The Building Environment
The Building Environment: Active and Passive Control Systems

THIRD EDITION

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This book is an introductory survey of the broad field of mechanical/electrical/plumbing (MEP) systems in buildings. It is intended to provide students of architecture with the information necessary to make proper provisions and allowances for these systems in their building designs.

Architects used to be responsible for designing entire buildings, including the heating and ventilation (usually steam radiators and operable windows), lighting, and power systems. These systems were much simpler than their sophisticated modern counterparts. With the advent of more and more complex systems, specialist consultants (structural, mechanical, electrical, civil engineering, fire protection, acoustical, lighting, elevator, etc.) are now usually required to design and handle the details of these technologies. Architects today find themselves more in the position of managing a team of engineers and other consultants than of designing entire buildings themselves.

Textbooks on building technologies, which have traditionally taught architects to be proficient in all the disciplines, have become unwieldy and cumbersome in their attempts to remain comprehensive. They contain much more detail and depth than is necessary for today’s architects, and as a result, many students lose the essential overview.

This book, a departure from that tradition, provides a nontechnical treatment of the physical principles and equipment related to building control systems. Only the pertinent aspects of HVAC, electrical, lighting, plumbing, and acoustical systems are covered. The higher mathematics used by specialist consultants in each field are, for the most part, avoided, and the text concentrates on concepts in order to give students an appreciation of the larger picture without getting bogged down in details.

The general purpose of this book is to provide only the information that an architect, as generalist and “orchestrator,” needs to communicate and coordinate with the consultants in all of the many disciplines. Detailed information and procedures for sizing and specifying mechanical and electrical systems are not included. Rather, the book emphasizes the conceptual understanding of the functions of the various systems and how they interact with the other building components. Items of equipment are regarded simply as “black boxes” having a given function.

The reader should come away with (1) an understanding of the environmental requirements of buildings, (2) a general sense of the systems and equipment typically used to satisfy those requirements, (3) an awareness of passive alternatives, (4) an awareness of the need to allow space and access for the necessary systems and equipment during the conceptual stages of design development, and (5) enough of a working knowledge of the terminology and requirements (spatial and structural) to ask the right questions of the consultants and, on occasion, to direct a mechanical or electrical contractor on projects too small to justify hiring an engineer.

Those interested in designing building control systems are referred to the bibliography at the end of each chapter. The references listed provide more detailed literature on specific topics. In addition, the end of each chapter contains a chapter summary, a list of key words, and study questions intended to stimulate thinking about, and retention of, the information presented.

ORGANIZATION

The book is organized into five parts. Part One presents the theoretical bases for thermal control, including the concepts of comfort, heat transfer, psychrometrics, building heat gains and losses, thermal mass, and condensation problems. It concludes with a chapter on load and energy-use calculations. The procedures presented in that chapter, based on the theory presented in the preceding chapters, are intended to demonstrate
the magnitude of the energy consequences of design decisions and material selections. All the necessary tables and charts from ASHRAE and other sources are included in the appendix at the back of the book for convenient reference.

Part Two describes the systems, both active and passive, used to control the thermal environment within buildings. It also addresses the environmental impact from active systems and how passive systems can be used to mitigate some of the environmental problems. Passive environmental control is dealt with only in a cursory way, not because it is unimportant (quite the contrary), but because this subject can take up many volumes in itself. Good reference works on the subject, listed at the end of Chapter 7, are readily available. The objective here is to provide a survey of the passive alternatives to active building control systems.

Part Three concentrates on electrical systems, including power and lighting, on-site generating systems, signal and communication systems, and conveying systems. Natural daylighting is included in the chapter on lighting.

Part Four covers the other piped systems in buildings (outside of HVAC): plumbing services and fire protection.

Part Five presents support services that can apply to all of the systems described in Parts Two, Three, and Four. These are noise control, building commissioning, and methods for making design decisions based on economics. With today’s high cost of maintenance and energy, the owning and operating costs of a building often overshadow the initial costs. The procedures introduced in Chapter 16 show how to make simple comparisons of life-cycle costs.

RECOMMENDATIONS FOR CLASSROOM USE

This book is intended to be a source of basic background information, which should be supplemented with classroom discussions and examples appropriate to the instructor’s emphasis. I have deliberately avoided filling up the book with specific examples of design solutions because it is impossible to include the number of examples necessary to cover all aspects of each subject. Instead, I have kept information general and inclusive. Class time can be used to answer questions, add specific information from the instructor’s own experience, go over examples of actual installations to clarify the concepts, and provide students with an opportunity to practice what they have learned.

The scope and depth of this book are appropriate for a well-rounded survey curriculum of one or two semesters (one to three quarters). Supplementary textbooks are recommended for more in-depth coverage of passive systems, lighting, acoustics, and energy where these subjects are especially emphasized or taught as separate courses. Appropriate specialized books may be selected from the bibliographies at the ends of the chapters.

OTHER USES

Although this book is directed to students of architecture and construction technology, it may also prove useful for building owners, designers, financiers, and others interested in how building control systems work. It is written primarily for instructional purposes, but the information is organized so that it can also serve the reader as a practical reference. Those who might benefit from it include architects, builders, developers, contractors, beginning HVAC designers and engineering students, building managers, and homeowners. While the book does not contain enough technical detail to be used as an engineering design manual on all subjects, it is useful as an overview for engineers and designers just entering the field.

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The cost of fossil fuels is of increasing concern to building users. It is also becoming increasingly evident that human activities are adversely affecting the global environment in significant ways. A new chapter accordingly has been added on the effect that buildings have on the environment. It includes discussions of ozone depletion, global warming, energy conservation, and green design or sustainable design.

Another new chapter has been added that addresses the subject of building commissioning, which helps to ensure the effectiveness of energy-conserving features included in a building’s design.

In addition, most of the photographs of fixtures and equipment have been updated, and the bibliographies at the end of each chapter also have been updated. Finally, improvements have been incorporated in response to a number of very useful comments from users of the book.

A NOTE ABOUT SI UNITS

The metric system originated in France and was adopted there during the French Revolution. It gradually gained
acceptance throughout Europe and in the French and Spanish colonies, and in 1875 the United States joined 16 other countries in signing the Treaty of the Meter. A revised metric system was introduced in 1960, named Système Internationale d’Unités (SI). Almost every country in the world has now committed to this universal system of units, which reduces the risk of mathematical errors.

In the United States, the Metric Conversion Act of 1975 prescribed a gradual voluntary conversion to SI units. U.S. industry, while reluctant to change, has begun shifting to SI units as the emphasis on foreign trade has increased. Several states already record surveys and plat plans in metric. The major organizations for building professionals, including ASHRAE and AMCA, are in the process of gradually shifting to metric units in their standards and publications.

The momentum of conversion to SI units in the United States is growing, but the English or inch-pound system of units is still in common usage. For that reason, all units in this book are still presented in English units with their equivalence in SI units following in parentheses.


The following table lists the numerical value of the standard metric prefixes. Appendix Table A1 lists equivalents of common English and SI units.

### SI PREFIXES

<table>
<thead>
<tr>
<th>Multiplying Factor</th>
<th>Prefix</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 000 000 000 000 = 10^{12}</td>
<td>tera</td>
<td>T</td>
</tr>
<tr>
<td>1 000 000 000 = 10^9</td>
<td>giga</td>
<td>G</td>
</tr>
<tr>
<td>1 000 000 = 10^6</td>
<td>mega</td>
<td>M</td>
</tr>
<tr>
<td>1 000 = 10^3</td>
<td>kilo</td>
<td>k</td>
</tr>
<tr>
<td>100 = 10^2</td>
<td>hecto</td>
<td>h</td>
</tr>
<tr>
<td>10 = 10^1</td>
<td>deka</td>
<td>da</td>
</tr>
<tr>
<td>0.1 = 10^{-1}</td>
<td>deci</td>
<td>d</td>
</tr>
<tr>
<td>0.01 = 10^{-2}</td>
<td>centi</td>
<td>c</td>
</tr>
<tr>
<td>0.001 = 10^{-3}</td>
<td>milli</td>
<td>m</td>
</tr>
<tr>
<td>0.000 001 = 10^{-6}</td>
<td>micro</td>
<td>µ</td>
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<tr>
<td>0.000 000 001 = 10^{-9}</td>
<td>nano</td>
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</tr>
<tr>
<td>0.000 000 000 001 = 10^{-12}</td>
<td>pico</td>
<td>p</td>
</tr>
</tbody>
</table>

*These prefixes are not normally used.*
A building’s form is an expression of the creativity and inspiration of the architect in response to the client’s objectives, under the limitations of the constraints imposed. The initial objectives typically include a projected building size and the intended functions of the facility. Limitations have traditionally been imposed by the local site characteristics of topography, orientation, and climate; the budget; owner preferences; and the legal conditions of building codes and zoning restrictions in the area. Today energy efficiency must be added as another strong influence on the design. During the design process, careful consideration must be given to the selection of building and system components with regard to energy efficiency.

Another related issue that must now be addressed is the selection of the energy source(s) for a building. In general, the energy resources we currently have available are solar, geothermal, fossil fuels, tidal, and nuclear. Solar energy accounts for 99.9776 percent of the total available. Wind, wood, alcohol (from plant biomass), and hydropower are all created by solar energy, and are considered renewable because they are continually being replenished.

Renewable fuel resources are available indefinitely but at a finite rate of replenishment. While the influx of solar energy varies from day to day at any given location on the planet, it supplies the earth as a whole at a relatively steady rate, and will continue to do so for the conceivable future. For example, a wood lot produces a limited amount of wood fuel each year, but it will repeat its production year after year if properly managed. Renewable fuels are analogous to a fixed but steady monetary income, such as a salary with no raises. By contrast, nonrenewable fuels are like savings accounts that draw no interest; once spent, they are gone.

The sun is also the ultimate source of fossil fuels, but the difference is that coal, oil, and natural gas are fossilized solar energy, collected and stored over hundreds of millions of years. Once they are used up, it will take a similar length of time for them to be replenished. For this reason, fossil fuels are called nonrenewable resources.

Technically, nuclear fission fuels and geothermal reserves are also exhaustible, but at the rate of current use, the supply is for all intents and purposes as limitless as solar energy itself.

Electricity can be generated from virtually any of these forms of energy. In the United States today, the vast majority is produced from coal, oil, and natural gas. Hydropower and nuclear power—although predominant in some regions—each carry only a minor share of the load nationwide. There are also a few solar thermal, solar photovoltaic, wind power, and geothermal power plants in operation.

Historically, the dominant fuel resource has shifted. Initially, human beings probably relied exclusively on renewable fuel resources: the sun directly for heat and light, supplemented by burning wood at night and on cold days. More sophisticated technology brought the use of the wind for transportation, processing (grinding grains), and other industrial purposes. The power in free-flowing streams and rivers was also tapped for stationary industries.

Before the nineteenth century, wood was used for most fuel needs. With mineral discoveries and mining, the vast reserves of fossil fuels (coal, petroleum, natural gas) became available, offering the advantages of portability, convenience, and reliability.

The 1800s saw the infancy of the coal industry. By the 1900s, coal had taken over as the predominant fuel. At the same time, hydropower and natural gas first began to be used on a significant scale. By 1950, petroleum and natural gas (cleaner-burning fuels) had taken the lead. Natural gas and petroleum presently have about even shares of the market, while coal use in buildings has been declining. Most of the coal currently consumed is for electricity generation and heavy industrial processes, where the problems of fuel storage and air pollution can be centrally
treated. Notwithstanding modern techniques for scrubbing and filtering out sulfur ash from coal combustion emissions, many large cities currently place limits on coal use in individual buildings.

Nuclear power has entered the fuel mix since the 1950s. A number of factors, however, render the future of nuclear power questionable. These include (1) the economics relating to long construction periods and the need to contain extremely high temperature, pressure, and radioactivity levels during operation, as well as (2) some serious public safety issues related to the normal release of low-level radiation over long periods of time and the risks of accidental high-level releases. The cost and safety considerations inherent in nuclear power limit its civilian use to research and electricity generation by utility companies.

As recently as 1950, the United States was completely energy self-sufficient; our power needs were easily met with relatively cheap and abundant domestic fuels—first with coal, and then increasingly with oil and natural gas—along with hydroelectric power. Since then, as demand has grown, our reliance on imports of crude oil and petroleum products has steadily risen.

Since 1973, the price of oil has fluctuated widely in response to geopolitical forces and increasing demand around the world. When the price is high, energy conservation and alternative energy resources are on people’s minds, and when the price drops, those interests are displaced by other matters.

But the instability of petroleum prices makes fiscal planning for building operations difficult, and when energy costs rise sharply, it has a significant impact on cash flow. Most building owners and developers have responded by placing a priority on energy efficiency to minimize the effect of energy cost increases. In addition, energy conservation standards are now included in virtually all building codes in the United States.

When fossil fuels began to be used the reserves seemed limitless, so no attempts were made to manage them for the most intelligent long-term benefit. Instead, their use was simply dictated by immediate economic factors such as the labor cost of mining, distribution costs, and the supply and demand forces. In fact, it was only in the latter half of the twentieth century that scientists tried to draw attention to the limitations in the fuels we rely upon so heavily.

The fact is that the worldwide supply of nonrenewable resources is dwindling, and energy costs will assuredly tend to rise over the long term. The exact amount of reserves of nonrenewable fuel resources is not known for sure. Two things, however, are certain: (1) there is a fixed limit to the nonrenewable fuel reserves, and (2) we are using them up at an ever-increasing rate. And regardless of how much is still in the ground, it will become increasingly expensive, and in some cases environmentally objectionable, to extract the remaining amounts.

The obvious ramification to this is that buildings built today with a 50-year functional life and 100-year structural life may very well outlast the supplies of fossil fuels. Designers are thus faced with the following challenges:

1. Use the minimum energy that can be justified by current economic conditions.
2. Design buildings so that they can eventually be weaned away from dependence upon nonrenewable fuels.
3. Use only a “fair share” of renewable fuels, recognizing that such resources are limited even if they continue to be available.

Building designs emphasizing energy conservation and the substitution of renewable for nonrenewable energy sources can have a significant impact. About 35 percent of all energy used in the United States is consumed directly in buildings; another 6 percent is consumed off-site in support facilities such as those for sewage treatment, water supply, and solid waste management; and approximately 7 percent more is used to process, produce, and transport materials used for building construction. Altogether, about 48 percent of all energy used is in and for buildings.

There are many ways of improving energy efficiency in buildings. It is the responsibility of a building’s occupants to operate it in an energy-conserving way, but the occupants can only operate within the capabilities provided by the building’s designers. It is ultimately up to the designers to provide the building’s owners and occupants with the advantage of the most energy-efficient building feasible. Not only is this a service from an economic standpoint, it will prevent the building from becoming obsolete in the future due to high energy costs.

The purpose of constructing buildings is to provide an artificial environment that is aesthetically appropriate and more conducive to the intended process or human occupancy than the natural environment. This implies, among other things, the maintenance of thermal and atmospheric conditions in enclosed spaces that differ from those existing concurrently outdoors. These conditions are controlled by the characteristics of the enclosure’s envelope (as conceived by the architect) and the equipment serving it (as devised by the engineers).

Traditionally, the building envelope has been regarded as a “barrier” separating the interior from the outdoor environment. The architect provided an isolated environment, and
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the engineers equipped it with energy-using devices to control the conditions. Now the need to conserve energy has brought a reevaluation of the envelope’s role, and it is conceived increasingly as a dynamic boundary, interacting with both external natural energy forces and the internal building environment. The concept of the envelope is evolving into that of an energy mediator—sensitively attuned to the indigenous natural resources of sun, wind, and water. These are viewed as resources to be manipulated in order to balance the energy flows between inside and outside, rather than as environmental intruders. The architect has the first crack at providing the proper thermal and lighting conditions by using the structure itself. Any remaining needs must be satisfied by the mechanical/electrical systems.

An important aspect of mechanical and electrical systems is that they use energy; the greater the dependency upon them, the more energy is consumed by the building. By displacing them with passive control mechanisms in the envelope itself, energy consumption can be minimized.

Architects are being called upon to provide new solutions to these new design challenges. Energy-conscious design requires that the total energy use of the building be thought out from its inception. The superior design is one that meets aesthetic, cost, and performance requirements in an elegant, energy-efficient manner.

The sophistication involved in energy-conscious design requires a team effort. The best solution to the control problem is arrived at through the close coordination of the entire design team from the earliest stage. The design process must be a cooperative effort between architects and engineers. Engineers can provide efficient equipment and systems, but in a sense, the control systems can only respond to the architectural decisions. While the mechanical system designer determines the efficiency of the equipment that consumes the energy, the building designer influences the extent to which that equipment must be operated. Thus, a finely tuned, energy-efficient structure requires close cooperation among all the disciplines.

But energy efficiency is not the only reason that engineers should be represented in the preliminary stage of design. Many building mistakes can be avoided by early communication. Just as a building must work architecturally, it must work mechanically, and the two are inextricably linked. Even though mechanical equipment is generally concealed and unnoticed until it doesn’t work, attention must be paid to the requirements that are crucial for proper operation. A beautiful building with a reputation for poor comfort conditions is less marketable.

In other words, rather than being considered as additional equipment to make an architectural design work, the mechanical and electrical control systems of a building should be considered integrally with the initial planning. They can have a strong bearing on the optimum form, location on a site, and orientation of a building. Any design can be made to work in terms of the thermal environment, lighting, plumbing, and acoustics—given enough money, and sometimes with a compromise of the original architecture. But by integrating their needs from the beginning, the most economical and elegant solution can be obtained.

Altogether, the design team should expect to spend increasing amounts of time considering strategies to reduce energy consumption in their buildings. The more scarce non-renewable fuels get, the more expensive they will get. It is to everyone’s advantage to create buildings that use fuels as efficiently as possible. The most efficient and self-sufficient buildings will only increase in value in the future.

Many clients today come to an architect with energy efficiency as a criterion. Others may not have considered it or don’t believe they can afford it. Considering the importance of energy in every building’s future, it is imperative that creative design make each building as energy efficient as possible within the program and budget constraints.
Energy conservation should not be regarded as cutting back on comfort conditioning to the limit of what the occupants can bear. The technology is available for maintaining perfectly acceptable comfort conditions at energy consumption levels much lower than those currently experienced. Sometimes, by taking advantage of innovative technology and new design concepts, and by applying a measure of creativity and imagination, this can be accomplished at little or no additional cost, and in some cases, it may actually be less expensive. But first, some basic information is needed to creatively apply energy-efficient innovations.

Chapter 1 covers occupant comfort, including thermal comfort, air quality, and air quantity. The chapter is intended to instill a sensitivity to comfort issues. Under most circumstances, standard design practices are sufficient, but it is important to be aware of what conditions need further attention.

Since heat loss plays a crucial role in maintaining the body’s thermal equilibrium, Chapter 2 elaborates on the physical principles of this interactive process in order to provide a basis for designing an environment that satisfies the objectives of comfort and health. A procedure is introduced for calculating the rate of heat flow. This knowledge of the fundamentals of heat transfer theory will be applied to buildings in Chapter 3, and will be used as the basis for learning how to perform building heat loss, heat gain, and energy use calculations in Chapter 4. Radiation heat transfer, in particular, will be important in the subject of solar energy utilization in Chapters 6 and 7.
Chapter 2 also includes an elaboration of psychrometrics and an introduction to the psychrometric chart. This information will be useful in understanding the sources of moisture problems discussed in Chapter 3. It will also be important background for the load calculations in Chapter 4 and the mechanical systems for heating, ventilation, and air conditioning in Chapter 6.

Chapter 4, the only one that is extensively numerical, is intended to give the reader a quantitative sensitivity to the various factors involved. It is more detailed than necessary for estimating building loads in standard practice. Readers are encouraged to develop their own rules of thumb and simplified procedures based on their own experience. The simplifications previously used are, for the most part, no longer accurate, since changing insulation standards, increasing attention to sealing air leaks, higher internal gains, use of passive solar heating, and increasing energy costs have invalidated old assumptions. Architects typically do not need to perform these kinds of calculations except for optimizing insulation levels and the number of panes in windows, for occasional sizing of residential heating and cooling systems, or for special energy-integrated designs. It is important to go through the exercise, however, in order to develop a general understanding of how design decisions influence energy consumption.
Human Comfort and Health Requirements

COMFORT CONDITIONS
HUMAN PHYSIOLOGY
HEAT VS. TEMPERATURE
BODY TEMPERATURE CONTROL
HEAT BALANCE
EVAPORATION
RADIATION
CONVECTION-CONDUCTION
COMBINED EFFECTS
METABOLISM
CLOTHING
ENVIRONMENTAL FACTORS
DRY-BULB TEMPERATURE
HUMIDITY
MEAN RADIANT TEMPERATURE
AIR MOVEMENT

THERMAL COMFORT STANDARDS
THERMAL INDICES
THE COMFORT CHART
ASHRAE’S THERMAL COMFORT STANDARD
DESIGN CONSIDERATIONS
INDIVIDUAL VARIABILITY
TEMPERATURE AND HUMIDITY EXTREMES
HEAT STRESS
RESPONSE TO EXTREME COLD
AIR QUALITY AND QUANTITY
AIR CONTAMINANTS
ODORS
VENTILATION
Thermal and atmospheric conditions in an enclosed space are usually controlled in order to ensure (1) the health and comfort of the occupants or (2) the proper functioning of sensitive electronic equipment, such as computers, or certain manufacturing processes that have a limited range of temperature and humidity tolerance. The former is referred to as comfort conditioning, and the latter is called process air conditioning. The conditions required for optimum operation of machinery may or may not coincide with those conducive to human comfort.

Process air conditioning requirements are highly specific to the equipment or operation involved. Specifications are generally available from the producer or manufacturer, and the ASHRAE Handbook of Applications provides a description of acceptable conditions for a number of generic industrial processes.

Once the necessary conditions for process or machinery operation are established, attention must be paid to providing acceptable comfort, or at least relief from discomfort or physiological stress, for any people also occupying the space.

Although human beings can be considered very versatile “machines” having the capacity to adapt to wide variations in their working environment while continuing to function, their productivity does vary according to the conditions in their immediate environment. Benefits associated with improvements in thermal environment and lighting quality include:

- Increased attentiveness and fewer errors
- Increased productivity and improved quality of products and services
- Lower rates of absenteeism and employee turnover
- Fewer accidents
- Reduced health hazards such as respiratory illnesses

Indeed, in many cases, air conditioning costs can be justified on the basis of increased profits. The widespread availability of air conditioning has also enabled many U.S. companies to expand into the Sun Belt, which was previously impractical.

Air conditioning and electric lights have eliminated the need for large windows, which provided light and ventilation in older commercial and institutional buildings. Although windows are still important for aesthetics, daylighting, and natural ventilation, windowless interior spaces may now be used to a much greater extent. Air conditioning allows for more compact designs with lower ceilings, fewer windows, less exterior wall areas, and less land space for a given enclosed area. Conditioned air, which is cleaner and humidity-controlled, contributes to reduced maintenance of the space. As a testament to the importance placed on air conditioning, over one-third of the entire U.S. population presently spends a substantial amount of time in air-conditioned environments. And all of this represents growth since the commercialization of refrigeration cooling in the early 1950s.

On the other hand, this improvement in comfort has come about at the expense of greater equipment installation, maintenance, and energy costs. A substantial portion of the energy consumed in buildings is related to the maintenance of comfortable environmental conditions. In fact, approximately 20 percent of the total U.S. energy consumption is directed toward this task.

But this doesn’t have to continue to be the case. With an understanding of the factors that determine comfort in relation to climate conditions, designers may select design strategies that provide human comfort more economically. Thus, prior to investigating the energy-consuming mechanical systems in buildings, we will begin by discussing the concepts of human comfort.

**Comfort Conditions**

Besides being aesthetically pleasing, the human environment must provide light, air, and thermal comfort. In addition, proper acoustics and hygiene are important. Air requirements and thermal comfort are covered in this chapter, while illumination and acoustical considerations will be presented in later chapters.

Comfort is best defined as the absence of discomfort. People feel uncomfortable when they are too hot or too cold, or when the air is odorous and stale. Positive comfort conditions are those that do not distract by causing unpleasant sensations of temperature, drafts, humidity, or other aspects of the environment. Ideally, in a properly conditioned space, people should not be aware of equipment noise, heat, or air motion.

The feeling of comfort—or, more accurately, discomfort—is based on a network of sense organs: the eyes, ears, nose, tactile sensors, heat sensors, and brain. Thermal comfort is that state of mind that is satisfied with the thermal environment; it is thus the condition of minimal stimulation.
of the skin’s heat sensors and of the heat-sensing portion of the brain.

The environmental conditions conducive to thermal comfort are not absolute, but rather vary with the individual’s metabolism, the nature of the activity engaged in, and the body’s ability to adjust to a wider or narrower range of ambients.

For comfort and efficiency, the human body requires a fairly narrow range of environmental conditions compared with the full scope of those found in nature. The factors that affect humans pleasantly or adversely include:

1. Temperature of the surrounding air
2. Radiant temperatures of the surrounding surfaces
3. Humidity of the air
4. Air motion
5. Odors
6. Dust
7. Aesthetics
8. Acoustics
9. Lighting

Of these, the first four relate to thermal interactions between people and their immediate environment. In order to illustrate how thermal interactions affect human comfort, the explanation below describes the body temperature control mechanisms and how environmental conditions affect them.

**HUMAN PHYSIOLOGY**

**Heat vs. Temperature**

The sense of touch tells whether objects are hot or cold, but it can be misleading in telling just how hot or cold they are. The sense of touch is influenced more by the rapidity with which objects conduct heat to or from the body than by the actual temperature of the objects. Thus, steel feels colder than wood at the same temperature because heat is conducted away from the fingers more quickly by steel than by wood.

As another example, consider the act of removing a pan of biscuits from an oven. Our early childhood training would tell us to avoid touching the hot pan, but at the same time, we would have no trouble picking up the biscuits themselves. The pan and biscuits are at the same temperature, but the metal is a better conductor of heat and may burn us. As this example illustrates, the sensors on our skin are poor gauges of temperature, but rather are designed to sense the degree of heat flow.

**Heat**

By definition, heat is a form of energy that flows from a point at one temperature to another point at a lower temperature. There are two forms of heat of concern in planning for comfort: (1) sensible heat and (2) latent heat. The first is the one we usually have in mind when we speak of heat.

**Sensible Heat.** Sensible heat is an expression of the degree of molecular excitation of a given mass. Such excitation can be caused by a variety of sources, such as exposure to radiation, friction between two objects, chemical reaction, or contact with a hotter object.

When the temperature of a substance changes, it is the heat content of the object that is changing. Every material has a property called its specific heat, which identifies how much its temperature changes due to a given input of sensible heat.

The three means of transferring sensible heat are radiation, convection, and conduction. All bodies emit thermal radiation. The net exchange of radiant heat between two bodies is a function of the difference in temperature between the two bodies. When radiation encounters a mass, one of three things happens: (1) the radiation continues its journey unaffected (in which case it is said to be transmitted), (2) it is deflected from its course (in which case it is said to be reflected), or (3) its journey comes to an end (and it is said to be absorbed). Usually, the response of radiation to a material is some combination of transmission, reflection, and absorption. The radiation characteristics of a material are determined by its temperature, emissivity (emitting characteristics), absorptivity, reflectivity, and transmissivity.

**Conduction** is the process whereby molecular excitation spreads through a substance or from one substance to another by direct contact. Convection occurs in fluids and is the process of carrying heat stored in a particle of the fluid to another location where the heat can conduct away. The heat transfer mechanisms of radiation, conduction, and convection are elaborated on in Chapter 2.

**Latent Heat.** Heat that changes the state of matter from solid to liquid or liquid to gas is called latent heat. The latent heat of fusion is that which is needed to melt a solid object into a liquid. A property of the material, it is expressed per unit mass (per pound or per kilogram). The latent heat of vaporization is the heat required to change a liquid to a gas. When a gas liquefies (condenses) or when a liquid solidifies, it releases its latent heat.

**Enthalpy.** Enthalpy is the sum of the sensible and latent heat of a substance. For example, the air in our ambient envi-
ronment is actually a mixture of air and water vapor. If the total heat content or enthalpy of air is known, and the enthalpy of the desired comfort condition is also known, the difference between them is the enthalpy or heat that must be added (by heating and humidification) or removed (by cooling and dehumidification).

**Units.** The common measure of quantity of heat energy in the English system of units is the British thermal unit (Btu). It is that heat energy required to raise 1 pound of water 1 degree Fahrenheit. The rate of flow of heat in these units is expressed in Btu per hour (Btuh).

In the International system of units (SI units), the corresponding measure is the joule. The rate of heat flow in SI units is joules per second, or watts (W).

**Temperature**

Temperature is a measure of the degree of heat intensity. The temperature of a body is an expression of its molecular excitation. The temperature difference between two points indicates a potential for heat to move from the warmer to the colder point.

The English system of units uses the Fahrenheit degree scale, while in SI units the Celsius degree scale is used. Note that temperature is a measure of heat intensity, whereas a Btu or joule is a measure of the amount of heat energy.

The dry-bulb temperature of a gas or mixture of gases is the temperature taken with an unwetted bulb that is shielded from radiant exchange. The familiar wall thermometer registers the dry-bulb temperature of the air.

If a thermometer bulb is moistened, any evaporation of water extracts sensible heat from the air surrounding the bulb. The sensible heat vaporizes the water and becomes latent heat. The exchange of sensible for latent heat in the air does not change the total heat content, but the air temperature is lowered. Thus, a thermometer with a wetted bulb (such as that shown in Figure 1.9) indicates a lower temperature than a dry-bulb thermometer. The drier the air, the greater the exchange of latent for sensible heat, making the wet-bulb temperature correspondingly lower.

The wet-bulb temperature is therefore a means of expressing the humidity of air. Dry- and wet-bulb temperatures that are the same indicate that the air has already absorbed all the water vapor it can hold, no evaporation can take place, and the percentage humidity is 100 percent. By comparing dry- and wet-bulb temperature readings, one can determine the level of humidity in the air. The larger the temperature difference, the lower the humidity.

The capability of air to hold moisture depends on the dry-bulb temperature. The higher the temperature, the more moisture the air can hold. Thus, as a mixture of air and water vapor is cooled, it becomes relatively more humid. At some temperature, the air becomes saturated with the given water content. In other words, the quantity of water vapor present is all that the air can hold at that temperature. Any further lowering of temperature will cause condensation of some of the water vapor. The temperature at which condensation begins is known as the dew-point temperature.

The temperatures of the surfaces surrounding an enclosed space in relation to the temperature of a body within the space determine the rate and direction of radiant heat flow between the body and the surrounding surfaces. The comfort of a person in a space is affected by this radiant exchange of heat. Therefore, it is useful to know the radiant surface temperatures or the average (mean) value of them. The equivalent uniform temperature of an enclosure causing the same radiant exchange as the given real conditions is known as the mean radiant temperature (MRT).

These concepts will be reviewed in Chapter 2 and are merely introduced here in order to provide an understanding of the following discussion of human physiology.

**Body Temperature Control**

Human beings are essentially constant-temperature animals with a normal internal body temperature of about 98.6°F (37.0°C). Heat is produced in the body as a result of metabolic activity, so its production can be controlled, to some extent, by controlling metabolism. Given a set metabolic rate, however, the body must reject heat at the proper rate in order to maintain thermal equilibrium.

If the internal temperature rises or falls beyond its normal range, mental and physical operation is curtailed, and if the temperature deviation is extreme, serious physiological disorders or even death can result. Sometimes the body’s own immunological system initiates a body temperature rise in order to kill infections or viruses.

The importance of maintaining a fairly precise internal temperature is illustrated in Figure 1.1, which shows the consequences of deep-body temperature deviations. When body temperature falls, respiratory activity—particularly in muscle tissue—automatically increases and generates more heat. Shivering is the extreme manifestation of this form of body temperature control.

An extremely sensitive portion of the brain called the hypothalamus constantly registers the temperature of the blood and seems to be stimulated by minute changes in blood temperature originating anywhere in the body (this could result from drinking a hot beverage or a change in skin
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The skin also has sensors that signal to the brain the level of heat gain or loss at the skin. It is the hypothalamus that appears to trigger the heat control mechanisms to either increase or decrease heat loss. This is accomplished by controlling the flow of blood to the skin by constricting or dilating the blood vessels within it. Since blood has high thermal conductivity, this is a very effective means of rapid thermal control of the body. By controlling peripheral blood flow, the body is able to (1) increase skin temperature to speed up elimination of body heat, (2) support sweating, or (3) reduce heat loss in the cold.

When body temperature rises above normal, the blood vessels in the skin dilate, bringing more heat-carrying blood to the surface. This results in a higher skin temperature and, consequently, increased heat loss. At the same time, sweat glands are stimulated, opening the pores of the skin to the passage of body fluids which evaporate on the surface of the skin and thereby cool the body. This evaporating perspiration is responsible for a great deal of heat loss. A minor amount of heat is also lost continuously by evaporation of water from the lungs and respiratory tracts.

When body heat loss is high, people experience a feeling of lassitude and mental dullness brought about by the fact that an increased amount of the blood pumped by the heart goes directly from the heart to the skin and back to the heart, bypassing the brain and other organs. A hot environment also increases strain on the heart, since it has to beat more rapidly to pump more blood to the periphery of the body.

When the body loses more heat to a cold environment than it produces, it decreases heat loss by constricting the outer blood vessels, thereby reducing blood flow to the outer surface of the skin. This converts the skin surface to a layer of insulation between the interior of the body and the environment. It has about the same effect as putting on a light sweater. If the body is still losing too much heat, the control device increases heat production by calling for involuntary muscular activity or shivering. When heat loss is too great, the body tends to hunch up and undergo muscular tension, resulting in a strained posture and physical exhaustion if the condition persists for any length of time.

Within limits, the body can acclimate itself to thermal environmental change. Such limits are not large, especially when the change is abrupt, such as when passing from indoors to outdoors. The slower seasonal changes are accommodated more easily. Changes in clothing assist the acclimatization. Whenever the body cannot adjust itself to the thermal environment, heat stroke or freezing to death is inevitable.

The physiological interpretation of comfort is the achievement of thermal equilibrium at our normal body temperature with the minimum amount of bodily regulation. We feel uncomfortable when our body has to work too hard to maintain thermal equilibrium. Under conditions of comfort, heat production equals heat loss without any action necessary by the heat control mechanisms. When the comfort condition exists, the mind is alert and the body operates at maximum efficiency.

It has been found that maximum productivity occurs under this condition and that industrial accidents increase at higher and lower temperatures. Postural awkwardness due to a cold feeling results in just as many accidents as does mental dullness caused by a too warm environment.

FIGURE 1.1. Physiological reactions to body temperature.

HEAT BALANCE

Like all mammals, humans “burn” food for energy and must discard the excess heat. This is accomplished by evaporation coupled with the three modes of sensible heat transfer: conduction, convection, and radiation. For a person to remain healthy, the heat must not be lost too fast or too slowly, and a very narrow range of body temperature must be maintained.
The body is in a state of thermal equilibrium with its environment when it loses heat at exactly the same rate as it gains heat. Mathematically, the relationship between the body’s heat production and all its other heat gains and losses is:

\[
\text{Heat production} = \text{heat loss}
\]

or

\[
M = E + R + C + S
\]  

(1.1)

where:

- \( M \) = metabolic rate
- \( E \) = rate of heat loss by evaporation, respiration, and elimination
- \( R \) = radiation rate
- \( C \) = conduction and convection rate
- \( S \) = body heat storage rate

Equation 1.2 is illustrated in Figure 1.2.

The body always produces heat, so the metabolic rate (\( M \)) is always positive, varying with the degree of exertion. If environmental conditions are such that the combined heat loss from radiation, conduction, convection, and evaporation is less than the body’s rate of heat production, the excess heat must be stored in body tissue. But body heat storage (\( S \)) is always small because the body has a limited thermal storage capacity. Therefore, as its interior becomes warmer, the body reacts to correct the situation by increasing blood flow to the skin surface and increasing perspiration. As a result, body heat loss is increased, thereby maintaining the desired body temperature and the balance expressed by Equation 1.2.

The converse condition—where heat loss is greater than body heat production—causes a reversal of the above process and, if necessary, shivering. This increased activity raises the metabolic rate.

Table 1.1 indicates the environmental and human factors that influence each of the major terms in Equation 1.2. Metabolism is discussed at greater length later in this chapter, while the other major factors—evaporation, radiation, conduction, and convection—are discussed below.

**Evaporation**

The body can either gain or lose heat by radiation (\( R \)) and conductive-convective heat transfer (\( C \)), depending on the temperature of the surrounding objects and ambient air. By contrast, evaporation (\( E \)) is exclusively a cooling mechanism.

Evaporative losses usually play an insignificant role in the body’s heat balance at cool temperatures. They become the predominant factor, however, when ambient temperatures are so high that radiant or convective heat losses cannot occur.

At comfortable temperatures, there is a steady flow of sensible heat from the skin to the surrounding air. The amount of this sensible heat depends upon the temperature difference between the skin and air. Although the deep body temperature remains relatively constant, the skin temperature may vary from 40°F to 105°F (4°C to 41°C) according to the surrounding temperature, humidity, and air velocity. During the heating season, the average surface temperature of an adult indoors wearing comfortable clothing is approximately 80°F (27°C). At lower surrounding temperatures, the skin temperature is correspondingly lower.

When the surrounding environment is about 70°F (21°C), most people lose sensible heat at a rate that makes them feel comfortable. If the ambient temperature rises to the skin temperature, the sensible heat loss drops to zero. If the ambient temperature increases, the body gains heat from the environment, and the only way it can lose heat is by increasing evaporation.

Evaporative heat losses also increase at high activity levels, when the metabolic heat production rises. A person engaged in strenuous physical work may sweat as much as a quart of fluid in an hour.

The rate of evaporation and evaporative heat loss is deter-
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mined by the evaporation potential of the air. It is dependent to a minor degree on the relative humidity of the surrounding air and, to a much greater extent, on the velocity of air motion. Moisture, which is evaporated from the skin surface, is carried away by the passing air stream.

Sufficient heat must be added to the perspiration to vaporize it, and this heat is drawn from the body. This heat loss equals the latent heat of vaporization of all the moisture evaporated. It is thus commonly known as the latent heat component of the total heat rejected by the body.

While the skin sweats only at moderate to high temperatures, evaporative losses of water from the respiratory passages and lungs occur continuously. The breath “seen” when exhaled in frosty weather is evidence that the air leaving the lungs has a high moisture content. We generally exhale air that is saturated (100 percent RH), and even at rest, the body requires about 100 Btuh (30 W) of heat to evaporate this moisture from the lungs into the inhaled air. Since it takes a considerable amount of heat to convert water into vapor, the evaporative heat loss from our lungs and skin plays an important role in disposing of body heat.

Radiation

Radiation is the net exchange of radiant energy between two bodies across an open space. The human body gains or loses radiant heat, for example, when exposed to an open fire, the sun, or a window on a cold winter day.

Each body—the earth, the sun, a human body, a wall, a window, or a piece of furniture—interacts with every other body in a direct line of sight with it. Radiation affects two bodies only when they are in sight of each other. This means that the energy cannot go around corners or be affected by air motion. For example, when we are uncomfortably hot in the direct light of the sun, we can cut off the radiant energy coming directly from the sun by stepping into the shade of a tree. Since air is a poor absorber of radiant heat, nearly all radiant exchanges are with solid surfaces to which we are exposed.

Radiant heat may travel toward or away from a human body, depending on whether the radiating temperatures of surrounding surfaces are higher or lower than the body’s temperature. In a cold room, the warmer body or its clothing transmits radiant heat to all cooler surfaces such as walls, glass, and other construction within view. If there is a cold window in sight, it will typically have the largest impact in terms of draining heat away and making the body feel colder. By closing the drapes, a person can block the radiant transfer in the same way that a person can cut off the radiant energy from the sun by stepping into the shade of a tree.

The rate of radiant transfer depends on the temperature differential, the thermal absorptivity of the surfaces, and the distance between the surfaces. The body gains or loses heat by radiation according to the difference between the body surface (bare skin and clothing) temperature, and the MRT of the surrounding surfaces.

The MRT is a weighted average of the temperatures of all the surfaces in direct line of sight of the body (see Figure

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**TABLE 1.1 FACTORS INFLUENCING THE HEAT BALANCE EQUATION**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Environment</th>
<th>Human</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metabolism (M)</td>
<td>Little effect</td>
<td>Activity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weight</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surface area</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Age</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sex</td>
</tr>
<tr>
<td>Evaporation (E)</td>
<td>Wet-bulb temperature</td>
<td>Ability to produce sweat</td>
</tr>
<tr>
<td></td>
<td>Dry-bulb temperature</td>
<td>Surface area</td>
</tr>
<tr>
<td></td>
<td>Velocity</td>
<td>Clothing</td>
</tr>
<tr>
<td>Radiation (R)</td>
<td>Temperature difference between bodies</td>
<td>Surface area</td>
</tr>
<tr>
<td></td>
<td>Emissivity of surfaces</td>
<td>Clothing</td>
</tr>
<tr>
<td>Convection (C)</td>
<td>Dry-bulb temperature</td>
<td>Clothing</td>
</tr>
<tr>
<td></td>
<td>Velocity</td>
<td>Mean body surface temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surface area</td>
</tr>
</tbody>
</table>

1.3). Although the MRT tends to stabilize near the room air temperature, it is also affected by large glass areas, degree of insulation, hot lights, and so on. The inside surface temperature of an insulated wall will be much closer to the room air temperature than will that of an uninsulated wall.

If the MRT is below the body temperature, the radiant heat term, R, in Equation 1.2 is a positive number, and the body is losing radiant heat. If the MRT is above the body temperature, R is negative, and the body is gaining radiant heat. This could be a benefit if the room air temperature is cool, causing excess body heat loss, while it would be detrimental if the ambient conditions are hot and humid, and the body is already having trouble rejecting heat.

It should be kept in mind that the body loses radiant heat according to its surface temperature. For a comfortable, normally dressed adult, the weighted average temperature of the bare skin and clothed surfaces is about 80°F (27°C). In still air at a temperature near skin temperature, radiant exchange is the principal form of heat exchange between the body and its environment.

To illustrate the body’s radiant interaction with surrounding surfaces, consider a person during the heating season working at a desk facing the center of an office with his or her back 5 feet (1.5 m) from an outside wall (see Figure 1.4a). The wall surface temperature is 59°F (15.0°C). If the room air temperature is 74°F (23.3°C) at the ceiling, 72°F (22.2°C) at the floor, and a uniform 73°F (22.8°C) in between, including the space between the person’s back and the wall, will he or she be comfortable? Probably not, because the radiant heat loss to the cold wall is so high that the office worker will feel chilly. (As a rule of thumb, if the MRT is 10°F (5°C) hotter or colder than comfortable room air conditions, an occupant will feel uncomfortable.) What can be done to correct this situation?

1. The wall surface temperature could be changed by adding insulation to the wall construction, or by hanging an insulative tapestry or wall hanging over the wall, as was done in medieval castles (Figure 1.4b).

2. The position of the desk might be changed, moving the person closer to an inside wall (Figure 1.4c). The radiant exchange would then be predominantly influenced by the surface temperature of the inside wall, which would be near the air temperature of 73°F (22.8°C). Thus, the radiant heat loss would be one-third of what it was: 80°F − 73°F = 7°F instead of 80°F − 59°F = 21°F (27°C − 15°C = 12°C instead of 27°C − 15°C = 14°C).

3. If the desk cannot be moved, the temperature of the air might be increased by turning up the thermostat. Increasing the air temperature would decrease the convective heat loss from the body. Suppose that setting the air temperature at 77°F (25°C) would decrease the convective heat loss by the same amount that the radiant heat loss would be decreased by moving the desk away from the outside wall. This would balance the heat loss from the body. The trouble is that everyone else in the room not sitting near an outside wall would be too warm.

Exactly the same thing might be true during the cooling season. A person might be too warm because of the radiant heat the body gains from a warm outside wall or window. In this case, the sensible heat loss from the body could be increased by decreasing the air temperature. This puts one person’s body heat loss in balance, but everyone else in the room would be too cool.

Thus, not only is good, properly operated heating and cooling equipment important for maintaining comfort, but the building construction itself can also have a strong influence. Poorly insulated walls and windows should be flagged as comfort problems. Furthermore, the type of occupancy must be borne in mind when analyzing the intended comfort conditions.
Convection-Conduction

Air passing over the skin surface is instrumental not only to the evaporation of moisture, but also to the transference of sensible heat to or from the body. The faster the rate of air movement, the larger the temperature difference between the body and surrounding air, and the larger the body surface area, the greater the rate of heat transfer.

When the air temperature is lower than the skin (and clothing) temperature, the convective heat term in equation 1.2 is “plus,” and the body loses heat to the air. If the air is warmer than the skin temperature, the convective heat term is “minus,” and the body gains heat from the air. Convection becomes increasingly effective at dissipating heat as air temperature decreases and air movement increases.

The conduction heat loss or gain occurs through contact of the body with physical objects such as the floor and chairs. If two chairs—one with a metal seat and the other with a fabric seat—have been in a 70°F (21°C) room for a period of time, they will both have a temperature of 70°F (21°C), but the metal one will feel colder than the one with the woven seat.

There are two reasons for this. First, metal is a good conductor, and it is the rate at which heat is conducted away—not the temperature—that we feel. Also, the metal chair has a smoother surface, which makes a good contact and thus
facilitates better conduction. Clothing also plays an important role in conductive heat transfer, insulating us from the warm or cold surface, just as a pot holder protects us from a hot pot.

**Combined Effects**

The physiological basis of comfort was previously stated as the achievement of thermal equilibrium with a minimal amount of body regulation of M, E, R, and C. Figure 1.5 shows the relation between all these factors for lightly clothed and unclothed subjects at rest. Note that convective and radiant heat loss is greater for the lightly clothed subjects. Also, the heat loss by convection and radiation decreases with increasing air temperature, while evaporative heat loss increases with increasing air temperature.

Heat loss by evaporation is relatively constant below certain air temperatures—approximately 75°F (24°C) for the heavily clothed subject and 85°F (29°C) for the lightly clothed subject. The metabolic rate at a given activity level is stable when the temperature ranges from about 70°F to 90°F (21°C to 32°C).

To illustrate the various modes of heat loss operating in conjunction, consider a person outdoors in 100°F (38°C) air temperature. Referring to Equation 1.2, the convective heat loss is “minus” because the body is gaining heat from the air. The MRT is much higher than the body surface temperature—the sidewalk, street, building walls, sunny sky, and everything else in the range of view of the body is warmer than the body surface temperature. Thus, the radiant heat term is also “minus” because the body is gaining radiant heat.

But as the person walks down the sidewalk, the metabolism produces about 700 Btuh (200 W), and all that heat must be lost in addition to that gained by convection and radiation in order to maintain the heat balance. The total the body must lose may be over 1,000 Btuh (300 W), all by evaporation. The sweat glands automatically open, and the resultant moisture emitted onto the body surface then evaporates. The heat drawn from the body to evaporate the moisture keeps the skin cool as long as the surrounding air will carry away the water vapor so that more can be evaporated. This in turn keeps the deep-body temperature close to 98.6°F (37.0°C).

As the dry-bulb temperature of the surrounding air rises from the comfortable 70s to the 80s and 90s, less sensible heat (convective and radiative) is lost by the body, while the latent heat (evaporation) loss increases. Thus, if a body at rest produces 400 Btuh (117 W), it may lose 290 Btuh (85 W) of sensible heat and 110 Btuh (32 W) of latent heat at 70°F (21°C). At higher temperatures, the sensible component drops to nearly zero, and the latent heat must increase to almost the full 400 Btuh (117 W) in order to lose the same amount of heat.