Introduction and Overview* 1

A Note to Instructors and Readers

As an introduction to *Mechanical and Electrical System in Buildings,* Chapter 1 contains topics that may be difficult to comprehend for students who are not familiar with some of the architectural and engineering terms. Feedback received from many instructors suggested that this chapter be divided into two chapters, with the more technologically related topics to be placed in a new chapter at the end of this book. The authors appreciate this valuable input and have transferred some of the energy-related topics to a new Chapter 19, entitled "Sustainable Design." We suggest that instructors and students may wish to study Chapter 1 in two steps—first, briefly familiarizing themselves with the topics appropriate to their background to get an overview of the building design process and topics of design concern and second, returning to Chapter 1 to better grasp the importance of these concerns.

Included in Chapter 1 is a new section introducing a flowchart of the building design and construction process that we believe will be beneficial to those unfamiliar with the process. In fact, because the same process applies to all branches of engineering covered in subsequent chapters, variations of this the flowchart will not be repeated in every chapter.

MODERN BUILDINGS ARE NO LONGER JUST SHELTERS from rain, wind, snow, sun, or other harsh conditions of nature. Rather, they are built to create better, more consistent, more productive environments in which to work and to live. Buildings must be designed with features to provide better lighting; comfortable space temperature, humidity, and air quality; convenient power and communication capability; high-quality sanitation; and reliable systems for the protection of life and property. All these desirable features have become a reality with recent advances in the technology of mechanical and electrical (M/E) systems.

These advances have opened the door for a wide range of architectural design innovations in style, form, and scope that are not achievable without the utilization of M/E systems. Block-type buildings without windows, such as department stores, are totally dependent on electrical lighting, ventilation, and space conditioning. High-rise buildings must rely on high-speed vertical transportation and high-pressure water for drinking and cleaning purposes and for protection against fire.

All these benefits, however, are not achieved without penalties. M/E systems demand considerable floor and ceiling space. Without proper space allocation during the preliminary planning phase of a project, the design process may have to be started over again, and often the system performances are compromised. Furthermore, M/E systems add to the cost of construction of a building, in some instances approaching or exceeding 50 percent of the total cost. Sophisticated buildings, such as research buildings, hospitals, and computer centers, are just a few examples.

M/E systems require energy to operate them. Energy consumed by occupied buildings, including residential, commercial, institutional, and industrial facilities, accounts for over 50 percent of all energy usage by an industrialized country. In addition, it accounts for a large portion of the operating costs of such buildings. The high and inefficient use of energy by buildings is the major contributing factor to the deterioration of our greater environment.

Properly designed M/E systems utilize space and energy efficiently, thereby reducing building costs and minimizing environmental impacts. This chapter provides an overview of building M/E systems and their

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*Peter Tao is the contributing author of this chapter. See Acknowledgments.

impact on space planning, architectural design, construction and operating costs, and the greater environment.

1.1 THE SCOPE OF BUILDING M/E SYSTEMS

The complexity of M/E systems varies with the living standards of the society, climatic conditions of the region, and occupancy and quality of the building. For example, a house located in a mild climate may not require either heating or cooling, regardless of the quality of the house; a warehouse for bulk storage may not require any heating, even in a freezing climate; a modern hospital must have a supply of medical gas, standby electrical power, and telecommunications systems to meet present health care standards; and a small office building may appropriately have window-type air conditioners, whereas an intelligent high-rise office building will most likely be designed with a central HVAC system complete with computer-based building automation and management controls.

Building M/E systems may be classified into three major categories containing the listed typical subsystems:

Mechanical Systems

- *HVAC* Heating, ventilating, and air conditioning
- *Site utilities* Water supply, storm-water drainage, sanitary disposal, gas supply
- *Plumbing* Water distribution, water treatment, sanitary facilities
- *Fire protection* Water supply, standpipe, fire and smoke detection, automatic sprinklers, annunciation
- *Special systems*

Electrical Systems

- *Electrical power* Normal, standby, and emergency power supply and distribution
- *Lighting* Interior, exterior, and emergency lighting
- *Auxiliary* Telephone, signal, data, audio/video, sound, fire alarm, security systems
- *Special systems*

Building Operation Systems

- *Transportation* Elevators, escalators, moving walkways
- *Processing* Production, food service
- *Automation* Environmental controls, management
- *Special systems*

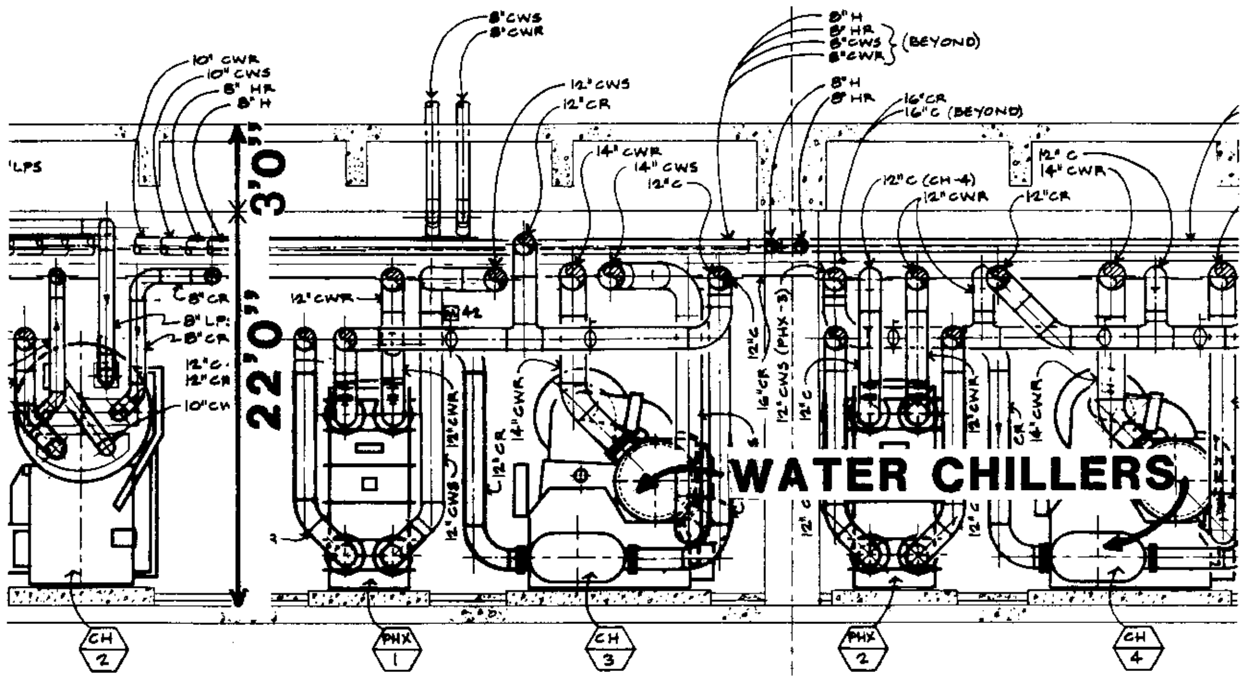
A checklist at the end of the chapter provides a more comprehensive identification of common M/E system features and design criteria that should be considered when initiating a new project. The checklist is an excellent guide for the owner and the architect/engineer to define the scope of services from which to generate a realistic budget, formulate spatial programs, and create architectural concepts.

1.2 THE IMPACT ON SPACE PLANNING

The floor area necessary for M/E systems in a building varies widely, depending on the occupancy, climatic conditions, living standards, and quality and general architectural design of the building. The M/E space affects the gross floor area, footprint (the size and shape of the building's ground floor), floor-to-floor height, geometry, and architectural expression. Reasonable allocations made during the space programming phase allow M/E space to be appropriately sized and strategically located. Space planning for M/E systems is one of the most challenging and least developed procedures in the architectural design process.

Central equipment used for large buildings is usually bulky and tall, requiring floor-to-floor heights of 1½ to 2 times the normal height. Figures 1–1 and 1–2 illustrate a chiller and pump room of a large office-computer building with a floor-to-floor height of 22 ft, about twice the normal height. Figures 1–3 and 1–4 illustrate the complexity of the ductwork, lighting, and wiring of a commercial building, which requires between 2 and 3 ft of ceiling cavity (the space above a suspended ceiling). (The ceiling cavity may be reduced in height if the structural beam can be penetrated.) Not illustrated, but frequently present in the ceiling cavity, is piping for HVAC and plumbing. This also demands ceiling cavity space and thus affects the floor-to-floor height. Figure 1–5(a) is a photo of the ceiling cavity with the ceiling tiles removed; Figure 1–5(b) shows the finished space; and Figure 1–5(c) illustrates exposed ductwork below the ceiling as a decorative feature of the space. In fact, a recent trend in modern architecture has been exposed ductwork, piping, and lighting.

The purpose of introducing the foregoing complex issues at the beginning of this book is to remind the reader how M/E systems can affect the overall planning of a building. For conceptual planning and budgetary purposes, Table 1–1 lists the range of M/E space requirements, based on building occupancies. Although the ranges are broad, they serve as a basis from which to begin the planning process. The actual space needs are formalized, modified, and refined as the building requirements become better defined.



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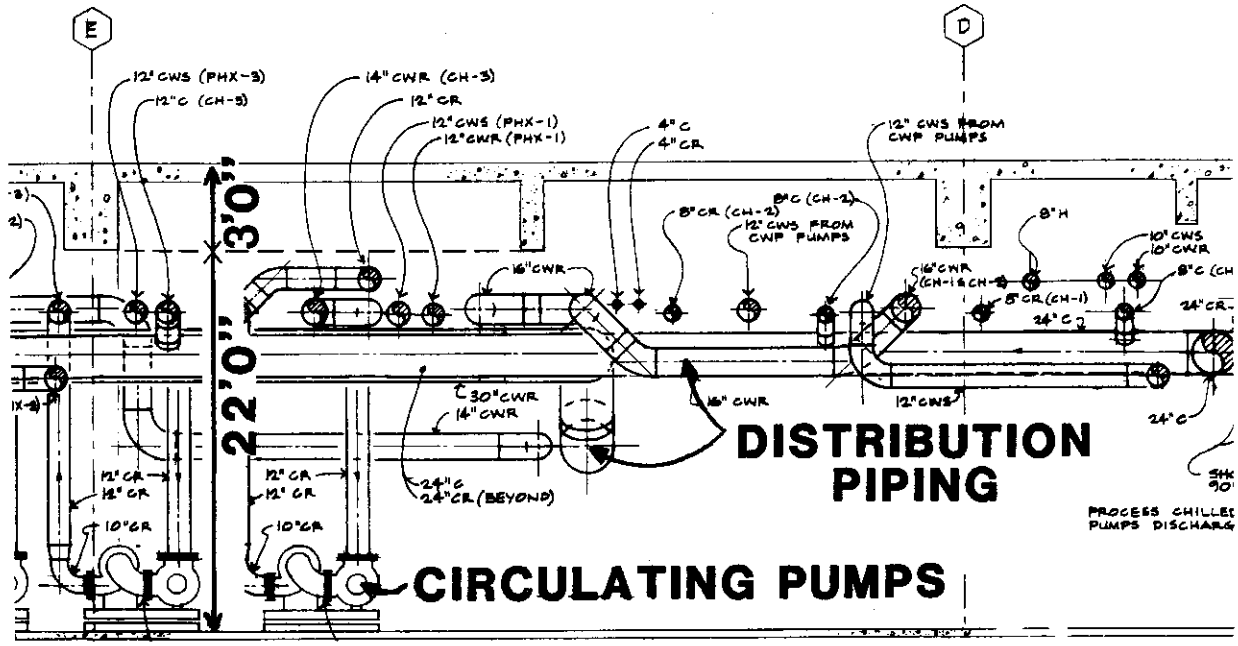
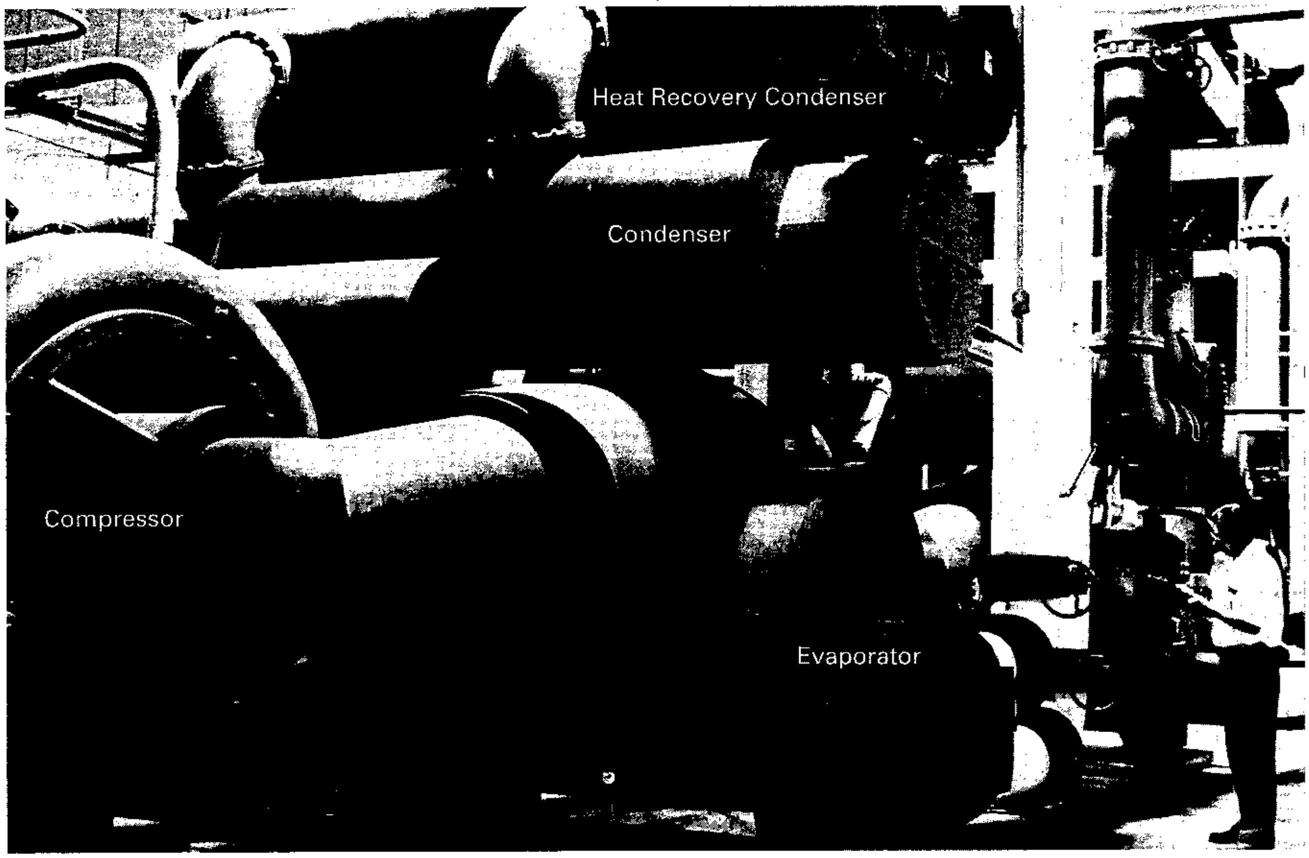


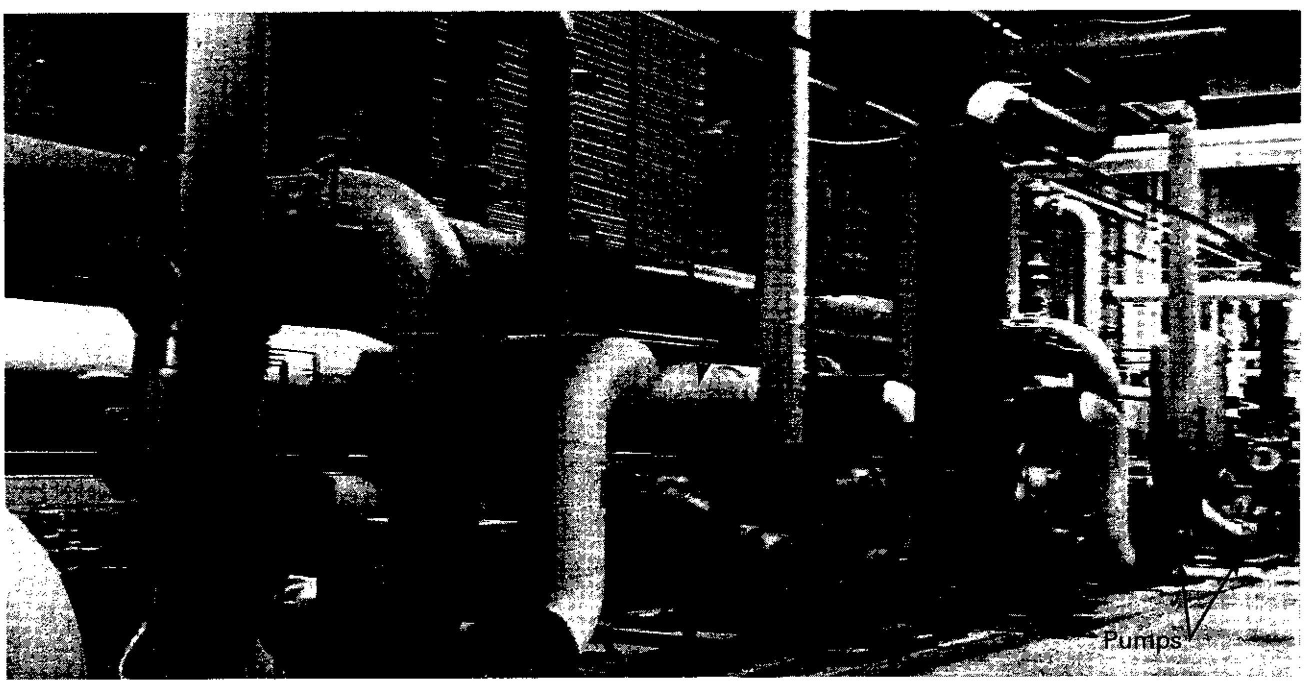
(b)

■ FIGURE 1-1
(a) Partial layout of mechanical equipment room, showing end elevation of water chillers. (Reduced scale of drawing: 1/8″ = 1′ − 0″.) (b) Partial elevation of main distribution piping and circulation pumps. (Reduced scale of drawing.) (*Note:* Building dimensions and equipment identifications) are specially enlarged for clarification in this book only.

This broad range of space requirements for M/E systems is primarily due to centralized systems versus decentralized systems. For example, if a building is to be heated and cooled by unitary window or through-the-wall heat pumps, then the need for central heating and cooling equipment can be eliminated; however, unitary equipment is noisy and less energy-efficient, requires high maintenance, and is unaesthetic. Thus

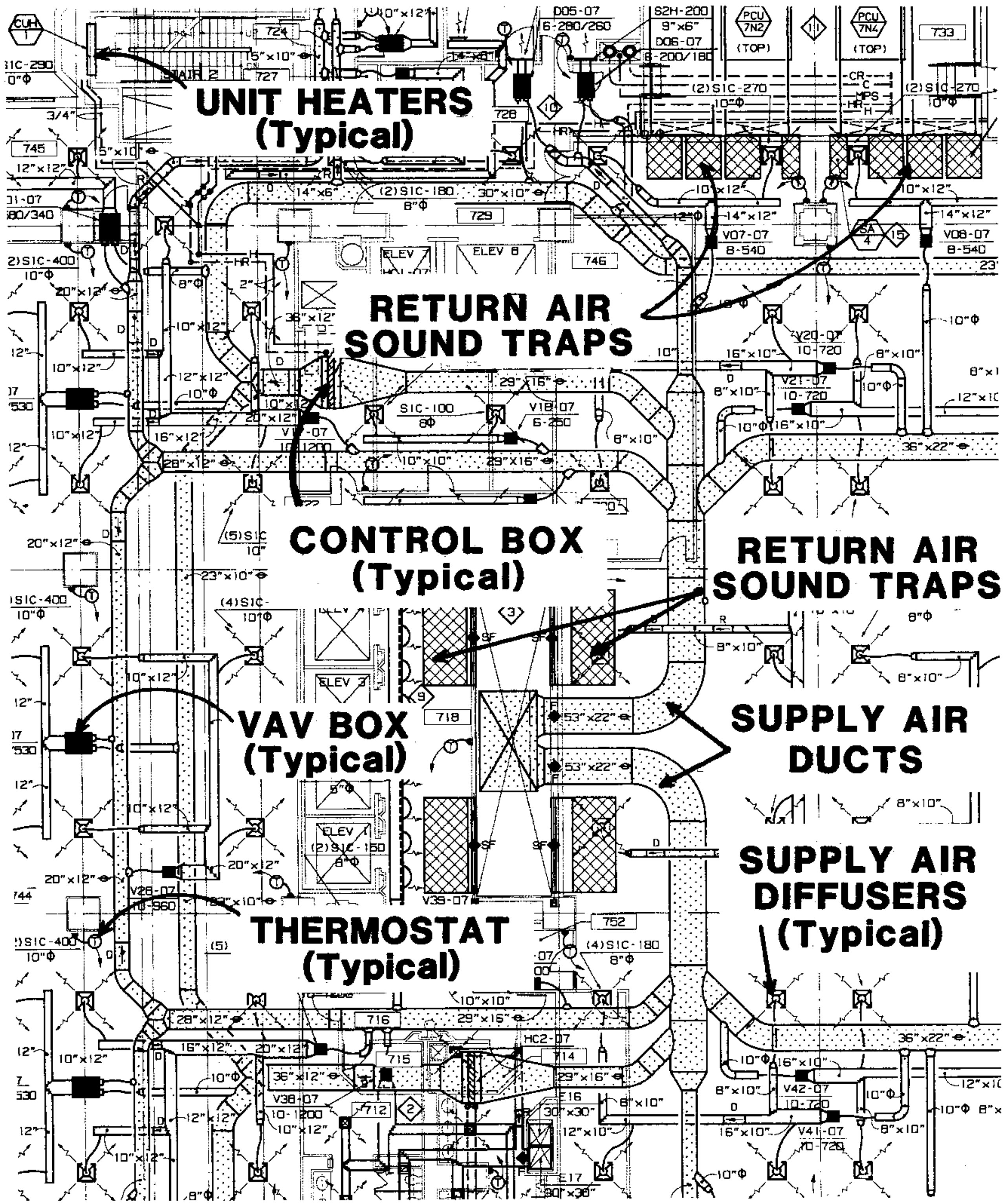


(a)



(b)

■ **FIGURE 1–2**
(a) 1500-ton chillers in a central plant. The maintenance man standing alongside indicates the size of the machine. The ceiling height in this space is 22 ft. (b) Chilled-water circulating pumps for the chillers in part (a). Pipe sizes range from 8 to 14 in. in diameter.

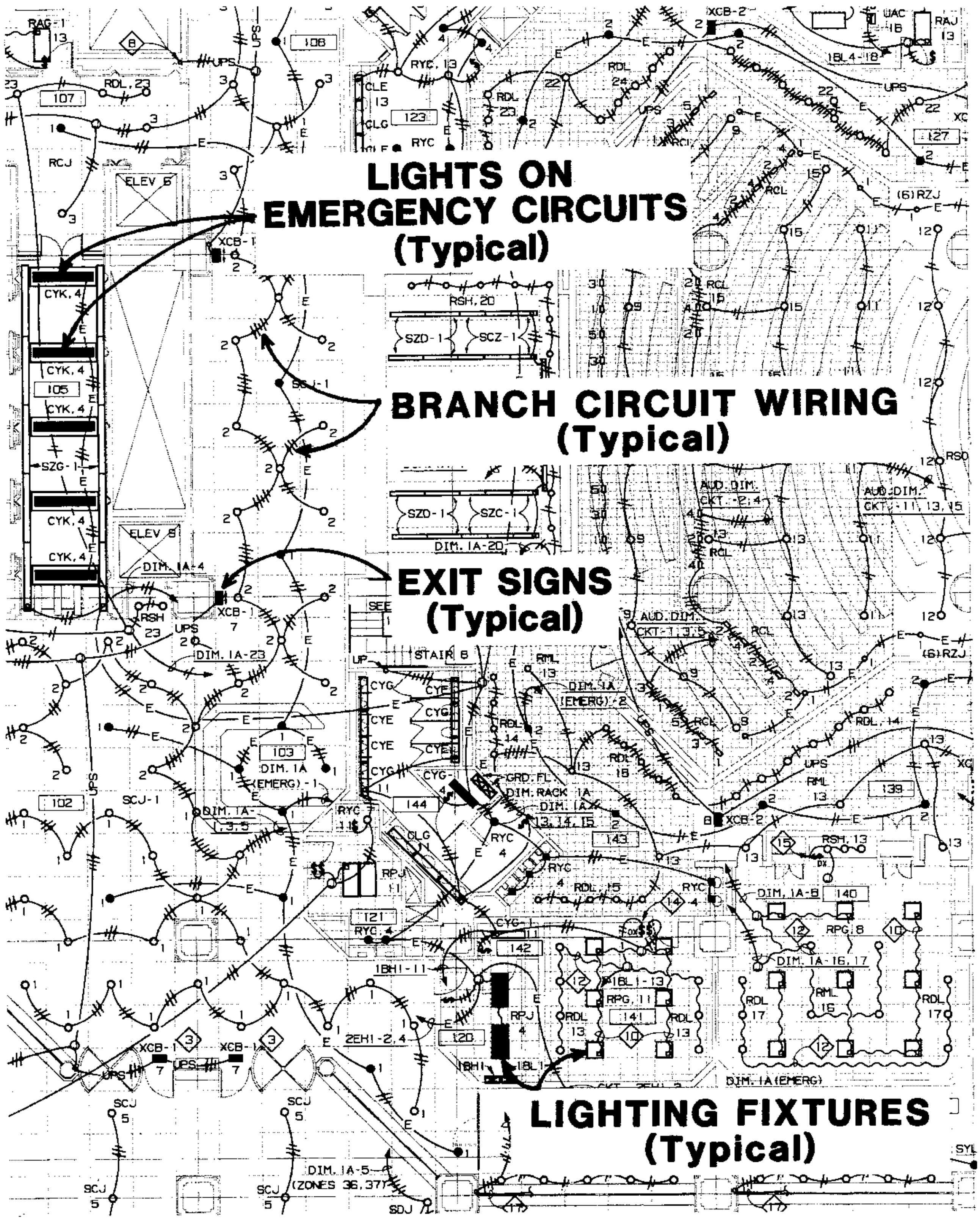


HVAC FLOOR PLAN–AIR DISTRIBUTION

■ **FIGURE 1-3**

A partial floor plan of a large computer center showing the location and size of supply air ducts, diffusers, and return air sound traps.

(*Note:* Equipment and component identifications are specially enlarged for clarification in this book only.)

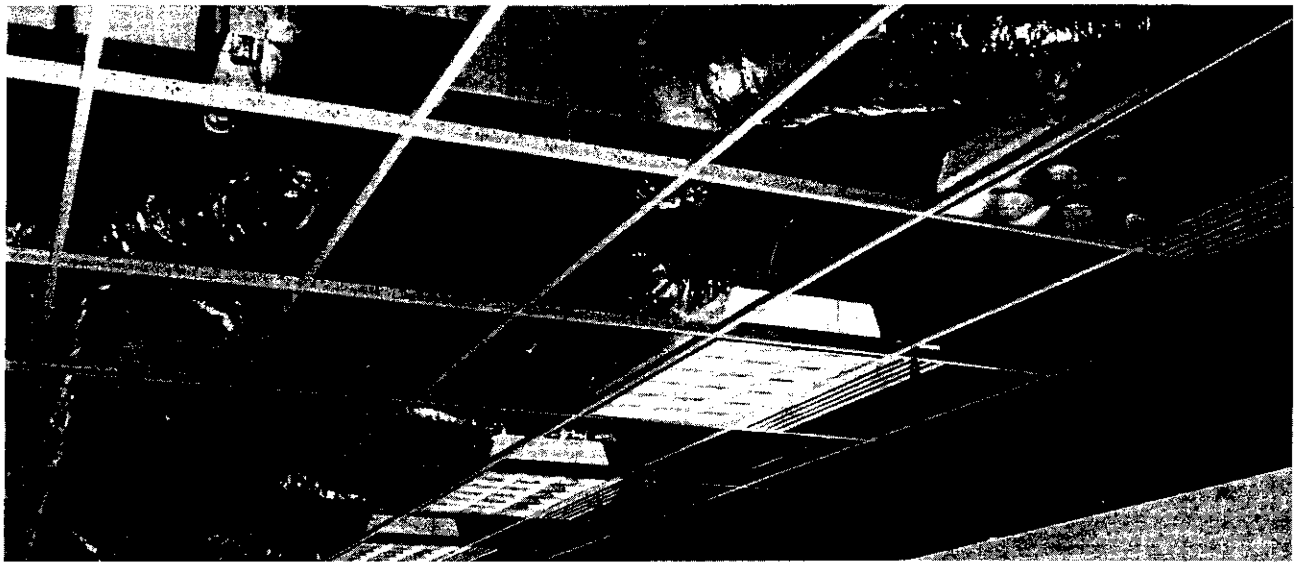


ELEC. FLOOR PLAN–BRANCH CIRCUITS

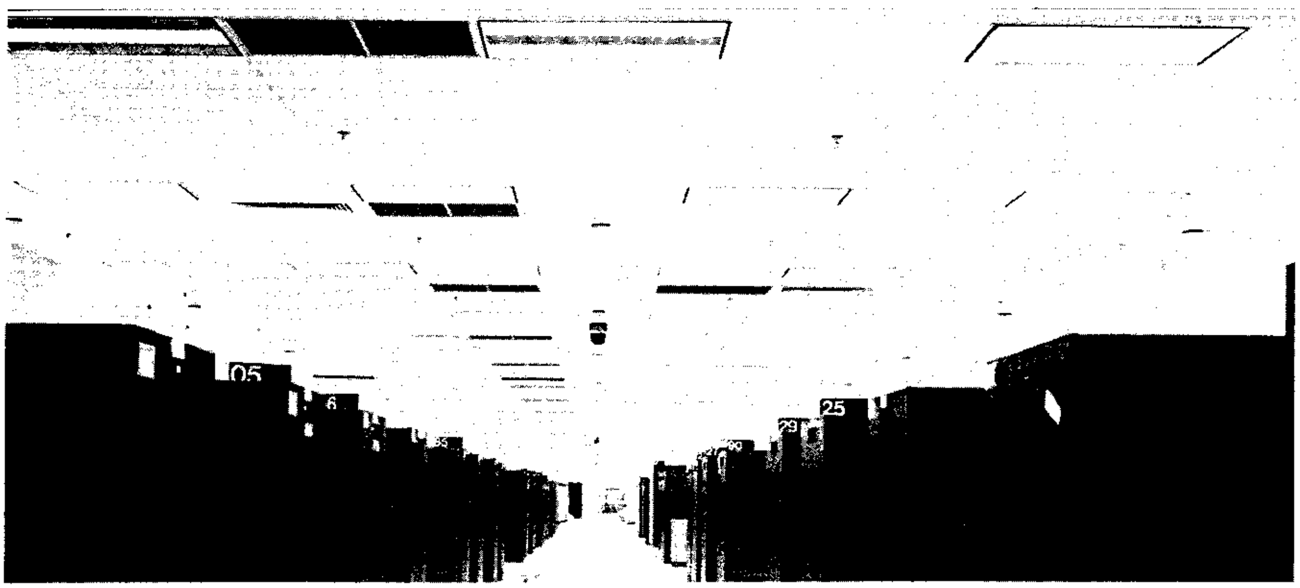
■ FIGURE 1–4

A partial floor plan of a large computer center showing branch circuiting of lighting fixtures in conduits. Hash lines indicating the number of wires in the conduit. All wires are No. 12 AWG unless otherwise noted.

(*Note:* Equipment and component identifications are specially enlarged for clarification in this book only.)



(a)



(b)

(c)

■ **FIGURE 1–5**
(a) Maze of sprinkler piping, air distribution boxes, flexible ducts, supply air diffusers, and fluorescent lights above a typical T-bar acoustic ceiling of a modern office building. (b) The finished space with only diffusers, lights, sprinklers, and smoke detectors shown. (c) Mechanical ducts, lighting fixtures, and illuminated signs are integrated as a dominant architectural design feature in the Lambert-St. Louis International Airport concourses.

TABLE 1–1
Range of M/E floor area required for buildings

	Percent of Gross Building Area		
Type of Occupancy	*Low*	*Medium*	*High*
Computer centers	10	20	30
Department stores	3	5	7
Hospitals	5	10	15
Hotels	4	7	10
Offices	2	4	6
Research laboratories	5	10	15
Residential, single-occupancy	1	2	3
Residential, high-rise	1	3	5
Retail, individual stores	1	2	3
Schools, elementary	2	3	4
Schools, secondary	2	4	6
Universities and colleges*	4	6	8

*Buildings other than those used for classrooms follow the space required for specialty buildings such as laboratories, computer centers, and residences.

most high-quality buildings have various central systems in spite of the increased requirements for equipment space, and initial construction investment.

1.3 THE IMPACT ON ARCHITECTURAL DESIGN

1.3.1 Early Building Forms

Prior to the development of reliable and affordable M/E systems, buildings designed for human occupancy followed a simple rule: every room must have exterior operable windows for the introduction of daylight and for natural ventilation. Accordingly, most buildings are L-, U-, or H-shaped, having either single- or double-loaded corridors. Deep block-type buildings usually have an open interior court for access to daylight and outside air. Figure 1–6 illustrates these basic building forms. It is not difficult to conclude that buildings of the designs shown in this figure have more exterior wall surface area than the deep block-type design and thus have more heat gain or loss, as well as a higher construction cost.

Great religious buildings, such as cathedrals, are exceptions to the preceding rule; however, they all have extremely high atriums (cathedral domes) to create a good natural draft, heavy exterior walls to retard solar heat gain, and a heavy mass to store thermal energy. Their interiors are usually dimly lit, even with converted electrical chandeliers and added spotlights. A visit to some famous cathedrals in Europe will easily confirm this fact.

1.3.2 Building Height versus Space Utilization

Buildings may be classified as low-rise, high-rise, and a number of other categories. Traditionally, a building of less than 7 stories or lower than 75 ft from street level is classified as low-rise. This is more or less determined by the height that can be reached by conventional fire-truck ladders. Of course, with modern firefighting equipment, that definition is no longer valid, but it is still used by most building codes as the basis for classifying buildings.

For the sake of differentiation, buildings from 7 to 29 stories are said to be high-rise; those from 30 to 50 stories are super high-rise; and those from 51 stories upward are skyscrapers.

It is not difficult to prove that low-rise buildings (6 stories or lower) are cheaper to build and more efficient to use than high-rise buildings; however, high-rise buildings and even skyscrapers have always been popular in urban settings, and the trend will continue as long as urban land is in short supply. No less important is the image associated with high-rise buildings, signifying status, identity, and prestige. These are intangible values to the owners and occupants of the building and are difficult to put into economic terms.

Historically, the height of a building has pretty much been limited by a human's ability to walk up and down stairs. Although monuments and bell towers are often built as high as is structurally sound, their stairs are not intended for routine use. The same cannot be said for office-type buildings, however, where stairs are the only means of communication between floors, and elevators are a luxury. Modern elevators for high-rise buildings are designed to travel between 500 and 2500 ft (150 and 750 m) per minute. At that speed, it would take less than 30 seconds to reach the top of a 30-story building, excluding the waiting and loading time at each stop.

As the height of the building increases, more floor space is required for stairs, structural elements, elevators, lobbies, M/E system shafts, etc. The result is a reduction in the net usable space on the floor.

Concern about building security and life safety in the aftermath of the September 11, 2001, World Trade Center tragedy in New York City caused a major reassessment of the building codes regarding structural integrity and the adequacy of building egress—the width and number of stairways and vertical transportation systems. These concerns affect the M/E codes such as ventilation, smoke removal, standby electrical power, fire protection

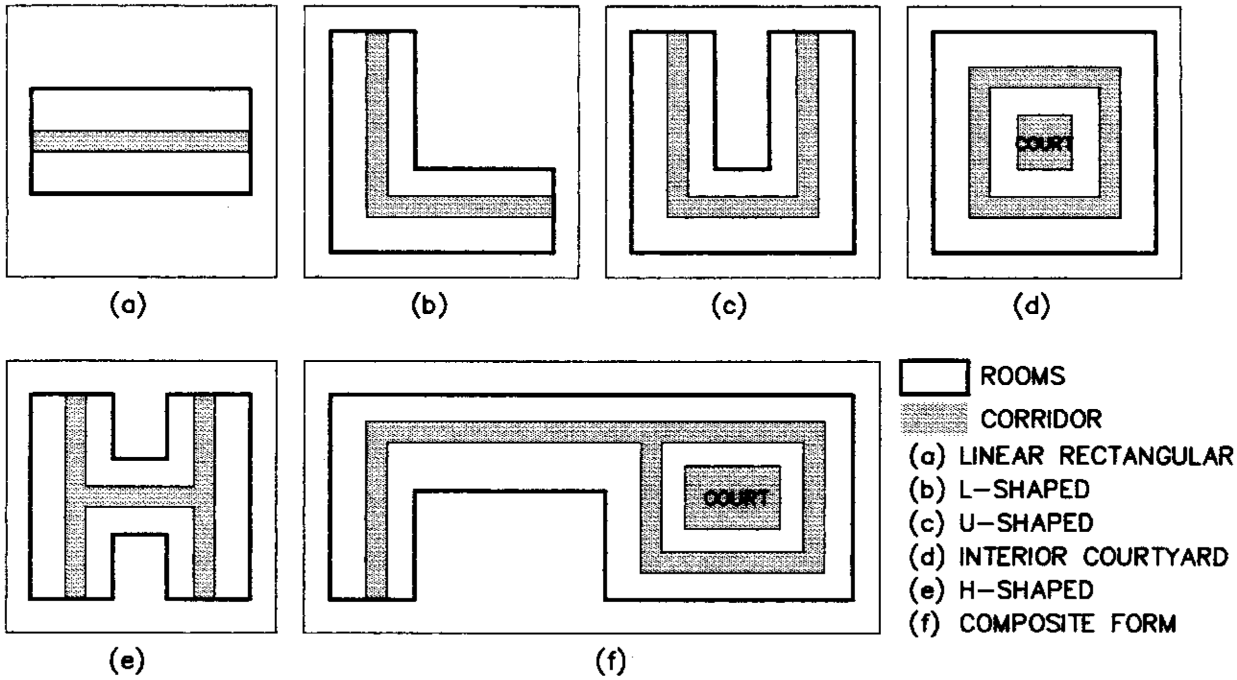


FIGURE 1-6
Common building geometry prior to the development of modern M/E systems.

provisions, and building automation and management systems. Changes in the codes would mean additional space encroachment on the net usable spaces in buildings, especially super high-rises. The next section discusses the efficiency of a building in terms of net-to-gross usable space ratios.

1.3.3 Building Efficiency Factors

Theoretically, a building is most efficient if 100 percent of the interior space can be utilized for occupancy. This is possible for a small, single-story building with all major M/E equipment located on the roof or at the exteriors. Multistory buildings gradually lose space utilization efficiency, owing to their need for stairways, elevators, and M/E equipment space. Building efficiency can be expressed by several ratio factors.

Depending on the objectives, one or more of the following factors may be used to evaluate the effectiveness of the building design:

- Net-to-gross ratio (NGR)
- Floor-efficiency ratio (FER)
- Volume-to-surface ratio (VSR)
- Area-to-perimeter ratio (APR)

The definitions and applications of these factors are explained below.

1. Net-to-Gross Ratio

The net floor area (NFA) of a building is the floor area that can be used by the occupants and is sometimes referred to as "net assignable area." NFA is typically defined as the gross floor area (GFA) excluding the area taken by stairs, circulation space, elevators, lobbies, structural columns, M/E equipment and shafts, etc. The net-to-gross ratio (percent) is therefore

$$\text{NGR} = 100 \times \text{NFA}/\text{GFA} \qquad (1\text{-}1)$$

where NFA = net floor area, sq ft, or m^2
GFA = gross floor area, sq ft, or m^2

The available NGR depends on the building's occupancy, M/E systems, and architectural design and usually ranges from 60 to 90 percent. The objective in space planning is to improve the NGR while maintaining a proper balance between occupants' comfort and productivity, M/E system performances, and initial and operating costs. The NGR of a building decreases as more space is occupied by building equipment, structural elements, and circulation spaces. The NGR of highly technical buildings, such as research laboratories, computer centers, and hospitals may even be below 50 percent.

Frequently, real estate agents like to use another criterion: the area to be rented by tenants, or net rentable area (NRA). The definition of NRA varies widely among regions or countries, depending on local customs and practices. Some NRA calculations include the proportionate share of public lobbies, part of the exterior walls, and mechanical equipment rooms, while others do not.

2. Floor-Efficiency Ratio

The floor-efficient-ratio (FER) is frequently used for office buildings to calculate the rentable space on typical rental floors. The FER of a typical floor is calculated as

$$\text{FER} = 100 \times (\text{NRA}/\text{GFA}) \qquad (1\text{–}2)$$

where NRA = net rentable area, sq ft, or m^2
GFA = gross floor area, sq ft, or m^2

A building with a high FER usually requires more central M/E space and a lower NGR. The trade-off between FER and NGR depends on many factors, such as site constraints, zoning restrictions on the height of a building, space programming, and architectural geometry. Normally, the FER of a high-rise office building with centralized M/E systems may be as high as 90 percent for single-story buildings but diminishes for multistory buildings. An FER of 85 percent is considered an excellent design. See Figure 1–7.

1.3.4 Geometric Factors

Two additional factors that can be used to evaluate economics and energy-effectiveness relative to building geometry and form are the volume-to-surface ratio (VSR) and the area-to-perimeter ratio (APR).

1. Volume-to-Surface Ratio

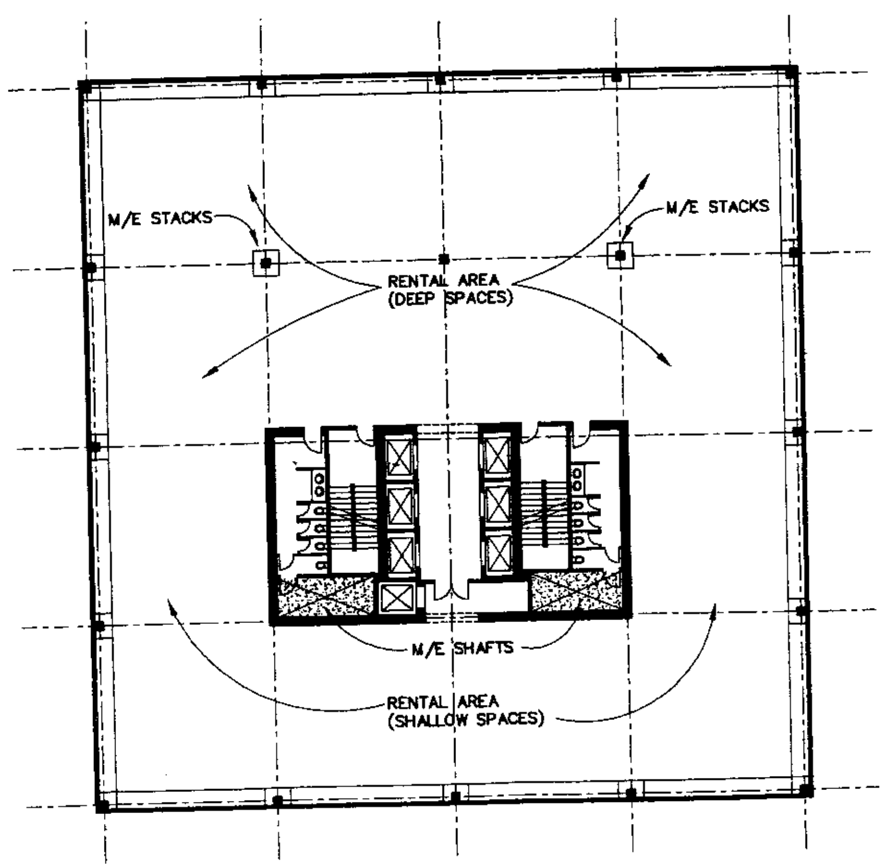
The volume-to-surface ratio (VSR) is a ratio of the total volume of the building divided by the total exterior wall areas of the building. The total volume is the total floor area of the building multiplied by its average floor-to-floor height. Thus, the VSR is actually the floor area per unit area of exterior wall of the building. Naturally, a larger VSR represents a more efficient building geometry.

$$\text{VSR} = V/S \qquad (1\text{–}3)$$

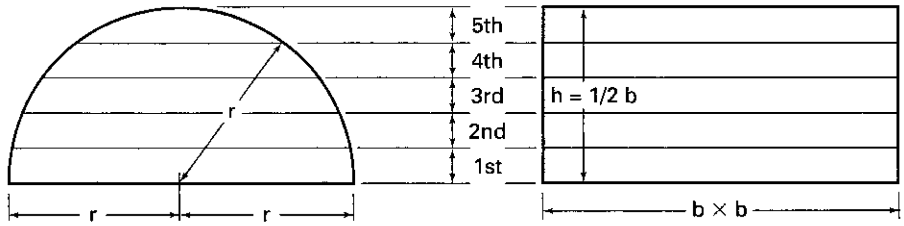
where V = volume of building, cu ft, or m^3
S = total exterior surface of building, sq ft, or m^3

VSR is thus in feet or meters, but the dimensional unit is not used.

To be cost-effective and energy efficient, the building geometry should minimize exterior surfaces (walls and roof) and maximize interior volume (floor area × height) and, thus, the VSR. Mathematically, the optimum



■ **FIGURE 1–7**
A typical rental office floor plan with excellent FER. This is a typical well-designed floor plan of a 17-story office building, with a compact core for elevators, stairs, toilets, and M/E shafts. The FER is in excess of 85 percent. (Illustrated: Pierre Laclede Building, St. Louis, MO.)



$V = 2\pi r^3 \div 3$; $S = 2\pi r^2$

VSR (optimum) $= \frac{r}{3}$

$V = b^2 \times h$; $S = 4bh + b^2$

VSR $= b \times h \div (4h + b)$

VSR (optimum) = 0.167b

■ **FIGURE 1-8**
The optimum VSR of a building is either a semispherical dome with diminishing upper floor areas or a semicubical building with equal floor areas and height half its base dimension. (*Note:* The optimum VSR is a variable depending on the building size.)

VSR of any geometric form is a sphere; however, for occupancy, a hemisphere such as a geodesic dome is the only practical equivalent to a sphere. A dome is ideal for an indoor sports arena, where the height of the dome can be fully utilized. A rectangular building has five exterior surfaces—four walls and one roof. The floor is excluded because it has nearly no energy transfer (gain or loss). Thus, in terms of energy gained or lost a rectangular building is treated as a five-sided structure. The optimum rectangular building is a half cube, or semicube, where the height of the building is one-half of its square base. The semispherical and semicubical building configurations are illustrated in Figure 1-8.

It can be shown that any building with height greater than half its base dimension is less energy efficient and more costly to build than one with height less than or equal to half its base dimension. High-rise buildings are in this category, and the taller the building, the less the energy efficiency. While no building will be built simply to achieve a better VSR, this criterion should not be overlooked in considering alternative designs of a comparable-size building.

The VSR can also be used to evaluate the optimum size of buildings by comparing smaller numbers of large buildings and larger numbers of small buildings. The answer is in favor of the larger buildings. For example, it should be obvious that the cost and energy consumption of one hundred 5000-sq-ft public housing units are considerably higher than those of ten 50,000-sq-ft housing units. While other factors, such as privacy, quality of life, security, zoning, community relations, etc., most likely favor the smaller units, an assessment of the VSR is still a valid criterion. (For additional information on the subject, see the reference section at the end of the chapter.)

2. Area-to-Perimeter Ratio

The APR is related to the *aspect ratio* (AR) of the building, which is defined as the length (longer dimension) divided by the width of the building. Assuming that most upper floors are substantially the same, then the APR is the typical floor area divided by the perimeter length of the floor, that is, the floor area per linear unit of the perimeter walls.

$$\text{APR} = A/P \qquad (1\text{-}4)$$

where A = typical or representative floor area of building, sq ft, or m^2
P = linear dimension of perimeter of a typical or representative floor, ft, or m

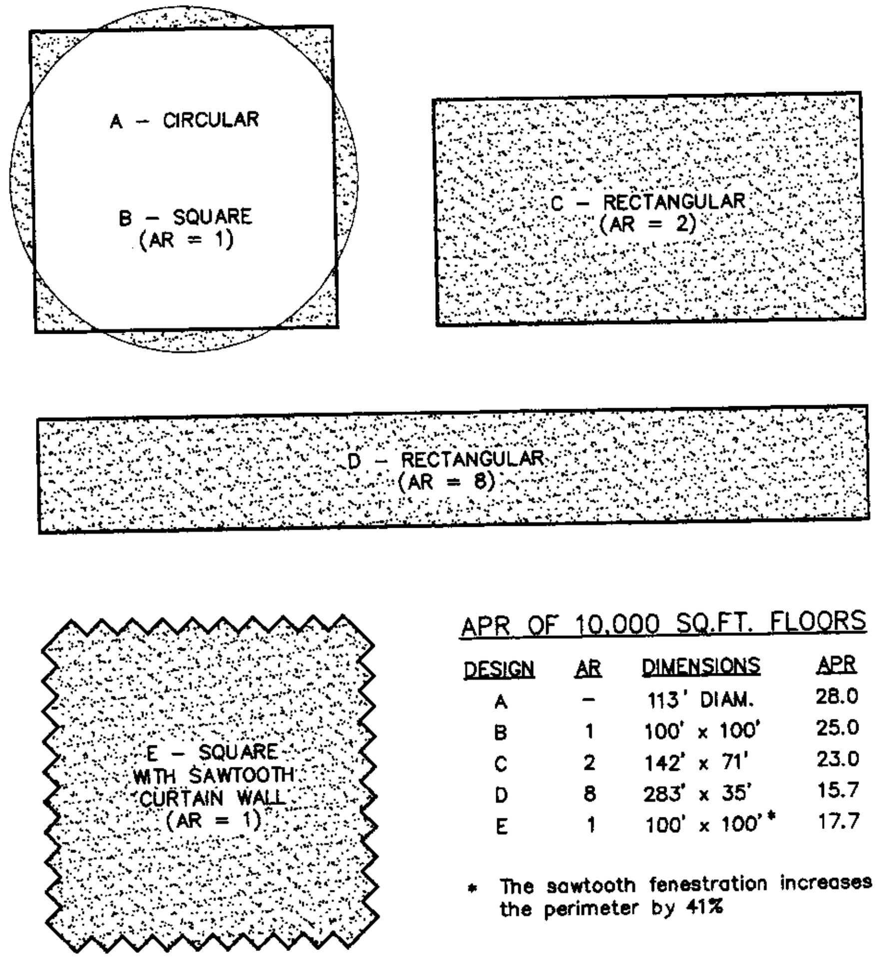
APR is thus in feet or meters, but the dimensional unit is not used.

Naturally, the larger the APR, the higher the energy efficiency. A round or square building should have the optimum APR. On the other hand, a rectangular building with maximum daylight and minimum solar heat gain in the cooling season could override the APR factors. The final design will depend on a computer simulation of the HVAC and lighting load on an hour-by-hour basis. Figure 1-9 illustrates the impact of aspect ratio (AR) on the value of APR. All five buildings have a floor area of 10,000 sq ft, but their APR varies from 28 for a square building to 17.7 for a fundamentally square building with sawtooth facade to 15.7 for an elongated building. The sawtooth facade means increased exterior walls as well as heat gain and loss. The value of such a sawtooth design has to be justified in terms of aesthetics and the views from the windows.

1.3.5 Impact on Building Exterior Design

The major influence of M/E systems on modern architecture has been not only in building height but in architectural style, facade, form, and expression. Architecture and structural systems have a long history of interfacing. Typical examples of modern architecture expressed by

■ **FIGURE 1-9**
Comparison of the APR values of several geometric configurations.



APR OF 10,000 SQ.FT. FLOORS

DESIGN	AR	DIMENSIONS	APR
A	–	113' DIAM.	28.0
B	1	100' x 100'	25.0
C	2	142' x 71'	23.0
D	8	283' x 35'	15.7
E	1	100' x 100'*	17.7

* The sawtooth fenestration increases the perimeter by 41%

structural columns and cross-bracing members are the John Hancock Building in Chicago, built during the 1970s, and the more recent Bank of China Building in Hong Kong. Architectural and M/E system interfacing became a reality only when the Pompidou Center Art Museum in Paris daringly exposed all M/E system ducts, pipes, and conduits on the exterior of the museum. After that the Hong Kong–Shanghai Bank in Hong Kong, built in the 1980s, created another sensation, with exposed structural and M/E elements as the main feature of its architectural design. In fact, most modern buildings are influenced by the presence of M/E systems, as evidenced by the following architectural design styles:

1. *Penthouse design* At the top of the roof is a smaller floor or screened structure to enclose the elevator equipment and elevator overtravel (the extension of the elevator shaft above the last floor to slow down the elevator, should it fail to stop as intended), cooling towers, exhaust fans, and other equipment. This is a fundamental design concept to conceal equipment on the roof and is a building code requirement in many cities and countries.
2. *Flattop design* The top one or two floors of a high-rise building are usually designed to house central M/E equipment and to conceal upper-level M/E equipment, such as cooling towers, air-handling units, and elevator equipment.
3. *Intermediate floor bands design* High-rise buildings of over 30 stories are usually designed with one or more intermediate floors to house central M/E equipment. Because extra floor-to-floor height is required for this equipment, the facade of these intermediate floors is usually treated differently from the adjacent occupied floors. Such floors are easily detected in most high-rise buildings.
4. *Signature design* Postmodern design in the 1990s deviated from the flattop style in favor of individuality and sculpture-type rooftops. With the sculptured roof design, cooling towers must be concealed in a different manner. They may be located at or near the ground level or may be concealed within the building.

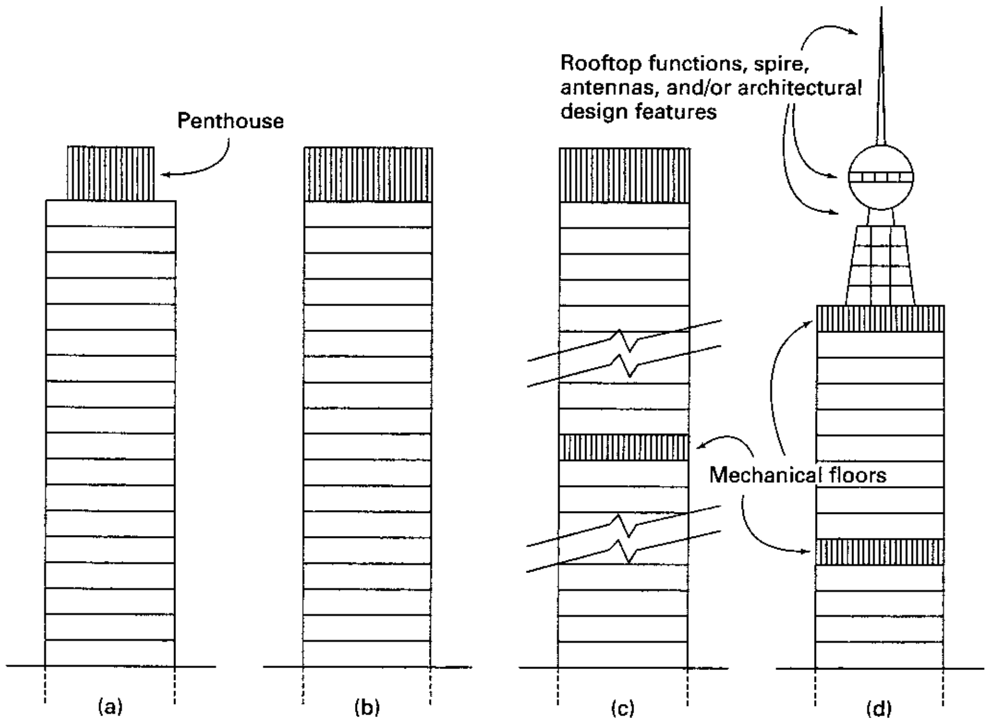


FIGURE 1–10
Fundamental style of modern high-rise buildings and skyscrapers. (a) Penthouse design, (b) flattop design, (c) floor bands design, and (d) signature design.

Illustrated in Figure 1–10 are the popular architectural design styles of modern high-rise buildings and skyscrapers:

- Penthouse design
- Flattop design with a full-size top floor
- Floor-band design with a number of M/E floors in between the regular floors
- Signature design with unlimited design configurations

Plates 1–8 (see color insert) show several world-famous high-rise buildings and skyscrapers. The Sears Tower in Chicago (Plate 1) has multiple flattop roof lines as the main M/E equipment floors. The extra-height M/E floors of the Far Eastern Plaza building in Taipei, Taiwan (Plate 2), on the lower, middle, and top levels are readily distinguishable from the rest of the occupied floors. The M/E floors for the Luijazui financial center to be constructed in Shanghai, China (Plate 3), are well concealed behind its fine-textured facade. Actually, there are principal M/E floors at 15-floor intervals that also accommodate refuge areas for emergency situations. Because of the unique linear roof line design, the cooling towers can be located only at the ground level. The regressed thirteenth floor of the Pierre Laclede building is an ingenious architectual design that transforms the mechanical floor into a positive architectual expression.

1.4 THE IMPACT ON CONSTRUCTION COST

1.4.1 Impact of Building Height on Construction Cost

When a building is taller it requires more time and hoisting equipment and complicated scheduling to raise the material to the upper floors. In fact, most construction workers may have to stay on the upper levels during the entire workday, losing productivity. The structural and M/E systems are more complex, and the method of construction is different. For a building taller than 10 stories, the unit cost per floor area increases about 5 to 15 percent for the next 5 stories and another 10 to 15 percent for each additional 5 floors. For example, if the unit cost for a 10-story building is \$150/sq ft, then the cost for a 25-story building, using 10 percent as the incremental cost, can be estimated as follows:

$$\begin{aligned}\text{Average unit cost} &= [(\$150 \times 10) + (\$165 \times 5) \\ &\quad + (\$182 \times 5) + (\$200 \times 5)]/25 \\ &= \$173/\text{sq ft}\end{aligned}$$

The wide spread in the incremental cost for the increased building height is to be expected, because the cost is very much affected by the site conditions, ease of material handling, architectural details, labor skills, and contractor's experience with constructing high-rise buildings. Nevertheless, the general rule can serve as a base for determining the impact of building height on the overall construction cost.

1.4.2 Impact of M/E Systems on Construction Cost

The impact of M/E systems on construction cost varies greatly depending on the type of building, standard of living of the country, architectural design, and M/E systems selected. The range of M/E systems costs in the United States for fully air-conditioned and high-quality buildings is given in Table 1–2. These values may serve as a general reference for modifying and refining the costs throughout the design process.

1.4.3 Impact on Operating Costs

The operating cost of a building includes the cost of routine maintenance, repairs, replacements, and utilities. Most architectural and structural components of a building (except the roof) are normally longlasting and do not need frequent replacement. This is not the case, however, for most M/E systems, which not only consume energy but also require ongoing maintenance and repair. Indeed, over a life cycle, the cost of owning and operating M/E systems may outweigh the initial capital investment of the entire building! Naturally, the importance of efficient M/E systems and management cannot be overemphasized.

TABLE 1–2
Range of M/E systems costs of buildings

	Percent of Total Building Cost		
Type of Occupancy	*Low*	*Medium*	*High*
Computer centers	30	45	60
Department stores	20	25	30
Hospitals (research)	30	40	50
Hospitals (clinical)	25	30	35
Hotels (residence)	20	30	35
Hotels (convention)	25	35	40
Offices (general)	20	25	35
Offices (high-tech)	25	35	45
Research laboratories	30	40	50
Residential, single-occupancy	10	15	20
Residential, high-rise	15	20	25
Retail, individual stores	10	20	25
Retail (department)	20	25	30
Schools, elementary	15	20	30
Schools, secondary	15	25	35
Universities and colleges*	20	30	40

*Buildings other than those used for classrooms follow the space required for specialty-type buildings such as laboratories, computer centers, and residences.

1.5 THE IMPACT ON HIGH-RISE BUILDING DESIGN

In high-rise building design, there is no single solution to a problem. Two buildings of similar size and configuration located on different sites may favor different M/E systems and central plant locations. Climate and the economic and cultural background of a country are other factors that affect the selection of an M/E system.

As indicated in Table 1–1, M/E system equipment takes considerable space. For example, the average M/E floor space in an office building is about 4 percent of the total building gross floor area. In other words, for a 25-story building with a gross floor area of 500,000 sq ft, 20,000 sq ft should be initially allocated as M/E equipment space. This is equivalent to one full floor of the building. Similarly, two floors are needed for M/E equipment in a 50-story building, and four floors in a 100-story building. Needless to say, these are not incidental spaces that can be added at will, except during the initial programming phase of the project. Optimum solutions are a result of close coordination between the architect and the M/E engineers.

Space for M/E equipment may be centralized or decentralized, depending on the system selected. With either plan, there is always a need for on-floor (local) equipment and distribution (shaft) space on every floor. The major difference is that centralized planning concentrates major equipment on one or two floors with smaller on-floor M/E spaces, whereas the decentralized plan is just the opposite.

Without exception, all high-rise buildings have one or more underground levels for utility service, delivery of supplies, fuel storage, parking spaces etc. Furthermore, underground levels provide better structural stability for the foundation of the building. More important, underground parking for automobiles is an unavoidable demand in most city codes. Normally, an M/E central plant should be located in an underground level; however, this is not always feasible, since M/E system risers must be close to the core of the building, which frequently hinders access to and from the parking garage. For this and other reasons, the M/E central plant may be located on the rooftop or on other, intermediate levels. Plate 10 shows the hoisting of the cooling tower to the roof, and the arrangement of M/E equipment in central

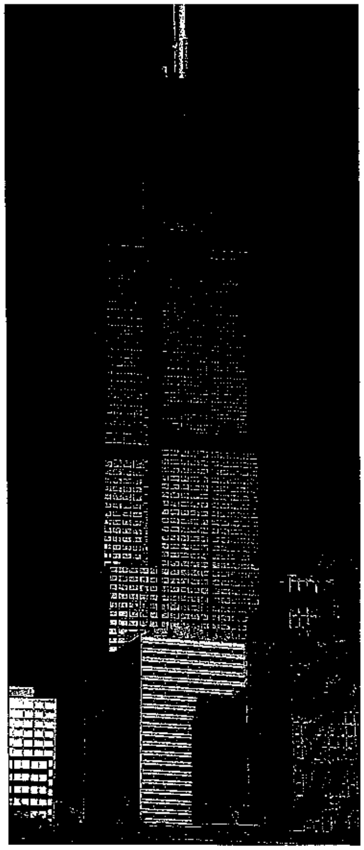


Plate 1 Sears Tower in Chicago, USA. (Roof: 1450 ft., antenna base: 1515 ft., 110 stories) *Owner:* Sears-Roebuck & Co. *Architect/Engineers:* Skidmore, Owings & Merrill, USA.

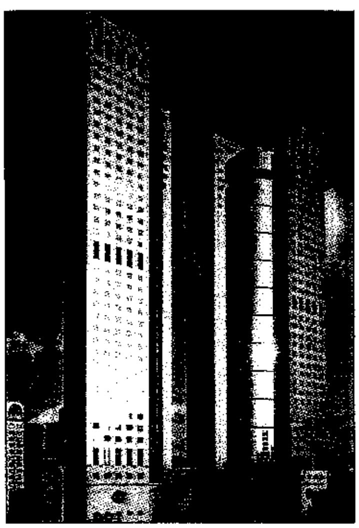


Plate 2 Far Eastern Plaza in Taipei, Taiwan. *Owner:* Far Eastern Company, Taiwan. *Architects:* P&T, Hong Kong and C.Y. Lee & Partners, Taiwan. *M/E Engineers:* William Tao & Associates, USA; H.C. Yu & Associates, USA; and Continental Engineering Consultants, Taiwan.

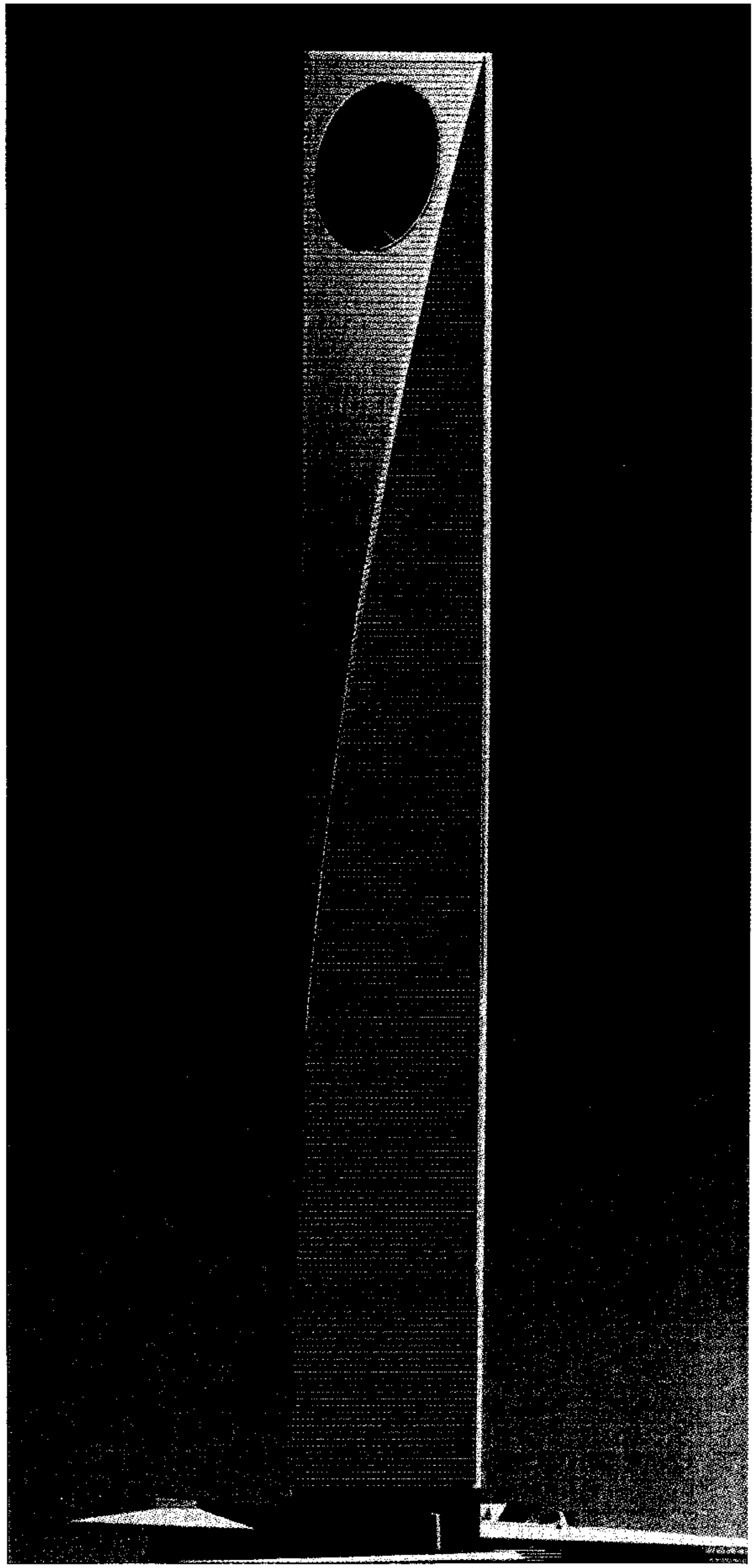


Plate 3 Luijazui Financial Center in Shanghai, China. (1509 ft., 95 stories) *Owner/Developer:* Mori Building, Japan. *Architects:* Kohn Pedersen Fox, USA; Mori Building, Japan; and East China ADRI, China. *M/E Engineers:* Shimizu Company, Japan.

Plate 8 Southwestern Bell Telephone Company in St. Louis, USA. *Architects:* Hellmuth, Obata & Kassabaum, USA. *M/E Engineers:* William Tao & Associates, USA.

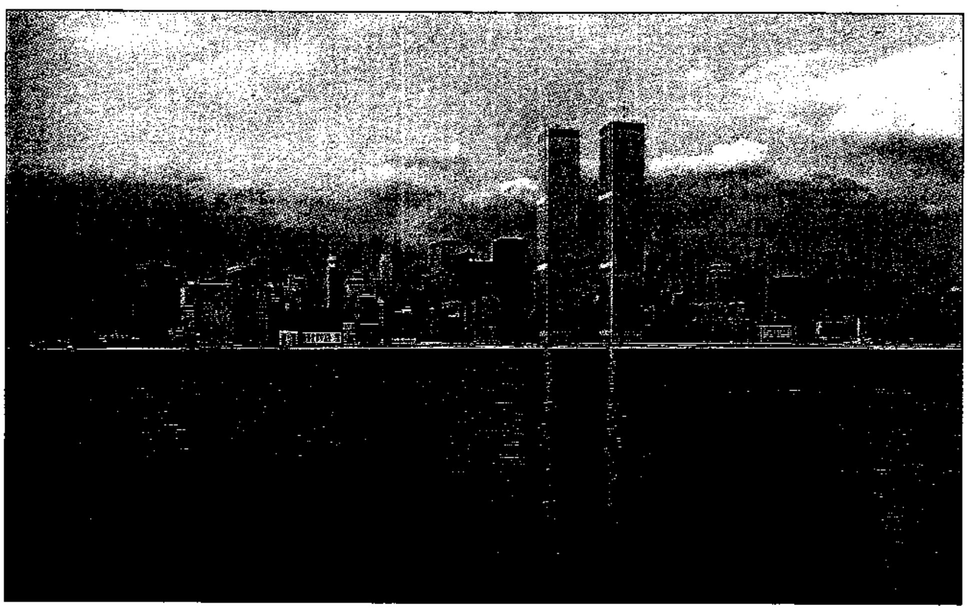


Plate 7 New York World Trade Center, USA. (110 stories, 1350 ft.) *Owner:* Port Authority of NY & NJ. *Architects:* Minoru Yamasaki Associates. *Mechanical Engineer:* Jaros Baum Bolles, NY. *Electrical Engineer:* Joseph R. Loring, NY.

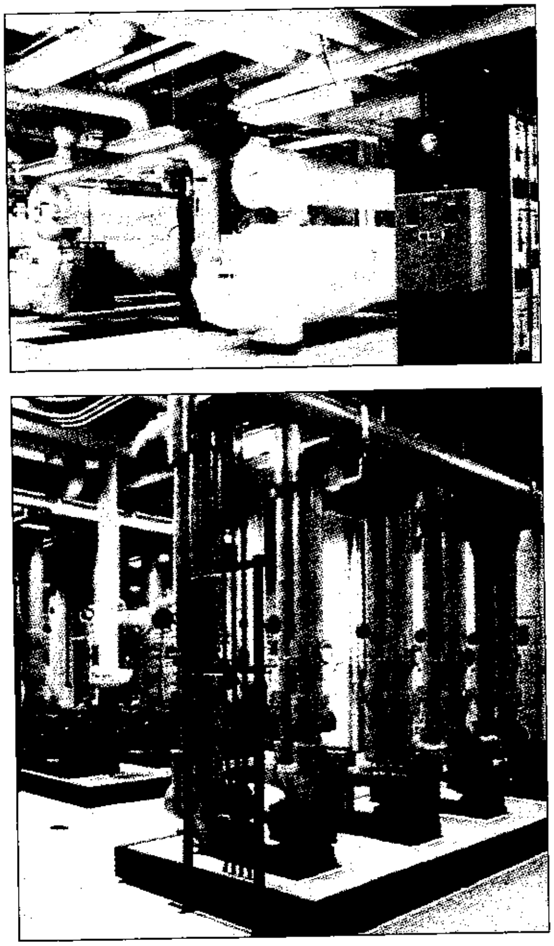
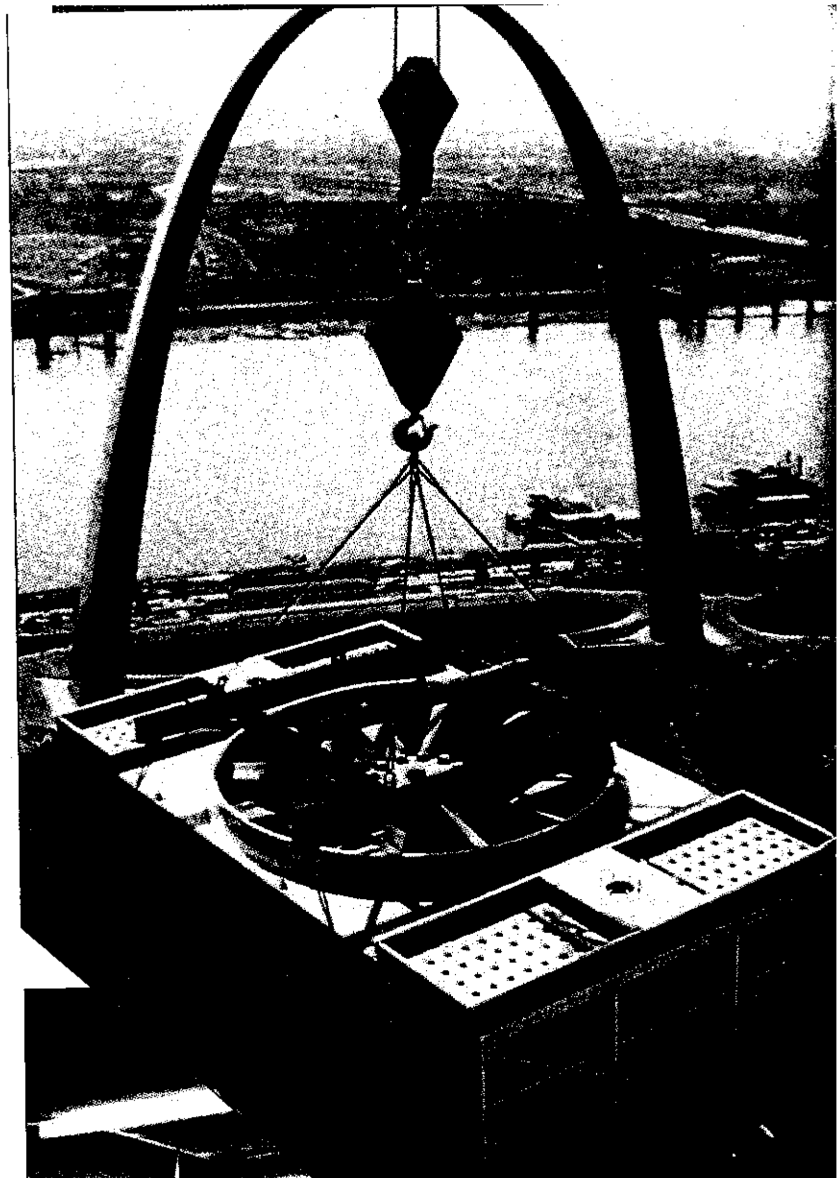


Plate 9 M/E equipment and cover photos: Pierre Laclede and Equitable Buildings. *M/E Engineers:* William Tao & Associates, USA.



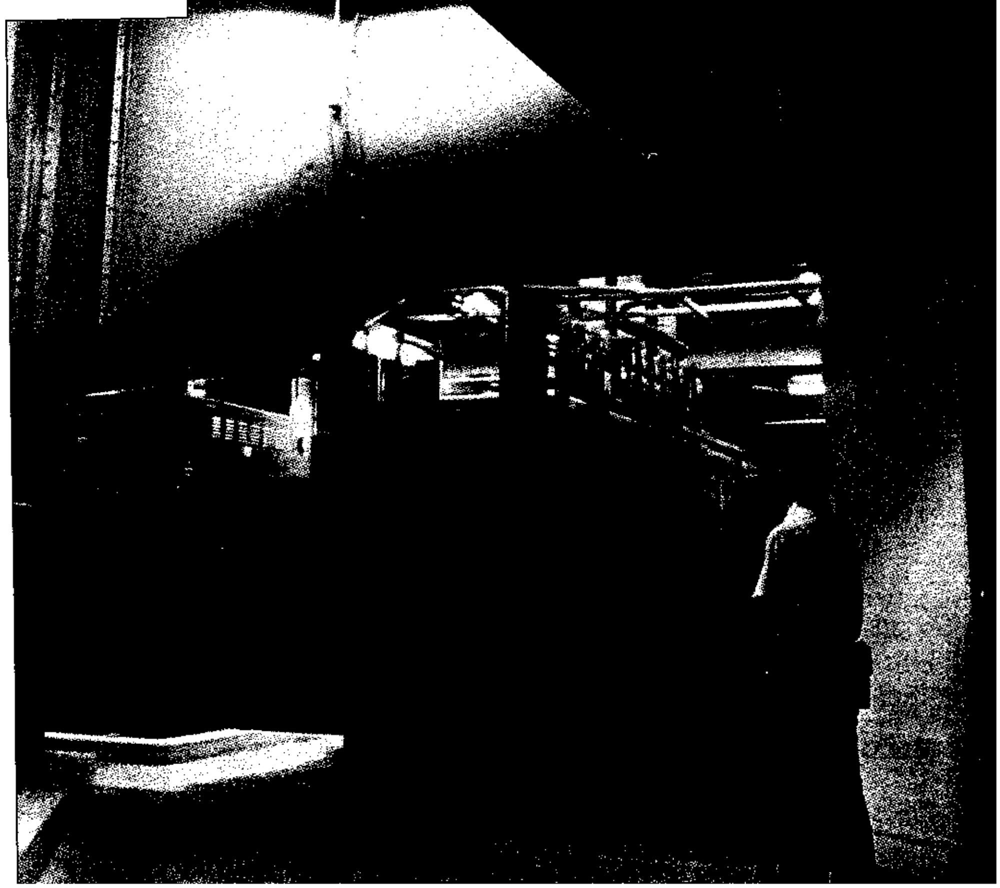


Plate 10 Gateway Arch and Westward Expansion Museum in St. Louis, USA. *Owner:* National Park Service, USA. *Architect:* Eero Saarinen, USA. *M/E Engineers (museum/arch HVAC upgrade):* William Tao & Associates, USA.

TABLE 1–3
Reasons favoring upper or lower central plant locations

In Favor of Upper Levels	*In Favor of Lower Levels*
▪ When a clean architectural roof line is desired. Elevator overtravel requires that the penthouse protrude over the topmost floor. If the central plant is located at the top, the elevator penthouse can be contained within the same space. ▪ When the cooling tower must be located on the roof. ▪ When a fuel-fired heating plant is used. Vertical shaft space for the flue stacks on all floors is eliminated. ▪ When the outside air quality is a concern. In general, the air quality in urban settings is better at higher elevations than at ground level. ▪ When exhaust/relief air, such as exhaust from chemical fume hoods, cannot be discharged near ground level. ▪ When locating the central plant at a lower level will interfere with an underground parking plan. ▪ When the reduction of roof heating/cooling load is significant; the central plant acts as a baffle zone.	▪ When cooling/heating energy is supplied from district sources remote from the building. ▪ When the rooftop is used for other purposes, such as swimming pools, a garden, or a restaurant, a club. ▪ When the construction schedule is such that earlier occupancy of the lower floors is desired. A lower floor location for the central plant allows an earlier start and completion of the M/E systems. ▪ When attenuation of vibration and noise in the central plant is too costly.

equipment spaces. Factors affecting the location of a central plant include the following:

- Accessibility for loading/unloading equipment.
- Proximity to the outside air supply and exhaust air discharge.
- Adequacy of floor height.
- Interference with a convenient parking plan.
- Safety. Some equipment, such as boilers, chillers, and liquid-filled transformers, contains considerable stored energy or toxic material. This equipment should be confined within fireproof walls.
- Proximity of system components, such as the chiller and the condenser, and the cooling towers.
- Ease of maintenance.
- Vibration and noise from equipment.
- Aesthetics. Last but not least, a central plant may detract from or enhance the architectural concept. A typical example is the Hong Kong–Shanghai Bank, in which exposed structural and M/E elements are a means of architectural expression.

Table 1–3 lists some of the reasons for locating the central plant on the lower or upper levels.

1.6 ENERGY AND ENERGY CONVERSION

1.6.1 Common Energy Sources

All buildings require electrical power, which is normally supplied by the electrical utility. When utility power is not available, or when an on-site electrical power source is required, the supply of fuels such as gas, oil, and even coal may need to be considered in the planning process. In addition, HVAC systems also require fuel for heating and cooling.

1.6.2 Efficiency of Energy Conversion Processes

Energy exists in the form of heat, light, chemical, sound, mechanical, and nuclear energy. According to the laws of physics, energy can be neither created nor destroyed but can be converted from one form to another. Energy conversion is never 100 percent efficient. The loss is usually in the form of low-level (temperature) heat, which is not readily useful. Table 1–4 indicates the normal conversion efficiency of common energy sources through the combustion process. The electric heat pump process utilizes electrical energy to "transport" heat energy from the building exterior to the building interior; this is really not an energy conversion process but rather a transfer process. This process is analogous to the transportation of goods by train or truck. The energy consumed by the train or truck is only for overcoming the friction loss of road and the wind resistance, not the mass of the goods. The performance (transport efficiency), called the coefficient of performance (COP), may vary from 1.5 to 3.0. A COP of 2.0 means that the electric heat pump process can transport two units of heat energy for each unit of electrical energy consumed, in consistent energy unit.

The efficiency of energy conversion depends on the datum selected for calculations, which differ drastically

TABLE 1–4
Common energy sources and conversion efficiencies

Fuel	*Unit of Measure*[1]	*Nominal Heating Value/Unit, Btu (kJ)*	*Combustion Efficiency, %*
Natural gas	cu ft	1000 (1055)	70–85
LP (propane gas)	gal	93,000 (98,000)	70–85
No. 1 oil (diesel)	gal	138,000 (146,000)	75–80
No. 5 oil (heavy)	gal	145,000 (153,000)	72–82
No. 6 oil (bunker C)	gal	153,000 (161,000)	75–80
Soft coal (bituminous)	lb	13,000 (14,000) 13,700 (14,800)	75–85
Hard coal (anthracite)	lb	12,500 (13,500) 13,200 (14,300)	75–85
Electrical resistance	kWh	3413 (3600)	100[2]
Electric heat pump	kWh	5100 (10,200)	150–300[3]

[1] 1 gallon = 3.78 liters; 1 cubic foot = 28.32 liters; 1 pound = 0.454 kilogram.
[2] Electrical to heat energy conversion efficiency.
[3] Denotes coefficient of performance (COP) percent or 1.5–3.0 per unit.

at the building boundary and at the initial energy source, as demonstrated in Figure 1–11.

1.7 THE IMPACT OF BUILDINGS ON GLOBAL ENVIRONMENT

1.7.1 Impact of Technology on Global Environment

Globally there has been an increased use of fossil fuels, including oil, coal, and natural gas, for industrial production, transportation, electrical power generation, building heating, cooling, and lighting. This has increased carbon dioxide (CO_2) levels in the atmosphere and its rate of absorbing solar energy. This phenomenon, known as the *greenhouse effect,* is suspected to be the primary cause of global warming.

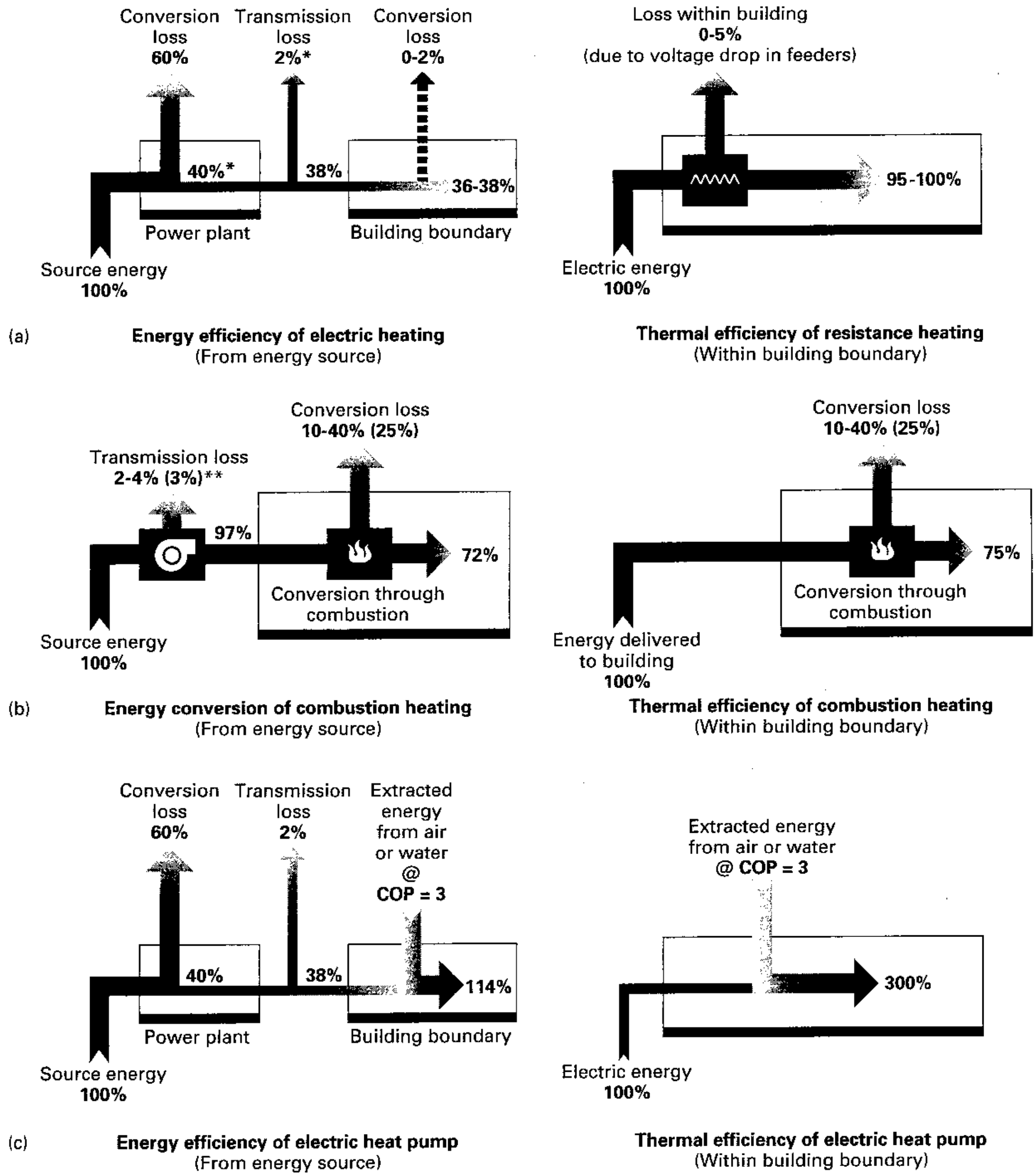
Until the 1990s, chlorofluorocarbons (CFCs) were the primary refrigerant in refrigeration and air-conditioning systems. CFCs are also used as cleaning and aerosol agents. Their increased use has caused the destruction of the ozone (O_3) layer in the lower part of the stratosphere, 15 to 20 miles above the earth. The ozone layer decreases the amount of ultraviolet energy that penetrates down to the earth's surface. With the destruction of the ozone layer, more harmful, cancer-causing ultraviolet energy reaches the earth. International agreement has banned the future use of CFCs and promotes the use of alternative chemicals such as hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), which do not deplete the ozone layers so much; however, these chemicals themselves are by no means harmless. The most effective way to reduce environmental damage from manmade pollutants is to minimize the use of energy through more efficient design and controls. See Chapter 19, "Sustainable Design," for current practice in building design practices.

1.7.2 Air Pollutants Due to Building Energy Consumption

According to statistics, the United States consumes more than 2 trillion kilowatt-hours of electrical energy annually, about one-third in buildings. If the annual energy consumption in buildings is reduced by a mere 20 percent through better design and management, total CO_2 emissions may be reduced by about 150 million tons, the equivalent of taking 30 million cars off the road. The impact of building energy conservation on the environment could not be more dramatically demonstrated.

Table 1–5 lists air pollutant by-products from energy conversion processes. For every kilowatt-hour of electrical energy (3413 Btu equivalent) consumed in a building, about 10,000 Btu of fuel is burned at a coal-fired power generation plant, releasing 2.4 lb (1.09 kg) of CO_2, 0.02 lb (9 g) of SO_2, and 0.01 lb (4.4 g) of NO_x.

The amount of each air pollutant due to combustion can be calculated by knowing the chemical composition of the fuel and the chemical reactions that occurred during combustion. In the combustion process, the chemical elements of fuel—carbon, having a molecular weight of (12), hydrogen (1), sulfur (32), and nitrogen (14)—react with oxygen (16) to form CO_2 (44), SO_2 (64), and NO_x (varies). For every unit weight of carbon combusted, (44/12) or 3.66 unit weights of CO_2 are generated. When the chemical content of a fuel is known, then the amount of each air pollutant can easily be calculated. Table 1–5 lists the amount of air pollutants



* Typical central plant efficiency varies from 35% to 45%; 40% represents the median value.

** Loss due to means of transportation, such as energy consumed by pumping stations or trucks

■ **FIGURE 1–11**

Energy conversion efficiencies of the heating process. The efficiencies differ drastically at the energy source and at the building boundary. (a) *Electric heating:* The conversion is between 95% to 100% efficient, since nearly all electrical energy is converted into useful heat within the building; however, for each unit of electrical energy (kilowatt-hour), approximately three units of fuel (coal, gas, or oil) energy are consumed at the power plant. Thus, the overall energy conversion efficiency is only 36 to 38% when energy source is the datum. (b) *Combustion heating:* To burn fuel in a building heating plant (boiler or heater), the efficiency is only about 75% at the building boundary, but it is nearly the same at the energy source when a small transportation loss is included. Thus, with building boundary as the datum, electric heating is most efficient, but with energy source as the datum, combustion heating is more efficient. (c) *Electric heat pump:* Using electrical energy to pump heat from outside air or underground water to heat the space is called the *heat pump process.* The COP may be as high as 3.0, or 300%, within the building boundary, and slightly better than 100% at the energy source.

TABLE 1-5
Air pollutants produced from energy conversion

	Air Pollutants Produced, g (lb)		
Energy Converted or Consumed	CO_2	SO_2	NO_x
1 gallon of fuel oil by combustion[a]	10,500 (23.1)	45.0 (0.10)	18.3 (0.04)
1 gallon of gasoline by automobiles[b]	8500 (18.8)	37.0 (0.08)	15.0 (0.03)
1 pound of coal by combustion[c]	1090 (2.4)	9.0 (0.02)	4.4 (0.01)
1 therm of natural gas by combustion[d]	6350 (14.0)	Nil (−)	24.0 (0.05)
1 kWh of electric energy generated by oil[e]	860 (1.9)	3.7 (0.008)	1.5 (0.003)
1 kWh of electric energy generated by gas[e]	635 (1.4)	Nil (−)	2.4 (0.005)
1 kWh of electric energy generated by coal[e]	1090 (2.4)	9.0 (0.02)	4.4 (0.01)

Notes: [a]Calculated by using fuel oil containing 85 percent carbon and 12 percent hydrogen, and 7.4 lb/gal.
[b]Calculated by using gasoline mixture of C_8H_{18} and (C_nH_{2n+2}) having 84 percent carbon and 15 percent hydrogen, and 6.1 lb/gal.
[c]Calculated by using bituminous coal containing 65 percent carbon and 3.8 percent sulfur.
[d]Calculated by using mixture of methane (CH_4) and ethane (C_2H_6) and 100,000 Btu/therm.
[e]Data from Green Light Program, Environmental Protection Agency.

generated by energy conversion or consumption. The amount is staggering.

For example, a large, 600,000-sq-ft office building has an average demand of 8 W/sq ft (0.008 kW/sq ft) of electrical power for its heating, air conditioning, lighting, plumbing, fire protection, elevators, and other equipment. If the building operates about 4000 hours a year, the annual electrical energy consumed will be

$$600{,}000 \text{ sq ft} \times 4000 \text{ hr/yr} \times 0.008 \text{ kW/sq ft} = 19{,}200{,}000 \text{ kWh/yr}$$

Assuming that the utility's power-generating plant is coal-fired, then from Table 1–5, the amount of each air pollutant generated by the power plant that is attributable to electrical usage in this office building is as follows:

- Carbon dioxide (CO_2): 19,200,000 × 2.4 = 46,000,000 lb/yr
- Sulfur dioxide (SO_2): 19,200,000 × 0.02 = 384,000 lb/yr
- Oxides of nitrogen (NO_x): 19,200,000 × 0.01 = 192,000 lb/yr

Measured by any scale, the amount of pollution attributable to the operation of this single building is staggering. If a 10 percent energy conservation can be achieved through better design and controls for this building then the CO_2 emission alone will be reduced by 3,600,000 lb/yr, and other pollutants proportionately.

1.8 ENVIRONMENTALLY RESPONSIVE AND INTEGRATED DESIGNS

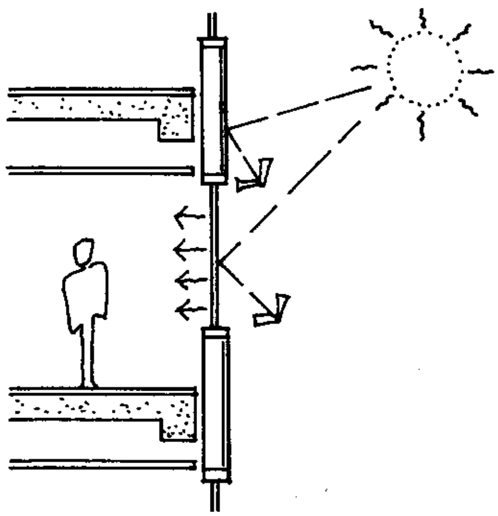
With the continued deterioration of our environment and consumption of our limited natural resources, we have pushed the environment to the threshold at which design alternatives must be seriously considered and pursued. The nations of the world have gathered together to discuss these alternatives and to develop a global framework for addressing them, with the consensus that it is everyone's responsibility to seek the means to conserve our resources by reducing energy consumption.

Historically, for a variety of economic, technological, or logistical reasons, building designs have not fully addressed environmental issues; however, the general public and various governments are seeking to make a committed change. This change has encouraged design teams, builders, and users to be more responsible and flexible in establishing building programs. The result has been the application of "green" issues to buildings, that is, creating environmentally responsive and integrated designs.

1.8.1 The Architectural Facade

A high percentage of the energy consumed in a building is due to the response of heating and cooling loads to solar (radiation) or conductive/convective heat gains or losses. There are some gains from the occupants and equipment in the building, but there are more solar gains through the external facade or "skin" of the building.

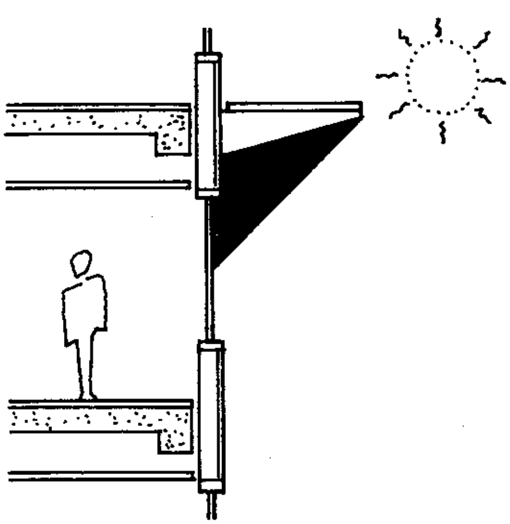
The conventional wall or "single-skin" facade (Figure 1–12) typically controls the solar gain by controlling the extent of transmittable surfaces, or windows/vision glazing in the building, or by adding reflective coatings and tints to the glass surfaces to reduce solar load. These solutions are effective but are not optimal, since they permit solar radiation to reach and penetrate the glazing. An equal concern from the user's point of view is that, owing to the reduced sizes of openings or the quality of coatings and tints, there is a reduction in natural daylight entering the building and a reduction in true or clear views of the exterior environment.



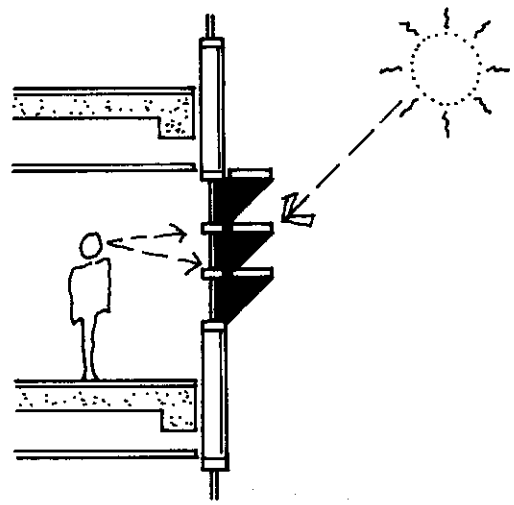
■ **FIGURE 1-12**
Single-skin facade.

The most effective way of controlling solar gain is to prevent the solar radiation from reaching the glazing surface. If this can be achieved, then less cooling system capacity (due to reduced heat gains) will be required, and consequently, there will be less energy consumption. Typical shading solutions following this approach include external shading devices, with a horizontal orientation for a high-angle sun and a vertical one for a low-angle sun.

To be effective, overhangs should have sufficient depth and cutoff angle; however, excessively deep overhangs or, alternatively, frequently spaced overhangs, may be considered visually distracting because they can cause "tunnel vision" (Figures 1–13 and 1–14).

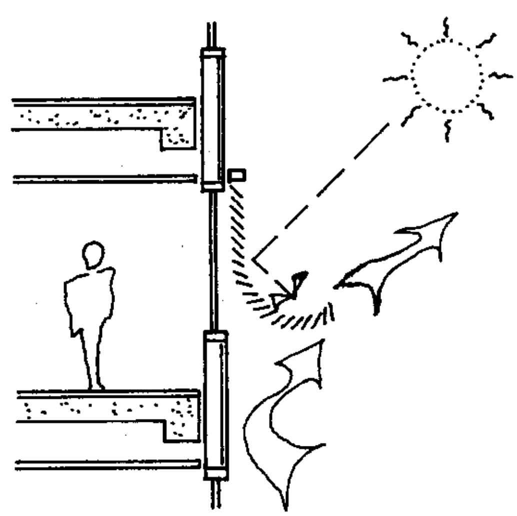


■ **FIGURE 1-13**
External shading.

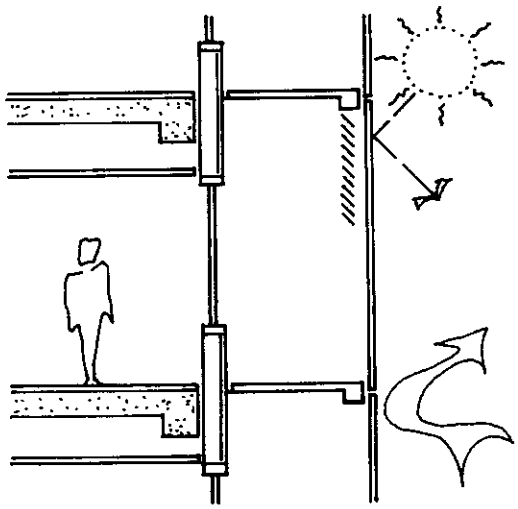


■ **FIGURE 1-14**
External shading.

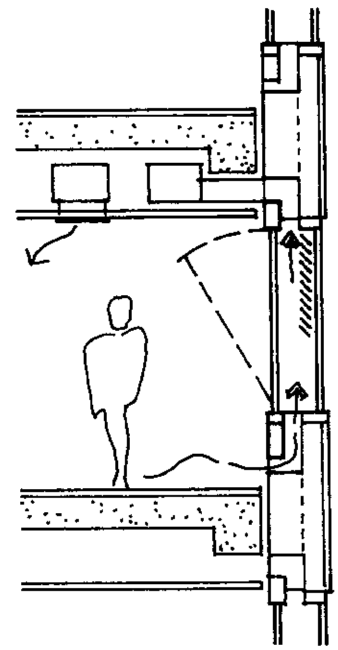
An additional problem with such external shading solutions is that they can be technically difficult to resolve, especially in buildings such as high-rises, where wind forces can be extreme, requiring highly engineered and uneconomical solutions (Figure 1–15). More recent solutions involve the "cavity" or "double-skin" facade (Figure 1–16). The principle here is that the cavity or zone between the two skins forms a buffer between the conditions of the exterior climate and the interior workplace. This zone can be utilized in a variety of ways to relieve the impact of the outside environment on the internal workplace. The buffering or moderating effect, in turn, leads to a wider range of M/E possibilities for the conditioning of the



■ **FIGURE 1-15**
Shading and wind.



■ **FIGURE 1-16**
Double-skin facade.



■ **FIGURE 1-17**
Double-skin cavity, 10″–18″.

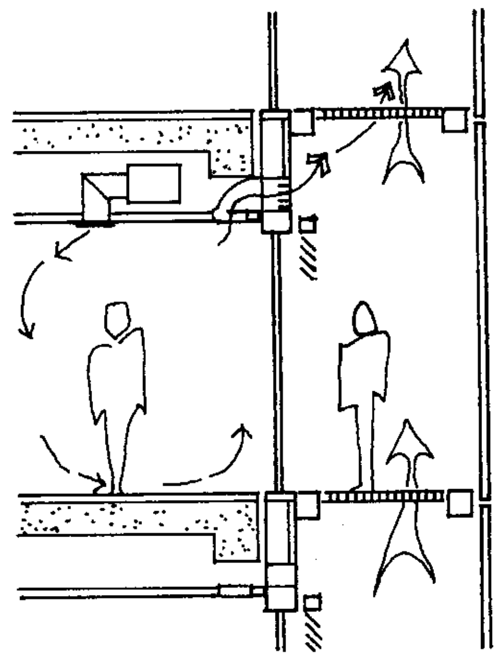
space—possibilities that cannot be considered in the conventional single-skin facade. Specifications for M/E solutions can be lowered or low-tech in nature, leading to a reduction in energy consumption.

The foremost advantage of the double skin is that, regardless of whether a building is low-rise or high-rise, the solar radiation can be effectively prevented from reaching the transmittable surface. The protection of the outer skin permits the use of more conventional shading devices such as blinds. The obvious advantage of the blind is that it is an economical alternative to an external shading device. But equally important is that it offers the user or the tenant the choice of lowering or raising the blinds when protection from the sun is not required; by contrast, tinted glass and external shading devices are permanent.

1.8.2 The Technically Integrated Building

In simple terms, a double-skin facade functions as, and can be compared with, an insulated glass unit (IGU), or double glazing. As with any IGU, heat builds up in the cavity between the skins, so a careful assessment must be made to ensure that there are no excessive temperatures that may lead to failure of the unit or breakage of glass. If one imagines expanding or pulling apart the skins and recognizes this heat buildup and the notion of thermal buffering, then the design opportunities become apparent.

Double-skin designs can take numerous approaches; however, there are two that are typically considered with cavities ranging in depth from 10 to 18 in. (250 to 460 mm) to 3 ft (915 mm) (Figures 1–17 and 1–18).

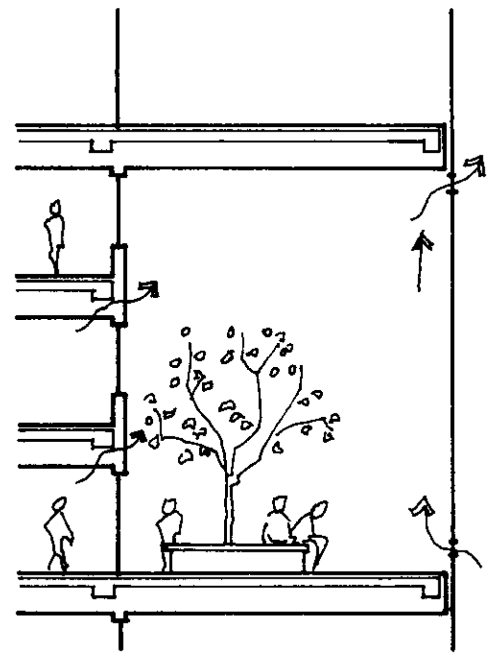


■ **FIGURE 1-18**
Double-skin cavity, 3′–0″.

First, controlling the temperature of the cavity can reduce the need for mechanical conditioning of the internal space. Blinds prevent the impact of direct solar radiation. Venting the cavity in summer can prevent heat from building up on the inner skin; such a buildup through convection would warm the space and increase cooling loads. Similarly, retaining the heat buildup in the cavity during winter assists in warming the inner skin and often leads to little or no additional heating requirements. This reduces not only operating costs and energy consumption but also capital costs. Alternatively, it allows the use of unitary electrical heaters in lieu of central heating systems, which require higher capital investment.

The cavity can also be utilized as a "thermal flue," drawing air (naturally or mechanically) from the internal space, which would normally require a ducted or ceiling plenum solution. This use of the cavity can reduce air distribution components (ducts and shafts); however, thermal calculations must be conducted to ensure that the humidity transferred from the internal space will not lead to condensation within the cavity.

Utilizing the flue aspect (this could also be an atrium) as a form of distribution can also lead to lower floor-to-floor heights by reducing distribution zone dimensions in the ceiling; lower heights mean less construction (and costs) or the ability to squeeze more floor area within the same height. This is particularly relevant where there are zoning restrictions on building height.



■ **FIGURE 1-19**
Communal atrium concept.

1.8.3 The Socially Interactive Design

In certain locales, there is increasing frustration among occupants of highly mechanically appointed buildings. The occupants feel removed from the natural environment, effectively trapped in a hermetically sealed environment and without any control over it. The cavity-wall concept gives people the possibility of opening the inner skin of the wall, as a window. Studies have demonstrated that the simple action of opening a window for ventilation and movement of air gives the occupant perceived comfort and satisfaction, even though the temperatures experienced from the cavity may be higher than those in the conditioned space. By acknowledging this user-participation factor, it may be possible for designers actually to raise the temperature criterion currently established for internal spaces, again reducing cooling loads and energy consumption. The pressure balance between floors in medium- or high-rise buildings must be carefully evaluated to control infiltration, exfiltration, smoke, and fire migration (this will be addressed in the chapters on HVAC and fire protection).

Taking the user-participation factor further by expanding the cavity into occupiable spaces in the form of communal atriums or ecocenters (Figure 1-19) provides an alternative to taking the elevator down 30 or 40 floors to get a breath of fresh air. These spaces, in turn, can make use of plants to consume CO_2, or can be utilized as chambers or plenums to mix fresh air with exhaust, thereby reducing vertical ductwork distribution and providing better zoning possibilities within the building.

1.8.4 Alternative Technologies

There are many new technologies that can be applied now or in the near future in building design. The following are just a few that have been adopted in some buildings, with varying degrees of success. They must be carefully analyzed for practicality and economic value.

Glass with Photovoltaic Cells

The glass industry has made great advances in recent years to explore environmentally responsive roles. The integration of photovoltaic cell technology into glazing units is an excellent example of utilizing solar energy by means of the vast surfaces that typically enclose a building.

Variable Transmittance of Glazing Material

The development of a glass that is translucent or opaque depending on the intensity of the sun, reducing solar transmittance as well as glare, is in the early research stage.

Radiant Ceiling

In certain geographical locations, the use of chilled ceilings may be an alternative solution. This method utilizes the distribution of moderately cool water through pipes or panels much like a heated ceiling uses hot water. Unlike a fan coil or VAV system, which uses low-temperature water, this system utilizes water at its natural temperature without refrigeration.

Wind Generation

Wind generators in the form of propeller blades or catenary structures are readily used in open field sites to generate electricity from wind power. As technology advances to reduce the size of these devices it may be feasible to utilize this form of free energy on high-rise buildings where winds are inherently strong at upper elevations.

Thermal Storage

Thermal storage in various forms such as chilled water, ice, hot water, or liquid refrigerants are increasingly used to reduce the peak building power demand. The stored energy will indirectly reduce the need for the construction of new power plants and their impact on the greater environment. The methods and techniques of thermal storage are discussed in Chapters 2 to 7.

1.8.5 LEED

The increased global interest and demand for environmentally responsive buildings has been the catalyst for the LEED which stands for Leadership in Energy and Environmental Design. Green Building Rating System is a voluntary rating system developed by the U.S. Green Building Council (USGBC) under contract for the U.S. Department of Energy (DOE). It is intended as a guide for use by commercial and public building project teams—owner, architect, engineer, and contractors—to promote green and sustainable buildings in both new construction and major renovation projects.

The rating system covers every aspect of a building project regarding the environment, natural resources, and indoor environmental quality. It provides a checklist of prerequisite minimum requirements as well as additional credits for specific design factors and alternatives in the following categories:

- *Sustainable sites* Prerequisites for erosion and sedimentation control; credits for site selection, impact of urban redevelopment, transportation, stormwater management, exterior design, and light-pollution control
- *Water efficiency* Credit for water use efficiency in landscape and building interiors
- *Energy and atmosphere* Prerequisites for fundamental building system commissioning, energy performance, and CFC refrigerant reduction; credits for optimizing energy performance of building HVAC systems, utilization of renewable energy, and minimizing the impact of ozone layer depletion of the atmosphere
- *Material and resources* Prerequisite for provisions for storage and collection of recyclables; credits for utilization of reused building materials, resources, recycled products, and locally or regionally available materials
- *Indoor environmental quality* Prerequisite for minimum indoor air quality (IAQ), tobacco-smoke control; credits for carbon dioxide monitoring, effective ventilation, the use of low-emitting materials, thermal comfort, daylight, and views to the outdoors
- *Innovation and design process* Credit for innovative designs that are not covered by LEED such as acoustic performance, education of occupants, community development, or life-cycle analysis of material choices

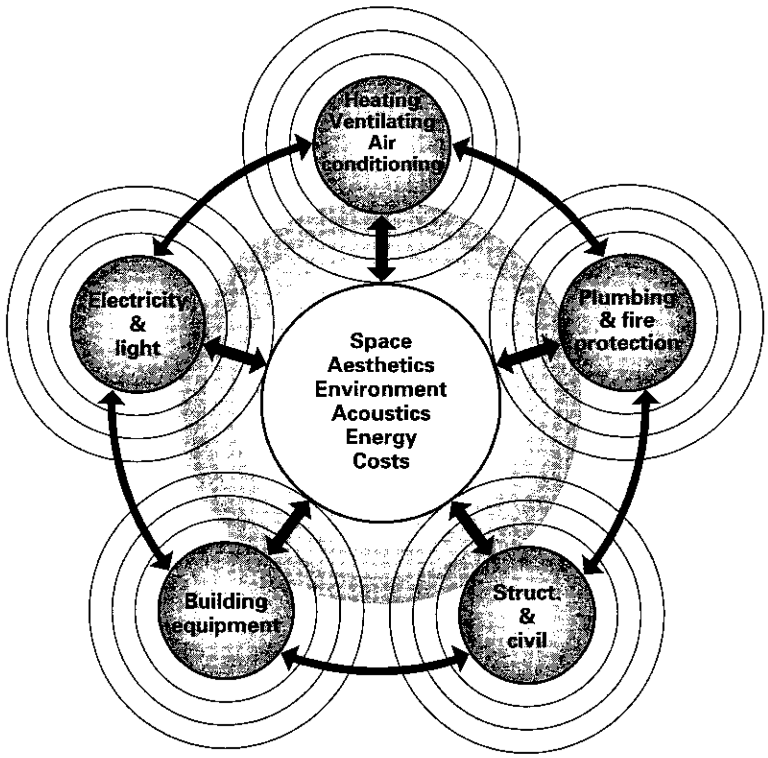
Certification is given to buildings that meet all prerequisites, and additional credits are awarded to recognize the efforts of the building team for their contribution toward a more sustainable world. LEED guidelines (currently pilot versions) are also available to cover existing building's operations and commercial interiors.

Sustainable design is not new. In fact, the concept was practiced in Europe long before it was recognized in the United States. Nevertheless, the LEED rating system promoted by the USGBC is certainly a step in the right direction. There are imperfections in the document process, which frequently lead to loopholes and misuse, but as the document continues to improve, it will serve the ultimate goal: a better world in which to live. Chapter 19 addresses the many issues concerning sustainable design of the building environment.

1.9 SYSTEM INTERFACING

The various topics covered in this chapter—from space planning and other architectural concepts to the global environment—are all interrelated. A decision in one area affects all the others. Figure 1-20 illustrates the need for close coordination and interfacing among the various design disciplines, revolving around architectural and engineering decisions.

The design of modern buildings requires a team effort. No single designer or professional knows all the solutions. Building design and construction is analogous to health care, in which the internist is the prime coordinator of a patient, with the support and



■ **FIGURE 1–20**
Interfacing is necessary among the design disciplines to achieve a balanced solution as to optimum spatial relations, aesthetics, environmental quality, acoustics, energy efficiency, and cost-effectiveness.
(*Note:* Although civil engineering is normally limited to work exterior to buildings, it can be needed to interface on issues such as water storage for building fire protection systems, or groundwater resources for building heating or cooling systems.)

consultation of specialists such as a cardiologist, radiologist, ophthalmologist, dentist, and pathologist, as well as the pharmacist, researcher, manufacturer, and hospital administration. In building design and construction, the architect is the prime professional on a project, with the support and consultation of specialists such as civil, structural, mechanical, electrical, lighting, and acoustical engineers as well as contractors and construction managers. Only through a close interface among all professionals can a building achieve its optimum value, balancing function, cost, and quality.

1.10 CHECKLIST OF BUILDING AND M/E REQUIREMENTS

This section presents a comprehensive checklist that serves to determine the scope of building operational requirements and from which one can determine the scope and criteria of M/E systems. The checklist also is valuable in formulating the architectural concept, building configuration, space programming, and opportunities for system interfacing. Early identification of these requirements aids the architect in evaluating construction costs as well as in allocating space for M/E equipment, both within and outside the building. The checklist is divided into two parts: mechanical systems and electrical systems.

1.10.1 Mechanical Systems

Building mechanical systems include heating, ventilating, and air conditioning (HVAC); plumbing and sanitation (P&S); fire protection (FP); and specialty or auxiliary systems. A comprehensive list of services is shown in Table 1–6. Obviously, not all buildings require all services, nor does the list include all building types; thus, the list should be tailored to the needs of a specific project. Items followed with an asterisk (*) are especially important to pin down during the conceptual phase, as they have a major impact on the architectural design of the building's roof lines.

1.10.2 Electrical Systems

Building electrical systems include power, lighting, and auxiliary systems. The proliferation of electrical and electronic systems in building applications has greatly expanded the scope of electrical systems and has had a dramatic impact on construction costs and the complexity of planning. A comprehensive list of services is shown in Table 1–7. The list should be expanded or condensed to fit the needs of a specific project.

TABLE 1–6
Checklist of mechanical systems

Systems/functions marked with an asterisk (*) should be carefully evaluated during the preliminary design phase so that the design process may be orderly and effective.

System/Function	*Major Planning Considerations*
▪ Energy source (*) for all M/E systems	Gas, oil, electrical power, coal, central (steam, hot water, chilled water), alternative energy, etc.
▪ Environmental issues (*)	Control zones (humidity, temperature), natural ventilation, daylighting, solar shading, integrated and socially responsive design (green building), etc.
▪ Heat rejection (*)	Cooling towers or condensers (water, air-cooled), and location, etc.
▪ Heating/cooling distribution (*)	Central or unitary systems, etc.
▪ Central plant (*)	Capacities and locations, etc.
▪ Ventilation and exhaust (*)	Outside air (minimum, 50%, or 100%); general, food preparation, toxic gas, and special exhaust, etc.
▪ Automation	BAS or BMS, etc.
▪ Water source (potable)	Pressure, capacity, size, location, etc.
▪ Water source (gray) (*)	Pressure, capacity, size, usage (sanitary, irrigation), etc.
▪ Hot water	Generators or heat exchangers, etc.
▪ Sewage disposal (*)	Storm, sanitary, sewage treatment (on site or in building), public sewers, etc.
▪ Storm water	Roof, ground, discharge locations, sewer, etc.
▪ Subsoil drainage	Drainpipes, sumps, pumps, discharge, location, etc.
▪ Sanitary facilities	Plumbing fixtures, water, waste, soil, and venting, etc.
▪ F.P. water storage (*)	Lake, pond, tanks, location, and capacities
▪ Fire and smoke detection	Thermal and smoke detectors, etc.
▪ Fire and smoke containment (*)	Fire shutters, building compartmentation (by zone or by floor) Smoke exhaust, floor pressure controls, stair pressurization, etc.
▪ Fire annunciation	Alarm, public address, fire department, etc.
▪ Fire extinguishing (*)	Portable, automatic sprinklers and types
▪ Firefighting	Fire hose and standpipe, Siamese, etc.
▪ Fire pumps (*)	Single or cascading, energy (gas, diesel, or electric), etc.
▪ Lightning protection	Air terminals, grounding, etc.

1.11 THE BUILDING DESIGN AND CONSTRUCTION PROCESS

1.11.1 The Owner–Designer–Constructor Team

Whether the project is complex or a simple building, there must be three basic players—the owner, the designer, and the constructor. Each is responsible for performing a specific set of functions. Frequently, the roles of one or more players may be combined or consolidated. The basic functions and responsibilities of each player are as follows:

- *The owner* Responsible for the property, capitalization, scope of the project, approval of the design, and final acceptance of the project. Owner may represent itself or be represented by an agent, a developer, or an owner-appointed project manager.
- *The designer* Responsible for interpreting the owner's desire or program and developing a set of construction documents from which the project is to be constructed. The designer's team usually includes the architect, consulting engineers, landscape architects, and specialty consultants such as cost, code, energy, lighting environmental, traffic, urban planning, insurance, process, interior design, safety, security, communications, and vertical transportation. For building projects, the designer's team is usually headed by the architect with others as consultants. For industrial plants, highways, and bridges, the designer's team is usually headed by the primary design engineer with others as consultants.
- *The constructor* Responsible for translating the set of the construction documents into reality. The construction team may include the general contractor and specialty contractors such as mechanical, electrical, plumbing, fire protection, concrete, masonry, structural steel, carpentry,

TABLE 1-7
Checklist of electrical systems

Systems/functions marked with an (*) should be carefully evaluated during the preliminary design phase so that the design process may be orderly and effective

System/Function	*Major Planning Considerations*
▪ Normal power source (*)	Utility or on-site power (capacity, phase, and voltage) service entrance, substations, vaults, etc.
▪ Emergency power source (*)	Separate service, on-site generation, etc.
▪ Power distribution	Primary or secondary voltages, panels, and substation locations
▪ On-floor distribution (*)	Underfloor ducts, cellular floors, raised floors, ceiling conduit network, poke-through, etc.
▪ Emergency power distribution	Critical equipment load, emergency lighting, etc. Critical building loads, power source (batteries, UPS, etc.)
▪ Power for building equipment	Mechanical, food service, process, transportation (vertical, escalators), etc.
▪ Major lighting systems (*)	Light sources and method of mounting (surface, lay-in, pendent), etc.
▪ Lighting design and layout	Light sources, fixture selections, layout, and controls, etc.
▪ Emergency lighting	Exit, exitway, critical, and emergency, etc.
▪ Feature lighting	Architectural expression and building features, etc.
▪ Daylighting (*)	Fenestration, skylights, controls, etc.
▪ Exterior lighting	Site, landscape, building facade, security, etc.
▪ Telephone communications	Type, lines, stations, switchboard, features, facsimile, modem, etc.
▪ Data distribution (*)	Cables, wire closets, LAN, etc.
▪ Public address (PA)	Intercom, paging, and music systems, etc.
▪ Audiovideo (A/V)	Radio, TV, and signal distribution systems, etc.
▪ Satellite dishes (*)	Number, diameter, orientation, and location, etc.
▪ A/V transmission towers (*)	Radio, TV, microwave, etc.
▪ Time and signal	Clock and program systems, etc.
▪ Fire alarm	Interface with FP, HVAC, BAS, etc.
▪ Security systems (*)	CCTV monitoring, detecting, alarming, etc.
▪ Automatic controls	Interface with HVAC, elevators, fire protection, lighting, security, etc.
Specialty systems (*)	Numerous specialty systems

drywall, acoustic ceiling, flooring, painting, waterproofing, fireproofing, vertical transportation, curtain-wall, site, civil, roofing, and landscape. The constructor's team is usually headed by the general contractor unless the project is limited to only the work of a specialty contractor, such as air conditioning, lighting, electrical power, or information communications. In such case, the specialty contractor will act as the prime contractor with others as the subcontractors.

The relationships among the three groups of players or team members may best be illustrated by the three-ring diagram shown in Figure 1–21. In many projects, the owner may double up as the constructor or the designer, or vice versa. Regardless of the organization, the functions represented by the team members remain unchanged, and all members must work closely and harmoniously for the construction project to proceed smoothly and effectively.

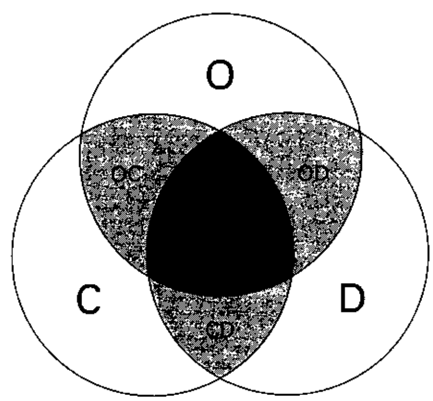


FIGURE 1-21
The interrelationships of the owner (O) designer (D) constructor (C) team of a construction project. Depending on the organization and complexity of a project, the team members may be combined, but the primary functions and coordination of those functions remain unchanged.

1.11.2 The Design and Construction Process

In the early years, buildings could be constructed without design, or could be designed while construction was in progress. Electrical wiring, lighting, and heating systems were usually installed with wiring and piping exposed on ceiling or walls. These crude and aesthetically unattractive methods are not acceptable in a well-developed society, as all building components must be properly integrated and concealed in walls, floors, or columns as appropriate. Furthermore, the structural and mechanical components can frequently be utilized to conserve space and reduce cost. Thus, precisely coordinated documents must be prepared before the construction can proceed. This approach is known as the *design–bid–construct* method: The owner selects an architectural–engineering team to prepare a set of complete drawings and specifications, which are then given to several qualified contractors, who submit bids stating a firm construction cost. When a contractor is selected construction proceeds, and the design team monitors the construction progress until the project is completed and accepted by the owner.

In the interest of shortening the total project time, several shortcut approaches can be used. In the *fast-track* process early design packages, such as the site work, the foundation work, and the structural steel work are issued to the contractor to start construction before the other packages are completed. The construction time is shortened considerably, but with increased risk of errors and construction variations. Designers and constructors must be experienced to work on a fast-track pace.

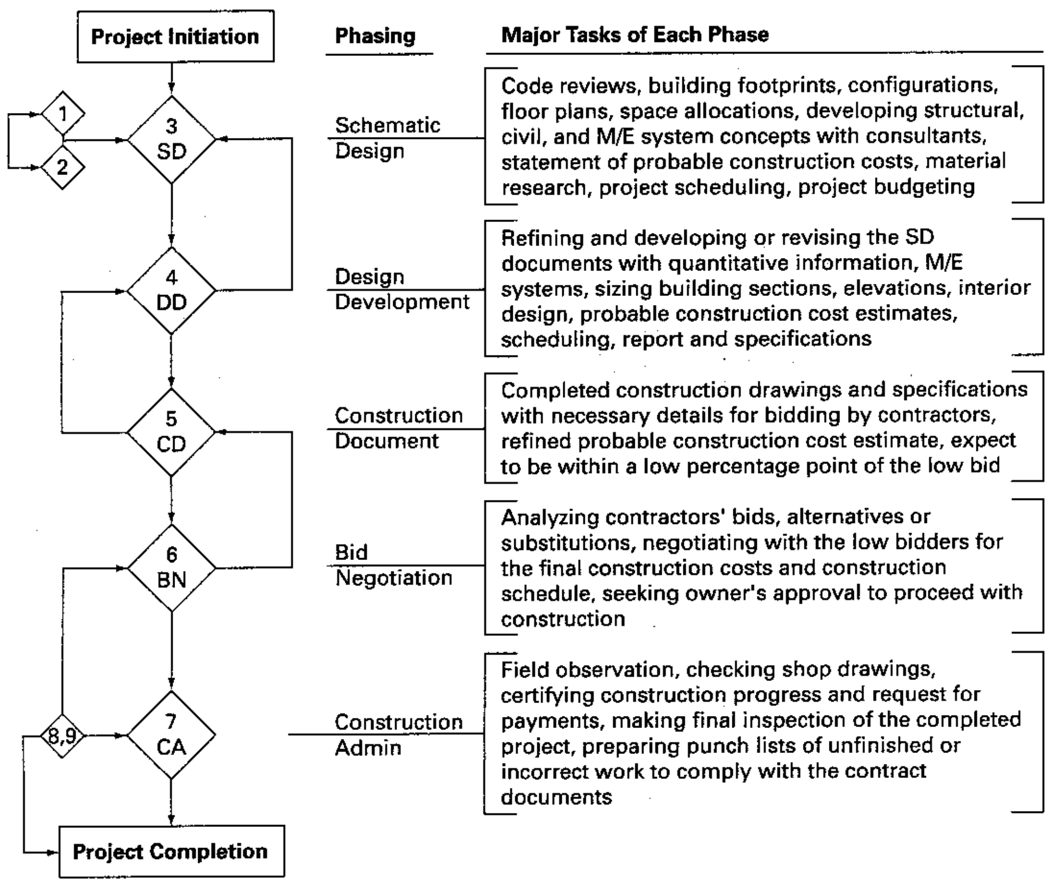


FIGURE 1-22
Building Design–Construction Procedure Flow Diagram
The flow diagram depicts the recommended procedure by the American Institute of Architects and its affiliated Engineering Societies and Construction Associations.
Phase 1—Predesign Services, Phase 2—Site Analysis Services, Phase 8—Post Construction Services, and Phase 9—Supplemental Services.
For a detailed description and additional information about each phase of services, please refer to Publications of the American Institute of Architects, 1735 New York Ave., N.W., Washington DC, 20006.

In the *design–build* approach certain phases of the project, such as the structural steel, electrical work, or HVAC systems, or the entire project is designed and constructed by the same firm. The respective contractors either team up with the designers or have their own in-house designers. The merit of the design–build approach is its inherent internal coordination; its drawback is the lack of competition in lowering the construction cost. There are pros and cons to every approach, but they are too complex to be dealt with in this text.

According to the American Institute of Architects (AIA), a construction project may be divided into nine phases. Of these nine phases, Phase I—Predesign Services, Phase II—Site Analysis, Phase 8—Post Construction Services, and Phase 9—Supplemental Services are not always required except for large projects. The fundamental phases for every construction project are the following:

- *Phase 3* Schematic Design Phase (SD)
- *Phase 4* Design Development Phase (DD)
- *Phase 5* Construction Document Phase (CD)
- *Phase 6* Bid Negotiation Phase (BN)
- *Phase 7* Construction Administration phase (CA)

The major tasks of each phase are listed in the flow diagram shown in Figure 1–22.

QUESTIONS

1.1 Name some features in modern buildings that are dependent on mechanical and electrical systems.

1.2 Prior to the installation of modern M/E systems, buildings designed for workplaces, such as offices, were usually limited to a few simple building configurations. Why?

1.3 What is VSR? What is the optimum VSR of a building?

1.4 What are the major categories of building M/E systems?

1.5 What are the major mechanical systems?

1.6 What are the major electrical systems?

1.7 What is the median M/E space to be allowed initially for an office building? Research building? Secondary school?

1.8 Building codes prohibit M/E components such as ducts, piping, and conduits to penetrate through structural beams. (True) (False)

1.9 What is NRA? How is it defined?

1.10 Central M/E systems tend to improve the FER. (True) (False)

1.11 Why does building design E (a sawtooth curtain wall) in Figure 1–9 have an APR of 17.7, whereas design B (a square) has an APR of 25?

1.12 A rectangular building of low APR is always less energy efficient than a building of higher APR regardless of its orientation and climatalogical conditions. (True) (False)

1.13 What is the APR of a 30-ft × 30-ft single-story building?

1.14 There is no strict definition of a high-rise building. The consensus is that buildings seven stories or higher are classified as high-rise. (True) (False) (Note: Seven stories, or approximately 70 feet to the top floor, were originally considered as reachable by fire-truck ladders. With modern firefighting equipment, this limitation has long been exceeded.)

1.15 Why is VCR a good measure of construction and energy efficiency for comparing buildings of similar floor areas?

1.16 High-rise buildings have a low VSR and are thus less energy efficient. (True) (False)

1.17 What is the median cost for M/E systems (in percent of total building construction) for an elementary school?

1.18 If the central M/E plant is located on the upper floor of a high-rise building, there is no need to have any M/E space on the ground or below ground level. (True) (False)

1.19 Give reasons that favor a central M/E plant on upper levels of a high-rise building.

1.20 What is the heating value of 1 kW-hr of electrical energy?

1.21 What is the nominal conversion efficiency of burning gas in a boiler?

1.22 An electric heat pump can have an energy efficiency (coefficient of performance, or COP) up to 300%. (True) (False)

1.23 CFC refrigerants are being replaced because they are too expensive. (True) (False)

1.24 How much carbon dioxide will be released into the atmosphere by using 1 gal of oil in a boiler?

1.25 If a building consumes 40,000 kWh of electrical energy per year, how many pounds of CO_2 are released at the coal-fired electrical power generating plant?

1.26 The modern building design process requires close interfacing of design professionals. Normally, the architect coordinates the team effort. (True) (False)

1.27 Create a comprehensive checklist of M/E scope and criteria for a small office building—say, for 20 occupants. (Note: This is purely a self-test. Do what you think is right at this time, and double-check your list when you have completed all the chapters.)

Do the same for a 100-room hotel. (Everyone should be able to generate some basic questions that are relevant to the operation of a hotel.) (Again, this is your own self-test.)

1.28 What influence does a building's facade have on M/E systems?

1.29 What is one of the greatest environmental impacts on a building's facade?

1.30 What is the most effective way of controlling solar gain?

1.31 What external devices can be incorporated into a building facade to control the impact of solar radiation?

1.32 Why are external sun shading devices not readily used on tall buildings?

1.33 What are the disadvantages of using only highly reflective/mirror coatings on glazed surfaces as the solution to control solar radiation?

1.34 What is the key principle of insulated glass?

1.35 How can a double-skin facade be compared with insulated glass?

1.36 What are some ways the cavity of a double-skin facade can moderate the impact of summer and winter conditions and influence M/E solutions?

1.37 Why should architectural/technical facade solutions concern M/E design?

1.38 Why should we be concerned about energy consumption and whether our buildings are "green"?

1.39 What does LEED stand for and what are its objectives?

1.40 Is LEED a building code that must be complied with in building design and construction in the United States?

1.41 Name some of the innovative design concepts or features of recently completed buildings in the United States, either from personal knowledge or from research.

1.42 Who are the three basic players in a construction project? Are they always independent of one another?

1.43 Describe the design–bid–construct approach to a construction project. What are the advantages and disadvantages of this process?

1.44 Describe the fast-track approach to a construction project. What are the advantages and disadvantages of this process?

1.45 Describe the design–build approach to a construction project. What are the advantages and disadvantages of this process?

1.46 What are the fundamental phases of every construction project?

1.47 The design–construction phases of a project follow a logical sequence.
- Is it possible to repeat an earlier process when a later phase is underway?
- Do you believe this happens often in most projects? Can you cite some examples?

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2

HVAC FUNDAMENTALS

THIS CHAPTER CONTAINS BASIC INFORMATION regarding comfort, properties of air, load estimation, and determining the proper flow of heat transfer fluids to satisfy loads. This information is a prerequisite for understanding how architecture affects the size of HVAC systems and how HVAC systems operate to control the environment.

The next five chapters describe, in turn, the following concepts, subsystems, and equipment used in HVAC systems:

- HVAC delivery
- Cooling production
- Heating production
- Air handling
- Piping systems

Figure 2–1 shows typical equipment used in an HVAC system for a large building. Illustrated are the subsystems described in the five chapters that follow.

2.1 ENVIRONMENTAL COMFORT

2.1.1 Comfort for Occupants

The temperature of a space is not the only factor affecting a person's comfort. Even if the temperature is within an acceptable range, the space may seem warm if the humidity is too high, the airflow is too low, or warmth is being radiated to the occupants. Conversely, a space may seem cool if the humidity is low, the space is drafty, or warmth is being radiated from the occupants to cold surfaces. Comfort for building occupants is affected by a number of environmental variables, including the following:

- Temperature
- Airflow
- Humidity
- Radiation

Indoor air quality is another aspect of comfort. In air of good quality, sufficient oxygen is present and objectionable impurities such as dust, pollen, odors, and hazardous materials are absent.

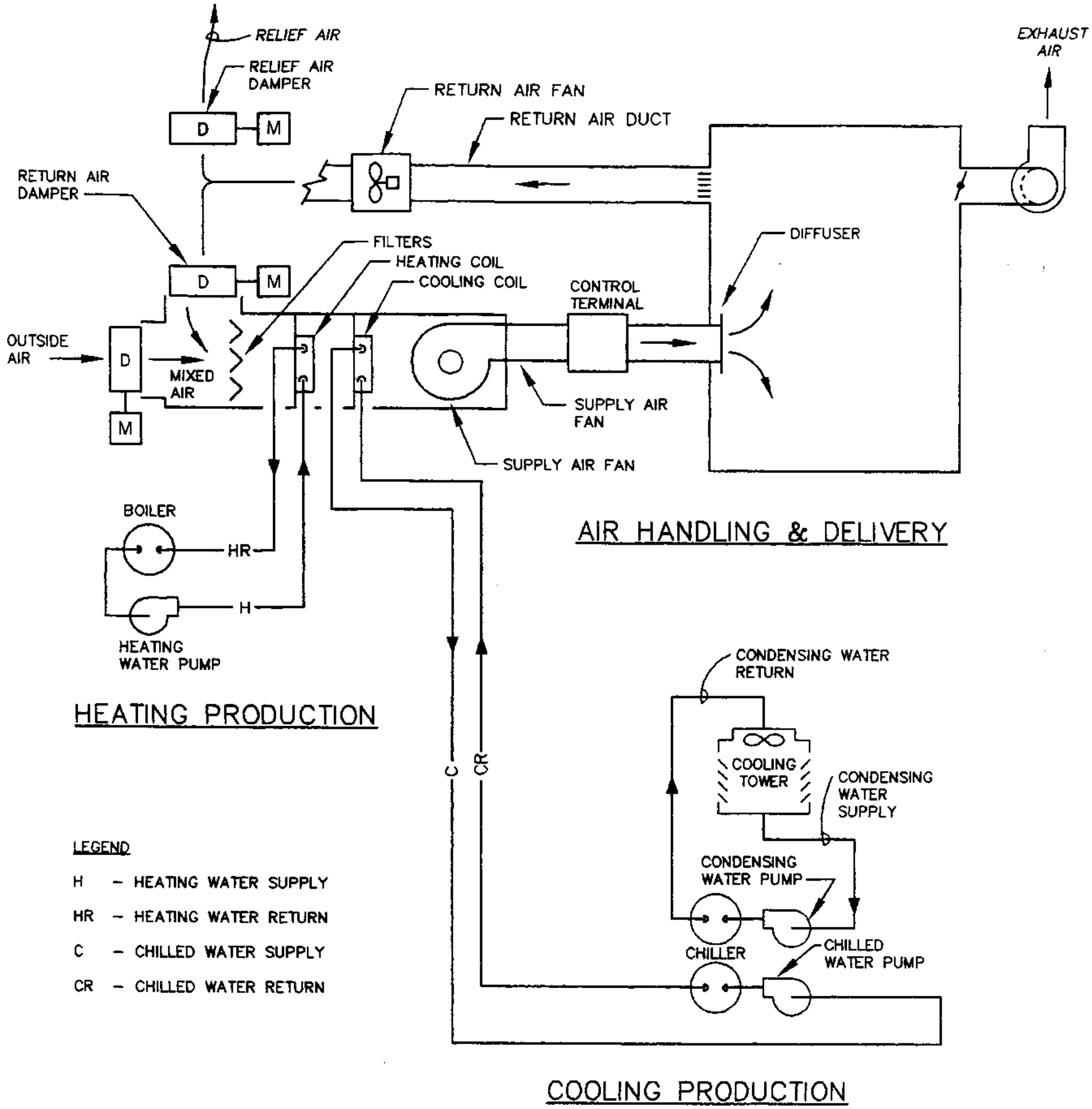
Different conditions may be deemed comfortable, depending on the type of activity that goes on in a space. Appropriate conditions for an office would be too warm for a gymnasium and too dry and cool for a natatorium. Expectations must also be considered: Saunas are hot on purpose, and a wide variety of conditions are commonly tolerated in factories. The physical condition of the occupants, including their age and health, also affects their comfort. Even the seasons affect comfort: Warmer environments are tolerated during the summer and cooler environments in winter, because of clothing and acclimatization.

Economics and concerns about energy conservation are also considered in defining comfort. People will be satisfied with less comfort when faced with a worthy cause or a mandate based on sound business practice.

2.1.2 Temperature and Humidity

Both temperature and humidity affect our sense of comfort. Figure 2–2 shows the acceptable range of each for persons wearing typical summer and winter clothing during sedentary activities. The lower comfort limit in cold weather is 68°F at about 30 percent relative humidity (RH), and the upper limit in hot weather is 79°F at about 55 percent RH. HVAC systems are generally designed to maintain temperature and RH within a tighter range than is indicated in the figure.

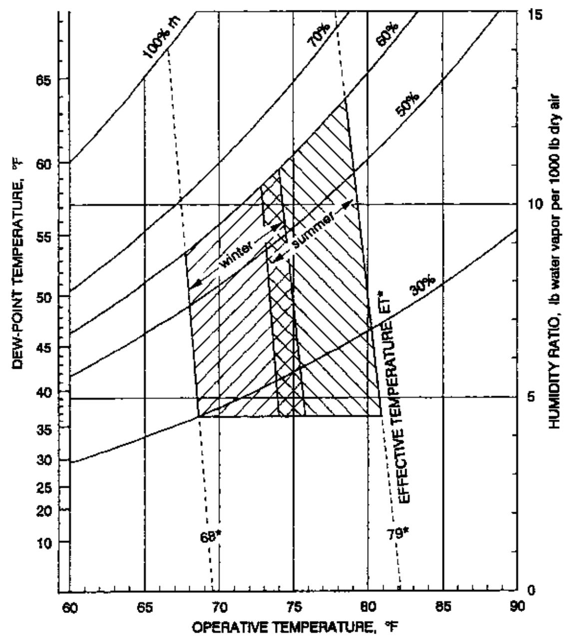
An interior design temperature of about 75°F is considered comfortable by most people in general-use spaces, as shown in Figure 2–2. During the summer, a slightly higher temperature may be appropriate because of light clothing and acclimatization to warm weather; this should be considered in designing air-conditioning



■ **FIGURE 2-1**
Components of a large HVAC system. (Based on hot–chilled water system.)

systems. Conversely, slightly cooler temperatures are acceptable and can be considered in the design of heating systems. Most air-conditioning systems are designed to maintain a summer temperature of 72°F–78°F. During winter, heavier clothing and acclimatization to cold weather result in a recommended design temperature of 68°F–72°F for heating systems. These interior design temperatures will be appropriate for the majority of buildings.

Humidity in excess of 60 percent is considered high in general-use spaces. High humidity not only is uncomfortable but also can result in indoor air-quality problems due to mold growth. Humidity lower than 25–30 percent can result in uncomfortable drying of breathing



■ **FIGURE 2-2**
Standard effective temperature and comfort zones. (Courtesy: ASHRAE.)

passages and problems with electronic equipment due to static electricity.

2.1.3 Airflow

Systems must be designed for adequate airflow to prevent complaints of "stuffiness" or drafts. The measure of airflow is velocity. Space air velocities less than 10 feet per minute will be stuffy; those more than 50 feet per minute will seem drafty.

2.1.4 Air Quality

Systems must provide sufficient amounts of clean air to keep oxygen at an acceptable level and to dilute contaminants generated within occupied spaces. Air should be reasonably free of dust, and spaces free of odors or other pollutants that may be hazardous or objectionable. These conditions are generally achieved through the use of filters and by the introduction of outside air into the system at rates specified in Table 2–8.

2.1.5 Radiant Effects

Even if the temperature, humidity, and airflow in a space are acceptable, the space may be uncomfortable owing to radiant effects from cold windows or walls. Systems must therefore compensate for these effects with radiant heat or higher temperatures. Similarly, cooler temperatures or higher air velocities will be needed to offset the effects of warm surfaces. Downdrafts from cold surfaces are also uncomfortable and can be offset by proper placement of heating devices.

2.1.6 Special Considerations

Buildings such as museums, computer rooms, and laboratories have special requirements for temperature, humidity, airflow, and air quality. In some instances these requirements are consistent with the comfort of the occupants, but in others they are at odds with comfort.

Interior environmental criteria are often based on specifications for equipment used within an occupied space. Computer rooms, for example, are often drafty and cool to suit the environmental requirements of the computing equipment. This will be an uncomfortable environment for operators of the computers, and special provisions may be desirable to provide better conditions in certain areas of the room. Similarly, materials stored in a warehouse may tolerate cold or hot temperature, but the warehouse employees need a refuge of human comfort.

Economics and expectations of comfort also affect design criteria. Despite the fact that warehouses and factories are occupied by people, it is deemed unnecessary to maintain these buildings at the same interior temperatures as an office building or hospital. The need for energy conservation may also temper expectations of comfort.

Ventilation rates for indoor air quality are also subject to special considerations. Historically, ventilation standards have varied depending on concerns for energy conservation and health. The values shown in Table 2–8 are much higher than those recommended during the energy crisis of the late 1970s.

2.1.7 Wind Chill Factor (WCF)

Both ambient air temperature and wind conditions affect discomfort associated with cold outdoor environment. Siple and Passel in 1945 introduced an empirical formula known as the wind chill index (WCI) to express the combined effect of wind velocity and air (dry-bulb) temperature on the heat loss of a cylindrical body. This formula was later adopted and modified by metereologists in weather reports to express the severity of cold environment as the equivalent wind chill

TABLE 2–1
Wind chill factor (WCF) of cold environments (in conventional and SI units)

Wind Speed, mph	Actual Thermometer Reading, °F											
	50	*40*	*30*	*20*	*10*	*0*	*−10*	*−20*	*−30*	*−40*	*−50*	*−60*
	Equivalent Chill Temperature, °F											
0	50	40	30	20	10	0	−10	−20	−30	−40	−50	−60
5	48	37	27	16	6	−5	−15	−26	−36	−47	−57	−68
10	40	28	16	3	−9	−21	−34	−46	−58	−71	−83	−95
15	36	22	9	−5	−18	−32	−45	−59	−72	−86	−99	−113
20	32	18	4	−11	−25	−39	−53	−68	−82	−96	−110	−125
25	30	15	0	−15	−30	−44	−59	−74	−89	−104	−119	−134
30	28	13	−3	−18	−33	−48	−64	−79	−94	−110	−125	−140
35	27	11	−4	−20	−36	−51	−67	−83	−98	−114	−129	−145
40	26	10	−6	−22	−38	−53	−69	−85	−101	−117	−133	−148

Wind Speed, km/h	Actual Thermometer Reading, °C												
	10	*5*	*0*	*−5*	*−10*	*−15*	*−20*	*−25*	*−30*	*−35*	*−40*	*−45*	*−50*
	Equivalent Chill Temperature, °C												
Calm	10	5	0	−5	−10	−15	−20	−25	−30	−35	−40	−45	−50
10	8	2	−3	−9	−14	−20	−25	−31	−37	−42	−48	−53	−59
20	3	−3	−10	−16	−23	−29	−35	−42	−48	−55	−61	−68	−74
30	1	−6	−13	−20	−27	−34	−42	−49	−56	−63	−70	−77	−84
40	−1	−8	−16	−23	−31	−38	−46	−53	−60	−68	−75	−83	−90
50	−2	−10	−18	−25	−33	−41	−48	−56	−64	−71	−79	−87	−94
60	−3	−11	−19	−27	−35	−42	−50	−58	−66	−74	−82	−90	−97
70[b]	−4	−12	−20	−28	−35	−43	−51	−59	−67	−75	−83	−91	−99

Little danger: In less than 5 hours, with dry skin. Maximum danger from false sense of security (WCI less than 1400).

Increasing danger: Danger of freezing exposed flesh within 1 minute (WCI between 1400 and 2000).

Great danger: Flesh may freeze within 30 seconds (WCI greater than 2000).

Source: Condensed from *ASHRAE Handbook—Book of Fundamentals,* 1997.

temperature (EWCT), commonly known as the wind chill factor (WCF). Table 2–1 gives the calculated WCF at various dry-bulb temperatures and wind velocities in conventional and SI units. For temperatures and wind velocities not listed in the tables, linear interpolation may be used. Wind velocity greater than 40 mph (70 km/h) has little added chilling effect.

2.2 PROPERTIES OF AIR–WATER MIXTURES

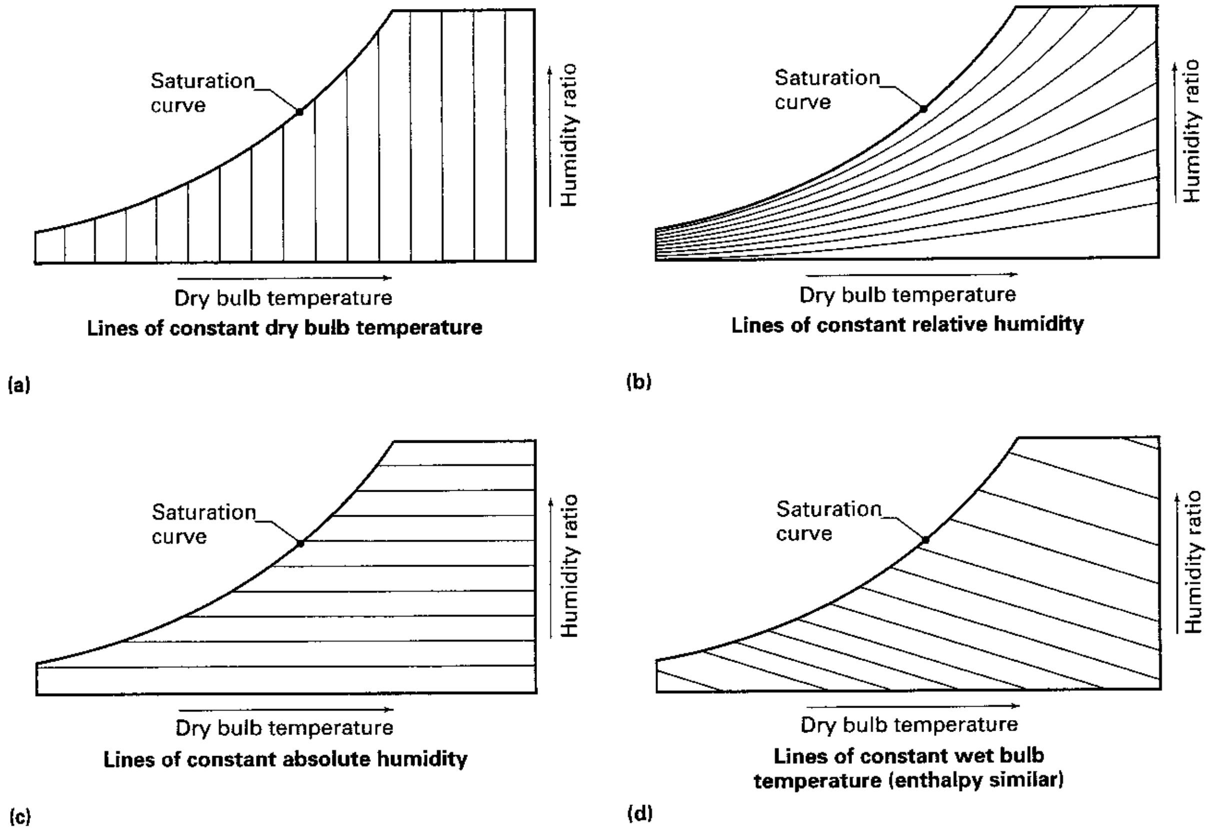
The design of environmental control systems relies on an understanding of the properties of air, including temperature and humidity. These properties affect loads on buildings, and HVAC systems are used to alter the properties of air and produce comfort.

2.2.1 Psychrometry

Psychrometry is the study of properties of air–water mixtures. A psychrometric chart is a convenient source for data on the properties of such mixtures. Figure 2–3 shows how important properties are presented on a psychrometric chart. Figure 2–4 is a complete chart that can be used in analysis of processes associated with HVAC.

2.2.2 Absolute and Relative Humidity

Two basic properties of air–water mixtures are temperature and humidity. The humidity of the air can be expressed in two ways: absolute and relative. *Absolute humidity,* also known as the *humidity ratio* (W), is the amount of water in the air and is measured in grains or pounds of water per pound of dry air. A grain is equiv-



■ **FIGURE 2-3**

Lines representing major properties of air–water mixture on the ASHRAE psychrometric chart. (a) Vertical lines: constant dry-bulb (DB) temperature. (b) Curved lines: constant relative humidity (RH). (c) Horizontal lines: constant humidity ratio (*W*), also commonly referred to as *absolute humidity.* (d) Sloped lines: constant wet-bulb (WB) temperature; lines with same slope: constant enthalpy (*H*).

alent to 1/7000 of a pound. This unit is preferred owing to the very small amount of water present in air. *Relative humidity* (RH) is the ratio of the actual water content to the maximum possible moisture content at a given temperature, expressed as a percent. If the air is currently holding all the moisture possible, the relative humidity is 100 percent, and the air is termed *saturated.*

2.2.3 Effect of Temperature on Humidity

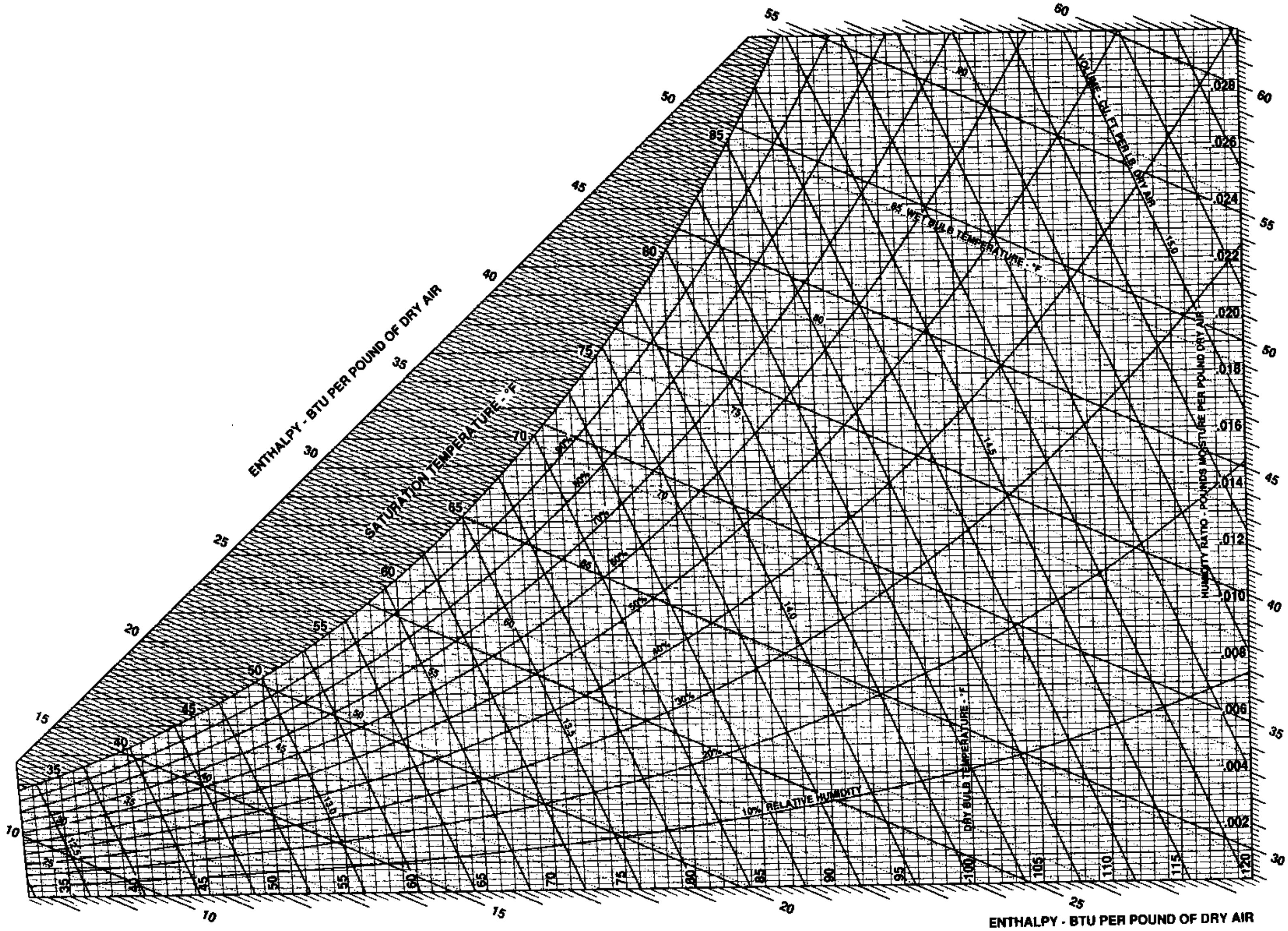
The moisture-holding capacity of the air depends on the air temperature. Warm air can hold more moisture than cold air. For this reason, the same absolute humidity results in different relative humidities at different temperatures. The psychrometric chart illustrates the relationship of temperature, absolute humidity, and relative humidity.

2.2.4 Wet-Bulb Temperature

If a wet sock is placed over the bulb of a conventional thermometer, a lower temperature will be recorded owing to evaporative cooling. The drier the air, the more effective will be the evaporative cooling, and the lower will be the temperature measured. If the air is saturated, then there will be no evaporation and the wet-bulb thermometer will measure the same temperature as a dry-bulb thermometer. The temperature and humidity of the air can be determined by measuring both dry-bulb and wet-bulb temperatures. A combination of wet- and dry-bulb temperature represents a discrete point on the psychrometric chart.

2.2.5 Sensible, Latent, and Total Heat

Air contains thermal energy in two forms: sensible heat and latent heat. Water vapor, or humidity, in the air contains the water's latent heat of vaporization



■ **FIGURE 2–4**
Psychrometric chart.
(Reprinted with permission of ASHRAE.)

(approximately 1000 Btu/lb of water). Temperature is a measure of sensible heat, while water vapor content is a measure of latent heat. Total heat—the sum of sensible and latent heat—is ***enthalpy,*** symbolized by the Greek letter eta, or by *H*. Enthalpy is expressed in units of Btu/lb of dry air. High temperature or high humidity constitutes high energy.

On the psychrometric chart, horizontal movement is associated with sensible heat change (no change in absolute humidity), and vertical movement is associated with latent heat change (no change in temperature). Moving upward or to the right indicates a higher energy level; moving downward or to the left indicates a lower energy level. Lines of constant enthalpy slope upward and to the left at approximately the same slope as lines of constant wet-bulb temperature. This is no coincidence, for wet-bulb temperature is a good measure of total energy.

Often, changes in air conditions result in changes in both humidity and temperature. The net change in energy level, or enthalpy, can be determined by plotting the initial and final conditions on the psychrometric chart, as shown in Figure 2–5.

2.2.6 Sensible Heating and Cooling

Sensible heating (cooling) occurs when the temperature of an air–water mixture is raised (lowered) but the absolute moisture content remains the same. Sensible heating or cooling occurs as air in spaces is warmed or cooled by building loads that do not change the moisture content of the air. Sensible heating or cooling is also performed by systems to compensate for loads. For instance, room air may be cooled by an outside wall during cold winter weather. To compensate, a heater at the base of the wall may warm the air. Sensible heating or cooling is represented by a horizontal movement along the psychrometric chart.

2.2.7 Processes Involving Latent Heat

Heating and cooling represent a change of sensible heat; humidification and dehumidification represent a change of latent heat. The amount of moisture liberated or absorbed by air is measured by its initial and final absolute humidities.

Air can be humidified either by adding dry steam to it or by evaporating moisture into it. If dry steam is added, the air will have a higher energy level, taking on the latent heat of the steam. (There will also be a slight increase in temperature owing to the sensible heat of the steam, but the effect is small and generally ignored in practice.) On the psychrometric chart, this process is represented by a vertical movement.

If water is evaporated into air, the air will cool, but the final energy level of the air does not change. The heat required to vaporize the water cools the air. The sensible heat loss equals the latent heat gain, resulting in constant enthalpy. This process is called ***adiabatic saturation.*** (No energy is added or removed.) Evaporative humidification is accompanied by evaporative cooling and is represented on the psychrometric chart by an upward movement along a line of constant enthalpy (approximately parallel to a line of constant wet-bulb temperature).

Cooling is a method for dehumidifying air. If moist air is cooled to the saturation curve, further cooling will not only reduce temperature but also remove moisture. The temperature at which moisture begins to condense is termed the ***dew point.*** Liquid moisture removed from the air by this process is termed ***condensate.*** The air that results from the process is both cooler and less humid than it was initially.

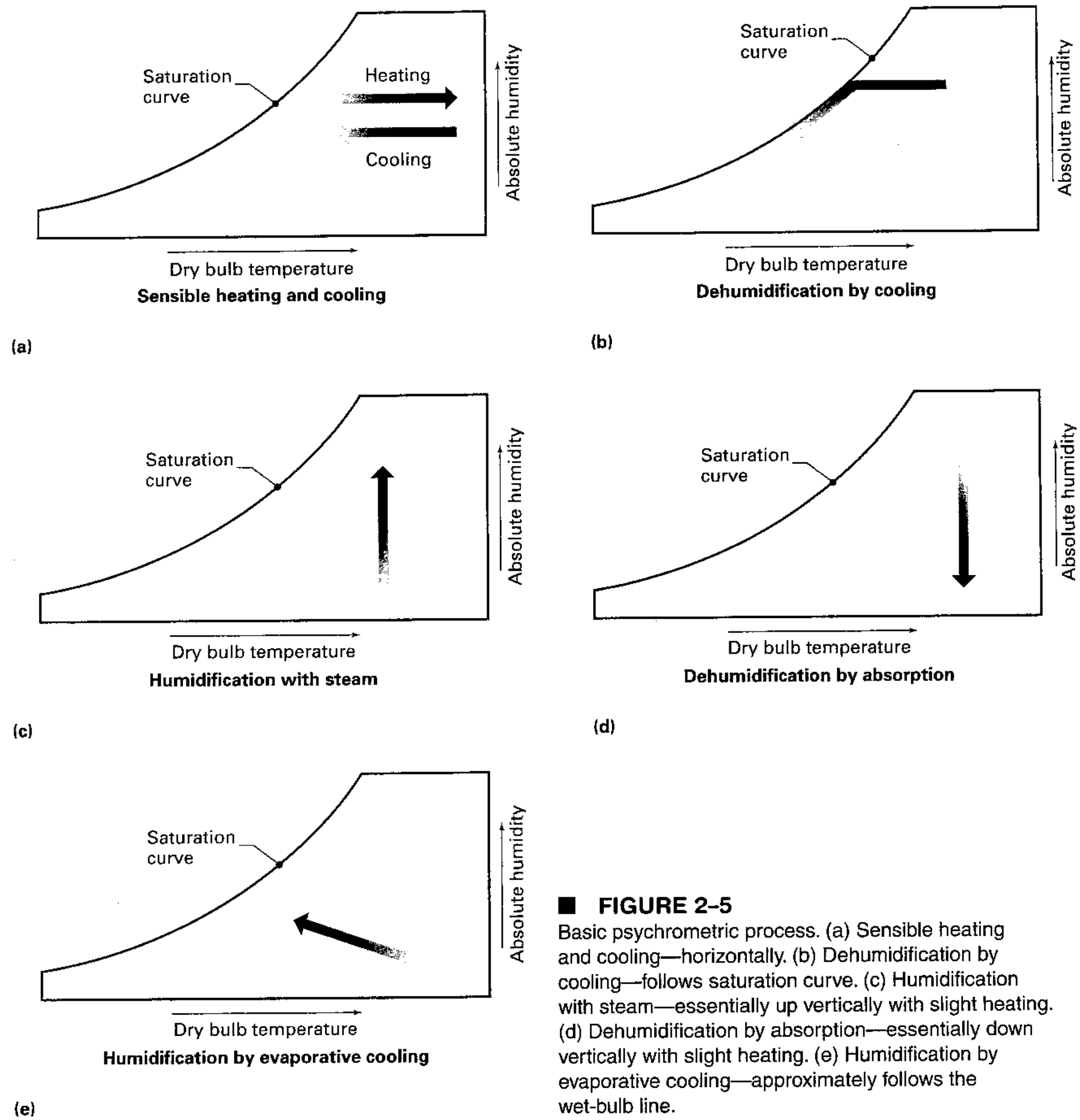
Air also can be dehumidified by absorption. Some substances are ***hygroscopic,*** meaning that they absorb moisture. Hygroscopic substances, or desiccants, such as silica gel and lithium bromide are used in certain applications to absorb moisture from the air. As moisture condenses in the desiccant its latent heat is liberated, heating the desiccant and the air. Absorption is represented by a downward movement on the psychrometric chart along a line of constant dry-bulb temperature.

2.2.8 Examples

1. Air at 70°F DB and 75% RH is heated to 84°F. What is the RH of the air at this higher temperature?

   Ans. In Figure 2–4, locate the air at the initial condition (70°F DB and 75% RH), and follow the horizontal line to the right until it meets the 84°F DB line (vertical). The heated air is now at 47% RH.
2. Air at 90°F DB and 70% RH is cooled to 75°F. What is the relative humidity?

   Ans. In Figure 2–4, from the intersecting point of 90°F DB and 70% RH, draw a line to the left. This line meets the saturation curve at 79°F, which is the dew point temperature of the air. The air is then cooled further, following the saturation curve until it stops at 75°F. Between 79°F and 75°F, the air is saturated, and moisture condenses out of it. The RH of the air is now 100%.



■ **FIGURE 2-5**
Basic psychrometric process. (a) Sensible heating and cooling—horizontally. (b) Dehumidification by cooling—follows saturation curve. (c) Humidification with steam—essentially up vertically with slight heating. (d) Dehumidification by absorption—essentially down vertically with slight heating. (e) Humidification by evaporative cooling—approximately follows the wet-bulb line.

2.3 ENERGY TRANSPORT IN HVAC SYSTEMS

2.3.1 Heat Transport by Fluid Flow

Figure 2–1 shows that HVAC systems use fluids to transport heat and cold to satisfy loads and maintain comfort. Such fluids include air, water, steam, and refrigerant. Equations are developed in this section that can be used to determine heat transport based on the flow rate and the initial and final conditions of the fluid. These equations can also be used in equipment design to specify flow rates or conditions, based on requirements for heat transport.

Heat is measured in *British thermal units,* or Btus. A Btu is the amount of heat required to raise the temperature of 1 lb of water 1°F. The rate of heat flow is measured in Btus per hour, or Btuh. Fluids are used to transport heat in HVAC systems.