined effects of convective and radiant heat exchange into a single parameter. Operative temperature is defined as the uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment. Operative temperature is the numerical average of the air temperature (t_a) and mean radiant temperature (t_r), weighted by their respective heat transfer coefficients (h_c and h_r).

$$t_o = \frac{h_c t_a + h_r t_r}{h_c + h_r} \qquad \text{[Eq 1]}$$

If the body's radiation and convective heat transfer coefficients are not known, another method can determine operative temperature by using the air temperature, mean radiant temperature, and air velocity of a space in the relation:

$$t_o = a \times t_a + (1 - a) t_r \qquad \text{[Eq 2]}$$

Where Table 1 shows (approximately) how factor *a* depends on air velocity *v*.

For air speeds of 80 fpm or less, and an MRT less than 120 °F, the operative temperature is approximately the simple average of the air temperature and MRT. Operative temperature is a very useful parameter as it offers a reasonable, single point measurement of thermal comfort under certain conditions often found in an office environment. It is approximately equal to the temperature of a 6-in. globe thermometer. A gray or pink globe is recommended since a black globe would overestimate the effect of direct solar radiation.

Table 1

Approximate Relation Between Air Temperature and Air Velocity

v(m/s)	a
0 – 0.2	0.5
0.2 – 0.6	0.6
0.6 – 10.0	0.7

The operative temperature is a rationally derived temperature scale. It is, in a sense, an adjusted temperature scale to account for both convective and radiative dry-heat exchange between the body and the environment. The operative temperature scale addresses an important component of assessing thermal comfort. The human body exchanges energy with the environment through radiation, conduction, and evaporation. Simply measuring air temperature or the mean radiant temperature of a space will not provide a comprehensive perspective of how the human body will respond to interpret the ambient environment.

Personal Parameters

The two quantifiable personal parameters used in calculating thermal comfort are activity level and clothing insulation.

Activity Level

There is a predictable correlation between most people's activity and their metabolic rate (the rate of energy production of the body). This rate of energy production changes with the level of activity. The more strenuous the activity, the more heat the body produces. Metabolism's standard unit is expressed in "met units," where 1 met is defined as 58.2 W/m^2 (18.4 Btu/h sq ft), which is equal to the energy produced per unit surface area of a seated person at rest. The surface area of an average person is about 1.8 m^2 (19 sq ft). A seated person at rest produces approximately 350 Btu/h (18.4 Btu/h sq ft x 19 sq ft).

Typical met units vary from 0.8 for an inactive reclining person to 3.0 for sustained, high activity work (Figure 16). (These values will vary from person to person depending on their physical health.)

Clothing Insulation

A person's clothing can have a strong influence on body heat transfer to the surrounding environment, and thus to the perception of comfort. Clothing or garment insulation is quantified in "clo units." The insulation provided by a suit of clothing is specified as "Icl," and the contribution of an individual garment to overall insulation is expressed in terms of its effective insulation Iclu. One clo unit equals 0.155 m2 °C/W (0.88 sq ft °F/Btu). Typical clo values for clothing ensembles range from 0.5 for light summer attire to 1.2 and above for heavy winter clothing (Figure 17). To get an exact value for a particular clothing ensemble, individual garment clo values are simply added together and multiplied by 0.82 to arrive at a total insulation value.

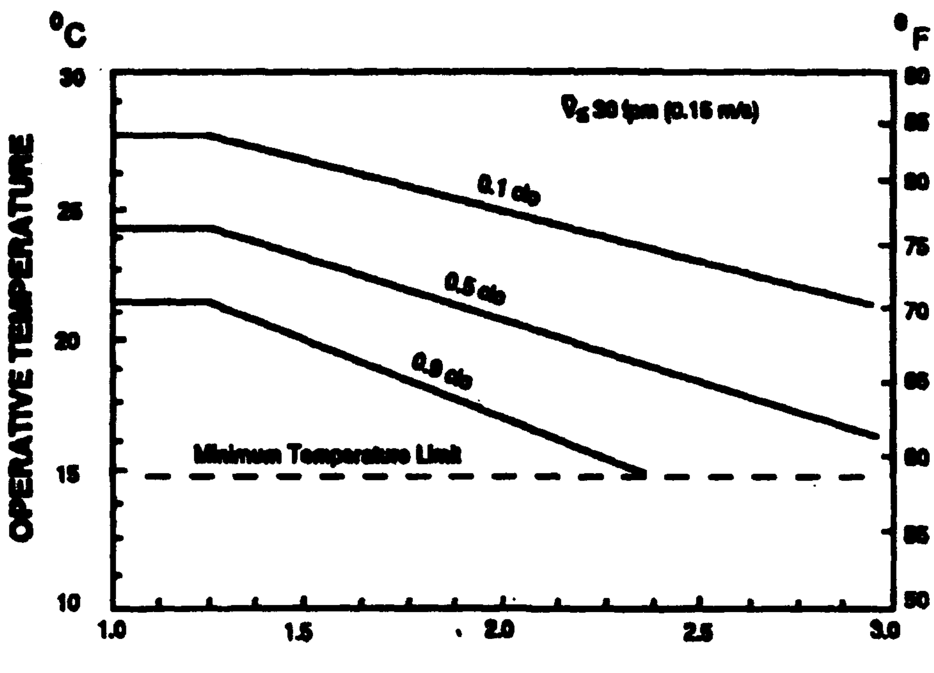


Figure 16. Typical clo Values for Various Activity Levels.

ASHRAE Criteria

Figure 18 shows thermal comfort boundaries with respect to humidity and operative temperature. As thermal comfort boundaries are not absolute; clothing, activity level, and increased air movement may cause the boundaries to deviate from "standard" conditions. Experimental studies of the relationship of

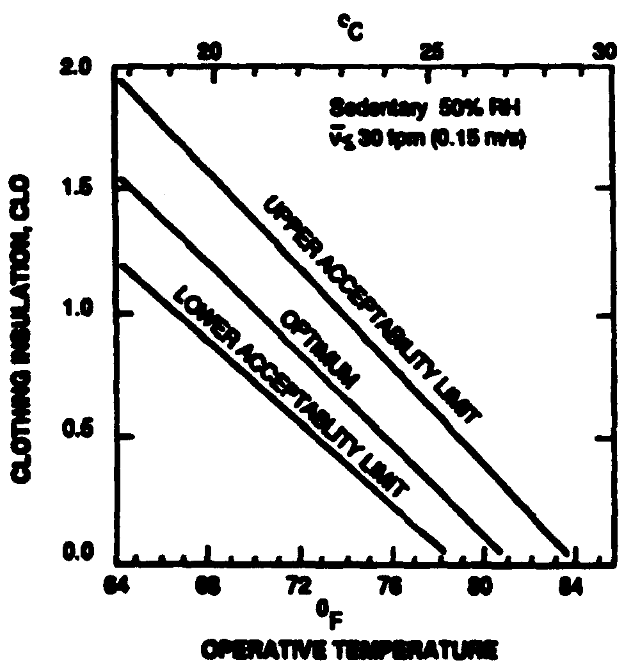


Figure 17. Typical clo Values for Various Clothing.

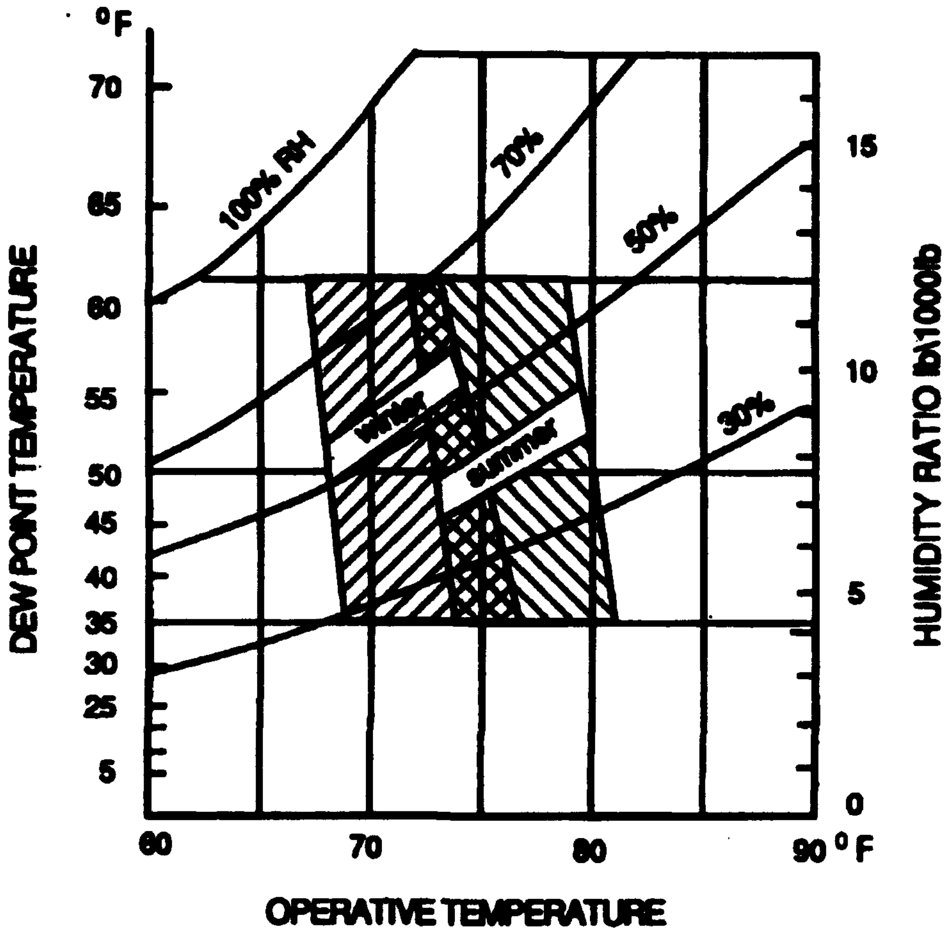


Figure 18. Thermal Comfort Boundaries Determined by Humidity and Temperature.

thermal comfort to the environment have been conducted since the 1920s. Sensation scales, such as the seven-point scale shown in Table 2, are common.

Empirical analysis of subject responses from these studies have related them to the environmental and personal factors mentioned above. The responses have also been related to physiological factors such as skin temperature, internal temperature, sweat rate, skin wettedness, and thermal conductance between the core and skin, and mathematical models have been formulated from these results.

A thermal comfort model will typically take the form of an energy balance equation. The heat transfer between the individual and the environment, as well as the resultant body temperatures and the rate of internal heat storage are determined. If the rate of internal heat storage is zero, and the body temperatures are at acceptable levels, then a thermally neutral, or comfortable, state is assumed.

Table 2

Seven-Point Comfort Index

Number Code	Thermal Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Comfort Equations

Three complex algorithms are used to predict comfort within a space, including the Pierce, Fanger, and KSU thermal comfort models. These equations can be used to predict a person's response to measured or hypothetical environmental parameters. The algorithms result in a Predicted Mean Vote (PMV) value, which is a mathematical function of activity, clothing, and the four environmental parameters. This value is an index that predicts the responses of individuals on the seven-point scale (-3 cold to +3 hot) for a given thermal environment. From the PMV index it is possible to determine the Predicted Percentage Dissatisfied (PPD) within a given thermal environment. PMV values between -0.832 and +0.841 are estimated to satisfy 80 percent of the occupants or to dissatisfy 20 percent (PPD). Equation 3 is an example of the Fanger algorithm used to calculate PMV.

$$\begin{aligned} PMV = {} & 0.352e^{-0.042M/A_{Du}} + 0.032)\,\{M/A_{Du}(1-n) - 0.35\,[43 - 0.061 \\ & M/A_{Du}(1-n) - p_a] - 0.42\,[M/A_{Du}(1-n) - 50] - 0.0023\,M/A_{Du} \\ & (44 - p_a) - 0.0014\,M/A_{Du}(34 - t_a) - 3.4 * 10^{-8} f_{cl} \\ & [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl}\,h_c\,(t_{cl} - t_a)\} \end{aligned} \qquad \text{[Eq 3]}$$

Where t_{cl} (mean temperature of outer surface of clothed body) is found iteratively from:

$$\begin{aligned} t_{cl} = {} & 35.7 - 0.032\,M/A_{Du}(1-n) - 0.18\,I_{cl}\,\{3.4 * 10^{-8} f_{cl}\,[(t_{cl} + 273)^4 \\ & - (t_r + 273)^4] + f_{cl}\,h_c\,(t_{cl} - t_a)\,(^{\circ}C)\} \end{aligned} \qquad \text{[Eq 4]}$$

and h_c (convective heat transfer coefficient) is determined by:

$$h_c = \begin{cases} 2.05\,(t_{cl} - t_a)^{0.25} & \text{for } 2.05\,(t_{cl} - t_a)^{0.25} > 10.4\,(v)^{0.5} \text{ (for high air movement env.)} \\ \text{or} & \\ 10.4\,(v)^{0.5} & \text{for } 2.05\,(t_{cl} - t_a)^{0.25} < 10.4\,(v)^{0.5} \text{ (for low air movement env.)} \end{cases} \qquad \text{[Eq 5]}$$

Some values are seasonal and need to be estimated, such as clothing insulation values and the clothing area factor. Naturally, more clothing increases the respective exterior surface area. Generating the PPD values depends on certain assumptions:

f_{cl} = Clothing area factor = 1.1 (summer); 1.15 (winter)
I_{cl} = Thermal resistance of the clothing = 0.5 clo (summer); 0.9 clo (winter)
M/ADu = Metabolic rate per unit body surface area (A_{Du} = DuBois area) (kcal/hr m^2) = 50 kcal/hr m^2 for sedentary work
n = External mechanical efficiency of the body = 0 for sedentary work.

Evaluation of Thermal Parameters

Determining these environmental parameters requires that measurements be taken at explicit locations to properly assess the effects on individuals. ASHRAE Standard 55-81R outlines proper instrument type, required measuring range, accuracy, response time, as well as the proper measurement location for various types of building structures.

The subjective nature of thermal comfort also lends itself to the use of questionnaire or survey measurements as illustrated in the 7-point PMV scale. Much effort has gone into determining proper scaling techniques.

Measurement Locations

Obviously, measurements should be made in locations where occupants reside. If the locations have not been determined, measurements should be taken in locations where the most extreme values of the thermal parameters are predicted to occur. Once locations have been determined, the height or position above the floor for measurement are stipulated. These heights vary depending on whether the person is seated or standing, and whether or not there is furniture in the way. ASHRAE Standard 55-81R, sections 7.1.1 and 7.1.2 expand on these subjects. Humidity is considered to be constant throughout the zone so that the location for measurement of this parameter is not critical.

Measurement Periods

Thermal property measurements must be taken over a period of time. Air speed, temperature cycles, drifts, clothing, and activity, also need to be observed over a certain time period. ASHRAE Standard 55-81R, section 7.2 details this subject.

Nonuniformity of Thermal Parameters

Within any room, various thermal characteristics can fluctuate from point to point. Air stratification, windows, uninsulated slabs, air leaks to the exterior, and other factors, can all affect localized thermal conditions. Fluctuating thermal characteristics are tolerable within limits.

Vertical Temperature Differences

Temperature differences within the occupied zone (assumed to be from 4 to 67 in. above the floor) should not exceed 3 °C (5 °F).

Radiant Temperature Asymmetry

Radiative temperature asymmetry should not be more than a 5 °C (9 °F) in the vertical direction, and 10 °C (18 °F) in the horizontal direction. Vertical positions where radiant temperatures are measured are 0.6 m (2 ft) above the floor for a seated person, and 1.1 m (3.6 ft) for a standing person.

Floor Temperatures

Floor surface temperatures for persons wearing typical footwear should be between 18 °C (65 °F) to 29 °C (84 °F).

Drafts

Drafts affect the body by providing unwanted cooling. The risk of draft depends on the mean air speed, the air turbulence intensity, and the air temperature. These values are then used to determine the percentage of people feeling a draft, which should be less than 15 percent at any point in the occupied zone. ASHRAE Standard 55-81R, sections 5.1.6.4, Appendix 1, and Figure 5.4, give more information on this subject.

5 INDOOR AIR QUALITY

Introduction

Over the past 15 years, a number of circumstances have contributed to a heightened awareness of indoor air quality:

1. In the late 1970s, the presence of friable asbestos in public schools became a health concern.

2. Owners of urea-formaldehyde foam-insulated houses often complained of odor and acute irritating symptoms.

3. Hundreds of outbreaks of illness among occupants of new or recently remodeled offices, schools, and other public access buildings were reported.

4. The potential for energy conservation measures to increase levels of indoor air contaminants was recognized by governmental authorities who advocated them.

5. Homeowners began seeking alternatives (e.g., kerosene heaters and wood-burning stoves) to the perceived high cost of central heating systems.

6. The environmental nature of allergies and asthma became better understood.

7. It became apparent that radon contamination of residences was not just a problem of uranium mill waste tailings and abandoned phosphate strip mines but a problem affecting millions of homes in the United States, Canada, and Northern Europe (Godish 1989, p 1).

Americans spend 68 to 70 of their time at home and 16 to 20 percent at work, or up to 90 percent of the time indoors (Figure 19). Obviously, most of the air we breathe is from indoor sources; exposure times for indoor air pollutants is much greater than for outdoor air pollutants. The greater exposure time is significant since adverse health effects from air pollutants are related to both the concentration of the pollutants and the exposure time.

Indoor air quality is an important consideration in the design, operation, and maintenance of buildings. In the workplace, indoor air pollution can increase absenteeism, decrease worker productivity, and invite lawsuits. Building designers and facility managers must therefore have access to timely and useful information about the relationship between indoor air quality and a building's attributes and operational parameters. The rest of this chapter reviews the current knowledge of indoor air quality. The first section helps define the area of indoor air quality.

Indoor Air Pollutants

Environmental Tobacco Smoke (ETS)

The chemical constituents found in an atmosphere filled with tobacco smoke are derived from two sources, mainstream and sidestream smoke. Mainstream smoke is what the smoker inhales and sidestream smoke rises directly from the burning tobacco. Sidestream smoke is more important to indoor air quality since this smoke contains a much greater concentration of toxic compounds than is found in mainstream smoke. More toxic compounds are produced in sidestream smoke because conditions are favorable for

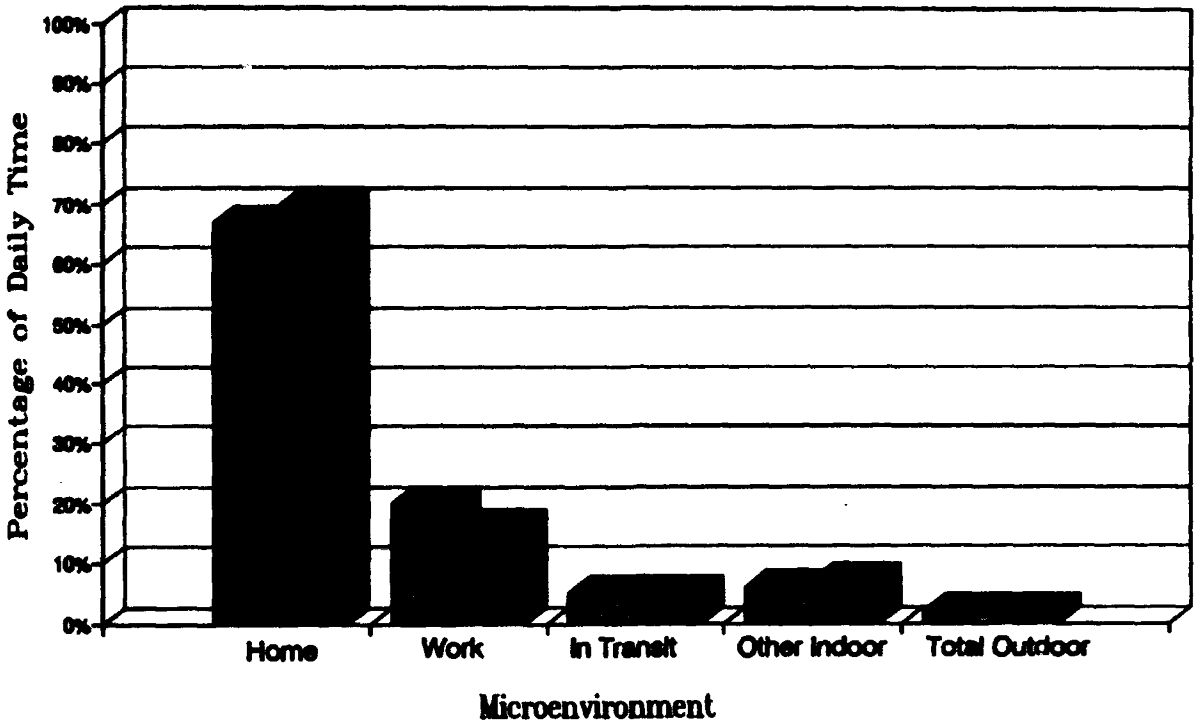


Figure 19. Time-Activity Patterns by Microenvironment.

the creation of incomplete combustion products. Table 3 shows a comparison of vapor-phase and particulate-phase compounds in sidestream and mainstream smoke.

Health Effects. Particulates released from smoking contribute greatly to the respirable particulate concentration in indoor air. In smoking areas, the indoor concentration of respirable particulates will almost always exceed outdoor concentrations and will often exceed outdoor standards. Respirable particles are those that can be inhaled into the lungs and deposited there. Compounds attached to these particulates are more likely to cause disease because of the extended contact time with respiratory tissues.

Carbon monoxide in smoking areas only rarely exceeds the U.S. Environmental Protection Agency's (USEPA's) 1-hour outdoor standard of 35 ppm, but can exceed the 8-hour standard of 9 ppm (Turiel 1985, p 74). Studies have shown that carboxyhemoglobin levels can rise from around 1 to 2 percent in nonsmoking individuals exposed to smoke-filled environments. This reduction in oxygen-carrying capacity is a potential health threat to people with angina pectoris (Turiel 1985, p 75).

The Surgeon General has extensively reviewed the health risks associated with involuntary smoking. Involuntary smoking has been causally linked with lung cancer in healthy nonsmokers and with increased frequencies of respiratory infections and respiratory symptoms in children of smoking parents.

Control Mechanisms. Control mechanisms for ETS include:

1. Creation of separate nonsmoking and smoking areas
2. Increased ventilation in smoking areas
3. Use of air-cleaning devices.

Table 3

Ratios of Selected Gas- and Particulate-Phase Components in Sidestream and Mainstream Tobacco Smoke

Vapor Phase	SS/MS Ratios	Particulate Phase	SS/MS Ratios
Carbon Monoxide	2.5-4.7	Particulate matter	1.3-1.9
Carbon dioxide	8-11	Nicotine	2.6-3.3
Benzene*	10	Phenol	1.6-3.0
Acrolein	8-15	2-Naphthylamine*	30
Hydrogen cyanide	0.1-0.25	Benzo-α-anthracene*	2.0-4.0
Nitrogen oxides	4-10	Benzo-α-pyrene*	2.5-3.5
Hydrazine*	3	N-Nitrosodiethanolamine*	1.2
N-Nitrosodimethylamine*	20-100	Cadmium	7.2
N-Nitrosopyrrolidine	6-30	Nickel*	13-30

*Suspected animal or human carcinogen.
Information source: U.S. Surgeon General, *The Health Consequences of Involuntary Smoking*, DHHS (CDC) 87-8398 (1986).

Volatile Organic Compounds (VOCs)

Because of the recent proliferation in the types and quantities of synthetic organic compounds used in construction materials, furnishings, and consumer products, most indoor air environments contain trace amounts of hundreds of organic compounds. The problem is especially severe in newly constructed, remodeled, or refurnished buildings where indoor concentrations of some compounds can be hundreds of times greater than outdoor concentrations. However, the concentrations of many of the compounds drop rapidly as the building ages.

Sources. Table 4 shows examples of organic compound types and potential indoor sources.

Health Effects. Some organic compounds found in indoor air are known or suspected carcinogens, including: benzene, tetrachloroethylene, trichloroethylene, and formaldehyde. In most indoor environments, the concentrations of any particular compound are so low that the risk of cancer is minimal.

Mixtures of organic gases and vapors have also been associated with "sick-building" syndrome complaints such as headaches, irritation of the eyes and mucous membranes, irritation of the respiratory system, drowsiness, fatigue, and general malaise. These symptoms occur despite concentrations well below occupational standards. It is believed that these standards may not be appropriate for predicting these types indoor air quality complaints for three reasons: (1) daily exposure may be greater than the typical 8-hour work day; (2) susceptible people can become sensitized to certain compounds; and (3) synergistic interactions among the compounds may occur.

Table 4

Sources and Types of Volatile Organic Compounds Found in Indoor Air

Pollutant Type	Example	Indoor Sources
Aliphatic hydrocarbons	Propane, butane, hexane, limonene	Cooking and heating fuels, aerosol propellants, cleaning compounds, refrigerants, lubricants, flavoring agents, perfume base
Halogenated hydrocarbons	Methyl chloroform, methylene chloride, PCBs	Aerosol propellants, fumigants, pesticides, refrigerants, and degreasing, dewaxing, and dry cleaning solvents
Aromatic hydrocarbons	Benzene, toluene, xylenes	Paints, varnishes, glues, enamels, lacquers, cleaners
Alcohols	Ethanol, methanol	Window cleaners, paints, thinners, cosmetics, adhesives, human breath
Ketones	Acetone	Lacquers, varnishes, polish removers, adhesives
Aldehydes	Formaldehyde, nonanal	Fungicides, germicides, disinfectants, artificial and permanent-press textiles, paper, particle boards, cosmetics, flavoring agents, etc.

Control Mechanisms. Control mechanisms for organics include:

1. Aging of materials capable of emitting organic compounds before their use
2. Increased ventilation of new buildings
3. Baking out compounds by raising the structure's temperature and ventilation
4. Use of local ventilation near known sources
5. Proper use of products that emit organic compounds
6. Use of air-cleaning devices.

Formaldehyde

Formaldehyde (HCHO) is a pungent colorless gas. Its odor can be detected as low as 0.05 ppm but most individuals notice it at a concentration of 1 ppm. Formaldehyde is often considered separately from other organic pollutants because of the large number of well publicized cases of adverse health effects attributable to formaldehyde contamination and because products capable of emitting formaldehyde are found in many locations in buildings.

Sources. Urea-formaldehyde foam insulation (UFFI) was installed in many locations in the mid to late 1970s. The Consumer Product Safety Commission received many complaints of adverse health effects due to formaldehyde emissions from UFFI and banned its use in 1982. Although the ban was lifted a year later, the adverse publicity and fears of liability have virtually eliminated UFFI use.

Urea-formaldehyde (UF) resins are the most common adhesives used in plywood, chipboard, and particle board. These materials are used widely in building construction. UF resins are also found widely in carpeting and furnishings.

Health Effects. Formaldehyde toxicity is caused by contact with the skin and mucous membranes of the eyes, nose, and throat. Connecting specific health effects to specific concentrations is difficult because people vary widely in their responses and complaints. Exposure can cause burning eyes and irritation to upper respiratory passages at concentrations as low as 0.05 ppm in sensitized individuals (Turiel 1985, p 17).

Formaldehyde is also a proven animal carcinogen (Environmental Health Perspectives 1982, pp 139-168). The USEPA has projected an upper bound risk of developing cancer among residents of mobile homes, exposed for more than 10 years to an average level of 0.10 ppm, to be 2 in 10,000; for residents exposed to an average level of 0.07 ppm in some conventional homes the risk is 1 in 10,000 (Hefter et al. 1987).

Control Mechanisms. Control mechanisms for formaldehyde include:

1. Exclusion of UF resin-containing materials
2. Alternate resin use in products
3. Modification of UF resin to limit formaldehyde release
4. Coating UF resin-containing products
5. Aging UF resin-containing products
6. Dehumidification
7. Increased ventilation, especially in new buildings or newly renovated areas.

Biogenic Particles

Biogenic particles are particulate irritants of biological origin. Biogenic particles are contacted through the inhalation of the biogenic particle itself or through the inhalation of a particle that contains a biogenic agent. These particles may include bacteria; fungi; viruses; amoebae; algae; pollen grains; plant parts; insect parts and wastes; animal saliva, urine, and dander; human dander; and a variety of organic dusts (Godish 1988, p 53).

Sources. Many pathogenic viruses and bacteria are generated by building occupants themselves. They are most often exhaled from the respiratory system by breathing, coughing, or sneezing. These infectious particles may remain airborne for a long time and in some cases be dispersed through buildings by the ventilation system. Air recirculation through faulty humidification systems and contaminated air ducts have, on occasion, placed individuals at risk to infectious airborne agents. Examples of these illnesses are Legionnaires disease, humidity fever (allergic alveolitis), and aspergillosis.

A number of allergens can be found in indoor air. Pollen found indoors is primarily produced from outdoor plants. Indoor pollen counts are normally lower than outdoor counts. Indoor fungal spore concentrations are also lower in most buildings than outdoors. However, in buildings where the relative humidity exceeds 75 percent, molds can flourish, elevating the concentration of fungal spores. Dust mites, which feed on human skin scales, feathers, and fungi, produce an allergenic excreta that can become incorporated into dust particles. These mites can flourish in climates where the winters are humid and mild.

Health Effects. Airborne microorganisms and allergens can cause allergic respiratory reactions as well as respiratory infections. Influenza, pneumonia, and other diseases may be spread through infection by airborne pathogenic bacteria and viruses. Dust, fungus spores, and plant pollen are important factors in provoking hay fever, asthma, or other allergy-related symptoms.

Control Mechanisms. Control mechanisms for biogenic particles include:

1. Better maintenance of cooling towers, filters, humidifiers, and air-conditioning systems
2. Lowering humidity levels
3. Use of air-cleaning systems.

Combustion Products

Nitrogen oxides, carbon monoxide, carbon dioxides, sulfur dioxide, volatile organic carbon compounds, and particulates are all products of combustion that can adversely effect indoor air quality. Products of combustion are more of a problem for residences because of unvented combustion sources.

Sources. Unvented gas appliances such as stoves can be a source of nitrogen oxides and carbon monoxide. Short-term indoor concentrations of carbon monoxide due to unvented gas stove use can exceed the 1-hour outdoor quality standard of 35 ppm (Sterling and Sterling 1979). Short-term indoor concentrations of nitrogen oxides can exceed the California outdoor air quality standard of 0.25 ppm (Traynor et al. 1981). Space heaters and fireplaces are other potential sources of the pollutants.

Health Effects. Carbon monoxide's toxicity is related to its ability to interfere with the uptake of oxygen by blood hemoglobin. Health effects associated with carbon monoxide include: decreased attention span, decreased reaction time, headaches, nausea, extreme drowsiness, and ultimately death by asphyxiation. However, indoor concentrations of carbon monoxide are normally well below the threshold associated with the onset of these health effects.

Long-term exposure to nitrogen dioxide has been associated with decreased lung function and disease. Some studies have indicated decreased lung function in children living in households using gas stoves when compared with children living in households with electric stoves (Melia et al. 1982, pp 164-168; Speizer et al. 1980, pp 3-10). Other studies dispute this relationship (Ware et al. 1984, pp 236-374).

Control Mechanisms. Control mechanisms for combustion products include:

1. Local ventilation of gas appliances and space heaters
2. Proper maintenance of gas appliances, space heaters, and fireplaces.

Radon

Radon (^{222}Rn) is a chemically inert radioactive gas formed during the radioactive decay series of ^{238}U. The radon decay chain is shown in Figure 20. The major health risks associated with radon result from the alpha decays of the two short-lived progeny, ^{218}Po and ^{214}Po.

Sources. There are three important ways that radon can enter buildings:

1. Transport from soil through cracks and openings in the structures or around the foundation
2. Emanation from earth-derived building materials such as concrete
3. Transport in water and natural gas.

Soil is considered to be the major contributor to indoor radon concentrations in most U.S. houses, but some building materials may contain large amounts of radioactive substances.

Health Effects. Indoor radon has been judged to be the most serious environmental carcinogen that the USEPA must address for the general public. Based on current EPA exposure and risk estimates, radon

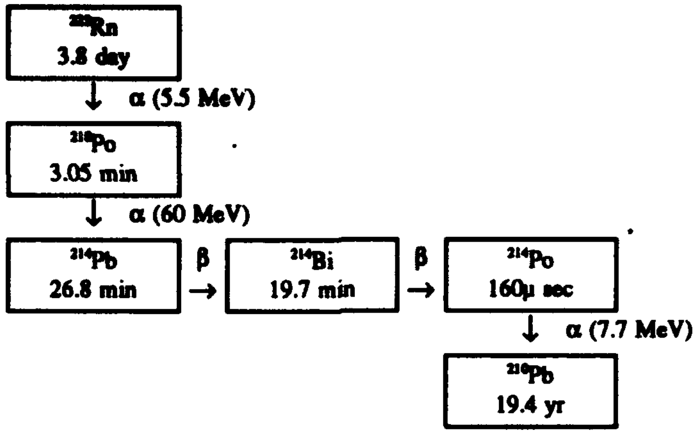


Figure 20. Radon Decay Chain.

exposure in single-family houses may be a causal factor in roughly 20,000 lung cancer fatalities per year (Puskin and Nelson, 1989, pp 915-919. Most of these projected fatalities are attributable to exposure in houses with average or moderately elevated radon levels (below 10 pCi/L).

Control Mechanisms. Control mechanisms for radon include:

1. Subfloor ventilation
2. Additional ventilation of high concentration areas
3. Proper construction to prevent radon entry pathways
4. Sealing of radon entry pathways
5. Proper building site selection
6. Removal of radon containing soil
7. Removal of radon from air.

Economic Impacts of Indoor Air Pollution

There is very little data available for estimating the economic impact of indoor air pollution. However, the EPA in its *Report to Congress on Indoor Air Quality* (1989) estimates some of the costs of poor air quality. The EPA report addresses three major types of economic costs:

1. Materials and equipment damage
2. Direct medical costs
3. Lost productivity.

Other costs not considered are:

1. Other welfare loss associated with pain and suffering due to health effects that are not fully alleviated by medical treatment

2. The value of unpaid time spent by persons taking care of those whose health is affected in the home

3. Losses due to reduced enjoyment of recreational and other activities affected by indoor air pollution.

In addition, the USEPA did not consider the effects of exposures to commercial or occupational sources other than those occurring in white collar work environments.

Material and Equipment Damages

Indoor air pollution can soil indoor surfaces and damage equipment and materials of various types. The costs associated with equipment and material damage includes costs incurred to mitigate the effects of contamination and the costs of repair or premature replacement of equipment and materials. Table 5 summarizes the damage to materials that can be caused by various indoor air pollutants. This table does not include microbial contamination that can result in significant damage to some materials. Although it is known that significant damage to materials and equipment does occur from indoor air pollutants, there is not enough data to calculate the costs associated with this damage.

Direct Medical Care Costs

The USEPA calculated direct medical costs for exposure to radon, Environmental Tobacco Smoke (ETS), and six Volatile Organic Compounds (VOCs) for both cancerous and noncancerous health effects. Costs for exposure to other indoor air pollutants were not calculated since data for national health impacts of these pollutants were not available. Table 6 shows the calculated direct medical costs.

Table 5

Air Pollution Effects on Materials

Materials	Type of Damage	Principal Air Pollutants	Other Environmental Factors
Metals	Corrosion, tarnishing	Sulfur oxides and other acid gasses	Moisture, air salt, microorganisms, particulate matter
Paint and organic coatings	Surface erosion, discoloration, soiling	Sulfur oxides, hydrogen sulfide, particulate matter	Moisture, sunlight, ozone, microorganisms
Textiles	Reduced tensile strength, soiling	Sulfur oxides, nitrogen oxides, particulate matter	Moisture, sunlight, ozone, physical wear
Textile dyes	Fading, color change	Nitrogen oxides, ozone	Sunlight
Paper	Embrittlement, soiling	Sulfur oxides, particulate matter	Moisture, physical wear
Magnetic storage media	Loss of signal	Particulate matter	Moisture, heat, wear
Photographic materials	Microblemishes, "sulfiding"	Sulfur oxides, hydrogen sulfide	Moisture, sunlight, heat, other acid gasses, particulate matter, ozone and other oxidants
Rubber	Cracking	Ozone	Sunlight, physical wear
Leather	Weakening, powdered surface	Sulfur oxides	Physical wear
Ceramics	Changes surface appearance	Acid gases, hydrogen fluoride	Moisture, microorganisms

Source: *Report to Congress on Indoor Air Quality*

Table 6

Summary of Annual Economic Costs of Indoor Air Pollution ($millions)

Pollutants	Direct Medical Cancer	Expenditures Noncancer	Lost Productivity	Materials and Equip. Damage	Total Calculated Costs*
Radon and radon daughters	$426	NC**	$1,991		$2,417
ETS	$274-385	$447-516	$2,457-2,974	NC	$3,178-3,875
Biological contaminants	NC	NC	NC	NC	NC
VOCs					
6 VOCs	$25-125	NC	$93-463		$118-588
Other VOCs	NC	NC	NC	NC	NC
Asbestos	NC	NC	NC		NC
Combustion gases	NC	NC	NC	NC	NC
Particulate matter	NC	NC	NC	NC	NC
Unspecified (sick building syndrome)	NC	(see text)	(see text)		(see text)

* Includes only costs associated with those types of cancer and other health effects for which estimates of numbers of annual health impairment were calculated in Chapters 3 and 4 of the source document. The estimated costs shown here are therefore understated. (Source: USEPA, *Report to Congress on Indoor Air Quality*).

** NC - Costs not calculated

Productivity Losses

Adverse health effects or general discomfort resulting from indoor air pollution may result in lost economic productivity, including:

1. Lost productive years due to major illness
2. Lost time due to increased number of sick days taken from the job
3. Lost productive efficiency on the job.

The USEPA calculated the costs associated with loss of earnings due to major illness for exposure to radon, ETS, and six VOCs (the same categories calculated for direct medical costs). Due to lack of data, costs for exposure to other indoor pollutants were not calculated. Table 6 shows the calculated lost productivity costs for these specific categories.

Lost productivity while on the job and from increased sick days was estimated from a recent survey of 94 state government office buildings in the New England states of Maine and New Hampshire. The New England survey sought information on the extent and effect of poor indoor air quality, including the losses in productivity, the increased number of sick days, and the frequency of doctor visits, attributed by respondents to poor indoor air quality. The New England survey was not scientifically administered and may have a significant bias. However, since it was the only survey which provides the necessary information to estimate productivity losses, a number of adjustments and very conservative assumptions concerning those not receiving or not responding to the survey were incorporated into this analysis.

Data from the New England survey would attribute an average productivity loss of 3 percent to poor indoor air quality. Respondents would also attribute an average of 0.6 added sick days per year to poor indoor air quality. When these results are applied to the nations white collar labor force, the economic cost to the nation would be on the order of $60 billion annually. While the USEPA does not regard this as a reliable estimate, it suggests quite strongly that productivity losses may be on the order of tens of billions of dollars per year. Tables 7 and 8 show the balance required in expenses to gain a personnel productivity increase.

Diagnosing Indoor Air Quality Problems

Investigations of indoor air quality are generally initiated in response to a perceived problem with the indoor air quality, to isolate and mitigate one or more sources of deteriorated air quality believed to be the cause of health or comfort complaints by the building's occupants. Traditional industrial hygiene

Table 7

Productivity Gains Necessary
To Offset Operating Cost Increases

Cost Increases		
Energy (%)	**Total Environment (%)**	**Offsetting Productivity Gain**
5%	1.67%	0.05
15%	5.00%	0.15
25%	8.33%	0.25
50%	16.67%	0.50

Base cost assumption:
Energy costs = $2 per sq ft per yr
Total environment costs = $6 per sq ft per yr

Table 8

Productivity Gains Necessary
To Offset Capital Expenditures

Capital Cost ($/sq ft)	Annualized Cost ($/sq ft)	Offsetting Productivity Gains: No Change in Operating Costs (%)	Offsetting Productivity Gains: Operating Costs (%) Increase by 15%
1	0.13	0.07	0.22
5	0.66	0.33	0.48
10	1.31	0.66	0.81
15	1.97	0.99	1.14
25	3.29	1.64	1.80
50	6.57	3.29	3.44

Base cost assumptions:
Energy costs = $2 per sq ft per yr
Annualized costs are capital costs amortized at 10% over a 15-yr life

Table 9

Background Information on Indoor Air Quality

1. Facility identification
   - A. Building name/number
   - B. Address
   - C. Location
   - D. Owner
   - E. Tenant

2. Contact person
   - A. Facility manager
   - B. HVAC operator
   - C. Maintenance supervisor
   - D. Primary client contact

3. Facility description
   - A. Nature of business or activities conducted by.
     - Tenant
     - Other occupants
   - B. Number of occupants in each space
   - C. Activities conducted in or near the facility.
     - Laboratory
     - Manufacturing
     - Industrial operations
     - Cafeteria
     - Parking garage
     - Other Chemical use
   - D. Time of day/days of week
     - Any employee on duty
     - Office employees on duty
     - Maintenance employees on duty
     - Facility open for business
   - E. Construction
     - Number of floors
     - Floor area per floor
     - Year constructed
     - Intended use
     - Major renovations (include dates)
   - F. Furnishings
     - Floor coverings
     - Wall coverings
     - Partitions
     - Ceilings

4. Neighborhood
   - A. Principal use (rural, urban, commercial)
   - B. Proximity to traffic
   - C. Density of traffic
   - D. Neighboring facilities in which traffic, construction, or chemical use might be suspected of adversely impacting neighborhood air quality.

5. HVAC system
   - Energy source (oil, gas, electric)
   - Primary fluids (steam, hot air/water)
   - Supply (pipe, duct, plenum)
   - Distribution (radiators, ceiling filters)
   - Return (pipe, duct, plenum)
   - Location of heat source
   - Local heating units
   - B. Cooling
     - Number and location of chillers
     - Number and description of distribution systems
     - Window units
   - C. Air intake
     - Location of air intake(s)
     - Means of controlling outside air
     - Design quantity/percent outside air
     - Open windows
     - Open doors
     - Local exhaust systems (restrooms, kitchen, laboratory)
   - D. Conditioning
     - Humidifiers
     - Dehumidifiers
     - Filters
     - Air cleaners
   - E. Operation of HVAC
     - Location of thermostats/zones
     - Access to thermostats/zones
     - Date thermostats last calibrated
     - Day/night controller (cycle)
   - F. Maintenance of HVAC
     - Date system last balanced
     - Schedule for filter change/clean
     - Schedule for other cleaning
     - Schedule for other maintenance

Source: Rafferty, P.J., "A Protocol for Initial Investigations of Indoor Air Quality," *Proceedings of the 82nd Annual Meeting and Exhibition of the Air and Waste Management Association*, paper 89-85.4 (Anaheim, CA, 25-30 June 1989).

Table 9 (Cont'd)

6. Facility maintenance
   Typical and atypical activities/products regarding:
   - Outdoor and indoor use of pesticides
   - Painting, staining, varnishing
   - Asbestos or other insulation removal
   - Insulation
   - New furniture or upholstery
   - Wax stripping
   - Leaking water pipes
   - Flooding
   - Electrical, plumbing or HVAC repair or renovation
   - New partitions, wall coverings, floor coverings
   - Cleaned floor covering, wall covering or upholstery

7. Health and comfort Complaints
   A. Number and location of persons reporting the following symptoms:
   - Eye irritation
   - Contact lens irritation
   - Nose irritation
   - Shortness of breath
   - Throat irritation
   - Nasal congestion
   - Skin irritation
   - Cough
   - Headache
   - Wheezing
   - Nausea
   - Chest tightening
   - Diarrhea
   - Fatigue
   - Dizziness
   - Fever
   - Allergies
   - Sick more often than usual

   B. Date of symptom onset
   C. Number of persons reporting the following complaints:
   - Too hot
   - Drafty
   - Too cold
   - Stuffy
   - Mold or mildew
   - Tobacco smoke
   - Damp
   - Dusty
   - Dry
   - Noisy
   - Odors
   - Dark

   D. Date complaints began
   E. Daily, weekly, or yearly patterns of reporting symptoms and complaints
   F. Complainant characterization
   - Work location
   - Work function
   - Percentage of total occupants in area
   - Sex distribution
   - Age distribution

8. Any other circumstances suspected of adversely impacting indoor air quality of the facility

methods that try to compare measured individual air contaminants with their respective occupational health standard, often fail. Alternate diagnostic protocols have been developed to deal specifically with the nonspecific symptoms of Sick Building Syndrome (SBS). These protocols typically involve three stages:

1. Consultation with building occupants and maintenance personnel
2. Qualitative characterization of sources and air movements
3. Quantitative evaluation of the HVAC system, potential air contaminants, and environmental parameters.

A properly conducted investigation of indoor air quality can identify indoor air problems and recommend remedial actions to address building design and operation difficulties.

The resolution of more difficult indoor air quality problems often requires the expertise of an indoor air quality specialist. However, the initial investigation of indoor air quality problems should be a low cost, semiquantitative analysis that professionals in the fields of HVAC engineering, air pollution engineering, or industrial hygiene can conduct. The initial investigation can solve many indoor air quality problems and can provide a more focused direction for more detailed investigations.

Consultation Stage

Table 9 outlines the types of information that should be gathered during the consultative stage of a preliminary investigation, including a description of the facility, its surrounding neighborhood, the HVAC system, maintenance activities, and health and comfort complaints of the occupants. An investigator acquires most of the information through extensive interviews with one or more individuals who are intimately familiar with the construction, operation, and maintenance of the physical plant. Information on the health and comfort complaints of the occupants can be obtained by interviews or a written survey.

During interviews, construction documents should be reviewed to identify materials of particular concern used in the construction of the facility. Floor plans should be marked to identify locations of reported complaints, suspected emission points, air-handling zones, and HVAC intake and relief points. The distance and direction of potential emission points outside of the building should be indicated. Material safety data sheets should be obtained for all chemical products suspected of being the source of the problem. Hypotheses on the cause of the indoor air quality problem are then developed based on the information collected during this stage of the investigation.

Qualitative Stage

The next stage of the preliminary investigation should be a qualitative survey of the facility. In this survey, all the senses are used to develop a body of data that is used to evaluate the various hypotheses developed during the consultative stage. Evidence of microbial damage and other contaminant sources can be seen. Odors are also important indicators of air pollution problems. The only device that should be used during this survey is a smoke-tube with an aspirator bulb. An investigator uses this device to characterize the air movement between the various rooms of the facility. Arrows sketched on a floor plan can indicate air movement patterns from each room to the next.

Quantitative Stage

The final stage of the preliminary investigation is a quantitative assessment of the HVAC system, some of the more likely air contaminants, and temperature and humidity. The results of this stage in combination with the other stages are used to develop mitigative measures, if possible, for the control of the indoor air pollution problem.

<u>HVAC Investigation</u>. An investigator should begin the evaluation of the HVAC system by analyzing the overall ventilation rate. Overall ventilation can be determined directly by measuring the flow through the outside air intake duct. However, the configuration of the intake sometimes makes an accurate measurement impossible. In these cases, the design ventilation rate can, in theory, be calculated by reviewing blueprint plans and analyzing fan curves for the system. The design of the HVAC system should be considered while making these determinations since the percentage of outside air may vary with the outside temperature or some other control parameter.

An investigator should then determine the effectiveness of local ventilation. This includes both local exhaust ventilation from potential significant sources of indoor air pollution and local ventilation provided by the HVAC system to occupied rooms. Potential significant sources include the laboratory, photographic darkroom, printing shop, and certain graphic arts operations. Local ventilation can be measured directly with an anemometer or velocity-measuring hood. However, an investigator should also note any potential for short circuiting of ventilation air. This potential exists if the supply and return air grills are located too close to one another.

Another useful method for determining adequate ventilation is a CO_2 concentration survey. Indoor CO_2 levels above the background concentration of 325 ppm are primarily the result of human exhalation and are therefore a good indicator of human bioeffluents and the effectiveness of ventilation to dilute them. Indoor CO_2 levels can be measured with portable CO_2 monitors or detector tubes. An investigator should collect a large number of samples with respect to occupancy, thermostat controls, HVAC supply zones, and suspected trouble spots.

Measurement of Indoor Air Pollutants. After the HVAC system has been evaluated, a number of likely indoor air pollutants can be measured. An investigator should identify which, if any, pollutants to measure based on the types of occupant complaints and other information developed during the preliminary investigation. VOCs, CO, and micro-organism levels are all likely air contaminants that can be semi-quantitatively measured during a preliminary investigation.

Rather than conducting compound-specific measurements of a variety of suspected VOCs, a useful screening approach to characterize VOCs emissions is the measurement of total VOC levels. Portable hand-held instruments to measure total VOCs are readily available and relatively inexpensive. These instruments can generally measure concentrations of total VOCs down to 1 ppm. Mixtures of VOCs at concentrations as low as 1 ppm have been associated with decreased concentration levels and mucous membrane irritation. Therefore a level of 1 ppm total VOCs is an acceptable indicator for deciding to pursue further investigation or mitigation.

Screening for contamination of nonspecific airborne micro-organisms is a controversial subject. Opponents to this practice fear that the method can provide a false sense of security since it can not identify many agents of airborne microbial contamination (such as Legionella). However, the method can be used to identify gross bacterial or fungal contamination in certain circumstances, provided the limitations of the technique are clearly understood. Air samples should be collected at several locations inside and outside of the facility. For certain media, the concentration of micro-organisms is considered significantly different if values exceed approximately twice the observed background levels.

Interpretation of Results

Interpreting findings of an initial investigation requires considerable professional judgment and some creativity. The process is frequently an iterative one in that portions of the facility may need to be retested using screening or more sophisticated techniques. Often, several mitigation measures are available to control a single identified problem. The options generally considered are to remove the source, to isolate and/or ventilate the source, to separate receptors from the sources, to enhance the control system, and to clean contaminated surfaces. Enhancing the control system may require a redesign of the HVAC system, or specific changes in its operation, control, or maintenance.

Source Control

The USEPA has classified source control strategies into four general categories: (1) source substitution and/or removal; (2) source encapsulation and/or confinement; (3) proper source operation and maintenance; and (4) source modification (USEPA 1989). Since source control strategies vary depending on the pollutant involved and the source of emissions, they are most easily discussed in the context of specific contamination problems. Emissions of ETS, organic compounds, biogenic particles, and asbestos are all potentially important indoor air pollutants in nonresidential buildings that can be reduced by various source control techniques.

Environmental Tobacco Smoke (ETS)

ETS source control is limited to removing or confining the source. ETS can be controlled either by banning smoking from the effected building or by providing designated smoking areas apart from the general habitable areas. Designated smoking areas must be depressurized and vented directly to the outside to avoid transportation of ETS into other indoor areas. A recent study has demonstrated the potential effectiveness of restricting smoking to designated areas (Vaughan and Hammond 1989). In this study, nicotine vapor (a surrogate for all ETS) was measured at a large number of representative sites before and after implementing a new smoking policy in a modern office building. The new policy restricted smoking to a snack bar on the 32nd floor and the eastern part of the cafeteria only. The researchers concluded from their measurements that:

1. After the smoking policy was implemented, general employee exposure to nicotine vapor was reduced by over 95 percent on most floors.

2. Even the highest concentrations in the general office areas (those adjacent to the designated smoking areas) were much lower after implementing the policy.

3. Improvement in air quality on the 31st and 32nd floors was not as great as on floors that did not share an air handling system with a floor containing a designated smoking area. The average level on the 31st floor was four times that on the 19th floor.

4. There was evidence that tobacco smoke vapors spilled over into office areas of the 32nd floor, probably through open doors and shared overhead plenums.

5. Under the new policy, the air quality of both the cafeteria and the 32nd floor snack bar was generally poorer. The snack bar was especially contaminated with worst case nicotine levels at least 1800 times higher than the typical office area.

Organic Compounds

Formaldehyde. Formaldehyde can be emitted from a wide range of building materials. Products capable of releasing formaldehyde include wood products bonded with urea-formaldehyde (U-F) resins, urea formaldehyde foam insulation (UFFI), and U-F wood finishes. Formaldehyde is emitted either through the direct release of loosely bound formaldehyde or through the reaction of U-F resins with water vapor.

Source Substitution/Removal. A seemingly simple way to minimize formaldehyde exposure is by avoiding the use of or removing formaldehyde-releasing products from the indoor environment. However, formaldehyde-releasing products are often less expensive, more durable, and/or more aesthetically appealing than available substitute products.

Wood products include hardwood plywood, particleboard, and medium density fiberboard. Products manufactured from solid wood, gypsum board products, metal, and plastic can be substituted for formaldehyde-releasing wood products. Substitution of particle board used as subflooring is particularly advisable because of the high formaldehyde concentration associated with its use.

UFFI has become relatively unavailable because of attempts by the Consumer Product Safety Commission to ban it and the associated bad publicity. UFFI is still used as an insulating medium for certain industrial and commercial applications. However fiberglass, cellulose, and styrofoam-substitute products are available for most insulation uses.

U-F-based finishes are widely used in North America on wood cabinetry and furniture. Many product substitutes are available; however, they do not have the scratch and chip resistance of U-F resin-based finishes.

Source Encapsulation/Confinement. Both manufacturers and end users of formaldehyde-emitting products can use a number of source encapsulation/confinement techniques to reduce emissions. Manufacturers apply a number of different coatings to hardwood plywood and particleboard products. The coatings prevent formaldehyde emissions both by impeding the transport of formaldehyde across the barrier and by impeding the transport of water vapor into the wood product (which hydrolyses the U-F resin). These coatings include varnishes and paints, some of which contain formaldehyde scavenging compounds to further reduce emissions. End users of formaldehyde emitting products can apply similar coatings. A recent study evaluated the effectiveness of some of these coatings applied to particleboard subflooring under whole house conditions (Godish 1987, pp 221-225). Formaldehyde reductions varied from 17 to 87 percent. All surface coatings appeared to provide long-term reductions in formaldehyde levels.

Source Modification. Manufacturers of U-F-based wood products and finishes use a number of source modification techniques to reduce formaldehyde emissions. These include:

1. Reducing the formaldehyde-to-urea ratio in resin formulations
2. Providing for ideal curing/production conditions
3. Adding formaldehyde-scavenging compounds to resins or finishes
4. Treating wood products with formaldehyde reactive gases such as ammonia
5. Using alternate resin systems when available.

When it is necessary to use U-F-based wood products and finishes, it may be advisable to use products manufactured with one or more of the formaldehyde emission reduction techniques mentioned above.

Source modification techniques for reducing formaldehyde emissions are also available to building occupants affected by excess formaldehyde emissions, including:

1. Ammonia fumigation
2. Climate control
3. Product aging.

Ammonia fumigation has been shown to be an effective long-term formaldehyde reduction technique for areas with large concentrations of formaldehyde releasing materials such as mobile homes (Jewell 1984). A recent study documented surprisingly effective formaldehyde control achieved through the regulation of indoor temperature and relative humidity (RH) (Godish and Rouch 1986, pp 792-797). For example, the authors reported that a decrease in temperature and humidity levels from 30 °C and 70 percent RH to 20 °C and 30 percent RH reduced formaldehyde concentrations in a mobile home by 80 percent. Aging of new formaldehyde-releasing products for several months can dramatically reduce exposures from these materials. Exponential decay in formaldehyde emissions is a widely reported phenomenon. Formaldehyde emissions tend to decrease rapidly at first and then almost level off in comparison after a few years. However, product aging can never completely halt formaldehyde emissions.

Formaldehyde will continue to be released as long as U-F based products are present. Hydrolysis of U-F resins and the subsequent release of formaldehyde will continue through the lifetime of the product.

Volatile Organic Compounds (VOCs). Source control techniques can be difficult to employ for VOCs since little information is available on the health effects of specific VOCs or VOC mixtures. VOCs vary widely in number, sources, and concentration. Individual VOCs are difficult to identify and quantify. Control becomes difficult when it is not clear which compound or group of compounds should be controlled. Even when it is clear which VOC must be controlled, it may be hard to locate a specific source of VOC contamination. This is especially true when building materials and furnishings are the source of emissions. These items are manufactured using a wide variety of organic solvents, which often remain in the product in small amounts where they can become a source of VOC emissions. Because of the limited knowledge of the health effects and sources of VOCs, most VOC source control techniques attempt to reduce the total VOC concentration in indoor air.

Source Substitution/Removal. Avoiding or removing products capable of high VOC emissions is difficult because of the lack of useful emissions data. A number of chamber studies, including a large effort sponsored by the USEPA, have reported VOC emissions from potential indoor sources (Molhave 1982, p 117; Girman et al. 1984, p 312; Tichenor and Mason 1988, p 264). The results of these studies sometimes conflict and are not directly comparable since the test conditions are not standardized. These studies also tend to report emission characteristics by broad product categories. Emissions for generic product names are generally unknown. These characteristics may also vary considerably for a specific product type from one manufacturer to another. Simply removing the source can be an effective technique when the offending VOC source can be identified. However finding an acceptable substitute product may be difficult.

Source Modification. Source modification techniques for high VOC emission products take advantage of the beneficial aging process observed in these products. A number of studies have shown that indoor concentrations of many VOCs decline rapidly during the first few months after the building's completion (Berglund 1982, pp 11-15; Sheldon et al. 1988 [Vol I & II]).

Table 10 summarizes the VOC results from a USEPA study of public buildings. In this study, the new hospital, nursing home, and office were completed 34, 4, and 1 week(s), respectively, before the first VOC-monitoring efforts. Table 10 shows significant declines in the total measured VOCs between trips 1 and 2 for the new nursing home and office. However, the hospital did not experience this type of VOC reduction. The authors concluded that the outgassing of VOCs was greatly reduced in the hospital by the time VOC monitoring began since the monitoring did not begin until 8 months after the buildings completion. Table 10 also shows that chlorinated VOCs did not follow the pattern of reduced concentrations and that the hospital and office building samples showed the highest concentrations. These results indicate that a renewable source for this type of VOC exists in these buildings such as photocopying or cleaning solvents. However, the aromatic and aliphatic VOCs, which had the highest initial concentrations in the new nursing home and office, were greatly reduced between trips 1 and 2.

The observed rapid decrease in VOC emissions suggests some practical source control methods. For a new or newly refurbished work space, it is a good idea to install all building materials and furnishings as soon as possible and to forgo occupancy as long as possible. For certain furnishings, such as office furniture and carpeting, aging of the materials in a warehouse before installation can reduce occupant exposures. After occupancy, increasing the ventilation rate during the first 6 months may also help to reduce the likelihood of VOC-related health and comfort complaints during this active VOC outgassing period.

Table 10

Concentration Data for Volatile Organics Summarized by Compound Class

	Concentration (ng/L)														
	Aromatic Hydrocarbons			Aliphatic Hydrocarbons			Chlorinated Hydrocarbons			Oxygenated Hydrocarbons					
	Indoor	Outdoor	In/Out Ratio	Indoor	Outdoor	In/Out Ratio	Indoor	Outdoor	In/Out Ratio	Indoor	Outdoor	In/Out Ratio	Indoor	Outdoor	In/Out Ratio
Hospitals															
Hospital (New)															
Trip 1	18	5.4	3.3	7.0	ND[a]	–[b]	8.1	3.7	2.2	1.3	ND	–	34	9.1	3.7
Trip 2	11	5.1	2.2	4.7	ND	–	6.0	5.3	1.1	ND	ND	–[c]	21	10	2.1
Trip 3	26	6.2	4.2	5.1	ND	–	26	3.2	8.1	ND	ND	–	57	9.4	6.1
Offices															
Office (New)															
Trip 1	270	16	17	810	ND	–	13	1.0	13	ND	ND	–	1100	17	65
Trip 2	54	13	4.2	98	ND	–	56	3.0	19	8.5	ND	–	220	16	14
Office(Old)															
Trip 1	74	50	1.5	5.1	ND	–	46	8.1	5.6	4.3	ND	–	130	58	2.2
Office/School (Old)															
Trip 1	30	12	2.5	18	ND	–	26	3.7	7.0	1.5	ND	–	75	16	4.6
Homes															
Nursing Home (New)															
Trip 1	93	8.5	11	173	ND	–	9.9	2.8	3.5	9.6	ND	–	286	11	26
Trip 2	22	17	1.3	7.3	ND	–	3.9	2.5	1.6	1.2	ND	–	34	20	1.7
Nursing Home (Old)															
Trip 1	12	7.8	1.5	1.9	ND	–	4.1	1.3	3.2	ND	ND	–	18	9.1	2.0

[a]Below the quantifiable limit.
[b]Not calculated. Detected in indoor but not outdoor samples.
[c]Not detected in indoor or outdoor samples.
SOURCE: Sheldon et al. 1988, Vol I, pp 231.

Another method for reducing VOC levels in new buildings that takes advantage of VOC product aging is a "bake-out." A bake-out procedure entails increasing the indoor temperature beyond comfort levels for a period of a few days in an unoccupied, fully furnished building. The elevated temperature increases the evaporation rate of residual organic solvents found in building furnishings and materials. Some ventilation is maintained during the period to flush out the VOCs. In effect, a bake-out accelerates the aging process on the furnishings and materials.

The California Air Resources Board (CARB) has sponsored studies of the bake-out procedure in an attempt to determine whether bake-outs are practical, and to develop the information needed to conduct successful bake-outs (Girman 1987, p 22; Girman 1990). In the most successful of the CARB sponsored bake-outs, supplemental electric heaters were used since the building was baked-out during a period when the outside temperatures were near the minimum design for the heating system. The thermostats were disconnected and the building temperature was allowed to float. Figure 21 shows the temperature profiles in three locations in the building during the bake-out. To conserve heat, the ventilation was kept to a minimum except during measurement periods when the ventilation was increased to pre-bake-out levels. Figure 22 illustrates the changes in total VOC levels before and after the bake-out. One day after the bake-out, the VOC concentration was not significantly lower. This occurred because the building materials and furnishings were still cooling off from the bake-out. One month later, the total VOCs were reduced to around 5 to 7 percent of the concentrations before the bake-out, apparently larger changes than can be accounted for simply on the basis of aging. However, it is impossible to estimate the benefits of the bake-out since a control house was not used in this or other bake-out research.

Pesticides. The most important aspect of source control for pesticides is proper application. Because most pesticides have a relatively low vapor pressure, indoor air concentrations are generally low if prescribed application procedures are followed. The semivolatile nature of many pesticides allows skin absorption to be a potentially significant exposure pathway. Good application practices include: use of no more than the manufacturer's suggested dosage; application away from HVAC ducts and air intakes; application during nonbusiness hours; and application away from surfaces that may come into contact with

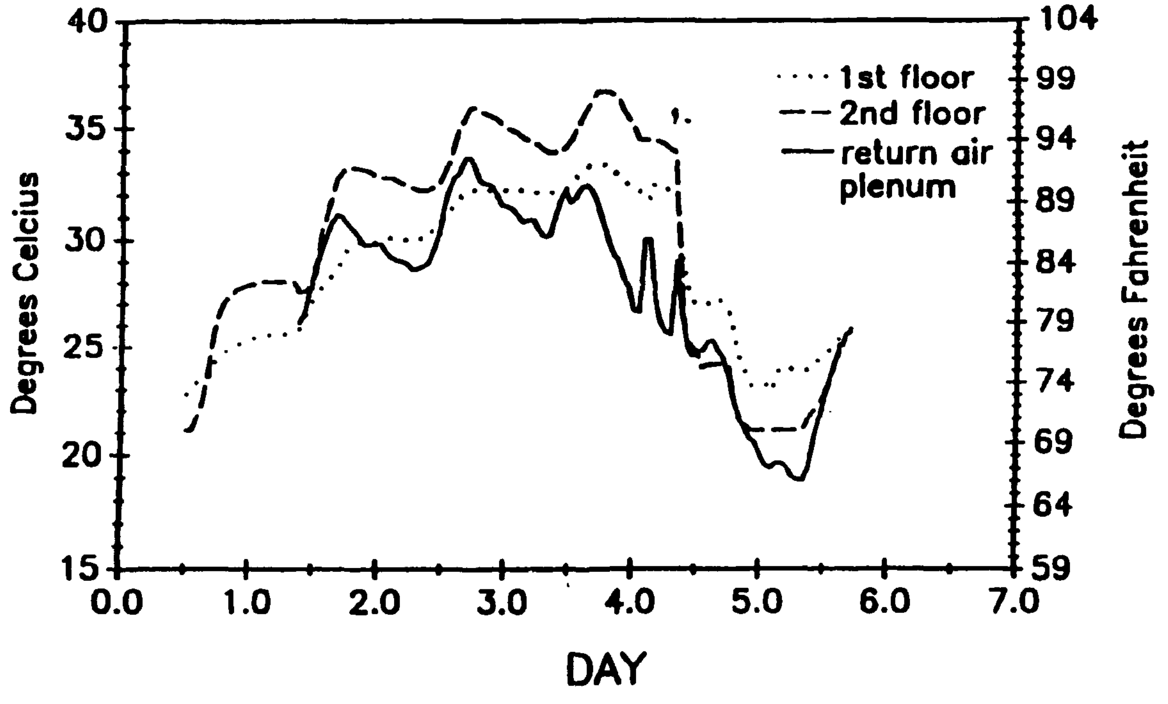


Figure 21. Temperature Profiles for Three Buildings During Bake-Out.

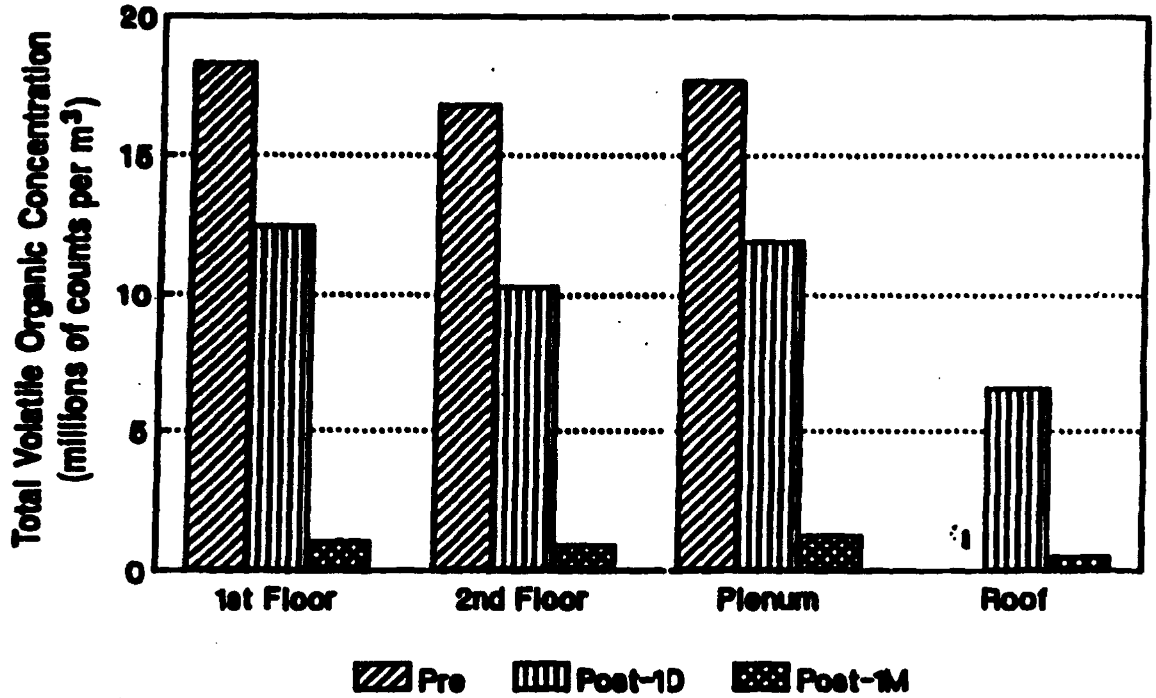


Figure 22. Changes in VOC Levels Before and After Bake-Out.

human skin. The pesticides found in foggers or bug bombs have somewhat higher volatilities than other pesticides. It is important to keep occupants away from areas where this type of product is used during the period of time recommended by the manufacturer. Injection of suspected carcinogenic pesticides, such as chlordane, underneath concrete slabs–at one time fairly common but now illegal practice–containing ventilation supply ducts is especially dangerous.

Biogenic Particles

Control of biogenic particles involves elements of source removal, proper source operation and maintenance, and source modification. Control measures for biogenic particles are designed to prevent or stop bacterial and fungal growths within an indoor environment or its HVAC system. In a recent paper the following recommendations were made for the prevention of biological contamination (Rask and Morey 1987):

1. Prevent excessive moisture entry into occupied spaces and HVAC system components
2. Remove stagnant water and slimes from building mechanical ventilation systems
3. Use steam as a moisture source in humidifiers
4. Eliminate water sprays as components of office building HVAC systems
5. Maintain relative humidity below 70 percent
6. Use filters with a 50 to 70 percent rated efficiency
7. Remove water-damaged material and furnishings
8. Provide a fastidious maintenance program for HVAC air-handling and fan coil units.

These eight control methods can be effective in preventing symptoms associated with exposures of mycotoxins and allergens. However, the prevention of outbreaks of Legionnaires' disease and Pontiac fever requires special considerations. Cooling towers should be well maintained and equipped with effective mist eliminators to prevent the drift of aerosols containing L. pneumophila into HVAC system components. Biocides have been shown to be largely ineffective in reducing populations of L. pneumophila in cooling towers (Godish 1989, p 161).

Asbestos

As described in an earlier section, friable asbestos-containing material (ACM) has been widely used as a fire and heat retardant material in a variety of nonresidential buildings. Asbestos-containing building materials of all types have been banned for use in new construction by the USEPA, so asbestos contamination should not be a problem in new buildings.

The only permanent asbestos control method is to remove ACM. However, other options that can help reduce asbestos fiber exposure include: special building operation and maintenance practices, repair, enclosure, and encapsulation. Asbestos contamination is a very well studied and understood problem. A large body of information on asbestos control has been published by the USEPA (1981, 1985a, 1985b) for general distribution, and by the U.S. Army Construction Engineering Research Laboratories for U.S. Army distribution. Detailed information about asbestos control is available from these sources.

Ventilation Control

A common way to control the quality of indoor air is to use outside air to dilute indoor concentrations of air pollutants. This approach to indoor air quality relies on a relatively clean outside atmosphere and mechanisms to exchange air between the inside and outside of a building system and to distribute outdoor air throughout the building. The following sections discuss indoor air quality control by general and specific ventilation strategies.

General Ventilation

General ventilation refers to the overall rate of supplying a percentage of outdoor air to a building's HVAC system. Since ventilation replaces indoor air with outdoor air, this control strategy effectively dilutes indoor airborne contaminants at a rate dependent on the effective rate of ventilation and outdoor pollutant concentrations.

Ventilation requirements, such as those incorporated in ASHRAE Standard 62-1989 are intended to control the products of human metabolism and other contaminants under most circumstances (ASHRAE 1989). However, source control, air cleaning, and increased ventilation may also be required in the presence of strong sources. The ASHRAE requirements provide minimum outdoor air ventilation rates for specific building types and usage.

Local or Exhaust Ventilation

Local ventilation, also called exhaust ventilation, controls indoor air quality by providing ventilation near a pollutant source. Local ventilation provides a separate exhaust system for a plume of contaminants from a pollutant source. Local ventilation is widely used to exhaust combustion products and odors from cooking in cafeterias, and odor from lavatories. In office environments, local ventilation may also be applied to exhaust ammonia from blueprint machines, ozone from office copiers, methanol from spirit duplicators, and acetic acid, formaldehyde, and other vapors from photographic film processing. Considering the noxious gas produced by such equipment and processes, it is ironic that they commonly occupy the most poorly ventilated spaces in the building. Local ventilation can also be effective for the control of ETS in designated smoking areas (Bearg and Turner 1987, pp 334-337).

Demand-Induced Ventilation

A sensor may be used to trigger increased outdoor ventilation rates when levels of some specified contaminant reach or exceed a specified level. This technique attempts to balance the need for adequate indoor air quality, thermal comfort, and energy conservation by integrating indoor contaminant and temperature levels in one control mechanism.

A CO_2 sensor has been suggested for use in general office environments (Vaculik 1987, pp 244-251). However sensors for other pollutants may also be used, singly or in combination, depending on the circumstances. In a demonstration of air quality control using this strategy, for example, an office building air quality problem caused by a parking structure was corrected, in part, by a CO sensor used to increase ventilation rates when CO levels from the garage reached a preset threshold (Boelter and Monaco 1987, pp 41-46).

Ventilation Efficiency

The extent to which ventilation air reaches the breathing zone of building occupants is termed ventilation efficiency. The condition where a portion of the supply air bypasses an occupied zone is termed "short circuiting." Short circuiting prevents a portion of the supply air from diluting and carrying away indoor air contaminants. Short circuiting is less prevalent when supply outlets are located on the floor and return outlets are located on the ceiling. However, for economic reasons, supply and return air outlets are often both located in ceilings. Partitions erected in open office plans can also interrupt the flow of ventilation air.

Air Cleaning

Air cleaning involves the physical or chemical removal of pollutants from the indoor air. Three basic technologies have been developed: filtration, electrostatic precipitation, and gas or vapor sorption. Air-cleaning devices that use filtration or electrostatic precipitation remove particulate matter from the air while devices containing sorbents remove gas or vapor contaminants.

Particulate Matter Control Devices

Particulate matter (dust) is the most common type of indoor air contaminant removed by air cleaning. Dust may contain materials from outdoor sources (flyash, pollen, oil, soot, etc.) or indoor sources (tobacco smoke, fabric lint, fungal spores, bacteria, etc.). Many dust particles can adversely affect occupant health and comfort directly because of their pathogenic, allergenic, or toxic properties. Dust particles also can indirectly affect occupant health and comfort. Inhalation of dust particles can provide the means of exposure for microbial agents, condensed organic compounds, and radon progeny that become attached to the dust. The two primary air cleaning methods for indoor dust control are filtration and electrostatic precipitation.

Filtration. Filters are the most frequently used air-cleaning device for removing dust from indoor air. Filters consist of a mat of fibers oriented perpendicular to the direction of air flow. Filters collect particles through a combination of complex processes including interception, impaction, diffusion, and electrostatic deposition. Small dust particles tend to follow streamlines as air flows around filter fiber elements. Impaction occurs when relatively large particles, because of their inertia, cannot follow the streamlines and collide with filter fibers. Interception occurs when particles follow the streamlines around fibers but still come in contact with the fibers because of the converging streamlines. Collection by diffusion occurs when the random Brownian motion of very small particles, usually less than 1 μm, cause the particles to impinge upon the filter fibers. During the process of electrostatic deposition, particles, which naturally carry a small electrical charge, are attracted to fibers that are oppositely charged. The relative importance of this collection process in filtration is not well defined.

Filters create an initial resistance to air flow that gradually increases as the filter becomes clogged with collected dust. This resistance to air flow can be measured as a static pressure drop across the filter. As the filter becomes clogged and the pressure drop across the filter increases, more energy must be supplied to keep the air flowing at the required rate. Since dirty filters can result in decreased air flows and increased operating costs, it is important that operators of filtration systems regularly maintain and replace filters.

Three types of filters are generally available for indoor use: dry, viscous impingement, and charged media filters (Godish 1989, p 253). Any of these may be disposable or renewable panel filters. Renewable filters present a fresh filter surface as needed to maintain an acceptable pressure drop or cleaning efficiency. Filters are primarily used to filter the air in ducts of centralized HVAC systems. The filters may be designed to protect the air-handling unit's fan or may be designed to reduce indoor particulate concentrations. Filters are also used in modular free-standing devices used for local air cleaning of small spaces.

Dry-Type Panel Filters. These filters have low collection efficiencies. They are typically used to protect mechanical equipment in air-handling units and home furnaces, and as prefilters for higher efficiency filters. Dry-type panel filters collect larger particles by impaction and interception. Typical air velocities range from 200 to 700 ft/min*. Initial pressure drops are low (0.05 to 0.25 in. H_2O) and filters are kept in place until pressure drops reach 0.5 to 0.75 in. H_2O (Godish 1989, p 253). Dry panel filter media may consist of open-cell foams, textile cloth nonwovens, paperlike mats of glass or cellulose fibers, wood fill, etc. (ASHRAE 1988).

Viscous Media Panel Filters. These filters contain coarse fibers coated with an oily substance. The oil improves the filter's ability to collect large particles such as fabric dust or lint. However, these filters have a low efficiency for collecting the small particles found in dust. Typical operating velocities range from 300 to 600 ft/min and filter change is required when the pressure drop reaches 0.5 in. H_2O (Godish 1989, p 254).

Extended Surface Dry-Type Filters. The previously discussed filter types can all be described as low efficiency for the large fraction of small-size particles found in dust. More efficient filters must have a greater thickness and/or density. However, increasing filter thickness or density significantly increases the pressure drop across a filter for the same flow rate of air through the filter. The pressure drop problem can be overcome by increasing the surface area of the filter. In this way, the velocity of the air moving through the filter is reduced and pressure drops are lowered to acceptable levels. Pleating the filter media is a common way of extending the filter's surface area.

Extended media filters are available in a variety of designs and performance levels. The media is usually supported in a panel frame or box. The filter depth may vary from 2 to 36 in. in depth, or even more in special applications (ASHRAE 1988). Table 11 shows performance and efficiency ratings for various types of dry media filters.

*1 ft = 0.305 m; 1 in. = 25.4 mm.

Table 11

Performance Levels of Dry Media Filters

Filter Media Type	Arrestance (%)	Dust Spot Efficiency (%)	DOP Efficiency (%)	Dust Holding Capacity (g/1000 CFM Cell)
Fine open foams and textile denier nonwovens	70-80	15-30	0	180-425
Thin paperlike mats of glass fibers, cellulose	80-90	20-35	0	90-180
Mats of glass fiber, multiply cellulose, wool felt	85-90	25-40	5-10	90-180
Mats of 5- to 10-μm fibers, 0.25 to 0.5 in. (6-12 mm) thickness	90-95	40-60	15-25	270-540
Mats of 3- to 5-μm fibers, 0.25 to 0.5 in. (6-12 mm) thickness	>95	60-80	34-40	180-450
Mats of 1- to 4-μm fibers, mixture of various fibers	>95	80-90	50-55	180-360
Mats of 0.5- to 2.0-μm fibers (glass)	NA	90-98	75-90	500-1000
Wet laid papers of mostly glass fibers, <1-μm diameter (HEPA)	NA	NA	95-99.999	500-1000
Membrane Filters (Cellulose, acetate, nylon) having holes ≤1μm in diameter	NA	NA	~100	NA

Source: ASHRAE 1988, pp 10.1-10.12.

Electronic Air Cleaners. Electronic air cleaners use the same principle of operation as industrial electrostatic precipitators. Most electronic air cleaners work in two stages. In the first stage, particles in the air are charged by thin high voltage wires oriented perpendicular to the flow. The high voltage applied across the wires produces a corona discharge that applies the positive charge to the passing particles. In the second stage, negatively charged plates attract the charged particles and collect them (Figure 23).

Electronic air cleaners typically operate at efficiencies well below their theoretical capability. A major factor in this less than theoretical operation is "sneakage" of particles through the electronic air cleaner. Sneakage can occur when a portion of the airflow does not pass through an effective charging or collection area. Researchers recently demonstrated dramatic improvements in collection efficiency when sneakage through an electronic air cleaner was prevented (Hanley et al. 1960).

Electronic air cleaners have a low resistance to air flow when compared to filters. The small pressure drops across these devices produce lower fan power requirements and operating costs. Maintenance is limited to cleaning the collection plates. Frequency of cleaning will depend on dust loading. Buildup of material on the collection plate will result in declining collection efficiencies.

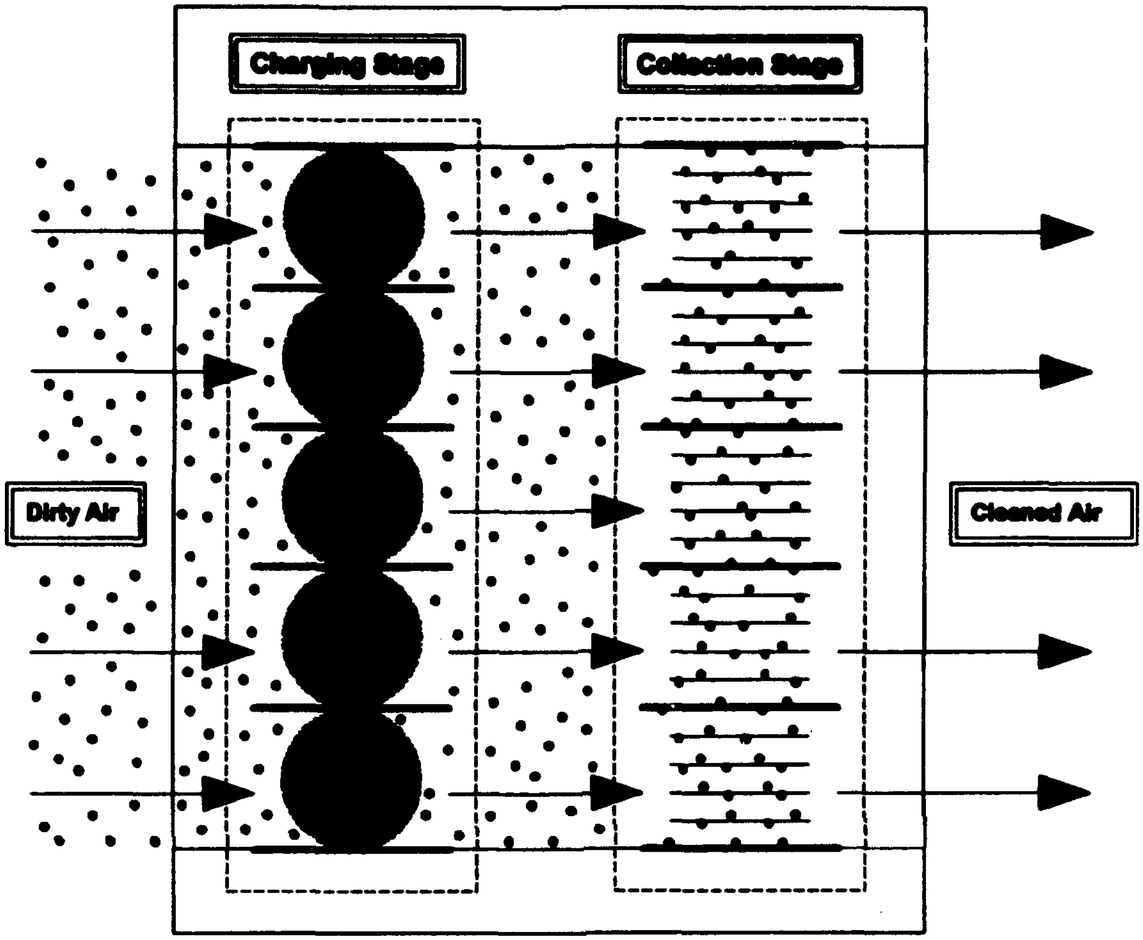


Figure 23. Two-Stage Electronic Air Cleaner Operation.

Performance Testing for Dust Control Devices. ASHRAE Standard 52-76 describes methods of testing the performance of particle collection devices (ASHRAE 1976). The ASHRAE testing protocol describes two measures of performance: arrestance and dust spot efficiency. Arrestance is the percentage of a standardized synthetic dust that is removed from an air stream by the collection device. Arrestance is a measure of a device's ability to remove relatively large particles. Dust spot efficiency measures the ability of a collection device to remove particles capable of soiling surfaces. This soiling property is associated with small particles found in dust.

The ASHRAE dust spot method is not intended to rate the performance of collection devices with efficiencies greater than 98 percent. For these devices, the di-octyl phthalate (DOP) smoke penetration method is most often used. This method measures the concentration of a smoke of essentially uniform DOP particles before and after the particle collection device. The particle diameter is 0.3 μm, with a cloud density of 80 mg/m^3 (Godish 1983, p 265).

Gaseous Contaminant Control Devices

The principles of absorption, thermal oxidation, catalytic oxidation or reduction, and adsorption are all used to control gaseous contaminant emissions from industrial processes. Of these only the principle of adsorption has been widely applied to indoor air cleaning devices. The following discussion focuses on these devices.

Adsorption. Adsorption is the adherence of gases, vapors, or liquids to a solid surface. The adherence is due to the same physical forces that hold atoms, molecules, and ions together in a solid state. The surfaces of solids exist in a state of unbalanced forces. Residual forces at the surface of a solid have the potential of holding molecules to the surface of the solid in an attempt to satisfy the unbalanced surface condition. The solid surface is called the adsorbent, and the substance attracted to the solid surface is called the adsorbate. Adsorbents used for gas cleaning typically have very porous structures and therefore large exposed areas capable of gas sorption.

Two basic types of adsorption are generally recognized: physical adsorption and chemisorption. Physical adsorption occurs as the result of the attractive forces between the molecules of the solid surface of the adsorbent and adsorbate. No chemical bond exists between the substances, and the adsorbate can be removed from the adsorbent in unchanged form. Chemisorption, however, is the result of a chemical interaction between the adsorbate and adsorbent. The adhesive force is generally much greater than in physical adsorption, and on desorption, the original substance will often have undergone a chemical change. Many cases of adsorption can be classified as purely physical adsorption or chemisorption. A continuum exists between the two types of adsorption, and in many cases, both processes occur at the same time.

Physical Adsorption. Activated carbons are the most commonly used adsorbents for indoor air cleaning. They remove contaminant gases primarily through physical adsorption. Activated carbons differ in their structural properties and their performance as adsorbents. In general, the ability of activated carbons to adsorb gases and vapors increases with the adsorbate's molecular size and weight. Gases such as oxygen, nitrogen, carbon monoxide, and methane are not adsorbed at room temperatures. Somewhat heavier gases such as ethylene, formaldehyde, ammonia, hydrogen chloride, and hydrogen sulfide are only moderately adsorbable at room temperature. Higher molecular weight, higher-boiling point vapors (above 0 °C) are well adsorbed (Godish 1983, p 284).

Adsorption in a fixed bed of activated carbon does not take place uniformly throughout the bed. A bed of activated carbon will contain a number of adsorption zones. The saturation zone is an area completely saturated with adsorbed material. At the edge of the saturation zone begins the adsorption zone. In the adsorption zone, adsorbate concentrations rapidly decrease as the material is adsorbed. All the adsorbate is essentially collected in this zone. At the end of the bed is a zone where little adsorption takes place since there is little adsorbate left to collect. The adsorption zone progressively moves along the bed with time. When the adsorption zone reaches the end of the bed, breakthrough occurs and the carbon bed reaches the end of its useful life.

Chemisorption. Physical adsorption is sometimes supplemented by chemisorption. The large internal surface area of sorbents can be impregnated with specialized chemicals. These chemicals can selectively react with and retain indoor air pollutants within the sorbent.

Activated carbons and activated alumina are often used to produce chemisorptive media. Impregnating activated carbons with certain chemicals can increase their ability to adsorb specific lighter gases such as formaldehyde, hydrogen sulfide, and ethylene. Carbon impregnants include bromine, metal oxides, elemental sulfur, iodine, potassium iodide, and sodium sulfide (Godish 1983, p 292). Activated alumina impregnated with potassium permanganate ($KMnO_4$) is widely used in air-cleaning systems. This material is able to effectively remove a number of indoor air contaminant gases and vapors. The contaminants are sorbed on the surface of the activated alumina where the $KMnO_4$ oxidizes them on a thin film of water (Turk 1977, pp 329-363).

IAQ Modeling

The ultimate goal of IAQ modeling is to predict the exposure of building occupants to indoor air contaminants. Many modeling techniques must be used to arrive at this prediction. The concentration of indoor air contaminants is a function of the location of emission sources, the emission rates from these sources, the dispersion of the contaminant, the removal rate of the contaminant, and the complex flow fields between the sources and human receptors. Personal exposure depends on the concentrations of contaminants and the probabilities of individuals being at a particular location and time. Modeling techniques include Source and Sink Modeling, Flow Field Modeling, and Concentration and Exposure Modeling.

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