ARCHITECT REGISTRATION EXAM

ARE REVIEW MANUAL

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BUILDING PROGRAMMING

Architectural programming is a process that seeks to analyze and define an architectural problem along with the requirements that must be met in its physical solution. It is a process of analysis, whereas design is a process of synthesis once the problem is clearly defined. The process can apply to an individual space or room, a building, or an entire complex of structures.

As building problems have become more complex and construction costs higher, determining the precise needs of the client has become more important than ever before. Programming helps the client understand the real problem and provides a sound basis for making design decisions. Sometimes it is provided by the architect as part of the entire range of design services, and other times it is performed as a separate service.

Thorough programming includes a wide range of information. In addition to stating the goals and objectives of the client, a program report contains a site analysis, aesthetic considerations, space needs, adjacency requirements, organizing concepts, outdoor space needs, codes, budgeting demands, and scheduling limitations. Refer to Chs. 2 and 4 for a review of site analysis, including soil and climatic investigation.

FUNCTIONAL REQUIREMENTS

The amount of space needed and the relationships needed among spaces are two of the primary factors in determining building size and configuration. The primary function of a building is housing a specific use, and in addition to that there are always support spaces required that add to the overall size. These include such areas as mechanical rooms, toilet rooms, storage, and circulation space.

Determining Space and Volume Needs

Space needs are determined in a number of ways. Often, when programming is begun, the client will have a list of the required square footage for the new facility in addition to special height requirements. These may be based on the client's experience or on corporate space standards, or they may simply be a list of what currently exists. For example, space standards of a corporation may dictate that a senior manager have a 225 ft^2 (21 m^2) office while a junior manager be allotted 150 ft^2 (14 m^2).

These types of requirements may provide a valid basis for developing space needs, or they may be arbitrary and subject to review during programming. Where areas are not defined by one of these methods, space for a particular use is determined in one of three ways: by the number of people that must be accommodated, by an object or piece of equipment, or by a specific activity that has its own, clearly specified space needs.

People engaged in a particular activity most commonly define the space required. For example, a student sitting in a classroom needs about 15 ft^2 to 20 ft^2 (1.4 m^2 to 1.9 m^2). This includes space for actually sitting in a chair in addition to the space required for circulating within the classroom and space for the teacher's desk and shelving. An office worker needs from 100 ft^2 to 250 ft^2 (9.3 m^2 to 23 m^2), depending on whether the employee is housed in a private office or in part of an open office plan. This space requirement also includes room to circulate around the desk and may include space for visitors' chairs, personal files, and the like.

Through experience and detailed analysis, general guidelines for space requirements for various types of uses have been developed and are commonly used. A representative sample of these is shown in Table 3.1. Occasionally, space needs can be based on something other than the number of people but something that is directly related to the occupancy. For instance, preliminary planning of a hospital may be based on an area per bed, or library space can be estimated based on the number of books.

Table 3.1

Some Common Space Planning Guidelines

offices	100–250 ft^2	net area per person	9.3–23 m^2
restaurant dining	15–18 ft^2	net area per seat	1.4–1.7 m^2
restaurant kitchens	3.6–5 ft^2	net area per seat	0.3–0.5 m^2
hotel (1.5 persons/room)	550–600 ft^2	gross area per room	51–56 m^2
library reading room	20–35 ft^2	net area per person	1.8–3.3 m^2
book stacks	0.08 ft^2	net area per bound volume	0.007 m^2
theaters with fixed seats	7.5 ft^2	net area per person	0.7 m^2
assembly areas; movable seats	15 ft^2	net area per person	1.4 m^2
theater lobbies	30%	of seating area	
classrooms	15–20 ft^2	net area per student	1.4–1.8 m^2
stores	30–50 ft^2	net area per person	2.8–4.6 m^2

Whichever way the planning is done, the number of people that must be accommodated is determined and is multiplied by the area per person. However, this only includes the space needed for the specific activity, not the space required to connect several rooms or spaces or for support areas such as mechanical rooms. These must be added to the basic area requirements.

The second way space needs are determined is by the size of an object or piece of equipment. The size of a printing press, for example, is part of what determines the area of a press room. Automobile sizes determine the space needs for parking garages.

The third way space needs are defined is through a built-in set of rules or customs related to the activity itself. Sports facilities are examples of such spaces. A basketball court must be a certain size regardless of the number of spectators present, although the seating capacity would add to the total space required. A courtroom is an example of a space in which the procedures and customs of a process (the trial) dictate an arrangement of human activity and the spacing of individual areas that only partially depend on the number of people using the space.

Determining Total Building Area

The individual areas determined by these methods, taken together, make up the net area of a facility. As mentioned, these areas do not include general circulation space between rooms, mechanical rooms, stairways, elevator and mechanical shafts, electrical and telephone equipment rooms, wall and structural thicknesses, and other spaces not directly housing the primary activities of the building. Sometimes the net area is referred to as the *net assignable area* and these secondary spaces are referred to as the *unassigned areas*.

The sum of the net area and the unassigned areas gives the *gross building area*. The ratio of the two figures is called the *net-to-gross ratio* and is often referred to as the *efficiency* of the building. Efficiency depends on the type of occupancy and how well it is planned. A hospital, which contains many small rooms and a great number of large corridors, will have a much lower efficiency ratio than a factory, where the majority of space is devoted to production areas and very little space is allowed for corridors and other secondary spaces.

Generally, net-to-gross ratios range from 60% to 80%, with some uses more or less efficient than these numbers. A list of some common efficiency ratios is shown in Table 3.2. In some cases, the client may dictate the net-to-gross ratio that must be met by the architect's design. This is usually the case when the efficiency is related to the amount of floor space that can be leased, such as in a retail mall or a speculative office building. Increasing the efficiency of a building is usually done by careful layout of the building's circulation plan. A corridor that serves rooms on both sides, for example, is much more efficient than one that only serves rooms on one side.

Table 3.2

Some Common Efficiency Ratios

offices	0.75-0.85
retail stores	0.75-0.90
restaurants	0.65-0.70
public libraries	0.75-0.80
museums	0.83-0.90
theaters	0.60-0.75
hospitals	0.50-0.65

Once the net area is determined and the appropriate efficiency ratio is established (or estimated), the gross area of the building is calculated by dividing the net area by the net-to-gross (efficiency) ratio.

Example 3.1

The net assignable area of a small office building has been programmed as 65,000 ft^2. If the efficiency ratio is estimated to be 73%, what gross area should be planned for?

$$\text{gross area} = \frac{65{,}000\ \text{ft}^2}{0.73}$$

$$= 89{,}000\ \text{ft}^2$$

The design portion of the ARE sometimes requires the examinee to provide various unassignable spaces within the context of the problem. The areas are not given. The examinee is expected to make a reasonable allowance for mechanical rooms, toilet rooms, elevators, and the like, if they are not specifically listed in the program. Table 3.3 lists some typical space requirements for projects of the size and type normally found in the design portion of the exam.

Determining Space Relationships

Spaces must not only be the correct size for the activity they support, but they also must be located near other spaces with which they share some functional relationship. Programming identifies these relationships and assigns a hierarchy of importance to them. The relationships are usually recorded in a matrix format or graphically as adjacency diagrams. See Fig. 3.1.

There are three basic types of adjacency needs: people, products, and information. Each type implies a different kind of physical design response. Two or more spaces may need to be physically adjacent or located very close to one another when people need face-to-face contact or when people move from one area to another as part of the building's use. For example, the entry to a theater, the lobby, and the theater space have a particular functional requirement for being arranged the way they are. Because of the normal flow of people, they must be located adjacent to one another. With other relationships, two spaces may simply need to have access to each other, but this can be accomplished with a corridor or through another intervening space rather than with direct adjacency.

Products, equipment, or other objects may move between spaces and require another type of adjacency. The spaces themselves may not have to be close to one another, but the movement of objects must be facilitated. Dumbwaiters, pneumatic tubes, assembly lines, and other types of conveying systems can connect spaces of this type.

Finally, there may be a requirement only that people in different spaces be able to exchange information. The adjacency may then be entirely electronic or be established through paper-moving systems. Although this is frequently the situation, personal, informal, human contact may be advantageous for other reasons.

Table 3.3

Space Requirements for Estimating Non-assignable Areas

mechanical rooms, total	5–9% of gross building area
heating, boiler rooms	3–5% of gross building area
heating, forced air	4–8% of gross building area
fan rooms	3–7% of gross building area
vertical duct space	3–4 ft^2 per 1000 ft^2 of floor space available (0.35 m^2 per 100 m^2)
toilets	50 ft^2 (4.6 m^2) per water closet
water closets	1 per 15 people up to 55; 1 per 40 people over 55
urinals	Substitute one for each water closet, but total water closets cannot be reduced less than $^2/_3$ of the number required
lavatories	1 per 15 people for offices and public buildings up to 60 people
	1 per 100 people for public assembly use
hydraulic elevator, 2000 lbm (1000 kg)	7 ft 4 in wide by 6 ft 0 in deep (2235 by 1830)
elevator lobby space	6 ft 0 in deep (1830)
main corridors	5–7 ft (1500–2100)
exit corridors	4 ft 0 in; 44 in minimum by code (1220; 1118)
monumental stairs	5–8 ft (1500–2400)
exit stairs	4 ft 0 in, 44 in minimum by code (1220; 1118)

The programmer analyzes various types of adjacency requirements and verifies them with the client. Since it is seldom possible to accommodate every desirable relationship, the ones that are mandatory need to be identified separately from the ones that are highly desirable or simply useful.

DESIGN CONSIDERATIONS

During programming, general concepts are developed as a response to the goals and needs of the client. These programmatic concepts are statements about functional solutions to the client's performance requirements. They differ from later design concepts because no attempt at actual physical solutions is made during programming; programmatic concepts guide the later development of design concepts. For example, a programmatic concept might be that

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STRUCTURAL FUNDAMENTALS

Nomenclature

A	area	in^2 or ft^2
b	base of rectangular section	in
d	depth of rectangular section	in
d	diameter	in
d	distance between axes	in
e	total deformation (strain)	in
E	modulus of elasticity	lbf/in^2
f	unit stress	lbf/in^2
F	force	lbf
I	moment of inertia	in^4
I_n	moment of inertia of transferred area	in^4
I_x	moment of inertia of area about neutral axis	in^4
L	original length	in
P	total force	lbf
r	radius	in
R	reaction force	lbf
T	temperature	°F
W	weight	lbf
α	coefficient of linear expansion	in/in-°F
ϵ	unit strain	decimal

STATICS AND FORCES

Statics

Statics is the branch of mechanics that deals with bodies in a state of equilibrium. *Equilibrium* is said to exist when the resultant of any number of forces acting on a body is zero. For example, a 10 lbm object on the ground is acted on by gravity to the magnitude of 10 lbf. The ground, in turn, exerts an upward force of 10 lbf and the object is in equilibrium.

Three fundamental principles of equilibrium apply to buildings.

- The sum of all vertical forces acting on a body must equal zero (as in the preceding simple example).
- The sum of all horizontal forces acting on a body must equal zero.
- The sum of all the moments acting on a body must equal zero.

Forces

A *force* is any action applied to an object. In architecture, external forces are called *loads* and result from the weights of such things as people, wind, snow, or building materials. The internal structure of a building material must resist external loads with internal forces of their own that are equal in magnitude and of opposite sign. These external loads are called *stresses*. The structural design of buildings is primarily concerned with selecting the size, configuration, and material of components to resist, with a reasonable margin of safety, external forces acting on them.

A force has both direction and magnitude and as such is called a *vector quantity*. Direction is shown by using a line with an arrowhead, and magnitude is indicated by establishing a convenient scale. For example, at a scale of 1 in equals 2000 lbf, a line 2 in long represents a force of 4000 lbf. An 8000 lbf force would therefore be shown with a line 4 in long.

The line of action of a force is a line concurrent with the force vector. A force acting anywhere along the line of action can be considered equal or unchanged as long as the direction and magnitude do not change. This is the principle of *transmissibility*.

There are several types of forces.

- *Collinear forces* are those whose vectors lie along the same straight line. See Fig. 12.1(a). Structural members subjected to collinear forces such as tension or compression are said to be two-force members.
- *Concurrent forces* are those whose lines of action meet at a common point. See Fig. 12.1(b).
- *Nonconcurrent forces* have lines of action that do not pass through a common point. See Fig. 12.1(c). A special case of this type that is commonly found in architectural applications is a parallel force system, such as a type that may be acting on a beam. See Fig. 12.1(d).
- *Coplanar forces* are forces whose lines of action all lie within the same plane. Noncoplanar forces do not lie within the same plane.

Structural forces in buildings can be any combination of these types. For example, a truss is a collection of sets of concurrent-coplanar forces, while a space frame is an example of a combination of sets of concurrent-noncoplanar forces.

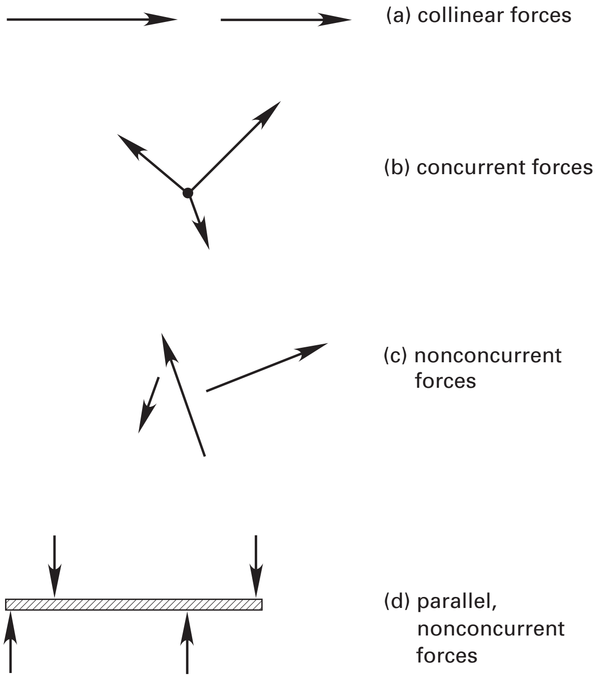

Figure 12.1 Types of Forces

It is often necessary to add two or more concurrent forces or to break down a single force into its components for purposes of structural analysis. The simplest combination of forces is represented by collinear forces. The magnitudes of the forces are added directly in the same direction of force. See Fig. 12.2.

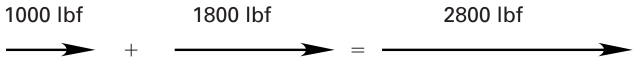

Figure 12.2 Addition of Collinear Forces

With concurrent and nonconcurrent forces, the effect of the direction of the force must be taken into account. The methods used to find resultant forces or to break down a force into its components will be discussed in the Structural Analysis section in this chapter.

Stresses

Stress is the internal resistance to an external force. There are three basic types of stress: tension, compression, and shear. Tension and compression stresses are known as *normal stresses*. All stresses consist of these basic types or some combination thereof.

Tension is stress in which the particles of the member tend to pull apart under load.

Compression is stress in which the particles of the member are pushed together and the member tends to shorten.

Shear is stress in which the particles of a member slide past each other.

With tension and compression, the force acts *perpendicular* to the area of the material resisting the force. With shear, the force acts *parallel* to the area resisting the force.

For these three conditions, stress is expressed as force per unit area and is determined by dividing the total force applied to the total area.

$$f = \frac{P}{A} \tag{12.1}$$

Example 12.1

A balcony is partially supported from structure above by a steel rod with a $1\frac{1}{4}$ in diameter. The load on the rod is 10,000 lbf. What is the stress in the rod?

The radius of the rod is

$$r = \frac{d}{2} = \frac{1.25\ \text{in}}{2} = 0.625\ \text{in}$$

The area of the rod is

$$\begin{aligned} A &= \pi r^2 \\ &= \pi(0.625\ \text{in})^2 = 1.23\ \text{in}^2 \end{aligned}$$

From Eq. 12.1, the stress is

$$f = \frac{P}{A} = \frac{10{,}000 \text{ lbf}}{1.23 \text{ in}^2} = 8130 \text{ psi}$$

Other types of stresses consist of torsion, bending, and combined stresses. *Torsion* is a type of shear in which a member is twisted. *Bending* is a combination of tension and compression like the type that occurs in beams. This will be discussed in more detail in Ch. 13. *Combined loads* can occur in many situations. For example, a column resisting loads from above and lateral wind loads is subjected to both compression and bending.

Thermal Stress

When a material is subjected to a change in temperature, it expands if heated or contracts if cooled. For an unrestrained material, the general formula is

$$e = \alpha x \Delta T \qquad 12.2$$

Some coefficients of common materials are shown in Table 12.1.

Table 12.1

Coefficients of Linear Expansion

material	coefficient (in/in-°F)
aluminum	0.0000128
brick	0.0000034
bronze	0.0000101
concrete	0.0000055
glass	0.0000051
marble	0.0000045
plastic, acrylic	0.0000450
structural steel	0.0000065
wood, fir parallel to grain	0.0000021

If the material is restrained at both ends, a change in temperature causes an internal thermal stress. The formula for this stress is

$$f = E\alpha\Delta T \qquad 12.3$$

Notice that the unit stress is independent of the cross-sectional area of the member if there are no other loads being applied to the member while it is undergoing thermal stress.

Strain and Deformation

As a force is applied to a material, the material changes size. For example, a tensile force causes a rod to elongate and narrow, while a compressive force causes a material to shorten and widen. *Strain* is the deformation of a material caused by external forces. It is the ratio of the total change in length of a material to its original length. As a formula, it is represented as

$$\epsilon = \frac{e}{L} \qquad 12.4$$

As a force is applied to a material, the deformation (strain) is directly proportional to the stress, up to a certain point. This is known as *Hooke's law*, named after Robert Hooke, the British mathematician and physicist who first discovered it. This relationship is shown graphically in Fig. 12.3. At a certain point, however, the material will begin to change length at a faster ratio than the applied force. This point is called the *elastic limit*. At any stress up to the elastic limit, the material will return to its original size if the force is removed. Above the elastic limit there will be permanent deformation, even if the force is removed.

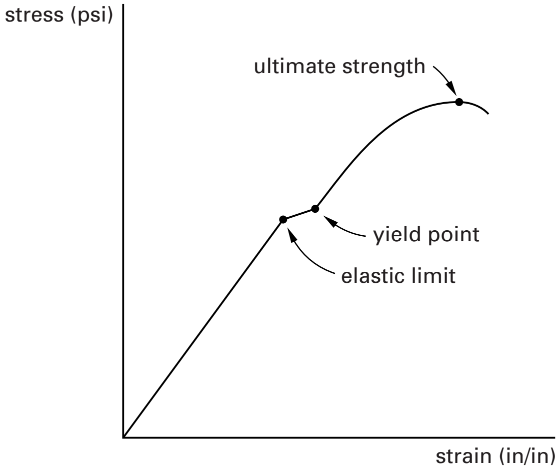

Figure 12.3 Hypothetical Stress-Strain Graph

With some materials there is also a point, slightly above the elastic limit, called the *yield point*. This is the point at which the material continues to deform with very little increase in load. Some materials, such as wood, have poorly defined elastic limits and no yield points.

If the load is continually increased, the material will ultimately rupture. The unit stress just before this occurs is called the *ultimate strength* of the material.

Although the entire range of a material's stress/strain relationship is interesting from a theoretical point of view, the most important portion from a practical standpoint is where the stress and strain are directly proportional, up to the elastic limit. Sound engineering practices and limitations set by building codes establish the working stresses to be used in calculations at some point below the yield point.

Every material has a characteristic ratio of stress to strain. This is called the *modulus of elasticity*, *E*, which is a measure

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HVAC SYSTEMS

ENERGY SOURCES

Regardless of what energy conservation measures are adopted for a building, either the primary or backup energy source will be one of the conventional fuels. The selection of fuel type depends on the fuel's availability and dependability of supply, its cost, cleanliness, convenience of storage, and requirements of the equipment needed to use it. For example, in an urban area steam may be readily available as a by-product of a local utility company, whereas in a suburban area oil may have to be the energy source. In some parts of the country electricity is inexpensive and readily available; in other locations its use for heating is cost prohibitive.

Natural Gas

Of all the fossil fuels, natural gas is the most efficient. It is clean burning and relatively low in cost. Depending on geographic location and local market conditions, however, it may not always be available, or the price may fluctuate widely. In remote locations it may not be available at all. It has a heating value of about 1050 Btu/ft^3 (39 100 kJ/m^3).

Propane is one type of gas that can be used in areas where natural gas is not available. It is delivered and stored in pressurized tanks and has a heating value of about 21,560 Btu/lbm, or 2500 Btu/ft^3 (93 150 kJ/m^3).

Oil

Oil is widely used in some parts of the country, but because it is a petroleum product, its cost and availability are dependent on world and local market conditions. It must be stored in or near the building where it is used, and the equipment needed for burning it is subject to more maintenance than that used for gas-fired boilers.

Oil is produced in six grades for residential and commercial heating use: no. 1, no. 2, no. 4, no. 5 light, no. 5 heavy, and no. 6. The lower the number, the more refined and the more expensive the oil. No. 2 fuel oil is the grade most commonly used in residential and light commercial boilers, whereas no. 4 and no. 5 grades are used in larger commercial applications. The heat value for no. 2 oil is from 137,000 Btu/gal to 141,000 Btu/gal (38 200 kJ/L to 39 300 kJ/L), and that for no. 5 is from 146,800 Btu/gal to 152,000 Btu/gal (40 900 kJ/L to 42 400 kJ/L).

Electricity

Electricity has the advantages of being easy to install, low in installation cost, simple to operate, easy to control, and flexible in zoning; and it does not require storage facilities, exhaust flues, or supply air. Its primary disadvantage is its cost in most parts of the country compared with other fuels. Because most electric utilities now charge more for peak use as well as total electricity consumed, heating during a cold period can be very expensive.

Electricity is ideal for radiant heating, either in a ceiling or in individual panels. It can be used in baseboard units as well as to operate electric furnaces for forced air systems. One of its most prevalent uses is for supplemental space heating. Electricity has an equivalent heating value of 3413 Btu/kW (3600 kJ/kW).

Steam

Steam is not considered a basic fuel as are gas and oil, but in many urban locations it is available from a central plant or as a by-product of the generation of electricity. Once piped into a building, it is not used directly for heating but can be used to heat water for water or air heating systems and to drive absorption-type water chillers for air conditioning.

Heat Pumps

A *heat pump* is a device that can either heat in the winter or cool in the summer. It works by transferring heat from one place to another, using the principles of refrigeration as discussed in a later section. In the summer a heat pump acts as a standard air conditioner, pumping refrigerant to the condenser, where it loses heat, and then to the evaporator indoors, where it absorbs heat. By means of a special valve, the refrigerant flow is reversed in the winter so that the heat pump absorbs available heat from the air outside and transfers it to the indoor space.

Because of this process, however, the efficiency of a heat pump for heating decreases as the outdoor air temperature decreases. Below about 40°F (4°C), a heat pump is not competitive with oil or gas as an energy source. It is more effective in mild climates where winter temperatures are usually moderate. For supplemental heating, electrical resistance coils are often placed in supply ductwork.

To extend its efficiency, a heat pump can be connected to a solar energy system. With this approach, solar energy provides heat when the outdoor temperature is between 47°F and 65°F (8°C and 18°C). Below the lower extreme, a heat pump automatically turns on and provides heat until the temperature becomes too cold for its efficient use. Then both systems are used: the heat pump to preheat air and the solar energy system to raise the temperature high enough for space heating. Electrical resistance heating is also available for very cold or cloudy days.

Natural Energy Sources

Other energy sources include solar (either passive or active), photovoltaic, geothermal, wind, and tidal. These are described in Ch. 29. Of these, solar energy is the one that has been developed to the point where it is readily available and efficient for residential and some commercial uses.

Photovoltaic panels are available, but the cost per kilowatt-hour is high, and their general use is limited. This is changing as more research is conducted and more efficient panels are manufactured. Refer to Ch. 29 for more information on photovoltaics.

Use of the other natural energy sources is still in the research and development stage and is limited to large-scale generation rather than use with individual buildings.

Selection of Fuel Sources

In addition to the considerations mentioned previously in regard to the selection of a fuel source, the number of degree days in a building's location and the efficiency of the fuel must be taken into account.

Degree days are a measure of the approximate average yearly temperature difference between the outside and the inside in a particular location. The number of degree days for a day is found by taking the difference between an indoor temperature of 65°F (18°C) and the average outside temperature for a 24-hour period. For example, if the 24-hour average is 36°F, then the number of degree days is $65 - 36 = 29$. The values for each day of the year are added to get the total number of degree days for the year. Degree days are used to calculate yearly fuel consumption, to size some passive solar energy systems, and to factor into other heating computations.

Because different fuel types convert energy into heat with varying levels of efficiency, efficiency is an important consideration in the selection of fuel, assuming all fuels are available. Table 28.1 shows the typical efficiency ranges of several fuels.

Table 28.1

Approximate Efficiencies of Fuels

fuel	efficiency (%)
natural gas	70–80
propane	70–90
no. 2 oil	65–85
anthracite coal	65–75
electricity	95–100

ENERGY CONVERSION

Whatever type of fuel is selected for heating and cooling, it must be converted into a useful form for distribution throughout a building. This usually requires additional energy, such as electricity, to operate fans, motors, and other components of the system. This fact applies to conventional fuels as well as to natural energy sources such as active solar energy systems.

Heat Generation Equipment

Two of the most common devices for converting fuel to heat are the furnace and the boiler. *Furnaces* burn either gas or oil to heat air, which is then distributed throughout the building. *Boilers* use fuel to heat water, and the steam or hot water is used to distribute heat.

A furnace burns fuel inside a combustion chamber around which air is circulated by a fan. As the cool air from return air ducts passes over the combustion chamber, it is heated for distribution to the building. The hot exhaust gases pass through a flue that is vented to the outside. Replaceable filters are used on the return air side of the furnace to trap dust and dirt in the system.

Forced air furnaces may be of the upflow, downflow, or horizontal type. In an *upflow furnace*, the return air is supplied at the bottom of the unit and the heated air is delivered to the bonnet above the furnace where it is distributed through ductwork. A *downflow furnace* operates in exactly the opposite way and is used in cases where ductwork is located in a basement or crawl space and the furnace is located on the first floor. A *horizontal furnace* is designed to be used in areas where headroom is limited, such as in crawl spaces.

Boilers use fuel to create hot water or steam. The fuel source can be gas, oil, electricity, or steam. In the typical boiler, tubes containing the water to be heated are situated within the combustion chamber where the heat exchange takes place. As with furnaces, the gases and other products of combustion are carried away through breeching into the flue or chimney. Of course, if the primary fuel source is electricity or steam, there is no need for an exhaust flue.

Principles of Refrigeration

There are two types of refrigeration processes that can produce chilled air or water: compressive refrigeration and absorption. A third type, evaporative cooling, can be used to produce cool air in some climates.

Compressive refrigeration is based on the transfer of heat during the liquefaction and evaporation of a refrigerant. As a refrigerant in a gaseous form is compressed, it liquefies and releases latent heat as it changes state. As the same liquid expands and vaporizes back to a gas, it absorbs latent heat from the surroundings into the gas. These principles are used in the basic refrigeration cycle shown in Fig. 28.1.

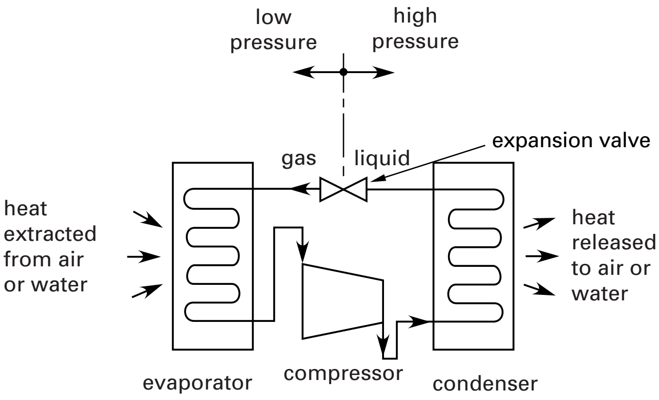

Figure 28.1 Compressive Refrigeration

In the past, refrigerants such as Freon were used in compressive refrigeration. However, these compounds contain chlorofluorocarbons (CFCs) that contribute to the depletion of the earth's ozone layer when leaked into the atmosphere. As a consequence, new refrigerants such as hydrofluorocarbons (HFCs) have replaced CFCs.

There are three basic components of a compressive refrigeration cycle: the compressor, the condenser, and the evaporator. The *compressor* takes the refrigerant in a gaseous form and compresses it to a liquid. The liquid refrigerant then passes through the *condenser* where the latent heat is released. This is usually on the outside of the building, and the heat is released to the outside air or to water. The refrigerant flows out of the condenser into the *evaporator* where it is allowed to expand. As it expands, it vaporizes back to a gas. In the process of vaporizing, it absorbs heat from the surroundings (either air or water) and then enters the compressor where it is cycled through the process again.

For many small cooling units, air is forced over the evaporator coils with a fan, and it is this cool air that is circulated through the space. However, water is a much more efficient medium to carry heat than is air. In larger units and in large buildings, water is pumped over the evaporator coils to produce chilled water, which is then pumped to remote cooling units where air is circulated over the chilled water pipes. On the condenser side, water is used to extract the heat from condenser pipes and carry it to remote cooling towers where the heat is released to the air.

Refrigeration by absorption produces chilled water and is accomplished by the loss of heat when water evaporates. This evaporation is produced in a closed system by a salt solution that draws water vapor from the evaporator. See Fig. 28.2.

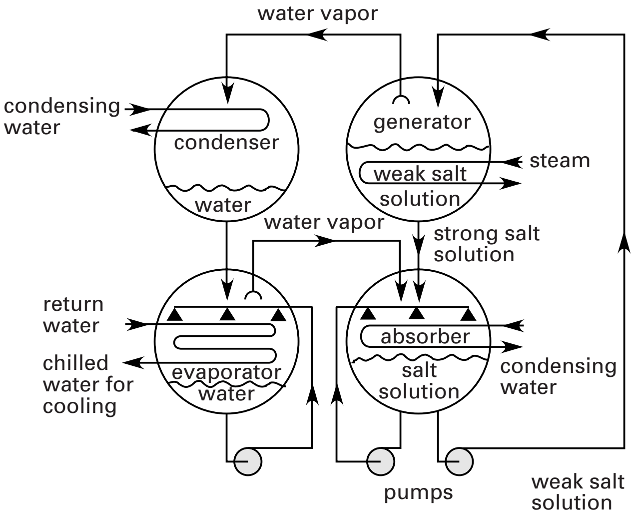

Figure 28.2 Absorption Cooling

As the salt solution absorbs water, it dilutes and must be regenerated by boiling off the water and returning the strong salt solution to the absorber. This is most often done with steam, but it can also be done with high-temperature water produced by solar collectors. The water boiled off in the generator is returned to a liquid state in the condenser and then returned to the evaporator. Both the condenser and absorber require condensing water, which removes the waste heat and carries it to cooling towers. Absorption systems are less efficient than compressive systems and are

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VERTICAL TRANSPORTATION

Vertical transportation is a term that describes all the methods used to move people and materials vertically. This includes passenger and freight elevators, escalators, dumbwaiters, vertical conveyors, moving ramps, wheelchair lifts, and platform lifts, as well as stairs, ramps, and ladders.

HYDRAULIC ELEVATORS

Hydraulic elevators are one of the two major elevator types used for the movement of people and freight; the other is electric elevators. Hydraulic elevators are lifted by a plunger, or *ram*, set in the ground directly under the car and operated with oil as the pressure fluid. As a consequence, the cylinder for the ram must be extended into the ground to a depth the same as the elevator's full height.

Because the ram must be set in the ground and speed is limited, hydraulic elevators are only used for passenger and freight loads in buildings from two to six stories high, or about 50 ft (15 m). They have speeds much lower than those of electric elevators, traveling from 25 fpm to 150 fpm (0.13 m/s to 0.75 m/s) and are therefore not appropriate for moving large numbers of people quickly. Single-ram elevators have weight capacities from 2000 lbm to 20,000 lbm (1000 kg to 10 000 kg), and multiple-ram units can lift from 20,000 lbm to 100,000 lbm (10 000 kg to 50 000 kg).

A few variations of the standard hydraulic elevator are available. The holeless hydraulic uses a telescoping plunger set in the shaft next to the cab. Lift is provided by applying force to the upper members of the car frame. Another type uses a roller chain mounted over a wheel mounted on top of the hydraulic plunger. With this type, the plunger is mounted above the ground in the side of the shaft.

ELECTRIC ELEVATORS

Electric elevators are the most common elevator type used for passenger service. They are capable of much higher lifts and greater speeds than hydraulic types and can be precisely controlled for accelerating and decelerating. The system employs a cab suspended by cables (known as *ropes*) that are draped over a sheave and attached to a counterweight. A motor drives the sheave, which transmits lifting power to the ropes by the friction of the ropes in grooves of the sheave. For this reason, electric elevators are also referred to as *traction elevators*. The common components of a traction elevator are shown in Fig. 44.1.

Electric passenger elevators travel from 250 fpm to 1800 fpm (1.25 m/s to 9 m/s) and have capacities from 2000 lbm to 5000 lbm (1000 kg to 2500 kg). Higher capacities are available for electric freight elevators.

Types

The two types of electric elevators are the gearless traction and the geared traction. *Gearless traction elevators* use a direct current (dc) motor directly connected to the sheave. The brake is also mounted on the same shaft. Gearless machines that are dependable and easy to maintain are used on high-speed elevators.

The *geared traction elevator* is used for slow speeds from 25 fpm to 450 fpm (0.13 m/s to 2.25 m/s). A high-speed DC or AC motor drives a worm gear reduction assembly to provide a slow sheave speed with high torque. With the many possible variations in gear reduction ratios, sheave diameters, motor speeds, and roping arrangements, geared traction machines provide a great deal of flexibility for slow-speed, high-capacity elevators.

Roping

Roping refers to the arrangement of cables supporting the elevator. The simplest type is the *single wrap*, in which the

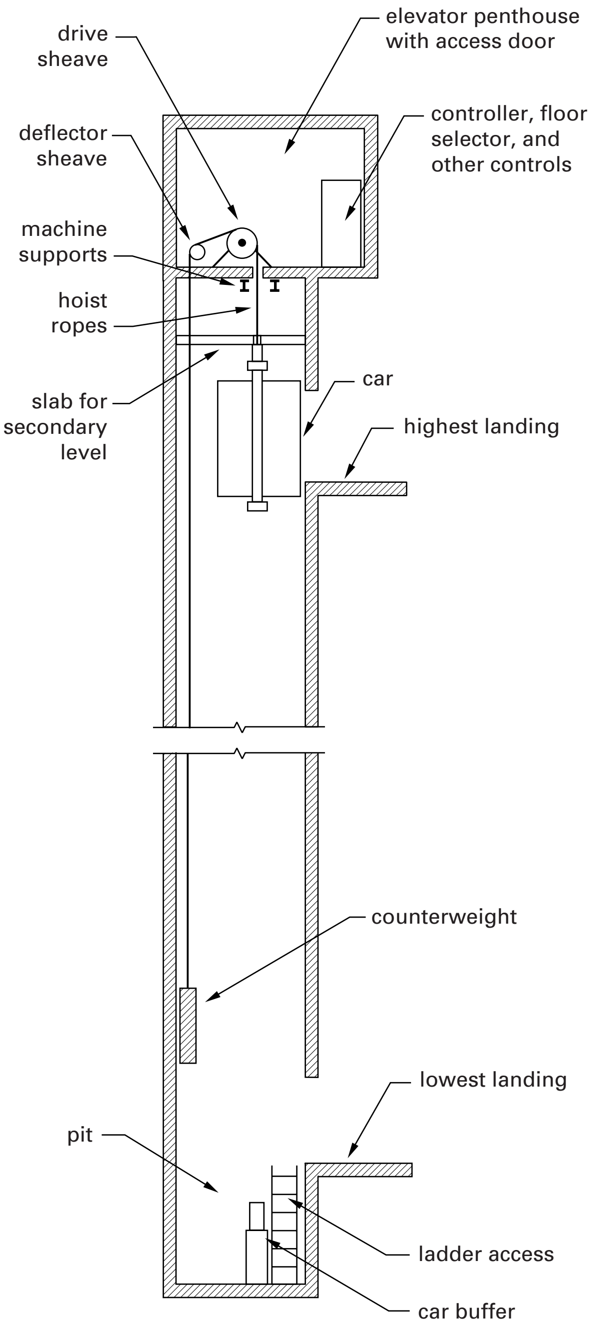

Figure 44.1 Traction Elevator

rope passes over the sheave only once and is then connected to the counterweight. For high-speed elevators, additional traction is usually required so that the rope is wound over the sheave twice. This is known as a *double-wrap* arrangement. The disadvantage to double wrapping is that there are more bends in the cable and consequently a shorter rope life.

When the rope is directly connected to the counterweight, the cable travels just as far as the car, only in the opposite direction. This is known as *1:1 roping*. When the rope is wrapped around a sheave on the counterweight and connected to the top of the shaft, the rope moves twice as far as the elevator cab. This is known as *2:1 roping* and requires that less weight be lifted. Therefore, a smaller, higher-speed motor can be used, which is desirable for speeds up to 700 fpm.

Operation and Control

Operation is the term used to describe the way the electrical systems for an elevator or group of elevators answer calls for service. *Control* describes the method of coordinating and operating all the aspects of elevator service, such as travel speed, accelerating and decelerating, door opening speed and delay, leveling, and hall lantern signals.

Many types of operating methods are available. The purpose of an operating system is to coordinate elevator response to signal calls on each floor so that waiting time is minimized and the elevators operate in the most efficient manner possible.

The simplest type of system is the *single automatic*. This was the first type of automated system for elevators without attendants and consists of a single call button on each floor and a single button for each floor inside the car. The elevator can only be called if no one is using it, and once inside, the passenger has exclusive use of the car until the trip is complete. This type of system has limited use, and is therefore best for small buildings with little traffic where exclusive use is desired.

The most common type of system for many buildings is the *selective collective operation*. With this system, the elevator remembers and answers all calls in one direction and then reverses and answers all calls in the opposite direction. When the trip is complete, the elevator can be programmed to return to a home landing, usually the lobby.

The selective collective system works well for light to moderate service requirements, but for large buildings with many elevators, *group automatic operation* is employed. This is simply the control of all elevators with programmable microprocessors to respond to calls in the most efficient manner possible, taking into account all the variables involved. In addition, such things as the time of day or day of the week can be included in the programming. This provides precise response to any building's needs.

Safety Devices

Modern elevators use many safety devices. The main brake on the sheave or motor shaft is normally operated by the control mechanism. If a power failure occurs, the brake is automatically applied. A governor also senses the speed of the car, and if the limit is exceeded, the brake is applied. There is also a safety rail clamp that grips the side rails if there is an emergency. In the pit of the elevator below the lowest landing, car buffers stop a car's motion if it over-travels the lowest stop; however, they are not designed to stop a free-falling elevator cab.

Hoistway door interlocks prevent the elevator from operating unless the hoistway door is closed and locked. In addition, various devices prevent the doors from closing on someone in their path. *Safety edges* are movable strips on the leading edge of the door that activate a switch to reopen the door if something contacts it. Photoelectric devices serve the same purpose. There are also proximity detectors that sense the presence of a person near the door and can stop the closing motion.

To prevent overloading of a car, sensors under the floor detect when the maximum weight is reached by deflection of the floor. This then makes a warning noise with additional loading and prevents the elevator from picking up any more people. Additional safety devices include multiple ropes, escape hatches in the top of the cab, alarm buttons on the car control panel, and telephones for direct communication in an emergency.

In the case of a power failure all cars will stop where they are, but most codes require that emergency power be available to operate at least one car at a time. This allows the unloading of occupied cars. Building codes require that if a fire alarm is activated, all cars return to the lobby without stopping and switch control to manual mode. The cars can then only be operated by fire fighting personnel using a manual key.

Elevators must also be accessible to the physically disabled. In lobbies this usually means visual signals that can be easily seen as well as audible signals indicating car approach, car landing, and directions of approach. Call buttons and raised and braille floor designations must be placed within certain height limitations. There is also a formula for calculating the minimum time between notification that a car has answered a call and the moment the doors of that car start to close, with a minimum time of 5 sec.

Elevator cars themselves must be sized to allow a person in a wheelchair to enter, maneuver within reach of the controls, and exit the car. Minimum clear door opening width is 36 in (915). All car controls must be no higher than 54 in (1370) for side approaches and 48 in (1220) for front approaches. The car controls must be designated by braille and by raised standard alphabet characters. Main entry floor, door open, door closed, emergency alarm, and emergency stop buttons must also be designated by standard raised character symbols.

ELEVATOR DESIGN

In simplest terms, elevator design involves selecting the capacity, speed, and number of elevators to adequately serve a particular building's population and then arranging the location of each elevator bank and the arrangement of the lobby. In addition, the roping method, machine room layout, control system, and cab decoration must be determined.

Capacity and Speed

Determining the number, capacity, and arrangement of elevators to serve a building is a complex process because there is an optimal interrelationship between the number of people to be served in a given time period, the maximum waiting time desired, cost, and particular requirements of the building. For example, a hospital elevator moves large numbers of people but also must have provisions for stretchers and large quantities of supplies. The elevator in a corporate headquarters building may handle a great deal of interfloor traffic, whereas one in an apartment building will primarily move people from the lobby up to their floors and back down again.

For most buildings the *handling capacity*, or number of people to be served, is usually based on a 5-minute peak period. For office buildings, this is usually the time in the morning when everyone is coming to work. The number of people a car can carry is a function of its capacity, which is measured in weight. Through experience, some general guidelines have been established for recommended capacities based on building types and rough building areas. These are shown in Table 44.1.

The capacities listed in Table 48.1 are in pounds. The equivalent SI units are approximate and are based on 1 kg being equal to 2.2 lbm. The corresponding SI units of elevator capacity are shown in Table 44.2.

The maximum number of passengers in a car is directly related to the capacity in weight. Table 44.3 gives the car passenger capacity based on weight capacity.

General recommended elevator speeds are also available based on the number of floors served and the general size of the building. The higher speed translates to shorter intervals, or waiting time, but there are some limits due to overall travel distance (number of floors). Higher-speed elevators also generally cost more. Recommended elevator speeds are shown in Table 44.4.

Number of Elevators Required

Based on the car capacity and speed, along with such particular characteristics of the elevator functioning as door opening and closing time, delays at stops, and so forth, the average round trip time can be calculated, and then the