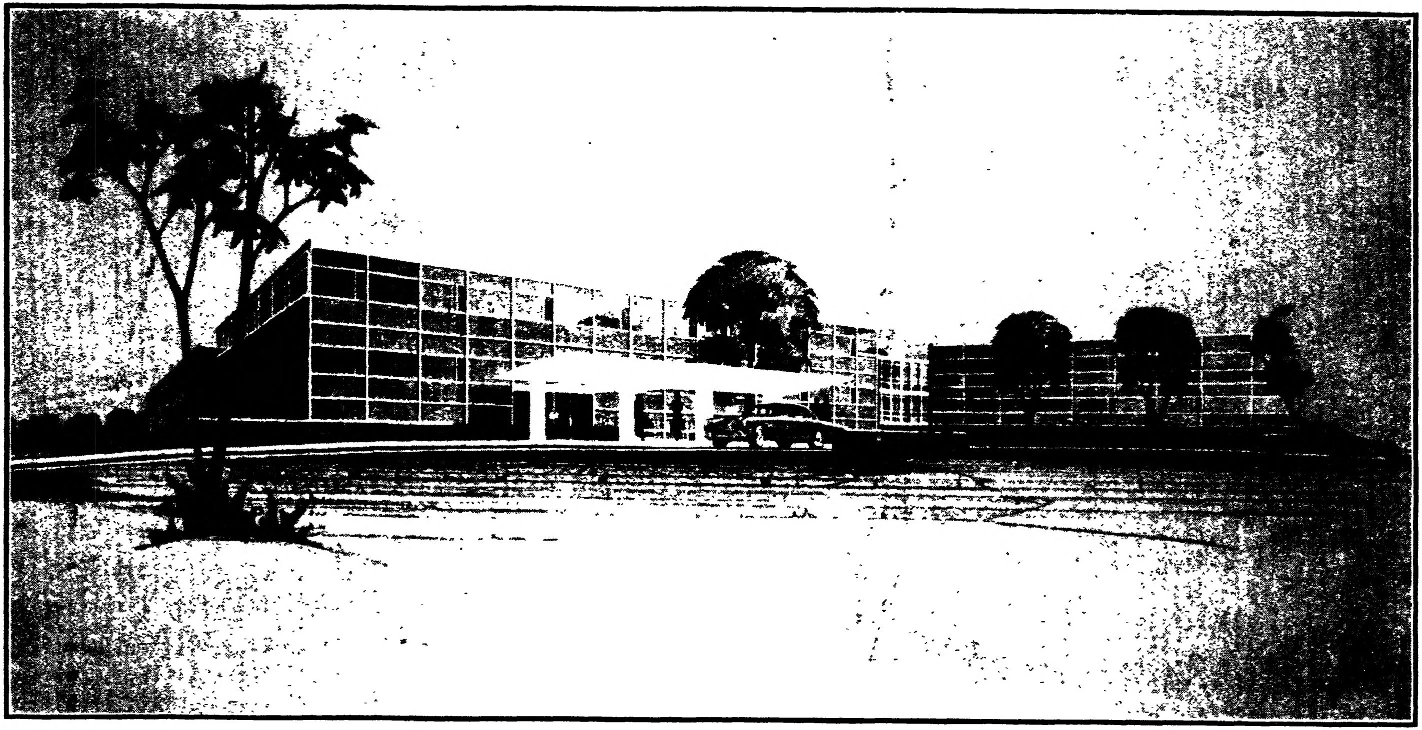
MECHANICAL AND ELECTRICAL EQUIPMENT FOR BUILDINGS



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MECHANICAL AND ELECTRICAL EQUIPMENT FOR BUILDINGS

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PREFACE TO THE THIRD EDITION

The increased size of this third edition has permitted us to improve the basic principles dealing with both mechanical and electrical equipments and to cover additional advanced practices in their selection, installation, operation, and maintenance. We have replaced certain mechanical equipment (Chapters 1 to 21) with more modern types. Turbine, jet, and submersible pumps have been illustrated and the subject of water impurities and treatment expanded. The prescribed relationship of the recovery rate of domestic hot water heaters and the capacity of storage tanks have been tabulated. Data will be found for the design of loop venting, septic tanks, and tile drain fields.

Basic heat conduction factors have been clarified and information added to the tables of heat transmission factors for building materials. Power-circulated warm air and hot water systems have entirely replaced those using gravity. The warm air section includes a discussion of perimeter heating, and the hot water section has been extended to include baseboard heating. Compact and efficient steam systems have replaced those typified by the bulky two-pipe open system using cast-iron radiators. The economical Metro system is described, and unit heaters are discussed.

A new chapter on radiant heating has been added. In the air conditioning section, data for computing heat gain have been increased. Procedure for designing air conditioning has been thoroughly revised. Appropriate examples have been added.

In the electrical section (Chapters 22 to 30), we have clarified the simple theories dealing with the definition of electricity and the applications of simple formulas involving Ohm's law both in series and in parallel circuits. Simple wiring diagrams and the use of the ammeter, voltmeter, and wattmeter for a-c single-phase circuits or d-c circuits are illustrated and explained. As in the preceding edition emphasis is given to the matter of personal safety through figures and explanations.

The single-line wiring diagram for 2-, 3-, 4-, and 5-wire circuits is referred to as applicable to any of the d-c and a-c single or polyphase basic wiring systems. Typical solutions of each of these systems are given in terms of the applied and load voltages and the current in amperes in the line conductors. Instructors may use these diagrams to determine the voltage line-drops and the impedance of the lines. All tables concerned with the selection and application of conductors, insulation requirements, and conduit sizes have been checked with the corresponding tables of the latest (1953) National Electrical Code.

In many cases typical physical arrangements of switchboards, duplex controlboards, and panelboards are shown; and approximate overall dimensions and weights are indicated. Also approximate plan layouts of an elevator machine room and of end and side views of an escalator are shown and described. Typical problems concerned with the selection of adequate elevator service and electric stairway service are presented and solved. Some appropriate line drawings cover the best plan layouts of elevator lobbies and of a number of typical electric stairway arrangements in plan and side elevations. In 1954 the escalator manufacturers standardized on only two widths: 32 in. and 48 in. Some approximate new cost data are given on the most-used types of elevators and electric stairways. We have added text material and illustrations on the design of elevator lobbies and escalator entrances and passageways. Design and installation data on elevators and escalators have been brought up to date.

The chapters on lighting (27 and 28) cover both fundamental principles and specific applications with typical problem solutions. Many modern types of fluorescent luminaires have replaced outdated former incandescent and fluorescent units. Considerable changes in tabular data of luminaires, lamps, and of recommended ft-c values will be noted. Some of the many new types and arrangements of materials for troffer lighting are presented.

The major portion of the chapter on acoustics has been retained, but new and improved types of the latest sound-absorbing materials have been substituted for many of the older types. A typical problem involving acoustical treatment of an auditorium is presented and solved.

The authors appreciate the continued use of this textbook in departments of architecture, architectural engineering, and architectural design in many universities and colleges. We have noticed that there is a growing interest in it among building equipment operators and among young men employed by consulting engineers, general contractors, and building managements.

We gratefully acknowledge continued contributions and cooperation of the following engineers and organizations in their respective fields: Mr. Daniel E. Eisenberg, Burroughs Corporation, vertical transportation and illumination; Mr. George H. Fischer, for many years with the Association of Fire Underwriters and now with Morris Newmark and Brother, Electrical Engineers and Contractors, NEC Code Interpretations; Mr. Jack Hanley, Bell and Gossett Co.; Mr. H. F. Metcalf and Mr. R. F. McCaw, Radio Corporation of America; Mr. Edgar H. Nelson, Westinghouse Electric Corporation, Elevator Division; Mr. A. W. Perryman and Mr. A. E. Feather, Otis Elevator Company, elevators; Dr. Harry Sohon, University of Pennsylvania, acoustics; Mr. Henry L. Shuldener, President, Water Service Laboratories.

Many suggestions for improvement in the preceding edition have been incorporated in this third edition. Such suggestions have come from teachers of architecture, architectural design, and architectural engineering; and from young men engaged on mechanical and electrical layout and design for consulting engineers. We most sincerely appreciate this cooperation.

In spite of our efforts to eliminate errors as the manuscript was prepared and the proof checked, some may have persisted. We invite the reader to call them to our attention.

Charles De van Fawcett
William J. McGuinness

November, 1954

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SECTION VI · ACOUSTICS

SECTION I · WATER SUPPLY

Chapter 1

SOURCES, PUMPING, TREATMENT, AND STORAGE

1. General. Although the details involved in the design of a public water supply seldom form a part of an architect's practice, the architect is often expected to develop the private water supply of isolated estates, institutions, and industrial plants when no public source is available. The following pages, therefore, cover the handling and treatment of water within buildings irrespective of the source of supply but will consider its procurement only when the source is private.

2. Sources of water supply. The primary source of water supply is rainfall. In Bermuda and a few other locations where surface and ground water are not available in pure form, rainwater is caught on roofs and watersheds and stored in large underground cisterns where coolness and purity are assured. This water is soft and reasonably pure. This method is cumbersome and not frequently chosen when other possibilities exist. The sources usually developed by municipalities and for private use are ground and surface water.

The abundance of these sources is directly dependent upon rainfall. Figure 1 shows the annual rainfall in inches of water from records such as those compiled by the Government Weather Bureau. A variation of less than 10 in. to more than 60 in. annually will be noticed. In localities of much rain the surface supplies will be abundant and the water table relatively high, depending also, of course, on the terrain and the strata through which the water flows. Areas of light rainfall will have a minimum of surface flow and low water tables. Reference to government records is valuable in planning private water systems.

Cities usually use water from large lakes. Although this water is too silty and impure for use by houses adjacent to the lakes, it is purified by natural aeration and the usual filtration and settlement before being delivered to the city. Individual houses, isolated industries, and small communities frequently choose deep wells. This water is inclined to be pure, cool, and clear but hard and sometimes requires softening. Springs and shallow wells are usable to a limited extent, provided careful attention is given to yield and purity. The flow can easily suffer

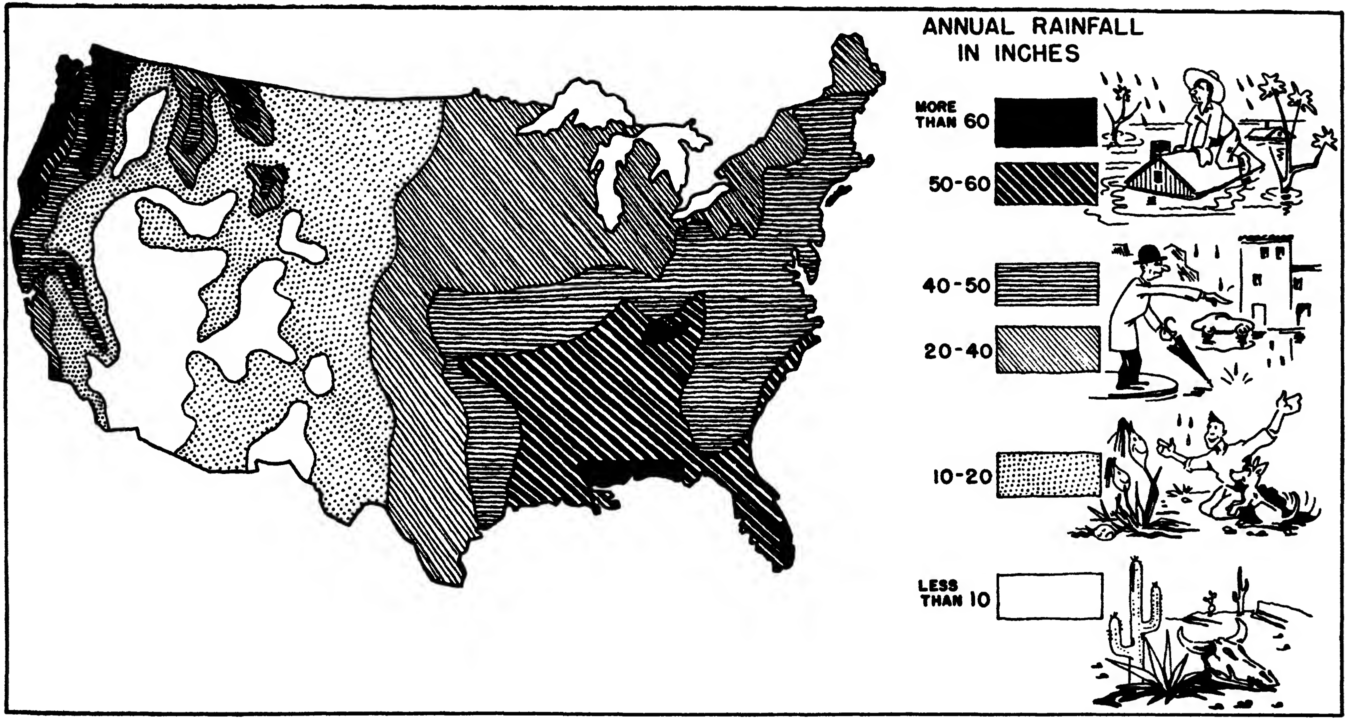


Fig. 1. Map of the United States showing mean annual precipitation. Reprinted with permission from *Progressive Architecture.* Drawing by Raniero Corbelletti.

in a drought, and near-surface water carrying organic matter and contamination can find its way into the spring or well.

If lakes furnish the water supply, rainfall records and observation over a period of years establish the dependence that can be put on the reliability of this source. Deep wells are dependent for their performance on both the rainfall and the geology of the region. This is often a difficult investigation. Records of adjacent wells are valuable, and when the well has been completed it can be pumped for long periods to establish its stability of flow. Except under unusual circumstances an established deep well will maintain a fairly steady water table which may not vary more than several feet in height through the year.

3. Surface and ground water. When there is a high impervious stratum below water-bearing soil, surface flow is predominant as shown in Fig. 2. There is a general gradient toward flowing streams. This is sometimes quite steep and may appear as swamps or springs. All these sources, including the shallow well shown at the right of Fig. 2, are subject to contamination by organic matter and may carry silt. The temperatures are generally warm. At the outcropping of impervious layers springs may appear. This is shown in Fig. 3, class 1 and class 3. When an impervious stratum has water-bearing soil below it, as in Fig. 3, class 4, a break-through may cause an artesian well which will flow of its own accord because of the pressure of the trapped water. The water, though taken from a point close to the surface may be cool, clear, and free from organic matter because of the filtration action of the soil trapped below the impervious layer and because of the probable long distance of flow of the water. The advent of a flowing well is rare, but it is evident that a well drilled and pumped at a similar point not under pressure might yield good water. This filtering action is beneficial to waters in deep wells also, because the water

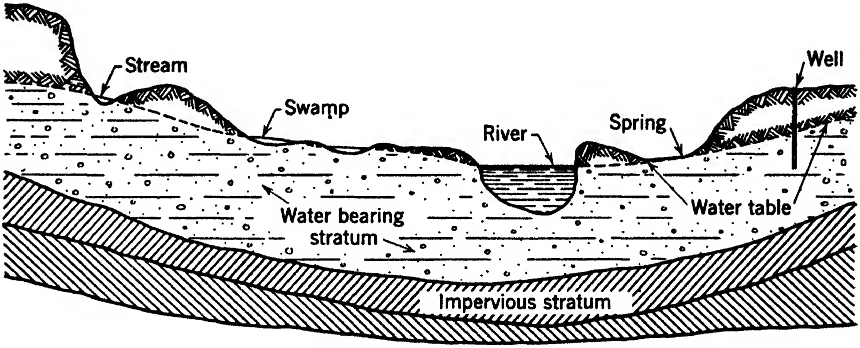


Fig. 2. Replenishing surface supplies from ground water.

is forced to flow for long distances through filtering earth before it is collected. It will be cool, clear, pure, but sometimes hard because of the absorption of minerals. Since hardness is easier to treat than impurity deep wells are frequently preferred for private water supply.

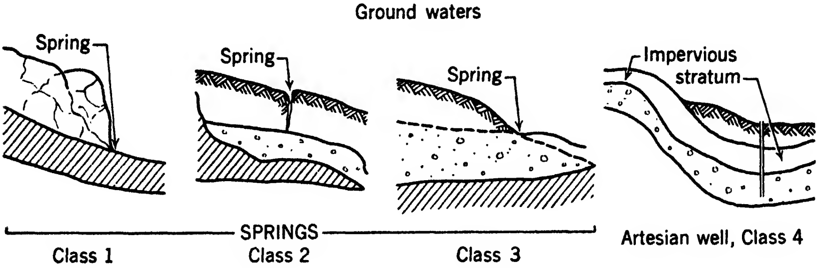


Fig. 3. Ground water conditions.

4. Development of water sources. Lake water so commonly used in municipal supply is dangerous in private systems. The arrangement in Fig. 4 may help to reduce the turbidity (silt), but it will still be necessary to make biological tests to find out whether chlorination is needed. Figure 5 shows the development of a spring that occurs at the outcropping of impervious material. A tight masonry casing excludes surface contamination, and a fence uphill from the spring keeps livestock at a distance.

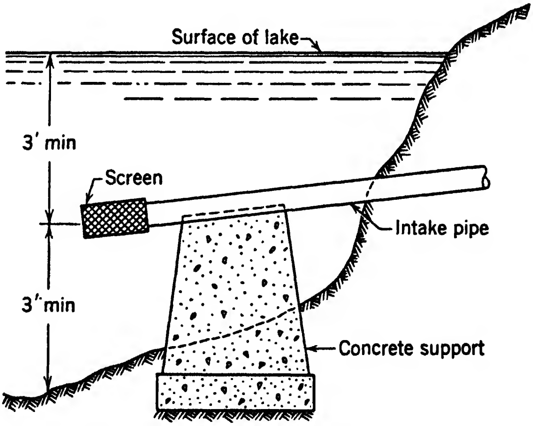


Fig. 4. Development of surface supply.

Shallow wells are protected by masonry similar to that surrounding a spring. It should be impervious for a depth of 10 ft (Fig. 6). Par-

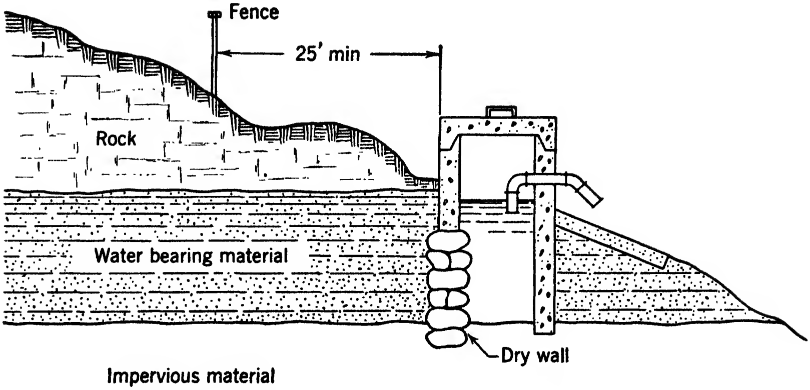


Fig. 5. Development of ground water from springs.

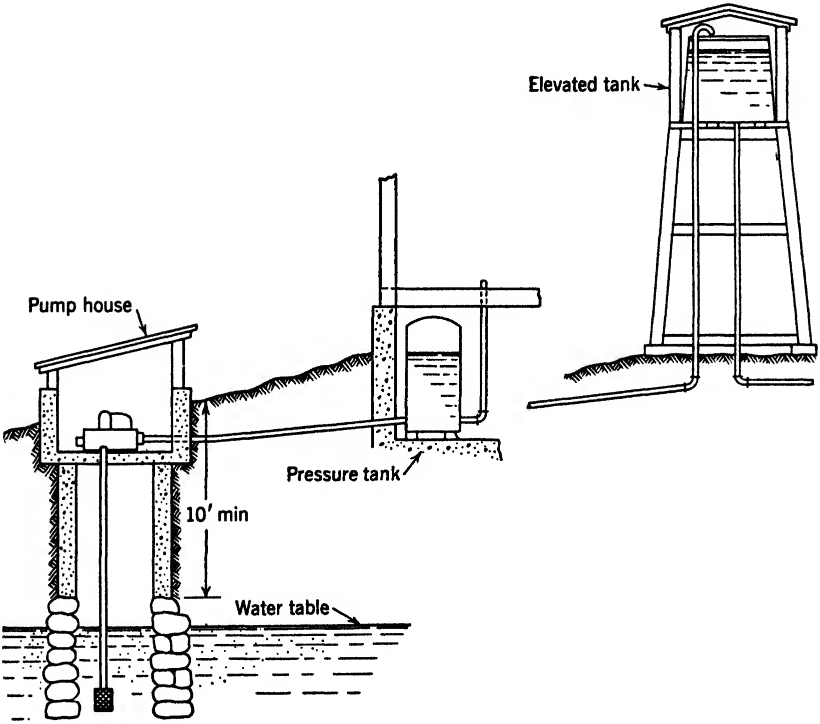


Fig. 6. Development of shallow wells.

ticular care must be taken in deep wells (Fig. 7) to see that the well screen and pump suction are well below the static water level and the "drawdown" caused by the pumping. The circles of influence of adjacent wells must not overlap, and it must be shown by pumping tests of 24 hr or more that the well can yield the rate required for the building. Deep wells are driven through earth and drilled through rock, the casing going down in sections. At the bottom of the well casing is a well screen of special alloy. The pump casing is lowered inside the well casing and may be withdrawn and dismantled for convenience in the process. The flow of such wells may be increased sometimes by backwashing or pumping water down through the screen to dislodge fine sand particles that would obstruct flow through the screen. Deep wells over 500 ft in depth are not uncommon. The number of gallons per minute pumped may be measured by putting a standard orifice (weir) on the discharge pipe and observing the pressure in the tube shown on this discharge in Fig. 7. In case of temporary turbidity the well should be pumped until it runs clear before being put into service.

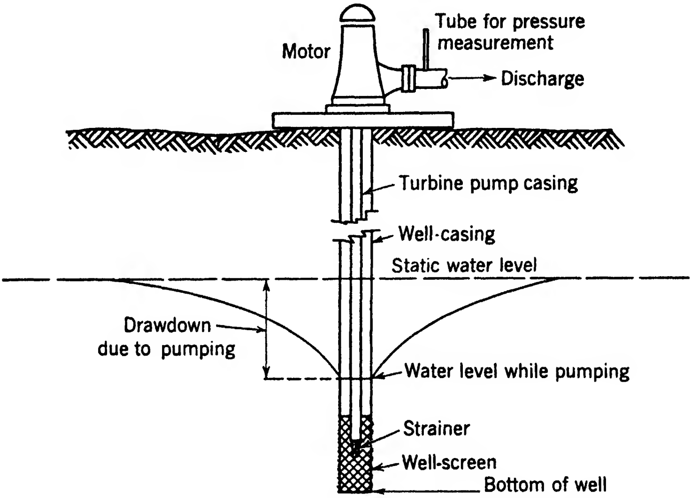


Fig. 7. Development of ground water supplies in deep wells.

5. Pumping equipment (Table I). For private supply from wells there are shallow-well and deep-well pumps. In buildings using municipal supply, it is necessary to pump into pneumatic or gravity storage tanks, which is usually done by triplex plunger pumps or by centrifugal pumps. Shallow-well pumps merely create a suction.

Table I. Pumps

Kind of Pump	Fig. No.	General Use	Pumping Characteristics	Qualities
Reciprocating	8	Boiler feed, shallow-well suction	Suction lift limited to 25′ *	Pulsations must be moderated by pneumatic chamber
Deep-well reciprocating	9	Deep wells	Must be submerged	Pulsations must be moderated by pneumatic chamber
Plunger	10	Pumping from city main to storage	Suction lift limited to 25′ *	3 cylinders (triplex) give smooth action
Deep-well ejector	11(*a*)	Deep wells	Must be submerged	Fewer parts than deep-well reciprocating
Multistage turbine	11(*b*)	Deep wells	Must be submerged	This type is usually used for high capacity
Multistage submersible	11(*c*)	Deep wells	Must be submerged	Very silent
Centrifugal	12	Pumping from city main to storage	Must remain primed to operate	Quieter than reciprocating types

* At sea level and 60°F. At higher elevations and higher temperatures the possible suction lift is less than 25′.

The atmospheric pressure which makes the water rise in the suction casing cannot sustain more than 25 ft of water. Theoretically the height is greater, but mechanical imperfections prevent perfect performance. This limits shallow wells to a depth of not more than 25 ft.

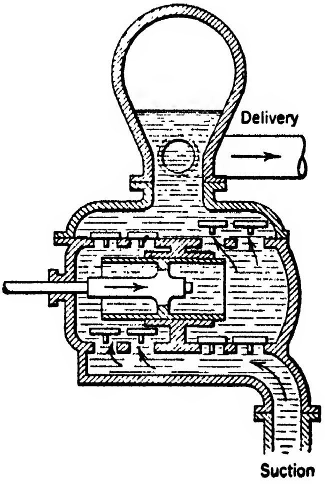


Fig. 8. Horizontal reciprocating pump.

The deep-well reciprocating pump, Fig. 9, is one of the oldest of the methods for extracting water from deep drilled wells. A vertical shaft, deep plunger, and two valves effect the pumping process. The deep-well ejector, Fig. 11(*a*), and the submersible pump, Fig. 11(*c*), have replaced it to some extent, as they are quieter, more uniform in discharge pressure, and easier to maintain. For high capacity the turbine pump, Fig. 11(*b*), is usually used.

For handling city water from mains or from suction tanks to pneumatic or gravity storage tanks the centrifugal pump, Fig. 12, is largely replacing the triplex plunger pump because it is quieter, steadier, and easier to maintain, having only one moving part, the impeller.

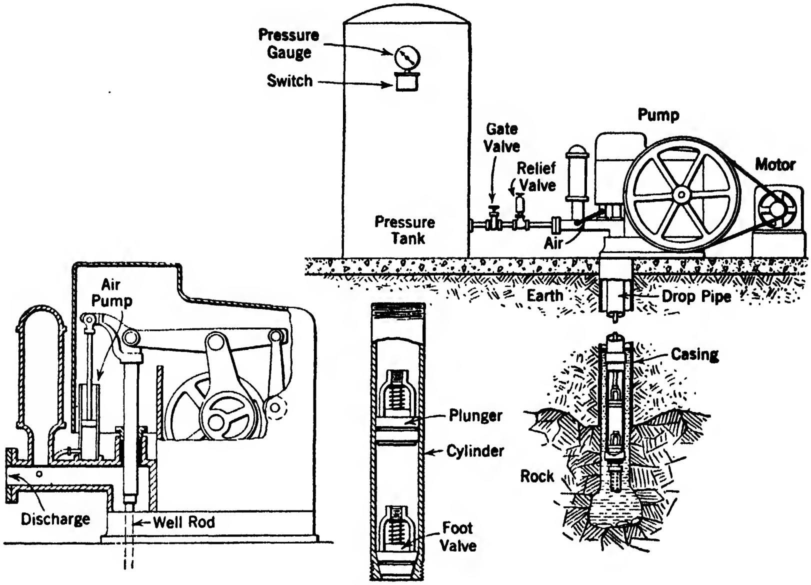


Fig. 9. Deep-well reciprocating pump.

6. Treatment (Table II). It is interesting to note that in regions of heavy rainfall where water is recovered from lakes, shallow wells, or freely fed deep wells there is usually an acid reaction from entrained oxygen and carbon dioxide. With little rainfall and water recovered after much travel through limestone and other minerals, hardness generally prevails. By consulting Fig. 1, the regions of hard water can be placed where the rainfall is least. Geological conditions also cause hardness. In the vicinity of the Great Lakes, large limestone deposits are the cause of great hardness in the waters.

Table II. Water Impurities and Treatment

Quality	Cause	Effect	Correction
Acidity	Entrained oxygen and carbon dioxide from surface flow	Corrodes nonferrous pipe. Rusts and clogs steel pipe	Add sodium silicate to neutralize the acid
Hardness	Magnesium and calcium salts from underground	Deposit fills pipe. Impairs laundry and cooking	Softening by a zeolite ion-exchanger
Silt	Turbidity from surface or underground flow	Discoloration and bad taste	Filtration
Pollution	Presence of *B*-coli from sewage or organic matter	Ill health	Chlorination to kill bacteria

Acid and alkaline reactions cannot, of course, obtain in the same water. Soft water is either neutral (no treatment needed) or acid. If water is sufficiently acid it will attack almost any metal used for piping and equipment. If the pipes are of ferrous metals rust results, which, being 10 times the size of the metal, will close the pipe by clogging sometimes within a very few years. Brass and copper are more resistant, but in brass pipes de-zincification will occur and small particles of zinc will be eaten away, resulting in leakage. Nonferrous pipes will leak instead of clogging. Acid water is corrected by a neutralizer which feeds an alkali into the water, neutralizing the acid.

Hardness is caused by mineral compounds of lime (calcium) and magnesium. If present in sufficient quantities these compounds will deposit upon the inner surface of pipes of any material and close them as quickly and effectively as a bad acid condition closes ferrous pipes. Hot water pipes and boiler tubes are most vulnerable because heat accelerates the depositing action. Soap will not form a lather in the presence of hard water, and insoluble deposits are left in the fabric of finished laundry work, rendering it unpleasant to the touch and faster to wear out. Laundering clothes and bathing are both affected adversely. Vegetables cooked in hard water are often unpalatable and tough. Hardness is corrected by a zeolite ion-exchanger. By passing the hard water through a filter bed laden with a sodium compound, a chemical reaction occurs which precipitates insoluble compounds into the filter and passes the soft sodium compounds into the system. Thus the mineral content delivered to the system is not reduced but is merely rendered harmless. The exchanger has to be flushed out periodically and regenerated by replenishing the sodium compound.

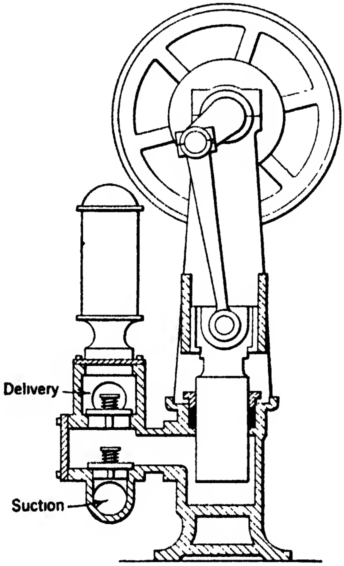
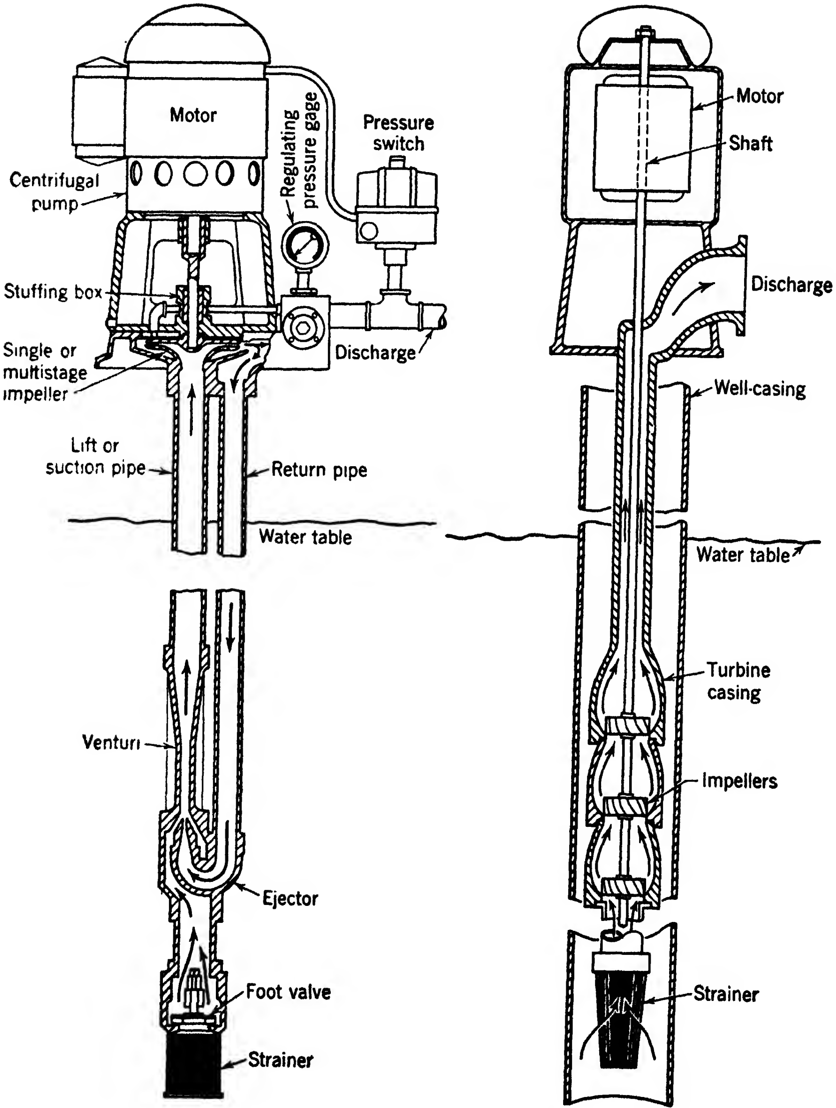


Fig. 10. Vertical reciprocating pump with plunger.

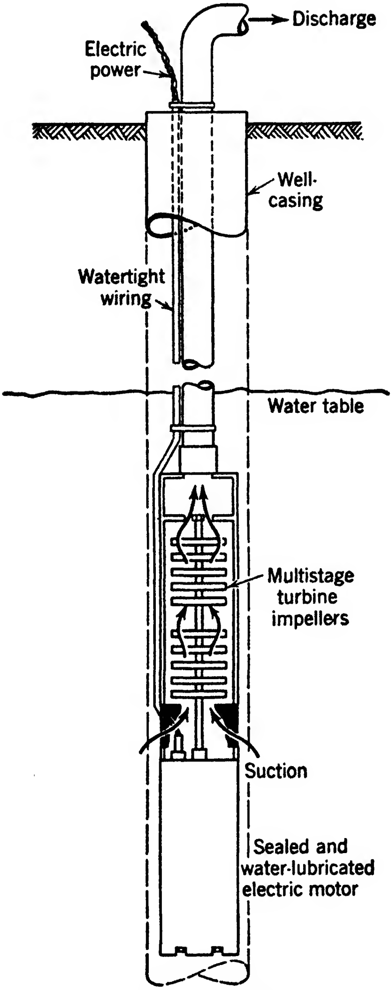
Turbidity caused by silt should be avoided in selecting a water source. In municipal supplies, most of it settles out in large reservoirs where the water speed is slowed to a minimum. The rest can be caught in filters. In private supplies filtration produces clear water. Filters need to be flushed out occasionally.



(*a*) Ejector (Jet)

(*b*) Turbine

Fig. 11. Deep well pumps using the centrifugal turbine principle.



(*c*) Submersible

Fig. 11 (Continued).

Bacteria-laden water is, of course, the worst menace, since it can affect health adversely. Human and animal wastes are the main cause of such pollution. Private wells should be located far from cesspools and livestock. Filtration of city supplies and the natural filtration of water supplying deep wells can eliminate much or all of the pollution. Any remaining pollution must be eliminated by chlorination. In city supplies chlorine is used directly; in private supplies it is fed in through a hypochlorite powder.

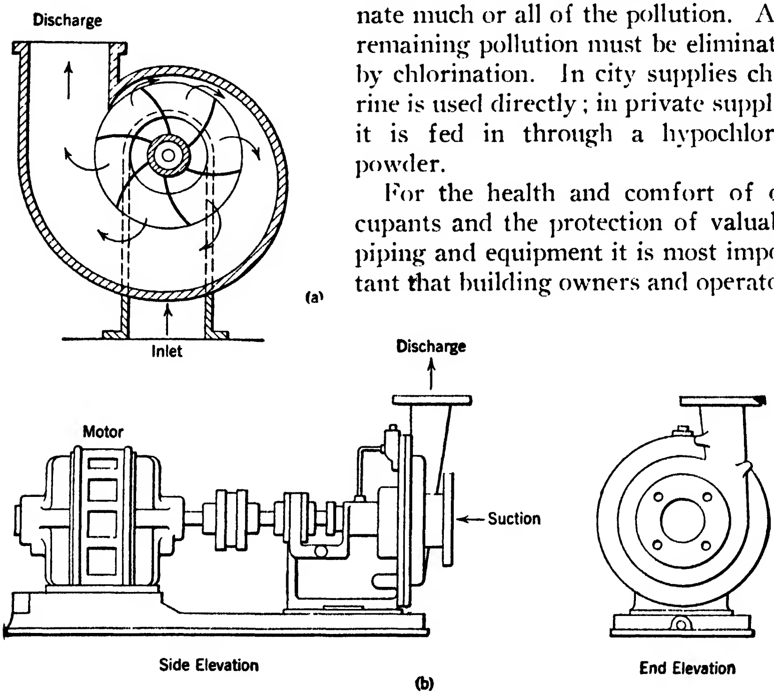


Fig. 12. Centrifugal pump.

For the health and comfort of occupants and the protection of valuable piping and equipment it is most important that building owners and operators have chemical and biological analyses made of the water to be used. Municipal supplies are no exception to this rule. Usually purity can be depended upon: the city has a responsibility in this regard. However, many cities deliver water untreated for acidity or hardness. Damage to equipment may result. The making and interpreting of analyses and the specification and maintenance of equipment for treatment should be in the hands of capable chemical engineers.

7. Storage and distribution. Water is seldom pumped from the source directly to the faucet. It flows from an elevated reservoir or gravity storage tank or from a pneumatic tank in which a pressure is maintained. The effective pressure available is measured in pounds per square inch or in feet of head, the latter being measured from the point of consideration up to the level of the supply. Pressure tanks in houses often operate at 40 lb per sq in., and city supplies often enter the building at about 50 lb per sq in. in residential areas and about 80 lb per sq in. in industrial areas. Gravity tanks should be set with the water level at least 20 ft above the highest fixture. At 60°F water weighs 62.4 lb per cu ft. A column of water 1 in. square and 1 ft high weighs 0.434 lb. Therefore the relations between pressure and head are as follows:

$$p \text{ (pounds per square inch)} = 0.434h \qquad (1)$$

$$h \text{ (head in feet)} = 2.3p \qquad (2)$$

In operation pressure is lost by flow through pipes. This is discussed in Chapter 3. For the purpose of the two following examples this loss is neglected and consideration is given only to the pressures and differences in level.

Example 1. If a faucet in the third story were 30 ft above the ground and a pressure of 25 lb per sq in. were desired at the faucet, the elevation of the source to give this pressure would be

$$2.3 \times 25 = 57.5 \text{ ft} \quad 57.5 + 30 = 87.5 \text{ ft}$$

Example 2. A spring is situated 63 ft above grade level of a building. What pressure would be obtained at a faucet in the second story, 17 ft above grade?

$$63 - 17 = 46 \quad 46 \times 0.434 = 19.96 \quad \text{say 20 lb per sq in.}$$

Storage tanks afford a steady pressure for use in distribution and permit reasonable periods of operation of the pumps that fill them. Pumps are seldom selected to have a capacity for the peak-load demand of the building. Instead they serve the average demand, and the tank is sized to hold a reserve to supplement the pump delivery for the several peak hours. At the end of those peak hours the tank water level is likely to be low.

8. Pneumatic and gravity tanks. Pneumatic tanks are usually below the fixtures to be supplied. When water is called for by the opening of a faucet or other device, air pressure in the top portion of the tank delivers water into the system. A float valve operates the pump to make up this water when the level has become low enough to actuate the starting switch. A high-level switch turns it off when the water is up to level. Gradually the air is absorbed by the pumped water, and the tank tends to become waterlogged. Automatic or manually operated compressors fill the air space again. Small vertical tanks such as that in Fig. 6 are common in house installations. When large-capacity tanks are needed they may be sunk into the earth with ends projecting into a cellar or submerged pump house. Pneumatic tanks are of steel and when buried should be protected with asphaltic paint.

Gravity tanks of wood are still much used because of saving in expense over steel tanks. Steel, however, is the more popular and efficient choice (Fig. 13). It requires less maintenance but needs protection against corrosion. Supported on the top of the structure, it imposes a heavy load which must be sustained by the structural frame. Humidity in the air condenses on the cold sides and bottom of metal tanks and must be caught in a copper pan. In large and busy buildings the tank is sometimes divided in half vertically and all of its piping and equipment are installed in duplicate. This permits valving off one half of the tank for cleaning while the other half operates. A fire reserve in the lower portion of the tank is quite common, and the house supply is taken from a point slightly above the level of the fire reserve (Fig. 14). When an elevated house tank requires water, a high rate of pumping can reduce the pressure in the city mains to the inconvenience of neighbors. If this happens a suction tank may be installed which will fill automatically by gravity from the mains between pumping periods. It is located in the basement and should have a capacity greater than the periodic demand of the house tank.

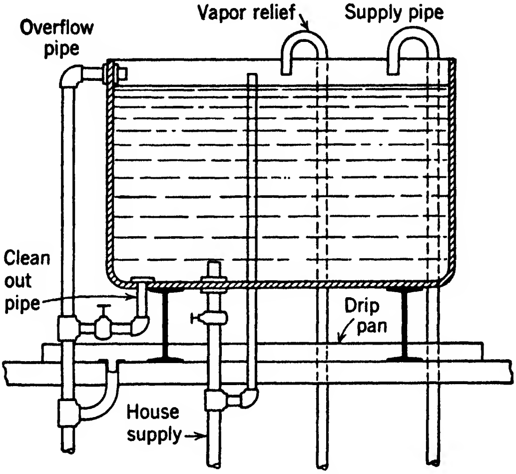


Fig. 13. House tank.

9. Pump and tank accessories. The main piping of the gravity house tank at the top of a building includes the pump discharge to fill the tank and the supply lines to the house and to the fire standpipes. It will be observed (Fig. 13) that the house supply line when attached to the bottom of the tank is raised a few inches to prevent its receiving sediment that might collect in the bottom of the tank. Auxiliary piping consists of the cleanout pipe, which is flush with the bottom of the tank, the overflow pipe, vapor relief from the hot water system, discharging here for convenience, and the drain for the drip pan. When the roof is properly equipped with storm drains the tank cleanout is sometimes led directly out to the roof instead of discharging as shown in Fig. 13. In no case may it be connected directly to any drainage system because of possible contamination of the drinking water supply by pollution in the drainage pipes.

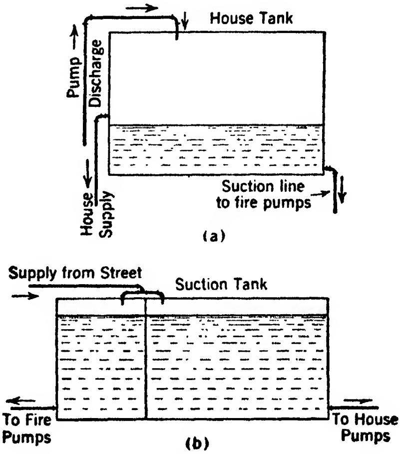


Fig. 14. House and suction tanks.

Float valves serve gravity tanks as they do pneumatic tanks for periodic pump operation, having high and low limits, and turning the pumps, usually in the basement, on and off on demand. In the event of the failure of the high-limit switch to operate, an alarm bell rings in the custodian's office. Exposed tanks must be equipped with submerged heating coils to prevent freezing.

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PROBLEMS

1. (*a*) How may water be contaminated, and what are the methods of removing the harmful elements?

(*b*) What is meant by hard and acid water? What are their characteristics and what causes them?

2. Describe ground and surface water, and compare them as sources of supply.

3. Describe the availability of the following sources of water supply and the methods of obtaining water from them: (*a*) streams, rivers, and lakes; (*b*) springs; (*c*) wells.

4. Derive the formula for water pressure in pounds per square inch in terms of head and for head in feet in terms of pressure.

5. A spring is situated 75 ft above the ground-floor level of a building with story heights of 10 ft. What will be the water pressure at the ground-floor level and at the second, third, and fourth floors? Neglect the effect of friction due to water flow in the pipes.

6. Upon what action is the operation of pump suction based?

7. Describe (*a*) reciprocating pumps as a class with special details of suction, triplex, and deep-well pumps; (*b*) centrifugal pumps; (*c*) ejector pumps; (*d*) submersible pumps.

8. Describe gravity and pneumatic tanks.

9. What type of pump should be used in the following cases? (*a*) a drilled well with water level 36 ft below the ground; (*b*) a shallow well with water at 15 ft below the ground; (*c*) to supply a house tank 80 ft above a water main where the pressure is 30 lb per sq in.

10. Describe the zeolite process of softening water.

11. State the function of each pipe connection which serves an elevated house tank.

Chapter 2

DISTRIBUTION

1. Pipes. Water-supply pipes within the walls of buildings are usually of wrought iron, steel, brass, and copper. Cast-iron and lead pipes may also be used for underground supply outside buildings in large or public installations but are seldom used in a private water supply. The steel and iron pipe should be galvanized or coated with bituminous materials such as hot coal tar, pitch, and asphalt for protection against exterior corrosion. Protection against corrosion from the water itself may be accomplished by galvanizing or using a corrosion-resistant alloy. Modern practice, however, inclines toward alkaline treatment of the water to neutralize the corroding acids. Oxygen and carbon dioxide are particularly corrosive, causing rust and clogging in iron pipe, loss of zinc in brass pipe, and dissolution and weakening in copper pipe. In municipal supplies, lime is an economical alkali, but for treatment within buildings sodium silicate applied by experts is more effective. This method is usually less expensive than the use of pipes of special alloys.

Chromium, nickel, and silicon in pipe alloys also help to minimize corrosion.

Pipe and tubing are known by their nominal inside diameters from 1/8 in. to 12 in., inclusive, and by their nominal outside diameters above 12 in.

The qualities of pipe materials are as shown in Table I, page 18.

2. Fittings include the equipment required for joining the various lengths of pipe, such as couplings for connection in a straight line, elbows for connections at 90° or 45°, tees for either 45° or 90° branches opposite each other. Types of fittings are threaded or screw, flanged, soldered, brazed, welded or compression. Screw connections are used for pipe up to 4 to 6 in. in diameter and consist of fittings provided with threads on the inside to receive the threaded outside ends of the pipe. Threads on the pipe are filled with red lead or joint compound before the connection is made to insure a tight joint. Flanged connections are seldom used on water-supply piping of ordinary buildings. They consist of fittings provided with projecting rims or flanges which are screwed over the two pipe ends to be joined.

Table I. Characteristics of Pipe

Kind of Pipe	Material or Manufacture	Connections	Qualities	Relative Cost	Notes
Steel	Butt welded to 2″ diam. seamless, large sizes	Threaded	Basic	Least expensive	Should be used only when water contains no impurities
Wrought iron	Butt welded to 2″ diam. seamless, large sizes	Threaded	More corrosion-resistant than steel	More expensive than steel	Identified by a red spiral stripe
Brass, yellow	67% copper 33% zinc	Threaded, "IPS," iron pipe size	More corrosion-resistant than steel	More expensive than steel	Bulky because of the need for threading
Brass, red	85% copper 15% zinc	Threaded, "IPS," iron pipe size	More corrosion-resistant than yellow brass	More expensive than steel	Bulky because of the need for threading
Copper tube, type "K"	Seamless	Sweat fittings	Corrosion-resistant and easy to fabricate	Less expensive than brass	Thinner-walled than brass. Easy to put together and dismantle
Copper tube, type "L"	Seamless, hard, thinner walls than type "K"	Sweat fittings	Corrosion-resistant and easy to fabricate	Less expensive than brass	Thinner-walled than brass. Easy to put together and dismantle
Nickel silver and chrome	Copper, nickel, and zinc, steel and chromium	Threaded	Corrosion-resistant	More expensive than steel	Polished surface does not chip like nickel-plate

The flanges are then bolted together with a gasket of rubber or metal between the flanges (Fig. 1).

Fittings for copper pipe are either of the compression or the soldered type, the material in the first case being brass and in the second copper. In the compression type (Fig. 2) the nut of the fitting is slipped over the end of one pipe and the body of the fitting over the other. The ends of the pipe are then flanged out with a special tool. and the nut is screwed down on the body, the flanged ends being clamped tightly between the seats.

The soldered or sweat type (Fig. 3) consists of a fitting in which the pipes are inserted. A hole is provided through the fitting corresponding to a channel on the inside surface. The pipes are inserted and the solder is applied to the hole from the outside. Upon being heated the solder fills the channel and is distributed by capillary attraction over the entire surface between pipe and fitting. A smooth and easy water channel is provided without inside projections. The entire layout may be set in place before the permanent soldering is begun, which is often an advantage.

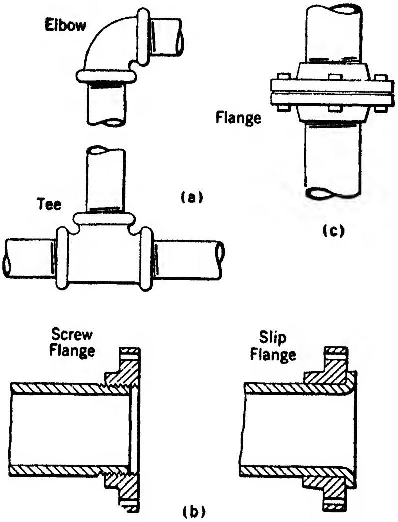


Fig. 1. Screw and flange fittings.

3. Valves and controls. Gate, globe, check, and angle valves are employed for control, isolation, and repair in water systems. Valves 1½ in. in diameter and under should be all bronze, and those 2 in. and over should have iron bodies and bronze disks and seats. The faucets most generally used are key cocks, compression cocks, and self-closing cocks. Valves control the water in pipes, and faucets, also called cocks and bibbs, serve plumbing fixtures.

(1) *Gate Valves* consist of a wedge-shaped plug which is screwed down to seat between two brass rings surrounding the inlet pipe, thus forming a double seal. The inlet and outlet are on a straight line offering little resistance to the flow when the valve is open. They are used when the stream is desired to be completely free or to be shut off entirely. Either end may be used as inlet [Fig. 4(*a*)].

(2) *Globe Valves* operate by screwing down a disk with soft packing until it presses tightly upon a metal seat. When the valve is open the stream is deflected up through the opening in the seat and the flow is restricted, sometimes causing an accumulation of sediment. They are

used when it is desired to throttle the water supply. The same end must always be used as inlet [Fig. 4(*b*)].

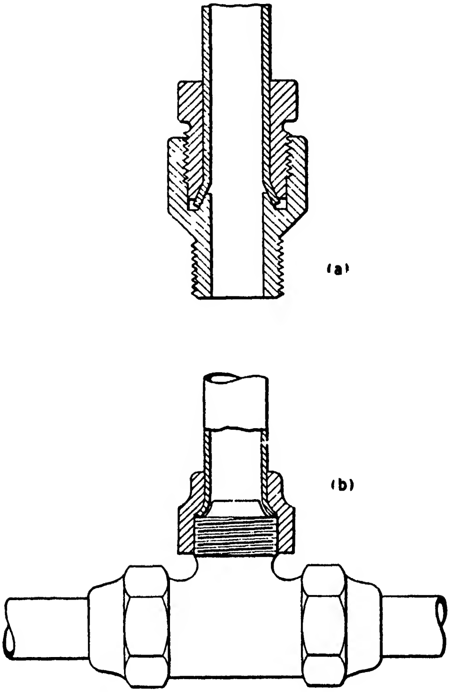


Fig. 2. Compression fittings.

(3) *Check Valves* close automatically under reverse flow and are used when there is possibility of a flow in a direction opposite to that desired.

(*a*) The lift valve consists of a loose disk which is lifted by the stream when the pressure on the inlet side is greater and closes down upon its seat when the pressure on the outlet or reverse side is greater. The amount of flow is reduced as in the globe valve [Fig. 5(*a*)].

(*b*) The swing valve has a pivoted flap readily pushed open by water pressure from one side but tightly closed on its seat by the force of a reverse flow. It resembles the gate valve in that the amount of flow is not reduced [Fig. 5(*b*)].

(*c*) Angle valves change the direction of flow and control it [Fig. 5(*c*)].

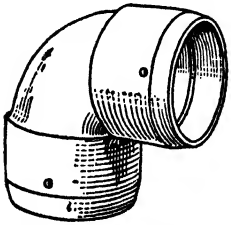
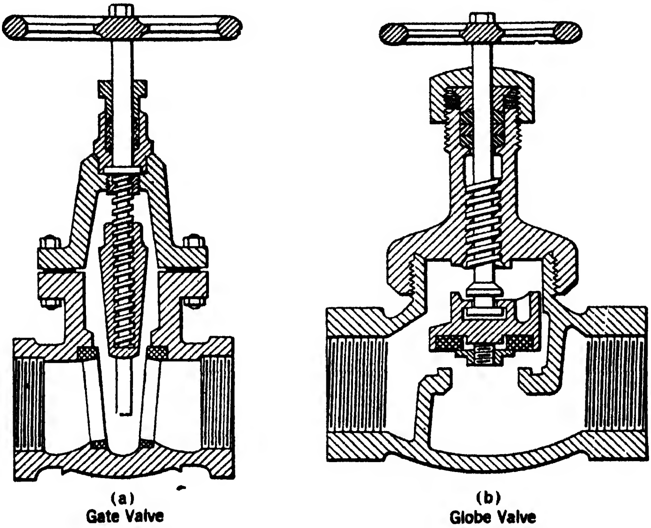


Fig. 3. Soldered fittings.

(4) *Key Cocks* operate by means of a round, tapering plug, perforated in one direction perpendicular to its axis and ground to fit in a metal seat. The faucet is open when the perforation is in line with the pipe and is quickly closed by turning the plug so that the perforation is across the line of flow. Stop cocks on pipes operate in the same manner [Fig. 6(*a*)].

(5) *Compression Cocks* operate by the compression of a soft packing upon a metal seat very much in the manner of the globe valve. They close against the flow of water and can be used upon high-pressure pipes without causing water hammer [Fig. 6(*b*)].


(a) Gate Valve

(b) Globe Valve

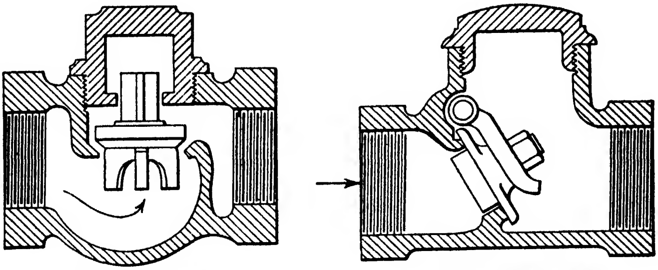
Fig. 4. Gate and globe valves.

(6) *Self-Closing Faucets* are arranged to discharge water while they are held open by the hand and to close by a spring inside the faucet as soon as the pressure of the hand is removed. Generally of the compression type they effect appreciable economy in water consumption when used in the large toilet rooms of institutions, factories, and office buildings. Such faucets are not liked, however, in residences or in the private bathrooms of hotels and apartments.

(7) *Pressure Regulators* are devices for limiting the pressure of the water discharged from a pipe to a fixed amount whatever may be the pressure of the water supplied to the pipe. Their action depends upon the relative areas of valve openings and upon the pressure of springs operating upon the valves. They are used to reduce the stress upon the piping within a building when the pressure in the street mains is

too high and to decrease the pressure upon the branch piping to fixtures on the lower floors of tall buildings using a down-feed water system.

4. Pipe hangers and supports should firmly support horizontal and vertical piping and allow for expansion and contraction and for adjustment in slope and drainage. Several types of hangers are shown in Fig. 7.


(a) Lift Check Valve
(b) Swing Check Valve

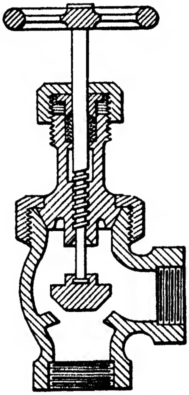

(c) Angle Valve

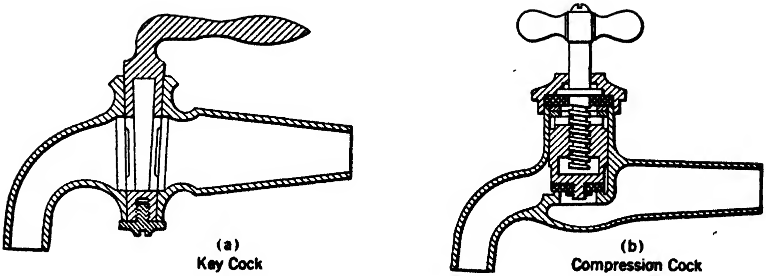
Fig. 5. Check and angle valves.

For wooden construction, hangers are supported by flanges or brackets attached directly to the beams. For steel construction, iron clamps are fastened to the steel framing members. For concrete or masonry construction, malleable iron concrete inserts or masonry expansion bolts provide the anchorage.

Spacing of hangers should, in general, be 10 ft for horizontal ¾-in. pipe and larger. For ½-in. and smaller they should be 6 to 8 ft apart. On vertical lines the supports should be one to each story for 1-in. pipe and smaller and may be one to each two stories for larger. Copper tubing must be attached at more frequent intervals.

A. Distribution in Buildings of Moderate Height

5. Installation procedure. The water-supply system in a building of less than 20 stories is usually designed as a single unit with one house tank, where required, and one set of piping. When the main supply, either public or from private source or outdoor tank, is under sufficient pressure to serve satisfactorily the highest fixture, an *up-feed distribution system* is indicated and no indoor pump or tank is required. This up-feed system consists essentially of vertical *risers*



(a) Key Cock

(b) Compression Cock

Fig. 6. Key and compression cocks.

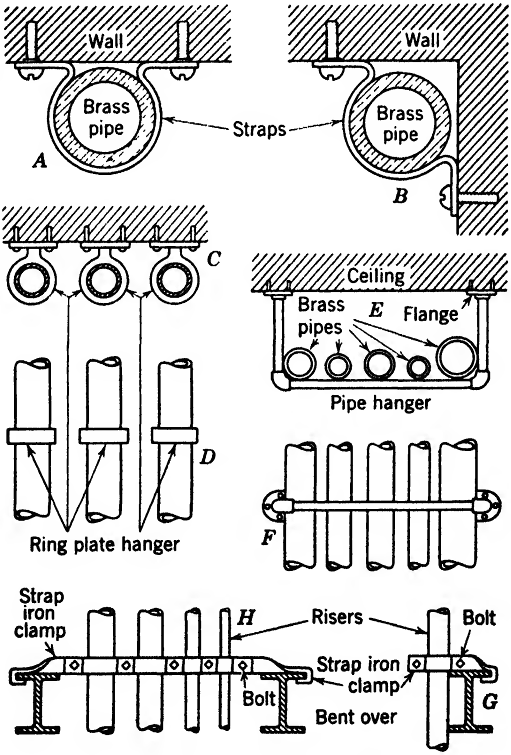


Fig. 7. Typical pipe hangers.

taken off horizontal *basement mains* and carrying the water directly upward to fixture branches (Fig. 8).

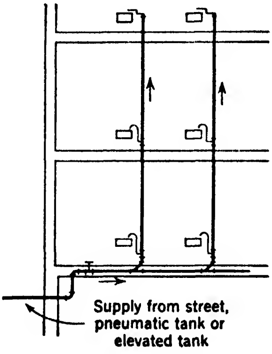


Fig. 8. Up-feed system.

When the main supply pressure is inadequate, however, elevated tanks are necessary, together with provision for filling them, and the distribution system would be the down-feed type. The *down-feed system* consists of a *supply main* from an elevated tank with one or more *down-feed risers* to carry the water down to the fixture branches. The tank may be filled by pumping or from street pressure, when adequate at night to supply the tank but insufficient during the daytime to serve the highest fixtures satisfactorily.

6. Public supply. In either event the installation connected with the public supply would proceed as follows: (*a*) A contract for water at agreed rates is signed by the owner. (*b*) A permit to excavate the street is obtained from the water company or municipal water department and paid for by the contractor. (*c*) Generally the water department opens the street main and a *corporation cock* is inserted by its own representatives; otherwise the contractor must obtain a permit to open the street main. It may be necessary in large structures to make several taps on the street supply since the size of the tap is often limited by regulations. (*d*) The water department generally furnishes the brass controls outside the building and completes the installation to the property line or to the curb cock. (*e*) The *curb cock* (Fig. 9), furnished and set by the department, consists of a cast-iron box at the sidewalk curb and contains a long valve stem connecting with a cock on the pipe to the building. It serves as a shut-off during discontinuations of supply. A flexible bend or gooseneck of lead or copper is attached to the corporation cock to allow for settling or expansion of main or building service. The remaining elements in the house supply are installed by the contractor.

The service pipe up to the building is generally of copper tubing to allow for settling of trenches and expansion and to resist corrosion. It enters the building through a pipe sleeve set in the basement wall with caulking between for flexibility and waterproofing.

Directly inside the basement wall is placed the *service cock,* a gate valve which controls the entire water supply within the building, and just beyond it the water meter is installed. Meter cocks and a locked by-pass are frequently installed for continuity of 'service when repair of the meter is necessary. Stop and drip valves are connected for drainage of the entire system, and testing tees and pressure-reducing valves are included for control of unusual conditions. Filters and soft-

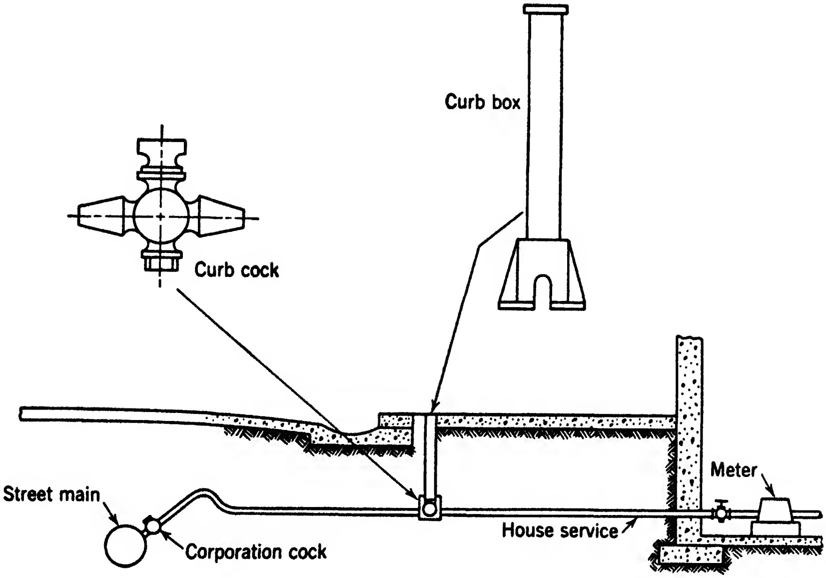


Fig. 9. Street services to house.

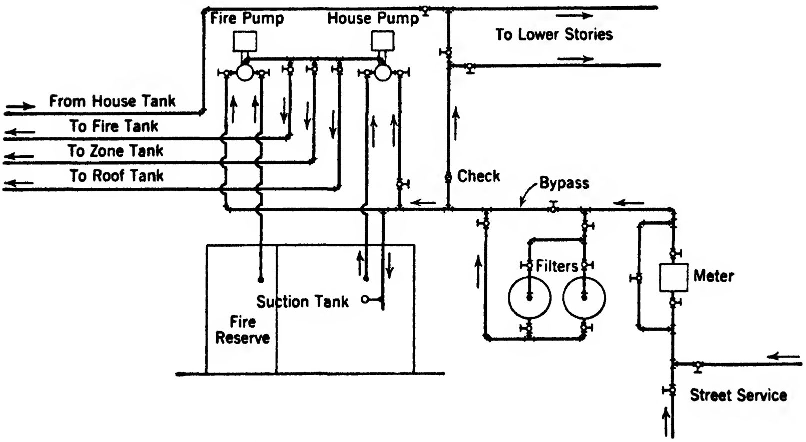


Fig. 10. Water supply layout plan.

eners are inserted just inside the meter with by-passes (Fig. 10). Fire-line connections often by-pass the meter and supply tanks and lines directly. (See Chapter 3.)

In residences and buildings of limited size the basement equipment generally consists only of the service cock, the meter, and the drip valves for drainage.

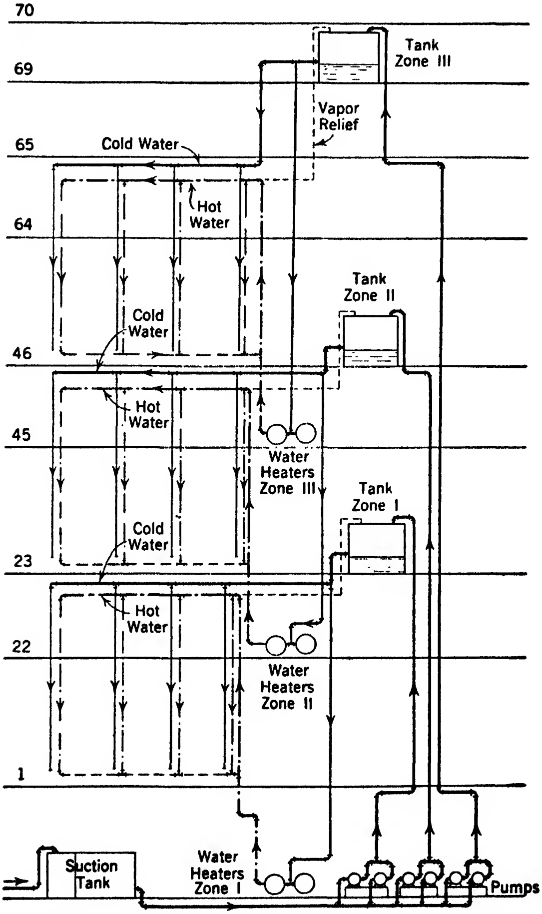


Fig. 11. Water supply zones. Down feed.

7. Up-feed distribution elements. From the meter is run the *main header,* or *basement main,* from which the up-feed *risers* are taken. Water headers are used where a number of varying-sized branches or risers taken off at one location would complicate the pipe fittings. Each riser or riser branch should be provided with an individual cutoff and drip or tee connection for cleaning and drainage.

Drips may drain to a concrete floor provided with floor drains or through piping directly to a sump.

Risers should run through in chases at such locations as will produce minimum lengths of horizontal branches. *Fixture branches* should be accurately located to match connections with plumbing fixtures already chosen. At the top of risers an extension of piping from 1 to 3 ft in length, capped at the end, will serve as an air chamber to minimize knocking due to water hammer. Where pressures are high, however, specially constructed air chambers or pressure-reducing devices should be installed.

8. Principles of good layout for economy and service. Water piping should be installed only after details affecting economy, adequate immediate service, probable future service, accessibility and control for maintenance, alteration and repair have been carefully considered. The following requirements should be met, if possible: (*a*) Building service connections from two or more street mains for larger installations. (*b*) Protection of water pipes from freezing including: placing them undergound below frost line; insulating them when on outside walls; installing in prepared channels or chases with removable fronts for access; providing sill cocks, hydrants, or other outside water connections with shut-offs and drains below frost line. (*c*) Allowance by goosenecks and sleeves for settlement or movement of building. (*d*) Provision of reducing equipment or air chambers to eliminate dangerous pressures. (*e*) Entire independence from each other of potable and nonpotable systems. (*f*) Separation of hot and cold water lines by at least 6 in. so that their temperatures will not affect each other. (*g*) Provision of valves for isolated fixtures not otherwise controlled in their branches. (*h*) Insulation of cold water pipes against condensation.

9. Private supply. When the source of supply is private, water department negotiations and equipment are obviously not required. Adequate frost-protected controls should, however, be installed at the lake, stream, spring, or well from which the supply is derived. If a water main supplies several buildings through long branches, a valve in a manhole or a stop with a long valve stem, similar to a curb cock, may be installed on each branch near its connection with the main.

The equipment, piping, and methods of distribution within the buildings depend upon their size and height and conform to the standards set forth in Art. 7, Chapter 3.

B. Distribution in Tall Buildings

10. Zoning. When the water supply of very tall buildings is designed as a unit the required capacities of tanks, pumps, and piping become unduly large, and excessive pressures are developed in the lower portions of down-feed risers. It is customary, therefore, to divide the height of the building into horizontal sections or ***zones*** and to design the cold and hot water supply, the heating, and the other distribution and waste systems separately for each zone, with a hung ceiling to cover the pipe loops of all the systems together. (See Chapter 11, Art. 13.)

With the possible exception of house pumps, all of which may be in the basement, each zone is furnished with its own feed pipes, risers, tanks, and water heaters. The number of zones is determined largely by the relative costs, since increasing the zones increases the number of tanks and pumps and the length of piping but decreases their capacities and the pressure at the outlets. More hung ceilings and heavy framing are necessary and rentable space is lost. In general, zones of 10 to 20 stories are found most practical, and sizes and pressures are therefore limited to those resulting from heights not exceeding 200 to 225 ft.

Owing to the heat losses and oversized piping resulting from long runs, horizontal zoning may be advisable in low buildings which cover a large area, especially as regards domestic hot water, heating, and ventilating systems.

11. Down-feed distribution. In tall buildings with down-feed risers the water flows by natural head through the meter to the suction tank, from which it is pumped to the house tank on top of the building or to zone tanks. From the house tank the horizontal distribution main is taken off to supply the down-feed risers, which in turn serve the fixture branches at the various floors (Fig. 11). Risers are provided with individual controls for maintenance and repair. To relieve tanks and pumps the lower floors, as far up as the pressure will permit, are sometimes supplied by an up-feed system directly from the street main. Down-feed and up-feed risers are cross-connected to serve the lower floors whenever the street supply is cut off, and the pumps operate directly from the street main in case of suction tank failure.

In zoned buildings the roof tanks are situated sufficiently above the top fixtures to acquire a satisfactory head, and the intermediate tanks are placed at least two stories above their respective zones. Intermediate tanks may be filled by individual pumps located in the basement, or they may be filled by gravity from the tank above or by intermediate booster pumps forming a relay system. Float valves starting and stopping the pumps control the supply.

The distribution mains of each zone are carried in a loop around the building concealed in hung ceilings. Risers are often run next to interior columns to provide convenient supplies for tenants. They are enclosed in fireproofing independently from column protection. The position and capacity of pipe shafts require careful study for economy of space in combined usage for water, plumbing, and heating pipes and for ease of service and repairs.

REFERENCE

Plumbing Practice and Design. Volumes I and II, Svend Plum, John Wiley & Sons, New York, N. Y.

PROBLEMS

1. In what two ways may the corrosion in pipes be reduced? Describe each method.

2. Describe the following accessories and tell under what circumstances each is used: (*a*) Gate valve. (*b*) Globe valve. (*c*) Check valves. (*d*) Key and compression cocks.

3. What is the procedure of installation of the water-supply piping from the public source in the street to the start of the risers in the basement? What is the procedure when the source is private?

4. What is the purpose of zoning and how is it arranged?

5. Describe up-feed and down-feed distribution.

6. In what two instances are pressure regulators necessary?

7. Discuss the spacing of hangers for horizontal piping and of supports for vertical piping as related to pipe size.

8. In public water supply to an individual building, what part of the installation is completed by the municipality and where does the work of the owner's contractor begin?

9. What protection against freezing must be given to water pipes outside and inside a building?

Chapter 3

DESIGN OF WATER SUPPLY

FIRE PROTECTION

A. Design of Water Supply

1. General. The design of the water supply of a building comprises first the determination of the total quantity required for the supply of plumbing, heating, air-conditioning, manufacturing, and fire-protection equipment. This question involves the satisfactory supply for a fixture of each kind and the number of fixtures assumed to be in use at the same time. This total having been calculated, the sizes of piping, tanks, and pumps must be decided to distribute the water to the various appliances in the proper quantities and under the desired pressures.

2. Water consumption. Table I presents generally accepted averages of water consumption for each occupant per day, which may vary according to circumstances.

Table I. Consumption of Water per Capita per Day (Gallons)

Apartments and hotels	50–120
Office buildings	15–30
Residences, each occupant, including kitchen, bathroom, and laundry	30–80
Horse (winter, 4 to 8 gal; summer, 8 to 18 gal)	12
Cow	12
Hog	1
Sheep	1
Chickens, per 100	4
Lawn and garden sprinkling (½-in. hose), per hr	200
Lawn and garden sprinkling (¾-in. hose), per hr	300
Lawn sprinkler, per hr	120

In apartments, hotels, and office buildings the requirements of laundries, kitchens, heating, condensers, and other equipment must be added to the personal consumption of the occupants.

Table II gives the rate of flow best suited to the common types of fixtures and the average pressure necessary to give this rate of flow.

Table II. Flow from Fixtures and Required Pressures *

(*A*) Fixture	(*B*) Size Fixture Branch (in.)	(*C*) Flow Pressure (lb per sq in.)	(*D*) Flow (gal per min)
Lavatory	⅜	8	3.0
Self-closing faucet	½	12	2.5
Public sink, ⅜ in.	⅜	10	4.5
Kitchen sink, ½ in.	½	5	4.5
Bath tub	½	5	6.0
Laundry trays—1, 2, or 3	½	5	5.0
Shower bath	½	8	5.0
Water closet, flush tank	⅜	8	3.0
Water closet, flush valve	1	10–20	20–40
Urinal, flush valve	1	15	15.0
Garden hose, 50 ft and sill cock	½	30	5.0

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 1046.

3. Fixture units. The load in gallons per minute required by each type of fixture is often computed in fixture units, each unit being equivalent to 7.5 gal per min or 1 cu ft of water.

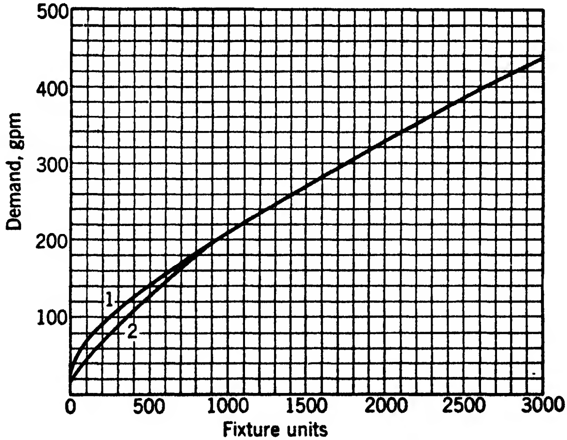


Fig. 1. Curves for demand load. No. 1 for system predominantly for flush valves. No. 2 for system predominantly for flush tanks. Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide, 1953,* page 1047.

4. Probable usage. For residences, farms, and buildings with little plumbing a maximum supply is advisable, because few fixtures

Table III. Demand Load of Fixtures in Fixture Units *

Fixture or Group	Fixture Units Public	 Private	Supply Control
Water closet	10	6	Flush valve
Water closet	5	3	Flush tank
Lavatory	2	1	Faucet
Bath tub	4	2	Faucet
Shower head	4	2	Mixing valve
Kitchen sink	4	2	Faucet
Service sink	3		Faucet
Pedestal urinal	10		Flush valve
Stall or wall urinal	5		Flush valve
Stall or wall urinal	3		Flush tank
Bathroom group		8	Flush valve for closet
Bathroom group		6	Flush tank for closet
Separate shower		2	Mixing valve
Laundry trays (1–3)		3	Faucet
Combination fixture		3	Faucet

Note. For fixtures with both hot and cold supplies the units for separate demands are taken as three-quarters of the listed demand.

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 1046.

are involved and all of them may be called into use simultaneously. An ample supply of water is a necessity; otherwise one fixture will rob another with most unsatisfactory results. For hotels, office buildings, schools, and apartment houses, however, it is reasonable and customary to assume that not all the fixtures will be used simultaneously. With an installation of two fixtures it is quite possible that both may be in operation together, but with 200 fixtures it is unlikely that all will be called upon at once. Curves based upon tests and experience set forth the probable maximum demand in gallons per minute, corresponding to any total number of fixture units in a building. Certain installations may present special requirements for which demand loads must be determined to fit the needs.

This maximum demand covers the peak requirements at certain times of day, such as at 9:00 A.M. in hotels and office buildings and during the preparation of meals in apartments. Requirements, such as hose connections and air-conditioning equipment, which impose continuous demand during times of peak load should be estimated separately and added to the demand for fixtures used intermittently.

5. Friction. Since the flow of water is greatly limited by the friction of the pipe surface, this factor has an important bearing upon the determination of the pipe size. The usual equation for loss of

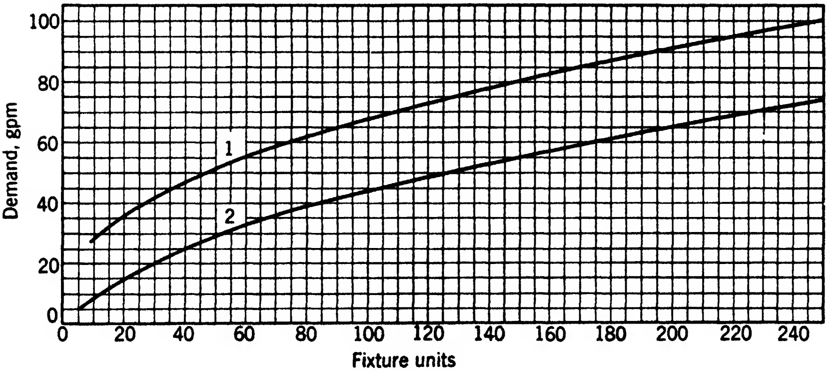


Fig. 2. Section of Fig. 1 on enlarged scale. No. 1 for system predominantly for flush valves. No. 2 for system predominantly for flush tanks. Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide,* 1953, page 1047.

head due to friction is

$$h_F = f\left(\frac{l}{d}\right) \times \frac{v^2}{2g}$$

in which l = length of pipe, d = diameter of pipe, v = velocity of water, and g = acceleration of gravity. From this equation it is seen that the friction losses depend upon the length of the pipe, the diameter of the pipe, and the velocity of the water. Since the velocity = Q/A and therefore depends upon the quantity of flow and the diameter of the pipe, tables or charts may be prepared giving the friction losses in head in pounds per 100 ft of straight pipe for various diameters and quantities of water. If a permissible friction loss in pounds has first been calculated from the pounds of available water pressure or head, then from these charts the proper size of pipe for a given flow of water may also be found.

The letter f in the above formula is a constant, depending upon the condition of the inner surface of the pipe, whether smooth or fairly rough. Copper, brass, and lead pipe, showing no roughness, are classed as smooth. Galvanized wrought iron and steel and cast-iron pipe after some years of service usually become fairly rough, and an allowance should therefore be made in their sizes.

Flow through water meters is subject to resistance by friction which must be added in pounds per square inch to the pressure losses in the piping itself and in the fittings and valves. Table IV gives the maximum flow through disk meters of various sizes.

With the demand flow in gallons per minute and the corresponding size of meter in inches, Fig. 5 may be entered and the pressure loss in pounds per square inch determined.

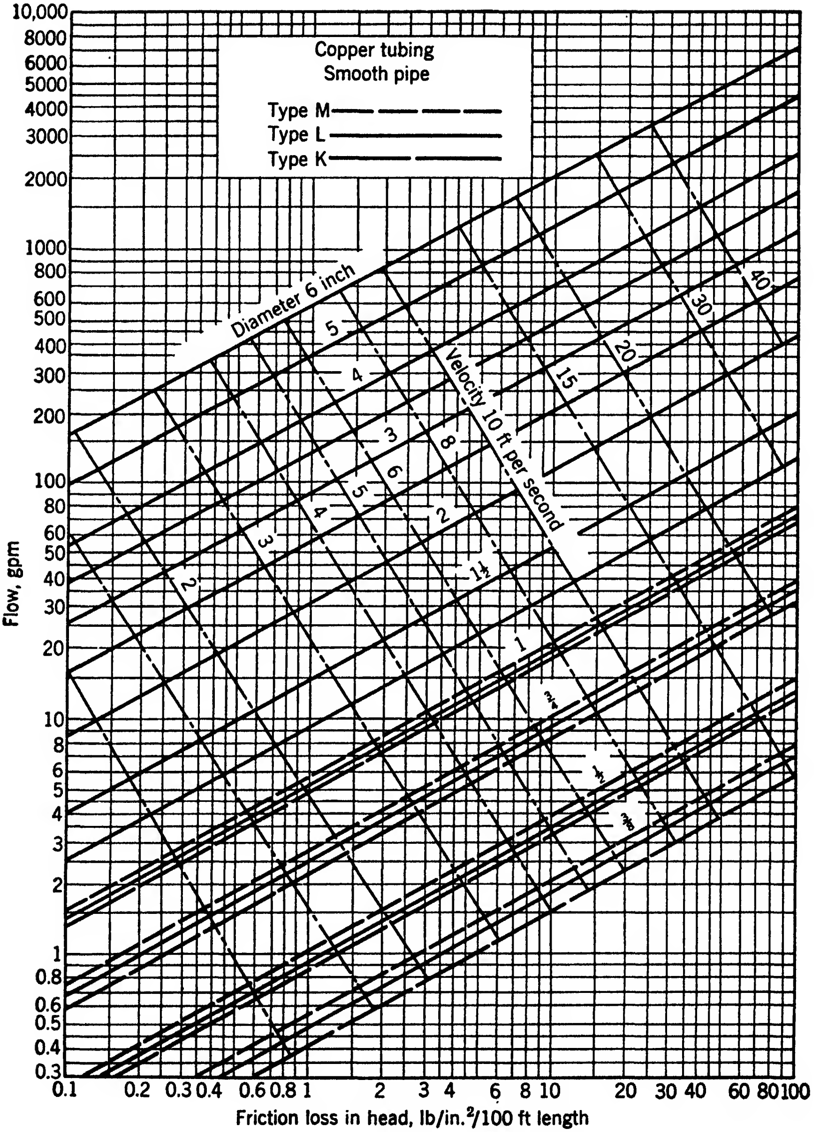


Fig. 3. Flow chart for copper tubing. Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide, 1953,* page 1048.

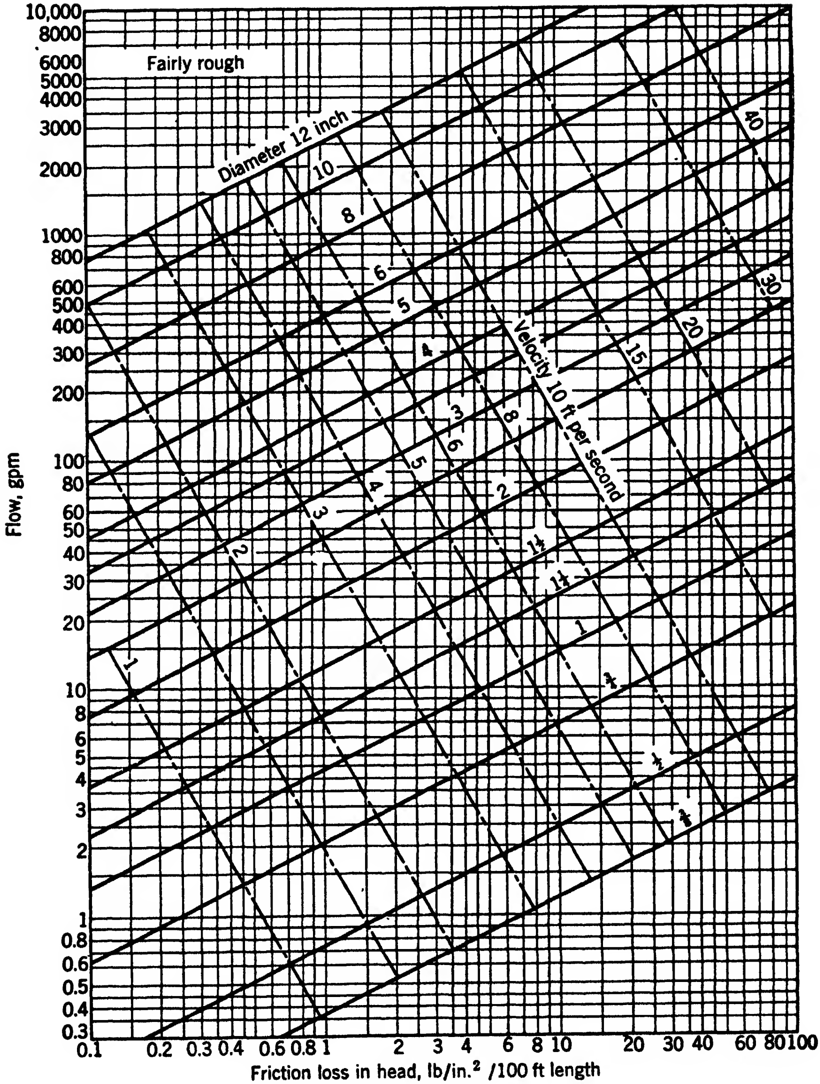


Fig. 4. Flow chart for fairly rough pipe. Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide,* 1953, page 1049.

Table IV. Performance of Water Meters *

Size (in.)	Normal Test Flow Limits (gal/min)	Size (in.)	Normal Test Flow Limits (gal/min)
5/8	1 to 20	2	8 to 160
3/4	2 to 34	3	16 to 315
1	3 to 53	4	28 to 500
1½	5 to 100	6	48 to 1000

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 1052.

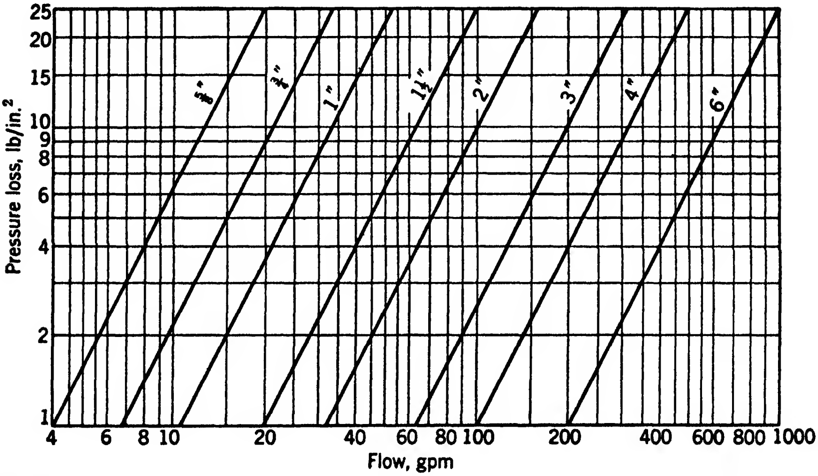


Fig. 5. Pressure losses in water meters. Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 1051.

6. Water pressure. It was shown in Chapter 1, Art. 7, that the pressure head of water in pounds per square inch, p, equals $0.434 \times h$, the height in feet to which the water is elevated, and that h equals $2.3 \times p$. Flush valves require 15 lb pressure, but 8 lb is considered sufficient for other fixtures. It is sometimes impracticable to obtain a street main pressure or a tank elevation sufficient for a 15-lb pressure at the highest fixture after allowing for pipe friction and gravity head. Consequently, tank fixtures are often used in the top story and valve fixtures on the floors below. The largest permissible pressure on fixtures is generally not over 50 lb per sq in. Higher pressures in mains should be limited in branches by pressure-reducing valves.

7. Pipe sizes. (*a*) *Up-Feed.* In the up-feed system the pressure required to overcome the gravity head in the vertical riser plus the pressure desired at the highest fixture is subtracted from the total pressure available from the street main or other supply. The remainder represents the pressure at hand to overcome friction losses from piping, meter, fittings, and valves. This total allowable friction loss in pounds per square inch is reduced to the allowable loss per 100 ft of pipe length. The quantity of water in gallons per minute required in each section having been determined, the pipe size for each section is found by applying the allowable friction loss per 100 ft of pipe to the rate of flow as shown in Figs. 3 or 4.

The rate of flow is likewise diminished by bends in the piping and by the installation of valves, the sharper turns being made by the introduction of angle fittings. (See Chapter 2, Arts. 2 and 3.) The losses caused by the valves and fittings may be changed into equivalent losses from straight runs of pipe, and these lengths added to the total run of pipe in determining the allowable friction loss per 100 ft.

Table V. Equivalent Lengths of Pipe in Feet for Loss in Fittings *

Diam. (in.)	90° Ell	45° Ell	90° Tee	Straight Run of Tee	Gate Valve	Globe Valve	Angle Valve
⅜	1	0.6	1.5	0.3	0.2	8	4
½	2	1.2	3	0.6	0.4	15	8
¾	2.5	1.5	4	0.8	0.5	20	12
1	3	1.8	5	0.9	0.6	25	15
1¼	4	2.4	6	1.2	0.8	35	18
1½	5	3	7	1.5	1	45	22
2	7	4	10	2	1.3	55	28
2½	8	5	12	2.5	1.6	65	34
3	10	6	15	3	2	80	40
3½	12	7	18	3.6	2.4	100	50
4	14	8	21	4	2.7	125	55
5	17	10	25	5	3.3	140	70
6	20	12	30	6	4	165	80

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Example 1. In a dormitory of 5 stories the height of highest fixture is 45 ft; street pressure is 55 lb per sq in. On the ground floor there is a bathroom, a kitchen sink, and 2 laundry trays. There are 2 bathrooms on each of the 4 upper floors. The water closets are flush-valve operated. Find size of supply main.

Solution. From Table III, a bathroom group with flush valve = 8 fixture units, and a kitchen-sink and laundry-tray combination = 3 fixture units. Total fixture units = $(9 \times 8) + 3 = 75$. From Fig. 2, the demand load is 60 gal per min. From Table IV, a 1½-in. meter is chosen, which from Fig. 5 carries a pressure loss of 9 lb per sq. in. With a requirement of 15 lb per sq in. pressure at the highest fixture the total pressure required to counterbalance highest fixture pressure, gravity head in main and meter friction is $15 + (45 \times 0.43) + 9 = 43.35$ lb per sq in. The pressure available to overcome the friction in the piping and fittings = $55 - 43.35 = 11.65$ lb per sq in.

To find the equivalent length of pipe for loss in fittings (Table V), it is necessary to assume pipe sizes and recheck, if necessary, after correct sizes are found. A detailed layout of piping and fittings is also needed. In its absence we will assume that the fittings offer a resistance equal to 90 feet of pipe. The permissible pressure loss per 100 ft of equivalent pipe is $\frac{11.65 \times 100}{90 + 45} = 8.6$ lb per sq in. Galvanized iron pipe in chosen and, from Fig. 4, a 2-in. main is adequate.

The sizes of the branches follow the same method. If a branch supplies two bathrooms back to back on one floor, the fixture units are 16, the demand 32 gal per min and the branch, from Fig. 4, using the permissible pressure loss of 8.6 lb per sq in., should be a 1½-in. pipe.

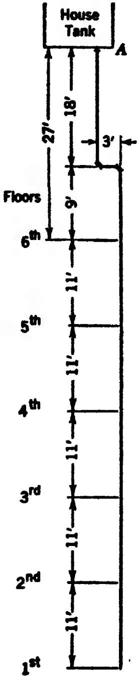
(*b*) *Down-Feed.* Since this system is generally used with an elevated tank, the first requisite is to raise the tank sufficiently to give the desired pressures in the highest fixtures. The possible use of 8-lb pressure fixtures on the upper stories and 15-lb below is explained in Art. 6. When the building is zoned, each section is designed separately. The necessary pressures are built up by the gravity head in the risers.

The available pressures on the lower floors are usually computed on a floor-to-floor basis. The pressure required on any one floor is supplied by the net remaining pressure in the riser plus the gravity head in the down-feed interval between that floor and the floor above. It is often necessary to select riser sizes for the upper stories to produce fairly low pressure drops from friction which will permit the net pressure in the riser to develop quickly and contribute the required fixture pressure on the floor below. Then for each lower story the static pressure built up in that story by gravity is entirely devoted to overcoming the friction in that run of pipe.

Example 2. An apartment house of 6 stories has 2 bathrooms and 2 kitchen and laundry combinations on each floor grouped around a down-feed riser. Floor to floor height, 11 ft. A gravity tank with 3-ft offset is 27 ft above the sixth floor fixtures. Flush tanks are used on the sixth and fifth floors, and flush valves on the remaining floors. Equivalent pipe length from tank to sixth floor, including valves and fittings, is 45 ft and from floor to floor is 16 ft 6 in. Compute pipe sizes.

Solution (Table VI). Adequate values should be added to the fixture pressures to overcome the friction in the fixture branches. In this example 2 lb per sq in. is assumed, giving a total desired fixture and branch pressure of 10 lb on the fifth and sixth floors and 17 lb on the lower floors.

Tab Example 2



	Fixture Units	Cumulative F.U.	Demand (gpm)	Pipe Length (ft)	Equivalent P.L. (ft)	Desired Pressure at Fixtures (psi)	Pressure Available for Fixtures and Friction (psi)	Pressure Available for Friction in Riser Interval (psi)	Pressure Drop due to Friction (psi per 100 ft)	Actual Pressure in Riser (psi)	Pipe Size (in.)
B 6th	22	148	80	30	45	10	27 × 0.434 = 11.7	11.7 − 10 = 1.7	$\frac{1.7 \times 100}{45} = 3.8$	10	2½
C 5th	22	126	74	11	16.5	10	10 + (11 × 0.434) = 14.77 17 is needed in *C–D* Use 10 drop/100 ft	$\frac{10 \times 16.5}{100} = 1.65$ 14.77 − 1.65 = 13.12	Use = 10.0	13.12	2
D 4th	26	104	68	11	16.5	17	13.12 + (11 × 0.434) = 17.89	17.89 − 17 = 0.89	$\frac{0.89 \times 100}{16.5} = 5.4$	17	2
E 3rd	26	78	62	11	16.5	17	17 + (11 × 0.434) = 21.77	21.77 − 17 = 4.77	$\frac{4.77 \times 100}{16.5} = 28.9$	17	1½
F 2nd	26	52	52	11	16.5	17	17 + (11 × 0.434) = 21.77	21.77 − 17 = 4.77	$\frac{4.77 \times 100}{16.5} = 28.9$	17	1½
G 1st	26	26	38	11	16.5	17	17 + (11 × 0.434) = 21.77	21.77 − 17 = 4.77	$\frac{4.77 \times 100}{16.5} = 28.9$	17	1¼

At the sixth floor the pressure is determined by the elevation of the tank, and, after deducting for fixture branches and friction, the actual pressure in the riser at the sixth floor level is 10 lb per sq in. At the fifth floor this pressure is increased by the head developed in the 11-ft run from sixth to fifth floor and equals 14.77 lb. But more than 17 lb per sq in. is desired at the fourth floor to provide for fixture branches and riser friction. An arbitrary value, say 10, is therefore chosen as the friction loss per 100 ft, and the size of riser from sixth to fifth floor is found from Fig. 4, using this value. The pressure loss from friction would then be $10 \times 16.5 \div 100 = 1.65$, and the net pressure in the riser at the fifth floor level is $14.77 - 1.65 = 13.12$.

At the fourth floor the total head = 17.89 lb. Since 17 lb are needed for the fixture branches, 0.89 lb remains to overcome friction. $0.89 \times 100 \div 16.5 = 5.4$ lb per sq in. per 100 ft. On each of the lower floors the net pressure in the riser will be 17 lb per sq in., which will be devoted to fixture branch pressure, and the static pressure increase, $11 \times 0.434 = 4.77$, in each riser interval will be used up in riser friction. The loss per 100 ft will then be $4.77 \times 100 \div 16.5 = 28.9$ lb per sq in.

B. Fire Protection

8. Requirements. The fire protection available through the hose streams, fire towers, and engines of the public fire departments is generally limited to buildings not over six stories in height. For higher structures and for lower structures with inaccessible areas containing fire hazards, protection must be provided through a system installed within the building. Benefits are realized in lower fire insurance rates and in protection of the immediate and surrounding property. As a result, minimum requirements for fire protection have been set up by underwriters and have, in the larger cities, been adopted or adapted in their building codes. Most buildings used for industrial or commercial purposes incorporate some form of fire protection. The methods generally employed are standpipe and sprinkler systems, the latter being of particular advantage in lowering insurance rates in both fireproof and nonfireproof structures.

Code requirements for fire protection in buildings cover by specification the following: fire rating of the building, height and area of the building, accessibility of areas from all sides, number and availability of fire hydrants, and purpose of building, whether used for the manufacture, sale, or storage of combustible goods or for the housing of public gatherings.

9. Standpipe installation. Standpipes or firelines consist of vertical pipes extending from the fire pump to the top or roof, an outlet being installed at each story for the attachment of a fire hose. The lines are cross-connected, so that either the fire pump or the house pump or both can supply the water. At the bottom of the lines, branches extend outside the walls and are provided with double or Siamese connections for the hose and pumps of municipal fire engines. Check valves on the line prevent water from any source being lost through the wrong outlets and relieve the pumps from backpressure in the system. The size of standpipes should be sufficient to supply all the outlets at the same time. Minimum diameters are 4 in. for buildings over 50 ft high and 6 in. for buildings over 75 ft, carried full size through the entire height. Standpipes should be located so that all parts of every floor area can be reached within 30 ft by a nozzle attached to 100 ft of hose. They should also be located with outlets within stairway enclosures or near fire escapes for easy access and for protection against mechanical and fire damage (Fig. 6).

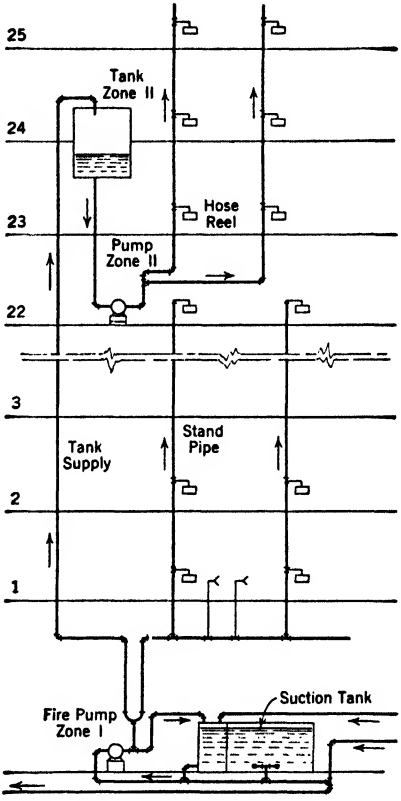


Fig. 6. Standpipe zones.

Outlets are usually 2½ in. in diameter, and the hose is 1¼ in. to 2½ in. in diameter, of long-fiber linen unlined in lengths of 50 to 100 ft and with nozzles of 1⅛ in. in diameter. Standpipes are of galvanized wrought iron and steel, designed to withstand 100 lb per sq in. in excess of static head. A maximum pressure of 50 lb per sq in. is usually maintained at the outlets, with the help of reducing valves when necessary.

Standpipes are classified as either dry or wet, depending on whether water stands within the pipe. Dry pipes are infrequently used and only in areas where there is danger of freezing. Water supply to wet standpipes may be directly from street mains, if pressure at the top outlet is at least 15 lb per sq in. with a flow of 500 gal per min from a hydrant within 200 ft of the building, from a gravity tank with a minimum of 5000 gal fire storage, from a pressure tank with a minimum of 4500 gal capacity (3000 gal of water) located on the roof, or from fire pumps and Siamese connections. Fire pumps must be provided in addition to storage in buildings over 150 ft in height. Capacity of such pumps should be a minimum of 500 gal per min or more for 4-in. standpipe, 750 gal per min for 6-in. standpipe, or 1000 gal per min for two or more 6-in. standpipes. One Siamese connection should be provided for each standpipe up to four and one for each building frontage over 50 ft in length. A check valve with an automatic drip to prevent freezing and no other gate or control valves should be installed between Siamese connection and standpipes.

Tall buildings generally require zoning of standpipes in a relay system to limit pressures at the outlets (Fig. 6). The same zones are used for fire protection as for the house water supply in order to make use of the same tanks, pumps, and hung ceiling spaces. Fire pumps are located in the basement and on the floors just below the intermediate tanks of the several zones. The basement pump draws water from the fire reserve in the suction tank and supplies the standpipes in the lowest zone. The fire pump of an intermediate zone draws water from the fire reserve of the adjacent house tank and supplies the standpipes of the zone above it. The standpipes in each zone also extend to the tank of the zone above so that, although the house tanks are normally filled by the house pumps in the basement, they may be supplied by the fire pumps in an emergency. No fire pump is connected with the roof tank.

10. Sprinkler installation. Automatic sprinkler systems consist of a horizontal grillwork of pipes placed near the ceilings of industrial buildings, warehouses, stores, theaters, and other structures where the fire hazard may be particularly great. These pipes are provided with outlets and nozzles or valves so constructed that temperatures of 135 to 160°F will cause them to open automatically and emit a series of fine water streams.

Sprinkler systems are (*a*) *wet pipe,* ordinarily with water constantly lying both in the mains and distributing pipes, (*b*) *dry pipe,* generally confined to unheated buildings in danger of freezing, with no water in the distributing pipes.

Operation of the wet-pipe system depends upon opening of nozzles in the area affected by sensitive elements within the nozzles themselves. Remote valves, in the dry-pipe system, may be hand-operated or actuated by sensitive elements to admit water to sprinkler heads.

Spacing of sprinkler heads is governed by several factors: fire rating of the building, construction of the ceiling, spacing of joists, type of occupancy, and total area. For example, for open joist construction in a nonfireproof building one nozzle is required for every 80 sq ft of floor space for light and ordinary hazard, and one for every 70 sq ft for extra hazard rating. For fireproof construction one nozzle is required for every 196 sq ft of floor space for a light hazard rating, one for every 100 sq ft for ordinary hazard, and one for every 90 sq ft for extra hazard ratings. Nozzles are set 8 to 12 ft apart on the supply pipes which, in turn, are spaced 10 to 14 ft apart and are usually run at right angles to exposed beams or panels.

Sprinkler systems are supplied with water in a manner similar to that for standpipe systems.

Special installation requirements for sprinkler systems include: (1) at least one fire department connection on each frontage; (2) a master control for all water supplies other than fire department connections, which must contain a check and drip connection but no other valves; (3) special fire walls between protected areas and unprotected areas; and (4) sloping waterproof floors with drains or scuppers to carry away waste water.

REFERENCES

1. Water Services Chapter, *Heating, Ventilating, Air Conditioning Guide,* 1951.

2. "Water Distributing Systems for Buildings," R. B. Hunter, *National Bureau of Standards Report BMS 66.*

PROBLEMS

1. What is the procedure followed in the design of a water supply?

2. What is meant by probable usage of fixtures, maximum possible and probable flow and demand load?

3. (*a*) In an up-feed water supply pipe how is the available net pressure to overcome friction computed? (*b*) What assumption is made in the allowance for friction from valves and fittings?

4. How does the calculation of pipe sizes for down-feed systems differ from those for up-feed?

5. A residence has 2 bathrooms on third floor, 3 bathrooms on second floor, 1 bathroom and 1 kitchen combination on first floor, supplied by 2 up-feed risers. Highest fixture, 27 ft above main. Pressure in main 40 lb per sq in. Longest run of pipe 60 ft, and length of pipe equivalent to fittings, 50 ft. Flush valves. No showers. Meter friction 6.5 lb per sq in. Design the water-supply system.

6. An 8-story apartment house has 3 bathrooms on each story supplied by down-feed riser *A* and 2 bathrooms on each floor supplied by down-feed riser *B*. The fixtures in each bathroom consist of a lavatory, a bath tub, and a water closet. Flush tank on two top stories, flush valves on remaining stories. House tank 30 ft above eighth floor. Run of pipe from tank to eighth floor fixture is 42 ft for riser *A* and 45 ft for riser *B*, and the fittings are equivalent to 50 per cent of straight pipe. Floor-to-floor height, 10 ft. Design pipe sizes, using a roof tank.

7. What is the approximate height limit in stories for buildings not served by fire standpipes or sprinklers?

8. What is the purpose of Siamese hose connection on the street in front of buildings?

9. What is the usual maximum pressure for standpipes?

10. Distinguish between wet-pipe and dry-pipe sprinkler systems. To what kind of building is each applicable?

Chapter 4

HOT WATER DESIGN AND EQUIPMENT

1. Hot water supply. Water expands and becomes lighter when heated above 39.2°F, as may be seen from Fig. 1. If heat is applied to the lower loop of a glass tube, both ends of which have been inserted in an inverted bottle containing water, the water will move from *A* to *B* and will rise through the tube *BC* into the bottle. It here becomes cooled and drops through the tube *DA* to *A*, is again heated, and rises in the tube *BC*, thus completing the circulation. Since the movement depends upon the difference in weight between the two columns of water, the velocity and consequent efficiency of the circulating system increase with the temperature of the water and the height of the circuit. Hot water supply systems therefore consist of a heater with or without a storage tank, piping to carry the heated water to the farthest fixture, and a continuation of this piping to return the unused cooled water back to the heater. A constant circulation is thereby maintained, and hot water may be drawn at once from a fixture without the necessity of first draining off through the faucet the cooled water which would be standing in the supply pipe if there were no return conduit for its escape. The chief retarding influence to the flow is friction; consequently, pipes must be smooth on the inside, reamed at cut ends, of ample size, and without sharp bends. Brass or copper pipe should always be used throughout hot water systems.

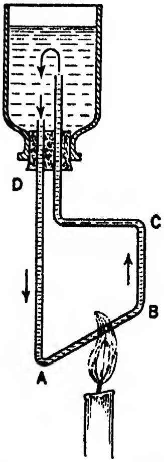


Fig. 1. Hot water circulation.

2. Consumption. Because many fixtures have no hot water supply, tests on actual buildings show that the consumption of hot water may be fairly assumed as about ⅓ of the total water consumption. In hotels and apartments the total water is estimated at 120 gal per day per person. The hot water consumption would then be 40 gal. For residences the daily hot water demand is taken at 20 to 40 gal per person. For offices, factories, restaurants, and other buildings the estimates depend upon the activities. In order to specify the size of the hot water storage tank and the load required of the heater, the following data must be known: (*a*) daily total quantity of water to be heated; (*b*) maximum demand in any one hour; (*c*) duration of peak demand; (*d*) storage and heating capacities in relation to day's use.

In dwellings, hotels, and apartments where the hot water demand is fairly uniform throughout the day, a small storage tank and a large heater are appropriate. In factories and other buildings with peak loads confined to several hours, a large tank and small heater are suitable. Between periods of peak demand the small heater can slowly replenish the supply of heated water in the tank.

Table I. Hot Water Demand per Person for Various Purposes *

140° temperature, except restaurants at 180°

Type of Building	Hot Water Required	Maximum Hourly Demand in Relation to Day's Use	Duration of Peak Load (hours)	Storage Capacity in Relation to Day's Use	Heating Capacity in Relation to Day's Use
Residences, apartments, hotels	40 gal per person per day	1/7	4	1/5	1/7
Offices	2 gal per person per day	1/5	2	1/5	1/6
Factories	5 gal per person per day	1/3	1	2/5	1/8
Restaurants	1.8 gal per meal per day			1/10	1/10
Restaurants (three meals per day)		1/10	8	1/5	1/10
Restaurants (one meal per day)		1/5	2	2/5	1/6

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The size of water-heating equipment may also be found from the number of fixtures. To obtain the *probable maximum demand* from Table II, multiply the total number of gallons by the *demand factor.* The heater or coil should have a water-heating capacity equal to this probable maximum demand. The storage tank should have a capacity equal to the probable maximum demand multiplied by the *storage factor.*

Table II. Hot Water Demand per Fixture *

Gallons of water per hour per fixture at 140°

	Apartment House	Club	Hotel	Factory	Office Building	Residence	School
Private lavatory	2	2	2	2	2	2	2
Public lavatory	4	6	8	12	6		15
Bath tubs	20	20	20	30		20	
Dishwashers	15	50–150	50–200	20–100		15	20–100
Kitchen sink	10	20	20	20		10	10
Laundry trays	20	28	28			20	
Pantry sink	5	10	10			5	10
Showers	75	150	75	225		75	225
Slop sink	20	20	30	20	15	15	20
Demand factor	0.30	0.30	0.25	0.40	0.30	0.30	0.40
Storage factor	1.25	0.90	0.80	1.00	2.00	0.70	1.00

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Example 1. Find the hot water demand and the capacities of the heater and the hot water storage tank for a residence with four occupants.

From Table I the daily requirement is 4 × 40 = 160 gal, the maximum hourly demand is 160 ÷ 7 = 23 gal, the storage capacity is 160 ÷ 5 = 32 gal, and the heating capacity is 160 ÷ 7 = 23 gal per hr.

The greater the capacity of the heater, the smaller will be the required size of the tank, but it is more economical of fuel and less likely to overheat the water to increase the size of the tank and thereby decrease the required capacity of the heater. This is the basis of most relationships between heater and tank, the heater, however, always being large enough to heat the water stored in the tank during periods of small demand. Experience has shown that not more than 75 per cent of the contents of a tank can be drawn out without undue cooling of the remainder.

Example 2. What size of heater and storage tank should be used in an apartment house to supply 250 persons?

Daily requirement is 250 × 40 = 10,000 gal; maximum hourly demand is 10,000 ÷ 7 = 1430 gal; water required for 4-hr duration of peak load is 4 × 1430 = 5720 gal. For a 1000-gal tank the net capacity is 750 gal. Water to be heated in 4 hr is 5720 – 750 = 4970. The heater capacity per hour must be 4970 ÷ 4 = 1240 gal.

If a 2500-gal tank were chosen the required heater capacity per hour would be

$$\frac{5720 - (2500 \times 0.75)}{4} = 960 \text{ gal}$$

The use of Table II may be illustrated by the following example:

Example 3. What are the heater and tank sizes for a club building with the following fixtures?

20 private lavatories × 2 = 40 gal/hr
15 public lavatories × 6 = 90
25 bath tubs × 20 = 500
9 showers × 150 = 1350
4 kitchen sinks × 20 = 80
2 pantry sinks × 10 = 20

Possible maximum demand = 2080 gal/hr
0.3

Probable maximum demand = 624 gal/hr
Heater or coil capacity = 624 gal/hr
0.9

Storage-tank capacity 561.6 gal

3. Water heaters may be conveniently classed, according to the agency employed to do the heating, as coal, gas, oil, steam, and electric heaters. The heating may be done directly by the fire or the hot gases of combustion in contact with a metal box or with coils containing the water, or indirectly by an intermediate carrier such as steam or hot water.

Domestic hot water is generally delivered at 130 to 140° temperature with 160 or 180° sometimes required for restaurants and other special purposes. The *heater recovery*, or the gallons per hour which a heater can raise through a required number of degrees, is its rated capacity. The required rise depends upon the temperatures of the entering and delivered water and is generally listed by manufacturers as 60° or a recovery from 70 to 130°. If the water enters at 40° a heater recovery of 90 to 100° is required. The capacity of the heater is thereby reduced in proportion, and a heater rated at 20 gal per hr at 60° rise will provide only 12 gal per hr at a 100° rise. Two systems are sometimes used, one for 130° water and the other for the higher temperature, or booster heaters are installed at the required locations.

Domestic hot water may be produced independently of the heating system of the building. This is done by means of separate gas or electric heaters. Two methods of using the existing heating system to make domestic hot water are the introduction of steam coils into the domestic hot water tank and the immersion of domestic hot water coils into the boiler water. In the latter method a short coil may serve a storage tank or a long coil may be used as a *tankless* system.

(*a*) *Gas Heaters.* Gas heaters are divided into two types, instantaneous heaters and storage heaters. Instantaneous heaters have no storage tanks, and the gas flame is regulated according to the amount of water to be heated. The opening of a faucet increases the flow of water through the heater, automatically increasing the gas flame. The water flows through copper coils, the gas flame being applied to the outside of the coils. Good water pressure and ample gas flow are needed.

Storage heaters consist of a tank served by a coil of lesser capacity than an instantaneous coil for the same demand. The gas flame heats the water in the coil periodically on demand from the tank which is kept at the desired temperature. When hot water is drawn from the tank cold water enters the bottom. In time the aquastat turns on the heater again. Tank capacities range from 80 to 700 gal.

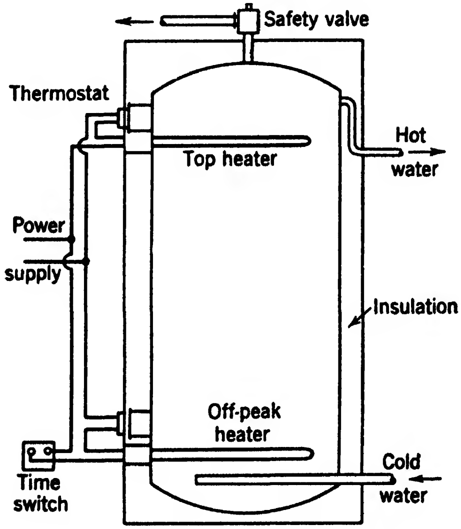

Fig. 2. Electric hot water heater.

(*b*) *Electric Heaters.* In an effort to reduce the higher cost of electric heating some localities have established lower rates for off-peak demand. Well-insulated tanks have been developed with peak and off-peak electrodes, automatic time switches, temperature and pressure controls. The off-peak element in the lower part of the tank is cut out by the time switch during peak hours. The peak element in the top of the tank is generally off but may be turned on by the top thermostat if hot water in the tank is exhausted. The off-peak element thus produces the bulk of the hot water at low rates, aided on demand by the peak element at somewhat higher cost (Fig. 2).

(*c*) *Steam Heaters.* Steam heaters may be employed when steam is available for other purposes in large installations like hospitals and industrial plants. Coils set low in a storage tank carry steam which condenses, giving up its latent heat to warm the water in the tank surrounding the coils. As the hot water leaves the top of the tank, cold water enters it through a bottom pipe and rises over the heating coils. Steam traps pass the condensate back to the boiler.

(*d*) *Hot Water Coils in Boilers.* A very common method of producing hot water is to immerse coils in the boiler water of steam or hot water heating boilers. This system can be used also during the summer by turning off the heating pipes and maintaining hot boiler water by means of a limited fire. The domestic hot water circulates from the coils to the storage tank and back again. Short coils of small fluid resistance facilitate this gravity circulation. Three hours' "recovery" time is generally allowed for the complete heating of the storage tank water. Hot water leaving the storage tank on demand induces flow of cold water into the bottom. The coils may be placed in an external tank (Fig. 3) which extends the effect of the hot boiler water to a point outside the boiler.

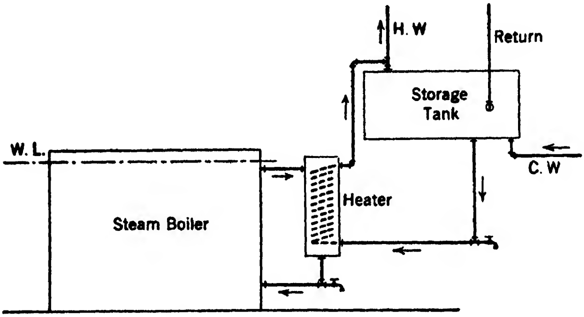

Fig. 3. Water heating by boiler water.

(*e*) *Tankless Heaters.* Tankless heaters operate on a variation of the method described above in (*d*). The storage tank may be eliminated by increasing very greatly the length of coil and connecting the cold water supply directly to this coil. Opening a faucet causes cold water to flow through the very long coil, emerging at a temperature suitable for domestic hot water. It is obvious that this method will fail if the boiler water is not kept up to a proper temperature at all times. Care must be taken when the boiler water in hot water heating systems is subject to the cooling effect of cold radiator water returning to the boiler. Tankless heaters are suitable only to serve a steady demand. If the peak demand exceeds its rate of flow, cool water will be delivered.

4. Clogging of pipes by incrustation of chemicals or rust is much increased by heating the water, harmful gases being forced out of solution and accumulated on the pipe. Therefore, copper, brass, or steel alloy pipes should be used for acid waters, or the water should be treated to remove or neutralize the elements causing encrustation and the acids producing corrosion.

5. Tanks. Galvanized welded steel tanks are widely used in hot water systems where the condition of the water permits it. Elsewhere copper-nickel alloy and silicon-bronze, which have taken the place of pure copper, should be chosen.

Range boiler tanks are made to withstand a working pressure of 150 lb per sq in. and in capacities from 30 to 100 gal. They are usually vertical and set on cast-iron stands.

Large tanks are made of galvanized or nickel-clad steel plate and of copper-silicon alloy. They are provided with handholes or manholes and are tested to withstand a pressure of 300 lb per sq in. The seams are riveted and welded to withstand a pressure of 120 lb per sq in. The heater coils are seamless drawn copper tubing or stainless steel bent into U shape and expanded into a steel tube sheet. Cylindrical steel tanks have capacities of 94 to 6000 gal.

6. Piping systems are two in number: the noncirculating or direct system and the circulating system. The first is not employed where there are long runs of pipe but is fairly satisfactory and less costly for small compact installations with short runs. The pipes pass directly from the heater, manifold, or main to the fixtures, with no return piping. The service is improved by using the smallest adequate sizes of copper tubing, thereby reducing corrosion and attaining high velocity and scouring action, ease of installation, wide bends, and a minimum of standing water (Fig. 4).

In the circulating system the risers serve the fixtures either by up-feed or down-feed and return to the heater, direct branches being taken off to supply the outlets. A continuous circulation of hot water is maintained by the difference in weight of the warmer supply water and the slightly cooler water in the return riser and main. (See Art. 1.)

In general the two methods of arranging hot water supply and return circulation lines are as follows:

(*a*) An up-feed supply riser with the return circulation taken off at a point just below the highest fixture connection [Fig. 5(*a*)]. This return pipe drops down parallel to the up-feed riser, is carried to the basement, and empties back into the water heater or into the main return line, which in turn is carried to the heater. This method is used in dwellings and other buildings of moderate size where the number of up-feed risers is small. The sizes of the supply risers are found in the same way and with the same pressure drop as for cold water up-feed risers. (See Chapter 3.) The return lines should not be less than ¾ in. in diameter and if situated some distance from the heater they should be at least 1 in. to assist the circulation.

(*b*) The second method, now the usual one in high structures, consists, as shown in Figs. 5(*b*) and 6, of a main up-feed supply to a distribution line at the top of the building from which down-feed risers

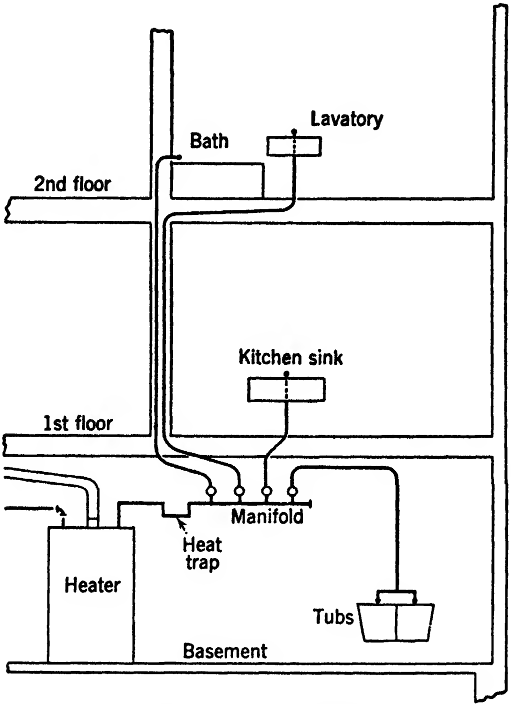

Fig. 4. Direct system.

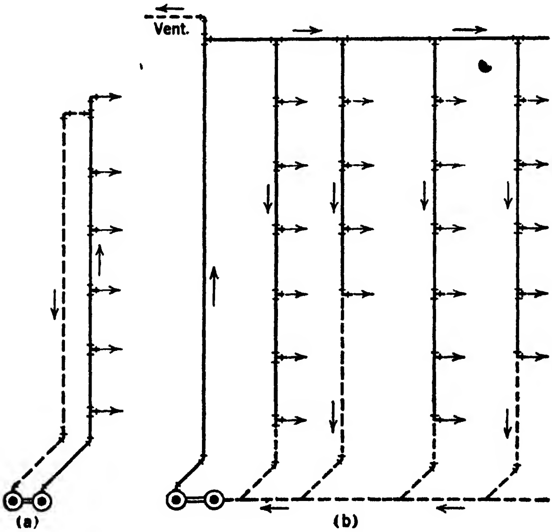

Fig. 5. Up- and down-feed circulating systems.

are taken off to feed the several stacks of fixtures. The lower ends of all down-feed risers are collected and continued back to the heater, thus completing the circulating loop. When the building is zoned, a hot water heater is located on the level below the lowest floor of each zone and is supplied from the house tank at the top of the same zone. The hot water is carried to a distributing feeder at the top of the zone from which risers drop down and connect back to the zone heater.

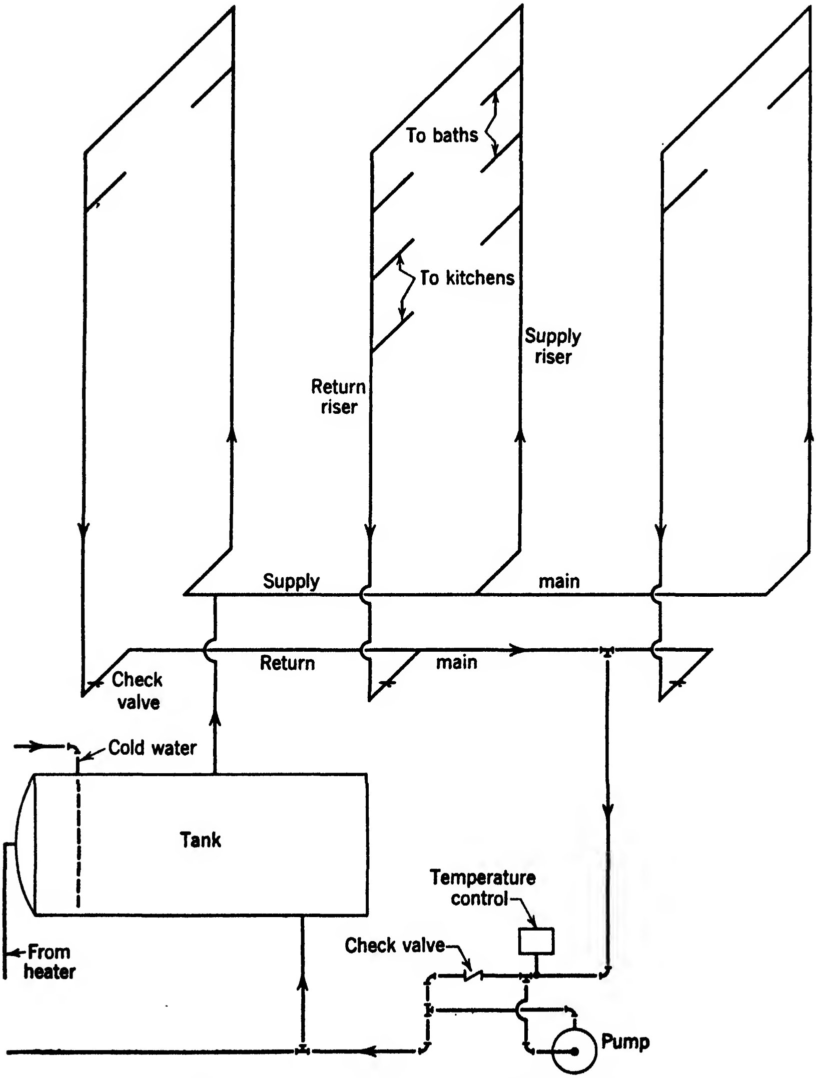

Fig. 6. Loop system with circulating pump.

A modification of the loop method is shown in Fig. 6. Fixtures of one kind, such as bathrooms, are connected to the up-feed supply risers, and those of another variety, such as kitchens, are connected to the down-feed return risers. Whenever a faucet is opened in a kitchen the water travels up through the bathroom riser and circulation is promoted, resulting in prompt supply. This method is adapted only to buildings where the groups of fixtures are situated practically directly over each other on the several floors and can be supplied from the same riser.

The flow of hot water may be improved in a large building by connecting a circulation pump into the return main near the hot water tank. The pump is thermostatically controlled and cuts in when the temperature of the return water drops below a predetermined point and cuts out when the temperature has risen to a higher point. The limits are often fixed at 110 and 125°.

Each hot water supply riser should have a valve at its lower end, and each return riser a valve and check. A vapor relief pipe should be run from the top of the circulation pipe discharging over the house tank.

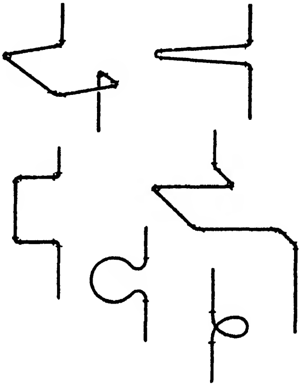

Fig. 7. Expansion loops.

Economy in water consumption is effected by short connections between risers and fixtures; otherwise much cold water must be drained from the branch pipe before hot water is delivered from the faucet.

7. Insulation. Since iron, steel, copper, and brass are all good heat conductors, very appreciable quantities of heat will be transmitted through pipes and tanks manufactured of these materials, the water contained therein being proportionately altered in temperature.

Insulating materials containing minute air cells are consequently employed as covering to reduce the heat losses to a minimum. In selecting the type of insulation the cost of the covering should for economy be compared to the value of the saving in heat. An efficient and generally used material is powdered magnesium carbonate and asbestos binder pressed into segments to fit the standard pipe sizes. Corrugated and laminated covering built up of asbestos sheets is fairly efficient at a low price. Rock wool furnishes effective insulation and packs together less readily than mineral wool. The usual thicknesses are 1 in. and 1½ in. for hot water mains and risers, the covering being finished with a canvas jacket secured with lacquered metal bands. All fittings should be covered in the same manner as the pipe or with asbestos cement 1 in. thick troweled smooth and covered with canvas sewn in place. The better types of hot water tanks and of gas and electric heaters are insulated by the manufacturers.

Cold water pipes are covered to prevent sweating caused by the condensation of moisture from surrounding warm air. Piping for drinking water is insulated also to reduce the conduction of heat from warm outside air through the pipe walls, thus raising the temperature of the cooled water within. Cork, rock wool, and hair felt are commonly used as insulation of cold water pipes, the thickness being approximately 1½ in., against both conduction and condensation.

8. Expansion. All metal pipes expand and contract with changes in temperature, and allowance must therefore be made for such movements in hot water pipes. Horizontal swing joints or pipe loops at floor levels are generally employed for this purpose, the main line of pipe being secured in place between floors, permitting expansion above and below the point of fastening (Fig. 7). The expansion loops may consist of curved bends or be made up of straight pieces with 90- or 45-degree ell fittings. Special expansion joints, which permit movement in the pipes without causing leakage, are used on large sizes. Swing joints are often used at connections to branches. It will be seen from Table III that 100 ft of steel pipe will expand about ¾ in. between the temperatures of 60 and 160°F, and the same length of copper pipe will become 1.12 in. longer. For 20-ft lengths of pipe the elongations will be 0.155 in. and 0.224 in., respectively. It is apparent that allowance must be made for elongation of piping in tall buildings with long runs of pipe but is not necessary in low buildings such as ordinary dwellings.

Table III. Thermal Expansion of Pipe

Increases in Temperature (degrees F)	Elongation in Inches per 100 Ft			
	Cast-Iron Pipe	Steel Pipe	Wrought-Iron Pipe	Copper Pipe
20	0.255	0.293	0.306	0.442
40	0.390	0.430	0.465	0.655
60	0.518	0.593	0.620	0.888
80	0.649	0.725	0.780	1.100
100	0.787	0.898	0.939	1.338
120	0.926	1.055	1.110	1.570
140	1.051	1.209	1.265	1.794
160	1.200	1.368	1.427	2.008
180	1.345	1.528	1.597	2.255
200	1.495	1.691	1.778	2.500
220	1.634	1.852	1.936	2.720

REFERENCE

"Indirect Water Heaters," *IBR Installation Guide Number 3*, The Institute of Boiler and Radiator Manufacturers, 60 East 42 Street, New York 17, N. Y.

PROBLEMS

1. What data are required in order to specify the size of a hot water storage tank and the load on the heater?

2. Upon what factors does the necessary quantity of hot water depend?

3. What is meant by heater recovery?

4. Describe hot water heaters of the following types: (*a*) hot water coils in boilers; (*b*) steam; (*c*) tankless.

5. Describe gas heaters of both the instantaneous and continuous flow and the storage types.

6. (*a*) Describe the noncirculating and the circulating pipe systems and their adaptability to conditions. (*b*) Upon what principles does the circulating of hot water depend?

7. Draw sketches of three different arrangements of hot water piping.

8. (*a*) What size of heater and tank should be used in an apartment house to supply 200 persons? (*b*) What size is needed in a residence with 8 occupants? (*c*) How is the size of the heater related to the capacity of the tank? Give a numerical illustration, using the problem in (*a*) of this question.

9. Describe the automatic operation of a circulating pump to improve the distribution of hot water.

10. What is the difference in the reasons for covering hot water and cold water pipes?

SECTION II · SANITATION

Chapter 5

FUNDAMENTALS AND EQUIPMENT

1. In general. The human occupancy of buildings necessarily results in the accumulation of fluid waste and organic matter very susceptible to rapid decomposition. It is the function of plumbing to dispose of these wastes as quickly as possible before the offensive and unwholesome products of decay can assail the senses or affect the health.

Pipes are consequently installed to conduct the wastes from the plumbing fixtures to the sewer. Gases of decomposition, however, are generated in these pipes or penetrate into them from the public sewer. Hence it becomes necessary to form a bar against the passage of the gases into the fixtures and through them into the living quarters. To erect this bar or seal an S-shaped pipe bend called a *trap* is connected close to the fixture into the drain pipe. This trap catches and holds at each discharge a certain quantity of water through which the gases cannot force their way. It would obviously be very costly as well as wasteful of space to carry a separate pipe from each fixture to the sewer; therefore the individual pipes or branches from the fixtures are connected at the several floor levels into a main vertical pipe or *stack* which in turn joins into the main horizontal drain in the cellar. However, the sudden and often rapid discharges of water into a closed stack would cause a variety of air currents and air pressures throughout the piping system and would probably empty the water from the traps either by propulsion or by suction. The stacks must, therefore, be opened at their tops to the atmosphere, and sufficient fresh air must be supplied to the stacks and branches through *vent pipes* to balance the air pressures, dilute the gases, and reduce corrosion.

The stacks, drains, and branches must be of suitable size to convey their contents at velocities which prevent fouling and clogging, and the areas and lengths of the vents must be proportioned to the demands of the stacks, branches, and traps. Piping may be decreased in size and quantity by ingenious combinations and simplifications and by grouping fixtures in close proximity to the mains. Hygienic requirements must, however, always be maintained; hence the science of plumbing is based upon hydraulics and pneumatics, and the efficient, sanitary, and economical design of pipe arrangements and sizes can result only from a thorough knowledge of the principles involved.

In most parts of the country, state and municipal regulations have been enacted in attempts to insure the installation of only such plumbing as may conform with the demands of hygiene and comfort. Architects must, therefore, lay out the drainage systems of their buildings in accordance with the local sanitary law in order to obtain the necessary permits to begin construction. These regulations have produced and insured vastly improved sanitary conditions, but they are not uniform and are often needlessly complicated and expensive. Constant progress is being made, however, toward simpilicity and standardization founded upon scientific theory and the teachings of exact tests on full-size installations. The U. S. Department of Commerce has published "Recommended Minimum Requirements for Plumbing" and "Plumbing Manual" based upon many careful tests and experiments carried out by the Bureau of Standards, which may be considered the latest scientific authority upon the subject. The recommendations embrace many simplifications which lead to economy and efficiency in both large and small structures.

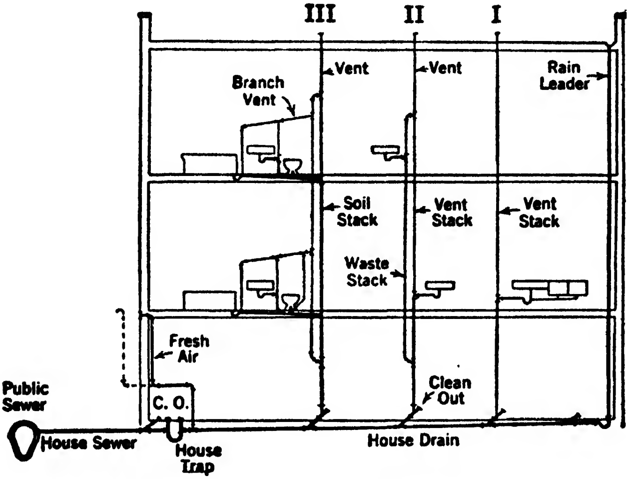

Fig. 1. Typical plumbing layout.

2. Plumbing equipment. Certain essential equipment is involved in all plumbing systems whether for a simple house or for a complicated institution. Figure 1 illustrates these constituent parts, which may be tabulated as follows:

(*a*) House sewer
(*b*) House drain
(*c*) House trap
(*d*) Fresh-air inlet
(*e*) Soil and waste stacks
(*f*) Vent stacks
(*g*) Fixture branches
(*h*) Traps

The house sewer extends from the public sewer in the street or from the private sewage-disposal tank to the wall of the house and is entirely outside the building. Just inside the foundation wall a house trap may be connected into the horizontal main or house drain. The fresh-air inlet protects the house trap from loss of seal. The house drain and the vertical soil and waste stacks collect the sewage from the fixtures through their branches. The vent stacks receive the vent branches from the fixture traps and connect through to the open air.

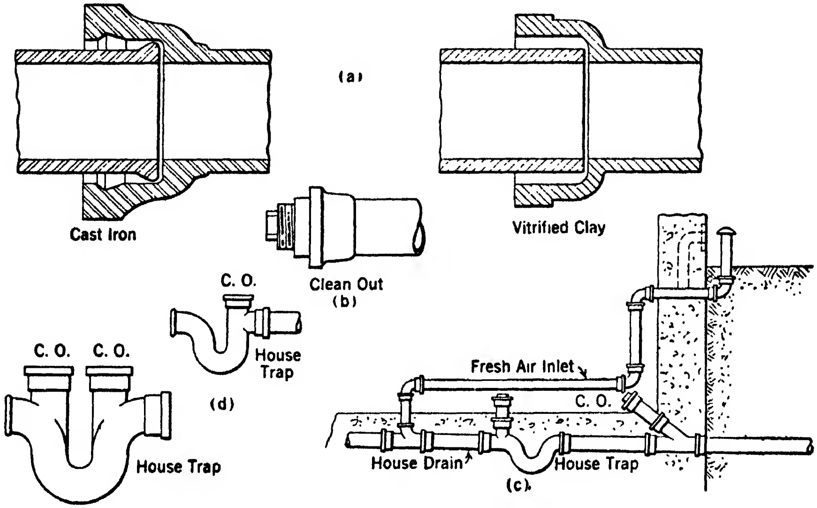

Fig. 2. House sewer details.

The traps are placed in the soil, and waste branches within or close to the fixtures.

Pipe of vitrified clay, steel, copper, brass, and wrought and cast iron should conform to the Standard Specifications of the American Society for Testing Materials. Lead pipe is generally restricted in use to short branches of soil and waste pipes, bends, traps, and leader roof connections. Details of steel, brass, copper, and iron pipes are given in Chapter 2, Art. 1.

3. The house sewer may be of glazed vitrified clay or of cast-iron pipe, both being of hub and spigot type, as shown in Fig. 2(*a*). When being laid the small or spigot end of a length of pipe is introduced into the hub end of the next length, and the joint is caulked. Vitrified clay pipe is less expensive than cast iron but it is not so strong. The joints are filled with hot bituminous compound or are caulked with oakum saturated in cement grout and filled with cement mortar, which is not always watertight and is likely to crack if the pipe settles. The joints of cast-iron pipe are made perfectly tight and at the same time slightly flexible by caulking with oakum and at least 1 in. of molten lead. Porous joints are undesirable because leaking sewage may be carried through the ground to contaminate wells and springs. Sewers are also often obstructed by the penetration of tree and shrubbery roots through the mortar joints of clay pipe, a condition seldom encountered with cast-iron pipe and lead joints. House sewers should have a grade of ¼ in. to the foot and should be not less than 6 in. in diameter if of vitrified clay or 4 in. if of cast iron. For large buildings they should be of the same diameter as the house drain. For a distance of 5 ft beyond the wall the sewer should always be of cast-iron pipe.

Clay pipe is manufactured in standard laying lengths of 2 and 3 ft. The diameters vary from 4 to 36 in. Cast-iron pipe is produced in 5-ft laying lengths and in two weights, standard and extra heavy, the latter coated with coal tar, pitch, or asphaltum being preferable for underground pipes. The diameters range from 2 to 15 in.

If the house sewer carries storm water as well as sewage, it should be proportioned for both quantities, as discussed in Chapter 6, Art. 4.

4. The house drain is the horizontal main into which the vertical soil and waste stacks discharge. Extra heavy cast-iron pipe with lead joints is used; clay pipe should never be employed inside the building. It should have a slope of at least ¼ in. per ft, and it connects directly into the house sewer. Primary horizontal branches or laterals lead from the base of a soil or waste stack to the house drain or to another primary branch. Secondary horizontal branches lead from fixtures to a stack. The location of the house drain depends upon the depth below grade of the public sewer, the contents of the drain in the majority of buildings being designed to flow by gravity into the sewer. The drain is most conveniently placed below the cellar floor, where it is sometimes laid in a concrete trench covered with removable cast-iron plates. If the depth of the sewer necessitates a higher position for the drain, it may be supported above the floor at intervals of 10 ft on masonry piers or on wall brackets, or be suspended from the first-floor beams by metal hangers. House drains above ground may be of cast iron or of galvanized wrought iron and steel. In large buildings with deep basements it may be necessary for the house drain to be below the level of the sewer. The drain then discharges into a receiver called a sump pit, the sewage being raised from the pit to the sewer by an electric pump or pneumatic ejector with an automatic float control.

A cleanout consisting of a branch pipe projecting through the floor is connected into the drain just inside the cellar wall to permit clearing the house sewer of obstructions. Cleanouts are also placed at the end of the house drain beyond the last vertical stack and at intermediate points not more than 50 ft apart to render the entire horizontal run accessible for cleaning. It is also good practice to introduce a cleanout at the foot of each waste and soil stack. Cleanouts are made up of an elbow and a length of pipe into the hub of which is caulked a cast-iron ferrule threaded on the inside. When the cleanout is not in use the ferrule is closed with a threaded brass plug and nut screwed in [Fig. 2(*b*)].

The house trap, when used, is connected into the house drain inside the cellar wall just beyond the sewer cleanout. The fresh-air inlet is placed next on the building side of the house trap [Fig. 2(*c*)]. No traps are placed at the foot of the stacks where they join the house drain.

Whenever there is a possibility of the street sewer's becoming overloaded because of excessive rains, high tides, or increased loading by change in the sizes of buildings, the house drain should be provided with backwater valves to prevent the contents of the street sewer from entering. Such valves should have all bearing parts of brass and should either insure a positive mechanical seal or be equipped with a fresh-air inlet.

House drains may be arranged to receive only the wastes from the plumbing fixtures, separate drains being installed with their own connections to the sewer to carry the rain water from the leaders. The latter method is advisable for buildings of more than moderate size. The house drains are then known as *sanitary* drains and the leader drains as *storm-water* drains.

Steam boiler exhaust, drip pipes, and blow-off pipes should not discharge into the house drain but should be led into a condensing tank from which the water is conducted to the house sewer outside the building. In low-pressure steam systems the condensing tank may be omitted, but the blow-off and drip pipes should discharge into the sewer without connection to the house drain.

5. House traps are required by some sanitary codes, their purpose being to furnish a water seal against the entrance of gases from the sewer into the piping system of the building. They are, however, considered unnecessary by the *Plumbing Report* of the U. S. Department of Commerce and other authorities, the argument being that they interfere with the flow of sewage and the air movements in the house drain and increase the possibility of backpressure in the soil pipes. Gastight stacks open to the outside air and fixtures protected by properly vented individual traps provide a multitude of outlets for the ventilating of sewers in place of manholes near pedestrians in the streets. House traps are of the running type, set perfectly level and provided with a cleanout in one or both horns. They should be the full size of the house drain [Fig. 2(*d*)].

6. Fresh-air inlets are intended to admit fresh air to the drainage system so that there will be a free circulation without compression throughout the house drain and stacks discharging above the roof. They are a necessary accessory to a house trap but are often omitted when the house trap is left out. The outer end is furnished with a cowl or gooseneck when standing free and with a brass grille when embedded in the wall. The pipe should have a diameter equal to half the diameter of the house drain with a minimum of 4 in. [Fig. 2(*c*)].

7. Soil and waste stacks are generally made of extra heavy cast iron, although brass, copper, galvanized steel, and wrought iron are permitted in most codes. Galvanized steel is often considered more practical for the stacks of very tall buildings. They should rest solidly at the bottom on masonry piers or heavy iron posts and be supported at intervals of 10 ft in their height by stout wall hangers or brackets. The upper ends extend through the roof at the full diameter and have no caps or cowl. When less than 4 in. in diameter the stacks should be increased to 4 in. at least 1 ft below the roof to prevent stoppage by snow or frost (Fig. 3). The open tops of the pipes should rise at least 1 ft above wall copings and should be not less than 12 ft distant from shafts, windows, skylights, and ventilators. The stacks should be as straight as possible, free of sharp bends and turns. Connections with branches and house drain are made at angles greater than 45° with the horizontal. No 90° ells are permitted except on those portions acting as vents above the highest fixture.

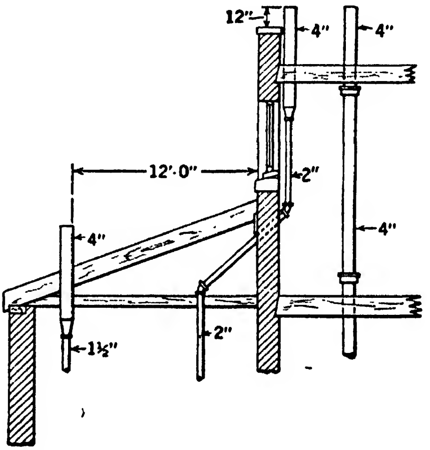

Fig. 3. Extension of stacks through roof.

The circulation of air throughout the stacks and drain retards the decomposition of organic matter, bacteria being unable to function in the presence of free oxygen. It dilutes poisonous gases, delays pipe corrosion, and maintains balanced atmospheric pressures in the various parts of the system. A proper relation and connection between the stacks, drains, vents, and outside atmosphere are consequently as important as the disposal of the sewage.

For economy the sets of stacks should be as few as possible. The groupings of bathroom, toilet, and other fixtures on the same and successive floors so that they may be served by a minimum number of stacks is, therefore, an important architectural consideration and should be carefully studied in the planning of every building.

8. Vent stacks provide the air circulation so necessary to the efficient functioning of a plumbing system. They may be combined and cross-connected with the waste and soil stacks in several ways to render them more effective and to reduce the amount of piping. Municipal codes require that all fixture traps susceptible of siphonage shall be vented to the atmosphere. This must naturally be done through those portions of the pipes which carry no sewage. In Fig. 1 it is seen that stack I is a waste from the first-floor fixtures to the house drain but becomes a vent stack above, since there are no fixtures over the first floor to discharge into it and the trap of the first-floor fixtures is sufficiently near to the stack to be vented by it. Stack II is a waste from the first-floor fixture to the house drain and acts as a vent above the first floor because the second-floor fixture does not drain into it but into a separate waste stack. This second stack acts also as a vent for the second-floor fixture and turns into the first stack above the highest and below the lowest fixture, thereby saving piping and fittings. Stack III is a soil stack and receives the branch connections from the water closets, lavatories, and bath tubs. It becomes a vent, however, above the highest fixtures and as such serves the near-by second-floor water closet directly. The traps of the lavatory and tub are, however. too far removed and are vented by branches to the special vent stack. This vent stack receives the branches from the first-floor fixtures and turns into the soil stack above the highest and below the lowest fixture. In no case is there a dead end; the waste, soil, and vent stacks offer continuous passages for air from the roof to the house drain, which in turn is ventilated through the fresh-air inlet. Vent stacks are of the same materials and connected in the same way as waste and soil stacks and are increased in diameter in a like manner when they extend above the roof.

9. Fixture branches connect the fixtures with the stacks and may be of cast iron, brass, copper, or galvanized steel. Waste and soil branches are connected to the trap of each fixture and have a fall of ⅛ to ½ in. per ft. Branches serving water closets, urinals, and slop sinks are run between the floor and the ceiling below; branches from other fixtures may be run in the floor or, when convenient, in the wall back of the fixtures. In general the length of a 1¼-in. horizontal branch measured from the vertical inlet of the trap to the vent opening should not be more than 5 ft. For branches larger than 1¼ in. the following lengths of branches are allowable with a ¼-in. slope: 1½-in. branch, 6 ft; 2-in. branch, 8 ft; 3-in. branch, 12 ft. In Fig. 4, *a* should not be less than 2 or more than 48 pipe diameters, *b* not more than 1 diameter (Fig. 4). Long unvented branches are likely to have too little slope or to necessitate dangerous cutting of framing timbers. They permit deposits from small discharges or siphoning out of trap seals when the discharges are large, and they encourage corrosion by loss of air movement and concentration of gases. When the vent opening is below the dip of the trap, many municipal codes limit the distance from trap to vent to 2 ft.

Branch vents should be graded to drip any moisture back to the fixture branch. It is important that discharges in the waste and soil lines should not rise in the vents to foul and clog them and so cut off the air supply. For this reason vents are never connected to the crowns of traps. For the same reason they should not be taken off the branches below the hydraulic grade, that is, a line connecting the high-water level of the fixture with the outlet from the waste pipe into the stack. If the waste is bent at right angles, the vent becomes a continuation of the vertical leg of the waste, and, if its connection is not below the hydraulic grade, as shown in Fig. 5, the vent will not become clogged.

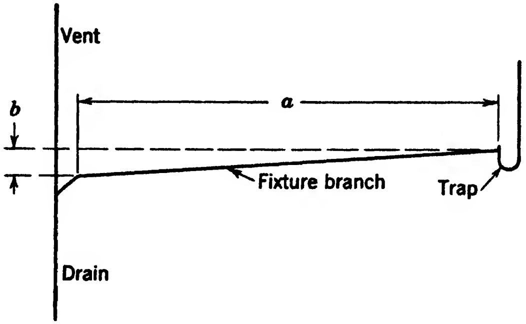

Fig. 4. Distance of trap from vent.

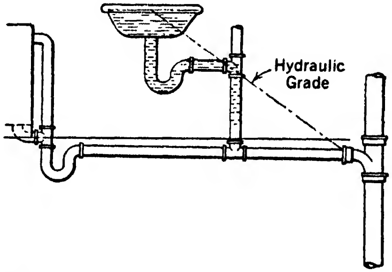

Fig. 5. Waste and vent connections.

10. Traps are classed as running traps, running Y traps, and S, ¾ S, and ½ S or P traps, as illustrated in Fig. 6(*a*). They are of steel, cast iron, or brass, except those of water closets and urinals, which are of vitreous china cast integrally with the fixture. The

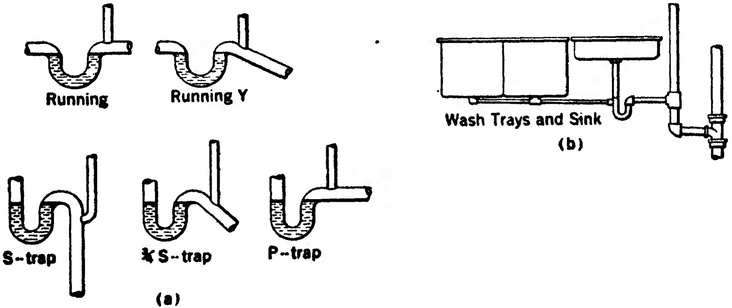

Fig. 6. Traps and trapping.

deeper the seal, the more resistance there is to siphonage but the greater the fouling area. Therefore a minimum depth of 2 in. and a maximum of 4 in. with no loss of seal over 1 in. is generally accepted [Fig. 7(*c*)]. All traps should be self-cleaning, that is, capable of being completely flushed each time the trap operates, so that no sediment will remain inside to decompose.

The only common occurrence in which a separate trap is not required for each fixture is the combination of two trays and a kitchen sink or of not more than three laundry trays or lavatories [Fig. 6(*b*)]. The sink is equipped with the trap and is set nearest to the stack, the wastes from the laundry trays connecting into the sink trap below the level of the water seal.

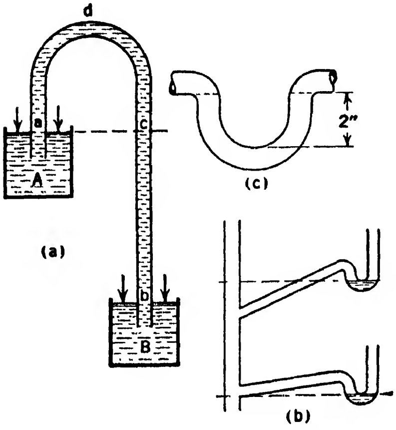

Fig. 7. Siphonage of traps.

Traps are set with their water seals level, are never placed, except in a few combinations, more than 2 ft away from the fixture, and when accessible are provided with brass screw caps below the water level for cleaning. Overflow pipes from fixtures are connected into the inlet side of the trap. Running traps are used only for floor, area, yard, and house drains and should have hand-hole cleanouts. The soil branch for a water closet or urinal is provided with a heavy brass floor plate to which the china trap of the fixture is securely bolted and made gastight.

Vent pipes are not taken off from the crowns of traps but from a point on the discharge side not less than 6 in. from the crown. The vent of porcelain water closets and urinals is connected to the pipe bend below the fixture [Chapter 7, Fig. 2(*b*)].

11. Siphonage is the flow of liquids through a bent tube like an inverted U with legs of unequal length, caused by the difference between the weight of liquid in the two legs acting against atmospheric pressure. In Fig. 7 (*a*), the upward pressure at *a* is equal to the atmospheric pressure, 14.7 lb per sq in., minus the weight of column *ad*, and the upward pressure at *b* equals the atmospheric pressure minus the weight of the column *bd*. The upward pressure at *a* therefore exceeds the upward pressure at *b* by the weight of the column *bc*. If a fluid such as water fills the tube it will flow from *a* to *b*, causing at the same time a partial vacuum in the tube. The atmospheric pressure on the surface of the water at *a* pushes more water up the tube through this lowered air pressure, and the flow continues until the end of the short leg is uncovered. The tube may be filled primarily by suction at the end of the long leg or by otherwise forming a partial vacuum within the tube. The end of the long leg must be lower than the end of the short leg for the siphon to function [Fig. 7(*b*)]. Since water in flowing out through the long leg forms a partial vacuum in the tube, any hole or vent in the tube allowing air to enter will destroy the vacuum and arrest the siphonic action.

Siphonage is usually applied in the operation of water closet and urinal tanks and of siphon water closet bowls. Its action is undesired in relation to plumbing traps.

12. Venting traps. Running and S traps form perfect siphons when airtight, and in such circumstances the water seal is likely to be lost, permitting foul gases to penetrate into the building. The siphoning of traps may be started by three different actions in the plumbing system.

(*a*) Backpressure or increase in air pressure above atmospheric, such as compressed air built up in front of water discharges through the stacks from above. It is at its maximum at the base of a stack and extends upward in proportion to the volume of the discharges.

(*b*) Partial vacuum or decrease in air pressure below atmospheric, generally caused by the suction or aspirating effect of a flow of water in a stack past the junction of a fixture branch. Partial vacuums and backpressures seldom occur in the same part of a stack.

(*c*) Self-siphonage caused by the discharge through the trap itself of the contents of its fixture.

These conditions can be obviated by providing an air passage between the stack or trap and the atmosphere by means of a vent pipe. In case *a*, the backpressure is relieved through the vent; in *b*, normal atmospheric pressure is maintained by the admission of air; in *c*, siphonic action cannot proceed because the siphon is not airtight. Hence every trap should be protected against siphonage and backpressure by ventilation to the atmosphere. As stated in Art. 10, the loss of trap seal should be limited to 1 in. Sizes and lengths of vent pipes are consequently designed for necessary air passages to balance the pressures in the stacks and branches which they serve, so that seal losses will not exceed this limit.

Susceptibility to loss of seal may be greatly reduced by maintaining the level of the junction between branch and stack above the dip of the trap, that is, the end of the long leg of the siphon above the end of the short leg [Fig. 7(*b*)].

Unless otherwise specified by local regulations, vents are not required on backwater traps or the traps of rain leaders, catch basins, and floor drains. When fixtures, such as those in bathrooms, are located on opposite sides of a partition they may have a common soil or waste stack and a common vent stack (Chapter 6, Fig. 5).

13. Nonsiphon traps. In order to avoid the vent-pipe connections necessary with S and running traps and to secure longer unvented wastes and thereby greater freedom in the location of fixtures, much study has been directed to the development of traps so designed that they will furnish an adequate water seal which cannot be destroyed by backpressure or siphonage. Such equipments, known as nonsiphon traps, although adopted in some localities, especially with so-called one-pipe plumbing systems, are not permitted by many sanitary codes. They usually consist of reservoirs so large that it is difficult to siphon out the contents under ordinary circumstances (Fig. 8). Some types of nonsiphon traps function also by means of baffles, check valves, or floating balls. When the traps are new and clean they may resist siphonage but they are not self-cleaning, soon become foul, and in such conditions can be siphoned without much difficulty. No moving parts, interior partitions, or mechanical devices should be permitted in locations where they come in contact with sewage. It is usually impracticable for branches from nonsiphon traps to main waste and soil stacks to be over 7 ft long, and because of fouling and corrosion even this length is objectionable.

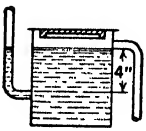

Fig. 8. Nonsiphon traps.

Plain siphon traps have the advantages of simplicity, freedom from fouling, and ease of cleaning. With reasonable and scientific methods of venting they afford ample range in the location of fixtures, and, except in situations where vents are impracticable, they should be preferred to nonsiphon traps without vents.

14. Yard, floor, and area drains are connected to the sewer in city installations but in the country may be drained into dry wells receiving no other sewage. When connected to the sewer they should have running traps at least 3 in. in diameter with full-size cleanouts. The inlet to the drain is usually protected with a removable brass or cast-iron grille which may serve as the cleanout. It is often practical to connect the yard, area, and cellar floor drains back of an inside rain-leader trap. If these drains discharge into a dry well, no trap is required since no foul gases are generated.

15. Rain leaders or conductors may be installed on either the outside or the inside of the exterior wall of a building. Outside leaders are usually of sheet metal and are not included in the plumbing work. Inside leaders, however, should be of cast-iron, wrought-iron, or steel plumbing pipe with gas- and watertight caulked or screwed joints similar to soil and waste stacks. But, unlike these stacks, they are usually provided with cast-iron running traps at their lower ends before connection with the house drain. They must not be used to conduct sewage or as vent pipes. The intersection of the leader and the roof must be carefully flashed to render it waterproof. Sloping roofs are generally provided with a gutter into which the leader is connected by means of a gooseneck or by a short flexible length of copper or lead pipe to take up expansion movements in the leader. Flat roofs may have gutters, or they may have gentle slopes directly to the leader opening; often they are provided with cast dome strainers, sediment cups, and rings clamped tightly down on the roofing material. On very tall buildings an expansion joint is connected between the top of the leader and the roof drain to allow for movement in the long pipe.

16. Grease traps are important equipment for hotels, restaurants, and institutions where large amounts of oils and grease are contained in the warm waste water. This grease on becoming solidified often causes trouble by completely stopping the pipes. It is advantageous, therefore, to eliminate the grease from the water before it enters the piping. This is done by passing the wastes through a container situated near the sink where they cool, the grease solidifies and floats on top and the purified water passes out from the bottom into the drains. The grease is removed from the trap periodically by hand. Grease traps may have an exterior jacket through which cold water flows and so quickly cools the contents of the trap. The cooling water may be piped to water heaters or other equipment. The capacity of the trap should be twice the volume of waste discharged in an hour. Grease traps are considered necessary for residences only when connected with septic tanks, whose operation is seriously hindered by the presence of grease in quantity.

17. Sewage ejectors. Whenever subsoil drainage, fixtures, or other equipment are situated below the level of the public sewer a sump pit or receptacle with airtight cover must be installed, into which the drainage may flow by gravity and from which the contents are then lifted up into the house sewer. The outlet is connected to the house drain on the sewer side of the house trap and of all other connections. A separate trap, fresh-air inlet, and 4-in. ventilating pipe to the roof should be provided on the inlet side of the sump. Sewage ejectors may be motor-driven centrifugal pumps, or they may be operated by compressed air. The latter have no revolving parts within the receptacle and are in much favor. An air compressor is started when the float within the sump reaches a certain level, and air at a pressure of 2 lb for each foot of lift is delivered into the space above the liquid. The

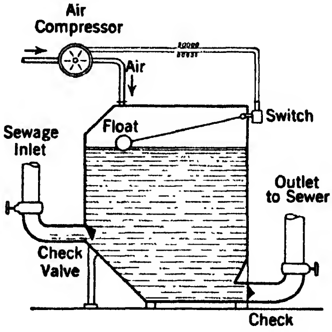

Fig. 9. Sewage ejector.

air pressure closes the inlet and opens the outlet check valves, expelling the contents of the sump and elevating it to the sewer. Centrifugal pumps are often used when the sump receives water from subsoil drainage only and no sewage (Fig. 9).

PROBLEMS

1. Give a full account of the basic reasons why plumbing fixtures are provided with traps and why air is admitted to traps and sewage pipes.

2. What is meant by the following terms? (*a*) Soil and waste stacks. (*b*) House sewer. (*c*) House drain. (*d*) Vents. (*e*) Traps.

3. (*a*) Describe siphonic action. (*b*) Give three ways in which siphonage may be started in traps, and explain how it is prevented in each case.

4. Discuss the necessity of house traps and their fresh air inlets in a plumbing system.

5. (*a*) Of what materials should the following be specified: house sewer; house drain; soil stack; waste stack? (*b*) How are soil, vent, and waste stacks supported, and what provisions should be made when they are extended through the roof?

6. In a simple layout for a 2-story residence what economical combinations of stacks are permissible? Make a sketch showing a bathroom, a separate lavatory, and a kitchen sink on the first floor, and a bathroom and a separate lavatory on the second floor. Use three stacks.

7. Under what circumstances may one trap be used for more than one fixture?

8. Describe the trap to be used when a vent is not possible.

9. When is a sewage ejector necessary? Describe the action of an ejector of the compressed-air type, including the operation of the float switch and check valves.

Chapter 6

FITTINGS, COMBINATIONS, AND PIPE SIZES

1. Fittings (Fig. 1). Changes in direction of drains and connections of stacks to drains and of branches to stacks should be made with easy bends in order that the flow of sewage may not be restricted. The standard plumbing fittings are the T or 90° bend, the Y or 45° bend, the TY, the $\frac{1}{6}$, $\frac{1}{8}$, and $\frac{1}{16}$ bends, and the $\frac{1}{4}$ bend of large radius. T fittings should never be used with pipes carrying sewage but may be used with vent pipes. A change of direction of 90° is made with a Y fitting and a $\frac{1}{8}$ bend, by a TY having a wide sweep or by a $\frac{1}{4}$ bend with a radius at least four times the pipe diameter. A satisfactory fitting for two branches connecting to a stack at the same level is the crowfoot fitting which gives effective protection against reduced air pressures arising from fixture discharges on the same floor. The connection of the base of a stack with a house drain requires attention to reduce backpressure. When the house drain is larger than the stack the connecting bend should be one size larger than the stack.

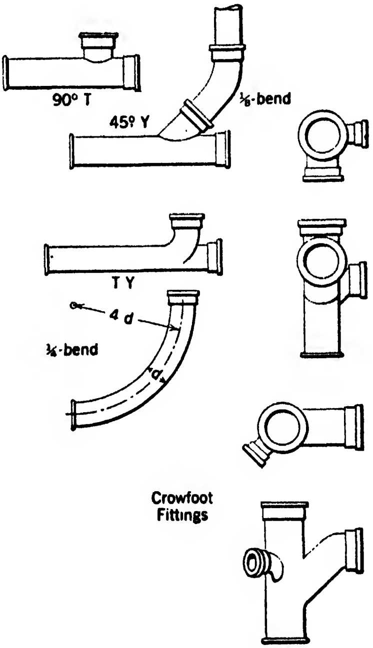

Fig. 1. Fittings.

Pipes of different sizes are connected in the same line by means of reducer or increaser fittings tapered at 45° between the pipe openings.

The intersections of stacks and roof construction must be carefully flashed to render them watertight. Cast-iron pipe are furnished with sheet copper aprons caulked into the hub and turned out on the roof 12 in. on all sides. Flashing on steel pipes is secured by a threaded ferrule which screws down over the pipe and the top of the flashing (Fig. 2).

2. Joints. All joints must be gas- and watertight and are generally made in the following manner:

(*a*) *Vitrified Clay and Cast-Iron Pipe* with caulked joints, as described in Chapter 6, Art. 3.

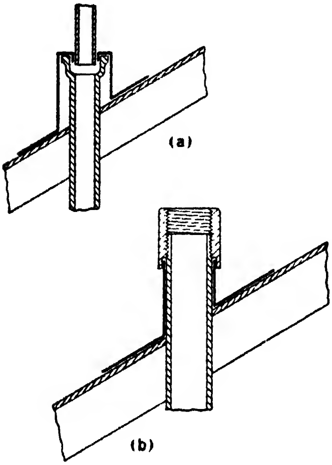

Fig. 2. Pipe flashing.

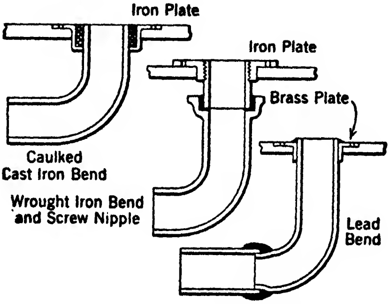

Fig. 3. Floor connections.

(*b*) *Wrought-Iron, Steel, and Brass Pipe* with American standard screwjoints made up with white or red lead and with all burrs and cuttings removed.

(*c*) *Lead Pipe* with a wiped joint consisting of solder fused over the joint and wiped to a smooth, even finish with a cloth. The solder should extend at least ¾ in. on each side of the joint and have a minimum thickness at the thickest part of ⅜ in.

(*d*) *Wrought Iron, Steel, or Brass to Cast Iron* with either screwed or lead-caulked joints.

(*e*) *Wrought Iron, Cast Iron, or Steel to Lead* with a caulking ferrule or wiped soldering nipple or bushing.

(*f*) *Floor Connections to Water Closets and Standard Urinals* and slop sinks with a brass or iron floor plate. Brass plates are used with lead bends connected by soldered and wiped joints. Iron plates are caulked to cast-iron bends and screwed or caulked to wrought-iron bends. The earthenware fixture is then bolted to the floor plate with a metal-to-metal, metal-to-earthenware, or a lead or asbestos gasket gastight joint. Brass floor plates are generally preferred and rubber gaskets are prohibited (Fig. 3).

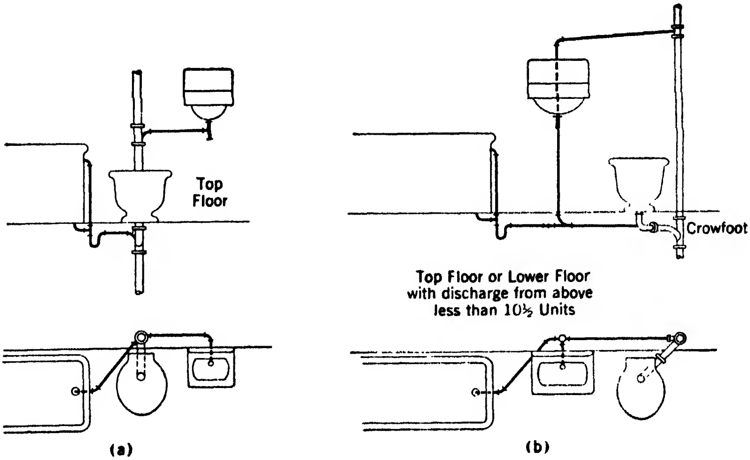

Fig. 4. Fixture combinations.

3. Details. The most usual combinations of fixtures are:

(*a*) The water closet, lavatory, and bath tub of the average bathroom.

(*b*) Kitchen sink and laundry tubs.

(*c*) Batteries of water closets, lavatories, or urinals in public toilets.

(*d*) Bathrooms on opposite sides of a partition.

(*e*) Bathrooms and public toilets repeated over each other on successive stories.

The examples shown in Figs. 4 and 5 illustrate the details of stacks, branches, and vents appropriate for the various combinations. Where

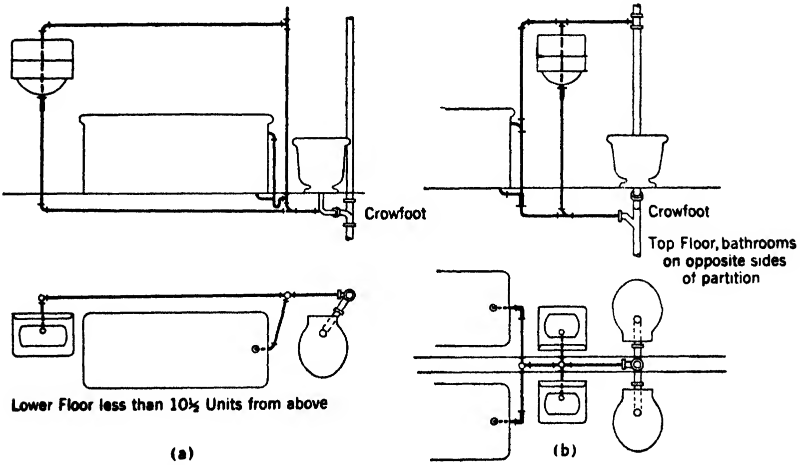

Fig. 5. Fixture combinations.

possible the fixtures are closely grouped around the stack, unvented waste branches are limited to 5 ft in length with slopes of ¼ to ½ in. per ft, and the outlets of the branches are above the dips of their respective traps. It will assist in carrying out these requirements if the stack is located in proper relation to the desired arrangement of the fixtures.

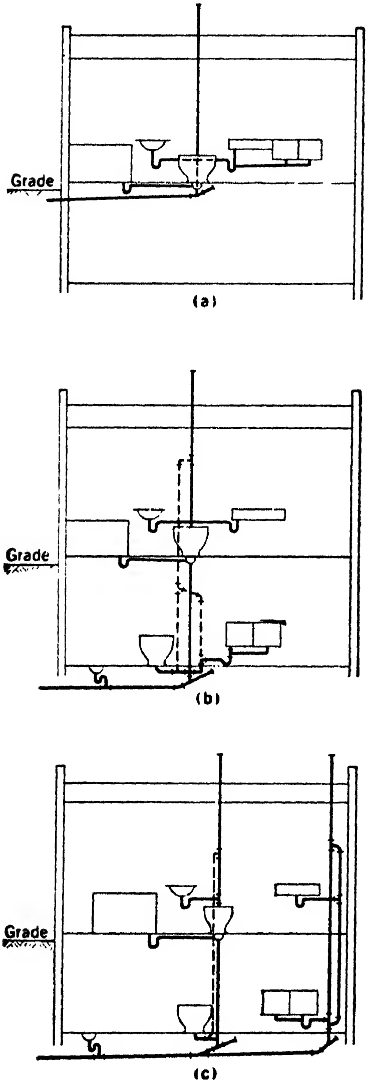

Fig. 6. One-story houses.

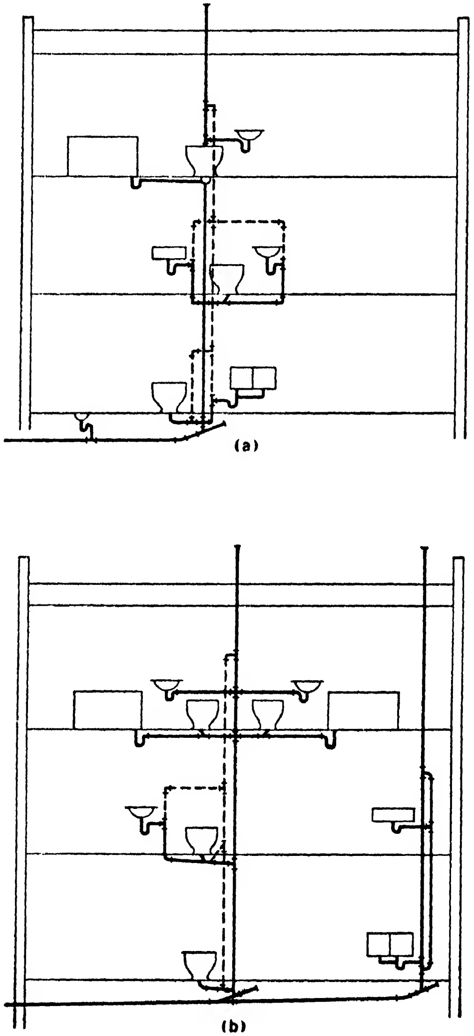

Fig. 7. Two-story houses.

Connections to fixtures in the cellar should be at least 3 ft above the house drain to avoid backpressure in case of flooding the drain by stoppage or storm water.

Figures 6 and 7 illustrate the piping and venting of one- and two-story houses with the fixtures grouped around the stacks. No house trap or fresh-air inlet is included since it is not considered necessary.

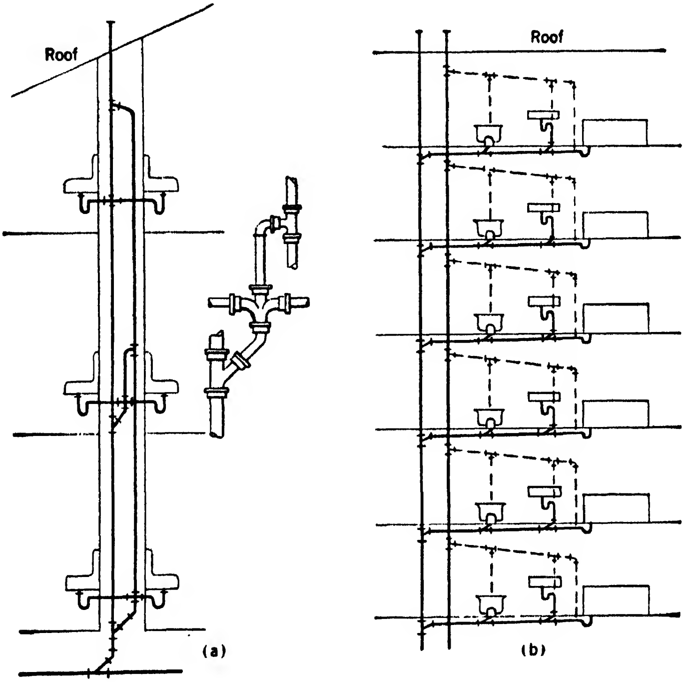

Fig. 8. Lavatories and bathrooms on successive floors.

They can be added next to the outside wall if they are required by the local sanitary code. It will be noted that the top-floor fixtures are vented through the stack with no separate vent pipe because there can be no unbalanced air pressures caused by discharges from higher levels. On lower floors separate vent pipes are installed to relieve the pressures arising from above. Figures 5 and 6 show the arrangement for two bathrooms back to back on the highest floor. Branch waste lines should be vented individually when connecting directly into a stack below a water closet connection to the same stack.

Figure 8(*a*) illustrates the drainage and venting of lavatories on two sides of a partition on successive floors, as often occurs in hotels and office buildings. The circuit-venting connection on the second floor may be used for an indefinite number of stories. For buildings of more than six stories the vent stack should continue independently through the roof. When bathrooms are located directly above each

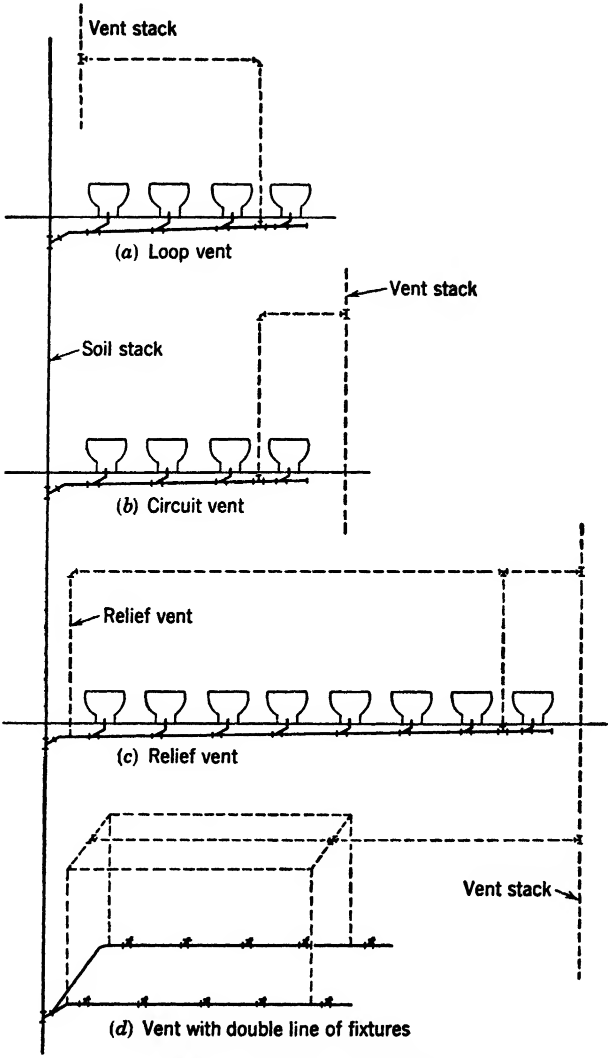

Fig. 9. Battery of fixtures.

other on numerous stories the piping is arranged according to Fig. 8(*b*).

A battery or group of fixtures on the same floor is allowable on one branch soil or waste pipe. It is vented by a circuit or a loop vent connected to the branch drain in front of the last fixture (Fig. 9). If the total fixture units on the branch exceed one-half the number permitted in Table I, relief vents are connected before the first fixture. A double line of fixtures is vented as shown in Fig. 9(*d*).

Table I. Limits for Circuit and Loop Venting

(1) Diameter of Horizontal Branch (in.)	(2) Water Closets and Pedestal Urinals (number)	(3) Fixture Units for Fixtures other than Those in Column 2 (number)
2	None	6
3	2	20
4	8	60
5	16	120
6	24	180

4. Pipe sizes. (*a*) *House Sewers* should be as large as the house drains with a minimum of 4 in. for cast iron and 6 in. for vitrified clay. Allowance should be made for the discharge from yard and storm drains, sump pits, and blow-offs entering the sewer beyond the house trap.

(*b*) *House Drains* should be as large as any pipe emptying into them with a minimum of 4 in. If rain leaders discharge into the house drain it is proportioned to the area of roof surface, as shown in Table II.

Table II. Storm Sewers and Drains

Pipe Diameter (in.)	Slope of Drains		
	⅛-in. Fall per Ft	¼-in. Fall per Ft	½-in. Fall per Ft
	Roof Areas (sq ft)		
3	750	1,050	1,500
4	1,550	2,150	3,100
5	2,700	3,600	5,400
6	4,200	6,000	8,400
8	8,700	11,900	17,400
10	15,200	19,600	30,400

On low buildings of wide area the rain water will probably exceed the sewage in volume, and house drains large enough to take the rain need not be further enlarged to accommodate the sewage. For tall buildings with comparatively small roof areas the probable volume of sewage passing at one time should be calculated to determine the drain areas. The same procedure is followed to design the house drain when rain water is discharged into a separate storm drain or by outside leaders into dry wells, the house drain caring only for the sewage. An approximate rule is to allow 1 sq in. of sectional pipe area for each 2 cu ft or 15 gal of sewage discharged per min.

For convenient study and rating of fixture capacities, units of fixture discharge have been established. The most common unit is the lavatory with a 1¼-in. trap and waste discharges approximately 7.5 gal or 1 cu ft of water per min. The rates of other fixtures are then expressed in terms of this unit. Several tables of fixture units differing slightly from one another have been published in municipal sanitary codes. Table III is taken from the report of the Department of Commerce referred to in Chapter 5, Art. 1. The capacities of house drains and soil and waste stacks can then be measured by the number of fixture units which they are capable of serving.

Table III. Fixture Units

Fixture	Number of Fixture Units	
	Private	Public
Lavatory	1	2
Water closet	6	10
Bath tub	2	4
Shower	2	4
Urinal		5 to 10
Kitchen sink	2	
Bathroom group	8	
Bathroom group with shower stall	10	
Two or three laundry trays, one trap	3	
Combination sink and laundry tray	3	

The quantity of sewage depends largely upon the amount of water used and may be estimated per person at from 50 gal per day for residences to 120 gal per day for hotels and apartment houses. (See Chapter 3, Art. 2.) The largest quantity per hour will be used at special periods of the day, depending upon the class of building, as from 8 to 9 A.M. in hotels and residences and at 9, 12, and 5 o'clock in office buildings. From 25 to 50 per cent of the daily consumption will be concentrated at these times. The quantity of sewage discharge at the peak hours will consequently determine the size of house drains and sewers. In small buildings with little equipment all the fixtures may be discharged at the same time and the drain is proportioned for this requirement, but in larger buildings the probable frequency of coincident discharges is much lower and pipes are designed upon a probability basis.

Table IV. Leader Sizes

Diameter of Leader (in.)	Roof Area (sq ft)
2	500
2½	960
3	1,500
4	3,100
5	5,400
6	8,400
8	17,400

Rainfall, 4 in. per hr.

(*c*) *Rain Leaders* are often selected upon the basis of 150 sq ft of roof surface to 1 sq in. of pipe area for a rainfall of 8 in. per hr. The maximum rate of rainfall in the United States and Canada varies from 4.5 to 8.7 in. per hr, such intensities lasting, however, for periods of a very few minutes. Table IV is based upon a rate of 4 in. per hr. Higher or lower intensities would modify the roof areas drained by each pipe size. It is recommended that leaders be spaced not over 75 ft apart. In tall buildings the leaders may for economy be combined into one or more large main leaders extending down through the building. A separate storm-water drain would then generally be a part of the installation.

(*d*) *Soil- and Waste-Stack* sizes vary according to the number and distribution of fixtures discharging into them, except that no stack serving a water closet should have less than a 3-in. diameter. Table V

Table V. Branch and Stack Sizes, One to Three Story Buildings

Diameter (in.)	Fixture Units	
	One Branch	One Stack
1¼	1	2
1½	3	4
2	6	10
3, waste	32	48
3, soil	20	30
4	160	240
5	360	540
6	640	960
8	1200	2240
10	1800	3780

gives the sizes based upon the allowable fixture units in each branch and stack. It is particularly applicable to buildings of one to three stories.

When buildings are of sufficient height for the probable use factor to operate and, therefore, more fixtures can be installed on a given stack than is allowable under Table V, it is economical to employ Table VI.

Table VI. Fixture Units on Soil and Waste Stacks

Multistory Buildings

Diameter (in.)	Branch Intervals										Fixture Units on One Stack
	1	2	3	4	5	6	7	8	9	10	
1¼	1	1	1	1	1	1	1	1	1	1	2
1½	3	2	2	2	2	2	2	2	2	2	8
2	6	6	6	6	6	6	6	6	6	6	24
3	32	16	13	12	11	10	10	10	9	9	80
4	240	120	100	90	84	80	77	75	73	72	600
5	540	270	225	202	189	180	173	168	165	162	1,500
6	960	480	400	360	336	320	308	300	293	288	2,800
8	1800	900	750	675	630	600	578	562	550	540	5,400
10	2700	1350	1125	1012	945	900	868	844	825	810	8,000
12	4200	2100	1750	1575	1475	1400	1350	1312	1283	1260	14,000

Tests upon vertical pipes flowing one-third full with both ends open show that, under the counterinfluences of gravity and friction, the velocity reaches a certain maximum in a comparatively short fall, after which it increases very slowly. Heights of stacks in tall buildings, therefore, need not be limited because of excessive velocities. Certain restrictions should, however, be placed upon local overloading of the stack, as at floor levels. For this purpose the stack may be divided into sections 8 ft long, called *branch intervals,* within which the num-

Table VII. Size and Length of Vent Stacks

Diameter of Soil or Waste Stack (in.)	Fixture Units on Soil or Waste Stack	Maximum Developed Length (ft)								
		1¼-in. Vent	1½-in. Vent	2-in. Vent	2½-in. Vent	3-in. Vent	4-in. Vent	5-in. Vent	6-in. Vent	8-in. Vent
1¼	2	75								
1½	8	70	150							
2	24	28	70	300						
3	40		20	80	260	650				
3	80		18	75	240	600				
4	310			30	95	240	1000			
4	620			22	70	180	750			
5	750				28	70	320	1000		
5	1500				20	50	240	750		
6	1440					20	95	240	1000	
6	2880					18	70	180	750	
8	3100						30	80	350	1100
8	6200						25	60	250	800

Table VIII. Capacities, Fixture Branches, and Primary Drain Branches

Diameter of Pipe (in.)	Permissible Number of Fixture Units				
	Fixture Branch at Minimum Slope or Greater	Primary Branches			
		1/16-in. Fall per Ft	1/8-in. Fall per Ft	¼-in. Fall per Ft	½-in. Fall per Ft
1¼	1			2	2
1½	3			5	7
2	6			21	26
3, waste	32		36	42	50
3, soil	20		24	27	36
4	160		180	216	250
5	360	360	400	480	560
6	600	600	660	790	940
8	1200	1400	1600	1920	2240
10	1800	2400	2700	3240	3780
12	2800	3600	4200	5000	6000

ber of fixtures or fixture branches is limited. According to the deductions from these tests and with the use of 45° Y or combined Y and ⅛ bend fittings on the branch inlets, Table VI is recommended by the Department of Commerce report. The capacities are larger than those specified in most municipal codes with corresponding savings in expense.

Zoning. To avoid unduly large sizes of stacks and rain leaders, tall buildings are divided into zones of 10 to 15 floors with separate stacks for each zone. For safety it is advisable to serve each zone with at least two stacks connected at alternate floors so that a complete breakdown will not result from a stoppage in one stack.

(*e*) *Vent-Stack* size depends upon the diameter of the soil or waste stack which it serves, the number of fixtures discharging into it and the lengths of the drain and vent stacks. The flow of air in the pipes is the controlling factor. The larger the diameter of the soil stack, the larger must be the diameter of the vent stack. Likewise the larger the diameter of the vent stack, the longer it may be. Table VII, adapted from the report of the Department of Commerce, presents the lengths of vent stacks of different diameters permissible in serving soil or waste stacks according to their diameter and the number of fixture units.

Vents for 1½-in. wastes should be the same diameter as the waste. No vent stack or branch should have a diameter less than half that of the soil or waste stack served. The length of a branch vent of any diameter should not exceed the length of a vent stack of the same diameter as given in Table VII.

(*f*) *Branch Soil and Waste Pipes* may be chosen from Table VIII. Bath tubs and laundry trays are often provided with 2-in. branches for rapid emptying.

Example 1. Assuming the fixture shown in Chapter 5, Fig. 1, floor heights of 9 ft and a roof area of 1200 sq ft, the pipe sizes derived from the foregoing tables would be as follows:

Table IX. Example 1

(For diagram, see Chapter 5, Fig. 1.)

Pipe	Diameter (in.)	Pipe	Diameter (in.)
Rain leader	3	Stack III	
		Soil stack	3
Stack I		Vent stack	2
Waste stack	1½	Soil branch	3
Vent stack	1½	Waste branch	2
Waste branch	1½	Vent branch	1½
Stack II		House drain	4
Waste stack	1½		
Vent stack	1½		
Waste branches	1½		

5. Tests. The sanitary codes of many cities include clauses which regulate the testing of plumbing systems, and an occupancy permit for a building will not be issued by the authorities until a satisfactory test has been made by a municipal inspector. Two tests are generally made, a water test and an air or smoke test.

(*a*) *Water Test.* When all rain-water leaders and all soil, waste, and vent pipes and branches, that is, all work known as roughing or underfloor work, have been installed from the house drain to points above the finished floor levels and beyond the finished lines of walls and partitions, the entire system is given a water test before any pipes are covered with plaster or any fixtures are placed. All pipe ends and other openings are closed with approved testing plugs and the entire system is filled with water or pumped full of air under a pressure of 10 lb per sq in. When no leaky joints appear and the pressure remains constant for 1 hour without further addition of water or air, the work is considered satisfactory. In tall buildings the system may be pumped full of water if the roof tanks have not been installed, or the pipes may be tested a few stories at a time, but no section should be under less pressure than a 10-ft head of water or 10 lb per sq in. of air.

(*b*) *Smoke Test.* After all fixtures are in place, the traps filled with water, and the entire installation is complete, a smoke machine is connected to a convenient opening and the system is filled with a pungent smoke under pressure. If there is no leakage of smoke or forcing of trap seals during 15 min the system is considered to be air- and gastight. Air is sometimes introduced under a pressure of 10 lb per sq in. If there is no leakage or forcing of traps during 15 min indicated by fluctuations on the air machine, the system is considered air- and gastight.

REFERENCE

Standard Plumbing Details, Louis Day, John Wiley & Sons, New York, N. Y.

PROBLEMS

1. (*a*) What is the important consideration in the design of fittings used when a drain changes its direction? (*b*) How are cast-iron and steel stacks flashed at their intersection with roof surfaces?

2. What are the five most usual combinations of fixtures, and what are the advantages of so combining them?

3. What is a fixture unit, upon what is it based, and why is it used?

4. Give a description accompanied by a sketch of the draining and venting of a battery of water closets on the same floor. What is done when the number of fixtures exceeds the permitted limits?

5. Stack *A* serves two bathrooms on the third floor, two bathrooms on the second floor, and a kitchen and a pantry sink on the first floor. Stack *B* serves one bathroom on the second floor and two laundry trays on the first floor. Each bathroom contains a water closet, a lavatory, and a bath tub. Vent stack, length, 35 ft; roof area, 1500 sq ft. Design soil, waste, and vent piping to street sewer.

6. How and at what stages of completion are plumbing systems tested?

7. What drainage sources enter the house sewer outside the house trap?

8. With a rainfall rate of 8 in. per hr what is the required cross-sectional area of a rain leader that drains 900 sq ft of roof area?

9. What safety measure is well observed in zoning a tall building having a number of soil and drainage stacks?

10. What relationship is there between sewage flow and water supply demand? At what times of day will there be maximum flow in (*a*) hotels, (*b*) office buildings?

Chapter 7

PLUMBING FIXTURES

SPECIAL DISTRIBUTIONS

1. In general. All the advantages of a well-designed plumbing system would be nullified if the fixtures absorbed liquid wastes or possessed either open or concealed roughened areas and projections to catch and hold foul matter. Plumbing fixtures of every kind must, therefore, be made of dense, impervious material with smooth surfaces exposed as far as possible to view. They should be set free from enclosures to give circulation of air and access for cleaning and should be well lighted by either natural or artificial means. Since plumbing fixtures are both the terminals of the water supply and the beginnings of the sewage systems they control to a large extent both the quantity of water which must be furnished and the amount of sewage which must be cared for by stacks, drains, sewers, ejectors, and pumps. Economy and efficiency, then, require a careful study of the number and disposition of the fixtures, their selection, and the standardization of their design. They should always be chosen from samples in the show rooms, not from catalogues.

2. Classification. Fixtures may be divided into three classes according to their use as follows:

(*a*) Soil	(*b*) Scullery	(*c*) Bathing
Water closets	Kitchen sinks	Lavatories
Urinals	Pantry sinks	Bath tubs
Slop sinks	Laundry trays	Shower baths

3. Water closets should be made of solid vitrified china not subject to crazing of the glaze, with the trap cast integrally with the bowl and rim. The passage through the trap to the outlet is at least 2½ in. and often 3 in. in diameter. The portion of the bowl containing water should be wide and comparatively shallow and the portion not covered by water reduced to a minimum. The flow of water or flush should be vigorous with a strong scouring action and expelling force. In the flush-tank closet the water is supplied from a 4- to 7-gal tank placed somewhat above the bowl; in the flush-valve closet the water enters the bowl directly from the supply piping. The flush-valve equipment is somewhat less expensive than that of the flush tank but necessitates a branch water connection of $1\frac{1}{4}$ in., a flush tank requiring only a $\frac{1}{2}$-in. branch. Flush valves are consequently seldom used in residences and small buildings but more often in large buildings equipped with a house tank. Closets are 14 to 15 in. high, 14 in. wide, and project 24 to 30 in. from the wall.

The most effective type of water closet is the *siphon-jet,* as illustrated in Fig. 1, consisting of a bowl encircled at the top with a hollow rolled flushing rim. Water enters the rim and flows down the sides of the bowl through a series of small outlets in the rim, scouring the inner surface of the fixture. The trap has the shape of a siphon, *a* being the short leg and *b* the long leg. The water from the flushing rim fills the bowl until it flows through the trap and siphonic action begins, assisted in quick and vigorous operation by the water jet at *c*. The siphonic action draws the contents of the bowl and some foul air through the trap and cleans the fixture without undue noise. The bowl is then refilled by the after-wash from the tank. The supply to the tank is controlled by a float which closes a valve on the inlet pipe when the tank is full. The opening of the outlet valve admits water to the flushing pipe connecting the tank with the bowl, thereby starting siphonic action in the tank and a vigorous discharge into the fixture. The flush pipe should be at least $1\frac{1}{4}$ in. in diameter.

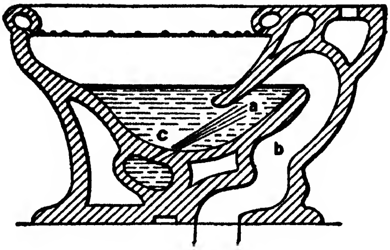

Fig. 1. Siphon-jet water closet.

Two other types of water closets are also acceptable: the *blow-out* for comfort stations and public institutions, with a strong water jet, and the *wash-down* for low-cost installations, with rim flush but no siphon jet.

Tanks are made of vitreous china, their rate of discharge into the bowl averaging 30 gal per min and the time of flush 6 to 10 sec. They are set just above the bowl and have china covers.

4. Urinals should likewise be made of vitreous china in one piece without joints, and all exposed surfaces should be thoroughly flushed. There are three types of urinals, the wall type, the stall, and the pedestal. The wall type is hung to the wall and is generally unsanitary. The stall type stands on the floor and is $3\frac{1}{2}$ ft high. When completely washed by each flush it represents a most satisfactory and sanitary fixture.

The pedestal type is also satisfactory and consists of a bowl 14 in. wide by 25 in. deep, standing 20 to 21 in. high upon a vitreous china pedestal.

5. Lavatories may be of vitreous china or enameled iron, the latter being most employed because it is less costly and is sufficiently durable for the usage ordinarily received. They may be hung on the wall by special hangers, supported on the floor by an enameled pedestal, or rest on one or two metal or enamel front legs and be braced to the wall at the back.

Lavatories stand 30 to 32 in. high and are 18 by 20 in. or 20 by 24 in. for the hung and legged types and 20 by 24 in. or 22 by 27 in. for the pedestal type.

6. Bath tubs are generally made of enameled cast iron since their usage is not severe and their size is too great for the firing of earthenware. Portable tubs rest on feet or a continuous cast-iron base, stand free of the wall and floor, and provide dirt-catching spaces beneath and around them. Built-in tubs rest on the floor without feet and are built into the wall at the back and at one or both ends. They are consequently very sanitary and much better looking than the portable tubs. Bath tubs are 30 and 36 in. wide and from 4 to 6 ft long, the 5-ft and 5½-ft lengths being generally selected.

7. Shower baths consist of an overhead spray nozzle which discharges water down upon the bather in a fine rain, the nozzle or shower head being about 4 in. in diameter, made of chrome- or nickel-plated brass and perforated with fine holes. The shower heads may be placed over a bath tub or over special watertight, 36 by 36 by 3¾ in., porcelain enamel receptors set upon or flush with the floor and connected to the draining system. In both cases the position of the bather is surrounded by a curtain to confine the water to the tub or the receptor. Showers are also placed in stalls with marble, tile, cement, or slate walls and floor.

8. Kitchen sinks are made of enameled cast iron which is now so perfected that the enamel withstands ordinary hard usage and the action of fruit and vegetable acids. However, the enamel may be chipped by an unusually severe blow. Sinks have been introduced of Monel metal, one-third copper and two-thirds nickel, and of chrome-nickel stainless steel. The bowls are drawn from one piece of sheet metal, and the backs, drainboards, and aprons are welded to the bowl with invisible joints. The sizes of sinks run from 16 in. square to 25 in. wide by 74 in. long.

9. Pantry sinks are similar in type to kitchen sinks and are made of the same materials but are of smaller dimensions. Electric dishwashing machines are sometimes combined with sinks, being placed on one side of the bowl and covered with a drainboard.

10. Laundry trays are made of enameled cast iron, vitreous earthenware, alberene or soapstone, and slate. Slate and alberene are open to the objection that the several slabs must be joined together and the joints are likely to catch grease and dirt. Vitreous earthenware is expensive; enameled cast iron appears to be the most practical material. The usual sizes measure from 23 to 27 in. square and 14 in. deep for each tray. They are often used in combinations, two or three trays being set side by side, and are also joined with the kitchen sink.

11. Slop sinks may be made of enameled cast iron when used in residences where they are not exposed to very hard usage, but for office buildings, hotels, and hospitals the material should be vitreous china. They range in size from 18 by 22 in. to 20 by 24 in., are 14 in. high, and are set 26 to 28 in. above the floor.

12. Water-closet connections [Fig. 2(*a*)]. The joint between the earthenware water closet and the soil pipe must, on account of the difference of materials, receive special attention in order to render it gastight. A metal joint ground to a tight fit in the factory or an asbestos gasket may be employed. Rubber gaskets are unsatisfactory. Brass floor plates are generally preferred to iron. The pipe connection from the fixture to the branch soil pipe, called the bend, may be of lead, cast iron, or steel, the lead bend being the most flexible.

The vent connection to a water closet is taken off the bend below the closet. Figure 2(*b*) illustrates the connection to a lead bend.

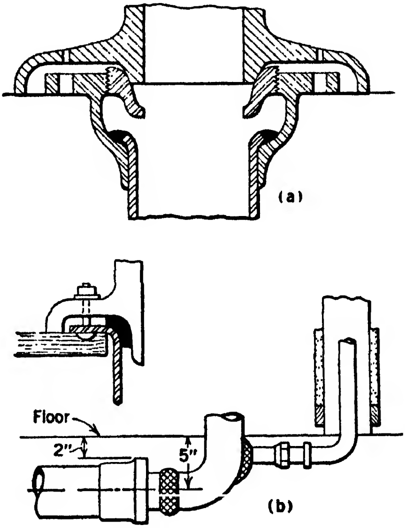

Fig. 2. Water-closet connections.

13. Fittings. The principal fittings of most plumbing fixtures consist of the inlet valve for the water supply and the outlet fitting for the control of the discharge. It is important that the supply should be so located that dirty water cannot enter it by gravity or by siphonage and that the waste fitting be sufficiently tight to hold the water in the fixture for a convenient length of time.

14. Supply fittings include (*a*) combination faucets which deliver hot, cold, or tempered water through one spout; and (*b*) mixing valves which maintain the water at a desired temperature.

(*a*) The combination supply unites the hot and cold hand valves with the spout, thereby mixing the water to a desired temperature, and is neater and more compact than separate faucets.

(*b*) Mixing valves may be hand-operated, pressure-regulating, or thermostatic. The hand-operated valve has no protection against sudden changes of temperatures due to slugs of hot or cold water and is consequently little different in its effect from the combination faucet. The pressure-regulating valve is a safeguard against changes in pressure. It is arranged to cut off the hot water supply if the cold water pressure is reduced. The thermostatic mixing valve is sensitive to changes in both temperature and pressure. The temperature of the water delivered by the mixer remains constant, regardless of temperature or pressure changes in the hot and cold water lines. Automatic temperature regulation is always desirable. It should be seriously considered for any shower bath and is essential for safety against scalding in public showers.

The best location for a bath-tub supply is in the wall just above the tub, the fitting being known as an overrim nozzle. With this type there is no danger of the supply being contaminated by dirty water.

15. Waste fittings. The oldest and most reliable waste fitting is the chain and plug consisting of a rubber stopper attached to the fixture with a chain. It is tight, simple, and cannot get out of order. It is sometimes necessary, however, to plunge the hand into the contents of the fixture to grasp the chain or remove the plug. On this account the pop-up waste has been devised. It consists of a metal plug with a ground seat operated by a lifting knob or lever above the water level.

16. Materials of fittings. All fittings should be noncorrosive and were originally made of plain brass or of brass nickel-plated. Chromium plate is now preferred because it is very hard and does not tarnish or rub through in the process of cleaning as does nickel plate.

17. Valves and other water-supply fixtures are described in Chapter 2.

18. Drinking devices. Bubbler fountains deliver a stream vertically or at an angle into a small bowl connected to a waste. A person may drink by bringing the mouth in contact with the stream. The bubbler may be connected to the iced-water supply piping, as discussed in Art. 20, or may be furnished by individual cooling cabinets. The pressure should be sufficient to raise the stream to a height so that the lips of the drinker will not touch the nozzle.

19. Soap-dispensing systems deliver flaked or liquid soap at the lavatories of large buildings. Soap thus furnished is said to be more economical and is cleaner and more sanitary than that provided in the form of solid cakes. Flaked soap is stored in glass or metal containers attached to each dispenser on the wall above the lavatory [Fig. 3(*a*)]. Liquid soap may be stored and supplied at individual fixtures or may be piped to the dispensers from a tank serving a battery of lavatories or from an elevated tank supplying an entire building. Individual dispensers and containers are often chrome-plated brass and operate with a valve and push button or are tilted over to discharge the soap [Fig. 3(*b*), (*c*)]. Pipe dispensers are actuated by a push button controlling a plunger and needle valve [Fig. 3(*d*), (*e*)].

Piping may be galvanized wrought iron or copper tubing. Mains are generally 1 in. in diameter and branches $\frac{1}{2}$ to $\frac{3}{8}$ in. Tanks of 1 to 5 gal are iron with vitreous enamel or aluminum finish.

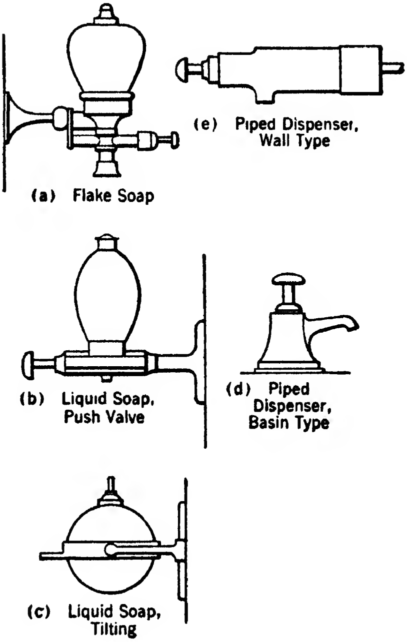
(a) Flake Soap
(b) Liquid Soap, Push Valve
(c) Liquid Soap, Tilting
(d) Piped Dispenser, Basin Type
(e) Piped Dispenser, Wall Type

Fig. 3. Soap dispensers.

20. Iced-water distribution. Cooled drinking water is often piped throughout hotels, offices, and public buildings, the cooling being done by mechanical refrigeration. To provide constantly cold water at the outlets a circulating system of insulated piping is necessary similar to that for hot water. If the water were allowed to stand in the pipes it would become warmed by the surrounding air; therefore, a small centrifugal pump taking suction from an insulated storage tank is generally used to maintain a constant flow through the piping. Up-feed risers are installed from the pump to a point above the highest outlet. From this point a return circulation pipe is run back to the cold water tank. The water is maintained at the proper temperature, usually 45 to 50°F.

21. Gas piping. The illuminating of buildings is now done almost exclusively by electric current, but artificial and natural gas are employed very generally for cooking and heating water and more recently for heating entire buildings. All the piping must be carefully done with tight joints and equipment, since gas is highly dangerous when mixed in any quantity with air. Discharge through vents must also be provided since the gases of combustion are extremely harmful. Municipal building and sanitary codes regulate the installation of gas piping with much detail, and their rules should be conscientiously followed. Gas is supplied by the public-service companies, which bring their pipes to the inside of the cellar wall and install a brass main valve and a gas meter. The plumber or gas fitter then runs the piping through the building to the several outlets. If gas is supplied at too high a pressure for use in the building, a pressure-regulating valve, generally furnished by the company, is connected on the house side of the main cutoff valve. A valve should also be placed on the house side of the meter.

Gas pipe should be best-quality, standard, black wrought iron or steel, the fittings of galvanized malleable iron, and the cocks and valves of brass. Black pipe is sometimes painted with asphalt before installation to prevent corrosion. A certain amount of moisture is contained in gas, and all pipes should therefore be without sags or traps and be so sloped that condensation will flow back into the service pipe or else the piping should be dripped. Unions and bushings are not used on gas piping and pipes should not be bent, connections and changes of direction being made with screw couplings and changes in size with reducing fittings. The pipe outlets extend about ¾ in. beyond the face of the plaster, and all heaters and kitchen ranges should be equipped with brass stop cocks on the service pipe. The entire gas system when complete is tested for 10 min under air pressure of about 6 in. of mercury. If the pipes and joints are not tight the pressure as shown on the gauge will immediately drop. Standard pressures at appliances are 3.5 to 4 in. of water for manufactured and 7 to 7½ in. for natural gas.

22. Pipe dimensions. The specific gravity and the heating value of artificial gas depend upon its composition, which differs according to methods of manufacture. The specific gravity varies from 0.35 to 0.70. The following heating values in Btu per cubic foot are often used in computations: Carbureted gas, 530; retort gas, 600; natural gas, 1100; mixed natural and manufactured gas, 800. For accurate design the actual specific gravity and heating value of the gas used should be learned from the authorities. The required heat inputs in cubic feet per hour of heating and cooking devices are in the manufacturers' lists.

Pipe sizes are determined by (*a*) length of pipe, (*b*) allowable pressure drop, (*c*) flow through the pipe.

(*a*) Length of pipe is measured at the building or from plans.

(*b*) Pressure drop from meter to appliance of 0.5 in. of water is generally allowed. If there is a vertical portion in the pipe, allowance for the tendency of gas to rise may be added to the 0.5 in. Table I shows the pressure gain in inches of water per 100 ft of pipe due to this rise.

(*c*) Flow of gas in cubic feet per hour is found by dividing the input rating of the appliance in Btu per hour by the heating value of the gas in Btu per cubic foot. This flow depends upon the specific gravity of the gas. The pipe sizes in Table III are based upon a specific

Table I. Pressure Increase in Vertical Pipes

Specific Gravity	Gain per 100 Ft of Pipe (inches of water)
0.35	0.96
0.40	0.89
0.45	0.81
0.50	0.74
0.55	0.66
0.60	0.59
0.65	0.52
0.70	0.44

gravity of 0.60. Therefore, before entering the table the actual gravity of the gas used is multiplied by a factor as shown in Table II to give a corrected volume for gas with a specific gravity of 0.60.

Table II. Specific Gravity Factor

Specific Gravity	Factor
0.35	0.77
0.40	0.82
0.45	0.87
0.50	0.91
0.55	0.96
0.60	1.0
0.65	1.04
0.70	1.08

Example 1. A small apartment house has a 4-burner 62,500-Btu gas range on each of two floors (Fig. 4). Gas has a heating value of 550 Btu per cu ft and a specific gravity of 0.50. Find sizes of pipes.

(*a*) Longest run of pipe = 25 + 5 + 10 + 20 = 60 ft.

(*b*) Rise to second floor = 5 + 10 = 15 ft. From Table I the gain in pressure for 0.50 gas is 0.74 in. per 100 ft, for 15 ft; the gain is $\frac{15 \times 0.74}{100} = 0.11$ in. Allowable pressure drop is then 0.5 + 0.11 = 0.61 in.

(*c*) Flow input to each range is 62,500 ÷ 550 = 113 cu ft per hr. From Table II the factor for 0.50 gas is 0.91. For 0.60 gas the equivalent volume is 113 × 0.91 = 103 cu ft.

Sizes of Pipes. Enter Table III with longest run, 60 ft. Pass to right to nearest lower pressure drop, 0.6 in. Pass downward to nearest greater flow, 135 cu ft, and pass to left to ¾ in., the pipe size from *A* to range No. 1.

The flow from the meter to *A* is 103 + 103 = 206 cu ft. The pressure drop is the same as before. From 0.6 in Table III pass down to the next

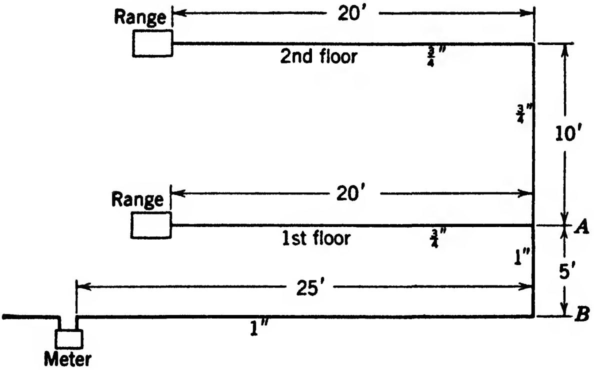

Fig. 4. Example 1.

greater flow, 249 cu ft, and pass to left to 1 in., the pipe size from meter to *A*.

For the branch from *A* to range No. 2, the pipe length is 25 + 5 + 20 = 50 ft. The rise is 5 ft, $\frac{5 \times 0.74}{100} = 0.03$ in., 0.5 + 0.03 = 0.53 = allowable drop. The flow is 103 cu ft per hr of 0.6 gas.

Entering Table III with 60 ft, next longer to 50 ft, pass to 0.48, next lower drop, pass down to 121, next larger flow, and at left the pipe size is ¾ in.

23. Toilet-room requirements. The finish, ventilation, and lighting of toilet rooms and the number of fixtures demanded are generally definitely specified in the municipal building codes. The following items present typical requirements of most of the codes as well as the essentials of good practice.

24. Ventilation and lighting. When possible bath and toilet rooms should be open to the outside light and air by windows or skylights upon a street or court. When windows cannot be arranged an individual bathroom may be vented by a separate flue or duct to the roof with a cross-sectional area of at least 1 sq ft. Interior toilet rooms with several water closets should have mechanical ventilation.

25. Finish. The floors of toilet and bathrooms and the walls to a height of at least 6 in. should be of an impervious material such as cement, tile, marble, or terrazzo. In large public toilets a floor drain with brass strainer plate should be installed. The floor in front of stall urinals should slope toward the urinals.

26. Toilet accommodations. Minimum requirements are as follows:

Apartment Houses. One or more bathrooms for each apartment.

Hotels. Usually have one bathroom for each room or suite of rooms.

Theaters. One water closet for every 100 to 200 women and every

Table III. Pipe Sizes

Length (ft)	Total Pressure Drop (inches of water)											
10										0.10	0.15	0.20
15									0.12	0.15	0.23	0.30
20								0.12	0.16	0.20	0.30	0.40
30							0.12	0.18	0.24	0.30	0.45	0.60
40						0.12	0.16	0.24	0.32	0.40	0.60	0.80
60					0.12	0.18	0.24	0.36	0.48	0.60	0.90	1.2
80				0.12	0.16	0.24	0.32	0.48	0.64	0.80	1.2	
100			0.10	0.15	0.20	0.30	0.40	0.60	0.80	1.0		
150		0.10	0.15	0.23	0.30	0.45	0.60	0.90	1.2			
200	0.10	0.13	0.20	0.30	0.40	0.60	0.80	1.2				
Size (in.)	Flow (cubic feet per hour)											
⅜	6.2	7.1	8.7	10.5	12.5	14.8	17.0	20.5	24.0	27.5	33	38
½	10.9	12.6	15.4	19.0	21.9	26.7	30.9	38	43.2	48	60	68
¾	30.2	35	42.5	52.5	60.5	74	85	105	121	135	168	191
1	55.5	64	78	97	111	137	158	191	221	249	304	348
1¼	115	132	161	200	230	282	325	397	460	510	630	720
1½	178	206	251	310	355	440	500	615	710	795	980	1110
2	365	420	510	630	720	890	1000	1250	1430	1600	2000	2280
2½	580	670	820	1000	1160	1420	1770	2000	2300	2600	3200	3650
3	1030	1200	1460	1800	2080	2550	2900	3600	4200	4650	5700	6500

150 to 250 men; one urinal for every 150 to 400 men. One lavatory for each two water closets, counting 2 urinals as one water closet. Additional provisions should be made for the stage and for moving-picture booths.

Banks. One for every 100 to 150 women and every 150 to 200 men; one urinal for every 25 to 35 men; one lavatory for every 15 to 25 persons.

Dance Halls. One water closet for every 100 to 150 women and every 300 to 400 men; one urinal for every 150 to 200 men.

Department Stores. One water closet for every 75 to 125 women and every 100 to 200 men: one urinal for every 250 to 300 men; one lavatory for 100 to 200 persons.

Schools. Elementary: one water closet for every 35 girls and every 100 boys; one urinal for every 30 boys. Secondary: one water closet for every 45 girls. Same as elementary schools for boys. One lavatory for every 60 persons in elementary and one for every 100 persons in secondary schools.

Factories. One water closet for every 15 to 20 women and for every 25 to 30 men; one urinal for every 50 to 60 men; one lavatory for every 20 to 30 persons.

27. Zoning. Tall buildings are divided into horizontal zones, usually corresponding to the water supply zones, in order to avoid excessively large pipe sizes. A soil stack serves its zone and runs down to the basement without receiving any branches below its zone. Although tests have shown that excessive velocities should not occur in tall stacks, it is recommended that stacks be offset at each zone to give solid support to the stacks to permit allowance for expansion and contraction and to limit any possible undue velocities.

It is well to serve each zone by at least two stacks connected at alternate floors and discharging into separate house drain branches, in order to escape complete isolation of a zone through loss of service in one stack.

PROBLEMS

1. What are the basic requirements of a good plumbing fixture?

2. (*a*) What are the three acceptable types of water-closet fixtures, and for what locations are they intended? (*b*) Describe fully the action of the siphon-jet closet and specify its structural material.

3. Of what materials are lavatories, bath tubs, kitchen sinks, and laundry trays constructed, how are they supported, what are their approximate dimensions, and how are they combined for drainage purposes?

4. (*a*) What are important considerations in the design and location of the fittings of plumbing fixtures, and of what materials should they be made? (*b*) Describe the following supply fittings: faucets; combination units; mixing valves (three types); bath-tub supplies. (*c*) What are the three types of waste fittings, and where are they used?

5. Describe the following devices: (*a*) drinking devices; (*b*) soap-dispensing systems; (*c*) iced-water distribution.

6. Give approximate heating values in Btu per cubic foot for manufactured gas, natural gas, and mixed natural and manufactured gas.

7. In computing the size of gas pipe, how are the following items determined? (*a*) length of pipe; (*b*) allowable pressure drop; (*c*) flow of gas through the pipe.

8. Design the gas-piping system for a small apartment house having a 62,500-Btu-per-hr gas range in one apartment on each of three stories. The ranges are supplied from the same vertical main by horizontal branches, each 18 ft long. The horizontal branch from the meter supplying the vertical main is 25 ft long and 6 ft below the ground-floor level. The gas has a heating value of 600 Btu per cu ft and specific gravity of 0.50. Floor-to-floor height, 10 ft.

9. What sanitary finishes are appropriate for the floor and wall surfaces of bathrooms and toilets?

10. What facilities are provided with relation to occupancy in the items of water closets, urinals, and lavatories in (*a*) theaters, (*b*) banks?

Chapter 8

SEWAGE DISPOSAL

1. In general. Deterioration and disintegration are incident to the nature of things, but the elements are not destroyed. They may form parts of new organisms which in turn disintegrate. Products of the decay of organic life are valuable in the feeding of vegetation; and the plants so nourished may serve as food for many types of animals. In the process of digestion portions are eliminated; the excretions decay and change once more into plant food to complete the cycle. It is the province of sewage disposal to permit the natural conversion of wastes to go forward without interruption but to control the process so that offensive attributes will not assail the senses of the community or dangerous properties menace its health.

The methods of sewage disposal differ somewhat according to the kind and quantity of the sewage, whether originating in a town, an industrial plant, or a single house. Architects are frequently confronted with the problem of a residence so situated that connection with a public sewer is impossible, but they seldom are professionally interested in the demands of larger installations. Hence only the requirements of domestic or institutional sewage-disposal plants of moderate size will be discussed in this book.

2. Composition of sewage. Sewage is composed very largely of water, only 800 parts in 1 million being organic and mineral solids held either in suspension or solution. The organic and especially the nitrogenous content of sewage, although proportionately small, is difficult to control because it putrefies very rapidly and with disagreeable accompaniments. The problem is also complicated by the necessary disposal of the large liquid portions. Consequently, the procedure is generally first to separate as far as possible the solids from the liquid by sedimentation and then to deal with the two components individually. When, however, the sewage can be discharged directly into the ocean or into large lakes or rivers and disposed of by dilution, preliminary treatment is generally not required.

3. Sewage treatment. The natural disintegration of sewage may be divided into two stages, putrefaction and oxidation. The first stage yields ammonia, carbon dioxide gas, and certain evil-smelling products, such as hydrogen sulphide, and causes dark discoloration. As the process continues methane gas is generated and the solids change into humus, the organic part of earth, and decompose no further. When oxygen is lacking the decay is slow but continuous and is performed by anaerobic bacteria which work in the absence of air. When oxygen is present, the changes are effected by the action of aerobic bacteria which work when air is supplied. The ammonia is oxidized to nitrates, and the sulphur compounds to sulphates, both of which together with carbon dioxide are available plant foods. Oxidation is attended by little unpleasant odor or other nuisance. The process of sanitary sewage disposal, then, consists first of removing the solids to a receptacle where they may putrefy without becoming offensive, and secondly of leading the liquid into the soil where it may oxidize without resultant unsightliness, bad odor, or danger to health. The first step is taken in the septic tank, and the second in the cesspool or tile drainage field.

4. Grit and grease removal. When grit or grease is present in an appreciable quantity, it should be removed before the sewage is treated.

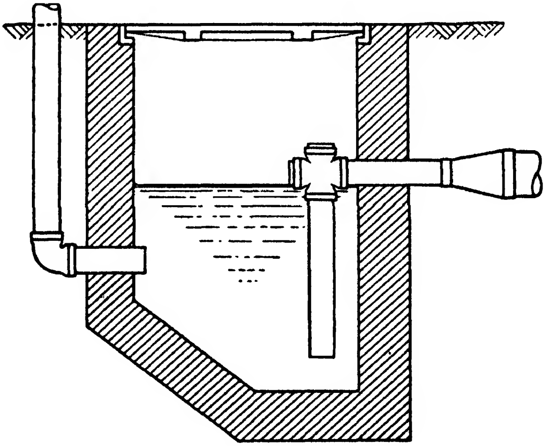

Fig. 1. Grease trap.

Grit may be practically eliminated by screens or by grit chambers. Screens consist of parallel bars, rods or wires, wire mesh, or perforated plates. Coarse screening has openings 1 to 2 in. in size, and medium and fine screening, 1 in. down to ⅛ in.

Grit chambers are concrete containers introduced in the sewer near its inlet for retarding the velocity of the sewage to about 1 ft per sec to permit heavy solid matter to be deposited for convenient removal.

Grease traps for kitchens are described in Chapter 5, Art. 16. For large institutions, hotels, and restaurants they may be of concrete with hopper bottom sunk in the ground near the building. The inlet from the kitchen waste is near the water line near the top of the container, and the outlet has an elbow and a length of pipe projecting downward to within 3 in. of the bottom. The grease solidifies and floats on the top of the sewage. The clearer water is drawn off from the bottom, and the outlet pipe is connected through an increaser to the sewer.

Grit chambers, screens, and grease traps are seldom required for residences but are often necessary for industrial plants, dairies, and barns.

5. Sedimentation. Certain solids are held in suspension by the movement of the liquid in the house sewer. These solids include the coarser particles, which settle with more or less rapidity, and the colloids, which settle very slowly. By bringing the liquid to rest in a tank for a period of time about 60 per cent of the solids will subside to the bottom, and the partially purified water may be led away for final disposal. The tank is a plain sedimentation tank or a septic tank.

6. Sedimentation tanks hold the liquid for 1½ to 4 hr to allow the particles to settle. Gases rising from the decomposing sludge tend to cause turbulence and interfere with the settling action. Hence the tanks are either in one story with frequent removal of the sludge, allowing little time for bacterial action, or in two stories. In the latter case the upper chamber has a hopper bottom which, with the aid of outdoor vents from the lower or sludge chamber, prevents the entrance of gases to the upper story. The sludge may then be removed at longer intervals. The capacity for residences should be one day's flow but not less than 300 gal. The depth should not be less than 5 ft.

7. Septic tanks retain the liquid for 24 hr and the sludge for much longer periods to undergo decomposition by the action of anaerobic bacteria. Private domestic sewage disposal generally employs the septic tank, the sludge being removed only once in 3 years. They are constructed of brick, stone, or concrete with watertight walls and floor and a concrete roof with a manhole and iron cover. The minimum capacity of the settling basin should be sufficient to retain sewage for 24 hours at the rate of 50 to 80 gal per person for residences or institutions. For buildings not occupied at night, such as day schools, with more than 100 occupants, the capacity may be 20 gal per person with a one-half day or 12-hr flow. The minimum area in this case should be at least 0.25 sq ft per capita to present sufficient surface for scum formation, and the minimum depth is 5 ft. Settling chambers are sometimes formed with hopper bottoms.

Septic tanks may have one, two, or three chambers, depending upon local conditions and the required capacity.

(*a*) Those with one chamber are appropriate for small families. Figure 2 illustrates a tank of 180 to 280 gal capacity for 4 to 7 persons.

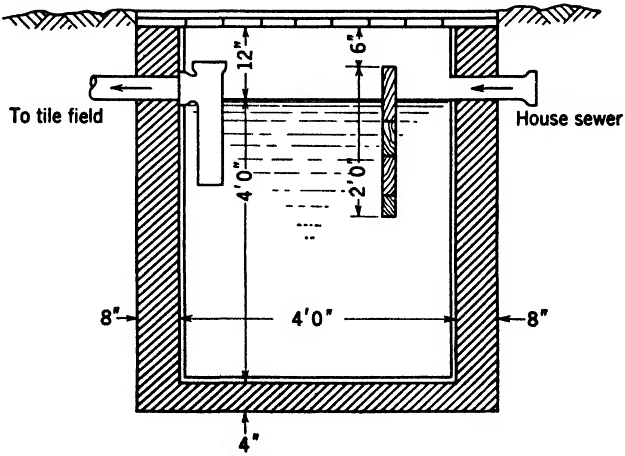

Fig. 2. One-chambered septic tank.

The outlet pipe has an elbow and a length of pipe projecting downward 18 in. below the level of the sewage. A baffle of wood or concrete is fixed across the tank 8 in. in front of the house sewer inlet. In this manner the surface scum is not disturbed, the flow is retarded, and the direct current from inlet to outlet is avoided.

The discharge from a tank of this size may be led to one or more leaching cesspools if the ground is sufficiently porous, otherwise to a tile drainage field.

(*b*) Figure 3 shows a two-chambered tank. In larger installations it is often advantageous to discharge the fluids from the tank in periodic doses rather than by an irregular trickle. For this purpose

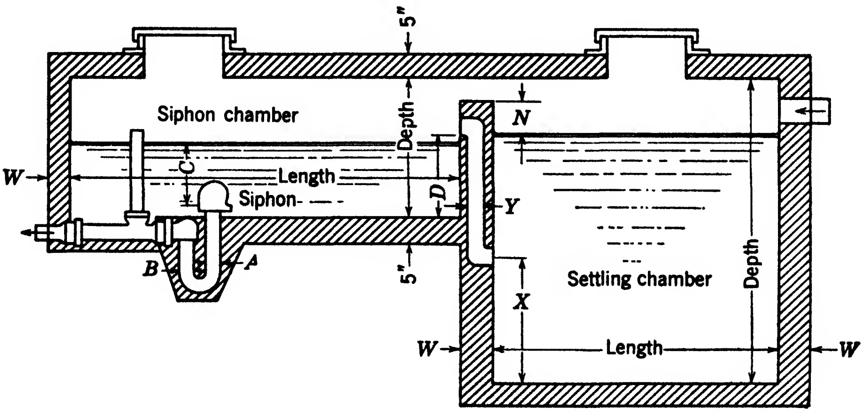

Fig. 3. Two-chambered septic tank.

a siphon is set up in a second chamber separated from the settling chamber by a concrete wall across the tank, reaching to within 6 or 8 in. of the roof. A drop pipe gives a water connection between the two chambers. The siphon can be designed to emit doses of the quantity and at the rate of flow desired.

Table I gives dimensions for two-chambered siphon tanks to serve 5 to 20 persons.

Table I. Dimensions, Two-Chambered Septic Tank

Number of Persons	Sewage in 24 Hours Gal	Settling Chamber							
		Capacity below Flow Line Gal	Length Ft In.	Depth Ft In.	Width Ft In.	*W* In.	*X* Ft In.	*Y* In.	*Z* In.
5	180–280	240	4 0	5 0	2 0	6	2 0	4	6
10	320–480	420	5 0	5 6	2 6	6	2 3	4	6
15	520–680	620	5 6	6 0	3 0	8	2 6	5	8
20	720–960	860	6 0	6 6	3 6	8	2 9	5	8

Number of Persons	Sewage in 24 Hours Gal	Siphon Chamber						
		Length Ft In.	Depth Ft In.	Width Ft In.	*A* In.	*B* In.	*C* In.	*D* In.
5	180–280	5 0	2 8	2 0	3	4	15	18¼
10	320–480	8 0	2 8	2 6	3	4	15	18¼
15	520–680	8 8	2 10	3 0	4	4	17	20¼
20	720–960	10 0	2 10	3 6	4	4	17	20¼

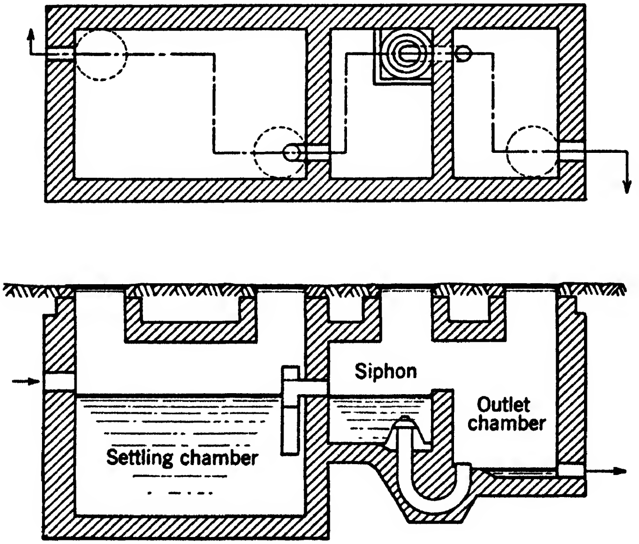

Fig. 4. Three-chambered septic tank.

(*c*) Figure 4 represents a three-part tank divided into settling, dosing, and outlet chambers. It furnishes a slower, more devious flow and greater efficiency.

Example 1. From Table I the size of a septic tank for a building with 15 occupants during 24 hr is found as follows:

Settling chamber	Length 5 ft 6 in., depth 6 ft, width 3 ft
Siphon chamber	Length 8 ft 8 in., depth 2 ft 10 in., width 3 ft
Total	Length 14 ft 2 in., depths 6 ft and 2 ft 10 in., width 3 ft

Example 2. For a larger institution such as a day school with 300 occupants during 12 hr the size of a septic tank may be found as follows:

Capacity of tank = $300 \times 20 \times \frac{1}{2} = 3000$ gal or 400 cu ft
The scum area = $300 \times 0.25 = 75$ sq ft
Assume 5-ft depth and 4-ft width
Area = $400 \div 5 = 80$ sq ft
Length = $80 \div 4 = 20$ ft

The total length is often divided into two equal parts by a cross wall, one part forming the settling chamber and the other part, divided again into halves, forming the siphon or dosing chamber and the outlet chamber.

Although sewage is purified to a very appreciable extent in the septic tank, the water flowing out of the tank is still contaminated and must be further treated before being exposed to the possibility of human contact. The effluent is, consequently, led into cesspools or subsurface tile drains, depending upon the nature and porosity of the soil.

8. Leaching. *Cesspools* or dry wells are underground tanks built with hollow tile, stone, or brick walls laid up in open joints and no mortar, to permit the water to seep through into the soil. The roof is of concrete with a manhole and iron cover and the bottom is of earth. The area of the walls and floor should approximate 15 sq ft per person in coarse soils. Cesspools are satisfactory in small installations when the soil is porous sand or gravel, but in tight clay the earth becomes clogged and the tank soon fills up and overflows. Charges of dynamite are sometimes exploded in the pit before the walls are built and in the surrounding soil to loosen it and to form cracks and fissures for the absorption of water. A second cesspool is sometimes built to relieve the first or to be used alternately with it. Neither a septic tank nor a cesspool should ever be depended upon alone for disposal of sewage. In combination, under suitable conditions, they give good results for years (Fig. 5).

9. Subsurface drainage presents a successful method of oxidizing the water from the septic tank and disposing of it without disagreeable odor or appearance. It consists of lines of drains of 3- or 4-in. agricultural tile without hubs laid in trenches 18 in. deep. The joints

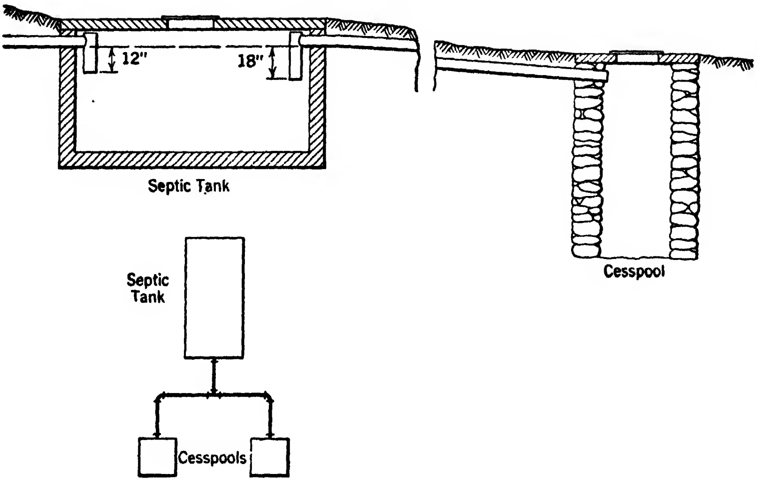

Fig. 5. Septic tank and cesspool.

should be covered on top and sides with strips of tarred paper 6 in. wide with bottom joints left open. The slope is generally 1 in. in 20 ft to allow the water to seep into the soil. When the earth is coarse and absorptive the drain branches or laterals are spaced from 4 to 6 ft apart and the tile is surrounded with 3 or 4 in. of gravel or cinders. Good loam several inches deep is spread over the tile field and seeded.

Because porous, well-drained, air-filled soil is necessary for proper oxidation and seepage of sewage in the tile field, nonporous soils should be broken up by explosive charges or by subsoil ploughing and cultivation to a depth of 3½ to 4 ft. The whole area is first underdrained with 4-in. tile in trenches at the bottom of the subsoiling 10 to 20 ft apart. Distribution tile is then laid in trenches 1¼ to 3 ft deep. All trenches are filled on top of tile with coarse material grading upward to sand and loose loam. The ground may be seeded as before (Fig. 6).

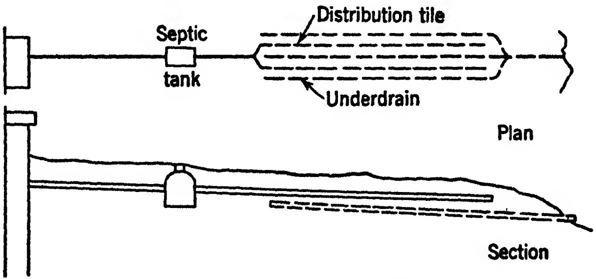

Fig. 6. Underdraining.

10. Design data. The Government publications recommend the following requirements:

Area of tile field should not be less than 100 sq ft per capita or 2 sq ft per gal of daily flow.

The spacing of the tile lines in feet should equal the gallons per capita divided by 10 but should not be less than 5 ft. Their length averages 20 ft but should be determined by percolation tests.

The number of daily discharges should equal the daily flow divided by contents of tile. The latter are given in Table II.

Table II. Contents of Tiles

Diameter (in.)	Volume (gal/ft)
3	0.367
4	0.652
5	1.02
6	1.46

11. Percolation tests are made in holes 1 ft square and 18 in. deep for the fields and one-half the proposed depth for leaching cesspools. The hole is filled with water for a depth of 6 in., and the time consumed by a 1-in. fall of water level is noted. Several holes and several tests should be made in each, and the average result determined. The allowable rates of sewage application and lengths of tile are found with the help of Table III.

Table III. Rates of Application per Square Foot per Day

Time of 1-In. Fall (min)	Rate in Trenches (gal)	Rate in Cesspools (gal)
1	4.0	5.3
2	3.2	4.3
5	2.4	3.2
10	1.7	2.3
30	0.8	1.1
60	0.6	0.8

Example 3. Flow, 750 gal per day. Drop of water, 1 in. in 10 min. Table III shows allowable rate of application in trenches to be 1.7 gal per sq ft per day. Total length of pipe is 750 ÷ 1.7 = 440 ft. For cesspools the total area including the bottom will be 335 sq ft.

12. Dosing or siphon tanks. When the subsurface drainage method is adopted, a secondary tight masonry tank called a dosing tank should be introduced between the septic tank and the tile field. The object is to collect sufficient water to form adequate intermittent doses for distribution throughout the drains instead of a feeble stream trickling from the septic tank. This is accomplished by means of an automatic siphon in the dosing tank which operates when the water reaches a predetermined height and discharges the contents of the dosing tank into the tile field. Each dose should approximately equal in quantity three-quarters of the capacity of the total length of tile. When the length exceeds 1000 ft, the tank should have two siphons, operating alternately, each serving half the field. A special dosing tank is generally not necessary if the septic tank includes a siphon and is near the field.

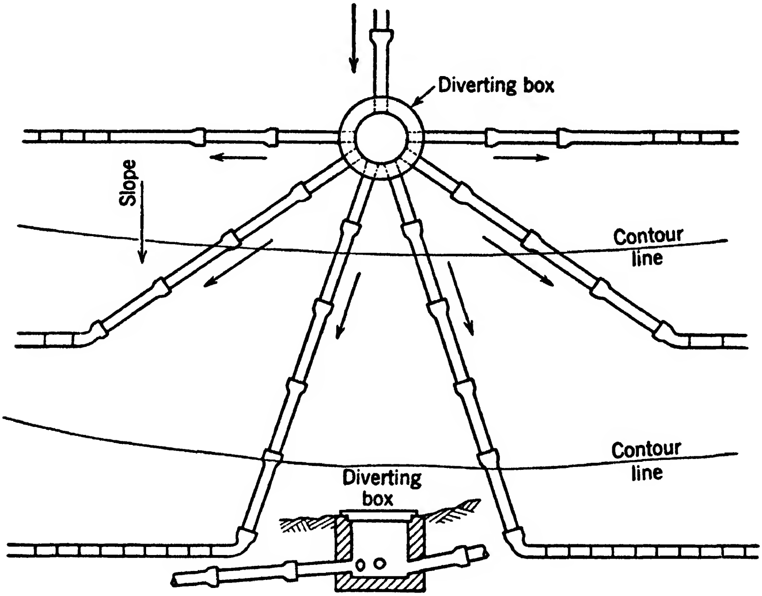

Fig. 7. Distribution on steep slopes.

13. Sludge removal. Sludge is the solid matter resistant to further disintegration which remains in the septic tank after bacterial action. It contains a large amount of liquid, is malodorous, and unless removed periodically will pass solids on into the cesspools and tile fields. Although clearing has been delayed for longer periods, best results require sludge removal every 3 years. The least disagreeable method is to drain off the sludge from the bottom of the tank through an 8-in. valved pipe to a pit, where the liquid portion soaks into the soil and the solids are devoured by worms. The sludge should be treated with chlorine water and the pit then filled with earth. If the ground slopes away from the septic tank this drainage method may be installed without great expense for excavation. If not drained away the sludge is bailed out by hand, chlorinated, and buried in pits or trenches. In both methods the pits and trenches should be so located that water supplies cannot be contaminated by seepage from them.

14. Choice of field. As already stated, the character of the soil, whether coarse and porous, sandy and gravelly, or relatively impervious and clayey, determines the method of distribution of the liquids after leaving the septic tank. If the soil is porous and the amount of sewage relatively small, cesspools are indicated. They should be constructed in duplicate so that one cesspool and the earth surrounding it may dry out and receive fresh supplies of oxygen while the other is in use. For larger installations or when the soil is less porous, the tile field with 18-in. trenches may be employed, this method offering more freedom of distribution than the cesspools. For impervious soils collection drains in deep trenches with sand filters and distributing cross-drains above them, as described in Art. 9, are satisfactory. The efficiency of tile fields is increased by the use of solid wood gates to divert the flow into one or another part of the field successively, thus allowing

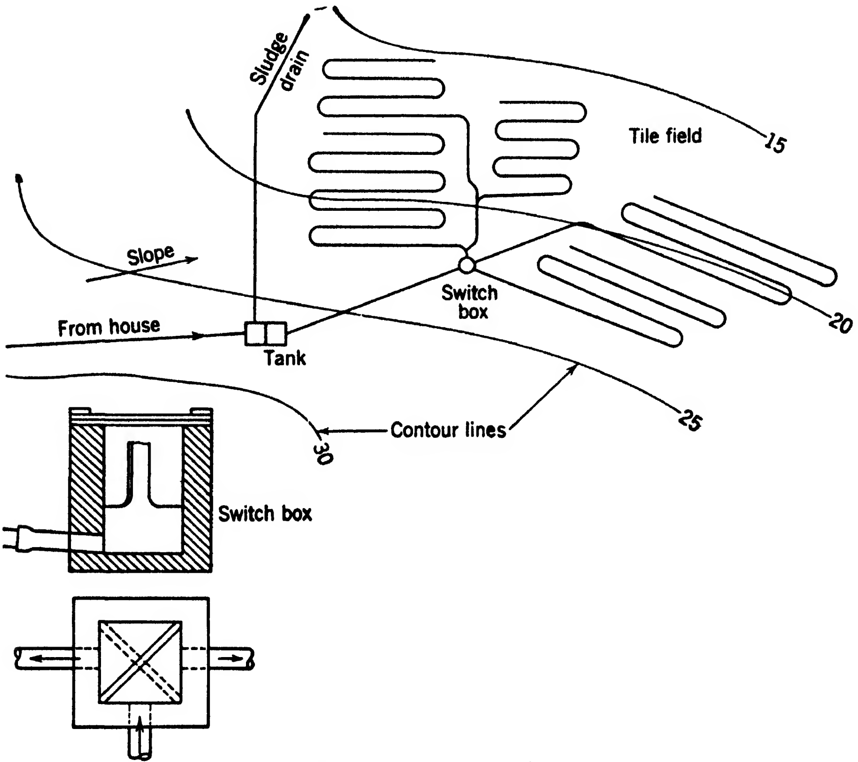

Fig. 8. Tile field on slopes.

periods of rest between doses. Excavation is saved when naturally sloping ground can be chosen so that sewage will flow by gravity through the various stages and away from any water supply. The flow in the distributing tile must be slow, however, so that the seepage will be adequate. The tile field must, therefore, be fairly flat if the tile lines are to follow the slope. When the slope of the field is too great the tile is laid across the slope as shown in Figs. 7 and 8.

15. Dilution. The indiscriminate dumping of sewage into small streams and bodies of water is a most reprehensible practice and has caused not only disgusting nuisances but also the spread of epidemics and disease. Domestic sewage should be so discharged only when the body of water, such as a harbor, a lake, or a river, is of a size to dilute the sewage sufficiently to avoid sludge banks and the contamination of water supplies, oyster beds, and bathing beaches. Disposal by dilution is most common at the seashore, and the action of tides and currents should be known before the drains are installed, the local authorities always being consulted. The house sewer should extend some distance beyond low-tide mark, and several openings are recommended for good distribution through the water. A check valve is often connected in the sewer to stop backflow. The changes are similar to those in the septic tank, the liquids being oxidized by the air in the water and the sediment sinking to the bottom where it is broken down by anaerobic bacteria. In proper functioning, the sludge should not be banked at the discharge but be thinly scattered and no floating matter should appear.

REFERENCE

"Architectural Graphic Standards" (for private sewage disposal), Ramsey and Sleeper, John Wiley & Sons, New York, 1951.

PROBLEMS

1. (*a*) What general principles and what basic processes are involved in sanitary sewage disposal? (*b*) What is the composition of sewage and what are the actions of aerobic and anaerobic bacteria?

2. Describe the design and functioning of (*a*) sedimentation tanks, (*b*) cesspools.

3. (*a*) Describe the design and functioning of septic tanks of three different types. (*b*) How and for what purposes are siphons used in sewage disposal?

4. Describe subsurface drainage, tile fields, and dosing tanks.

5. Draw in plan and section a complete sewage disposal plant for a residence with 9 occupants. Include pipe and tile sizes and dimensions of septic tank and tile field.

6. What portion of sewage is represented by organic and mineral solids?

7. Describe grit removal in sewage treatment.

8. For what type of drainage are grease traps most used?

9. Numerically what area of drain field is required for a given occupancy or daily rate of flow?

10. Describe percolation tests.

SECTION III HEATING

Chapter 9

PROPERTIES AND TRANSMISSION OF HEAT

1. Heat is a form of kinetic energy conceived to be expressed by the molecular motion within a substance, solid, liquid, or gaseous. The more violent the motion of the molecules and the less cohesion between them, the greater is the intensity of the heat (Chapter 17, Art. 2).

Since the molecules of higher kinetic energy will transmit a part of their energy to adjacent molecules of lower kinetic energy, heat transfer will occur from higher to lower intensities. An illustration is the passage of heat through a wall from a room at 70°F to the outside air at 40°F. If the room and the outdoor air were both at 70°F, no potential difference would exist to cause the flow of heat and no heat would be transferred. Heat is measured in intensity in units of temperature and in quantity by units of heat.

2. Intensity. Temperature may also be considered as representing the violence of the molecular motion. Two scales of measurement are in general use. On the Fahrenheit scale the melting point of ice is taken at 32° and the boiling point of water at 212°, the scale of the thermometer between these points being graduated in 180 degrees. Zero on this scale was supposed by Fahrenheit in 1714 to represent the lowest temperature obtainable in the laboratory.

The centigrade scale was devised in 1742 by Celsius of Sweden. On this scale the melting point of ice and the boiling point of water are represented by 0° and 100°, respectively, and the scale between is graduated in 100 parts or degrees. Centigrade thermometers are used in most scientific work in the United States and for all purposes in countries adopting the metric system of measurement. The Fahrenheit scale is the common household thermometer in England and the United States and is in general use in the design of heating and ventilating systems. A difference of 5 centigrade degrees equals a difference of 9 Fahrenheit degrees. Hence, if t_c = centigrade temperature and t_f = Fahrenheit temperature,

$$t_c = \tfrac{5}{9}(t_f - 32^\circ) \qquad \text{and} \qquad t_f = (\tfrac{9}{5}t_c) + 32^\circ$$

Temperatures cited in this textbook always refer to the Fahrenheit scale.

3. Quantity. Heat, not being a substance, cannot be measured as to quantity by pounds or cubic feet but must be measured by the effect it produces. It requires a certain quantity of heat to raise 1 lb of water from 32 to 212° in temperature. It therefore would require an average of $\frac{1}{180}$ of this quantity to raise 1 lb of water 1°. This quantity of heat, called the British thermal unit or Btu, is used in this country and in England as the unit of quantity.

4. Passage of heat. Heat passes from bodies of higher to those of lower temperature by means of conduction, convection, or radiation, or by combinations of these means. The quantity transmitted is usually expressed in Btu per hour per square foot of area per degree of temperature difference between outer and inner surfaces, or between a surface and the air.

(*a*) *Conduction* is a transfer of heat energy from particle to particle in the same body or between bodies in close contact in any direction. Materials differ greatly in their ability to conduct heat, and the rate of flow varies with the character of the material, its thickness, and the temperature difference. The transfer of heat from the hot end of an iron bar to the cooler end or from a warm room to the cold outside air through a wall or a pane of glass is an example of conduction.

Conductivity (k) refers to the ability of a homogeneous substance such as wood, brick, or stone to conduct heat per inch of thickness.

Conductance (C) is the rate of heat flow from surface to surface of a material which may be homogeneous or heterogeneous.

Film or *surface conductance* (f) is the rate of heat flow between a surface and the surrounding air.

Air space conductance (a) is the rate of heat flow through an air space per unit of temperature difference between the boundary surfaces.

(*b*) *Convection* is the process of receiving and transporting heat by the flow of liquids or gases after contact with a heated source. Heat passes to the fluid by conduction, the density of the fluid is reduced, it expands and is forced to rise carrying heat by convection, and colder particles take its place. Heating by convection consequently causes a movement in the liquid or gas: the higher the velocity, the greater is the rate of heat transmission. The shape of the source affects the heat losses since it influences the rate of flow, as is seen in the design of radiators and boilers. The flow is sometimes increased by the use of pumps or fans. Heat may also be transmitted from warm room air to cold bodies, in which case the air becomes more dense and falls, warmer air taking its place from above.

Transferring heat from hot boiler tubes and fire boxes to water and air, causing them to rise through pipes and ducts, is an example of transporting heat by convection. The loss of heat from warm room air to cold window panes, causing the air to fall, is also an example of convection and explains the draught of air sometimes felt in the vicinity of even the tighest windows.

(*c*) *Radiation.* Rays of heat flow forth from all bodies and are received by other bodies of lower temperature much as rays of light are emanated and received. Heat rays flow in a straight line and their emission depends upon the nature of the radiating surface and the temperature difference. The intensity received by a body varies inversely as the square of the distance from the source to the body. Some substances, such as dry gases and glass, are transparent to radiant heat; that is, the rays pass through them without appreciably warming them and are not radiated. Other substances, such as water, iron, and wood, absorb and store the rays, are warmed by them, and radiate them. Pure air is not perceptibly influenced by radiant heat, but air containing water vapor or dust will absorb some heat. Smooth and light-colored objects usually absorb heat slowly and are good reflectors; rough or dark objects absorb heat more freely and are good radiators. In general, materials will radiate the amount of heat that they have absorbed with reversed temperature differences. The sun's rays and the heat emanating from a lamp, radiator, or open fire are examples of radiant heat.

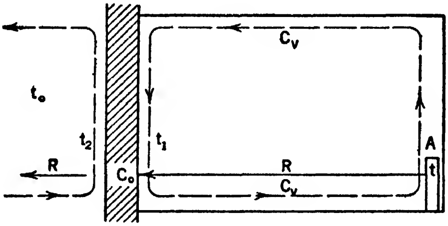

Fig. 1. Heat transmission.

Figure 1 shows the three ways of heat transmission. Let *A* represent a radiator or stove with a temperature *t*. The air next to the stove will be heated by conduction; it will rise and circulate by convection until it comes in contact with the colder outside walls where it gives up a certain amount of heat to the wall, drops, and returns to the source to be reheated. Radiant heat likewise flows from the stove or radiator in a straight line to the wall. Through radiation and convection the inner surface of the wall is thus raised to a temperature t_1, higher than the outer face of the wall. Heat will then be transmitted by conduction through the wall, producing a temperature t_2 at its outer face where it is dissipated to the outdoor air partly by convection and partly by radiation. t_1 is lower than t and t_2 lower than t_1. t_o, outside air, lower than t_i, inside air. C_v = convection. C_d = conduction. R = radiation.

5. Heat losses. Heat is lost from a building in two ways: (*a*) by direct transmission through the walls, roof, and floor; and (*b*) by infiltration through the cracks around windows and doors. The total loss is the sum of the heat escaping by direct transmission and by infiltration.

6. Transmission. The capability of a substance to transmit heat is retarded by certain thermal properties of the substance known as resistances. Since these resistances vary widely according to the composition of the substance, the heat transmissions of different substances will also vary widely. The total resistance in any substance will be the sum of the individual resistances of the components of the substance, or

$$R_T = R_1 + R_2 + R_3 + \cdots + R_n$$

Heat flow (*H*) is therefore inversely proportional to the resistance and directly proportional to the temperature difference, or

$$H = \frac{1}{R_T} \times (t_i - t_o)$$

where t_i = indoor temperature; t_o = outdoor temperature, and conductance is the reciprocal of resistance, or

$$C_T = \frac{1}{R_T} = \frac{1}{R_1 + R_2 + R_3 + \cdots + R_n}$$

where C_T = total conductance; R_T = total resistance; R_1, R_2, R_3, etc. = component resistances.

7. Losses by transmission. Because materials differ so widely in their resistances to the flow of heat and consequently in their capabilities to transmit heat, coefficients of transmission in Btu have been determined by tests for a large number of building materials such as masonry, wood, glass, and insulators.

These individual coefficients have also been united in overall coefficients of heat transmission designated by U, which combine the coefficients of the various elements of a construction together with the surface coefficients as consistent with the conditions. U designates the amount of heat in Btu transmitted in 1 hr by 1 sq ft of surface for each degree of temperature difference between inside and outside air. Its value may be determined by tests or computed from known coefficients of the various elements. U is the reciprocal of the total resistance R_T, or $U = 1/R_T$.

The amount of heat in Btu, H, transmitted in 1 hr by a wall or roof will depend upon its area A, its overall coefficient of transmission U, and the temperature difference between inside and outside air $(t_i - t_o)$, or

$$H = AU\,(t_i - t_o) \tag{1}$$

U has the same value for heat loss in winter heating calculations with a temperature difference of $(t_i - t_o)$ as for heat gain in summer cooling with a difference of $(t_o - t_i)$.

Surface or film *transmission* is effected through a combination of conduction, radiation, and convection. The amount of heat transferred depends upon a variety of conditions such as the nature of the surface, air movement over the surface, and temperature difference. Consequently, there may be variations in the conductance coefficients, f_i and f_o. Experience has shown that 1.65 for inside film coefficient (f_i) with still air and 6.0 for outside film coefficient (f_o) with 15-mile wind velocity are acceptable averages for practical purposes. (See Table VIII.)

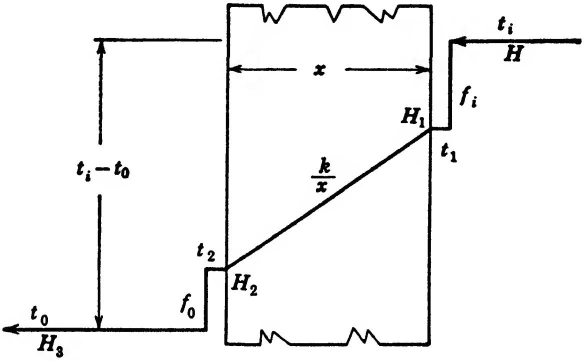

Fig. 2. Heat transmission through a wall.

The amount of heat transferred *across air spaces*, as between rafters or studs, depends upon the nature of the surface, the depth and shape of the space, and the temperature differences between the boundary surfaces. A generally adopted average coefficient, a, is 1.10 for unlined spaces. The larger part of the heat is transferred by radiation. Therefore, linings of low heat emission and high reflection, such as aluminum foil with an emissivity of 0.05, are in use, which reflect back the radiant heat to a substantial degree and prevent it from entering the surface so lined. The remaining heat transferred is largely due to conductance, for which a coefficient of 0.46 is recommended for vertical, horizontal, and sloping air spaces.

If a wall or roof is constructed of one homogeneous material of conductivity k and thickness in inches x with surface coefficients f_i and f_o, then

$$R_T = \frac{1}{f_i} + \frac{x}{k} + \frac{1}{f_o} \qquad \text{and} \qquad U = \frac{1}{R_T} = \frac{1}{\frac{1}{f_i} + \frac{x}{k} + \frac{1}{f_o}} \tag{2}$$

For a wall or roof built up of several materials with one or more air spaces between them Formula 3 applies:

$$U = \frac{1}{\frac{1}{f_i} + \frac{1}{f_o} + \frac{1}{a} + \frac{x_1}{k_1} + \frac{x_2}{k_2} +, \text{ etc.}} \tag{3}$$

where a = conductance of the air space.

Example 1. Compute the overall coefficient of transmission (U) for a wood frame wall with 1-in. fir sheathing, building paper, and yellow pine lap siding on outside of studs, air space between studs, and wood lath and plaster on inside of studs.

By consulting Table I the component coefficients are found for substitution in Equation 3. Then

$$U = \frac{1}{\frac{1}{1.65} + \frac{1}{6} + \frac{1}{1.10} + \frac{1}{0.50} + \frac{1}{2.50}}$$

$$U = \frac{1}{0.606 + 0.167 + 0.9 + 2.0 + 0.4} = 0.245, \text{ say } 0.25$$

$U = 0.25$ Btu per hour per sq ft per degree difference in temperature between the air on the two sides.

Inside Surface Temperatures. The formula for determining the temperature of surfaces inside a building is based upon the ratio between the resistance from the inside air to the surface and the overall resistance of the wall from inside air to outside air. Thus

$$\frac{R_1}{R_2} = \frac{(t_i - t)}{(t_i - t_o)} \tag{4}$$

where R_1 = resistance of inside air; R_2 = resistance of wall; t_i = inside air temperature; t_o = outside air temperature; t = required temperature.

Example 2. Find the inside surface temperature for a wall with 70° inside air temperature and 0° outside air temperature. Overall coefficient of wall, $U = 0.25$.

$$R_1 = \frac{1}{f_1} = \frac{1}{1.65} = 0.606 \quad R_2 = \frac{1}{U} = \frac{1}{0.25} = 4.0$$

Table I. Conductivities and Conductances of Building Materials *

Materia	Conductivity or Conductance	
	k	*C*
Exterior finishes		
Brick veneer, 4 in.		2.27
Stucco, 1 in.	12.50	
Wood shingles		1.28
Y.P. lap siding		1.28
Fir sheathing, paper and siding		0.50
Insulating materials		
Bats and blankets, mineral wool	0.27	
Cork board	0.30	
Insulating board, fiber	0.33	
Loose mineral wool	0.27	
Masonry materials		
Brick, common		1.25
Brick, face		2.30
Cement mortar	12.00	
Clay tile, hollow, 4 in.		1.00
Clay tile, hollow, 8 in.		0.60
Clay tile, hollow, 12 in.		0.40
Concrete, lightweight	2.50	
Concrete, sand and gravel	12.00	
Concrete block, cinder, 4 in.		1.00
Concrete block, cinder, 8 in.		0.60
Concrete block, gravel, 8 in.		1.00
Concrete block, gravel, 12 in.		0.80
Concrete block, lightweight, 8 in.		0.50
Gypsum tile, hollow, 4 in.		0.46
Tile and terrazzo floor	12.00	
Roofing materials		
Asbestos shingles		6.00
Built-up roofing		3.53
Heavy roll roofing		6.50
Slate	10.00	20.00
Wood shingles		1.28
Sheathing		
Insulating board, $^{25}/_{32}$ in.		0.42
Fir or yellow pine, $^{25}/_{32}$ in.		1.02
Interior finishes		
Gypsum plaster	3.30	
Gypsum lath and plaster		2.40
Insulating board and plaster		0.60
Metal lath and plaster		4.40
Wood lath and plaster		2.50

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 180.

From Equation 4,

$$\frac{0.606}{4.0} = \frac{70 - t}{70 - 0}; \quad t = 59.4°$$

Tables II to X, showing the values of U for several frequent combinations, are derived by means of Table I and Equation 3.

Insulating board refers to stiff panels of insulating material which may be used as sheathing or as a base for plastering. Bats and blankets refer to flexible containers of insulating material, such as mineral wool or vegetable fiber, placed between studs, joists, and rafters. U = Btu per hour per square foot of surface per degree temperature difference. Outside wind velocity, 15 miles per hr.

8. Losses by infiltration. Outside air may leak into a building through the material of the walls and through the cracks around doors

Table II. Coefficients of Transmission (U) of Frame Walls *

Exterior Finish	Interior Finish	Type of Sheathing					
		$^{25}/_{32}$-in. Wood, Building Paper			Insulating Board $^{25}/_{32}$ in.		
		Uninsulated between Framing	Blanket or Bat 2-in. Mineral Wool or Fiber	Loose Mineral Wool	Uninsulated between Framing	Blanket or Bat 2-in. Mineral Wool or Fiber	Loose Mineral Wool
Wood siding or clapboard	Metal lath and plaster	0.26	0.096	0.072	0.20	0.086	0.066
	Wood lath and plaster	0.25	0.094	0.071	0.19	0.084	0.065
	Insulating board, 1 in., plaster	0.15	0.075	0.059	0.12	0.067	0.053
Wood shingles	Metal lath and plaster	0.21	0.088	0.067	0.17	0.080	0.062
	Wood lath and plaster	0.20	0.086	0.066	0.160	0.078	0.060
	Insulating board, 1 in., plaster	0.13	0.070	0.055	0.110	0.063	0.051
Stucco	Metal lath and plaster	0.32	0.10	0.077	0.23	0.091	0.069
	Wood lath and plaster	0.30	0.10	0.075	0.22	0.089	0.068
	Insulating board, 1 in., plaster	0.16	0.078	0.060	0.14	0.072	0.057
Brick veneer, 4 in.	Metal lath and plaster	0.28	0.098	0.073	0.21	0.088	0.067
	Wood lath and plaster	0.27	0.097	0.073	0.20	0.086	0.066
	Insulating board, 1 in., plaster	0.15	0.075	0.059	0.13	0.070	0.055

⅜-in. gypsum lath and plaster same as wood lath and plaster.

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 180.

Table III. Coefficients of Transmission (*U*) of Masonry Walls *

	Interior Finish					
Type of Masonry	Plain Walls, No Finish	Plaster (½ in.) on Walls	Metal Lath Plastered, Furred	Gypsum Lath (⅜ in.) Plastered, Furred	Insulating Board (½ in.) Plastered, Furred	Gypsum Lath Plastered plus 1-in. Blanket Insulation, Furred
8-in Solid brick	0.50	0.46	0.32	0.31	0.22	0.14
12-in. Solid brick	0.36	0.34	0.25	0.24	0.19	0.13
4-in. Brick, 8-in. hollow tile	0.34	0.32	0.25	0.23	0.18	0.13
4-in. Brick, 8-in. cinder concrete block	0.34	0.33	0.25	0.24	0.18	0.13
4-in. Cut stone, 8-in. hollow tile	0.36	0.34	0.25	0.24	0.19	0.13
12-in. Poured concrete	0.57	0.53	0.35	0.33	0.23	0.15
12-in. Hollow tile, stucco	0.30	0.28	0.22	0.21	0.17	0.12
12-in. Hollow concrete blocks, gravel	0.49	0.46	0.32	0.30	0.22	0.14
12-in. Hollow concrete blocks, cinder	0.38	0.36	0.26	0.25	0.19	0.13
12-in. Hollow concrete blocks, lightweight †	0.34	0.33	0.25	0.24	0.18	0.13

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 188.

† Expanded slag, burned clay, or pumice.

Table IV. Coefficients of Transmission (*U*) of Wood Frame Partitions *

Type of Wall	Air Space between Studs	2-in. Mineral Wool Bats between Studs	Loose Mineral Wool Fill
Wood lath plastered	0.34	0.10	0.078
Metal lath plastered	0.39	0.11	0.081
⅜-in. Gypsum lath plastered	0.34	0.10	0.078
½-in. Insulating board plastered	0.18	0.082	0.063

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 190.

Table V. Coefficients of Transmission (*U*) of Masonry Partitions *

Type of Wall	Plain Wall No Plaster	Plastered One Side	Plastered Both Sides
4-in. Hollow clay tile	0.45	0.42	0.40
4-in. Common brick	0.50	0.46	0.43
4-in. Hollow gypsum tile	0.29	0.28	0.27
2-in. Solid plaster			0.53
4-in. Hollow cinder tile	0.45	0.42	0.40
4-in. Lightweight tile	0.35	0.34	0.32

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 190.

Table VI. Coefficients of Transmission (*U*), Frame Ceilings and Floors *

	No Flooring on Joists			Flooring on Joists		
Type of Ceiling	No Insulation at Joists	4-in. Loose Mineral Wool Insulation between Joists	2-in. Bat Insulation between Joists	Single Wood Floor, No Insulation	Double Wood Floor, No Insulation	Double Wood Floor, 2-in. Bat Insulation between Joists
Metal lath and plaster	0.69	0.077	0.12	0.30	0.25	0.094
Wood lath and plaster	0.62	0.076	0.12	0.28	0.24	0.093
⅜-in. Gypsum lath, plastered	0.61	0.076	0.12	0.28	0.24	0.093
1-in. Insulating board, plastered	0.23	0.081	0.089	0.16	0.14	0.072

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 191.

Table VII. Coefficients of Transmission (*U*), Concrete Ceilings and Floors *

3-in. Concrete Slab Type of Ceiling	No Flooring, Concrete Bare	Tile or Terrazzo Flooring on Concrete	Parquet Flooring in Mastic on Concrete	Double Wood Flooring on Sleepers
No ceiling	0.68	0.65	0.45	0.25
½-in. Plaster, applied to concrete slab	0.62	0.59	0.43	0.24
Metal lath, plastered, suspended, or furred	0.38	0.37	0.30	0.19
⅜-in. Gypsum board plastered, suspended, or furred	0.36	0.35	0.28	0.19
½-in. Insulating board, plastered, suspended, or furred	0.25	0.24	0.21	0.15

For concrete floors on ground, *U* is generally taken as 0.10. For small areas heat loss may be calculated as proportional to the length of the exposed edge of the floor rather than the total area. The loss is 0.81 Btu/hr/linear ft of edge/degree, difference in temperature, room air and outside air which can be reduced by insulation.

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 192.

Table VIII. Coefficients of Transmission (*U*), Flat Roofs with Built-Up Roofing *

Type of Roof Deck	No Ceiling						Wood or Metal Lath-Hung Ceiling					
	No Insulation		Insulation on Top of Deck				No Insulation		Insulation on Top of Deck			
			1-in. Insulating Board		2-in. Insulating Board				1-in. Insulating Board		2-in. Insulating Board	
	W	*S*	*W*	*S*	*W*	*S*	*W*	*S*	*W*	*S*	*W*	*S*
1-in. Precast Tile	0.84	0.67	0.24	0.22	0.14	0.13	0.43	0.38	0.19	0.18	0.12	0.12
2-in. Concrete	0.82	0.65	0.24	0.22	0.14	0.13	0.42	0.37	0.19	0.18	0.12	0.12
4-in. Concrete	0.72	0.59	0.23	0.21	0.13	0.13	0.40	0.36	0.18	0.17	0.12	0.12
1-in. Wood	0.49	0.43	0.20	0.19	0.12	0.12	0.31	0.29	0.16	0.15	0.11	0.11
2-in. Wood	0.32	0.29	0.16	0.16	0.11	0.11	0.24	0.22	0.14	0.13	0.09	0.09

W = Winter coefficient based on outside conductance of 6.0 for 15-mile wind velocity and inside conductance of 1.65.

S = Summer coefficient based on outside conductance of 4.0 for 7.5-mile wind velocity and inside conductance of 1.20.

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, pages 193–194

and window sash. Tests show that proper workmanship, insulation, and plastering reduce the infiltration through the walls themselves to such an extent that it can be neglected, but that the leakage between window sash or doors and their frames is sufficiently large to require careful attention. Wind velocity increases this leakage and, in very important work, the U. S. Weather Bureau reports for the locality should be consulted for the average wind velocity during the three winter months. Tables based upon tests have been prepared giving the air leakage in cubic feet per hour per foot of crack for various wind velocities.

Leakage values for a well-fitted door may be taken as that for a poorly fitted double-hung window, for a poorly fitted door twice, and for a weatherstripped door one-half this value.

From these tables the total quantity of infiltrating air per hour is determined by measuring the lengths of the cracks. With double-hung sash the length of the meeting rail is the same as the width of the window. The total length of crack for one window therefore equals 3 times the width plus 2 times the height of the sash. In measuring the amount of crack to be used for computations, the following method is recommended by the ASHVE:

Table IX. Coefficients of Transmission (U), Pitched Roofs *

Type of Ceiling Applied to Roof Rafters	Wood Shingles on 1 × 4 Wood Strip		Asphalt Shingles or Roll Roofing on Wood Sheathing		Slate, Tile, or Asbestos Shingles on Wood Sheathing	
	Insulation between Rafters					
	None	2-in. Bat	None	2-in. Bat	None	2-in. Bat
No ceiling on rafters	0.48	0.10	0.52	0.11	0.55	0.11
Metal lath and plaster	0.31	0.10	0.33	0.10	0.34	0.10
Wood lath and plaster	0.29	0.10	0.31	0.10	0.32	0.10
⅜-in. Gypsum lath, plastered	0.29	0.10	0.31	0.10	0.32	0.10
1-in. Insulating board, plastered	0.16	0.078	0.10	0.079	0.17	0.066

Combined coefficients for pitched roofs with horizontal ceilings below them are found by the following formula:

$$U = \frac{U_r \times U_c}{U_r + \frac{U_c}{n}}$$

where U = combined coefficient to be used with ceiling area.
U_r = coefficient of transmission for roof.
U_c = coefficient of transmission for ceiling.
n = ratio of roof area to ceiling area.

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 195.

Room with one exposed wall: Use all the cracks

Room with two, three or four exposed walls: Use wall with most cracks

But in no case use less than one-half the total cracks in the room. The usual wind velocities employed are 10 and 15 miles per hr.

The chimney effect in tall buildings arises from the fact that at the bottom of the building cold outer air enters against the lesser pressure of the warm inner air, the temperature difference and stack effect producing a head which will increase the effect of the wind at lower

Table X. Coefficients of Transmission (U), of Doors, Windows, Skylights, and Glass-Block Walls *

Windows and Skylights	U	Single 1.13	Double 0.45	Triple 0.28

	Nominal Thickness (in.)	Actual Thickness (in.)	U Exposed Door	U with Glass Storm Door
(*a*) Solid wood doors	1¼	1 1/16	0.59	0.32
	1½	1 5/16	0.52	0.30
	1¾	1⅜	0.51	0.30
	2	1⅝	0.46	0.28
	2½	2⅛	0.38	0.25

	Number of Sheets	One	Two		Three	
(*b*) Vertical glass sheets	Air space, in.	None	¼	½	¼	½
	U	1.13	0.61	0.55	0.41	0.36

	Number of Sheets	One	Two	
(*c*) Horizontal glass sheets	Air space, in.	None	¼	½
	U	1.40	0.70	0.66

	Description	U
(*d*) Walls of hollow glass blocks	5¾ × 5¾ × 3⅞	0.60
	7¾ × 7¾ × 3⅞	0.56
	7¾ × 7¾ × 3⅞, with glass fiber screen in cavity	0.48

For cooling problems in summer, U for single glass is often taken as 1.04.

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 197.

Table XI. Infiltration through Windows *

Cubic Feet of Air per Foot of Crack per Hour

Type	Description	Wind Velocity (miles per hour)				
		5	10	15	20	25
Unlocked double-hung wood sash and frame	Masonry wall, around uncaulked frame	3.0	8.0	14.0	20.0	27.0
	Masonry wall, around caulked frame	1.0	2.0	3.0	4.0	5.0
	Wood wall, around frame	2.0	6.0	11.0	17.0	23.0
	Sash cracks, 1/16-in. crack, 3/64-in. clearance					
	Not weatherstripped	7.0	21.0	39.0	59.0	80.0
	Weatherstripped	4.0	13.0	24.0	36.0	40.0
Double-hung metal sash	Not weatherstripped, locked	20.0	45.0	70.0	96.0	125.0
	Not weatherstripped, unlocked	20.0	47.0	74.0	104.0	137.0
	Weatherstripped, unlocked	6.0	19.0	32.0	46.0	60.0
Rolled section steel sash	Industrial pivoted, 1/16-in. crack	52.0	108.0	176.0	244.0	304.0
	Residential casement, 1/64-in. crack-hinged	6.0	18.0	33.0	47.0	60.0
	Heavy casement projected, 1/32-in. crack	8.0	24.0	38.0	54.0	72.0
Hollow metal	Vertically pivoted sash	30.0	88.0	145.0	186.0	221.0

72-in. Revolving doors: Infrequent usage, 75 cu ft per person per passage.
Average usage, 60 cu ft per person per passage.
Heavy usage, 40 cu ft per person per passage.
36-in. Swinging doors: 100 cu ft per person per passage.

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levels. The warm inner air rises under pressure and, seeking to escape near the upper levels, opposes the infiltration due to wind velocity. If it be assumed that a neutral zone exists at the midheight of the building, a lower wind velocity may be used in computing the infiltration above the zone than that employed below it. The following formulae are applicable for Table XI:

$$V_e = \sqrt{V^2 - 1.75a} \tag{5}$$

$$V_e = \sqrt{V^2 + 1.75b} \tag{6}$$

where V_e = equivalent wind velocity; V = wind velocity if chimney effect is disregarded; a = distance in feet of window above midheight; b = distance in feet of window below midheight. The coefficient 1.75 allows for one-half head resulting from an outside and inside temperature difference of 70°. In very tall buildings negative infiltration has been found to exist in the upper stories. The chimney effect should be avoided as far as possible by sealing off stair wells and elevator shafts by solid self-closing doors.

9. Air-change method. For approximations the method of air changes may be used in calculating losses by infiltration. By this method a certain number of complete changes of air content by infiltration per hour for each room is assumed, the number of changes depending upon the type and exposure of the room.

The quantity of infiltrating air having been determined, the amount of heat in Btu required to raise the air to the desired temperature is then calculated. For air-crack method,

$$H = 0.018 \times \text{Cubic feet per hour} \times (t_i - t_o) \tag{7}$$

For air-change method,

$$H = 0.018 \times \text{Cubic contents} \times (t_i - t_o) \times \text{Change per hour} \tag{8}$$

in which $0.018 = 0.24 \times 0.075$. 0.24 = specific heat of air, Btu per pound; 0.075 = density of air, pounds per cubic foot.

Table XII. Air Changes per Hour *

Average wind velocity, 15 mi per hr

Rooms, no windows or outside doors	½ to ¾
Rooms, exposure 1 side	1
Rooms, exposure 2 sides	1½
Rooms, exposure 3 sides	2
Rooms, exposure 4 sides	2
Entrance halls	2 to 3
Reception halls	2
Bathrooms	2
Stores	1 to 3

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 223.

10. Calculation of heat losses. The desired inside temperature and probable outside temperature are first estimated. The comfortable inside temperature depends upon the use of the room and the amount of moisture and air movement. With a relative humidity of 30 per cent a dry-bulb temperature of 70°F is assumed.

Outside temperatures should represent the most unfavorable conditions likely to happen in the locality. Because the lowest temperature recorded by the U. S. Weather Bureau Reports is of short duration and is rarely repeated, a temperature 15° above the lowest recorded is generally assumed. In Philadelphia, New York, and Boston 0° is commonly used in practice. In the South higher, and in the Northwest lower, temperatures would naturally be chosen.

Not only the outdoor temperature as affecting outside walls is considered in computations but also the temperature of any adjoining building space as affecting the losses through interior partitions, floors, ceilings, and roofs. If the temperatures of unheated rooms at the side, below, and above the room in question are unknown, they are usually taken at a mean between the desired and the outdoor temperatures, or at 35° for inside and outside temperatures of 70° and 0°, respectively. For great accuracy a factor of transmission (U) may be determined for an unheated attic without dormer windows or skylight by combining the factors for the roof and the room ceiling. In common practice, however, unheated attics, especially those with dormer windows, ventilators, or vertical walls, are considered as approximately the outside air in temperature. Unheated basements may be assumed to be at 32°, and the earth under the floor of a heated space at 50°.

To determine the total heat per hour in Btu to be supplied to balance the amount lost and to maintain the building at the desired temperature, the losses for each room, hall, vestibule, or other space are computed separately, and their sum denotes the total heat required. The procedure follows:

(*a*) Select the inside temperature desired in coldest weather.

(*b*) Assume an average minimum outdoor temperature.

(*c*) Select from table coefficients of transmission for glass and for materials of outside walls and roofs and of inside floors, ceilings, and partitions.

(*d*) Measure the areas of glass, walls, floors, ceilings, and roofs involved. Compute the transmission losses by multiplying the areas in square feet by the proper coefficient U and by the temperature difference between inside and outside air $(t_i - t_o)$.

(*e*) Compute infiltration losses by multiplying cubic feet of air entering per hour by temperature difference and by 0.018 (Formula 7 or 8).

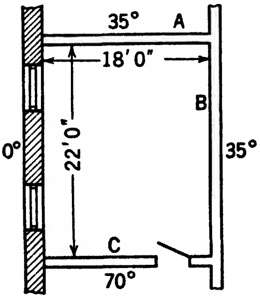


Fig. 3. Example 3.

(*f*) Add the transmission and infiltration losses together to find the total heat losses.

Example 3 (Fig. 3). Find heat in Btu to be supplied to a room 18 ft by 22 ft by 9 ft to maintain a temperature of 70° with outside temperature at 0°. One outside wall of brick 12 in. thick, furred and plastered on metal lath, and two single glazed weatherstripped windows, each 4 ft by 6 ft. Rooms above and adjoining partition C also maintained at 70°. Rooms adjoining partitions A and B unheated (35°). Basement below unheated (32°). Partitions, wood stud plastered both sides on wood lath. Floor, wood joists, double wood floor, no insulation, plaster on metal lath. Wind 15 mi per hr.

Areas. Window glass $2 \times 4 \times 6 = 48$ sq ft. Exposed wall, gross, $9 \times 22 = 198$ sq ft. Exposed wall, net, $198 - 48 = 150$ sq ft. Partitions A and C, $18 \times 9 = 162$ sq ft.; B, $22 \times 9 = 198$ sq ft; floor, $18 \times 22 = 396$ sq ft.

Transmission Losses. $H = A \times U \times (t_i - t_o)$.

			Btu
(*a*)	Through brick wall,	$H = 150 \times 0.25 \times (70 - 0) =$	2,625
(*b*)	Through glass,	$H = 48 \times 1.13 \times (70 - 0) =$	3,797
(*c*)	Through partition *A*,	$H = 162 \times 0.34 \times (70 - 35) =$	1,928
(*d*)	Through partition *B*,	$H = 198 \times 0.34 \times (70 - 35) =$	2,356
(*e*)	Through partition *C*,	No loss	0
(*f*)	Through floor,	$H = 396 \times 0.25 \times (70 - 32) =$	3,762
(*g*)	Through ceiling,	No loss	0
			14,468

Infiltration Loss. $H = 0.018 \times \text{Cubic feet per hour} \times (t_i - t_o)$.

$$\text{Length of crack, 2 windows} = 2[(3 \times 4) + (2 \times 6)] = 48$$

From Table XI, for 15-mile wind,

$$\text{Infiltration} = 24 \text{ cu ft per hr per ft of crack}$$

$$H = 0.018 \times 48 \times 24 \times 70 = 1452 \text{ Btu}$$

Total losses from room and total heat to balance losses = 14,468 + 1452 = 15,920 Btu.

11. Sources of heat. Most heating problems are concerned with the design of a central heating plant and of ducts, pipes, registers, convectors, and radiators for the handling of the heat. The systems generally employed are furnaces supplying warm air carried to the rooms in ducts, and boilers generating steam or hot water which rises to the rooms through pipes and whose heat is given off by means of radiators, convectors, unit heaters, or coils. Several methods of operation are employed in each system which will be described in the following chapters.

12. Insulation. The great value of the different types of insulators as means of reducing heat losses and cooling loads and their importance in the economical operation of the smallest to the largest buildings may readily be appreciated from a study of the foregoing tables.

REFERENCES

1. "Concrete Floors for Basementless Houses," *Circular Series, Index Number F 4.3,* University of Illinois, Urbana, Illinois.

2. "Insulation," *Circular Series, Index Number F 6.0,* University of Illinois, Urbana, Illinois.

3. "Measurement of Heat Losses from Slab Floors," Richard S. Dill, William C. Robinson, and Henry E. Robinson, *National Bureau of Standards BMS 103,* Superintendent of Documents, Washington, D. C.

4. "Design of Insulated Buildings for Various Climates," Tyler Stewart Rogers, F. W. Dodge Corporation, New York, N. Y.

5. "Air Infiltration through Weatherstripped and Non-weatherstripped Windows," C. E. Lund and W. T. Peterson, University of Minnesota Institute of Technology, *Engineering Experimental Station Bulletin 35.*

PROBLEMS

1. How and under what circumstances is heat transmitted?

2. What is the coefficient *U*, and how is it applied?

3. Find from the tables the value of *U* for a wood-frame wall with sheathed and shingled exterior finish, loose mineral wool between framing and wood lath, and plaster interior finish.

4. Find the value of *U* for a wall consisting of an outer section of 4-in. hollow clay tile with a 1-in. outer finish of cement mortar, a 1-in. air space lined on one side with aluminum foil and an inner section of 4-in. hollow clay tile with a 1-in. interior finish of gypsum plaster.

5. (*a*) What total length of sash crack should be used for a double-hung window? What net length should be used for a room with windows on three exposed walls? (*b*) Explain the existence of chimney effect in tall buildings. What assumption is made in computing the infiltration at various floor levels?

6. A room 24 ft wide and 40 ft long has on the long north and short west sides exposed common brick walls 12 in. thick with ½-in. gypsum plaster on interior surface. The long south and short east sides are separated from adjoining rooms by wood-frame partitions with wood lath and plaster on both sides. There are five windows in the north wall and three windows in the west wall. Each window is double-hung, single glass, 3 ft 6 in. by 7 ft, wood sash, weatherstripped. There is one wood door, 3 ft by 7 ft by 1½ in. thick in each frame partition. The floor is wood frame with double wood floor and metal lath and plaster on under side of joists. The ceiling is wood frame with wood lath and plaster and double wood floor on upper side of joists. No insulation. Floor to ceiling height, 11 ft.

Temperatures: Outdoor, 0°; indoor, 72°; adjoining rooms, 65°; room above, 60°; cellar below, 54°. Wind velocity 15 mi per hr.

Calculate hourly heat losses.

7. Distinguish between a *k* factor and a *C* factor.

8. What is the usual heat loss in Btu per hour per linear foot of edge per degree difference in inside and outside temperatures for a concrete slab on the ground?

9. Why is the outside surface conductance factor greater than the inside surface conductance factor?

10. How do rough and dark surfaces compare with smooth shiny surfaces in the matter of absorbing heat received radiantly by them?

Chapter 10

MECHANICAL WARM AIR HEATING

1. Characteristics and scope. An air heating system equipped with a fan for power circulation of the air and with a complete system of supply and return ducts is known as a mechanical warm air system. It has definite advantages over gravity systems and can be used in quite large buildings. The distinction between mechanical warm air heating and air conditioning is only the item of cooling in summer which is necessary if a system is to be classified as air conditioning. All the other possibilities of air conditioning are achieved in mechanical warm air heating. These are filtration, humidification, control of air speed, and control of outside air supply if desired. Mechanical warm air installations for houses and other small buildings are designed in accord with the scheme given in this chapter. Larger mechanical systems exceeding in capacity a limit of 120,000 Btu per hr are designed on the basis of air conditioning practice set forth in Chapters 17 through 21. Mechanical warm air heating is sometimes referred to as winter air conditioning.

2. Advantages. In comparison with gravity systems the following good qualities of mechanical warm air heating may be noted.

a. The use of the fan makes possible smaller basement ducts and eliminates the need for pitch. Basement ductwork can therefore be much less bulky and may even be concealed.

b. Because nearly all rooms have return as well as supply ducts, circulation is more positive, with fewer unheated spots, and balancing of the system is more effective. Room doors may be closed without affecting the air flow.

c. The use of the fan increases the volume of air handled, thereby drawing more heat from the same heating area of the furnace and assuring better air distribution in a large room.

d. Control and supply of humidity are better.

e. The use of filters is made possible by the pressure created by the fan.

f. The furnace does not have to be placed in the center of the basement area, but may be set in any part of the basement, or even on the first or second floor.

g. Air for ventilation may be introduced and heated more efficiently.

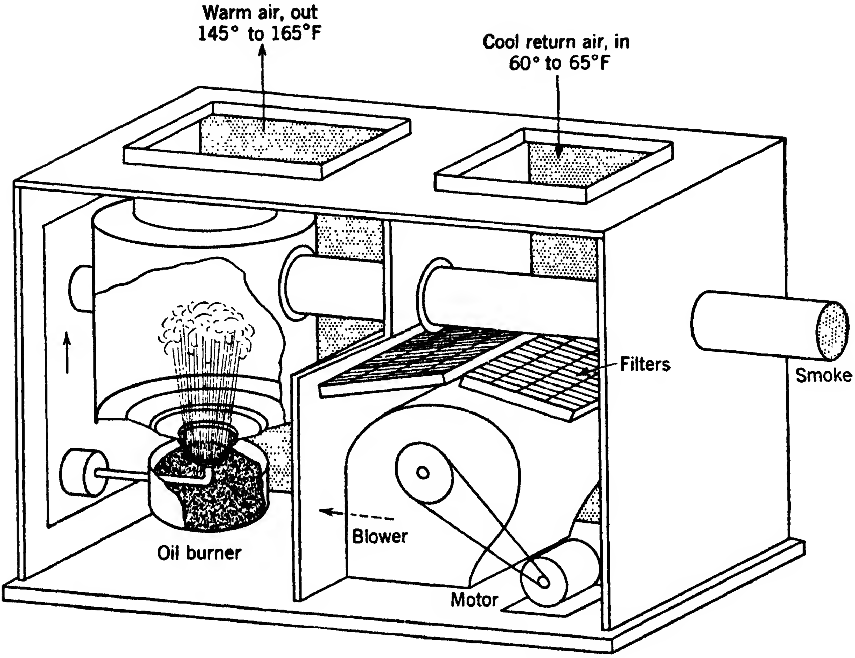


Fig. 1. Mechanical warm-air heating furnace.

h. In summer the fan and duct system may be used for the circulation of air for ventilation.

3. Equipment. (*a*) *Furnace.* Figure 1 represents a typical furnace which embraces within its housing the fan, motor, filters, oil burner, and heat-transfer surfaces. A humidifier can be added to this assembly. Arrows indicate the direction of the air. In passing through the fan or blower the air enters at the end of the cylinder opposite the pulley and is forced into the warming chamber by a cylindrical impeller unit.

(*b*) *Ducts* are of sheet metal, either round or rectangular. The rectangular type is usually preferred because it is more compact. For carrying the return air back to the furnace, spaces between studs or joists may be enclosed, the air flowing in contact with the wood. This method is not permitted in supply ducts where hotter air is handled. When used as return ducts the enclosed spaces must be made very tight to prevent air leakage. Ductwork will conduct noise unless the following suggestions are followed.

Do not place the fan too close to a return grille.
Select quiet motors and cushioned mountings.
Do not permit connection or contact of conduits or water piping with the fan housing.

(*c*) *Dampers* will be necessary to balance the system and adjust it to the desires of the occupants. *Splitter dampers* are used where *branch ducts* leave the larger *trunk ducts*. Each riser can have its flow controlled by an adjustable damper in the basement at the foot of the riser. Labels should indicate the rooms served. Some codes require dampers of fire-resistant material actuated by fusible links in order to prevent the possible spread of fire through a duct system.

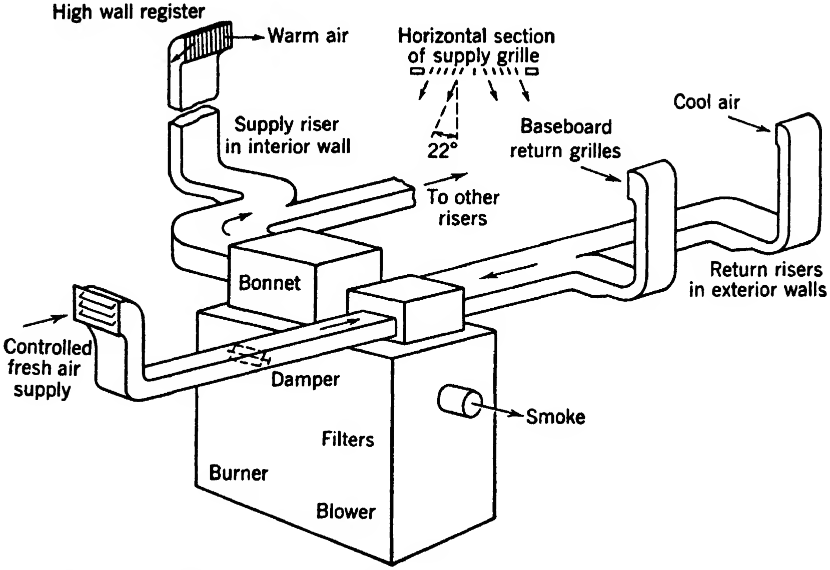


Fig. 2. Schematic duct system for mechanical warm air heating.

(*d*) *Registers.* Supply registers should be equipped with dampers and should have their vanes arranged to disperse the air and to reduce its velocity as soon as possible after entering the room. A common method is to provide vanes which divert the air half to the right and half to the left, independently of whether the register location is high or low. When a supply register is in the corner of a room it is best practice for the vanes to deflect all the air in one direction, away from the corner. Return grilles in walls are of the slotted type and grid type in floors. All registers and grilles should be made tight at the duct connection.

4. Controls. (*a*) *Thermostat.* The fan and burner are actuated by the thermostat which is placed in the living room or other preferred location that is stable and away from draughts and direct sunlight.

(*b*) *High Limit Switch.* The circulation of air at temperatures too high for comfort or safety is prevented by this switch, located in the bonnet of the furnace and set to turn off the blower when the bonnet temperature exceeds 175°.

(*c*) *Fan Switch.* A cut-in temperature between 110 and 130° is selected, at which point the fan switch in the bonnet starts the blower. It also turns off the blower when the temperature drops about 30° below the selected cut-in temperature.

(*d*) *Flue Temperature Control.* In gas- and oil-fired furnaces a safety control is placed in the flue to turn off the burner if ignition fails.

(*e*) *Humidistat.* The moisture content of supply air is controlled by the humidistat which can be placed in a room or in the return duct near the furnace.

5. Layout and design.

Example 1. Design a mechanical warm air heating system for the house shown in Fig. 3(*a*). Tables I and II are the work sheets for this problem. Reference is made to Tables III through VI and Fig. 4(*a* and *b*) for design data, reprinted by permission from the *ASHVE Guide*, 1951. The suggested steps and procedure in this design are as follows.

(*a*) *Heat Losses.* These are computed in accord with the principles in Chapter 9 and are recorded for each space to be heated.

(*b*) *General Arrangement.* Locate on the plans of the floors and basement all supply and return ducts and leaders. Indicate the method of combining them into trunk ducts. Consult Fig. 4, and indicate on the plans the code letter of each typical fitting as dictated by architectural considerations. In this problem all the return ducts and leaders are of metal, but joist spaces may be used for economy and compactness. Spaces having large heat losses should be served by two or more ducts in order to avoid excessive sizes. Decisions are made as to whether ductwork shall be insulated and about the location of supply registers and return grilles. These are noted on the work sheets. In this problem ductwork is left uninsulated because some heat is desired in the basement. In cold, exposed basements or crawl spaces, leaders should be insulated. All supply grilles are placed by choice in this problem at a high wall position, where there will be no direct draught on occupants. Also, as indicated in Table II, baseboard return intakes are used except in the lower hall where two floor-type intakes are chosen. The fresh air is drawn in at position *U*, which is a wall-type intake on the outside of the basement wall. Generally the supply ducts are placed in the warmer interior walls, and the returns in exterior walls. An exhaust fan disposes of the kitchen air which is balanced by the amount of the intake of fresh air. There is no return in the bath or upper hall, these spaces being served by the two intakes *R* and *O* in the lower hall. The direct return of air from bathrooms is not recommended.

(*c*) *Horizontal Leaders.* The capacity of a duct system is affected by the horizontal distance of air travel, that is, the horizontal length of the supply and return leaders in feet from bonnet to vertical stack. Include horizontal sections of any crossover at the second floor if such exist. In this example there is no additional crossover length in any leader. These horizontal distances are entered in the work sheets for supply and return ducts, Tables I and II column 4.

(*d*) *Resistance and Equivalent Length of Fittings.* The kinds of fittings chosen are already marked on the plans. Each offers resistance equal to a certain number of feet of straight duct. Add up the equivalent resistance of the fittings in each run, and enter this in column 5 of the work sheets. The resistance of the bonnet is included in each run, but no resistance is assumed where the main air stream passes an elbow to another riser. An example of the computation of an equivalent length, that for supply duct *A*, is given (refer to Fig. 4).

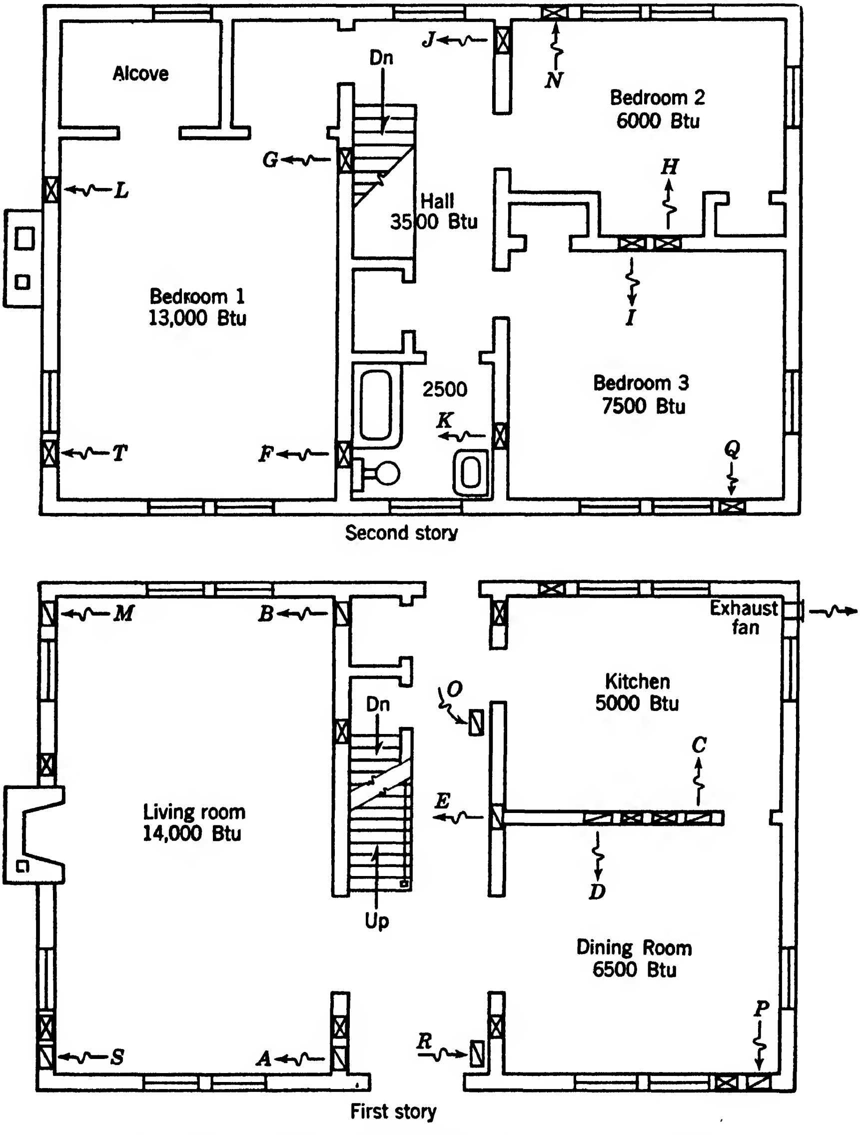


Fig. 3(*a*). (Example 1). Mechanical warm-air design.

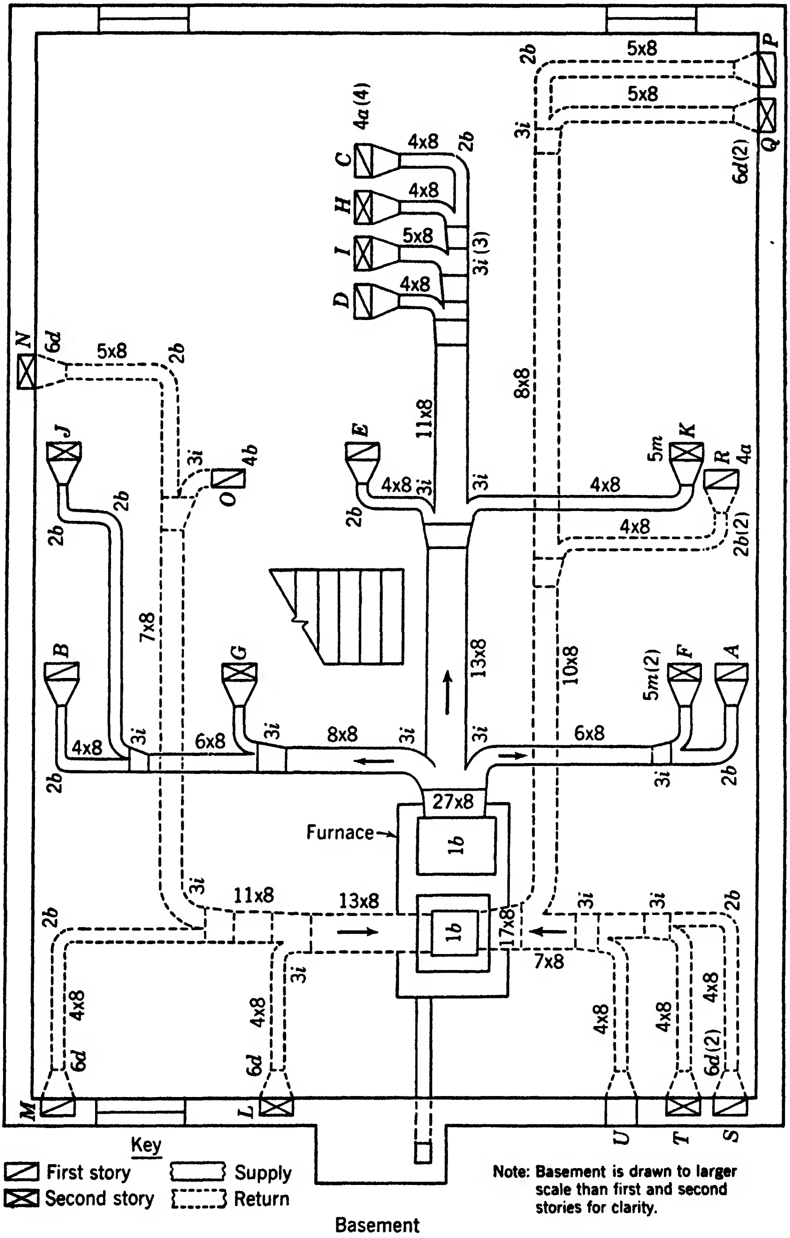


Fig. 3(*b*). (Example 1). Mechanical warm-air design.

Table I. (Example 1) Work Sheet. Supply-Duct System, Mechanical Warm Air Design (Fig. 3)

	Reference Column Number									
	1	2	3	4	5	6	7	8	9	10
	Space	Btu/hr	Plan Ref.	Length, Horiz. Leader (ft)	Equiv. Length Ftgs. (ft)	Combination Number	Stack Size (in.)	Branch Duct Size (in.)	Register * Size (in.)	Increase in Trunk (in.)
First Story	Living room	14,000	*A*	16	85	42	10 × 3¼	4 × 8	10 × 6	2
			B	22	95	42	10 × 3¼	4 × 8	10 × 6	2
	Kitchen	5,000	*C*	27	95	42	10 × 3¼	4 × 8	10 × 6	2
	Dining room	6,500	*D*	21	95	42	10 × 3¼	4 × 8	10 × 6	2
	Lower hall	3,000	*E*	17	85	41	10 × 3¼	4 × 8	10 × 6	1
Second Story	Bedroom 1	13,500	*F*	14	85	42	10 × 3¼	4 × 8	10 × 6	2
			G	17	85	42	10 × 3¼	4 × 8	10 × 6	2
	Bedroom 2	6,000	*H*	25	95	42	10 × 3¼	4 × 8	10 × 6	2
	Bedroom 3	7,500	*I*	23	95	43	12 × 3¼	5 × 8	12 × 6	3
	Upper hall	3,500	*J*	31	95	41	10 × 3¼	4 × 8	10 × 6	1
	Bathroom	2,500	*K*	22	85	41	10 × 3¼	4 × 8	10 × 6	1
		61,500								

* All supply registers are high wall type, 22° deflection of air. Ducts are uninsulated metal. *A* and *B* carry 7000 Btu/hr each. *F* and *G* carry 6750 Btu/hr each.

Table II. (Example 1) Work Sheet. Return Duct System, Mechanical Warm Air Design (Fig. 3)

	Reference Column Numbers										
	1	2	3	4	5	6	7	8	9	10	11
	Space	Btu/hr	Plan Reference	Length, Horiz. Leader (ft)	Equiv. Length Ftgs. (ft)	Combination Number	Stack Size (in.)	Branch Duct Size (in.)	Intake Type	Intake Size (in.)	Increase in Trunk (in.)
First Story	Living room	14,000	*M*	20	70	52		4 × 8	Baseboard	10 × 6	2
			S	15	70	52		4 × 8	Baseboard	10 × 6	2
	Dining room	6,500	*P*	39	80	53		5 × 8	Baseboard	12 × 6	3
	Hall	9,000	*R*	26	95	52		4 × 8	Floor	10 × 6	2
			O	30	90	52		4 × 8	Floor	10 × 6	2
Second Story	Bedroom 1	13,500	*L*	13	70	52	10 × 3¼	4 × 8	Baseboard	10 × 6	2
			T	13	70	52	10 × 3¼	4 × 8	Baseboard	10 × 6	2
	Bedroom 2	6,000	*N*	35	80	53	12 × 3¼	5 × 8	Baseboard	12 × 6	3
	Bedroom 3	7,500	*Q*	37	80	53	12 × 3¼	5 × 8	Baseboard	12 × 6	3
Bsmt.	Fresh air	5,000	*U*	9	55	51	10 × 3¼	4 × 8	Ext. wall	10 × 6	1
		61,500									

Ducts are uninsulated metal. Kitchen air, exhausted through kitchen fan, is replaced through fresh air intake. Bath and upper and lower halls are served by lower-hall returns, *R* and *O*. *M* and *S* carry 7000 Btu/hr each. *L* and *T* carry 6750 Btu/hr each.

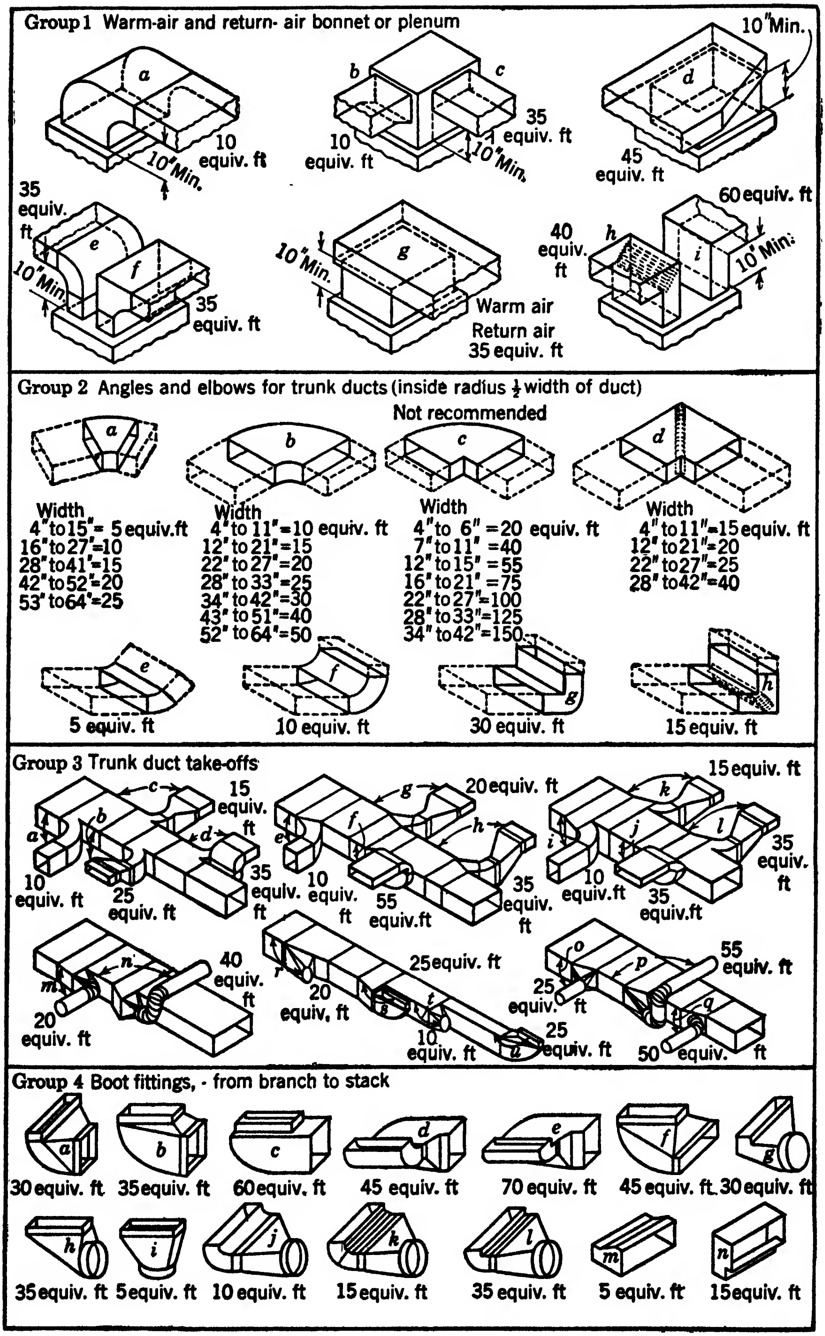
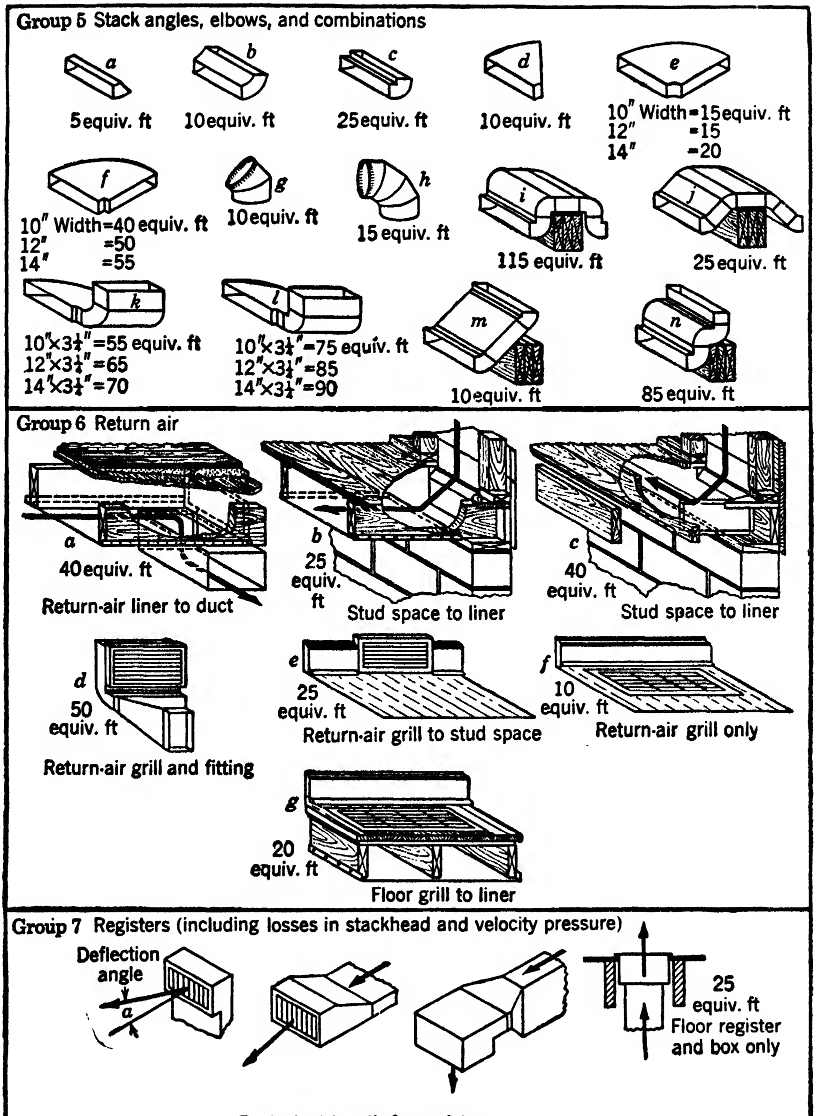


Fig. 4(*a*). Equivalent lengths of fittings. Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide, 1951,* page 446.



Equivalent length for registers

Deflection angle *a*	0°	15°	22°	30°	45°
Baseboard, high or low sidewall register, equiv. ft	35	40	45	60	115
Floor register with box only, equiv. ft	25				

For two-way deflection registers, add the vertical and horizontal deflection angles together and multiply by 0.7. Select closest angle *a* in table.

Fig. 4(*b*). Equivalent lengths of fittings. Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide, 1951*, page 447.

Plenum (at bonnet)	Type 1*b*	10 feet
Trunk duct take-off	Type 3*i*	10
Trunk elbow	Type 2*b*	10
Stack angle	Type 5*m*	10
Register (group 7, 22°)		45
		—
		85 feet equivalent length

The equivalent length of fittings in return ducts is computed in the same way. The results are entered in column 5 of the work sheets.

(*e*) *Combination Numbers.* Selection of a combination number from the standard combinations of sizes fixes the dimensions of the stack and the branch duct. For a chosen location of intake or register it also establishes the size of these elements. Lastly it indicates the required addition to the width of a standard 8-inch-deep trunk to accommodate the added capacity of the run in question. The combination is fixed by three factors—the number of Btu per hour to be supplied, the horizontal leader length, and the equivalent length of the fittings. The selection of combination numbers for return ducts is similar. Although the return ducts do not actually supply heat, their size is determined by the Btu per hour of the space served by the return and the two other items. To summarize in terms of the work sheets—columns 2, 4, and 5 determine the combination number shown in column 6. Column 7 and the columns following it through 10 and 11 are tabulations of the sizes indicated by the combination numbers. The intake and register sizes are affected further by the choice of a location for these outlets. Tables III and IV are used for the selection of combination numbers.

(*f*) *Stack Size.* After establishing the combination numbers, the sizes of the required stacks may be found in Tables V and VI for the supply and return stacks, respectively. These sizes must be indicated on working drawings similar to Fig. 3 but to larger scale.

(*g*) *Branch Duct Sizes.* These are found in the same tables and entered on the work sheets and the working drawings.

(*h*) *Registers and Intakes.* Tables V and VI make separate listings for registers in the wall and in the floor and for return air intakes in the baseboard or floor. Select the proper sizes, and write them on the work sheets and on the working drawings.

(*i*) *Increase in Trunk Width.* For this type of design 8 in. is usually selected as the standard depth for trunk ducts. When a branch duct joins the trunk, the 8-in.-deep trunk is widened one or more inches to increase its capacity. Where main trunks join, their widths are added to establish the width of the trunk to which they join. Four in. is the minimum width.

(*j*) *Sizing the Trunk Ducts.* The trunk widths and depths are indicated on the working drawings represented by Fig. 3. At the bonnet a transition piece will usually be necessary to adapt the shallow and wide trunk to a squarer opening.

(*k*) *Selection of a Furnace.* A furnace including fan and filters is selected on the basis of the total of the heat losses from all the rooms, 61,500 Btu. The input or bonnet capacity is greater than this net output and

Table III. Capacity Table, Mechanical Warm Air and Return Air Branches

First Story *

For Uninsulated Metal Ducts	Actual Length (from Bonnet to Boot) or (from Return Plenum to Boot) in Feet							Warm Air Combination No.	Return Air Combination No.
	1 to 7 ft	8 to 12 ft	13 to 17 ft	18 to 24 ft	25 to 34 ft	35 to 44 ft	45 to 54 ft		
	Col. A	Col. B	Col. C	Col. D	Col. E	Col. F	Col. G		
Section A 40 to 69 equivalent ft for fittings and register	7,200	6,700	6,100	5,600	4,800	4,100	3,500	41	51
	12,500	11,700	10,800	9,900	8,500	7,400	6,400	42	52
	16,000	15,000	14,000	13,000	11,300	9,900	8,700	43	53
	19,100	18,000	17,000	16,000	14,200	12,500	11,000	44	54
	25,000	23,400	21,600	19,800	17,000	14,800	12,800	45 [c]	55
	32,000	30,000	28,000	26,000	22,600	19,800	17,400	46 [c]	56
	80,000	75,000	70,000	65,000	56,500	49,500	43,500	..	57 [c]
Section B 70 to 99 equivalent ft	5,500	5,100	4,800	4,500	3,900	3,400	3,000	41	51
	9,900	9,200	8,600	8,100	7,100	6,200	5,400	42	52
	13,100	12,300	11,600	10,900	9,700	8,500	7,500	43	53
	16,300	15,400	14,500	13,700	12,200	10,800	9,500	44	54
	19,800	18,400	17,200	16,200	14,200	12,400	10,800	45 [c]	55
	26,200	24,600	23,200	21,800	19,400	17,000	15,000	46 [c]	56
	65,500	61,500	58,000	54,500	48,500	42,500	37,500	..	57 [c]
Section C 100 to 129 equivalent ft	4,600	4,300	4,100	3,800	3,300	3,000	2,700	41	51
	8,500	7,900	7,400	6,900	6,100	5,300	4,700	42	52
	11,300	10,600	10,000	9,400	8,400	7,400	6,500	43	53
	14,300	13,500	12,700	11,900	10,500	9,300	8,300	44	54
	17,000	15,800	14,800	13,800	12,200	10,600	9,400	45 [c]	55
	22,600	21,200	20,000	18,800	16,800	14,800	13,000	46 [c]	56
	56,200	52,600	50,200	47,300	42,000	37,000	32,400	..	57 [c]
Section D 130 to 164 equivalent ft	4,100	3,800	3,600	3,400	2,900	2,600	2,300	41	51
	7,300	6,900	6,400	6,000	5,300	4,700	4,200	42	52
	9,800	9,100	8,600	8,100	7,200	6,400	5,600	43	53
	12,300	11,700	11,000	10,300	9,100	8,100	7,100	44	54
	14,600	13,800	12,800	12,000	10,600	9,600	8,400	45 [c]	55
	19,600	18,200	17,200	16,200	14,400	12,800	11,200	46 [c]	56
	49,200	45,800	41,900	40,300	36,000	31,800	28,100	..	57 [c]
Section E 165 to 200 equivalent ft	3,800	3,500	3,300	3,100	2,700	2,400	2,100	41	51
	6,500	6,100	5,700	5,400	4,800	4,300	3,800	42	52
	8,800	8,200	7,700	7,200	6,400	5,700	5,000	43	53
	11,000	10,500	9,900	9,300	8,300	7,300	6,400	44	54
	13,000	12,200	11,400	10,800	9,600	8,600	7,600	45 [c]	55
	17,600	16,400	15,400	14,400	12,800	11,400	10,000	46 [c]	56
	44,100	41,500	38,800	36,000	32,000	28,200	24,700	..	57 [c]

For Insulated Ducts	Col. A	Col. B	Col. C	Col. D	Col. E	For ducts that are *completely insulated* with $\frac{1}{2}$-in.-thick insulation from bonnet to boot, use these column headings.
	1 to 9 ft	10 to 17 ft	18 to 24 ft	25 to 34 ft	35 to 54 ft	

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[a] These tables are for use in sizing both the warm air and the return air branches.

[b] Frictional resistances and temperature drops in ducts have both been accounted for in these tables.

[c] Use these items only when the building construction, or capacity requirements, necessitate the use of two adjoining stacks or floor registers.

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Table IV. Capacity Table, Mechanical Warm Air and Return Air Branches

Second Story *

For Uninsulated Metal Ducts	Actual Length (from Bonnet to Boot) or (from Return Plenum to Boot) in Feet							Warm Air Combination No.	Return Air Combination No.
	1 to 7 ft	8 to 12 ft	13 to 17 ft	18 to 24 ft	25 to 34 ft	35 to 44 ft	45 to 54 ft		
	Col. A	Col. B	Col. C	Col. D	Col. E	Col. F	Col. G		
Section A	6,300	5,700	5,200	4,800	4,100	3,500	3,100	41	51
	10,900	10,000	9,200	8,500	7,300	6,400	5,600	42	52
40 to 69 equivalent ft for fittings and register	14,000	13,000	12,100	11,400	10,000	8,800	7,800	43	53
	17,000	15,900	14,900	13,900	12,400	11,100	9,900	44	54
	21,800	20,000	18,400	17,000	14,600	12,800	11,200	45[c]	55
	28,000	26,000	24,200	22,400	20,000	17,600	15,600	46[c]	56
	70,000	65,000	60,500	57,000	50,000	44,000	39,000	..	57[c]
Section B	5,000	4,600	4,300	4,000	3,400	3,000	2,700	41	51
	9,000	8,200	7,600	7,100	6,200	5,400	4,700	42	52
70 to 99 equivalent ft	11,900	11,000	10,300	9,600	8,400	7,500	6,700	43	53
	14,800	13,900	13,000	12,200	10,800	9,600	8,500	44	54
	18,000	16,400	15,200	14,200	12,400	10,800	9,400	45[c]	55
	23,900	22,000	20,600	19,200	16,800	15,000	13,400	46[c]	56
	59,500	55,000	51,500	48,000	42,000	37,500	33,500	..	57[c]
Section C	4,200	3,900	3,700	3,500	3,000	2,600	2,400	41	51
	7,700	7,200	6,700	6,200	5,400	4,700	4,100	42	52
100 to 129 equivalent ft	10,400	9,700	9,000	8,400	7,400	6,500	5,800	43	53
	13,000	12,100	11,300	10,600	9,400	8,300	7,400	44	54
	15,400	14,400	13,400	12,400	10,800	9,400	8,200	45[c]	55
	21,700	19,400	18,000	16,800	14,800	13,000	11,600	46[c]	56
	52,200	48,400	45,300	42,300	37,000	32,500	29,000	..	57[c]
Section D	3,800	3,500	3,200	3,000	2,700	2,300	2,100	41	51
	6,800	6,300	5,800	5,500	4,800	4,200	3,700	42	52
130 to 164 equivalent ft	9,100	8,400	7,900	7,400	6,300	5,700	5,000	43	53
	11,400	10,500	9,800	9,200	8,100	7,200	6,400	44	54
	13,600	12,600	11,600	11,000	9,600	8,400	7,400	45[c]	55
	18,200	16,800	15,800	18,400	12,600	11,400	12,800	46[c]	56
	45,500	42,000	39,600	36,800	32,200	28,200	25,100	..	57[c]
Section E	3,500	3,200	2,900	2,700	2,500	2,100	1,900	41	51
	6,100	5,700	5,300	5,000	4,400	3,900	3,400	42	52
165 to 200 equivalent ft	8,200	7,600	7,100	6,700	5,700	5,100	4,500	43	53
	10,300	9,500	8,900	8,300	7,400	6,500	5,800	44	54
	12,200	11,400	10,600	10,000	8,800	7,800	6,800	45[c]	55
	16,400	15,200	14,200	13,400	11,400	10,200	9,000	46[c]	56
	41,000	38,300	35,800	33,400	29,000	25,800	22,800	..	57[c]

For Insulated Ducts	Col. A	Col. B	Col. C	Col. D	Col. E	Col. F	For ducts that are *completely insulated* with ½-in.-thick insulation from bonnet to boot use these column headings.
	1 to 8 ft	9 to 14 ft	15 to 20 ft	21 to 27 ft	28 to 42 ft	43 to 54 ft	

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[a] These tables are for use in sizing both the warm air and the return air branches.

[b] Frictional resistance and temperature drops in ducts have both been accounted for in these tables.

[c] Use these items only when the building construction, or capacity requirements, necessitate the use of two adjoining stacks or floor registers.

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Table V. Mechanical Warm Air Duct System Combination of Parts Selected as Standard

Combination No.	Stack Size (in.)	Branch Pipe Size (in.)		Register Size (in.) (See Figs. 1 and 2)		Required Increase in Width of Trunk Duct (in.)
		Round	Rectangular	Baseboard High or Low Sidewall	Floor Registers *	
1	2	3	4	5	6	7
41	10 × 3¼	6	4 × 8	10 × 6	8 × 10 *	1
42	10 × 3¼	6	4 × 8	10 × 6	8 × 10 *	2
43	12 × 3¼	7	5 × 8	12 × 6	9 × 12 *	3
44	14 × 3¼	8	6 × 8	14 × 6	9 × 12 * or longer	4
45	10 × 3¼ (2-Stacks)	9	8 × 8	(2) 10 × 6 or (1) 24 × 6	10 × 12 *	5
46	12 × 3¼ (2-Stacks)	10	10 × 8	(2) 12 × 6 or (1) 30 × 6	12 × 14 *	7

* Use these items only when the building construction or capacity requirements necessitate the use of floor registers. The sizes listed for floor registers correspond to the standard sizes for gravity warm air furnace systems, except for the sizes of the floor box collars. The use of standard blind boxes is suggested. A 12 × 5¼ in. stack may be used on Combination 45, and a 14 × 5¼ in. stack on Combination 46 with floor registers.

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depends upon the type of fuel. The ratings of manufacturers should be consulted.

6. Perimeter heating. A solution to the problem of heating small houses on concrete slabs by means of forced warm air has been found in the development of perimeter heating. Perimeter heating consists of a down-flow air furnace which supplies warm air into a pit and thence radially, as shown in Fig. 5, to a subfloor perimeter duct system. The air is then discharged through floor or baseboard grilles into the space to be heated. The grilles are usually located under windows. Return air is carried back to the furnace by a series of short ducts in the attic space or ceiling. This arrangement compensates for the large heat loss and resulting low temperature around the edge of slabs on the ground. The heating effect is partly radiant because of the embedment of the radial and peripheral ducts in the concrete.

This method has been proved satisfactory by research at the University of Illinois and by use in many houses. A design manual is now issued by the National Warm Air Heating and Air Conditioning Asso-

Table VI. Mechanical Warm Air Return Air Duct System Combination of Parts Selected as Standard

Combination No.	Return-Air Intake Size (in.)		Riser Size (in.), Where Stack Is Used in Stud Space	Branch Pipe Size (in.)		When Joist Lining Is Used † Number of Joist Spaces Lined and Minimum Depth of Space Required	Required Increase in Width of Trunk Duct (for 8-in. Depth of Duct) (in.)
	Baseboard	Floor *		Round	Rectangular		
1	2	3	4	5	6	7	8
51	10 × 6	6 × 10 or 4 × 14	10 × 3¼ †	6	4 × 8	1 space of 3-in. depth	1
52	10 × 6	6 × 10 or 4 × 14	10 × 3¼ ‡	6	4 × 8	1 space of 3-in. depth	2
53	12 × 6	6 × 12 or 6 × 14	12 × 3¼ §	7	5 × 8	1 space of 4-in. depth	3
54	14 × 6	6 × 14	14 × 3¼ §	8	6 × 8	1 space of 5-in. depth	4
55	24 × 6 or 30 × 6	6 × 30	Two stacks each 10 × 3¼ ‡	9	8 × 8	1 space of 6-in. depth or 2 spaces of 3-in. depth	5
56	30 × 6	6 × 30	Two stacks 12 × 3¼ §	10	10 × 8	1 space of 7-in. depth or 2 spaces of 4-in. depth	7
57	....	8 × 30	....	12	15 × 8	1 space of 9-in. depth or 2 spaces of 5-in. depth	12

* Use these items only when building construction, or capacities, require the use of floor intakes. The sizes listed correspond to standard sizes for gravity installations, except floor box collars. The use of standard blind boxes is suggested.

† Based on 14 in. space between joists. Use full depth of joist, except when joist depth is less than minimum depth required, in which case a *drop pan must be used.* This may occur when two or more return ducts are connected to the same joist space.

‡ If it is desired to use 14 in. × 3⅝ in. stud space, it makes no difference whether this space has protruding keys or not.

§ If it is desired to use 14 in. × 3⅝ in. stud space, the plaster base must be smooth, without any protruding plaster keys to interfere with the flow of air.

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The capacities shown in Tables III and IV are based on a 100° temperature rise in the air, and a static pressure available for overcoming friction in the external duct system alone of 0.20-in. water gauge.

ciation, by whose permission Figs. 5 through 8 are reprinted here. Installations are limited to houses of compact shape.

Waterproofing, good drainage, and perimeter insulation are very important. Since the ground heat loss is greatly increased under wet conditions houses should be located in dry or well-drained soil. Two in. of fiberboard 16 in. deep are necessary between the slab and the

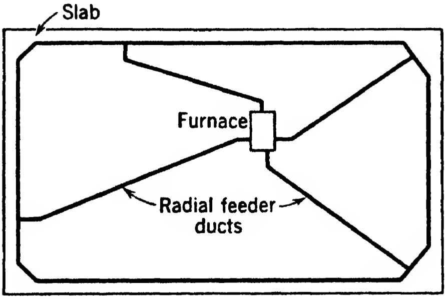

Fig. 5. Typical duct system. Reprinted by permission from *Manual 4* of the National Warm Air Heating and Air Conditioning Association.

outside foundation. The sub-bed should be gravel, not cinders, and over it is laid 55-pound roofing felt as a moisture barrier. It must be continuous, dipping under the metal duct forms (later surrounded by concrete) and sealed at all joints (Fig. 6). Form boxes are set for register outlets and the concrete poured around them. When floor registers are used the duct can be placed close to the foundation. Baseboard registers, however, require that the duct be moved in to permit the placing of an adapter. In both situations long, narrow registers give best results. Where bathroom or kitchen fixtures prevent the placing of registers at the outside wall, they may be set in an inside partition near the exterior. The concrete cover above the perimeter ducts is 2 in. thick, but the radial supply ducts pitch so that the con-

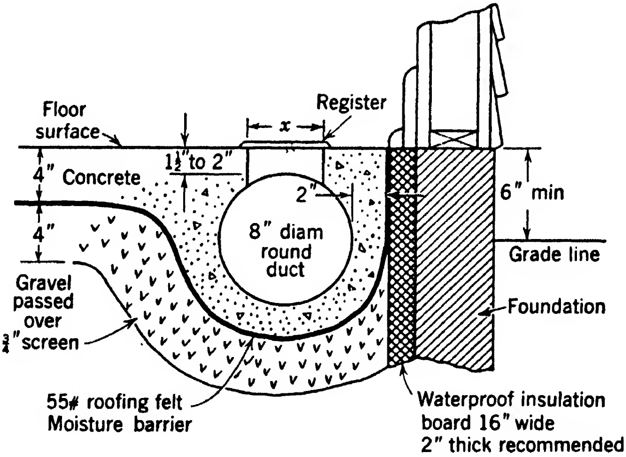

Fig. 6. Details of insulation, waterproofing and concrete cover. Reprinted by permission from *Manual 4* of the National Warm Air Heating and Air Conditioning Association.

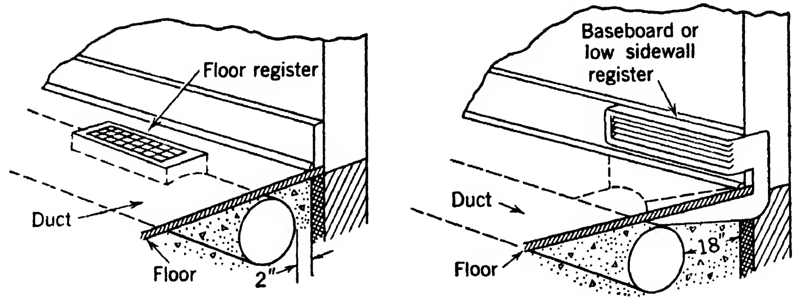

Fig. 7. Register outlets. Reprinted by permission from *Manual 4* of the National Warm Air Heating and Air Conditioning Association.

crete cover near the furnace is about 5 in. thick (Fig. 8), the greater thickness retarding the flow of heat into the room at this central location.

One of the advantages of this method of heating is the reversal of the downward cold air currents which usually occur at cold walls and windows. This is achieved by the warm air rising from the heated floor area near the walls and still more vigorously at the windows by the warm air rising from the registers.

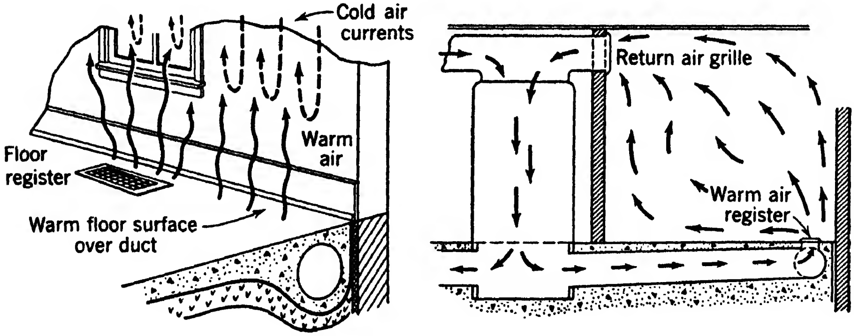

Fig. 8. Convection currents and method of warm air circulation. Reprinted by permission from *Manual 4* of the National Warm Air Heating and Air Conditioning Association.

7. Gravity warm air heating. Gravity warm air has been largely superseded by mechanical warm air. A number of compact, ductless gravity units are available for heating small open spaces. They have been modernized in style and can be used below the floor in a small crawl space with great efficiency. The large gravity furnace with round leaders is now seldom specified, although many fine installations are still operating. The *Heating, Ventilating and Air Conditioning Guide* has standard information on the design and operation of these systems.

REFERENCES

1. "Warm Air Perimeter Heating," Manual 4, National Warm Air Heating and Air Conditioning Association, 145 Public Square, Cleveland 14, Ohio.

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3. "Code and Manual for Winter Air-Conditioning Systems," Manual 7, National Warm Air Heating and Air Conditioning Association.

4. "Code and Manual for Ceiling Panel Systems," Manual 7-A, National Warm Air Heating and Air Conditioning Association.

5. "Warm Air Heating and Structure," William J. McGuinness, *Progressive Architecture,* September, 1951.

6. "Crawl Space Perimeter Heating," William J. McGuinness, *Progressive Architecture,* May, 1952.

PROBLEMS

1. What are the advantages that distinguish mechanical warm air heating from gravity warm air heating?

2. Since ducts transmit noise readily, what steps should be taken to reduce noises at their source in mechanical warm air systems?

3. What is the total equivalent length in feet of the following series of fittings: 1 type *f* plenum take-off; 1 elbow in an 8 in. × 8 in. trunk; 1 type *i* trunk take-off; 1 type *b* boot; 1 high wall register with 22° angle of deflection?

4. A duct supplies 7300 Btu per hr to a second floor room in a mechanical warm air system. The horizontal length from furnace to stack is 20 ft, and the length equivalent to the fittings is 160 ft. If the duct is uninsulated, what combination number will be used in designing this part of the system?

5. Number 44 has been chosen as combination needed for a certain mechanical warm air supply duct. Give the resulting sizes of the stack, the rectangular branch, a high wall register for a 12-ft room, and the required increase in the width of the trunk.

6. What air control is possible by splitter dampers and by registers?

7. Describe the operation of (*a*) the high limit switch and (*b*) the fan switch.

8. What are the functions of the thermostat and the humidistat?

9. Discuss the insulation of supply and return ducts.

10. What are the advantages of warm air perimeter heating as used in basementless houses with concrete slabs on grade?

Chapter 11

STEAM HEATING SYSTEMS

1. Steam. When sufficient heat is supplied to water to cause it to boil and vaporize, the resulting vapor is called *steam.* As the boiling point of water in a container is reached, bubbles of water vapor or steam are formed in the bottom and rise to the surface where they escape. If a thermometer were placed in the container it would be seen that the temperature of the water and of the steam does not rise above the boiling point, that is, 212°F at the atmospheric pressure at sea level or 14.7 lb per sq in. It is evident that bubbles of vapor will not form unless the pressure exerted outwardly by the vapor is at least equal to the exterior atmospheric pressure upon the surface of the water; otherwise the bubble would collapse at once. If the exterior pressure were greater than 14.7 lb per sq in., the heat required to form the vapor bubbles would be greater and the boiling point of the water and the temperature of the resulting steam would be above 212°F. If the exterior pressure were less than 14.7 lb per sq in., less heat would be required for boiling and the temperature of the generated steam would be below 212°. This relationship between pressure and steam temperature is important in the study of heating because it permits temperature regulation of the steam supplied to radiators as illustrated in the vapor and vacuum heating systems. Table I shows the changes in the temperature of boiling water and in the properties of steam below and above normal atmospheric pressure. Absolute pressure is the sum of the atmospheric pressure (14.7 lb) at sea level and the pressure shown on the steam gauge. Absolute pressure of 16.7 lb therefore signifies a gauge pressure of 2 lb per sq in.; and absolute pressure of 10 lb, a gauge pressure of −4.7 lb or a 4.7-lb vacuum. Absolute pressure is therefore independent of elevation above sea level or atmospheric changes in pressure as indicated by barometer readings.

While steam is in contact with the water in a boiler it is called *saturated steam* and is at the temperature of the boiling point. It is known as *wet steam* or *dry saturated steam* according to whether it does or does not contain suspended moisture. If dry saturated steam be removed from contact with the boiler water and further heated at the same pressure, its temperature will rise above boiling and it is known

Table I. Properties of Saturated Steam

Absolute Pressure (lb per sq in.)	Temperature (degrees F)	Heat of Liquid (Btu per lb)	Latent Heat of Evaporation (Btu per lb)	Total Heat or Enthalpy (Btu per lb)
6	170	138	996	1134
8	183	151	988	1139
10	193	161	982	1143
12	202	170	977	1146
14.7	212	180	970	1150
15.7	215	184	967	1151
16.7	219	188	965	1153
17.7	222	190	963	1154
18.7	225	193	961	1155
19.7	228	196	959	1156

as *superheated steam.* The steam generated in heating boilers is generally very close to wet saturated steam. It is in contact with the water and is at the boiling temperature as determined by the pressure upon it. *Vapor* is steam at a pressure equal to or slightly above atmospheric pressure. The difference between vapor and steam is one of pressure only.

As explained in Chapter 9 the intensity of heat is measured in degrees Fahrenheit and its quantity in British thermal units. The quantity of heat contained in a pound of steam can therefore be ascertained, and it is important since it is an evidence of the heating value of the steam. Heat added to a substance without changing its state will raise the temperature of the substance. If, however, the state of the substance is changing, as from solid to fluid or from fluid to vapor, additional heat does not increase the temperature. As an example, heat applied to water at 32° will raise its temperature to the boiling point corresponding to the surface pressure, and as more heat is applied the boiling water will be converted into steam but the temperature of the water and the steam will not be further changed. *The heat of the liquid* or *sensible heat* is the heat in Btu required to raise the temperature of 1 lb of water from 32° to the boiling point. The *latent heat of evaporation* is the heat in Btu required entirely to vaporize 1 lb of water at the boiling point into dry saturated steam at the same temperature. The *total heat of the steam* or *enthalpy* is the sum of the heat of the liquid and the latent heat of evaporation.

Quality of steam is the percentage of dry saturated steam in wet steam. The total heat of wet steam is consequently the sum of the heat required to raise 1 lb of water from 32° to the boiling point plus the heat required to vaporize the percentage of dry steam.

As is seen from Table I, the heat of evaporation contained in steam is very large compared to the heat contained in water at the boiling point. This property renders steam a very efficient heating medium, since it may be piped to the point where heat is desired and there, while condensing, it gives off approximately 1000 Btu of its latent heat per lb, the hot condensate water returning to the boiler.

2. Steam heating is based upon the generation of steam in a centrally placed boiler and the transportation of the steam through pipes from the boiler to the various locations in the building where heat is desired. Upon arrival at these locations the steam gives up its latent heat by conduction through the walls of its container, either pipe coil or radiator, changes its state by condensation from vapor to liquid and flows back to the boiler through the return piping.

3. Steam heating systems. All systems must transport steam freely and uniformly to all the heating units, return the condensate easily and noiselessly and remove the air in the radiators and piping to the extent desired. The systems may be broadly classified as *gravity systems* when the condensate flows back to the boiler by gravity and *mechanical systems* when pumps are used to return the condensate to the boiler against its pressure.

The heating systems now in general use are:

(*a*) Air-vent system (gravity).
(*b*) Vapor system (gravity).
(*c*) Vacuum system (mechanical).

In all systems the horizontal supply pipes from the boiler are called the *mains,* the vertical pipes to the various floors are the *risers,* and the pipes carrying the condensate back to the boiler are the *return risers* and *return mains.*

4. Air-vent systems. One of the basic requirements is the removal of air from the piping and radiators, in order to avoid a cushion ahead of the steam which would prevent it from flowing freely in the pipes and entering the radiators. In the air-vent systems an air valve is installed on each radiator and the air is eliminated through the valves into the rooms by the pressure of the steam behind it. The orifices in the air valves must be very tiny so that air alone will pass and steam and water will be retained. Consequently a pressure of 1 to 5 lb with a proportional increase in steam temperature must always be maintained in the boiler, supply piping, radiators, and returns in order to force the air through the air valves and the condensate back into the boiler. The steam supply valves at the radiators must therefore be entirely open if any heat at all is desired. If the supply valves are throttled, that is only partially open, there will not be sufficient steam pressure to drive out the air through the tiny orifices of the air valves. The heat derived from the radiators cannot be regulated, which often results in over-heating and wasteful fuel consumption in mild weather. The condensate flows back to the boiler by gravity, the pressure in boilers, mains, and radiators being the same except for loss due to friction.

The air-vent system was, however, the original system to be developed and is now the simplest and most economical to install. It is therefore still much used especially in moderate-sized buildings. In this one-pipe system the same pipe carries both the steam supply from the boiler to the radiators and the water of condensation from the radiators back to the boiler. The supply main rises from the top of the boiler to a point near the basement ceiling and then grades down uniformly at a pitch of 1 in. in 10 ft, the vertical risers being taken off at convenient points to serve the radiators on the upper floors. The end of the main drops down below the level of the boiler water line and returns to the boiler as a wet return. If more convenient the main may loop back at its end and run to a point near the boiler as a dry return and there drop down below the water-line level. Since this is a gravity system the boiler water line must be at such a distance below the lowest radiators that the condensed water in the return will have sufficient static head to overcome the pressure loss due to friction and be received back into the boiler against the initial boiler pressure. This requirement generally necessitates a height of at least 18 in. for the end of the steam main or the loop of the dry return above the water line. (See Chapter 12, Art. 13.) It is sometimes necessary in buildings with low basement ceilings to set the boiler in a pit below the floor in order

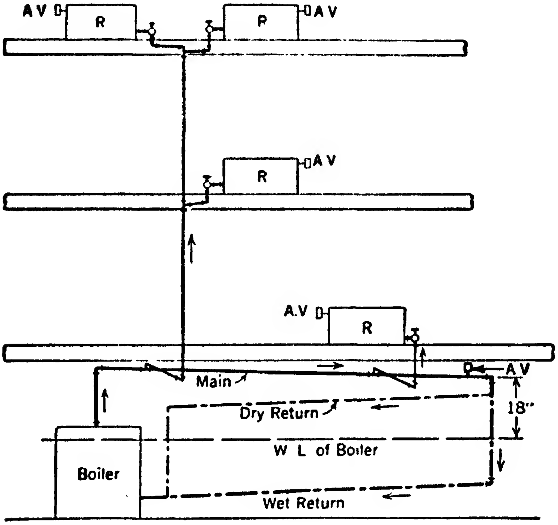


Fig. 1. One-pipe system. Up-feed.

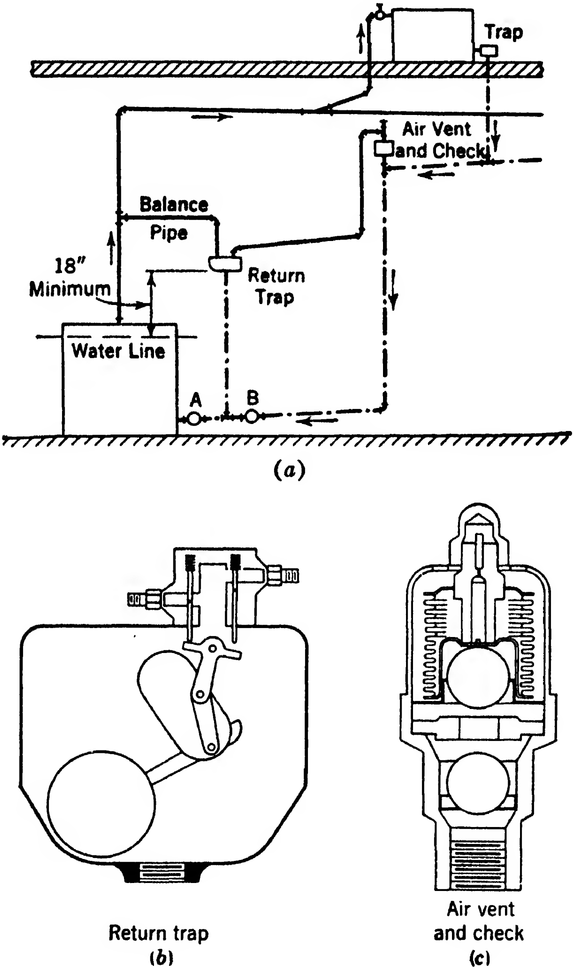
to obtain this required height. An air vent is always fitted at the end of the supply main and an air valve and steam supply valve on each radiator, the air valve being at the opposite end from the supply valve (Chapter 12, Fig. 5).

The one-pipe system is employed in small buildings only, the great main and riser diameters required to accommodate the water and steam rendering it uneconomical and inefficient for large installations. The mains, returns, and radiators should be uniformly graded with no pockets or depressions to collect water. It is seen in Fig. 1 that the steam and the condensate flow in the same direction in the mains but in opposite directions in the risers, where interference between steam and water is not likely to occur in small installations.

5. Vapor system (Fig. 2). The intention in the design of the vapor system is to reduce in mild weather the steam pressure in the boiler and the amount of heat emitted from the radiators, and yet to maintain in cold weather a higher pressure in the boiler and adequate heating effectiveness in the radiators. It is most often a two-pipe system and differs from the air-vent type in that the steam is admitted at the top of the radiators through graduated valves, thermostatic traps on the return connections of the radiators take the place of air valves, and an air vent and check and an automatic return trap are installed on the dry return main [Fig. 2(*b*, *c*)]. The thermostatic radiator trap is devised to pass air and water but to cut off the steam. Its orifice is amply large so that a steam pressure is not required in the radiators to force the air and water through it. When the fire is started the steam pressure drives out the air from the radiators through the dry return main to the air vent and check. Outside air is prevented by the check from re-entering the returns, and as the fire dies down the whole system is under a slight vacuum.

By means of these devices vapor is generated and circulated at a low temperature and a partial vacuum. The steam supply to the radiators may be reduced in mild weather by partly closing the inlet valves, and the condensate will flow out by gravity. The steam will consequently circulate at atmospheric pressure or a few ounces below, with a corresponding reduction in steam temperature. A low fire may be maintained and the system more economically operated than the air-vent system.

When more heat is required, as in cold weather, steam may build up in the boiler, and the condensate, under only atmospheric pressure, cannot enter the boiler. A device is, therefore, installed to produce an increased pressure in the return main to balance the pressure in the boiler. The alternating return float trap, a device very generally used, consists of a closed container with an air connection to the air vent on the return main and a steam connection, called the balance pipe, from the supply main. When the pressure becomes greater in the boiler than in the return main the check valve *A* (Fig. 2) automatically closes and the condensate mounts up into the trap. When the float in the trap is sufficiently raised by the incoming water, the valve in the steam balance pipe opens and the valve in the air line is closed. Steam is admitted to the trap, producing enough pressure upon the water to open check *A* and close check *B* and to force the condensate into the boiler. The float then drops to a low level, closes the steam valve, opens the air valve, and the action recommences.



(*a*)

Return trap
(*b*)

Air vent and check
(*c*)

Fig. 2. Vapor system.

The vapor system is well adapted to residences and medium-size buildings since it combines improved air removal, ease of control, more even heating, and economy of fuel. The special devices are proprietary, and, although cheaper to operate, the vapor system is more costly to install than the air-vent systems. A boiler with a low water line is an advantage, and a dry return is necessary up to the air vent and check.

6. Vacuum system. The air-vent and vapor systems are called gravity systems because the condensate flows back to the boiler by gravity. The two-pipe vacuum system is known as a mechanical system because a pump is used to draw air and condensate from the return lines, producing a partial vacuum and making circulation more positive, especially in large buildings where gravity flow is difficult to accomplish owing to pressure drop in the long runs of pipe. (See Fig. 3.)

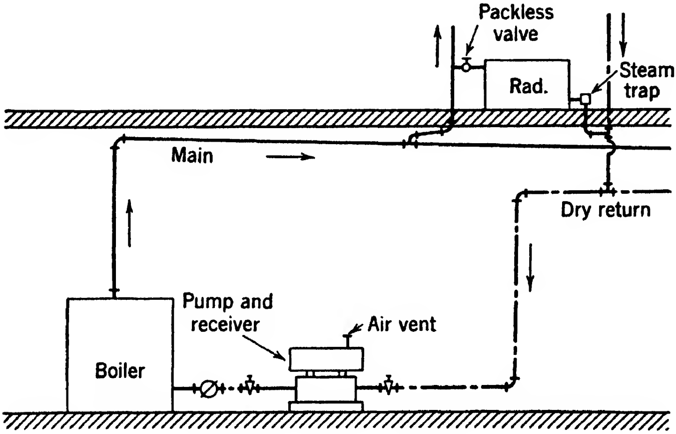


Fig. 3. Vacuum system.

The radiators are equipped with graduated valves regulating the supply of steam and with thermostatic traps passing air and condensate but holding steam, as described for the vapor system. Thermostatic traps should also be installed on all drips before connecting with the return mains. Branches are pitched as described for air-vent systems, depending upon whether the risers are dripped or not dripped. A vacuum pump on the return line delivers air and condensate to an air-liberating tank with a float control. The rising of the float closes the air vent, and the pumped water and air produce a pressure exceeding the boiler pressure. The condensate can then pass from the tank to the boiler; the float drops, opening the vent; and the air in the tank is allowed to escape. The action then recommences. By this means a partial vacuum is maintained in the returns, a pressure above atmospheric exists in the steam supply and the air and condensate are freely removed from the returns. The partial vacuum does not extend to the boiler, the steam mains, or the radiators, control of the temperature being obtained by partially closing the radiator valves or by thermostatic adjustment of the dampers on the boiler. By the use of proper lift fittings on the return line, radiators may be located below the vacuum pump inlet.

7. Steam control. The supply of steam to radiators in the vapor and vacuum system is controlled by special inlet valves, known as modulating or graduated valves. (See Chapter 12, Fig. 2.) These valves may be throttled by hand and may also be so adjusted that varying amounts of steam are admitted to the different radiators, depending upon their capacities in square feet of radiation or upon the heating demand. In the vacuum systems orifice plates are sometimes inserted at the radiator valves and in branch steam mains. These plates contain holes at their centers whose diameters vary with the amount of steam desired in the individual radiators or in the different branches.

8. Vacuum pumps. Since air as well as water is being withdrawn from the return main it is necessary to eliminate the excess air before the water can be returned to the boiler. Pumps adapted to the vacuum system are therefore generally of the motor-driven centrifugal type with two impellers mounted on the same shaft, one handling the water and the other the air. The water and air from the return main enter a receiving tank maintained under a vacuum, from which the two impellers respectively discharge the air to the atmosphere and deliver the water to the boiler. Automatic control is furnished, depending upon both the water level in the receivers and the vacuum in the system.

Where high-pressure steam is available steam reciprocating pumps may be used as vacuum return equipment. Two pumps are required. One withdraws both air and water from the return line and delivers them to a separating tank which is vented to the atmosphere, thus allowing the air to escape. A second pump draws the water from the separating tank and discharges it to the boiler. Both pumps may be steam-driven, or one may be a steam reciprocating and the other a motor centrifugal pump.

Vacuum pumps are rated according to the square feet of equivalent direct radiation (EDR) which they will serve. The volume of air to be handled is in general proportional to the radiation, and the water capacity should be calculated at the rate of ⅔ lb of condensate at 180°F per hr per sq ft of radiation.

9. High-pressure steam. When high-pressure steam boilers are part of the equipment of a building or when the exhaust steam from engines is available, it is often economical to use this steam for heating rather than to install special low-pressure boilers for the purpose. In these cases the pressure of the steam is limited by reducing valves (Chapter 12, Fig. 4) and relief valves upon the mains or at the heating units. Backpressure valves are likewise used on exhaust steam lines to vent steam to the atmosphere and so relieve backpressure on the engine if more steam is delivered than the heating system can absorb. Pumps may be of steam turbine type.

10. Condensation or boiler feed pumps. When condensate under atmospheric pressure is to be returned to the boiler, either reciprocating or centrifugal pumps may be used with either steam or electric power. Such pumping is required in gravity systems when heating units are below the boiler level, or when the boiler pressure is greater than the pressure in the heating units, as in the case of high-pressure steam supplied through reducing valves. The water flows by gravity to a receiving tank from which it is pumped into the boiler. Two-stage vertical-shaft centrifugal pumps operating inside a vertical receiving tank are effective for this duty and occupy little space.

11. Metro system (Fig. 4). A convector system, economical to install and efficient in operation is being used in many large housing developments and also in buildings of moderate size. It is suitable for vapor or vacuum systems and is often installed as a subatmospheric system controlled by an outdoor thermostat. It can operate at 218°F

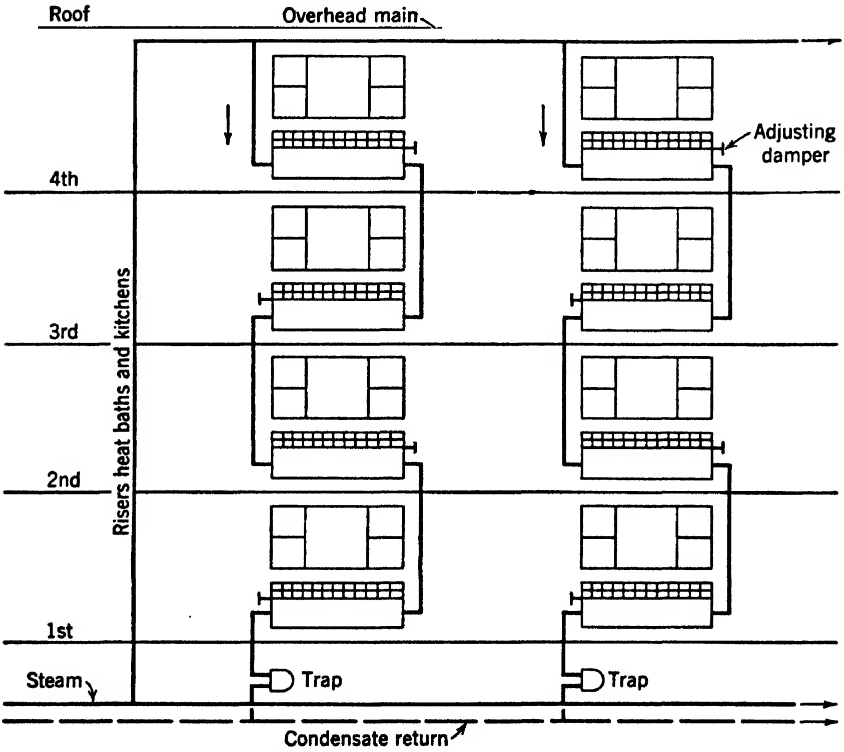


Fig. 4. Down feed through convectors (vapor or vacuum) inside elevation.

under pressure to 125°F at 26 in. of vacuum. The down-feed pipe supplies steam directly through the convectors on all stories of each vertical series of windows. There is no valve or trap on any convector. A common trap in the basement ahead of the connection to the return main serves the entire stack.

Control of heat in each room is possible at the individual convector as shown in Fig. 5. An enclosure consisting of a front and sides of sheet metal is fitted tightly against the wall. The bottom is open, and there is an open grille at the top. Above the convector element there is an adjustable damper of sheet metal which can be rotated to a vertical position, permitting full convection currents to pass, or be set horizontally to cut off all air currents. When the damper is closed, uncondensed steam passes through to other convectors on the lower floors. Thus the steam always has continuous flow from top to bottom through an unvalved pipe, heat being obtained in varying degree by inducing or retarding the convection air currents in the several rooms. If desired, convectors and piping may be recessed into the wall.

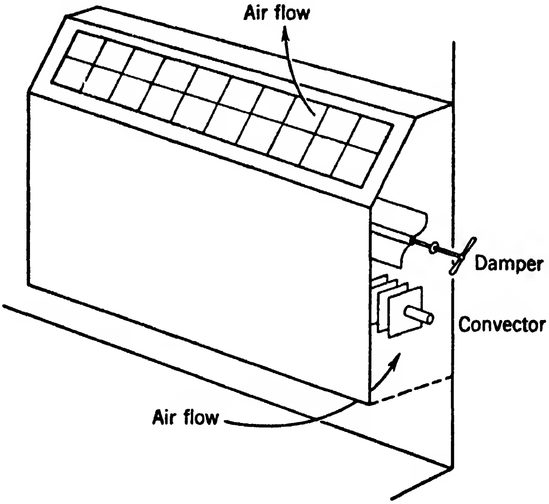


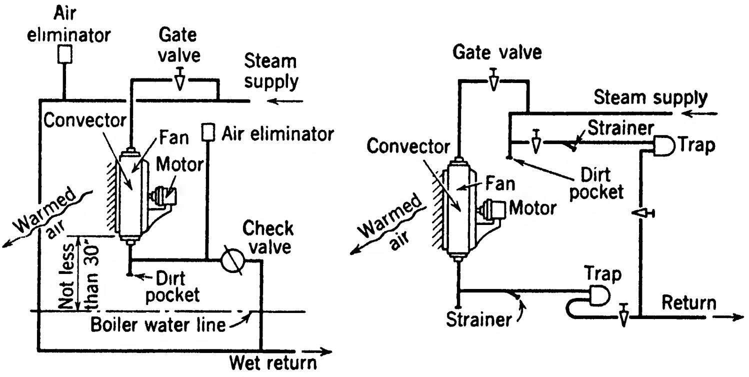
Fig. 5. Convector and cover (with end removed) indicating air currents and adjustable damper.

Savings in pipe, traps, and valves are quite evident in this scheme. Economy of operation is the same as in any vapor or vacuum system, including the economy, which is still possible, of shutting off the heat in individual rooms. The servicing of traps and valves is much less frequent than in other systems and is confined to the convenient location of the basement or access tunnel. Convector risers may serve 2 to 16 stories.

There are patents applying to this kind of heating.

12. Unit heaters (Fig. 6). For the heating of large volumes as in factories, stores, and other commercial and industrial buildings unit heaters are frequently used. A fan blows air over convector elements, resulting in a large output for a fairly compact unit. Figure 6 shows connections for such a system when steam is used with a propeller-type fan.

Unit heaters must have a proper rating in Btu per hour to make up the heat loss in the space to be heated. The location of the heater is most important. It is necessary to keep the air-intake side in a location of free air circulation and to point the blower in the direction for most effective use. It should be placed to create a rotary circulation in the room, starting parallel to an exterior wall. It must not blow directly on working areas and should aim above the head line.



(*a*) One-pipe gravity steam system (*b*) Vapor or vacuum steam system

Fig. 6. Unit heaters.

Rapid condensation of steam is a characteristic of steam unit heaters. This suggests a number of precautions shown in Fig. 6. When a one-pipe air-vent system is used the supply branch rises vertically from the top of the main and thus the condensate already in the main continues and drops to the return without passing through the unit. The condensate from the unit leaves by a special return branch to the return main instead of flowing back into the supply main, as when regular radiation is used in a one-pipe system. Air eliminators, strainers, and dirt pockets aid in keeping the pipes clear for steam, and gate valves are chosen because of the small resistance they offer to flow of steam and water.

Vapor or vacuum supply mains are dripped and trapped to eliminate water in the vicinity of unit heaters. As in the case of one-pipe systems, the supply branch rises from the main before dropping and there is a separate return branch. In vapor and vacuum systems this return branch is trapped to prevent the passage of steam into the return main.

13. Zoning. Very tall buildings are often divided into horizontal zones of approximately the same height in order to equalize the heating demands throughout the structure. Large structures may also be divided into zones with reference to weather exposure or to hours of occupancy. In both methods pressures, pipe sizes, and steam consumption are reduced and greater efficiency at less cost is attained.

When zoned for equalization of conditions each section has its own vertical supply main from the boiler in the basement connected to a horizontal supply main at the top or bottom of the zone. Either up-feed or down-feed risers are taken off as convenient for the radiators on the various floors of the zone. The Empire State Building in New York, Shreve, Lamb, and Harmon, Architects, may be taken as an example. The building comprises 86 stories and tower, with setbacks at the sixth and thirtieth stories, and is divided into four zones. The heating system is two-pipe vacuum with steam-driven pumps. The zones are heated by up- and down-feed risers from distributing mains in the basement and in the twenty-ninth and fifty-fourth story ceilings as shown in Fig. 7. Extra height is given to these stories providing additional hung-ceiling space to accommodate the horizontal piping. Even with this method of zoning the main to the twenty-ninth story is 24 in. in diameter and diminishes above. The fact that heated air rises within tall buildings due to flue action is considered in computing the heating requirements in the higher zones. Otherwise the upper floors would become overheated when the system is full of steam.

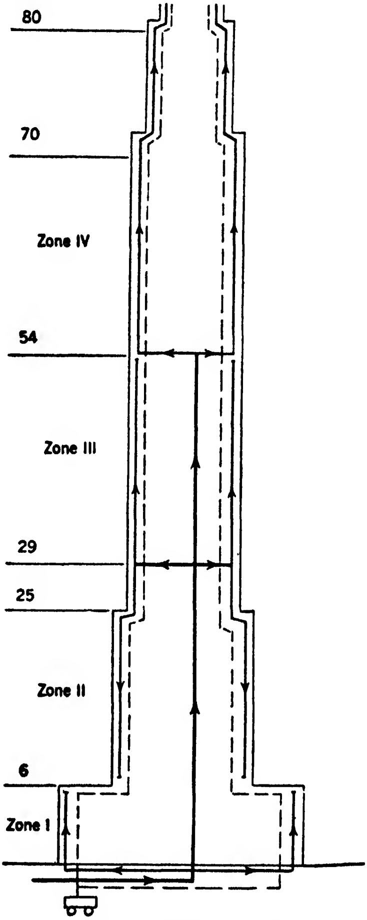


Fig. 7. Heating zones.

When zoned with respect to exposure, the effect of wind, sunshine, and other weather conditions, the building is often divided into two sections, the north and west quarters which usually require more heat and the south and east which require less. Each zone is controlled by a thermostat placed at a suitable point or key room. Parts of buildings are often used for storage and manufacturing requiring cooler temperatures, or by clubs and restaurants with short hours of occupancy. Such portions may well be divided into zones with thermostatic control. By these means a correct heating of all sections and a maximum conservation of steam may be secured.

REFERENCES

1. "One-Pipe Steam Heating Systems," *Installation Guide Number 2,* The Institute of Boiler and Radiator Manufacturers, 60 East 42 St., New York 17, N. Y.

2. "One-Pipe Steam Systems," William J. McGuinness, *Architectural Record,* August, 1949.

PROBLEMS

1. A pound of water is converted to steam. What is its total heat in Btu per pound at 212° and atmospheric pressure? What are the component values of the heat of the liquid and the heat of evaporation that comprise the total heat? Above what temperature is the total heat of the liquid measured in steam systems?

2. What are the different principles upon which the air-vent and the vapor systems of steam heating are based?

3. What is the vacuum system of steam heating?

4. How are steam unit heaters kept free of condensate?

5. What is the purpose of establishing heating zones in tall buildings, and how is it done?

6. Why is the vacuum system the only one in which the radiators may be below the level of the boiler?

7. Describe the action of the alternating receiver in a vapor system.

8. What economies of installation, operation, and maintenance can be expected in the Metro system?

9. What are the principal differences in the piping and controls of unit heaters using (*a*) one-pipe steam supply and (*b*) vapor or vacuum supply?

10. What are the determining factors in the placing of unit heaters for the warming of large open areas?

Chapter 12

STEAM HEATING EQUIPMENT AND DESIGN

1. Piping. Steel and wrought-iron pipes are most generally used in steam heating. For diameters up to and including 6 in., piping of steel and wrought iron is furnished with threaded ends and is screwed together. Above 6-in. diameters these pipes are connected by flanges bolted to each other with a gasket between. Pipe drawn from a solid billet and known as seamless tubing is frequently used for high pressure, there being no welded joint to split during bending. Standard-weight black iron and steel pipe is generally employed in heating, although wrought iron and copper-bearing steel are frequently used for return lines. The characteristics of pipe are described in more detail in Chapter 2.

2. Pipe fittings. Lengths of pipe are connected either in the same direction or at an angle by special pieces called fittings, made of cast iron, malleable iron, steel, or bronze. They are connected to the pipes by screw thread in sizes up to 6-in. diameter and by flanges in sizes over 6 in. and are known as *low-pressure* fittings for steam up to 25 lb pressure, *standard* for steam up to 125 lb, and *extra heavy* for steam to 250 lb. *Ells* or *elbows* and *return bends* are used to change the direction of a pipe line, *tees, crosses,* and *Y's* to take off branches, *bushings* and *reducers* to reduce a threaded or tapped opening, and *nipples* to form short straight connections. *Unions* are employed to join pipe, valves, or other apparatus with easy disconnection for repairs. Screw unions are convenient for pipe up to 2-in. diameter; flanged unions are more reliable for larger sizes. *Couplings* are used to join the smaller sizes of pipes but do not permit disconnection as readily as unions.

3. Welding. Welded instead of screwed or flanged connections are becoming more used for heating work, the electric arc and oxyacetylene methods being equally successful. The pipes may be joined directly to each other or welding fittings may be used, the fittings giving the better-finished installation. The work should be entrusted to none but expert welders, and, because of the expense of the equipment and the necessity of a skilled crew of mechanics, welding is found less costly than screwed or flanged connections only in large operations. Savings in weight of pipe, insulation, and repairs, however, are possible. Socket fittings with fillet welds are used with pipe sizes of ¼ in. to 3 in., and butt welded fittings with beveled ends for 1 in. to 12 in.

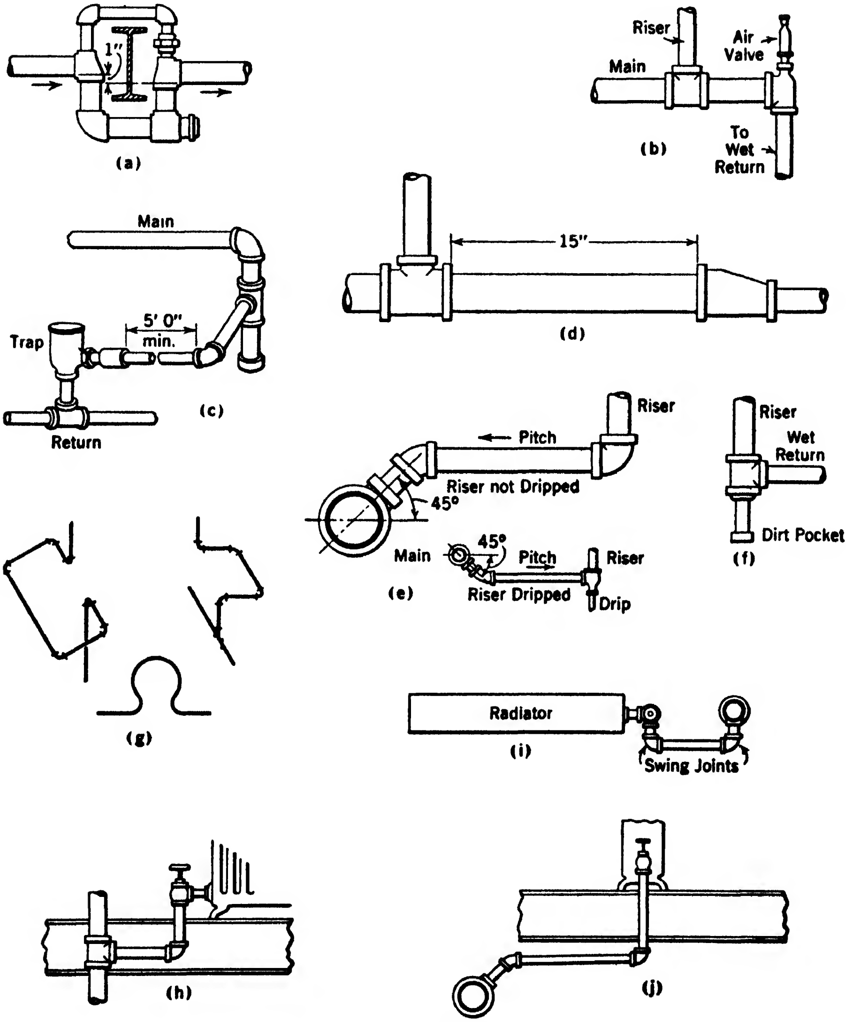


Fig. 1. Pipe details.

4. Pipe details. In pipe detailing the following considerations should be borne in mind: economy, safety, accessibility, ease of repair, sources of possible trouble, removal of air and water, obstruction of flow, and pipe expansion. Drips, dirt pockets, thermostatic traps, easy bends, loops and sliding joints are therefore introduced where required to improve the operation of the system. The water and air should be removed by drips and thermostatic traps from all points where they may accumulate and retard the flow of the steam; obstructions caused by right-angle turns should be avoided where possible, and pipe expansion under heat should be taken up in loops and swing connections.

The steam main should have a uniform slope of at least $\frac{1}{8}$ in. in 10 ft. If necessary to lift the main over a beam, doorway, or other obstruction a drip connection with clean-out plug should be installed below the obstruction [Fig. 1(*a*)]. With air-vent systems an air valve is placed upon the end of the steam main as it turns down to the wet return [Fig. 1(*b*)]. With vapor and vacuum systems and a dry return there is no air valve at this point, the end of the supply main connecting through a trap to the return main [Fig. 1(*c*)]. When mains or other horizontal steam pipes are reduced in size an eccentric fitting is used to procure a level bottom to the connection so that the flow of condensate is not impeded [Fig. 1(*d*)].

Branches to risers and radiators should be taken off mains in one- and two-pipe systems from the top of the main and should pitch $\frac{1}{2}$ in. in 10 ft toward the main when the riser is not dripped. When the riser is dripped, branches should be taken from the bottom of the main and pitch toward the riser drip [Fig. 1(*e*)]. The foot of a riser should be dripped to the return main when more than four stories high, and dirt pockets are often installed at the lowest point [Fig. 1(*f*)]. Elongation caused by a rise in temperature is most noticeable in the mains and risers since they contain the longest runs. It is seen from Table III, Chapter 4, that the elongation resulting from an increase in temperature from 60 to 220° in 100 ft of pipe is sufficient to produce excessive stress upon the fittings. Expansion loops and swing connections consisting of bent pipes or of a combination of straight pipe and ells [Fig. 1(*g*)] are introduced to take up the elongation by a bending in the loop or by a slight turning in the threaded joints.

Branches or runouts from radiator to riser should have a minimum pitch of $\frac{1}{2}$ in. in 10 ft and should be installed with a loop to protect the radiator from movement in the riser. In air-vent systems the branch may be arranged as in Fig. 1(*h*) if the movement is small, and as in Fig. 1(*i*) when the movement is more pronounced. First-floor radiators are often served directly from the basement main with a branch as in Fig. 1(*j*). When bends and loops are not practicable to install, expansion joints consisting of a sleeve free to move in a packed gland are available or a copper bellows may be employed.

5. Valves. Gate, globe, check, and angle valves as described in Chapter 2 for water supply are also used for heating systems. Gate valves are most frequently employed because they offer very little obstruction to the flow of steam and water. They must, however, be either completely open or completely closed; consequently when throttling action is desired globe valves are substituted particularly in vertical lines. Special valves used in heating are radiator valves, thermostatic traps, air eliminators, pressure-reducing valves, and air valves.

Valves for steam radiators were originally angle valves very like those already described, requiring packing with cotton or asbestos. Types have now been developed which require no packing and are based upon brass or bronze bellows and diaphragms which encase the spindle and elongate as the valve disk descends (Fig. 2). Valves which do not permit the leakage of air into the radiators and piping are very necessary in vacuum and vapor systems since the maintenance of a vacuum prolongs the heating period on a declining fire and is a basic principle of these methods of heating. Orifice plates can also be inserted in the unions of packless valves to regulate the steam supply to each radiator so that there will be no inequality of flow and irregularity in receiving heat when the fire is starting. Graduated valves may be used on vapor and vacuum systems which, by multiport or other arrangement, permit only a fractional part of the steam to enter the radiator, the fraction depending upon what portion of the radiator it is desired to heat in mild weather.

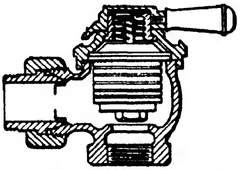


Fig. 2. Packless radiator valve.

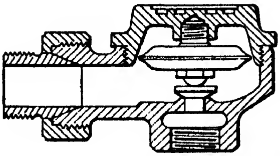


Fig. 3. Thermostatic radiator trap.

6. The thermostatic trap consists of a cast-iron body enclosing a bronze bellows containing a volatile fluid. This fluid is not affected by the heat of the air or water in the radiator but vaporizes and expands from the heat of steam, extending the bellows and pushing the valve down against its seat. When steam enters a cold radiator at the top it forces out the air and condensate water through the trap into the return piping. After filling the radiator, the steam comes in contact with the trap, which automatically closes and excludes the steam from the returns (Fig. 3).

7. Pressure-reducing valves are used when the steam furnished by the boilers or the street supply is at too high a pressure for the heating system. The valves are operated by the rising or falling of the diaphragm which in turn is actuated by the changes in pressure in the low-pressure main. When the pressure becomes too high on the low-pressure side, the steam pressure through the balance pipe raises the diaphragm, which closes the valve, allowing less steam to pass from the inlet to the outlet. When the pressure becomes too low on the low-pressure side the diaphragm drops and the valve opens, admitting more steam. The action of the diaphragm is regulated by moving the weight on the arm or adjusting the tension of the spring. The balance pipe is generally $\frac{1}{2}$ in. and should be connected to the low-pressure pipe 15 or 20 ft from the reducing valve [Fig. 4(*a, b*)].

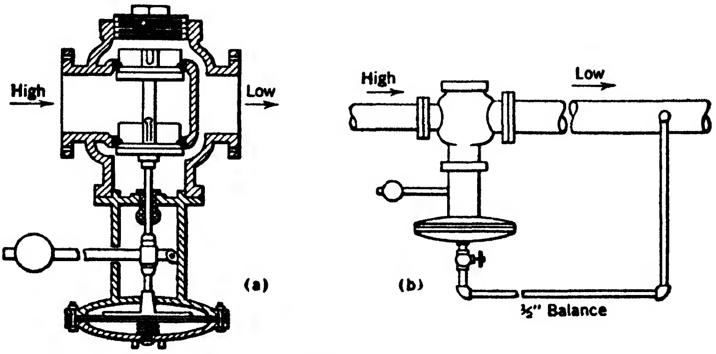


Fig. 4. Pressure-reducing valve.

8. Air valves (Fig. 5) are necessary on the radiators and at the end of the steam main in air-vent systems to allow the air to escape and so prevent obstruction to steam and water flow. In steam systems the air valve is rendered automatic by incorporating a metal float within the valve casing. The buoyant effect of water or the heat of steam will cause the float to rise and close the tiny air vent at the top of the casing. The float generally contains a volatile fluid which vaporizes and expands under the heat of steam and so enlarges the flexible diaphragm bottom of the float. The bottom presses against a boss on the floor of the casing and forces up the float until the pin at the top closes the air vent. Any water in the casing is siphoned back to the radiator through a tube. Air valves are connected on the end of the radiator opposite the steam supply at two thirds of the height above the floor. They are not used on vapor or vacuum systems, traps taking their place.

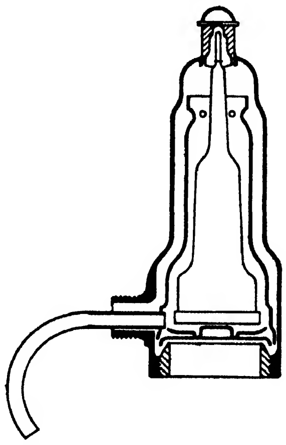


Fig. 5. Radiator air valve.

9. Selection of a system. The choice between steam heating systems is governed by the size of the building and by expense. The one-pipe air vent is the cheapest in first cost, but the piping and radiators must be very carefully designed and installed because the condensate must flow back to the boiler through the same pipe which carries the steam to the radiators. The steam and water must often flow in opposite directions; consequently the piping must be amply large to avoid interference between the two elements, causing unpleasant crackling noises, water hammer, and inefficient operation of the system. The one-pipe system is best adapted to small residences and buildings with less than 2000 sq ft of radiation. The additional equipment and piping employed with the vapor system renders its first cost somewhat higher, but its flexibility and adaptability to changing outdoor temperatures have given it wide popularity. The operating expense is less than for the air-vent systems. The above-mentioned systems use gravity return and are proper installations for small and moderate-sized buildings.

For large operations such as institutions, theaters, and tall office buildings the vacuum system with mechanical condensate return and air removal by means of a pump is most generally employed. Its first cost is higher than that of the gravity systems, but its action is definite and its automatic adjustment to the varying demands of weather and of occupancy give it the preference for large installations.

10. Pipe sizes. The calculation of pipe sizes is affected by the relative directions of flow of the steam and the condensed water. When they flow in the same direction the influences of pipe friction, causing pressure drop in the steam, should be considered. When they flow in opposite directions the velocity of the steam must be limited to secure proper functioning of the system.

11. Pressure drop. Steam and condensate flow in the same direction in riser branches of two-pipe systems and in down-feed risers of both one- and two-pipe installations. For satisfactory operation the supply mains and riser branches should be pitched in the direction of the steam flow and dripped, that is, connected at their low ends by a small pipe to the return main. In these cases of parallel flow the pipes must be of sufficient size to carry the steam and condensate without excessive loss of pressure due to friction. This loss is rated in ounces per 100 ft of pipe or in ounces for the entire system.

Pressure drop should not exceed half the initial or gauge pressure, should not cause such velocities as impede counterflowing condensate, and should not necessitate inconvenient distances between boiler water line and lowest point of supply main or of dry return. (See Art. 13.) Steam heating should be designed with low initial pressures of not over 2 to 5 lb gauge and with small pressure drops, usually taken for air vent and vapor types at not over 1 oz in 100 ft of pipe or 2 to 4 oz total for the entire system, and at not over 4 to 8 oz total for the vacuum type, depending upon the equivalent length of pipe.

12. Steam velocity. The condensate flows in the opposite direction to the steam in the up-feed risers of one-pipe systems and in the up-feed risers and riser branches of two-pipe systems when not dripped. With a low steam velocity the condensate runs down the sides of the pipe and the steam flows up the center with little interference between them. As the steam velocity becomes greater, however, the quantities of both steam and condensate increase until a critical velocity is reached at which the steam stops the water and forces it back into the radiator, causing unpleasant noises, water hammer, and resistance to steam flow in pipes and radiators. The critical velocity depends upon the size of pipe, the friction, and the quantity of condensate. It is lower in horizontal and sloping pipes than in vertical pipes. Branches to risers and radiators should, therefore, be relatively larger than vertical risers. Up-feed risers in two-pipe systems also carry some counterflowing water condensed in the pipes themselves, but the volume is small compared to that from the radiators, and, when dripped and the pipes designed for a low pressure drop, no interference should occur.

It is seen, then, that pipe sizes are determined by either one of two considerations, pressure loss or steam velocity, depending upon the circumstances of the design, and that these considerations are related since a higher velocity produces a greater friction with the same quantity of flow. In order to simplify the design of steam heating systems, tables based upon the foregoing formulae and upon tests for critical velocities have been prepared by the American Society of Heating and Ventilating Engineers. These tables are here reproduced with the permission of the Society.

13. Water-line distances. The pressure loss in the piping often causes the water line in the vertical pipe draining the end of the supply main to stand about 2 in. higher than the boiler water line for every ounce pressure drop in the system under normal working conditions. When cold piping and radiators are heating up, the steam pressure in the boiler may be considerably higher than normal. Consequently, to provide sufficient static head to force the condensate into the boiler without backing into the main, a difference of at least 24 in. should be allowed between the boiler water line and the low point of a supply main or of a dry return. Since 1 in. of water exerts a pressure of 0.036 lb this difference should be increased by approximately 2 in. for each ounce of design pressure drop in the system; that is, for a drop of 2 oz the difference should be $24 + 4 = 28$ in., and for a drop of 8 oz, $24 + 16 = 40$ in. If the main were 100 ft long with a grade of ¼ in. for 10 ft or 2½ in. for 100 ft, if the water-line difference were 26 in. and if 6 in. were allowed between high point of main and basement ceiling, a distance of 34½ in. would be required between the boiler water line and the ceiling. If the floor-to-ceiling height were 90 in. and the boiler water line were 70 in. above the floor, a pit would be necessary for the boiler with a depth of (34½ + 70) − 90 or 14½ in. An automatic return trap, shown in Chapter 11, Fig. 2(*b*), may be used when an adequate static head cannot be obtained.

14. Illustrative problems. The general procedure consists in first calculating the heat losses which must be supplied by the radiators in the rooms as explained in Chapter 9. By dividing the heat loss from each room by 240 Btu the square feet of radiation for that room is determined. The sum of these radiations gives the total radiation for the building. The distance is then measured from the boiler to the farthest radiator. To this distance or run must be added the resistance of the fittings in equivalent lengths of straight pipe. Since the resistance of fittings varies with the pipe size, it is necessary either to assume an average pipe size for the system and to calculate the resistance of the fittings in equivalent lengths of pipe, or to assume a total length of pipe including both the actual length to farthest radiator and the equivalent lengths corresponding to the resistances of the fittings. In both cases the assumptions must be verified after the pipe sizes are obtained. The second method is found to be more reliable, the length of run to the farthest radiator usually being doubled to allow for the resistance of the fittings. Thus if the length to the farthest radiator were 200 ft a total equivalent length of 400 ft would be selected for purposes of design. The total allowable pressure drop must then be chosen.

As stated in Art. 11, the modern tendency is toward low initial pressure at the boiler and small pressure drops in the piping. Far better operation is obtained in average weather under low pressure, and likewise no difficulty is encountered when higher pressures are required. The total pressure drop is divided by the total equivalent length of pipe to obtain the pressure drop per 100 ft. Thus, if the selected total drop is 4 oz and the equivalent length 400 ft, the drop per 100 ft will be $4/4 = 1$ oz or $1/16$ lb. Likewise if the total drop be 2 oz and the equivalent length 300 ft the drop per 100 ft will be $2/3 = 0.66$ oz or $1/24$ lb. The same pressure drop is customarily used in both the steam supply and return sides of a system.

Example 1. The initial gauge pressure at the boiler is limited to 1 lb and the run of pipe to the farthest radiator is 400 ft. What pressure drop per 100 ft should be used?

The total drop should not exceed ½ the gauge pressure or ½ lb. Double the longest run to obtain total equivalent run including resistance of fittings. $400 \times 2 = 800$. Drop per 100 ft is $\frac{1}{2} \div 8 = \frac{1}{16}$ lb.

With the total equivalent direct radiation and the pressure drop per 100 ft of pipe, Table I is consulted to determine the steam pipe sizes and Table II for the return pipe sizes.

The pipe capacities in the tables are based upon ¼ lb of condensation per hr per sq ft of equivalent direct radiation (EDR) and upon actual diameters of reamed standard pipe. Proper reaming of pipe after cutting is im-

Table I. Steam Pipe Capacities for Low Pressure Systems

(Reference to this table will be by column letter *A* through *L*)

This table is based on pipe-size data developed through the research investigations of the American Society of Heating and Ventilating Engineers *

Pipe Size (in.)	Capacities of Steam Mains and Risers								Special Capacities for One-Pipe Systems Only		
	Direction of Condensate Flow in Pipe Line										
	With the Steam in One-Pipe and Two-Pipe Systems						Against the Steam Two-Pipe Only		Supply Risers Up-Feed	Radiator Valves and Vertical Connections	Radiator and Riser Run-outs
	1/32 psi or 1/2 oz Drop	1/24 psi or 2/3 oz Drop	1/16 psi or 1 oz Drop	1/8 psi or 2 oz Drop	1/4 psi or 4 oz Drop	1/2 psi or 8 oz Drop	Vertical	Horizontal			
A	*B*	*C*	*D*	*E*	*F*	*G*	*H* [a]	*I* [c]	*J* [b]	*K*	*L* [c]
	Capacity Expressed in Square Feet EDR										
¾	...	...	30	...	...	...	30	...	25	...	...
1	39	46	56	79	111	157	56	34	45	28	28
1¼	87	100	122	173	245	346	122	75	98	62	62
1½	134	155	190	269	380	538	190	108	152	93	93
2	273	315	386	546	771	1,091	386	195	288	169	169
2½	449	518	635	898	1,270	1,800	635	395	464	...	260
3	822	948	1,160	1,650	2,330	3,290	1,130	700	800	...	475
3½	1,230	1,420	1,740	2,460	3,470	4,910	1,550	1,150	1140	...	745
4	1,740	2,010	2,460	3,480	4,910	6,950	2,040	1,700	1520	...	1110
5	3,210	3,710	4,550	6,430	9,090	12,900	4,200	3,150	...	...	2180
6	5,280	6,100	7,460	10,550	14,900	21,100	7,200	5,600	...	...	...
8	11,000	12,700	15,500	21,970	31,070	43,900	15,000	12,000	...	...	...
10	20,000	23,100	28,300	40,100	56,700	80,200	28,000	23,000	...	...	...
12	32,000	37,100	45,500	64,300	91,000	129,000	46,000	38,000	...	...	...
16	61,000	69,700	84,800	121,000	170,000	242,000	88,000	76,000	...	...	...
	All Horizontal Mains and Down-Feed Risers						Up-Feed Risers	Mains and Undripped Run-outs	Up-Feed Risers	Radiator Connections	Run-outs Not Dripped

Note. Steam at an average pressure of 1 psig is used as a basis for calculating capacities. All drops shown are in psi per 100 ft of equivalent run—based on pipe properly reamed.

[a] Do not use Column *H* for drops of 1/24 or 1/32 psi; substitute Column *C* or Column *B* as required.

[b] Do not use Column *J* for drop 1/32 psi except on sizes 3 in. and over; below 3 in. substitute Column *B*.

[c] On radiator runouts over 8 ft long increase one pipe size over that shown in Table I.

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 476.

Table II. Return Pipe Capacities for Low Pressure Systems

Capacity Expressed in Square Feet of Equivalent Direct Radiation

Reference to this table will be by column letter *M* through *EE*)

This table is based on pipe size data developed through the research investigations of the American Society of Heating and Ventilating Engineers *

Pipe Size (in.)	Capacity of Return Mains and Risers																	
	Mains																	
	$\frac{1}{32}$ psi or $\frac{1}{2}$ oz Drop per 100 ft			$\frac{1}{24}$ psi or $\frac{2}{3}$ oz Drop per 100 ft			$\frac{1}{16}$ psi or 1 oz Drop per 100 ft			$\frac{1}{8}$ psi or 2 oz Drop per 100 ft			$\frac{1}{4}$ psi or 4 oz Drop per 100 ft			$\frac{1}{2}$ psi or 8 oz Drop per 100 ft		
	Wet	Dry	Vac.	Wet	Dry	Vac.	Wet	Dry	Vac.	Wet	Dry	Vac.	Wet	Dry	Vac.	Wet	Dry	Vac.
M	*N*	*O*	*P*	*Q*	*R*	*S*	*T*	*U*	*V*	*W*	*X*	*Y*	*Z*	*AA*	*BB*	*CC*	*DD*	*EE*
¾	.....	.....	.....	.....	.....	326	.....	.....	400	.....	.....	568	.....	.....	800	.....	.....	1,130
1	500	248	.....	580	285	570	700	320	700	1,000	412	994	1,400	460	1,400	.....	.....	1,980
1¼	850	520	.....	990	595	976	1,200	670	1,200	1,700	868	1,700	2,400	962	2,400	.....	.....	3,390
1½	1,350	822	.....	1,570	943	1,550	1,900	1,060	1,900	2,700	1,360	2,700	3,800	1,510	3,800	.....	.....	5,370
2	2,800	1,880	.....	3,240	2,140	3,260	4,000	2,300	4,000	5,600	2,960	5,680	8,000	3,300	8,000	.....	.....	11,300
2½	4,700	3,040	.....	5,300	3,470	5,450	6,700	3,800	6,700	9,400	4,900	9,510	13,400	5,450	13,400	.....	.....	18,900
3	7,500	5,840	.....	8,500	6,250	8,710	10,700	7,000	10,700	15,000	9,000	15,200	21,400	10,000	21,400	.....	.....	30,200
3½	11,000	7,880	.....	13,200	8,800	13,000	16,000	10,000	16,000	22,000	12,900	22,700	32,000	14,300	32,000	.....	.....	45,200
4	15,500	11,700	.....	18,300	13,400	18,000	22,000	15,000	22,000	31,000	19,300	31,200	44,000	21,500	44,000	.....	.....	62,190
5	.....	.....	.....	.....	.....	31,500	.....	.....	38,700	.....	.....	54,900	.....	.....	77,400	.....	.....	109,000
6	.....	.....	.....	.....	.....	50,450	.....	.....	62,000	.....	.....	88,000	.....	.....	124,000	.....	.....	175,000
	Risers																	
¾	.....	190	.....	.....	190	570	.....	190	700	.....	190	994	.....	190	1,400	.....	.....	1,980
1	.....	450	.....	.....	450	976	.....	450	1,200	.....	450	1,700	.....	450	2,400	.....	.....	3,390
1¼	.....	990	.....	.....	990	1,550	.....	990	1,900	.....	990	2,700	.....	990	3,800	.....	.....	5,370
1½	.....	1,500	.....	.....	1,500	3,260	.....	1,500	4,000	.....	1,500	5,680	.....	1,500	8,000	.....	.....	11,300
2	.....	3,000	.....	.....	3,000	5,450	.....	3,000	6,700	.....	3,000	9,510	.....	3,000	13,400	.....	.....	18,900
2½	.....	.....	.....	.....	.....	8,710	.....	.....	10,700	.....	.....	15,200	.....	.....	21,400	.....	.....	30,200
3	.....	.....	.....	.....	.....	13,000	.....	.....	16,000	.....	.....	22.700	.....	.....	32,000	.....	.....	45,200
3½	.....	.....	.....	.....	.....	17,900	.....	.....	22,000	.....	.....	31,200	.....	.....	44,000	.....	.....	62,200
4	.....	.....	.....	.....	.....	31,500	.....	.....	38,700	.....	.....	54,900	.....	.....	77,400	.....	.....	109,000
5	.....	.....	.....	.....	.....	50,500	.....	.....	62,000	.....	.....	88,000	.....	.....	124,000	.....	.....	175,000

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portant, tests showing that unreamed pipe may reduce the capacity of a 1-in. riser as much as 28.7 per cent. In using the tables the following considerations should be noted for practical reasons:

(*a*) Radiator runouts over 8 ft long should be increased 1 pipe size.

(*b*) Pitch of mains should be not less than ⅛ in. in 10 ft.

(*c*) Pitch of horizontal runouts to risers and radiators should not be less than ½ in. in 10 ft.

Example 2 (Fig. 6). *One-Pipe Air Vent.* Radiation 420 sq ft. Longest equivalent run, 90 × 2 = 180 ft. Drop 1/16 lb per 100 ft. Riser runouts not dripped. Up-feed.

Pipe Section	Radiation (sq ft)	Pipe Size (in.)
Supply main AB	420	2½
Supply main BC	350	2
Supply main CD	230	2
Supply main DE	160	1½
Supply main EF	70	1¼
Dry return main	420	1¼
Wet return main	420	1
Riser runouts	120	2
Riser runouts	90	1½
Riser runouts	70	1½

Pipe Section	Radiation (sq ft)	Pipe Size (in.)
Riser I—Lower	70	1¼
Upper	20	¾
Riser II—Lower	120	1½
Upper	50	1¼
Riser III—Lower	70	1¼
Upper	20	¾
Riser IV—Lower	90	1¼
Upper	20	¾
Riser V—Lower	70	1¼
Upper	50	1¼
Radiator branch	20	1
Radiator branch	50	1¼
Radiator branch	70	1½

As noted below it is better practice, however, that return mains be not less than 2 in.

When the equivalent length of run does not exceed 200 ft it is recommended to use 1/16-lb drop per 100 ft. Tables I and II should be consulted in the following manner:

(*a*) For steam main and dripped riser runouts: column *D*.

(*b*) For riser runouts not dripped and radiator runouts: column *L*.

(*c*) For up-feed risers: column *J*.

(*d*) For radiator valves: column *K*.

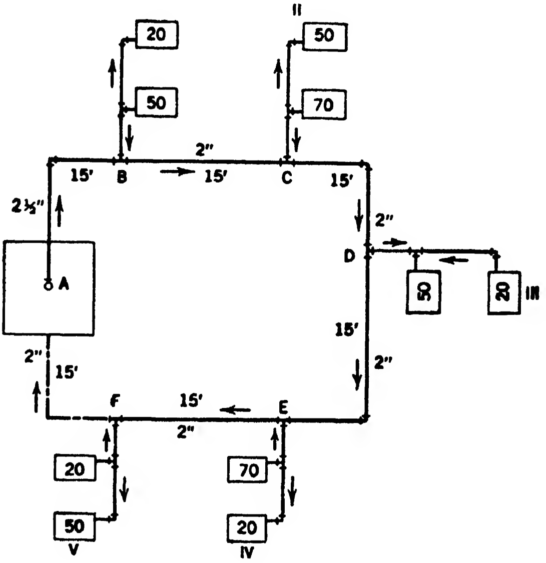
(*e*) For dry return main: column *U*.

(*f*) For wet return main: column *T*.

When the equivalent length of run exceeds 200 ft it is recommended that the total drop be not over ¼ lb. The drop per 100 ft is then obtained and the corresponding columns entered for the pipe sizes. It should be noted that column *H* refers to drops of 1/16 lb and over. For drops of 1/24 and 1/32 lb, column *C* or *B* should be used.

In general it is not desirable that steam supply and return mains be less than 2 in. or that the diameter at the far end of the supply main be less than ½ its largest diameter. It is recommended that supply mains, risers, or riser branches be freely dripped.

Example 3 (Fig. 7). *Two-Pipe Vacuum.* Radiation 5380 sq ft. Longest equivalent run, 320 × 2 = 640 ft. Drop per 100 ft ½ ÷ 6.4 = less than 1/12 lb. Use 1/16 lb. Riser runouts dripped.



Pipe Section	Radiation (sq ft)	Pipe Size (in.)
Supply main AB	5380	6
Supply main BC	5020	6
Supply main CD	4620	5
Supply main DE	4220	5
Supply main EF	3720	5
Supply main FG	3320	5
Supply main GH	2960	5
Supply main HI	2460	4
Supply main IJ	2060	4
Supply main JK	1660	3½
Supply main KL	1160	3
Supply main LM	760	3
Supply main MN	400	2½
Supply risers, I, VI, XII	360	2
II, III, V, VIII, IX, XI, XIII	400	2½
IV, VII, X	500	2½
Riser runouts, I, VI, XII	360	2
II, III, V, VIII, IX, XI, XIII	400	2½
IV, VII, X	500	2½

Pipe Section	Radiation (sq ft)	Pipe Size (in.)
Return main Z_1Z	360	¾
Return main ZY	760	1¼
Return main YX	1160	1½
Return main XW	1660	2
Return main WV	2060	2
Return main VU	2420	2
Return main UT	2920	2
Return main TS	3320	2
Return main SR	3720	2½
Return main RQ	4220	2½
Return main QP	4620	2½
Return main PO	4980	2½
Return main OA	5380	2½
Return risers, I, VI, XII	360	¾
II, III, V, VIII, IX, XI and XIII	400	¾
IV, VII, X	500	¾

Fig. 6. Example 2.

In vacuum systems as in the other systems low pressure drops should also be aimed for. Since this system, however, is generally employed for large buildings with long runs of pipe, a saving in pipe size and consequently in cost is attained by using drops of not less than $\frac{1}{24}$ lb per 100 ft. Thus, if the longest equivalent run were 900 ft and the desired drop per 100 ft were $\frac{1}{24}$ lb, the system would be designed for a total drop of $\frac{9}{24}$ or $\frac{3}{8}$ lb. The total pressure-drop should not exceed 1 lb, however, nor $\frac{1}{8}$ lb drop per 100 ft of equivalent run.

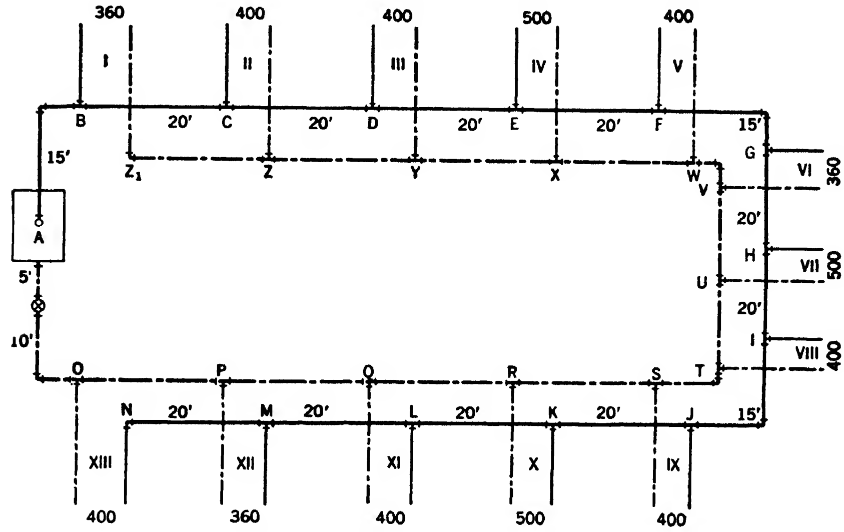


Fig. 7. Example 3.

The supply main should not be less than 2 in. and when 3 in. or over at the boiler or pressure-reducing valve it should be at least $2\frac{1}{2}$ in. at the far end. Supply mains, supply risers, and riser branches should be dripped separately through a thermostatic trap into the vacuum return.

PROBLEMS

1. What characteristic of packless valves makes them well suited for use on the radiatiors of vapor and vacuum systems?

2. List air-vent and vapor systems in the order of (*a*) economy of installation; (*b*) economy of operation.

3. In a one-pipe air-vent system using a pressure drop of $\frac{1}{32}$ lb sq in. per 100 ft of equivalent length of pipe, what size main will supply 800 sq ft of equivalent direct radiation (EDR)?

4. Give (*a*) the square feet of radiation required, (*b*) the riser sizes, and (*c*) the runout sizes of three separately connected radiators, respectively 20,000, 16,000 and 3000 Btu per hr. They are part of a one-pipe air-vent system using a pressure drop of 1/24 lb per sq in. per 100 feet equivalent length of pipe.

5. A two-pipe vacuum system supplies 1,500,000 Btu per hr. The longest run of pipe measures 400 ft, and the total pressure drop in the system is 1/2 lb per sq in. What size main is needed?

6. What is meant by a dripped riser?

7. In tall buildings why are swing joints necessary in radiator runouts from vertical risers?

8. Describe the thermostatic principle as applied to radiator air-vent valves and radiator traps.

9. When are unions preferred to couplings in steam piping?

10. In vapor and vacuum systems why are radiators and the ends of mains trapped?

Chapter 13

HOT WATER HEATING SYSTEMS

1. In general. Hot water heating consists of the circulation of hot water from a central heater through pipes to radiators and back to the heater. A centrifugal circulating pump is the usual motive power. The use of baseboard elements or radiant coils is described in later chapters. The entire system, boiler, pipes, and radiators is full of water under slight pressure to avoid the formation of steam at the usual operating temperature (for radiators) of 212°F. Vents keep the system free of air. In operation the heat emission is based on a cooling range for water of about 20°F.

Gravity systems are no longer frequently specified. They operate at lower average temperatures and through a greater range of cooling. Data for their design may be found in the *Heating, Ventilating, Air Conditioning Guide.*

Hot water heating is not so frequently used in very large buildings but in residences and buildings of moderate size is sometimes preferred to air-vent steam systems. Its response is fast and the radiators do not cool off as much between heating cycles. It is usually more economical to operate although sometimes more expensive to install.

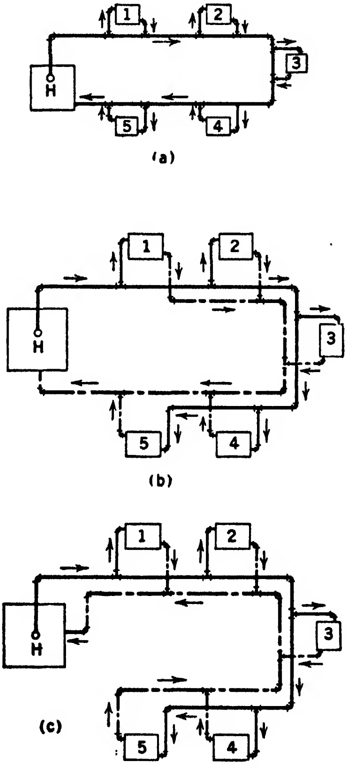
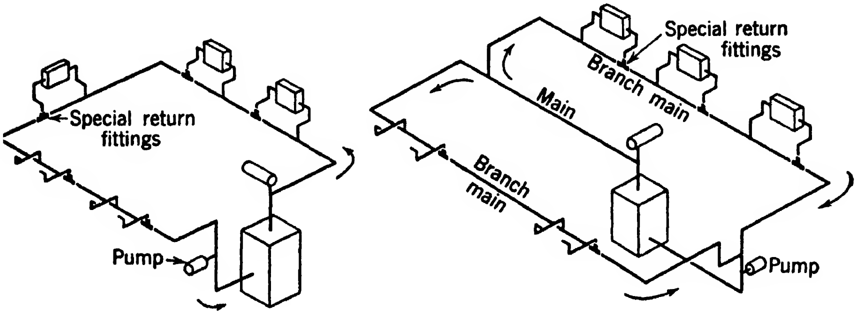


Fig. 1. Supplies and returns.

2. Piping circuits. The one-pipe system [Fig. 1(*a*)] is effective, economical of pipe, and is the one most frequently used. The two-pipe reversed return system [Fig. 1(*b*)] is sometimes preferred for larger installations. Using more pipe, it effects a better distribution of water. The two-pipe direct return [Fig. 1(*c*)] should be avoided when possible because of the inequality in the length of circuits between various radiators and the boiler. Thus radiators 1 and 2 would have to be throttled by pipe orifices (plates with holes of various sizes) or radiators 4 and 5 would have to be increased in size.

3. One-pipe system. Figure 2(*a*) shows the usual single-circuit one-pipe system. Hot water is carried in the main and diverted to the several radiators. A number of special tee fittings have been devised to accomplish this. One kind (Fig. 3) constricts the main, forcing water into the radiator supply branch. A venturi-type jet reduces the pressure in the return fitting, inducing flow of water out of the radiator branch return. The first radiators receive slightly warmer water than the later ones in the circuit, but this difference is negligible. A double-circuit system [Fig. 2(*b*)] is sometimes used for better distribution particularly in larger installations. More than two circuits may be used. In double and multiple circuits no radiation is taken directly off the master main.



(*a*) Single circuit (*b*) Double circuit

Fig. 2. One-pipe forced circulation systems.

4. Two-pipe system (Fig. 4). In a two-pipe system no cool water from radiators is taken back into the supply main, this water being collected in a separate return main. Faster heating with greater uniformity in radiator temperature is accomplished. The system shown is one employing the reversed-return principle. The piping length from the boiler through any radiator and back to the boiler is the same, assuring equal flow because of equal friction. No special fittings are necessary because there is pressure in the supply main and suction in the return main. Piping in any system, either one- or two-pipe, needs no pitch except for drainage.

5. Radiators and air removal. Tubular cast-iron radiators are the most frequently used heating elements in hot water heating. Unlike steam systems where the constant steam temperature makes for a uniform radiator output, hot water systems use radiators fixed in size by the temperature of the water. If water is maintained in the boiler at 215°F and cools 20° through the system, the average water temperature is 205°F and the radiators are chosen on the basis of the output at this temperature. For lower average water temperatures the radi-

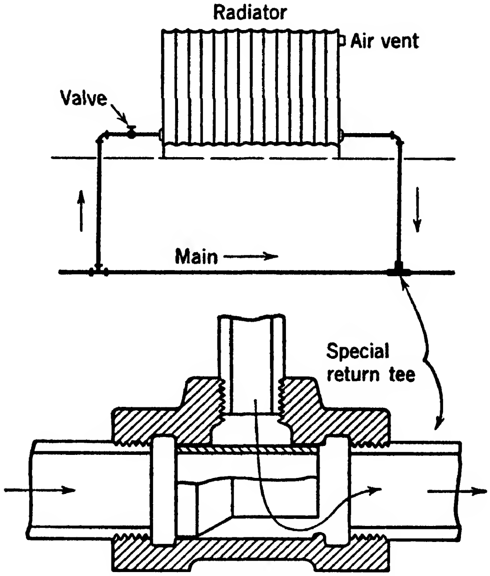


Fig. 3. Special fitting for one-pipe systems.

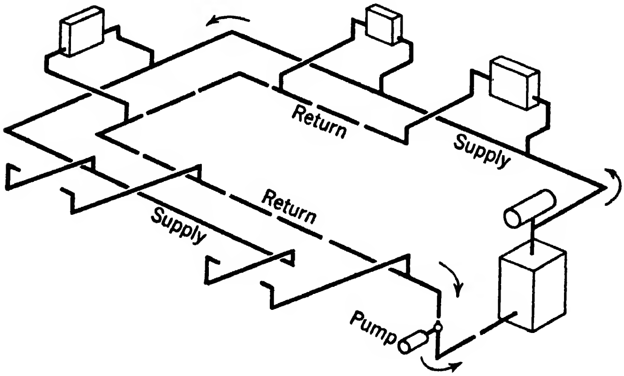
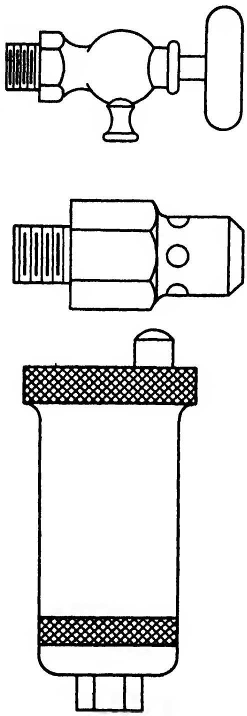


Fig. 4. Two-pipe reversed return forced circulation system.

ator output per square foot of radiation is less and larger radiators must be used. The number of square feet of radiator surface at a fixed room demand in Btu per hour and a fixed average water temperature may be computed from data in Table II, Chapter 16, and a specific radiator of this size may be chosen from Table I of that chapter.

If convectors are used, consult manufacturers' rating of output in Btu per hour at various temperatures. The output of baseboard radiation is discussed in Chapter 14 and of radiant coils in Chapter 15.



(*a*) Manual (for radiators)

(*b*) Automatic (for radiators)

(*c*) Automatic (for piping)

Fig. 5. Air vent valves.

Air must be eliminated from hot water heating systems or they will become air-bound and sluggish in flow. At the boiler the air is vented into the compression tank by means of the fittings shown in Fig. 13. High points in mains are vented by automatic vents [Fig. 5(*c*)]. Radiators are vented at the top where the air collects by manual [Fig. 5(*a*)] or automatic [Fig. 5(*b*)] vents. Manual vents are purge cocks which must be opened to let out the air periodically during the heating season.

6. Use in basementless houses. Although radiator heating is not generally advised for use in houses having concrete slabs on the ground, basementless houses with a crawl space below the first floor can be served well by a hot water radiator system. In this case the boiler could be at the same level or above the radiators, and there would be a down-feed supply main and up-feed branches as shown in Fig. 6. The system illustrated is a one-pipe installation, but a two-pipe system can be used. The pump is placed in the vertical part of the supply main instead of in its usual place in the vertical part of the return main.

7. Adaptability to zoning (Fig. 7). Based on the one-pipe principle in multiple circuits, each having its own pump and flow-control valve (which is a check valve), hot water systems are very well suited to zoning. This installation comprises three separately heated areas—basement, first floor, and second floor. Each can be heated to different temperatures as called for by thermostats in each separate apartment.

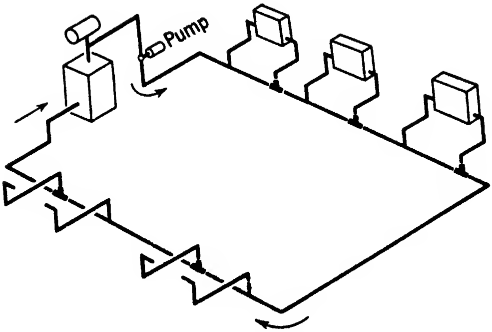


Fig. 6. System for basementless house.

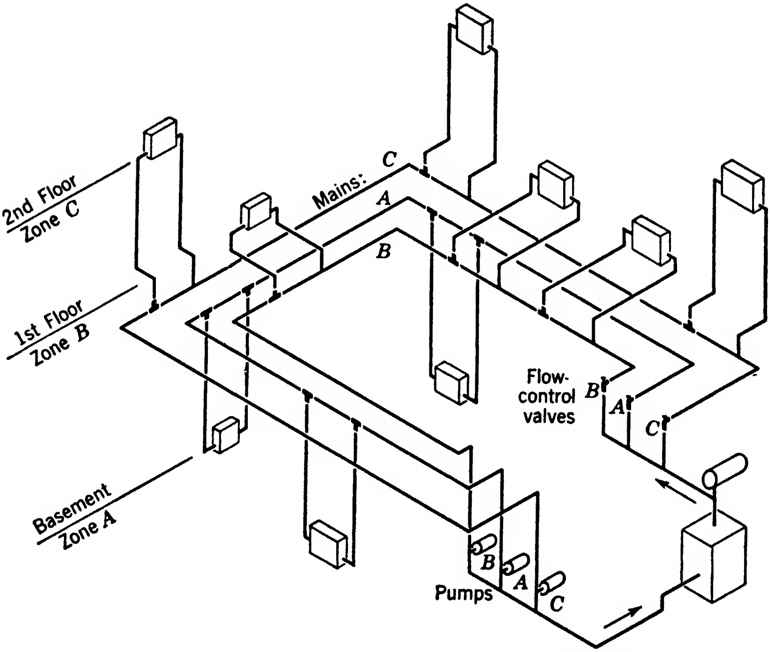
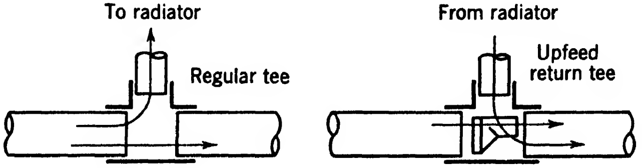
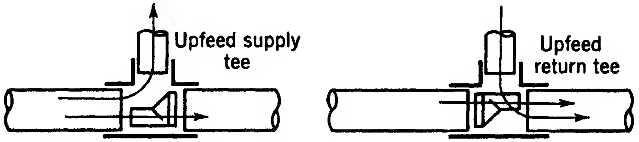


Fig. 7. Three-zone, one-pipe forced circulation system.

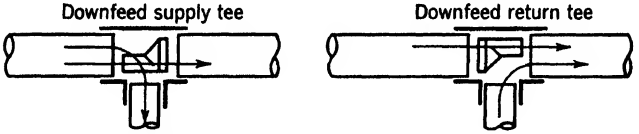
For example, if the thermostat serving the first floor (zone *B*) calls for heat, it turns on pump *B*. The pressure is then relieved in main *B*. Flow control valve *B* opens admitting hot water from the boiler header to main *B*. Flow control valves *A* and *C* remain closed, preventing flow in mains *A* and *C*. Any or all of the zones may operate at one time. The boiler keeps a supply of hot water continually on hand to supply any zone upon demand. This is achieved by an aquastat (water thermostat) immersed in the boiler water. When the boiler water drops below the prescribed temperature it turns on the firing device, such as an oil burner or gas burner, which brings the water up to temperature. If an overhead main supplies down feed, as in the basement of this installation, special down-feed supply and return fittings are necessary. For the first and second floor zones, one special return tee is sufficient. If the designer elects to use also a special up-feed supply tee of the venturi type, higher outputs of the radiators will result, as indicated in Table III, Chapter 14. (See Fig. 8 for illustrations of special fittings.) The system shown in Fig. 7 is a multicircuit one-pipe system. It is possible to apply this same principle of zoning to a multicircuit two-pipe system for very large installations.



(*a*) Usual upfeed connection.



(*b*) Upfeed connection for greater output



(*c*) Required downfeed connection

Fig. 8. Branch radiator connections in one-pipe forced circulation systems. (See Fig. 3 for details of special tee.)

8. Boiler controls (Fig. 9). At the left in Fig. 9 is the main circuit consisting of boiler water circulated to the radiators through a

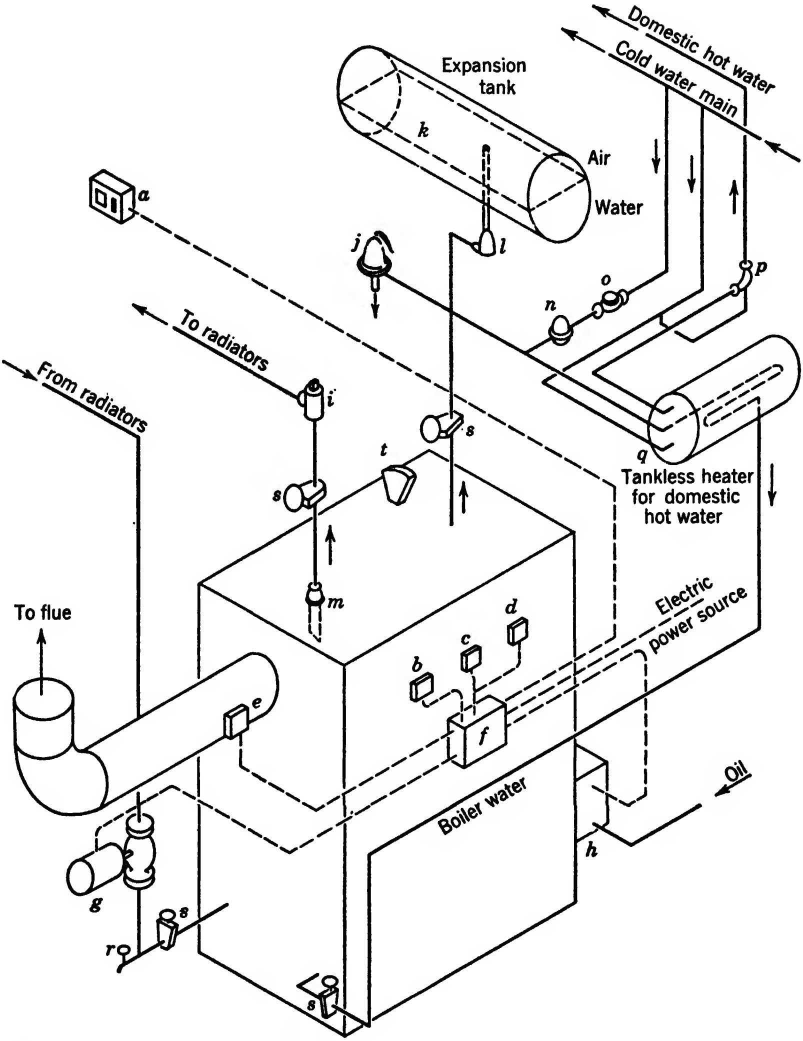


Fig. 9. Electrical and mechanical controls for a hot water forced circulation heating plant.

flow-control valve *i* which opens when circulating pump *g* on the return line starts. At the right is the circuit which operates the domestic hot water system. Boiler water passes through tankless heater *q* and back to the bottom of the boiler. The passage of this hot water heats cold water for use as domestic hot water at sinks and lavatories. Tempering valve *p* prevents the delivery of excessively hot water by mixing cold water as necessary. Coils in tank *q* facilitate the heat transfer without permitting the mixing of boiler water and domestic water. The coil shown is schematic and would be relatively longer. Above the boiler is expansion tank *k* and relief valve *j*, which, respectively, cushion expansion and relieve excessive pressure. When the boiler needs water it is fed in through pressure-reducing valve *n*, back flow into the cold water main being stopped by check valve *o*. The function of each control is as follows:

(*a*) *House Thermostat.* When the room air temperature falls below the setting of the thermostat, the house thermostat turns on the pump and oil burner simultaneously. When satisfied it turns them both off.

(*b*) *Low-Limit Control.* This control turns on the oil burner when the boiler water falls below a chosen temperature (about 160°F).

(*c*) *High-Limit Control.* "Runaway" performance is prevented by this device, which turns off the oil burner when the boiler water starts to exceed a chosen high temperature (often about 200°F).

(*d*) *Reverse-Acting Control.* To prevent the circulation of cold water in the radiators, this control stops the circulating pump when the water falls below 160°F until the burner has had time to raise the temperature again to the desired degree.

(*e*) *Stack-Temperature Control.* After the burner starts, the stack-temperature control waits for the resulting rise in stack temperature. If it does not come in a short time, it turns off the burner which has failed to ignite. This is a safety control.

(*f*) *Junction Box and Relays.* This central control station transmits the impulses of the controls previously described.

(*g*) *Circulating Pump* (Fig. 10). This electrically driven centrifugal pump turns on whenever heat is called for and the boiler water is hot enough (above 160°F). Performance curves for pumps of this type are given in Chapter 14, Fig. 1.

(*h*) *Oil Burner.* Reheat may be needed for a number of reasons. From lack of use the boiler water may have cooled below 160°F. The water may have been cooled in making domestic hot water. Finally, when circulation starts, cold radiator water is returned to the boiler and needs to be heated.

(*i*) *Flow-Control Valve* (Fig. 11). The precise temperature control possible in forced circulation systems is assured by the flow-control valve, which closes when the pump stops, thus preventing gravity circulation which would result in a further rise in room temperature. In principle it is a check valve.

(*j*) *Pressure-Relief Valve* (Fig. 12). When the pressure in the system exceeds 30 lb per sq in., the spring-loaded valve opens, bleeding water out of the pipes and relieving the pressure which might otherwise cause breakage. It should be placed where its discharge will do no damage. With proper system design and adjustment it should not operate except in an emergency.

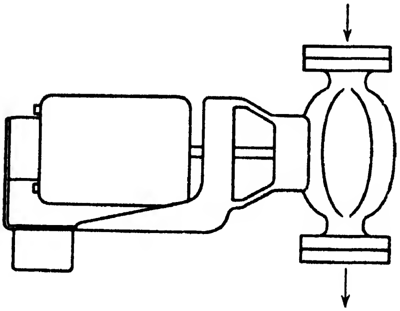


Fig. 10. Circulating pump.

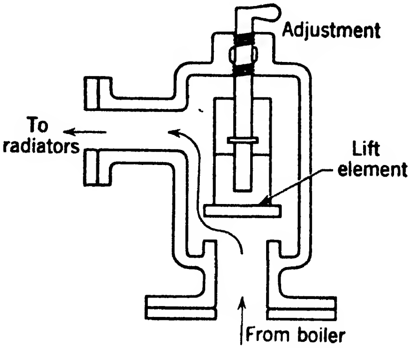


Fig. 11. Angle pattern flow-control valve.

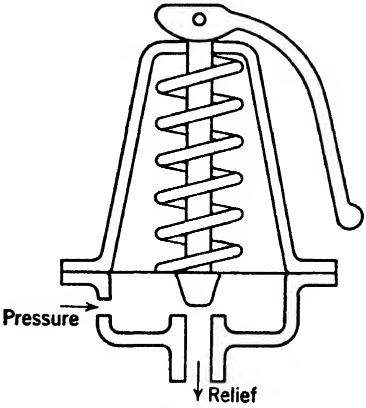


Fig. 12. Pressure relief valve.

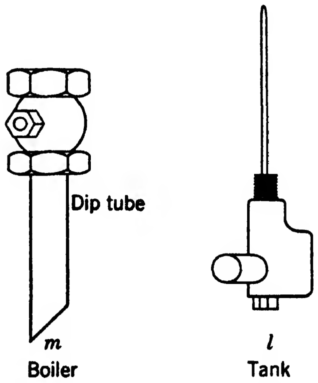


Fig. 13. Air control fittings.

(*k*) *Expansion Tank.* This is sometimes known as a compression tank in closed systems. A cushion of air remains in the top of the tank to adjust for the varying volume of water in the system as the temperature changes.

(*l*) and (*m*) *Tank and Boiler Air-Control Fittings* (Fig. 13). Much of the air in the system is eliminated at once by these fittings, which lead the air to the expansion tank. Air accumulating in the boiler cannot leave through the dip tube *m* but finds its way to *l*, where it is led to the top of the expansion tank.

(*n*) *Pressure-Reducing Valve* (Fig. 14). This is the automatic fill valve. It opens when the pressure in the system drops below 12 lb per sq in. and closes with a check action against higher pressures. It keeps the system full.

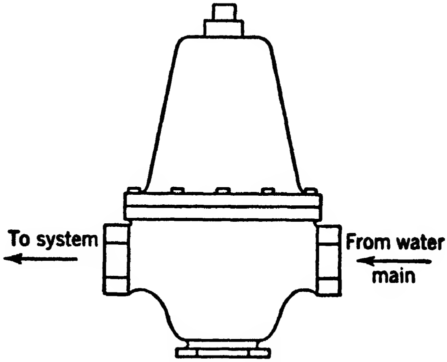


Fig. 14. Pressure reducing valve.

(*o*) *Check Valve.* In an emergency where pressure-relief valve *j* did not open and the pressure-reducing valve failed in its checking action, the check valve *o* prevents the boiler from putting the house cold water system under pressure that would be dangerous.

(*p*) *Tempering Valve* (Fig. 15). This mixing valve operates automatically by a mechanical thermostat to add cold water in sufficient quantities to deliver the domestic hot water at exactly the required temperature.

(*q*) *Tankless Heater.* This generates domestic hot water for use in the various plumbing fixtures Its function and selection is further discussed in Chapter 4, Art. 3(*e*).

(*r*) *Drain.* At this or other low points means of draining the system must be provided.

(*s*) *Gate Valve.* The location of gate valves is determined by the need for shutting off sections of the system for repair or servicing without draining the entire water content. Their selection in preference to globe valves is due to the smaller resistance they offer to the passage of water.

(*t*) *Temperature and Pressure Gauge.* The operating pressure of the system may be observed as a check on the operation and setting of the pressure-relief valve and on the cushioning effect of the compres-

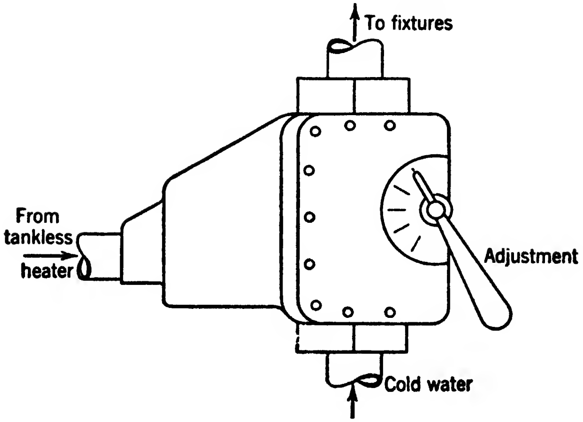


Fig. 15. Temperature valve for domestic hot water.

sion tank. Observation of the boiler temperature is a check on the operation of the aquastat which sets this temperature.

PROBLEMS

1. What are the principles upon which forced circulation hot water heating systems are designed?

2. Explain the nature and effect of the direct return and the reversed return systems.

3. Why are expansion tanks used?

4. How may an adaptation of the one-pipe forced circulation system be used in a two- or three-story building where the stories must be separately controlled?

5. In a closed forced-circulation hot water heating system, using a compression tank and operating under pressure, how are the following functions automatically controlled?

(*a*) Elimination of air from the boiler before it can enter the main.

(*b*) Elimination of air from the radiators.

(*c*) Relief of excessive pressures in the system.

(*d*) Addition of water when necessary.

6. Describe the operation of high- and low-limit controls.

7. How does a special return tee operate in one-pipe systems?

8. Explain the joint operation of the circulating pump and the flow control valve.

9. Describe the action of the stack-temperature control.

10. Why are gate valves preferred to globe valves in water systems?

Chapter 14

DESIGN OF HOT WATER HEATING SYSTEMS

1. Definitions and design principles. In hot water heating systems the following principles are recommended:

(*a*) *Total Equivalent Length.* The length of the longest circuit through which the water is pumped plus a length equivalent to the resistance offered by the fittings, boiler, etc., is the total equivalent length.

(*b*) *Pressure Drop in the Pipe.* This drop due to friction, expressed in milinches of water per foot of pipe is the difference in pressure caused by friction in 1 ft of pipe and represents the static height of water in thousandths of an inch capable of being sustained by this difference in pressure.

(*c*) *Total Friction Head.* Expressed in feet, this head is the column of static water that could be sustained by the difference in pressure in the entire system owing to friction. Thus, if a system were 300 ft long and had a unit frictional resistance of 300 milinches per foot, the total friction head would be $\frac{300 \times 300}{1000 \times 12} = 7.5$ ft. Check this by Table II.

(*d*) *Required Flow.* The required flow is the water flow in gallons per minute to be circulated to make up the hourly heat loss in the building. It is determined by the hourly heat loss and the selected drop in the water temperature.

(*e*) *Pump Rating.* The pump size is selected on the basis of the required flow and the total friction head (Fig. 1).

(*f*) *Required Volume of Expansion Tank.* This is related to the volume of water in the system and the overall rise in temperature from cold water supply temperature to boiler water operating temperature. For maximum rise it can be related to the square feet of radiation in the system (Table IV).

2. Design procedure. The procedure may be outlined as follows:

(*a*) Add to the length of the longest circuit the friction in the various fittings in their equivalents in 90° elbows as taken from Table I to determine the total equivalent length of pipe in the longest circuit. A 90° elbow produces approximately the same friction as a straight pipe of the same diameter 25 diameters long. It is, therefore, necessary to assume an average size of pipe for the system which is later checked.

(*b*) The rate at which the water is to be circulated is then chosen. High velocities reduce the size of pipe but increase the cost of the pump and its operation. A cooling of the water or drop of 20° has proved satisfactory and economical in average systems, on the basis of a reasonable velocity from the pump and a logical relationship between the flow and the size of pipe. A mean temperature of 215° has been found practicable for a system using forced circulation and a closed pressure tank.

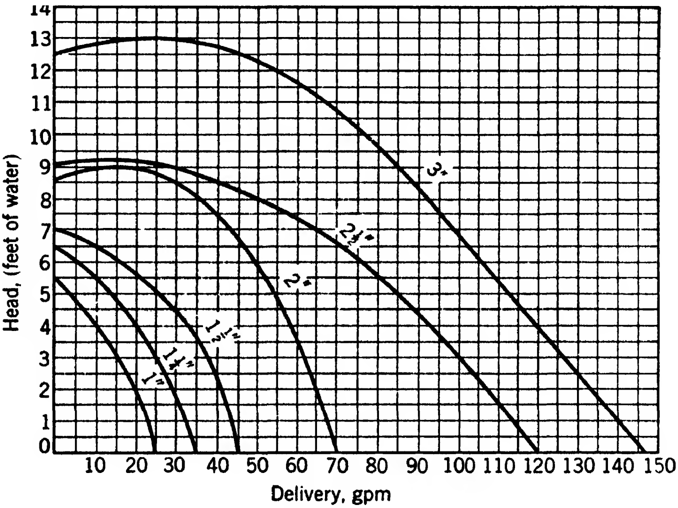


Fig. 1. Performance chart for circulating pump. Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 512.

Table I.* Iron and Copper Elbow Equivalents †

Fitting	Iron Pipe	Copper Tubing	Fitting	Iron Pipe	Copper Tubing
Elbow, 90	1.0	1.0	Angle radiator valve	2.0	3.0
Elbow, 45°	0.7	0.7	Radiator or convector	3.0	4.0
Elbow, 90° long turn	0.5	0.5	Boiler or heater	3.0	4.0
Elbow, welded, 90°	0.5	0.5	Tee, per cent flowing through branch:		
Reduced coupling	0.4	0.4			
Open return band	1.0	1.0	100	1.8	1.2
Open gate valve	0.5	0.7	50	4.0	4.0
Open globe valve	12.0	17.0	25	16.0	20.0

* Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 503.

† The friction in one 90° standard elbow is approximately equal to the friction of a length of straight pipe of the same nominal size and 25 diameters long. Hence, one elbow equivalent in feet of pipe equals 25 diameters (in inches) divided by 12.

(*c*) At the temperatures used in heating, water has approximately a

Table II.* Pipe Sizing Table for Mains, Forced Circulation Hot Water Systems

Section A

Booster Head Pressures (ft)	Total Equivalent Length of Pipe in Feet								
2	40	48	60	68	80	96	120	160	240
2½	50	60	75	86	100	120	150	200	300
3	60	72	90	103	120	144	180	240	360
3½	70	84	105	120	140	168	210	280	420
4	80	96	120	137	160	192	240	320	480
4½	90	108	135	154	180	216	270	360	540
5	100	120	150	171	200	240	300	400	600
5½	110	132	165	188	220	264	330	440	660
6	120	144	180	206	240	288	360	480	720
6½	130	156	195	223	260	312	390	520	780
7	140	168	210	240	280	336	420	560	840
7½	150	180	225	257	300	360	450	600	900
8	160	192	240	274	320	384	480	640	960
8½	170	204	255	291	340	408	510	680	1020
9	180	216	270	308	360	432	540	710	1080
9½	190	228	285	325	380	456	570	760	1140
10	200	240	300	342	400	480	600	800	1200
10½	210	252	315	360	420	504	630	840	1260
11	220	264	330	377	440	528	660	880	1320
11½	230	276	345	394	460	552	690	920	1380
12	240	288	360	411	480	576	720	960	1440

Section B (Based on 20° Temperature Drop)

Main Capacities (in Thousands of Btu)

Pipe Size (in.)	Pressure Drop in Pipe in Milinches per Foot								
	600	500	400	350	300	250	200	150	100
½	19	18	16	15	13	12	10	9	7
¾	41	37	33	30	28	26	23	20	15
1	80	71	64	59	53	48	42	37	31
1¼	170	160	140	130	118	102	90	78	63
1½	260	240	210	185	175	156	140	121	94
2	500	450	410	360	322	294	261	227	182
2½	810	750	670	610	551	523	460	385	310
3	1600	1400	1300	1150	1000	900	800	680	550
3½ †	2300	2100	1850	1650	1500	1350	1190	1020	825
4 †	3200	2900	2600	2300	2100	1950	1700	1350	1140

* Courtesy of Bell and Gossett Co.

† Trunk main capacities only. Fittings are not made larger than 3".

Note. The figures shown in these tables apply to both steel pipe and Type L copper tubing, as capacity differences are not sufficient to cause design errors.

Table III.* Pipe Sizing Table for Risers, One-Pipe Forced Circulation Hot Water Systems with Special Fittings

(Based on 20° Temperature Drop)

Capacity of Risers with Two Fittings (In Thousands of Btu). See Fig. 8(*b*) and (*c*), Chapter 13.

	Pipe Size (in.)	Milinches								
		600	500	400	350	300	250	200	150	100
		Up-Feed Risers—First Floor (See Note 1)								
A	½	23	22	19	18	17	16	14	12	10
	¾	43	41	37	33	30	28	26	22	20
	1	80	73	64	60	55	50	45	39	32
	1¼	180	140	120	110	100	93	80	74	62
		Up-Feed Risers—Second Floor (See Note 2)								
B	½	16	15	14	13	11	10	10	8	7
	¾	31	28	25	24	22	21	18	15	13
	1	58	52	45	43	37	33	32	28	25
	1¼	122	108	92	90	79	72	68	59	50
		Up-Feed Risers—Third Floor (See Note 2)								
C	½	14	12	11	10	9	8	8	7	6
	¾	26	24	23	21	19	18	16	14	12
	1	47	43	38	36	34	31	29	28	25
	1¼	99	91	81	77	70	66	59	56	46
		Down-Feed Risers (See Note 3)								
D	½	16	15	14	12	11	9	8	For less than 200-milinch resistance, base calculations on pump with higher head pressure	
	¾	33	30	26	24	20	18	14		
	1	58	52	43	41	34	29	25		
	1¼	117	106	86	83	69	59	49		

Note. The figures shown in these tables apply to both steel pipe and Type L copper tubing, as capacity differences are not sufficient to cause design errors.

Capacity of Risers with One Fitting (In Thousands of Btu). See Fig. 8(*a*), Chapter 13.

	Pipe Size (in.)	Milinches								
		600	500	400	350	300	250	200	150	100
		Up-Feed Risers—First Floor								
E	½	16.5	15	13	12	11	10.6	10	9.2	8
	¾	29	27	25	24	21	19	18	17	15
	1	50	48	44	41	37	35	33	31	28
	1¼	95	88	78	76	69	62	55.6	48	40
		Up-Feed Risers—Second Floor								
F	½	11	10	9	8	7	7	6	6	4
	¾	20	19	17	16	14	13	12	11	11
	1	34	32	29	28	25	24	22	21	18
	1¼	70	68	59	57	51	49	45	43	36
		Up-Feed Risers—Third Floor								
G	½	9	8	7	7	6	6	6	5	4
	¾	18	16	14	14	12	12	11	10	9
	1	31	29	28	27	24	22	21	20	18
	1¼	63	60	56	52	48	45	43	41	36

Read these notes carefully before sizing risers:

Note 1. First floor up-feed risers—Capacities shown in the table are based upon horizontal branches not more than 3 ft long, with stubs 18″ long, or a total of 9 ft of pipe. 6 elbows, one valve and one union ell, and one C.I. radiator are added for the equivalent length.

For each additional 10 equivalent ft of pipe, move 2 milinch columns to the right.

Note 2. Second and third floor up-feed risers—Capacities shown are based upon horizontal branches not more than 3 ft long, with risers 10 ft high and 20 ft high, respectively. 8 elbows, one valve and one union ell, and C.I. radiator are added for the equivalent length.

For each additional 10 equivalent ft of pipe, move 2 milinch columns to the right.

Note 3. Down-feed risers—Capacities shown are based on a drop of 7 ft to the *center of the radiator*, with not over 3 ft total in horizontal branches, 6 elbows, one valve and one union ell, and one C.I. radiator. For every additional 2 ft of vertical drop, move 1 column to the right in milinch table. On down-feed jobs the main *must* be pitched up and a vent installed on end of main.

* Courtesy of Bell and Gossett Co.

specific heat of 1.0 and a weight of 8 lb per gal. The flow in gallons per minute to produce the total heat required in the radiators is then

$$\frac{\text{Total heat}}{\text{Drop} \times 60 \times 8} = \text{Gallons per minute}$$

or for a drop of 20°

$$\frac{\text{Total heat}}{9600} = \text{Gallons per minute}$$

(*d*) To select the pump the rate of flow and the pressure head must be known. From Table II a friction head and pressure head are chosen which will permit the transmission of the required heat and flow of water through the total length of piping without unreasonably high or low friction and pressure. The friction head in milinches per foot of pipe is found by dividing the total pressure head in milinches by the total equivalent length of pipe; 300, 250 and 200 milinches are frequently satisfactory in systems of medium size. Higher friction heads while permitting smaller pipe, cause high water velocity accompanied by noise. Lower friction heads require larger pipes and cause sluggish water flow.

(*e*) With the friction head in milinches, and the heat loads, the proper size of pipe for each section of the system may be determined from Table II or III.

(*f*) With the rate of flow in gallons per minute and the pressure head in feet the pump may be chosen from Fig. 1.

(*g*) With the total radiation in the system in square feet of cast iron a compression tank of proper size may be selected from Table IV.

Table IV.* Required A.S.M.E. Size of Closed Expansion Tank

Sq Ft of Equivalent Direct Radiation Installed	Gallon Tank	Sq Ft of Equivalent Direct Radiation Installed	Gallon Tank
Up to 350	18	Up to 1400	40
Up to 450	21	Up to 1600	2—30
Up to 650	24	Up to 1800	2—30
Up to 900	30	Up to 2000	2—35
Up to 1100	35	Up to 2400	2—40

For systems with more than 2400 sq ft of installed equivalent direct water radiation, the required capacity of the cushion tank shall be increased on the basis of one gallon tank capacity per 33 sq ft of additional equivalent direct radiation.

* Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 516.

Example 1. Design piping for a forced reversed return system (Fig. 2). Water for each radiator travels through boiler, flow-control valve, radiator, radiator valve, 135 ft of pipe, 10 ells, and 2 tees. Use iron pipe. (A flow-control valve offers resistance equivalent to 20 elbows.)

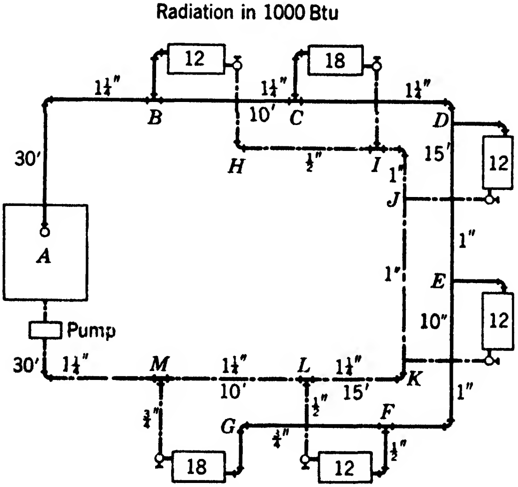


Fig. 2. Example 1.

(*a*) From Table I, friction heads in terms of one elbow are:

1 boiler	3
1 radiator	3
1 radiator valve	2
2 tees	8
10 ells	10
1 flow-control valve	20
	—
	46 elbows

Assuming average pipe diameter to be 1 in., $\frac{46 \times 25 \text{ in.}}{12} = 95$ ft 10 in. Then 135 ft + 95 ft 10 in. = 230 ft 10 in., say 231 ft total equivalent length.

(*b*) Select 215° as average temperature with a 20° drop.

(*c*) Total heat from radiators = 84,000 Btu. Rate of flow = 84,000 ÷ 9600 = 8.75 gal per min.

(*d*) From Table II select 250 milinches as friction loss per foot of pipe. For 231 ft of pipe the pressure head will be 5 ft.

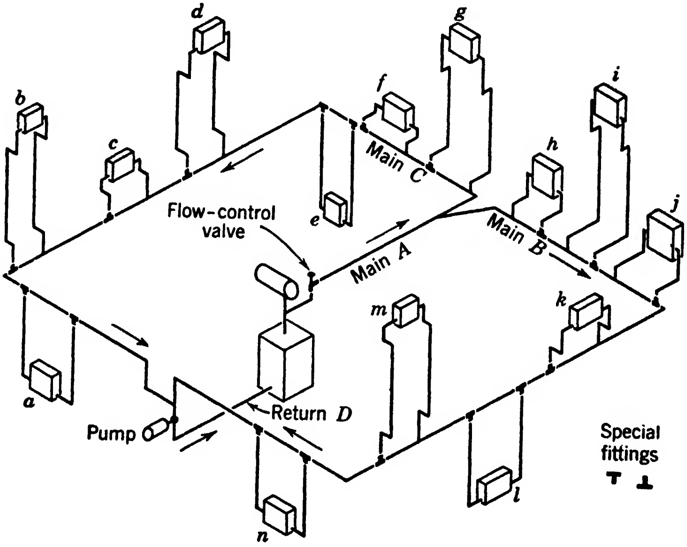
(*e*) From Table II the following pipes are selected for each section:

Pipe Sections, Fig. 2	Heat Supplied (Btu)	Pipe Size (in.)		Pipe Sections, Fig. 2	Heat Supplied (Btu)	Pipe Size (in.)	
		Supply	Return			Supply	Return
AB, AM	84,000	1¼ .	1¼	DE, KJ	42,000	1	1
BC, ML	72,000	1¼	1¼	EF, JI	30,000	1	1
CD, LK	54,000	1¼	1¼	FG, IH	18,000 12,000	¾ ½	¾ ½

(*f*) In Fig. 1 the intersection of lines representing 8.75 gal per min and a pressure head of 5 ft is closest to the performance curve of a 1¼ in. pump. This pump is chosen.

(*g*) 84,000 Btu ÷ 240 = 350 sq ft of radiation. Use an 18-gal expansion tank (Table IV).

Example 2. Design piping for a two-circuit one-pipe forced circulation system (Fig. 3). In passing through the longest circuit (to one of the upstairs radiators) the water travels through boiler, flow-control valve, radiator valve, radiator, 134 ft of pipe, 3 tees, 18 ells. Copper tubing is to be used. The position of special fittings is indicated in Fig. 3 by heavy lines.



Radiation in 1000 Btu per hr (Mbh)

Main *B*	*h*	4	Main *C*	*a*	3
	i	3		*b*	4
	j	9		*c*	8
	k	5		*d*	6
	l	4		*e*	5
	m	6		*f*	4
	n	9		*g*	9
Total		40 Mbh	Total		39 Mbh

Through Main *A* and Return *D* 79 Mbh
Through Main *B* 40 Mbh
Through Main *C* 39 Mbh

Fig. 3. Example 2.

(*a*) From Table I, friction heads in terms of 1 elbow are:

1 boiler	4
1 radiator	4
1 radiator valve	3
3 tees *	12
18 ells	18
1 flow-control valve	20
	61 elbows

* Tees along the run of the main other than those serving 1 radiator are not considered as adding resistance to the flow.

Assuming average pipe diameter to be 1 in., $\frac{61 \times 25 \text{ in.}}{12} = 126$ ft. Then $134 + 126 = 260$ ft total equivalent length.

(*b*) Select 215°F as the average temperature and a 20° drop.

(*c*) Rate of flow through the system: $\frac{79{,}000 \text{ Btu per hr}}{9600} = 8.2$ gal per min through main *A* and return *D*, of which (by a similar calculation) 4.15 gal per min passes through main *B* and 4.05 gal per min passes through main *C*.

(*d*) Select 300 milinches per foot as the pressure drop. For 260 ft equivalent length the pressure head will be 6½ ft (Table II).

(*e*) From Table II it is found that main *A* and return *D* must be 1¼ in. Branch mains *B* and *C* will both be 1 in.

The sizes of risers (from Table III) are as follows:

Second Floor (Table III, *F*)			First Floor (Table III, *E*)			Basement (Table III, *D*)		
b	4 Mbh *	½ in.	*c*	8 Mbh	½ in.	*a*	3 Mbh	½ in.
d	6	½	*f*	4	½	*e*	5	½
g	9	¾	*h*	4	½	*l*	4	½
i	3	½	*j*	9	½	*n*	9	½
m	6	½	*k*	5	½			

* Mbh = 1000 Btu/hr.

(*f*) Reference to the pump performance curves in Fig. 1 indicates that a 1½-in. pump will deliver 8.2 gal per min against a friction head of 6½ ft.

(*g*) 79,000 Btu ÷ 240 = 330 sq ft of radiation. Use 18-gal tank (Table IV).

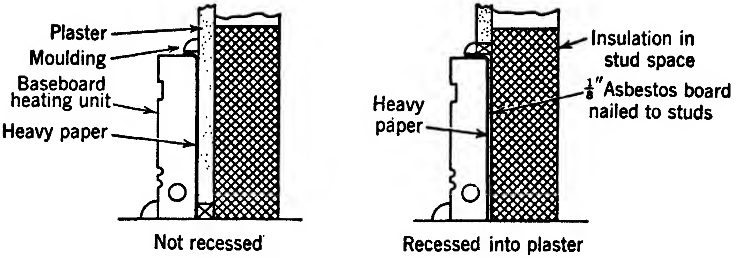
Note. Tables II and III may be used for either steel pipe or Type L copper tubing, as capacity differences are not sufficient to cause design errors.

3. Baseboard heating. This new system of hot water heating consists of passing hot water through low and long cast-iron radiators or sheet-metal convectors shaped like finishing baseboards. The heating units are placed principally on the exterior walls and are connected together by short pipes. The water passes through each heating element in turn. Thus the middle and later units need to be increased in size, as in gravity hot water heating with conventional radiators. This system makes for an economical piping installation and is known as the series loop. For better distribution of the hot water the one-pipe system with special fittings may be used. In that event each unit receives water from the main and discharges back into the same main. Most efficient and suitable for the largest installations is the two-pipe reversed return system. Because of the horizontal position of the heating units, gravity flow is impracticable and forced circulation is quite universal for baseboard heating, regardless of the scheme of the piping.

The one-pipe steam systems found in residences are not suitable for use with baseboard heating because of the difficulty of getting the condensed water out past the entering steam in the same pipe. Hot water is also preferred because the high temperature of steam induces fast convection currents of air past the base elements, which cause dirt streaks on the walls. In closed systems hot water may be used at the same temperature or higher than that of steam, but approved practice is to maintain an average water temperature of not more than 200° in baseboard systems. Lower temperatures are even more desirable since the length of the units must increase for the same room output, and greater comfort and better distribution of heat are the results. The cost of installation is somewhat higher.

4. Characteristics. In some installations baseboards may be preferred to conventional radiation. Architecturally they are less conspicuous than radiators, interfere less with draperies, and can conform to the wood baseboards in appearance. The distribution of air currents is better and there are fewer hot and cold spots in the room. When baseboards are properly installed and a low water temperature is maintained, dirt streaks and dark areas on walls and ceilings are minimized. The difference of temperature between floor and ceiling is often only 4 or 5 degrees compared to 10 or 12 degrees for radiators. The lower outside walls are maintained at a surface temperature higher than in other systems, which increases the comfort of people sitting near them. Baseboards compensate efficiently for the great perimeter heat loss from houses on concrete slabs. They can be installed before plastering begins and used during its progress.

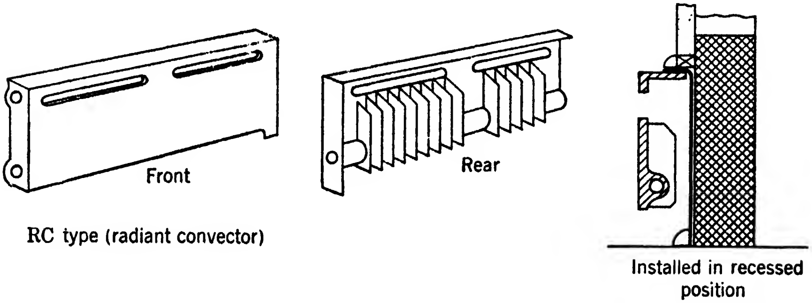
5. Types and ratings (Figs. 4 and 5). Baseboards are made in cast-iron and in the sheet-metal fin and tube type of convector with front casing. The cast-iron units are called radiant because the water flows against the inside of the front face, creating a radiant surface. A further division in this category is between the R and RC types. The RC style has cast-iron fins in a convection chamber, and the unit is raised off the floor to permit air flow. Both R and RC are divided into high height and low height with varying ratings as shown in Fig. 4. They can be installed recessed or flush; in either position heavy paper must be placed in back and turned forward at the top to prevent wall streaking. The Institute of Boiler and Radiator Manufacturers has



Not recessed

Recessed into plaster

R type (radiant)



RC type (radiant convector)

Installed in recessed position

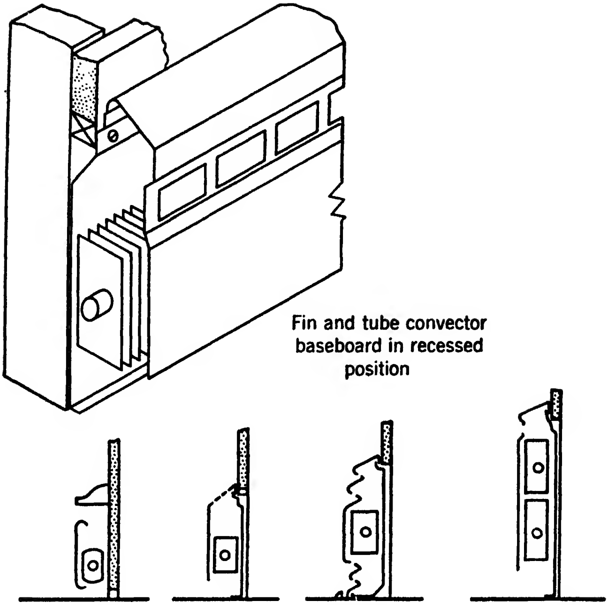
Avg. Water Temp. (°F)	R		RC	
	Low Height 1¾" × 6¾"	High Height 1¾" × 9⅞"	Low Height 2⅛" × 8"	High Height 1⅞" × 9⅞" *
170	182	258	304	426
180	206	292	344	481
190	231	328	385	540
200 †	257	365	429	601
215	300	425	500	700

Output, Btu per hour per linear foot.

* Base dimensions (vary with manufacturer).

† Recommended maximum.

Fig. 4. Cast-iron radiant baseboard.



Various Manufacturers

Avg. Water Temp. (°F)	Reference Number			
	1	2	3	4
	2″ × 8¼″	1⅜″ × 8″	2½″ × 10″	2¼″ × 14″ *
170	310	369	562	872
180	350	421	636	994
190	400	469	722	1110
200 †	450	523	807	1249
215	—	600	948	1420

Output, Btu per hour per linear foot.

* Thickness from plaster, and height.

† Recommended maximum.

Fig. 5. Convector baseboard.

standardized the rating given; most manufacturers adhere to these ratings although not all models are made by every manufacturer.

Ratings of some convector (fin and tube sheet metal) types are shown in Fig. 5. The four types illustrated are of different manufacture and indicate the range of output available. They are off the floor or perforated to permit air flow, and all but one or two types can be recessed. Less wall streaking is found with front-grille than with top-grille units.

Example 3 (Fig. 6). Design a baseboard heating system for the house shown, using series loop piping serving the living room first. The units are to be cast-iron radiant baseboard. The hourly heat losses are indicated. Use 200° water.

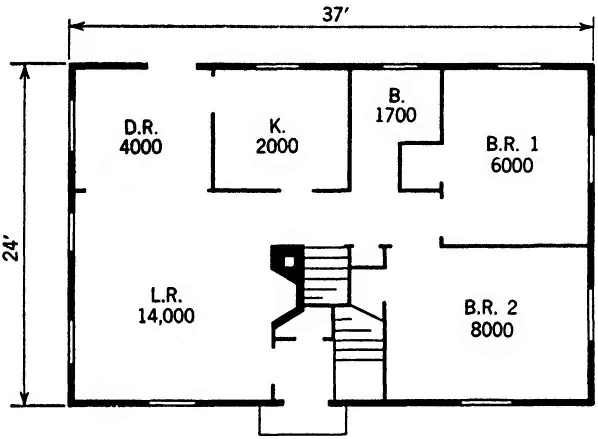


Fig. 6. Example 3.

(*a*) Establish the heat loss from each room and the total for the house. Tabulate the length of exterior wall available for baseboard. Dividing the room heat loss by the available length, find the minimum required output for the baseboard. Select a type of baseboard having an output somewhat greater than required. Find the length of baseboard needed in each space based on the revised output. Divide the radiation roughly into thirds. Increase the middle third by 7½ per cent and the last third by 15 per cent (Table V).

(*b*) Find the flow required at a selected temperature drop of 20°. 32,700 ÷ 9600 = 3.4 gal per min.

(*c*) Find the total equivalent length of piping. Using the perimeter of the building and a drop and rise of 7 ft, the actual pipe circuit is 36 + 36 + 23 + 23 + 7 + 7 = 132 ft. To allow for the piping equivalent to the fittings and equipment, 50 per cent can be added to this. 132 × 1.50 = 198 (say 200 ft).

Table V. Design of Baseboard Heating, Example 3

Space	Hourly Heat Loss (Btu)	Ext. Wall (ft)	Minimum Output	Unit Selected and Output	Revised Base Length (ft)	Correction	Final Base Length (ft)
LR	12,000	28	428	RC low 429	28	×1.00	28
DR	4,000	13	307	RC low 429	10	×1.075	11
K	2,000	9	220	R high 365	5.5	×1.075	6
B	1,700	6	280	R high 365	5.5	×1.075	6
BR 1	6,000	21	283	R high 365	16	×1.15	19
BR 2	7,000	23	305	R high 365	19	×1.15	22
	32,700						

(*d*) Select a pressure drop and find the head in feet of the system. 300 milinches per foot will be used. Table II indicates a head of 5 ft in this column for an equivalent length of 200 ft.

(*e*) Select a size for the main. Table 11, Section A, in the 300-milinch column indicates that a 1-in. main will supply this heat load.

(*f*) Choose a pump. Figure 2 shows that a 1-in. pump is correct to supply 3.4 gal per min against a head of 5 ft. A 1-in. pump is chosen (Fig. 1).

(*g*) Lay out the system (Fig. 7).

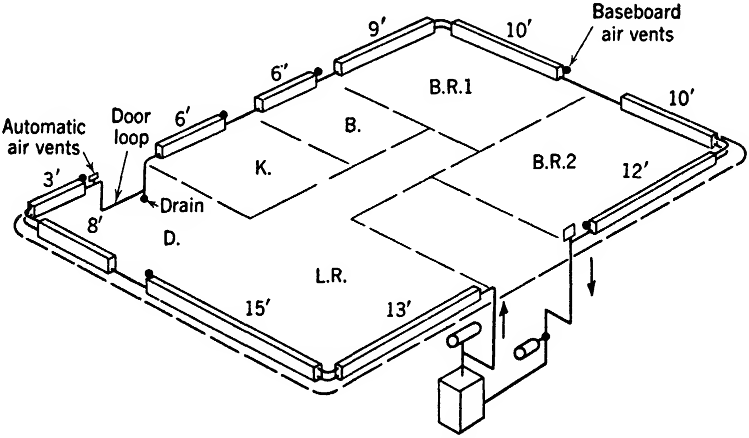


Fig. 7. Example 3.

6. Installation details. In the use of the series loop it is necessary to provide a door loop to depress the main below the base level. These low points should be drained. Air is vented at several places. The expansion tank collects air released in the boiler. Each baseboard is provided with a radiator air vent. When two radiators in the same room are connected together at both top and bottom, only one needs a vent as the air will flow to it through the upper connection. Automatic air vents are advisable just ahead of door loops and where the main drops to return to the boiler. Expansion must be taken into account by allowing 1/8 in. for each 10 ft of radiator. In long buildings where no door loop exists, a horizontal expansion loop is usually placed in a partition to absorb the expansion. Hollow sheet-metal base sections are obtainable to house the pipe between base heating units.

7. Hot water heating in large buildings. Although particularly suitable to dwellings and buildings of moderate size, hot water heat is also satisfactory in very tall buildings. It was adopted for the 60 Wall Tower in New York with perfect success. The water is heated in converters by central station steam and is pumped by turbine steam pumps to overhead horizontal distributing mains in the several zones. The radiation consists of direct-indirect copper convectors enclosed under the window sills and is supplied by down-feed risers from the distributing mains. In ordinary winter weather the water temperature reaches 185° during the morning warm-up, continues at 160° during the day, and drops to 60° at night. Closed expansion tanks are installed in each zone.

Acknowledgment. For permission to reprint Tables II and III and for other design data in this chapter the authors are indebted to the Bell and Gossett Company.

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2. *The B&G Handbook*, 2nd Ed., Bell and Gossett Co., Morton Grove, Illinois.

3. "Study of a Baseboard Convector Heating System in a Test Bungalow," *National Bureau of Standards BMS 115*, Superintendent of Documents, Washington, D. C.

PROBLEMS

1. A forced hot water heating system has a total design output of 60,000 Btu per hr. The total equivalent length of piping including an allowance for the resistance of fittings is 310 ft. The temperature drop in the system is 20°F. Using a pressure drop due to friction of 250 milinches per foot of pipe, select a supply main and a pump.

2. A living room has a heat loss of 10,200 Btu per hr and an available exterior wall length of 28 ft. Using 200°F as an average hot water temperature, select a type of cast-iron baseboard for the room.

3. What are the advantages of hot water heating over a one-pipe air-vent steam heating system?

4. What advantages do radiant baseboards have over conventional cast-iron radiators?

5. What principles govern the size of an expansion tank?

6. What adjustment needs to be made in the selection of heating units in the middle one-third and the last one-third for a series loop baseboard installation?

7. What is the difference in the R and RC types of cast-iron baseboard?

8. What is the range of sizes for fin-tube baseboard elements?

9. What is the function of a door loop in a series loop baseboard system?

10. Where no door loop exists how is expansion provided for in a series loop system?

Chapter 15

RADIANT PANEL HEATING

1. Panel heating in general. When heat losses in rooms are made up by means of warmed panels or sections of ceilings, walls, or floors the heating system is known as panel or radiant heating. The larger part of the heat is given off radiantly rather than by convection as in many other schemes. There are several methods of warming the panels. Hot water circulated in pipes which are imbedded in concrete or plaster is a common method as is also the passage of warm air in floor tiles or in the space above hung ceilings. Electricity may be used to warm large sections of room surfaces or to provide more concentrated, smaller radiant panels. Owing to its high temperatures, steam is unsuitable.

As in other heating systems, the function of radiant heating is not only to balance the heat losses from rooms but also to maintain bodily comfort. When the average temperature of the floor, walls, and ceiling is increased the emission of radiant heat from the body of an occupant to those surfaces is decreased. Since the air in the room is appreciably warmed only by the low rate of convection, the convective body heat loss continues. Thus the occupant feels warmth and comfort while at the same time enjoying the proximity of refreshing cooler air.

2. Kinds of systems. Because of discomfort to occupants and cracking of plaster, temperatures are limited. Ceilings commonly do not exceed 115°F, and floors are often held to 85°F. Hot water is quite universally used in pipes which are laid in concrete or covered by plaster. The temperature of the water is lower than that used in conventional forced hot water heating systems, being not higher than an average of 150°F for ceilings and 140° for floors.

For one-story or multistory buildings with cellars, ceiling installations consisting of thin copper tubing in the plaster are common. For one-story structures with no cellar and with a concrete slab on the ground, copper tubing, or for greater ruggedness wrought iron or steel, imbedded in the concrete floor is a popular choice. The floor systems are somewhat less expensive. The bulk of the concrete in floors has a large thermal storage capacity and creates a slow response to change in the heating requirements in the room. Thus for stable requirements the floor system is quite suitable for structures with walls of high thermal resistance, whereas the quick changes needed in a solar house of large glass areas often suggest the use of the faster-responding ceiling panels.

3. Advantages and disadvantages of radiant heating. For houses on concrete slabs with no crawl space or cellar, radiant heating is one of the few systems that is effectively usable. From the standpoint of comfort, floor panels are preferred. In any radiant system the temperature at the floor is higher, and in general there is better temperature distribution throughout the room than in other methods of heating. No system compares with it architecturally because no heating element is visible in any living space. Lower air temperatures can be maintained which result in a superior feeling of well being and in a greater relative humidity, usually desirable in winter. Operating costs may be slightly lower because the air temperature is lower, reducing the actual heat loss from the structure. Installation costs are the same or a little more than in other systems. The lack of concentrated heating elements reduces the convection currents and prevents dirt streaking on the walls and ceiling. Floor and ceiling systems make possible the shifting of partitions if the panels are planned to occupy the entire ceiling or floor space.

On the other hand, leaks, though not common, are costly to repair. There may be discomfort at peak operation when the panels are hottest. Under these conditions the air temperature should be somewhat reduced but it usually rises. Even with outdoor thermostat or anticipator controls many panel installations are sluggish and may be overhot or overcold until the compensation is made. Finally, alterations involving large openings in the floor or ceiling are difficult.

Systems Using Hot Water

4. Choice of a panel. It is possible to use ceiling, wall, or floor panels in water radiant systems. For various reasons the wall has not proved a very popular location in average cases. As between ceiling and floor, the ceiling is usually more expensive because of the greater trouble involved in installing the coils. The structural building plan may suggest at once the best location. From the utilitarian point of view a building with a stable heat loss can use floor coils in concrete, whereas another with speedy changes in heat loss or gain should be equipped with a ceiling installation. Greater outputs are possible in ceiling surface; therefore in an installation that is short of available panel area ceilings are preferred. Since this difference in output calls for different water temperatures, the hotter water of the ceiling coils may have to be reduced in temperature for an auxiliary floor coil. It is, therefore, the simplest practice to use all floors or all ceilings in any given building.

5. Material for coils. Steel and wrought iron are somewhat more rugged and suitable for floor coils where injury may occur before concreting. With care copper may, however, be used in floors. Being weldable, steel or wrought iron is easily formed off the job into grids which are efficient in reducing friction, whereas copper is more adaptable to the continuous loop coil. Copper tubing ($3/8''$) is often used for ceiling coils placed under the lath and plastered from below. Larger sizes of tube may be placed above the lath, and the plaster may be pushed through to imbed them.

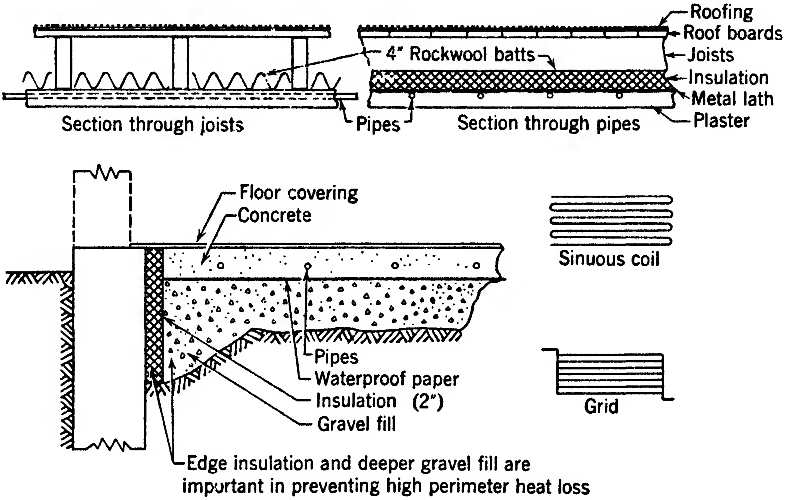

Fig. 1. Typical ceiling and floor installations of radiant pipe coils.

6. Type of coils (Fig. 1). The grid type and the reversed return are efficient but it is not necessary to adhere strictly to this system. The slightly increased pumping cost caused by the friction in the loop style is not great, and if some coils are reversed return and some direct the resulting inequality of flow can be adjusted at the balancing valves. The loop coil is known also as a sinuous or serpentine coil.

7. Emissivity of surfaces. Plaster, concrete, and other usual surfaces emit heat about 90 per cent as efficiently as a perfect radiating surface. On floors, wood in mastic, asphalt tile, or light carpeting may be used without serious interference with the efficiency. Where a great deal of heavy carpeting and much furniture is expected a ceiling installation should be chosen. The most usual detail of imbedment of coils in plaster and concrete is shown in Fig. 1.

8. Routing of pipes. Headers, together with manual vents and adjusting valves, can all be placed in the utility room, making centralized control. In large houses mains can serve remote headers and control points located conveniently in closets or similar space. The best arrangement is for the hot pipes supplying each room to go direct to the most exposed wall and be led inward as the water cools.

9. Venting. In floor systems where the coils are below the boiler an air vent can be placed in the high piping at the boiler and at one or two remote points in the piping, rising to an air reservoir and vented there. Air that collects in ceiling systems is carried along by the high velocity of the water in the small pipes and may be released through the vent valves or pet cocks near the return headers. Automatic vent valves in the return headers are additional safeguards against air binding. (See Fig. 8.)

10. Coil layout. Coils of the sinuous type should not exceed the lengths recommended below; otherwise the friction becomes excessive.

Recommended Maximum Length of Individual Loops (Sinuous Coils)

Nominal Diameter (in.)	Maximum Coil Length	
	Tube (ft)	Pipe (ft)
3/8	120	
1/2	150	250
3/4	250	350
1	500	500

11. Methods of design. A number of variations in the selection of the panel location, size of pipes, type of coil whether grid or serpentine, water temperature, water temperature drop, and the varying temperature conditions of the surrounding surfaces are possible. The output of a panel of fixed temperature depends partly on the average temperature of the unheated surfaces. Because part of the output is convective it depends also on the air temperature. It is usual to establish an average temperature between the mean radiant temperature (MRT) of the unheated walls, and the temperature of the air. For residential design 70°F is frequently used for this purpose and is the basis of Fig. 2. The temperature drop in the system is usually 20° for ceilings and 10° for floors. Reverse flow or output in the direction away from the desired output surface is subject to exact calculations and dependent upon the nature of the construction on the side of the pipes away from the room heated. For the construction of the floor above the panel in zone *A* (Fig. 6) and the ceiling above the panel in zone *B* (Fig. 7), the reverse flows are approximately 25 per cent and 10 per cent, respectively, of the value of the direct output and are in addition to it. Thus the direct output is used for the room below,

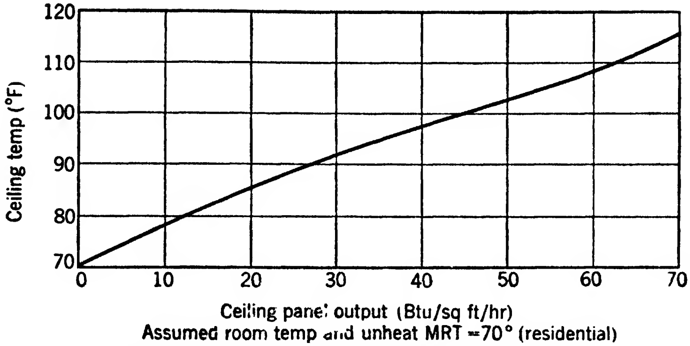

Fig. 2. Output at various ceiling temperatures.

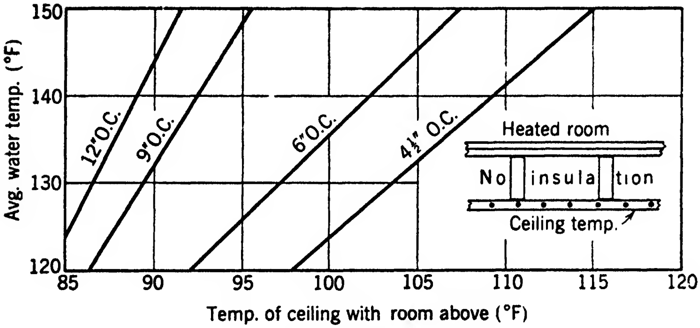

Fig. 3. Spacing of ⅜" tubing.

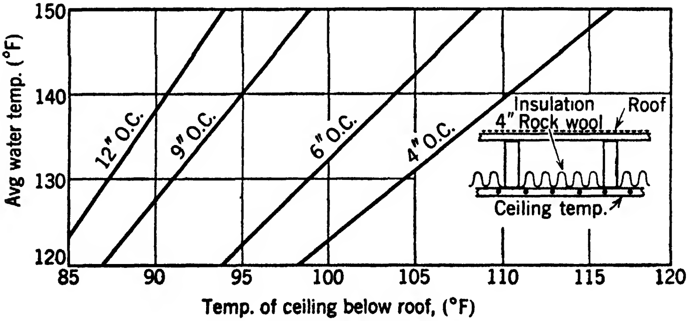

Fig. 4. Spacing of ⅜" tubing.

and the reverse flow is to the credit of the room above (or lost to attic space as in zone *B*). In computing the amount of water circulated through a given panel, the amount of reverse flow must be added to the direct output to determine the heat to be made up.

12. Typical design of a ceiling-type hot water radiant system.

Example 1. Figure 5 shows floor plans of a residence for which a design summary follows. Table I is a design schedule showing the sequence

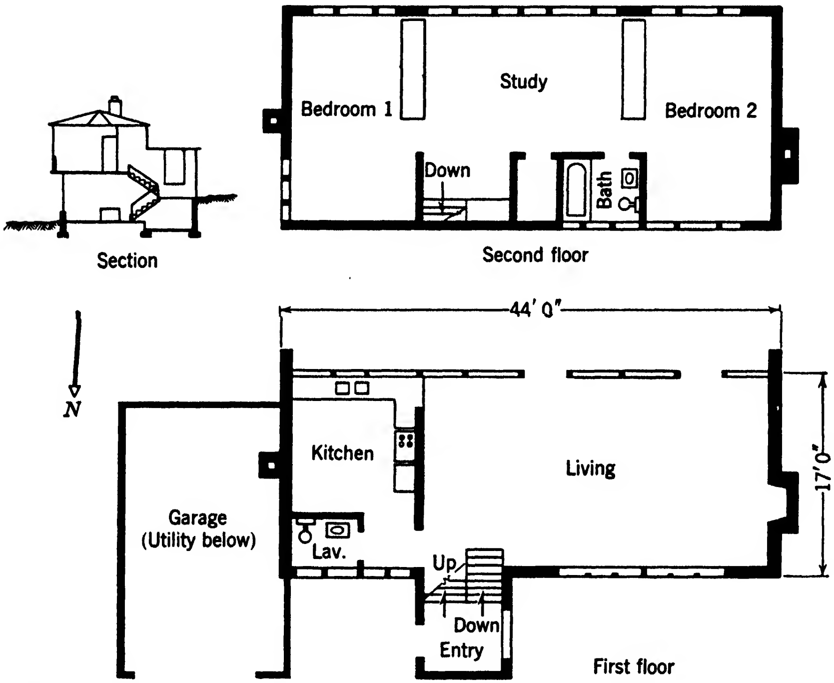

Fig. 5. Floor plans for design of radiant system, Example 1. Courtesy of Olindo Grossi, Architect.

of steps. The first step is to compute the area available in each ceiling for radiant panels. The heat loss is computed for each room but does *not* include the usual loss through the ceiling panel. The required output of the panel is computed from the room heat loss but the water passing through the coils must make up the output and also the reverse flow. Columns 4 and 5 list the adjustments for reverse flow. Column 6 is the design column for coils and represents the net room heat loss for the first story and the net room heat loss (*less* the gain from the lower rooms) of the rooms in the upper story. If all the ceiling areas were used for pipes, the required output would be as shown in column 7. The living room shows a need for 61 Btu per hr per sq ft. Figure 2 indicates that this amount

Table I. System Design Schedule (Example 1)

Average water temperature, 140°
Temperature drop in system, 20°
Use ⅜" copper tube

Column No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			Heat Losses (Btu/hr)												
	Space	Ceiling Area (sq ft)	From rooms not including reverse flow	Reverse flow from coils through roof	Reverse flow from coils to 2nd story	Corrected heat loss for coil design, (3) − (5)	Required Output if Entire Ceiling Is Used, (6) ÷ (2) (Btu/sq ft/hr)	Spacing Selected (inches o.c.)	Ceiling Panel Temperature Required, °F (Fig. 5)	Actual Panel Output (Btu/sq ft/hr) (Fig. 4)	Panel Area Required (6) ÷ (10) (sq ft)	Factor to Convert to Lin Ft of Tube (lin ft/sq ft)	Lin Ft of Tube Required	No. of Coils per Room (limit = 120')	Coil Identification Number
Zone A First story	Liv.-Din. Kit.-Lav. Entry	443 173 66	22,000 8,000 2,500	250		22,000 8,000 2,500	50 46 30	4½ 4½ 6	109 109 102	61 61 48	360 131 52	2.67 2.67 2.00	960 350 104	8 3 1	1–8 9–11 12
	Totals		32,500	250		32,500							1414		
	For water circulation, zone A 32,500 + 9110 + 250 = 41,860 Btu		$\frac{41,860}{9600} = 4.36$ gpm (Fig. 6)												
Zone B Second story	B.R. 1 B.R. 2 Study Bath	200 228 269 38	6,000 6,600 8,500 2,000	600 620 850 200	2500 2820 3320 470	3,500 3,780 5,180 1,530	17 17.5 19 40	9 * 9 9 6	95 95 95 102	35 35 35 48	100 108 148 32	1.33 1.33 1.33 2.00	133 143 197 64	2 2 2 1	13–14 15–16 17–18 19
	Totals		23,100	2270	9110	13,990							537 1951 †		
	For water circulation, zone B 23,100 + 2270 − 9110 = 16,260 Btu		$\frac{16,260}{9600} = 1.70$ gpm												

For boiler capacity 41,860 + 16,260 = 58,120 Btu/hr net connected load (exclusive of domestic hot water demand).

* 9" o.c. is maximum recommended spacing for ceiling panels.

† Total for house.

requires a ceiling temperature of 109°, close to the maximum permitted which is about 115°. Figure 3 indicates a required 4½-in. spacing of ⅜-in. tubes at an average water temperature of 140°. Since this is the critical output it sets the water temperature (average) for the entire installation. Now it is possible to fill the other ceilings with pipes on wider spacings. However, for economy the pipes are often limited to a portion of the ceiling only, stressing the locations of greatest heat loss, as over the vicinity of large glass areas. A selection of pipe spacings is made in column 8 and the corresponding output (from Figs. 3 and 4) is listed in column 10 after the ceiling temperature has been established in each case (column 9). The area of panel required in each room is shown in column 11. In the living room, kitchen, entry, and upstairs bath a large percentage of the ceiling area is used, but the other rooms are served by smaller portions of their ceilings. Multiplying by the factor in column 12, the linear footage of pipe is arrived at and listed in column 13. This is useful in ordering. Limiting the coil lengths to about 120 lin ft and attempting to equalize them results in the number of coils per room shown in column 14.

13. Coil layout and circuits. The arrangement of the building will shape the coils and their connection to the headers. Figures 6 and 7 summarize the most desirable coil placement and connections. Note that the hottest water flows first along the coldest area over windows and that the return water is drawn back in the interior areas of the house. No attempt was made here to equalize exactly the length or resistance of each coil circuit or to achieve a reversed return hook-up. Equalization can be accomplished by means of the balancing valves. This house suggests the use of a two-zone system which is one of the advantages of forced hot water radiant schemes. This is made possible by using two pumps and two sets of controls. Thus the upstairs rooms, used largely for sleeping, can be maintained at a different temperature than the downstairs living space. Coil 12 rises to an intermediate ceiling level and drops again to join the other coils in zone *A*. It operates with the living-space coils. (See cross section in Fig. 5.)

14. Equipment and controls. The piping arrangements from the headers to the boiler are shown in Fig. 8. Boiler water is maintained at about 200° by means of an aquastat-controlled oil burner or gas unit. The regulating valves use this boiler water and mix it with 130° return water to produce the 150° water temperature for delivery to the coils. The flow-control valves insure individual action of the zones in response to their respective pumps and prevent water flow in summer when the system is used for domestic hot water only. The balancing valves are shown as well as the manually operated vent valves or pet cocks to rid the system of air. Automatic vents supplement these. Changes in room temperature or outdoor temperature affect the operation of the zone pumps. Each zone indoor thermostat turns

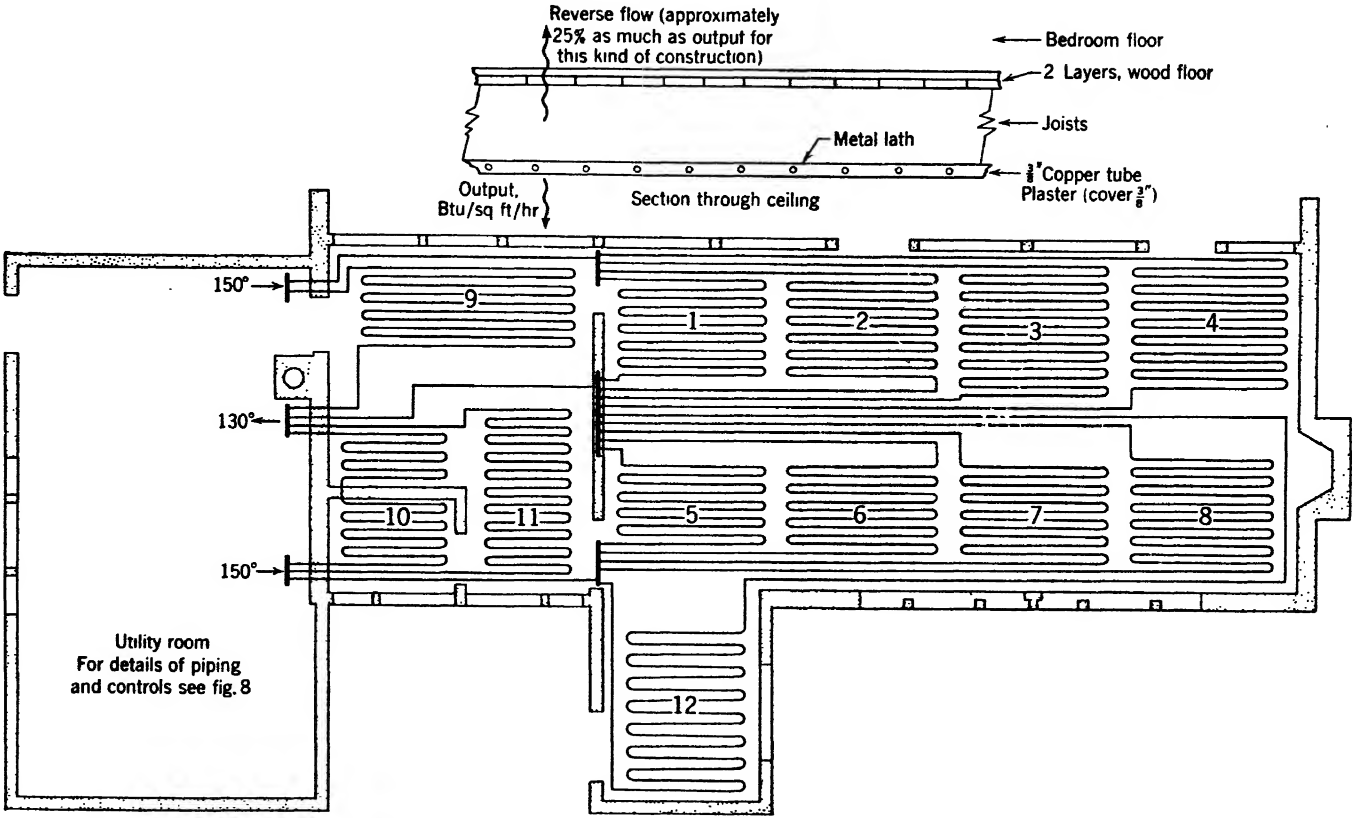

Fig. 6. Zone *A*, ceiling of the first story. Note that coils lie in a plane and do not cross each other.

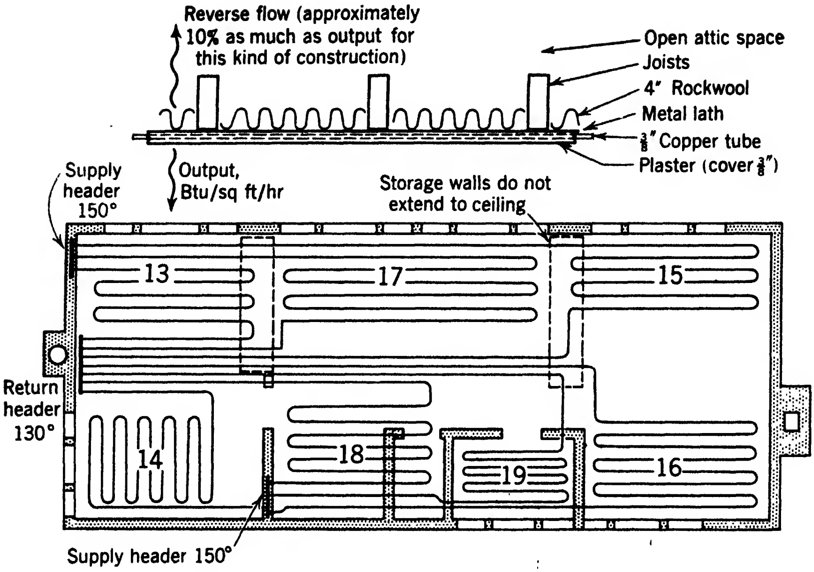

Fig. 7. Zone *B*, ceiling of the second story.

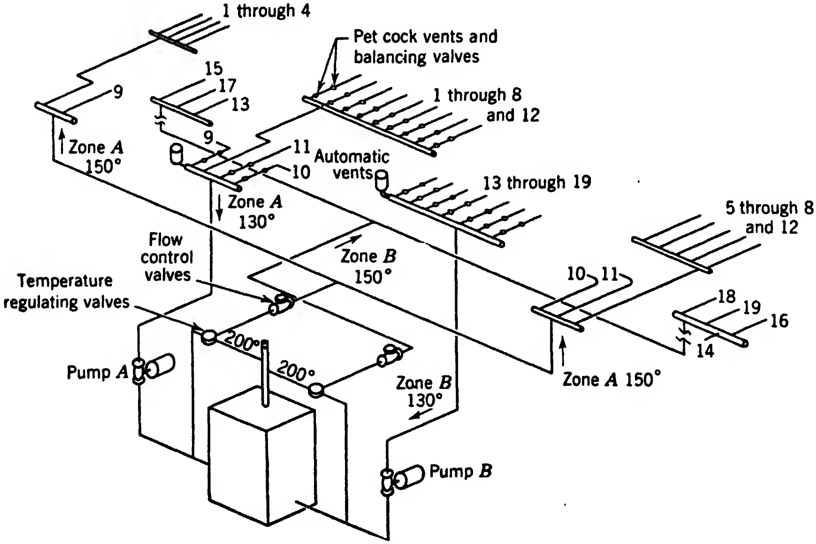

Fig. 8. Piping diagram for 2-zone ceiling-type radiant heating system for house shown in Fig. 5.

off its own pump when satisfied, and both pumps are turned on by the action of an outdoor thermostat or anticipator, which starts the system when the outside temperature drops, thus preparing the panel surface to work at higher capacity as the room heat loss increases. The calculation of water flow and the selection of main and pump sizes follow the usual procedures for hot water systems. With a 20° drop 1 gal per min delivers 9600 Btu per hr. (Refer to Chapter 14, Art. 2.) Table I gives 41,860 Btu per hr as the requirements of zone *A*. Dividing by 9600, we arrive at a required flow of 4.36 gpm. In this case 1-in. pumps and 1-in. supply mains are used. Headers are often 1½ or 2 in. for good flow.

15. Installation and testing. Where possible the tubing should run across the joists since this makes the easiest fastening. For convenience of repair and adjustment, balancing valves, vents, boiler connections, and similar equipment must all be in accessible places, preferably the utility room. Mains, tubing, controls or vents in outside walls, attic space, or other exposed locations must be insulated to protect against freezing. If the piping to be buried in the ceiling or floor holds a test pressure of 200 lb per sq in. for 8 or 10 hr without leakage, it can be considered safe. Other more accessible parts can be easily repaired in case of leakage. The contractor should guarantee to balance the system during the first heating season.

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PROBLEMS

1. What are the characteristics of ceiling installations as compared to floor installations of radiant pipes in regard to the following items? (*a*) maximum possible output capacity; (*b*) maximum permissible temperature; (*c*) speed of response; (*d*) expense of installation.

2. Compare the following in respect to the items mentioned: (*a*) grid and coil piping in regard to friction and resistance to flow; (*b*) wrought-iron pipe and copper tubing in regard to the location of installation.

3. A living room 13 × 20 ft in size is served by a ceiling system. The ceiling is conventional frame construction with a heated room above. The living room heat loss is 13,000 Btu per hr and the average water temperature to be used is 140°F. Select a spacing of ⅜-in. diameter copper tubes to give the required output.

4. A living room ceiling radiant panel is 250 sq ft in area. What is (*a*) its maximum possible output, (*b*) average water temperature and spacing of ⅜-in. copper tubes? Ceiling condition same as in question 3.

5. A room on the top story of a house of conventional frame construction has radiant piping in plaster below 4 in. of rock-wool insulation. The average water temperature is 130°F, and the spacing of ⅜-in. tubing is 4½ in. What is (*a*) the ceiling surface temperature? (*b*) The output rate?

6. How may water at 140°F be delivered to radiant coils in a system where the boiler operates at 200°F?

7. Where should air vents be located?

8. Where is insulation placed with relation to (*a*) ceiling panels, (*b*) floor panels in concrete slabs.

9. What is the function of an outdoor anticipator?

10. What test insures the tightness of piping to be buried in plaster or concrete?

Chapter 16

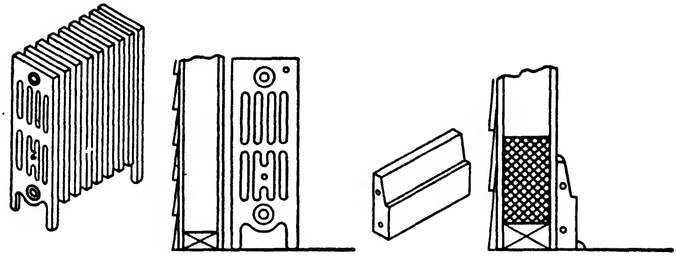
RADIATORS, BOILERS, AND FUEL

1. Types of radiators (Fig. 1). Steam and hot water heating systems utilize various types of radiators. The most common type is the small-tube cast-iron radiator [Fig. 1(*a*)], which is now quite standardized and discussed more fully in Art. 2 of this chapter. It has pipe tappings top and bottom at both ends as well as vent tappings at top and at midheight. With varying pipe and vent connections it is suitable for either steam or hot water. Figure 1(*b*) is a slightly different form of cast-iron radiator suitable for recessing. When equipped with a bottom grille it presents a flush front, which interferes very little with room cleaning or furniture arrangement. Types *c* and *d* are convector units housed in sheet-metal enclosures which can extend into the room or be recessed. They are often provided with dampers to control convection currents. For use in residential hot water systems, baseboard units 1(*e*) and 1(*f*) are popular. They are discussed in Chapter 14. Industrial planning often favors types 1(*g*) and 1(*h*), which are wall-hung and permit easy cleaning and maintenance of floors.

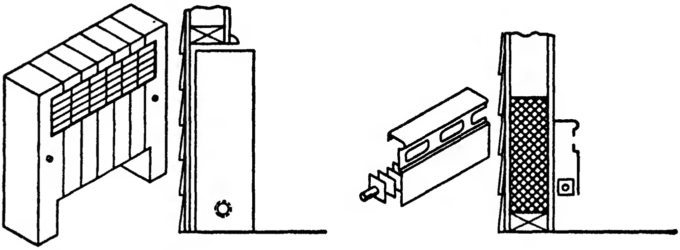
2. Small-tube cast-iron radiators (Fig. 2). The standard length of section in this kind of radiator is 1¾ in. Radiator output depends upon height, number of tubes, and number of sections. If the temperature of the heating medium is less, the output of the radiator is less. Reference to Table II indicates that the output of 1 sq ft of cast-iron radiation at the steam temperature of 215° is 240 Btu per hr.

Example 1 (Fig. 2). Select a small-tube cast-iron radiator to make up the heat loss in a room losing 5000 Btu per hr. Steam is used. Dividing the hourly heat loss of 5000 by 240 indicates a need for 20.8 sq ft of cast-iron radiation. If a five-tube radiator is used with a height of 22 in., each section will provide 2.1 sq ft (Table I). Dividing 20.8 sq ft by 2.1, it is found that 10 sections are required. Several combinations of height, number of tubes, and number of sections will result in the same output. A choice can be determined by window-sill height and area available for the radiator.

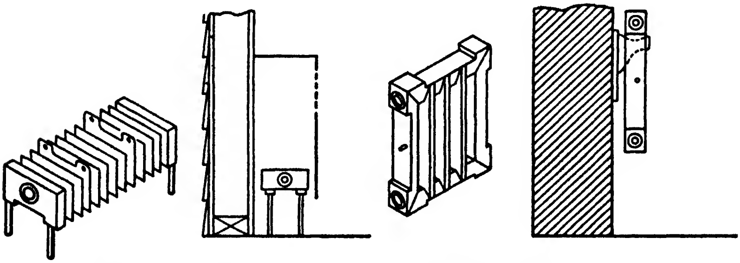
If, in the same room, hot water heat were used instead of steam with an average water temperature of 195°, 1 sq ft of cast-iron



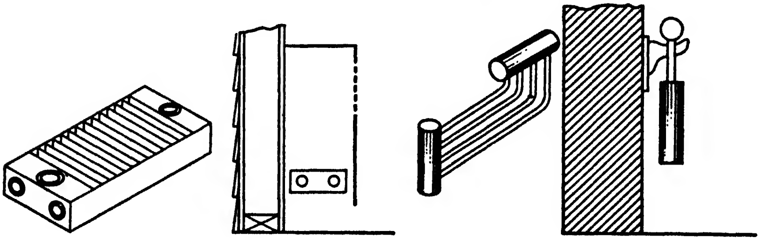
(*a*) Small-tube cast-iron (*e*) Cast-iron baseboard



(*b*) Cast-iron recessed (*f*) Fin-tube baseboard



(*c*) Cast-iron convector (*g*) Cast-iron, wall-hung



(*d*) Fin-tube convector (*h*) Pipe coils

Fig. 1. Types of radiation.

radiation would yield 200 Btu per hr. The hourly heat loss 5000 divided by 200 calls for 25 sq ft of radiation. The radiator for this condition would be larger than the one used in Example 1.

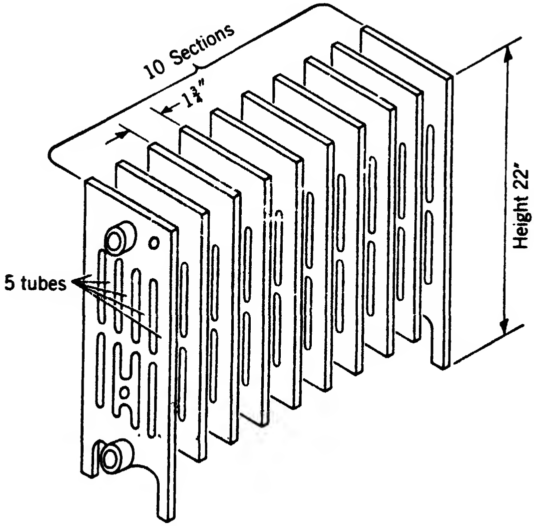


Fig. 2. (Example 1). A small-tube cast-iron radiator serving a room with an hourly heat loss of 5000 Btu per hr. Steam is used.

3. Ratings of other types. For a fixed room temperature of 70°, other forms of radiation, particularly the convector types, are rated in Btu per hour for a unit of a certain size and type. These ratings vary, depending upon the temperature of the heating medium. It is very important to consult the manufacturers' rating catalogues in this matter. Fundamentally, the output of any radiating unit depends on the size and type of unit, the room temperature, and the temperature of the heating medium. If the space to be heated is not at 70° it should be borne in mind that the output will be different from the output if the space to be heated were at 70°.

4. Boilers. Heating boilers may be of cast iron or steel, the former being available for capacities up to 18,000 sq ft of radiation and the latter for 600 sq ft up to very large loads.

5. Cast-iron boilers are intended for a maximum steam pressure of 15 lb per sq in. and a water pressure up to 30 lb per sq in. They consist of an assembly of hollow cast sections containing the water, connected by tapered push nipples or by outside headers. The sections may be circular, assembled horizontally one above the other to form a *round sectional boiler* [Fig. 3(*a*)], or they may be joined vertically in a

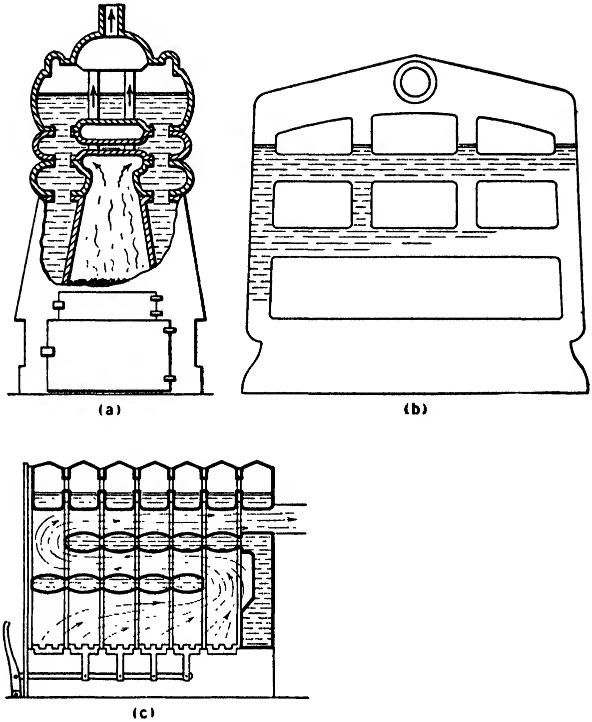


Fig. 3. Cast-iron boilers.

Table I. Small-Tube, Cast-Iron Radiators
(standard section length, 1¾″)

No. of Tubes per Section	Height (in.)	Sq Ft of Radiation per Section
3	25	1.6
4	19	1.6
	22	1.8
	25	2.0
5	22	2.1
	25	2.4
6	19	2.3
	25	3.0
	32	3.7

Table II. Heat Transmission Rates, Cast-Iron Radiation
(room temperature 70°)

Average Radiator Temperature, °F	Btu per Hour per Sq Ft of Radiation	Average Radiator Temperature, °F	Btu per Hour per Sq Ft of Radiation
165	140	195	200
170	150	200	210
175	160	205	220
180	170	210	230
185	180	215	240
190	190	220	250

series to form a *rectangular sectional boiler* [Fig. 3(*b, c*)]. The fire and hot gases are in contact with the outside of the sections and transmit their heat through the walls to the water within. There are two kinds of heating surfaces: the direct, which receives radiant heat from the fire; and the indirect, which is in contact with the hot gases only. The direct is the more effective, and cast-iron boilers are generally designed with a proportion of ⅔ direct surface to ⅓ indirect. Round boilers are provided with water passages from one section to the next through the nipples. Square sectional boilers may be assembled in the same way or may have each section connected to a main supply header above the boiler and to two main return headers at the sides. Round boilers have capacities of 300 to 1600 sq ft of radiation and square sectional boilers of 500 to 18,000 sq ft. Both the round and sectional are obtainable with steel enameled jackets over the cast-iron sections, giving a very neat and finished appearance to the installation.

Steam boilers may be used for hot water heating systems although the steam dome at the top is not required.

6. Steel boilers consist of a shell made of riveted or welded steel plates with tubes running longitudinally through the cylinder and have working pressures from 50 to 150 lb per sq in. When the hot gases pass through the tubes, giving off their heat to the water which surrounds the tubes, the boiler is known as *fire tube*. When the tubes contain the water and the gases pass over and around the tubes the boiler is called *water tube*. The steel boiler in use for many years is the horizontal return tubular consisting only of a cylindrical steel shell with fire tubes, the furnace, combustion chamber, and enclosure being built of brick.

For heating purposes the type now most generally used is the *portable* fire box boiler which has a steel fire box and cast-iron grate attached, with water surrounding the fire box as well as the fire tubes (Fig. 4). It is shipped complete from the factory and does not need brick setting.

Water tube boilers are more costly than fire tube boilers but can be built in larger sizes and for higher pressures. They are encased in brick with insulated steel covering to reduce heat losses. Baffles are constructed between the tubes to direct the gases and produce efficient gas passages and velocities. They are better suited to stoker firing and in the larger sizes require less floor space. Their operating pressures should be maintained above 15 lb per sq in., and reducing valves are consequently used on the heating supply.

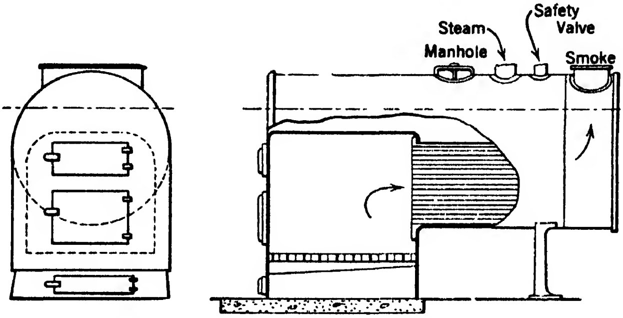


Fig. 4. Steel portable fire tube boiler.

7. Boiler capacity. The output from a boiler is the quantity of heat furnished at the supply outlet when the boiler is normally insulated. Manufacturers rate in their catalogues the gross output of heating boilers in Btu and in square feet of equivalent radiation. If these ratings are the result of actual tests carried out according to the Test Code of the American Society of Heating and Ventilating Engineers, they should be reliable and the listed performances may be used in the selection of boilers for design purposes. The capacity must be adequate to furnish the heat required by the radiators and connected water heaters and the heat lost from mains and risers, the lost heat being generally taken as 25 per cent of the connected radiation for steam and 35 per cent for hot water. A further demand upon the boiler arises from the increase in the normal load due to warming up cold radiation in the morning or after periods of disuse. This allowance is often taken as 50 per cent of the sum of the connected load and the pipe losses. The hot water supply load may be considered as 4 sq ft of equivalent radiation for each gallon of water raised in temperature 100° per hr, as from 50° to 150°.

Some boilers for houses and other small buildings are now rated on the basis of the net output instead of the gross output. The net output is the Btu per hour heat loss of the house, or, differently expressed, the direct connected load in square feet of cast-iron radiation. Thus, if a house actually has 300 sq ft of cast-iron radiation in place, a boiler with a net rating of 300 is acceptable. The manufacturer makes this boiler large enough to include normal demand for domestic hot water, for piping heat loss, and for pick-up from a cold start.

8. Oil and gas boilers. Oil-fired burners are generally of intermittent action, the flame being turned entirely on or off. A boiler with larger convection heating surface is therefore more economical. If the firing is continuous the same boiler as that designed for coal is satisfactory. Although many coal-burning furnaces and boilers have been satisfactorily converted into oil burners, boilers specially designed for oil fuel have been developed. They are generally of copper or steel tube type with increased indirect convection heating surfaces, and they are from 5 to 15 per cent more efficient than converted coal boilers. In all of them unprotected metal surfaces of the combustion chamber and ash pit must be lined with fire brick.

Gas-fired boilers are far more satisfactory if specially designed for gas fuel, and the development of such boilers has been rapid. They are rated by heat emission in Btu in the manufacturers' catalogues according to the code of the American Gas Association and are guaranteed to deliver 240 Btu per hr per sq ft of steam rating and 150 Btu per hr per sq ft of water rating at the boiler supply outlet. The water rating is based upon the output per square foot of cast-iron radiation using gravity hot water, which usually averages about 170° and therefore causes radiator heat emission of 150 Btu per hr per sq ft (Table II). The additions to connected radiation to cover loss of heat from piping and allowance for warming are approximately the same as for coal-burning boilers.

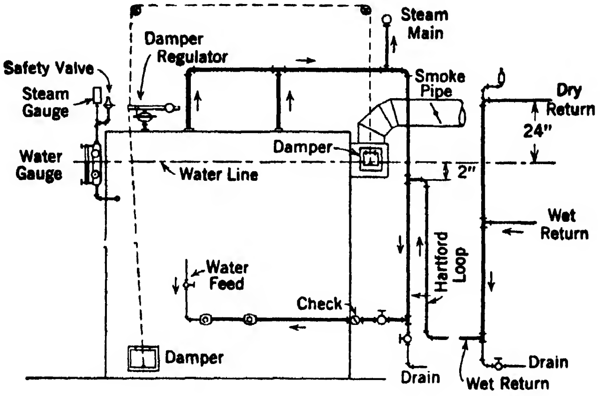
9. Boiler connections for both steam and hot water are as follows:

(*a*) *Flow Connections.* Large boilers are provided with two or more outlets connected into a header from which the supply main is taken [Fig. 5(*a*, *c*)]. Small boilers have only one outlet connected directly to the main [Fig. 5(*b*)]. The outlets should extend vertically above the boiler as high as possible, usually within 6 in. of the basement ceiling, and should be of ample diameter. Good height and area are required to reduce the steam velocity to 15 to 25 ft per sec to prevent carrying entrained water. Allowance should be made for expansion in the main by pipe bends, especially when the main is long or extends upward to supply down-feed risers.

(*b*) *Return Mains* are brought to the bottom of the boiler. In steam systems the return enters through a Hartford loop or hydraulic connection placed as near as possible to the boiler and consisting of a loop turned downward with its upper bend within 2 in. of the water line and connected to the header or main [Fig. 5(*a*, *b*, *c*)]. This loop prevents water from backing out of the boiler because of unequal pressures or carelessness in closing valves.

(*c*) *Blow-Off Connections* are made at the low point of the return main near the boiler and should be capable of draining the entire system by opening the valve.

(*d*) *Cold Water Supply* for filling and for make-up water is usually of galvanized-iron pipe and is connected to the return main near the boiler.



(a) Coal-fired

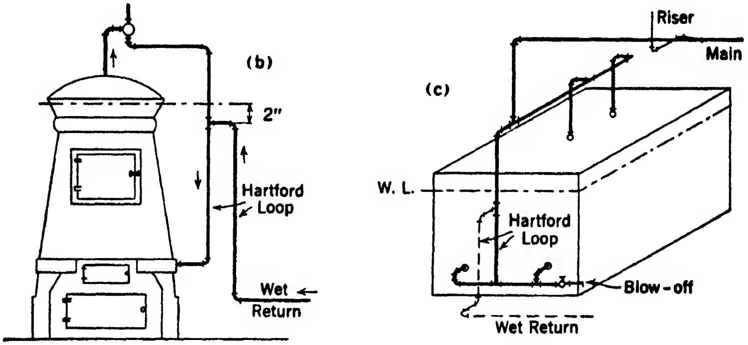


Fig. 5. Steam boiler connections.

10. Boiler accessories. Low-pressure steam boilers require a safety valve, pressure gauge, water gauge, and, when coal fired, a damper regulator.

(*a*) *Safety Valves* should be of sufficient size to discharge all excess steam generated so that the pressure never rises above the limit at which the valve is adjusted, generally 15 lb per sq in. The spring-loaded type is in most general use, the force of the spring being controlled by a set screw. It may be operated manually if desired [Fig. 6(*a*)].

(*b*) *Gauges.* Steam pressure gauges consist of a curved hollow brass tube which tends to straighten out under internal pressure. As the tube straightens it turns a gear sector which rotates the needle on the dial.

Water columns and gauge glasses are required on steam boilers to indicate the height of the water line. The column is a cast-iron tube furnished with two or more try cocks and a glass gauge tube. It is connected to the boiler as shown in Fig. 5(*a*), so that the center of the glass and the middle try cock are level with the normal water line. The height of water in the boiler may be read in the glass tube, the try cocks being for use in the event of accident to the glass [Fig. 6(*b*)].

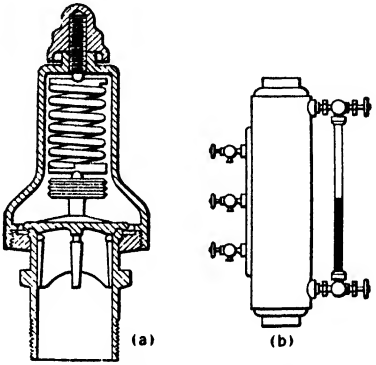


Fig. 6. Safety valve and water gauge.

(*c*) *Damper Regulators* are important on both steam and hot water coal-fired boilers to obtain automatic control of the fire and prevent over- and underheating. The regulator for steam consists of a sensitive brass bellows enclosed in a case. Steam is admitted to the case and by its pressure expands the bellows which rises and pushes up one end of a balance arm. A chain is attached to the arm and, passing over pulleys, runs down to the front damper below the fire and to the check draught damper in the smoke breeching [Fig. 5(*a*)]. Tilting of the arm in one direction opens the front damper and closes the check damper, thereby starting up the fire; tilting in the other direction shuts the front damper and opens the check damper in the smoke breeching, thereby cutting off the draught and checking the fire. When used with vapor systems great sensitiveness and flexibility are attained by having a large bellows of thinner metal and increasing the distance *A*, Fig. 7, between the knife edge and the pivot. The regulator can be adjusted by moving the weights upon the arm.

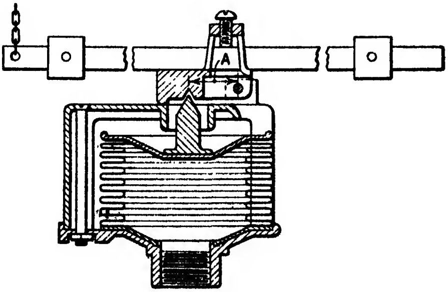


Fig. 7. Damper regulator.

The damper regulator for hot water is similar in construction, the bellows containing a volatile fluid which expands under the influence of increasing water temperature, tilting the rocking arms, and moving the dampers. The operation is reversed as the water temperature falls.

(*d*) *Thermometers* on hot water boilers are attached to the boiler near the flow outlet or to the flow line itself. The mercury is usually in a separate well immersed in the boiler water, the glass bulb of the thermometer tube extending into the well. Their scales read from 60 to 260°.

11. Fuels. The fuel used in heating furnaces and boilers may be (*a*) solid, such as coal and coke; (*b*) liquid, such as petroleum oil; and (*c*) gaseous, such as natural and artificial gas.

12. Coal, with its derivative coke, is the most commonly used solid fuel. It was formed by the partial decomposition of enormous masses of vegetable matter in prehistoric times under tremendous heat and pressure without free access of air. Coal is found in all stages of this change, from peat through lignite and bituminous to anthracite coal. The chief constituents are carbon, hydrogen, and oxygen, the carbon being partly combined with the hydrogen and oxygen forming hydrocarbons, and partly uncombined or fixed carbon. The hydrocarbons are volatile and escape as gases upon the application of heat. Coals are classified as anthracite or bituminous according to the relative proportions of fixed carbon and volatile matter.

The noncombustible constituents are the ash and moisture. The ash varies from 3 to 30 per cent of the total weight and moisture from 0.75 to 25 per cent. An excessive amount of ash and moisture reduces the calorific value of the coal and retards rapid combustion.

Anthracite coal is dense, hard, and clean. It ignites slowly but burns freely with great radiant heat when started. It has a short flame and burns uniformly and with practically no smoke, cakes very little, and requires a minimum of attention between firings. The usual sizes are given in Table III.

Table III. Sizes of Anthracite Coal

Kind of Coal	Size (in.)	Kind of Coal	Size (in.)
Rice	⅛–¼	Chestnut	¾–1⅝
Buckwheat	¼–½	Stove or range	1⅝–2½
Pea	½–¾	Egg	2½–3¼

13. Mechanical stokers. Two types of mechanical stoker are most commonly used with heating boilers and furnaces, the underfeed and the overfeed. In the first type (Fig. 8) coal is fed from a hopper by means of a conveyor screw to the under side of the fire. The screw and a blower are operated by an electric motor. As the coal approaches the fire the volatile gases are given off, begin to burn, and are forced up through the fire by the blower. Air in proper quantity is also introduced to the fire through small pipes called tuyères. The speed of the screw and the volume of air may be controlled by thermostat, steam pressure, hot water and furnace temperatures, or time period.

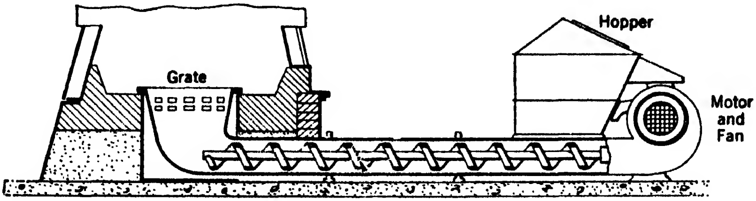


Fig. 8. Mechanical stoker.

Plungers or rams with reciprocating motion are sometimes used instead of conveyor screws to feed the coal to the retort, and automatic ash removal and discharge into ash cans are possible additions to the equipment. The overfeed type consists of an elevated coal magazine from which the fuel feeds down by gravity to a sloping grate.

Mechanical stokers can handle the smaller and cheaper sizes of coal, require attention only at long intervals, produce excellent uniform firing, and in many cases offer definite economy in heating costs.

Table IV. Properties of Fuel Oil

Commercial Standard No.	Approximate Gravity Range (Baumé)	Calorific Value (Btu per gallon)
1	38–40	136,000
2	34–36	138,000
3	28–32	141,000
5	18–22	148,000
6	14–16	152,000

14. Oil fuel has gained greatly in popularity in recent years owing to increased facility of procurement and transportation, capability of complete automatic control, absence of smoke and ashes, and small required storage space. Fuel oil is the residue after gasoline, kerosene, and naphtha have been distilled off from crude petroleum. It is manufactured in various grades, the lighter and more refined types having a low flash point or temperature from 110 to 165°F at which their vapor will ignite in a flash. The fire point or temperature at which an oil burns with a steady flame is about 20° above its flash point. The heavier low-grade oils are more viscous, begin to burn at higher temperatures, and in some cases must be preheated before being introduced in the burner. Lighter oils, Nos. 1 and 2, consequently, are better adapted for intermittent automatically controlled heating systems and the heavier oils for large continuously fired power plants. The lighter oils are, however, more expensive, and for this reason burners for domestic service have been developed to make use of oils much heavier than heretofore considered possible. The heat content is from 136,000 to 141,000 Btu per gal at 60°F. The heavier more viscous oils, Nos. 5 and 6, are used in larger installations such as hotels, office buildings, and stores where economy rather than convenience is important. The burners are adapted to the low-grade oils, and the boilers may be in multiple with two to five burners to each unit.

Oil is stored in steel tanks either buried outside the building or placed in the basement. Local regulations and the code of the Fire Underwriters should be followed in each installation. Tanks of 275-gal capacity are generally convenient in basements when local oil deliveries are frequent, and tanks of 550 to 10,000 gal are permitted for outside use. Copper pipe is considered better than steel pipe for connection from tank to burner for the lighter oils.

15. Oil burners. To burn properly, oil must be changed from a liquid to a vapor. The conversion is accelerated by atomization or breaking the liquid up into tiny globules. This atomization is effected in domestic burners by centrifugal force produced by a rotating cup or by forcing the oil under pressure through a nozzle. In both methods air is blown into the burner for perfecting the atomization and combustion, ignition being produced by an electric arc. A motor, fan, and pump with electrical connection form part of the equipment. Combustion takes place in the lowest part of the boiler, corresponding to the ash pit in a coal burner, which is lined with fire brick to protect

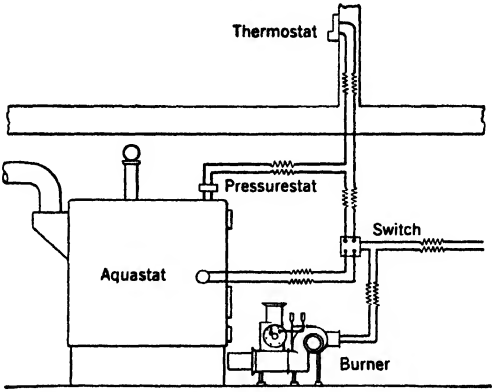


Fig. 9. Automatic control of oil burner.

the metal sides from contact with the flame and to assist the combustion of the oil.

The burner is controlled by a thermostat placed where most effective in the building. For safety the burner is automatically cut off if the pressure in steam boilers or the temperature in hot water heaters and warm air furnaces should rise above a predetermined point, or if the fuel or the ignition should fail (Fig. 9).

Indirect hot water supply heaters can be conveniently connected with oil-burner installations, the heater being set outside the boiler and furnished with heat by circulation of boiler water through it. In summer the burner is started by the aquastat whenever the water drops to a temperature of about 160° or other setting of the aquastat.

16. Gas fuel consists of natural gas found in the earth in petroleum regions, and artificial gas manufactured for cooking purposes. Natural gas was formerly restricted to the localities where it was found, but since the discovery of vast new sources of supply and pipe-line transportation its use is increasing. It is of organic origin, consists largely of the hydrocarbon methane (CH_4) or marsh gas, and has a heat value of about 1000 Btu per cu ft. Manufactured gas is made by the destructive distillation of coal in a gas generator, by-products being coke, tar, and ammonia. It consists largely of methane and hydrogen with some carbon monoxide and has an average heat value of 535 Btu per cu ft.

Gas firing is most successful when the boiler is especially designed for the fuel. The boilers generally consist of sections placed together with a separate gas burner under each section, the effort being to divert the hot gases into thin streams flowing in close contact over the water-containing sections. The velocity of the gas produced by the initial pressure in the pipes supplies sufficient energy to draw in the air for combustion; consequently no fan or motor is required. Because this pressure often varies, however, pressure regulators should be a part of the equipment to give a uniform head at all times. Ignition is provided by a pilot light. Automatic operation is more nearly complete with gas than with any other fuel, since it is not only operated by thermostats and safeguarded by pressurestats and temperature control similar to the oil burners, but the gas itself is piped to the premises so that the owner is relieved of all responsibility of supply.

17. Comparison of fuels. Although it is evident that oil and gas fuels are cleaner, require far less service in supply, control and ash removal, occupy little or no storage space, and are more completely automatic than coal, their installation may be more expensive and the question of the cost of operation must be considered.

18. Space allowance for boilers. Sufficient space, 3 ft wider than the fire box, should be allowed in front of boilers for ash removal, stoking, and firing. Since oil burners and mechanical stokers often operate at the ash-pit level, a pit of ample depth and area is sometimes necessary to accommodate them without unduly raising the boiler. As explained in Chapter 12, Art. 13, the distance between the end of the steam main and the boiler water line should not be less than a fixed amount, and a pit under the boiler may be necessary for this reason also.

19. Automatic control. Thermostatic and other automatic controls of oil- and gas-fired steam and water boilers and hot air furnaces are treated in Chapter 20.

PROBLEMS

1. A hot water heating system uses water at an average temperature of 190°F in the radiators. Find the number of square feet of cast-iron radiation needed for a room having an hourly heat loss of 6000 Btu, and select a small-tube cast-iron radiator to fit under a 23-in. sill.

2. Describe three types of radiators or convectors and the principles upon which they function.

3. Discuss the following boiler connections: (*a*) supply and return mains and Hartford loop; (*b*) safety valves; (*c*) gauges; (*d*) damper regulators; (*e*) thermometers.

4. Discuss and compare the following fuels: coal, coke, oil, and gas.

5. Describe mechanical stokers and oil burners.

6. Describe the tappings on a cast-iron radiator.

7. What capacity of oil storage tank may be located in the basement, and what sizes must be buried outdoors?

8. What refractory protection must be provided in oil-fired boilers?

9. How is the draught improved in automatic coal stokers using small-size coal?

10. What are the advantages of anthracite over bituminous coal?

SECTION IV · AIR CONDITIONING

Chapter 17

AIR-CONDITIONING STANDARDS

1. Introductory. It is now well established that air conditioning is a necessity for human comfort and efficiency, for the proper operation of hospitals, offices, stores, hotels, theaters, and residences and for the successful processing and good quality of manufactured goods. The significant elements consist of heating and humidifying, cooling and dehumidifying, cleaning and circulating air. An understanding of these elements and a knowledge of their treatment is, therefore, the basis of air-conditioning design.

2. Properties of heat. Heat is a form of energy conceived to be expressed in the molecular motion within a substance, the greater the intensity of the heat the more violent being the motion of the molecules and the less the cohesion between them. (Chapter 9, Art. 1.) It is transferred by virtue of a temperature difference.

(*a*) *Absolute Temperature* is a convenient scale for the study of heat. It is reckoned from absolute zero, a point presumed to be 459.8°F below 0°F.

(*b*) *Specific Heat* is the amount of heat in Btu absorbed (or given up) to raise (or lower) the temperature of a unit of weight of a substance 1°F. Between 0 and 200°F the mean specific heat of dry air at standard atmospheric pressure is generally taken at 0.24 Btu per lb and of saturated water vapor at 0.45 Btu per lb.

(*c*) *Change of State* from solid to liquid and from liquid to gas is produced by the addition of sufficient heat energy to increase the action within the substance until the freer and more violent activity of the molecules is manifested in the changed characteristics of the new state. The substraction of heat causes an opposite change of state, from gas to liquid and from liquid to solid.

(*d*) *Enthalpy* designates the quantity of heat in Btu per pound in a fluid of gas. In relation to the total heat its symbol is h.

Two recognized manifestations of heat are convenient in air-conditioning problems, sensible and latent heat.

(*e*) *Sensible Heat* is the heat in Btu absorbed by a substance, such as a fluid, in raising its temperature without changing its state. It is the enthalpy of the saturated liquid and is designated by h_f.

(*f*) *Latent Heat* or *Enthalpy of Vaporization* is the heat energy required to change the state of a substance. In the case of water vapor it is the heat in Btu added to the water to increase its kinetic energy, the energy of molecular activity, sufficiently to change the state from fluid to gas without changing the temperature. The quantity of latent heat added is equal to the change in enthalpy and is designated by h_{fg}.

The total heat or enthalpy of the dry saturated vapor (h_g) after its change from water equals the sum of the enthalpy of the saturated liquid (h_f) and the enthalpy of vaporization (h_{fg}):

$$h_g = h_f + h_{fg}$$

3. Properties of dry air. Dry atmospheric air is a mixture of several gases with the following practically constant composition:

	Per Cent	
	By Volume	By Weight
Nitrogen	78.03	75.47
Oxygen	20.99	23.19
Argon, carbon dioxide, hydrogen, and other gases	0.98	1.34
	100.00	100.00

In air-conditioning design, air is usually free to expand against the constant atmospheric pressure. Calculations, therefore, take place at the constant standard pressure of air at sea level of 14.7 lb per sq ft or 29.92 in. Hg. For appreciable elevations equations have been derived correcting the sea-level calculations to render them accurate for the given elevation.

The volume of dry air in cubic feet per pound depends upon the temperature and pressure, increasing as the temperature increases and as the pressure decreases. The density or weight per unit of volume is the reciprocal, increasing as the pressure increases and as the temperature decreases. For standard dry air at 70° dry bulb at sea level the density is taken as 0.075 lb per cu ft.[1]

4. Properties of moist air. Psychrometry is a study of moist air, that is, of physical mixtures of dry air and water vapor, air absolutely devoid of moisture not being found in our atmosphere. Since the quantity of water vapor varies, however, dry air, which is constant in composition, is used in many air-conditioning problems, and the prop-

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[1] Abbreviations: wb = wet-bulb temperature; db = dry-bulb temperature; dp = dew-point temperature; gr = grains; R.H. = relative humidity; SHF = sensible heat factor.

erties of moist air are expressed per pound of dry air in the mixture.

Dalton's Rule. Each constituent, such as dry air and water vapor, in a gas mixture occupies the whole volume of the mixture as if no other constituent were present. It therefore exerts a partial pressure equal to the pressure it would exert if alone in the mixture, and the observed pressure of the mixture is the sum of these partial pressures of the constituents.

5. Humidity. If water is placed in proximity to dry air at a higher temperature a portion of the water will evaporate and become mixed with the air in the form of water vapor. Because of the intimate mixture of the air and vapor their temperatures become the same. With a further rise in temperature the volume of the dry air in cubic feet per pound will expand, and its partial pressure and density will decrease. Since the total atmospheric pressure remains the same, the density and partial pressure of the possible water vapor content of the moist-air mixture will increase. Corresponding to every temperature, however, there is a point at which a balance of the vapor phase and the liquid phase takes place and no more weight of water can be associated with the vapor without condensation. This is the *saturation* pressure for the given temperature, the air and the vapor being defined as *saturated.* On the other hand, if a saturated mixture is cooled the original saturation pressure is exceeded, some water is condensed from the vapor in drops, and the saturated vapor pressure is decreased to that corresponding to the new temperature.

A very common condition occurs when the mixture is only partially saturated at a given temperature. The actual vapor pressure will then be less than the saturation pressure corresponding to its temperature, and the vapor will be *superheated.* The saturation temperature corresponding to the actual vapor pressure in the mixture is called the *dew point.* If the mixture is cooled at constant vapor pressure it will reach saturation at the dew point, and below this point condensation will begin.

6. Humidity ratio. The ratio by weight of the actual water vapor to the dry air in a mixture, pounds of water vapor per pound of dry air, is called the humidity ratio (W). When the weight of the water vapor, pounds per pound of dry air, is at the maximum possible for the temperature without condensation the ratio is known as the humidity ratio at saturation (W_s).

7. Degree of saturation and relative humidity. The degree of saturation (μ) in terms of weights per pound of dry air in a mixture is defined by the equation

$$\mu = W/W_s \tag{1}$$

Relative humidity is designated by *RH* or by ϕ and is the ratio of the partial pressure, p_w, of the actual water vapor in a mixture to the pressure of saturated vapor, p_s, at the same dry-bulb temperature.

$$RH \quad \text{or} \quad \phi = p_w/p_s \tag{2}$$

Both μ, the degree of saturation, and RH or ϕ, the relative humidity, can have any value between zero (dry air) and unity (moist air at saturation) and are generally expressed as percentages. Although these two properties of moist air are not identical, they are sufficiently close at the lower temperatures used in air-conditioning design. Both properties are used in current practice.

8. Relation of volume, pressure, and temperature. By Dalton's rule dry air and water vapor act as ideal gases. Therefore, upon dividing the universal gas constant 1545.31 by 28.966, the molecular weight of dry air, a constant (R_a) or 53.349 for dry air is obtained. Likewise the constant R_w 85.774 for water vapor is obtained by dividing 1545.31 by 18.016, the molecular weight of water. A mole is the weight of a gas numerically equal to its molecular weight.

Since both the dry air and the water vapor occupy the entire volume and the total pressure equals the sum of their partial pressures,

$$V_m = V_a = V_w \quad T_m = T_a = T_w \quad p_m = p_a + p_w$$

where subscripts m = mixture, a = air, w = vapor, and

$$v_T = \frac{w_a RT}{p_a} = \frac{w_w RT}{p_w} = \frac{(w_a + w_w)RT}{p} \tag{3}$$

where v_T = volume at absolute temperature T.
w_a = air weight in pound-moles.
w_w = water vapor weight in pound-moles.
p_a = partial air pressure.
p_w = partial water vapor pressure.
p = total pressure.
R = gas constant, 1545 ft-lb per lb-mole per °F absolute.
T = absolute temperature.

The general relation of pressure, volume, and temperature is

$$V = wRT/P \quad \text{or} \quad PV = wRT \tag{4}$$

where P = absolute pressure of the gas in pounds per square foot.
V = its volume in cubic feet.
w = its weight in pounds.
T = its absolute temperature ($T = t + 459.7$).
R = a constant for the particular gas.

9. Volume. The volume of moist air per pound of dry air at temperatures below 150°F and at any degree of saturation, μ, is found by the equation

$$v = v_a + \mu v_{as} \qquad (5)$$

where v_a = specific volume of dry air in cubic feet per pound.
v_{as} = difference between volume of moist air at saturation per pound of dry air and the specific volume of the dry air itself $(v_s - v_a = v_{as})$.

10. Enthalpy. The enthalpy or heat content of moist air is the sum of the enthalpies of the dry air and the water vapor.

For the moderate temperatures of air-conditioning design the following empirical equations provide satisfactory accuracy:

$$h_a = 0.24t \quad h_w = W(0.444t + 1061) \qquad (6)$$

and

$$h = h_a + h_w \qquad (7)$$

where h = total heat of the mixture in Btu per pound of dry air.
h_a = total heat of the air in Btu per pound of dry air.
h_w = total heat of the water vapor in Btu per pound of dry air.
t = temperature of the mixture in degrees Fahrenheit.
0.24 = specific heat of air in Btu per pound.
0.444 = specific heat of water vapor in Btu per pound.
W = weight of water vapor in pounds per pound of dry air.
1061 = latent heat of water in Btu per pound.

11. Wet- and dry-bulb temperatures. The moisture content of air may be determined by means of the psychrometer, which consists of two thermometers, the one of standard type with a dry bulb and the other furnished with a moistened bag or wick to keep its bulb continually wet. Because the evaporation of moisture from the wick extracts a corresponding amount of heat, the bulb is cooled and the wet-bulb thermometer will indicate a lower temperature than the dry-bulb instrument.

The temperature difference between the two thermometers depends upon the degree of saturation, that is, relative humidity, of the air. If the air were perfectly dry the wet bulb would show the greatest possible depression because the greatest amount of moisture would have been evaporated into the air from the bulb's wick with a corresponding loss of heat. Proportionately smaller degrees of depression would indicate correspondingly greater degrees of saturation of the air. When the air is 100 per cent saturated no evaporation will occur at the wet bulb, and it will indicate the same temperature as the dry bulb, which is the dew point for the existing condition of temperature, pressure, and moisture. With a degree of saturation less than 100 per cent, the dry bulb stands above the wet bulb and the wet bulb above the dew point. The higher the dry-bulb temperature, the greater the weight of moisture the air can carry before saturation occurs. The quantity of moisture yielding 50 per cent saturation at 40° would produce only 21 per cent in 75° air.

12. Adiabatic saturation of air is the introduction of water into unsaturated air to increase its humidity ratio, but without transfer of heat to or from an outside source and without gain or loss of enthalpy of the mixture. The added water vaporizes and mixes with the air, the heat necessary for the evaporation being supplied from the air and the superheat of the original quantity of water vapor. The original dry-bulb temperature therefore falls until the air is saturated, at which point it will approximately coincide with the dew point at the wet-bulb temperature. If the supply water is recirculated it will ultimately assume the temperature at which the air is saturated, the wet-bulb temperature of the air. Proportions of heat will be transferred from the air (h_g) to the water vapor (h_{fg}) and the fluid water (h_f), but the total enthalpy will remain the same.

13. Psychrometric chart. The chart shown in Fig. 1 is devised by the American Society of Refrigerating Engineers and is used by permission. It is based upon the preceding formulae and is of the greatest assistance in air-conditioning calculations.

Relative humidities of various percentages are represented by the lines curving upward to the right. *Dry-bulb* temperatures are indicated along the lower edge of the chart on the 0 per cent line of relative humidity and refer to the vertical lines. *Wet-bulb* temperature, represented by diagonal lines, is read at the intersection of those lines with the saturation curve. *Weight of water* in grains or pounds per pound of dry air, represented by horizontal lines, is read on the scales at the right-hand side of the chart. *Dew-point* (saturation) temperatures, constant along the horizontal lines, are read along the saturation curve to the left horizontally from the point where dry-bulb, wet-bulb, and dew-point temperatures coincide. *Enthalpy* or total heat at saturation is read by extending the wet-bulb lines to intersections with the diagonal scale beyond the saturation curve. *Volume* per pound of dry air is indicated by diagonal lines with values marked thereon.

If a mixture of dry air and water vapor has dry- and wet-bulb temperatures of 70° and 61°, respectively, its properties may be found upon the chart as follows: The intersection of the diagonal 61° wet-bulb line and the vertical 70° dry-bulb line determines the relative humidity to be 60 per cent and the volume of the mixture to be 13.55 cu ft per lb of dry air. Passing horizontally from the intersection to the scales on the right margin, the humidity ratio is found to be 66 grains or 0.00943 lb per lb of dry air.

The dew-point temperature lies on the saturation curve horizontally opposite the intersection at 55.5°. The total heat or enthalpy is shown on the diagonal scale and is found by following the 61° wet-bulb line to be 27.2 Btu per lb of dry air.

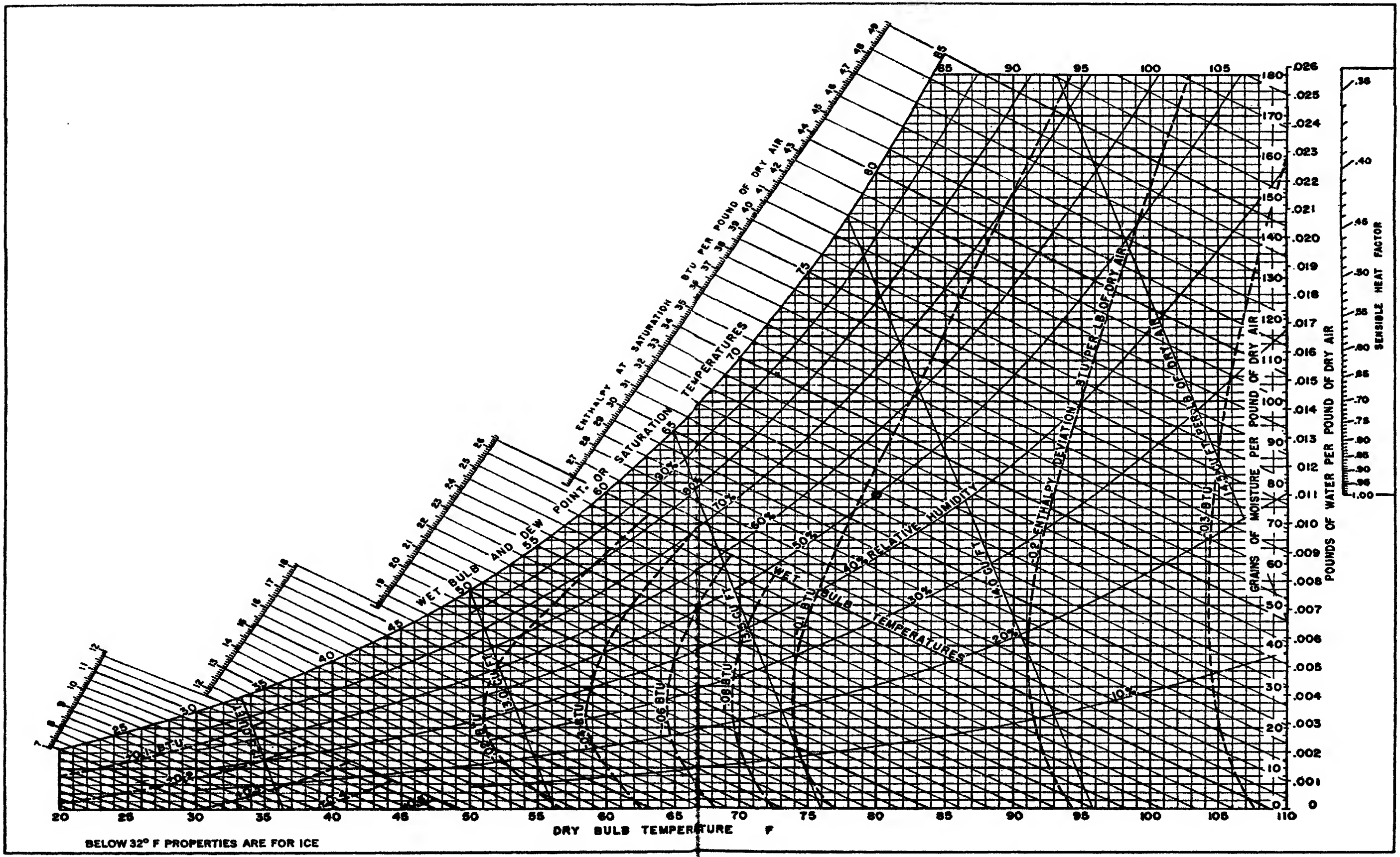

Fig. 1. Psychrometric chart. Reprinted from ASRE Brochure on Psychrometry, *Misc. Publn. #7*, 1947; Preprinted from 6th Edition *Basic Volume Data Book*, 1948. Published by The American Society of Refrigerating Engineers, 40 West 40 Street, New York, N. Y. Copyright 1946 Carrier Corporation. Abbreviations: *wb* = wet-bulb temperature; *db* = dry-bulb temperature; *dp* = dew-point temperature; *gr* = grains; *RH* = relative humidity. *SHF* = Sensible heat factor.

14. Air-conditioning methods. Experiments prove that the need of air conditioning arises from the initial temperature and humidity of the air together with the heat, moisture, and contamination yielded by lighting, machinery, industrial processes, and occupants. In order to secure comfort, health, and efficiency, the effort is to balance the heat losses of the human body and to improve the quality and movement of the air rather than to increase its quantity.

15. Comfort. Temperature, humidity, and air motion are of nearly equal importance in inducing comfort. When indoor air is very dry, evaporation of perspiration is increased with consequent cooling of the skin. Accordingly, a higher temperature is necessary for comfort than when more moisture is present with slower evaporation. Undue drying of the mucous membranes and nervous tension likewise result. Conversely, high humidity on hot days prevents free evaporation of perspiration, and the body and clothing become damp and uncomfortable. Lassitude and lack of energy are a natural accompaniment. Air movement, in its turn, precludes stagnation and stratification in winter heating and increases loss of heat from the body through evaporation and convection and stimulates the nervous system in summer.

Experiments by various laboratories upon a number of subjects at rest have shown that there are definite relationships between the proportions of heat, humidity, and air movement producing comfort. Different combinations of these proportions yielding the same sensation of warmth have been tabulated, and a *comfort chart* (Fig. 2) has been constructed which presents for summer and winter the various proportions of heat, humidity, and air motion found comfortable by 97 or 98 per cent of the subjects tested. An arbitrary index called effective temperature (*ET*) has been introduced, serving as a scale for use with the comfort chart, indicating in a single value the amount of warmth or cold experienced under the various combinations. It is divided into degrees of temperature whose numerical values are fixed by the temperatures of saturated air inducing identical sensations of warmth as the effective temperature combinations. The chart shows that a maximum number of subjects were comfortable at effective temperatures of 71° in summer and at 68° in winter. These effective temperatures may be produced by a dry-bulb temperature of 76.5° and a relative humidity of 50 per cent in summer, and by a dry-bulb temperature of 74° and a relative humidity of 30 per cent in winter. From the chart it may be seen that the same *ET* may be produced by other combinations of dry-bulb temperatures and relative humidities. The air movement is 15 to 25 ft per min.

Mr. C. S. Leopold has called attention to the fact that in large office buildings inspections of thermostat settings, adjusted either by the occupants or by obliging building superintendents, show an average 75° setting for both summer and winter to be the most desired by the occupants. With this setting the humidity control varied from 50 per cent in summer to 30 per cent in winter. Such settings as these have

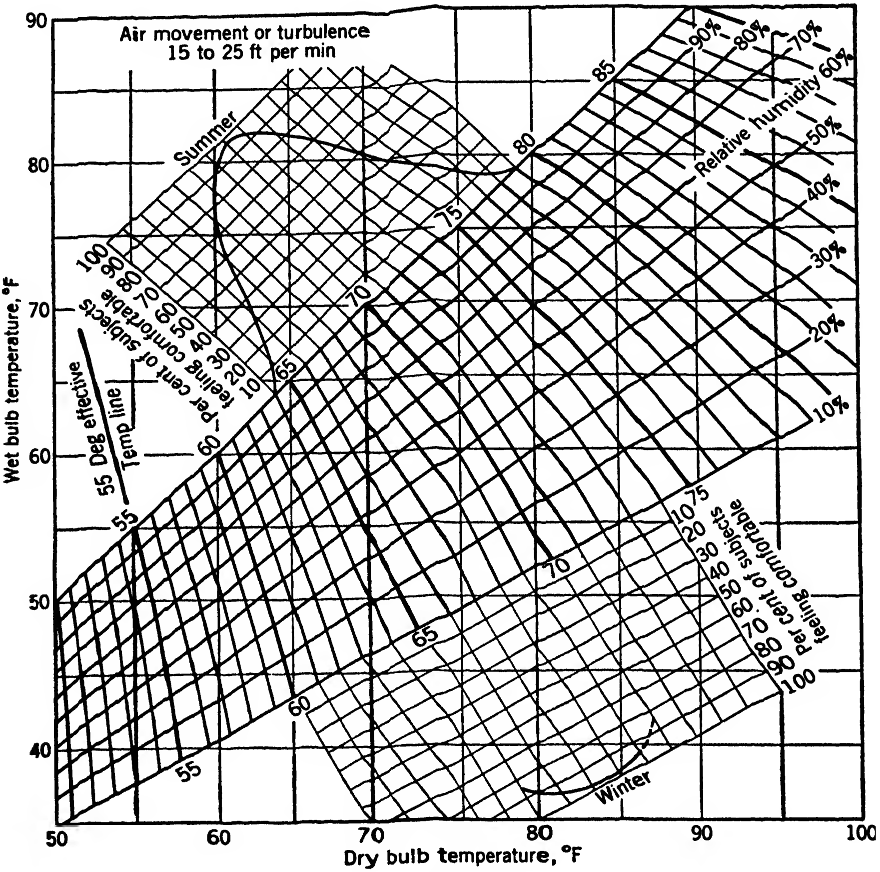

Fig. 2. A.S.H.V.E. comfort chart for still air.[a, b] Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1953, page 126.

[a] *Note.*—Both summer and winter comfort zones apply to inhabitants of the United States only. Application of winter comfort line is further limited to rooms heated by central station systems of the convection type. The line does not apply to rooms heated by radiant methods. Application of summer comfort line is limited to homes, offices and the like, where the occupants become fully adapted to the artificial air conditions. The line does not apply to theaters, department stores, and the like where the exposure is less than 3 hours. The optimum summer comfort line shown pertains to Pittsburgh and to other cities in the northern portion of the United States and Southern Canada, and at elevations not in excess of 1000 ft above sea level. An increase of one deg ET should be made approximately per 5 deg reduction in north latitude.

[b] Dotted portion of winter comfort line was extrapolated beyond test data.

the virtue of producing comfort for a mass of occupants in the absence of those conscious factors that may occur when a few trained subjects are employed in laboratories.

The foregoing discussion treats only of persons at rest and with terms of occupancy of 3 to 8 hr. When the occupants are actively employed or are present for periods of less than 1 hour the temperatures and humidities should be varied according to the circumstances.

16. Air-conditioning standards. The following standards should be followed to provide satisfactory conditions in spaces intended for human occupancy.

17. Heating. Sufficient heat should be provided in winter for comfort, which depends upon the humidity and the activity of the occupants. For persons at rest 72° is an acceptable dry-bulb temperature for a humidity of 30 per cent. When the occupants are in active motion the temperatures should be reduced. For certain special purposes, such as the operating rooms and nurseries of hospitals, the required temperatures are higher, and both higher and lower temperatures are needed in industry, depending upon the product.

Table I. Winter Indoor Temperatures

	Degrees F		Degrees F
Offices	74	Stores	65–68
Schools	70–72	Factories and machine shops	60–65
Hospital wards	68–70	Foundries and garages	50–60
Operating rooms	72–85	Paint shops	80
Theaters	68–72	Residences	70–72
Restaurants	70–72	Boiler shops	50–60

18. Humidifying. A relative humidity of 30 or 35 per cent is generally found most satisfactory in winter. With this proportion 70 to 75° is comfortable, whereas a higher temperature would be required in drier air. A smaller percentage of humidity affects the membranes of the nose and throat and causes warping and cracking of furniture and woodwork. A greater moisture content produces condensation on cold window panes and in some cases on exterior walls. When industrial processes require high humidity additional wall insulation and double window sash must be installed. The desired quantity of moisture is added by passing the air through sprays of water.

19. Air motion. That a gentle movement of air produces a refreshing and stimulating effect has always been recognized. Air motion is likewise required to distribute heat and humidity uniformly throughout a room. The movement should not be so violent as to cause draughts but should be at sufficient rate to preclude stagnant air, which is always depressing. The velocity should average 15 to 25 ft per min, measured at 36 in. above the floor. Such uniformity can be accomplished only by a fan, the intermittent action of radiators and registers always causing greater or less degrees of stratification.

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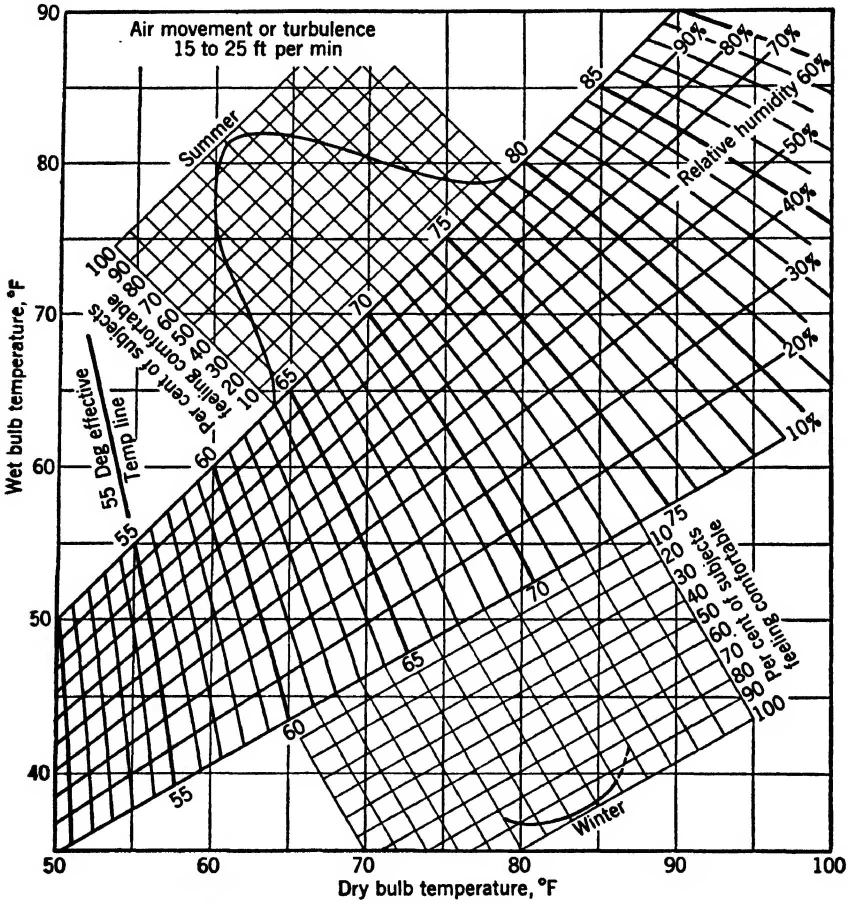

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Air changes per hour, as required in ventilation work, are dependent upon the velocity of the air and the size of the ducts. High-velocity air should, therefore, be well diffused and introduced into a space only at points well above the heads of the occupants to obviate the discomfort of draughts.

20. Air cleaning. Air may contain large quantities of dust, cinders, soot, smoke, fumes, pollen, grit, bacteria, and odors which when breathed induce discomfort and disease. It carries grime and discoloration to furniture and decorations. Filters, air washers, and eliminators have been developed to remove such contamination, and fans are required to give proper velocity to the air for efficient passage through these cleansers. (Chapter 20, Art. 2.)

21. Cooling. Comfort in hot weather is much increased by cooling the air and reducing its moisture content. However, a limit should be set upon the difference in temperature between inside and outside air since too great a drop produces an unpleasant shock and sense of chill when one enters a room. A shock of intense heat may also be experienced when one emerges from the cooler air of a conditioned building into high summer temperatures. The human body is capable of adjusting itself to moderate changes in temperature after an exposure of ¾ to 1 hr. The permissible difference between outdoor and indoor temperature, therefore, varies with the type of building, being less in shops, theaters and restaurants where the patrons remain only temporarily than in offices, schools and residences where the occupants spend from 3 to 8 or more hr continuously. For exposures of less than 1 to 2 hr a temperature difference of 10 to 12° is acceptable, and for longer exposures a 15° difference may be used. For persons at rest 76 to 80° and 50 per cent relative humidity are a frequent design average. Greater outdoor heat than 90 to 95°F is generally not considered in design because such temperatures are of short duration and are usually accompanied by lowered humidity. In general, human beings, because of acclimatization and lighter clothing, are comfortable under somewhat higher temperatures in summer than in winter.

22. Dehumidifying. In summer the relative humidity of outdoor air averages higher than in winter, and comfort in hot weather often requires a reduction in air vapor quite as much as a decrease in temperature. In most parts of our country, therefore, dehumidifying is closely related in importance to air cooling, and only in the very dry atmosphere of the West and Southwest is cooling alone relied upon to procure comfortable conditions. Cooling and dehumidifying are accomplished by passing the air through sprays of cold water or over refrigerating coils which reduce the temperature sufficiently to condense out some of the moisture. The cool air is then reintroduced into the room where the natural warmth raises it to a comfortable temperature lower than the original temperature and with a smaller percentage of humidity.

23. Air supply. The quantity of outdoor air to be supplied depends largely upon the activity of the occupants, the cubic feet of air space per person, and the type of building. Many local codes require about 30 cu ft per min per person. These conditions were formulated before the conditioning of air was developed. The present tendency is to recirculate and re-use the indoor air and to supply smaller proportions of outdoor air, 5 to 10 cu ft per person being considered sufficient to remove objectionable body odors and to maintain desirable pressures. The total air, therefore, equals the recirculated air plus the portion from outdoors. Air from kitchens, toilets, and smoking rooms should not be recirculated but should be exhausted directly out-of-doors, the exhaust being in excess of the supply. This wasted air must be made up in the fresh-air supply. For general applications the cubic feet per minute for a person not smoking may be taken as 5 to 7½ and for one smoking as 25 to 40. With a space of 400 cu ft per person 1½ air changes per hr will give a rate of 10 cu ft per min per person.

In buildings such as residences with very few occupants infiltration often provides all the necessary outdoor air.

REFERENCE

"Planning for Residential Air Conditioning," William J. McGuinness, *Progressive Architecture*, February, 1954.

PROBLEMS

1. Describe changes of state in relation to solids, fluids, and gases, and the connection of specific and latent heat with these phenomena.

2. Describe fully the process that takes place when water is placed in proximity to dry air at a higher temperature. What is the limit to this process? What action arises when moist air is cooled?

3. Define fully the following terms: (*a*) degree of saturation and relative humidity; (*b*) wet- and dry-bulb temperatures; (*c*) dew point.

4. (*a*) What is adiabatic saturation? (*b*) What are the relationships between the volume, pressure, temperature, and weight of air?

5. What is the psychrometric chart? Explain fully its assistance in air-conditioning calculations.

6. Upon what properties of air does comfort to occupants depend, and how is air modified to avoid discomfort in winter and summer?

7. Discuss (*a*) heating and humidifying; (*b*) cooling and dehumidifying; (*c*) ventilating outdoor air supply.

8. What is the composition of air?

9. State Dalton's rule.

10. What happens to the moisture in saturated air when it is cooled?

Chapter 18

DESIGN METHODS

1. Air-conditioning equipment. An air-conditioning unit may be arranged approximately as shown in the simplified diagram of Fig. 1. Here the fan is located in a compartment at the right and draws the air through the unit, exhausting it into the delivery duct system at a slight pressure. Usually part of the air returned from the rooms is recirculated, a predetermined proportion of outdoor air being mixed with it. The entering fresh air is controlled by louvers or dampers and is admitted through a *filter*. The mixed air is then warmed or tempered, if required, by passing over a bank of steam coils, called a *preheater,* to prevent freezing the spray in the air washer or to avoid heating the spray water. Treatment in the *spray chamber* follows to

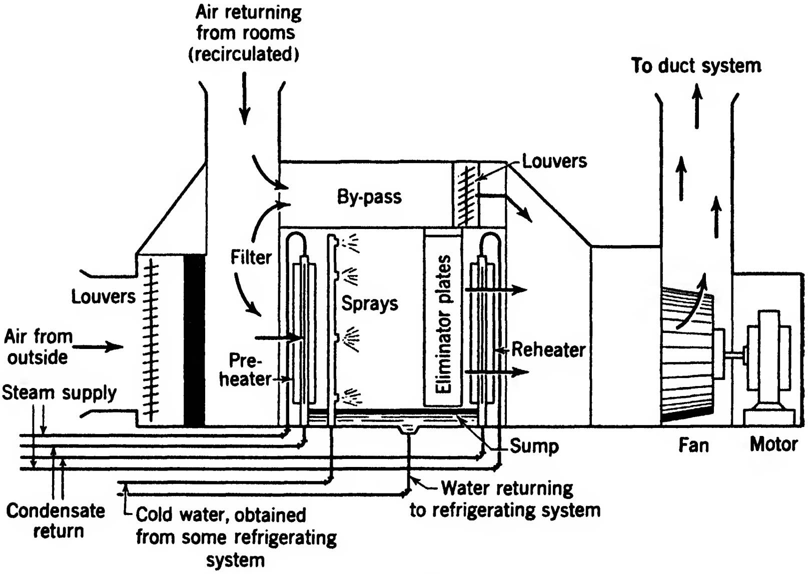

Fig. 1. Air-conditioning unit.

increase the moisture content of the air, to saturate it completely at some previously determined dew point, or to cool the air and condense out a percentage of the moisture. The spray chamber may also act as an *air washer* to cleanse the air. *Eliminator plates* next baffle the air flow, removing dust and entrained moisture. A final heating element then reheats the air, if necessary, to such a temperature that, when delivered to the rooms, it will establish the temperature and humidity desired.

The by-pass shown above the spray chamber is provided when part of the return air does not pass through the conditioner. In summer cooling the sensible heat in the by-passed air reduces very considerably and often avoids the reheating.

2. Heating and humidifying. Since human comfort depends upon the moisture content of the air as well as upon the temperature, the air-conditioning equipment must be adjusted to maintain in the given space the quantity of moisture required for comfort and economy at the design temperature.

The air may be taken entirely from outdoors or may be entirely borrowed from the room. In either event it is passed through the conditioner, treated as required by the design, and discharged into the room. Outdoor air alone is generally used only in certain industrial plants where a high rate of ventilation is a necessity. Recirculated room air alone is most frequently employed in moderate-sized buildings such as residences heated by hot air. Infiltration of outdoor air is then relied upon for ventilation.

The more usual and economical method in large buildings treated for human comfort is to recirculate a portion of the room air and to mix with it the required amount of ventilating air from outdoors, the mixture then being passed through the conditioner and introduced to the room.

Figure 2 shows three methods of treating the heating air.

(*a*) All air is taken from outdoors at 0°. The room air is to be at 70° with 44 grains of moisture per lb or 40 per cent R.H. The dew point of 70° and 40 per cent R.H. is 45°, which at saturation also carries 44 grains. By calculation it is found that, if the entering air is heated to 73° dry bulb and 45° wet bulb in the preheater, it can be saturated adiabatically in the washer, leaving at approximately 45° dew point with 44 grains of moisture. It is then raised to 70° in the reheater [Fig. 2(*a*)].

(*b*) If air is to be at 70° and 30 per cent R.H. and adiabatic saturation is not feasible the outdoor air is preheated to 33° dry bulb to avoid freezing of the spray. It is then warmed by the heated spray to the design dew point of the room air, is thereby saturated with the design weight of moisture, and is then reheated to the desired room temperature [Fig. 2(*b*)].

(*c*) A portion of the air is recirculated. The outdoor and recirculated air are mixed, the mixture is adiabatically saturated at the dew point of the room air, and the mixture is then reheated to the desired

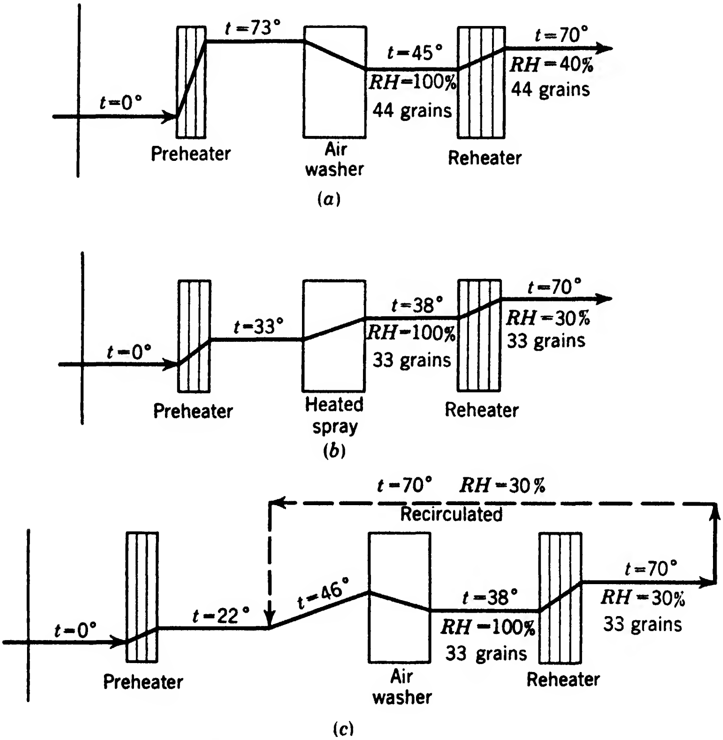

Fig. 2. Heating and humidifying.

temperature. It is necessary to preheat the outdoor air to a computed degree so that the air mixture will be at the proper entering wet-bulb temperature to leave the washer at the approximate dew point when the saturation is completed [Fig. 2(*c*)].

3. Cooling and dehumidifying. In summer, outdoor air in most inhabited parts of the United States contains more moisture than in winter. Comfort is consequently gained in hot weather by cooling the air and removing a portion of its humidity, just as in cold weather the air is heated and its moisture increased. We have seen that, by adiabatic saturation, air may be cooled to its wet-bulb temperature by passing through a spray of recirculated water, in which event the water also approaches closely to the wet-bulb temperature of the air. In summer with a high percentage of relative humidity the difference between the wet-bulb and dry-bulb temperatures, known as the *wet-bulb depression*, will be comparatively small. Consequently relatively little heat can be removed from the air. It is, therefore, seldom practicable in localities of high summer humidities [Fig. 3(*a*)].

In order to cool the air to a still lower degree and to remove a part of its moisture, the spray water must be maintained at a lower temperature than the dew-point temperature of the air. If sufficiently cold water from a deep well is obtainable it may be used in the spray and allowed to waste. If, however, the water supply cannot be wasted and is recirculated, then refrigeration of some sort is used either to hold the spray water at a desired low temperature or to cool the air itself by passing it over refrigerating coils. In both situations the intention is to reduce the air temperature below its original dew point so that precipitation of moisture will take place and the air will be both cooled and dehumidified [Fig. 3(*b*)].

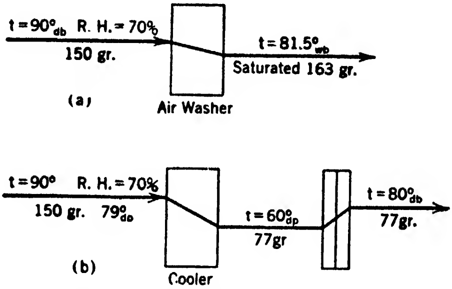

Fig. 3. Cooling and dehumidifying.

4. Dehumidifying by adsorption. A method of dehumidifying has been introduced depending upon the ability of certain substances to condense vapor and hold the condensate on the surface of the substance without physical or chemical change in the substance. Such substances, adaptable to air conditioning, are silica gel and activated alumina.

Silica gel is manufactured with the same chemical formula as sand (SiO_2) and is very porous. The dehumidifying and cooling action consists in passing the air through filters to clean it, then over silica gel beds to remove its moisture, and finally over cooling coils to lower its temperature. When the silica gel has adsorbed moisture to the limit of its capacity it may be reactivated by heat, which evaporates the moisture but otherwise leaves the substance in its original condition.

The action of activated alumina is approximately the same as that of silica gel. It is more often used for drying industrial products than in air conditioning.

5. Dehumidifying by absorption. Liquid absorbents such as calcium chloride, lithium chloride, and lithium bromide are also used for dehydrating air. The air stream is brought into intimate contact by passing it through a tower into which the absorbent is blown as a fine spray. The water vapor gives up its latent heat in condensation and the absorbent is changed both chemically and physically and is diluted by the water condensed from the air. This excess water is removed by evaporation through the application of heat which reconcentrates the absorbent liquid.

Both sorbents are best adapted when low relative humidities are required with only moderate cooling, as in some industrial processes and storage conditions. They are also used in work rooms where the moisture load is high compared to the heat load.

6. Heating load. The computation of heat losses from a building in winter is illustrated in Chapter 9, Art. 10.

7. Cooling load. The computations of heat gains in summer comprise many interrelated factors due to the importance of solar radiation and time lag in heat transmission and, therefore, require more involved study than in winter design.

8. Indoor conditions. For comfort to persons at rest 80° should not be exceeded and for occupancies of over 1 or 2 hr the tendency is to reduce to 78 or 76°. An average of 50 per cent R.H. is generally used.

For industries the requirements of the products and processes, as well as the efficiency of the occupants, determine the condition. Each type of industry should be consulted for its special needs.

9. Outdoor conditions. For most parts of the United States the design dry- and wet-bulb temperatures have been tabulated and the corresponding design relative humidity may be found from them. They range from 90 to 105° dry bulb and 72 to 78° wet bulb with averages of 95 and 75°.

10. Components of cooling load. Gains in *sensible heat* to be removed may occur through conduction, convection, and radiation and may arise from:

(*a*) Heat transmitted through walls, roofs, floors, partitions, ceilings, and glass, owing to difference between outdoor and indoor air temperatures.

(*b*) Heat of solar radiation striking upon the exterior surfaces of walls, roofs, and glass, absorbed by them and conducted through to the interior.

(*c*) Heat carried in by infiltrating or ventilating outside air.

(*d*) Heat given off by occupants.

(*e*) Heat given off by lights, cooking, motors, fans, and industrial processes within the conditioned space.

Gains in *latent heat* are considered to occur when there is an addition of water vapor to the indoor air. They may come from the following sources:

(*a*) From outside air entering through infiltration.
(*b*) From occupants.
(*c*) From cooking or industrial processes within the given space.

To balance the moisture added to room air through gains in latent heat, the cooler must condense an equal amount of water vapor from the treated air at the same rate as that acquired in the room.

11. Solar radiation. The amount of direct radiant heat energy from the sun in Btu per hour is partially reduced as it passes through the earth's atmosphere, a portion being scattered by contact with the air, smoke, moisture, and dust and a portion absorbed by water vapor, carbon dioxide, and ozone. The net energy striking the earth at normal incidence is called the direct solar radiation. A diffuse sky or reradiation is also received by the earth as a partial result of absorption of a portion of the solar energy by the atmosphere itself. The radiation transmitted to the earth is, therefore, the sum of the direct solar and the sky radiation.

When the radiation strikes upon a building material on the earth's surface it is partly reflected, partly absorbed, and partly transmitted through the material. Also building surfaces themselves radiate heat to the sky.

Therefore the heat entering the outer surface equals the sum of the direct solar radiation and the sky radiation minus the reflected direct radiation, the reflected sky radiation, and the radiation emitted to the sky by the outer surface.

There is also a heat transfer by convection and radiation to or from the outer surface, depending upon the relative temperatures of the surface and the air. Its magnitude is affected by the position of the surface and the velocity of the air currents.

12. Sol-air temperature conveniently combines the effects of solar and sky radiation, solar absorptivity, convective heat exchange, temperature, and air movement and avoids cumbersome calculations. It is the temperature of outdoor air which, when in contact with the shaded outside surface of a building, would give the same rate of heat entry to the surface as would exist were the surface in the light of the sun.

By definition the sol-air temperature (t_e) must give the same rate of heat entry to a surface as the sum of the solar and sky radiation as modified by the absorptivity of this surface, the outdoor temperature, and the surface conductance, or

$$t_e = t_o + \frac{bI_t}{f_o} \tag{1}$$

where t_o = outside dry-bulb temperature in degrees.

b = absorptivity of outer surface for incident solar and sky radiation.

I_t = rate of solar and sky radiation in Btu per hour per square foot.

f_o = unit of surface conductance, radiation, and convection combined in Btu per hour per square foot per degree.

Example 1. $t_o = 88°$; $b = 0.7$; $I_t = 220$ Btu per hr per sq ft; f_o is generally taken at 4 in summer. What is the sol-air temperature?

$$t_e = 88 + \frac{0.7 \times 220}{4} = 126.5°$$

Equation 1 does not apply to glass areas, which are customarily treated separately (Art. 15).

Sol-air temperatures vary with t_o, I_t, and b/f_o. Values of I_t depend upon the orientation of the receiving surface, the latitude, the time of day, the sun's altitude, and the season; b/f_o depends upon the absorptivity of the material and the surface conductance. Table I gives the summer sol-air temperatures for 40° N. latitude and 18° north declination of the sun.

13. Time lag. Tables and computations relating to heat transmission through materials deal with instantaneous rates of gain. However, a very definite passage of time may elapse between the entry of heat into a wall and its emergence from the other side. This delay is due to the storage of heat and its subsequent release by the structure. As the amount of heat entering a wall or roof varies in cycles according to changing hourly outdoor conditions, so a related cycle variation of heat flow is produced throughout the mass. As the wave passes through the wall its maximum temperatures, therefore, reach successive points at times progressively later than the start of maximum heat at the outside surface. This time lag varies from fractions of an hour to 15 hr and is important in fixing the time of maximum heat gain in the room.

As the heat wave passes through the wall or roof its amplitude, that is, the difference between the maximum and the mean temperatures of the wave, will progressively decrease. The factor of this decrease, or *amplitude decrement factor*, depends upon the thickness, material, and orientation of the wall or roof. It is expressed by the Greek letter lambda (λ).

Table II gives heat flow data for several homogeneous materials.

For a composite wall or roof made up of two or more layers of different materials the total time lag is the sum of the time lags for each material with an additional lag for a suitable estimate. Use ½ hr additional for two layers and light construction, and 1 hr for three or more layers and heavy construction.

Table I. Sol-Air Temperatures for 40° North Latitude, 18° Declination *

Mean Sun Time	Sol-Air Temperature, t_e: August 1					
	Any Surface	Horizontal	North	East	South	West
Ratio b/f_o	0	0.25	0.25	0.25	0.25	0.25
8 A.M.	77	119	81	137	86	81
9	80	136	85	134	99	85
10	83	149	88	124	110	88
11	87	160	92	111	119	92
12 Noon	90	165	96	96	124	96
1 P.M.	93	166	98	98	125	117
2	94	160	99	99	121	135
3	95	151	100	100	114	149
4	94	136	98	98	103	154
5	93	120	101	96	97	150
24-hr average t_m	83.1	109.1	86.5	95.8	92.2	95.8

The value of 0.25 is arbitrarily chosen for b/f_o. Temperatures at other values of b/f_o may be found by interpolation.

If absorptivity = 0.7, $v/f_o = 0.7/4 = 0.175$. For wall facing south at 2:00 P.M., $t_e = 94° + (0.175/0.25)(121 - 94) = 112.9°$.

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 273.

The time of maximum heat entry into the outer surface of a wall or roof is found in Table I as the time of maximum sol-air temperature. The time of maximum heat gain to the room is found by adding the time lag from Table II to the time of maximum heat entry to the outer surface. The corresponding maximum rate of heat gain to the room, including adjustment for time lag, is found from Equation 2.

$$q/A = U[(t_m - t_i + \lambda(t_e - t_m)] \text{ Btu/hr/sq ft} \qquad (2)$$

where q = rate of heat entry.
A = area in square feet.
t_m = 24-hr average sol-air temperature.
λ = amplitude decrement factor.
t_e = sol-air temperature at time earlier by value of time-lag.
U = overall coefficient of heat transfer.

Table II. Periodic Heat Flow, Homogeneous Walls or Roofs *

Material	Thickness (in.)	Overall Coefficient Btu per hr (°F)(sq ft) U	Thermal Resistance of Solid Material (hr)(sq ft)(°F)/Btu L/k	Time Lag (hr)	Factor λ, in Equation 2			
					Horizontal and North	East	South	West
Stone	12	0.55	0.96	8.0	0.28	0.19	0.26	0.22
	16	0.47	1.28	10.5	0.17	0.10	0.15	0.13
Solid concrete	2	0.98	0.17	1.1	0.93	0.87	0.92	0.89
	4	0.84	0.33	2.5	0.79	0.68	0.76	0.72
	6	0.74	0.50	3.8	0.61	0.46	0.58	0.51
	8	0.66	0.67	5.1	0.49	0.33	0.46	0.39
	12	0.54	1.00	7.8	0.29	0.17	0.26	0.22
Common brick	4	0.60	0.80	2.3	0.83	0.75	0.81	0.78
	8	0.41	1.60	5.5	0.51	0.39	0.49	0.44
	12	0.31	2.40	8.5	0.26	0.17	0.25	0.21
Face brick	4	0.77	0.44	2.4	0.81	0.70	0.78	0.74
Wood	½	0.68	0.62	0.17	1.0	1.0	1.0	1.0
	1	0.48	1.25	0.45	1.0	0.99	0.99	0.99
	2	0.30	2.50	1.3	0.98	0.91	0.96	0.94
Insulating board	½	0.42	1.51	0.08	1.0	1.0	1.0	1.0
	1	0.26	3.03	0.23	1.0	1.0	1.0	1.0
	2	0.14	6.05	0.77	1.0	1.0	1.0	1.0

Based upon outdoor and indoor surface conductances of 4.0 and 1.65, respectively.

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 276.

Example 2. Find rate of heat gain through an 8-in. brick west wall in 40° N. latitude at 5 :00 P.M. $b = 0.7$; $f = 4.0$; inside temperature, 80°.

Solution. From Table II, $U = 0.41$, time lag = 5½ hr (11 :30 A.M.), $\lambda = 0.44$. By interpolation in Table I, the 24-hr average sol-air temperature, on the basis of $b/f_o = 0.7/4.0$, is

$$t_m = 83.1 + \frac{0.175(95.8 - 83.1)}{0.25} = 83.1 + 8.9 = 92°$$

The sol-air temperature at 11 :30 AM. is

$$t_e = 88.5 + \frac{0.175(94 - 88.5)}{0.25} = 92.4°$$

Indoor gain at 5 :00 P.M. = 0.41 [(92 – 80) + 0.44 (92.4 – 92)] = 5 Btu per sq ft per hr.

14. Equivalent temperature differentials. Practical tables have been developed based upon the use of sol-air temperatures in estimating solar heat gain. They present equivalent temperature differentials in degrees which may be multiplied by the overall heat transfer coefficient (U) to obtain directly the total heat flow in Btu per square foot from solar radiation and from the temperature difference between outside and room air. They thereby combine several laborious steps and simplify the calculations. The values may be used for latitudes from 0° to 50° N. or S. For differences greater or less than 15° between outdoor and indoor design temperatures, add the excess to or subtract the deficiency from the values. For daily temperature ranges greater or less than 20°, subtract 1° for every 2° excess or add 1° for every 2° deficiency.

15. Heat gain through glass. The net indoor heat gain through glass involves differing phenomena in the radiation and transmission of heat as received directly from the sun and as received from outdoor convection and radiation. It is, therefore, found convenient to calculate separately the forms of solar radiant energy and the forms of radiant energy derived from other sources. The complete heat balance for a unit of time is illustrated in Equation 3.

$$\overset{A}{\begin{bmatrix}\text{Total heat}\\ \text{flow through}\\ \text{glass}\end{bmatrix}} = \overset{B}{\begin{bmatrix}\text{Transmitted}\\ \text{solar}\\ \text{radiation}\end{bmatrix}} \pm \overset{C}{\begin{bmatrix}\text{Heat flow by convective}\\ \text{and radiative exchanges}\\ \text{at indoor surfaces}\end{bmatrix}} \tag{3}$$

Tables have been developed giving the instantaneous values of heat gains for single panes of unshaded common window glass and for hollow glass blocks. Table V sets forth the transmission of solar heat according to term B of Equation 3 and depends upon the solar and sky radiation and upon the transmittance of the glass. Table VI represents the heat flow by convective and radiative exchanges according to term C of Equation 3. It is based upon a 75° indoor temperature and a 95° maximum outdoor temperature cycle. A surface conductance of 4.0 is used as a combined convection and radiation heat exchange. The total heat flow through a single sheet of common unshaded glass will be the sum of the values found in Tables V and VI.

In order to obtain the total heat gain for other types and combinations of glass, the solar radiation values in Table V are multiplied by the factor in Table VII appropriate to the type and combination selected. The convection and radiation X values in Table VI are multiplied by the appropriate X factor in Table VII, and the Y values in Table VIII by the appropriate Y factor in Table VII. The three corrected values are then added together to obtain the total heat gain.

Table IX presents the heat gain from solar and sky radiation through hollow glass blocks, and Table X the gain from convection and radiation.

From Table XI the corrections are found for single and double glass sheets and for glass blocks with outdoor and indoor temperatures above 95° and 75°, respectively.

Table III. Equivalent Temperature Differentials, Sunlit and Shaded Roofs *

Description of Roof Construction (Includes $\frac{3}{8}$-in. felt roofing with or without slag. May be used for shingle roof)	Sun Time								
	A.M.		P.M.						
	8	10	12	2	4	6	8	10	12
Light Construction Roofs—Exposed to Sun									
1-in. Wood, or 1-in. wood plus 1-in. or 2-in. insulation	12	38	54	62	50	26	10	4	0
Medium Construction Roofs—Exposed to Sun									
2-in. Concrete or 2-in. concrete plus 1-in. or 2-in. insulation or 2-in. wood	6	30	48	58	50	32	14	6	2
2-in. Gypsum or 2-in. gypsum plus 1-in. insulation 1-in. Wood or 2-in. wood or 2-in. concrete or 2-in. gypsum } plus 4-in. rock wool in furred ceiling	0	20	40	52	54	42	20	10	6
4-in. Concrete or 4-in. concrete with 2-in. insulation	0	20	38	50	52	40	22	12	6
Heavy Construction Roofs—Exposed to Sun									
6-in. Concrete	4	6	24	38	46	44	32	18	12
6-in. Concrete plus 2-in. insulation	6	6	20	34	42	44	34	20	14
Roofs in Shade									
Light construction	−4	0	6	12	14	12	8	2	0
Medium construction	−4	−2	2	8	12	12	10	6	2
Heavy construction	−2	−2	0	4	8	10	10	8	4

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* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 280.

Table IV. Equivalent Temperature in Differentials, Sunlit and Shaded Walls *

North latitude	Sun Time																	
	A.M.					P.M.												
	8		10		12		2		4		6		8		10		12	
Wall facing	Exterior Color of Wall – D = Dark, L = Light																	
	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L
	Frame																	
E	30	14	36	18	32	16	12	12	14	14	14	14	10	10	6	6	2	2
S	−4	−4	4	0	22	12	30	20	26	20	16	14	10	10	6	6	2	2
W	−4	−4	0	0	6	6	20	12	40	28	48	34	22	22	8	8	2	2
N (Shade)	−4	−4	−2	−2	4	4	10	10	14	14	12	12	8	8	4	4	0	0
	4-in. Brick or Stone Veneer plus Frame																	
E	2	0	30	14	31	17	14	14	12	12	14	14	12	12	10	8	6	6
S	−4	−4	−2	−2	12	6	24	16	26	18	20	16	12	12	8	8	4	4
W	0	−2	0	0	4	2	10	8	26	18	40	28	42	28	16	14	6	6
N (Shade)	−4	−4	−2	−2	0	0	6	6	10	10	12	12	12	12	8	8	4	4
	8-in.Brick or 12-in. Hollow Tile or 12-in. Cinder Block																	
E	8	6	8	6	14	8	18	10	18	10	14	8	14	10	14	10	12	10
S	4	2	4	2	4	2	4	2	10	6	16	10	16	12	12	10	10	8
W	8	4	6	4	6	6	8	6	10	6	14	8	20	16	24	16	24	16
N (Shade)	0	0	0	0	0	0	0	0	2	2	6	6	8	8	8	8	6	6
	12-in. Brick																	
E	12	8	12	8	12	8	10	6	12	8	14	10	14	10	14	8	14	8
S	8	6	8	6	6	4	6	4	6	4	8	4	10	6	12	8	12	8
W	12	8	12	8	12	8	10	6	10	6	10	6	10	6	12	8	16	10
N (Shade)	4	4	2	2	2	2	2	2	2	2	2	2	2	2	4	4	6	6

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* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 282.

Table V. Heat Gain, Solar and Sky Radiation through a Single Sheet of Common Glass, 40° N. Latitude; Btu per Hour per Square Foot; August 1st *

A.M. → ↓		β	North	γ	East	γ	South	γ	West	γ	Horizontal
8	4	34.5	14	Shade	205	5	18	85	12	5	137
9	3	45.5	15		180	16	42	74	14	16	188
10	2	56	16		127	31	69	59	16	31	229
12		68	17		19	90	98	0	19	90	259
	↑ P.M. →		North		West		South		East		Horizontal

β = altitude of sun in degrees. γ = wall solar azimuth in degrees.

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 290.

Table VI. Heat Gain from Convection and Radiation through a Single Sheet of Common Glass, for 75° Indoor Temperature *

Sun Time	Dry-bulb Temp.	40° N. Latitude, Gain in Btu per Hour per Square Foot; August 1st				
		North	East	South	West	Horizontal
8 A.M.	77	2	6	3	2	5
9	80	5	9	6	5	8
10	83	8	11	10	8	13
12	90	17	17	19	17	21
2 P.M.	94	21	21	23	24	26
3	95	22	22	24	26	26
4	94	21	21	22	25	24

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 291.

Table VII. Factors to Be Applied to Tables V, VI, and VIII for Various Types and Combinations of Glass *

Glass	Normal Incidence Transmittance	Factors for Table V	X Factor for Table VI Y Factor for Table VIII
Single common	0.87	1.00	$1.0(X) + 0.0(Y)$
Single plate	0.77	0 87	$1.0(X) + 0.25(Y)$
Single heat-absorbing	0.41	0.46	$1.0(X) + 1.00(Y)$
Double common, ¼-in. space	0.76	0.76	$0.6(X) + 0.10(Y)$

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 292.

Table VIII. Values of *Y* to Be Used with Factors in Table VII *

Sun Time	Gains in Btu per Hour per Square Foot, August 1st, 40° N. Latitude				
	North	East	South	West	Horizontal
8 A.M.	2	33	2	2	21
9	2	30	8	3	32
10	3	25	14	3	37
12	3	3	19	3	45
2	3	3	16	24	41
3	3	3	10	31	35
4	3	3	4	36	26

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 292.

Table IX. Heat Gain, Solar and Sky Radiation through Hollow Glass Blocks, 40° N. Lat., Btu per Hour per Square Foot, August 1st *

		Type A				Type B				Type C			
A.M. →		N	E	S	W	N	E	S	W	N	E	S	W
↓													
8	4	5	90	5	4	3.5	54.0	3.5	2.8	2.7	27.0	2.70	2.2
9	3	5	59	10	5	3.5	38.3	6.5	3.5	2.7	17.7	6.00	2.7
10	2	6	29	15	6	4.2	20.3	9.7	4.2	3.3	10.1	7.50	3.3
12		6	6	17	6	4.2	4.2	15.3	4.2	3.3	3.3	7.65	3.3
	↑												
	P.M. →	N	W	S	E	N	W	S	E	N	W	S	E

Type A. Smooth outer faces, one inner face with vertical ribs, one with horizontal ribs.

Type B. Light diffusing; outer faces with narrow vertical ribs, inner faces etched or stippled, glass fiber screen partition in cavity.

Type C. Light diffusing; outer faces with close deep horizontal corrugations, inner faces with vertical prisms.

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 293.

Table X. Heat Gains from Convection and Radiation through Hollow Glass Blocks, Types A, B, and C, for 75° Indoor Temperature *

Sun Time	Dry-Bulb Temp.	40° N. Lat. Btu per Hour per Square Foot			
		N	E	S	W
8 A.M.	77	2	28	3	2
9	80	2	35	7	4
10	83	4	38	14	6
12	90	8	18	25	10
2 P.M.	94	11	17	27	30
3	95	13	18	23	43
4	94	13	17	18	46

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 294.

Table XI. Corrections for Deviations from Design Temperatures *

Glass Type	Correction (Btu/hr/sq ft)
Single glass	1.0
Double glass	0.5
Glass block	0.5

Subtract correction for each degree design room temperature above 75°. Add correction for each degree design outdoor temperature above 95°.

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 296.

Example 3. Find the total heat gain through double common window glass in a west wall in 40° N. lat. at 3:00 P.M. Temperatures, outdoor 95°, indoor 80°.

Solution. $180 \times 0.85 + 0.6 \times 0.10 \times 31 - 0.5(80 - 75) = 169.2$ Btu/hr/sq ft.

Example 4. Find the total heat gain through a south wall of 8-in. type B hollow glass blocks, at 12:00 noon, in 40° N. lat., temperatures 98° outdoor, 75° indoor.

Solution. $15.3 + 25 + 0.5(98 - 95) = 41.8$ Btu/hr/sq ft.

16. Window shading.

(*a*) *Setbacks.* Glass set back from the outer building face may be more or less shaded by the edges of the window openings. If h = the height, w = the width, and s = the setback of the window sash, the percentage of the area receiving direct sunlight is

$$G = 1 - \frac{r_1 \tan \beta}{\cos \gamma} - r_2 \tan \gamma + \frac{r_1 r_2 \tan \beta \tan \gamma}{\cos \gamma}$$

where $r_1 = s/h$; $r_2 = s/w$; β = solar altitude, γ = azimuth angle between the horizontal projection of sun's rays and the jambs of the window opening. Values of β and γ are given in Table V.

When the principal heat gain is through a wall containing a large proportion of windows with deep setbacks, the shading may considerably affect the heat load; otherwise it can generally be neglected.

(*b*) *Shades.* Windows, particularly when sunlit, are customarily provided with some means of shading. The usual devices are awnings, shades, blinds, or screens. Inside shades are effective only to the extent of their reflectivity toward the outside. The solar radiation absorbed by the shade is transferred by convection to the room air and by radiation to the solid surfaces within the room.

17. Heat gains through interior partitions, ceilings, and floors. If the temperature of adjacent spaces is higher than that of the air-conditioned space, heat gains will be the result.

Table XII. Effect of Shading through One Thickness of Window Glass *

Type of Shading	Finish on Side Exposed to Sun	Fraction of Gain through Unshaded Window
Canvas awning	Dark	0.20 to 0.35
Inside roller shade, fully drawn	White	0.45
Inside roller shade, fully drawn	Medium color	0.63
Inside roller shade, fully drawn	Dark color	0.80
Inside roller shade, half drawn	White	0.72
Inside roller shade, half drawn	Medium color	0.81
Inside roller shade, half drawn	Dark color	0.90
Inside Venetian blind, slats set at 45°	White	0.62
Inside Venetian blind, slats set at 45°	Medium	0.74
Inside Venetian blind, slats set at 45°	Aluminum	0.70
Inside Venetian blind, slats set at 45°	Dark color	0.86
Outside Venetian blind, slats set at 45°	Cream	0.30
Outside shading screen, slats at 45°, as awning †	Any color	0.40
Outside shading screen, solar altitude 0–20°	Dark color	0.75 to 0.43
Outside shading screen, solar altitude 20–40°	Dark color	0.43 to 0.22
Outside shading screen, solar altitude above 40°	Dark color	0.22

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 298.

† Metal slats 0.05 in. wide, spaced 0.063 in. apart, and set at 17° angle with horizontal.

Actual temperatures in the adjacent spaces should be measured when possible. Kitchen and boiler rooms may be many degrees higher than outdoor temperature. If the adjacent space contains no heat sources and is not conditioned, it is often considered to be at a temperature 5° F lower than that of outdoors. The heat gain through the partition will then be periodic, and the shaded wall values in Table IV should be used. The heat transfer is usually neglected for floors directly on the earth or over underground basements which are neither ventilated nor warmed.

18. Outside ventilation and infiltration. The outside air introduced for ventilation is not included in the space cooling load but does affect the capacities of the conditioning apparatus and the air ducts.

Its temperature and degree of saturation will be that of the outside air, and its quantity and rate of entry are determined by the employment of the space and the number of occupants or by local building codes. For spaces of ceiling heights of 10 ft or less the rate should be at least one volume change per hour (Chapter 9, Art. 9).

Infiltration is calculated as explained in Chapter 9, Art. 8. For an entire building in summer one-half the total crack length with a wind velocity of 10 mi per hr is generally taken. When economically possible, sufficient outdoor air to produce an indoor pressure capable of overcoming the wind pressure and infiltration is introduced through the conditioner, maintaining an outward escape of air through cracks and door openings. Infiltration is thereby eliminated.

The sum of the rates of entry from ventilation and infiltration being found in cubic feet per minute, the following equations will give the cooling load:

$$\text{Sensible load} \quad q_s = Q \times 1.08(t_o - t_i) \text{ Btu/hr} \tag{4}$$

$$\text{Latent load} \quad q_L = Q \times 4840(W_o - W_i) \text{ Btu/hr} \tag{5}$$

where Q = rate of entry of outside air in cubic feet per minute.
t_o = outdoor dry-bulb temperature.
t_i = indoor dry-bulb temperature.
W_o = moisture in outdoor air in pounds per pound of dry air.
W_i = moisture in indoor air in pounds per pound of dry air.
1.08 = 60 min × 0.24 × 0.075, where 0.24 = specific heat of air in Btu per pound, and 0.075 = standard air weight in pounds per cubic foot.
4840 = 60 × 0.075 × 1076, where 1076 = average latent heat in Btu to condense 1 lb of water vapor from air.

19. Heat gains within the room are made up of heat given off by occupants, lights, and appliances.

20. Occupants (Table XIII). Table XIII is based on 80° dry-bulb room temperature. For 78° the sensible heat value should be increased and the latent heat value decreased by 10 per cent each, the total heat remaining the same. The adjusted total heat gain is based upon the normal percentage of men, women, and children for the application listed, the gain from a woman being 85 per cent, and from a child 75 per cent of that from a man.

For a person at rest the total heat given off in normal indoor temperature is often averaged at 400 Btu per hr.

21. Lights. The heat equivalent of one watt is 3.41 Btu per hr. The total rate of heat gain from electric lighting would then equal the total wattage × 3.41 Btu. This total heat gain may be modified by a usage factor representing the fraction of the total installed wattage

Table XIII. Heat Gain from Occupants *

Degree of Activity	Typical Application	Total Heat Adults Male (Btu/hr)	Total Heat Adjusted (Btu/hr)	Sensible Heat (Btu/hr)	Latent Heat (Btu/hr)
Seated at rest	Theater, matinee	390	330	180	150
	Theater, evening	390	350	195	155
Seated, very light work	Offices, hotels, or apartments	450	400	195	205
Moderately active work	Offices, hotels, or apartments	475	450	200	250
Standing, light work or walking slowly	Department store, retail store	550	450	200	250
Walking, seated, or standing, walking slowly	Drug store, bank	550	500	200	300
Sedentary work	Restaurant	490	550	220	330
Light bench work	Factory	800	750	220	530
Moderate dancing	Dance hall	900	850	245	605
Walking, 3 mi/hr, or moderately heavy work	Factory	1000	1000	300	700
Bowling or heavy work	Bowling alley, factory	1500	1450	465	985

* Abstracted by permission from *Heating, Ventilating, Air Conditioning Guide*, 1951, page 303.

generally in use at one time. A special allowance factor of 1.20 should be included for fluorescent lights.

$$q = \text{Total light wattage} \times \text{Use factor} \times 3.41 \text{ Btu per hr} \qquad (6)$$

22. Appliances. All appliances, electric, gas or steam, whether for cooking, manufacturing, or other use, must be carefully studied to determine the heat equivalent of their operation and included in the cooling load. Information may be obtained from the manufacturers as to their heat output and other characteristics.

When appliances are provided with a positive fan exhaust through a hood, 50 per cent of the recommended rate of both the sensible and the latent heat gains is considered carried away and 50 per cent dissipated in the conditioned space.

A general *power load* equation is

$$\left(\frac{\text{Horse power}}{\text{Motor efficiency}}\right) \times (\text{Load factor}) \times 2544 \text{ Btu/hr} \qquad (7)$$

When the motor is not within the conditioned space, omit "efficiency" from Equation 7.

23. Moisture transfer through walls and roofs. Since the penetration of moisture into and through walls and roofs is very harmful for structural reasons, great care is generally taken in the composition of walls and roofs to avoid such action. In the usual comfort air conditioning, moisture transfer of this kind can therefore be neglected.

For certain industrial and storage processes calling for low moisture content, however, the moisture transfer and its latent heat load should be considered.

PROBLEMS

1. Describe and illustrate with a sketch an all-season air-conditioning apparatus, showing usual arrangement and sequence of parts.

2. Describe three methods by which air may be heated and humidified to a predetermined degree.

3. Under summer conditions what is the end in view in passing the air through a water spray, and what is the controlling temperature of the spray?

4. What are the five sources of gains in specific heat and the three sources of gains in latent heat in a building in hot weather?

5. Describe the effects of solar radiation, and explain the meaning of sol-air temperature and why it is employed.

6. What is meant by equivalent temperature differentials?

7. Discuss heat transfer through window glass and the effects of shading the windows.

8. How are the heat gains from occupants, lights, and appliances calculated?

9. What is the purpose of a preheater in winter operation?

10. What chemical substances are used for dehumidifying by adsorption?

Chapter 19

DESIGN COMPUTATIONS

1. General considerations.

(*a*) If heat losses in winter are made up by radiators or convectors placed within the room, the conditioned air is introduced at room temperature (split system). If the conditioned air must also offset the heat losses in addition to maintaining the room at design conditions, it is supplied at a sufficiently higher temperature to accomplish that purpose. In both cases moisture may be added to the air to maintain the desired degree of humidity. A definite amount of air is consequently passed through the conditioning apparatus.

(*b*) In summer there are no practicable means, corresponding to the split system in winter, of separating the duties of counterbalancing cooling loads and of maintaining desired room conditions. To maintain the design state in a space, a definite quantity of air must, therefore, be passed through the conditioner and introduced into the room at such a temperature and degree of saturation that its effect will be to counterbalance or remove the unwanted amounts of heat and moisture.

(*c*) The required amount of air, known as the *effective air quantity,* is supplied by a mixture of the specified quantity of outdoor ventilating air and a certain amount of recirculated indoor air from the space in question. The weight of dry air introduced into the room with the conditioned air will necessarily be the same as that withdrawn from the room. Consequently, the quantity of recirculated air to be conditioned and returned to the room will equal the total quantity of air withdrawn less the quantity of ventilating air, the surplus air withdrawn from the room being exhausted out of doors before entering the conditioner. Since the ventilating air does not enter the room until after it has been processed, it does not affect the heating or cooling load in the room. It is, therefore, customary to use the space sensible heat load without regard to the ventilating load in calculating the effective or required air quantity.

The equation is

$$Q_a = \frac{Q_h}{1.08(t_1 - t_2)} \qquad (1)$$

where Q_a = effective air quantity in cubic feet per minute.
Q_h = total sensible heat load in space in Btu per hour.
t_1 = design temperature of space.
t_2 = apparatus dew point.
1.08 = 0.24 × 0.075 × 60 = Specific heat × Density × Minutes per hour.

Example 1. Sensible heat load = 90,000 Btu/hr. Design temperature of room = 80° db, 50 per cent saturated. Apparatus dew point = 54°. Efficiency of apparatus 100 per cent. Find effective air quantity.

$$Q_a = \frac{90,000}{1.08(80 - 54)} = 3205 \text{ cu ft/min}$$

$$\frac{3205 \times 60}{13.84} = 13,894 \text{ lb/hr}$$

where 13.84 = volume in cubic feet of 1 lb air at 80° db and 50 per cent saturation. If the apparatus were 85 per cent efficient, 0.85 would be introduced in the denominator and the effective air quantity would be 3770 cu ft per min.

(*d*) *Mixture of Two Air Streams.* The mixing of two air streams, such as outdoor ventilating air and recirculated air from the conditioned space, is a common air-conditioning practice. The quantity of dry air in pounds, the enthalpy, and the weight of water per pound of dry air in each stream are generally known. With these values the corresponding values for the mixture may be obtained by the following equations:

$$\frac{(Q_1 \times h_1) + (Q_2 \times h_2)}{Q_1 + Q_2} = h_3 \tag{2}$$

$$\frac{(Q \times w) + (Q_2 \times w_2)}{Q_1 + Q_2} = w_3 \tag{3}$$

$$Q_1 + Q_2 = Q_3 \tag{4}$$

where Q_1 = pounds of dry air, stream 1.
Q_2 = pounds of dry air, stream 2.
Q_3 = pounds of dry air, mixture.
w_1 = pounds of water, stream 1.
w_2 = pounds of water, stream 2.
w_3 = pounds of water, mixture.
h_1 = enthalpy Btu, stream 1.
h_2 = enthalpy Btu, stream 2.
h_3 = enthalpy Btu, mixture.

Example 2. If 10,000 lb of air with $h = 0.29$ and $w = 0.00895$ are to be mixed with 4000 lb of air with $h = 0.668$ and $w = 0.000629$, find temperature and degree of saturation of the mixture.

$$h_3 = \frac{(10{,}000 \times 29) + (4000 \times 0.668)}{14{,}000} = 20.92 \text{ Btu/lb dry air}$$

$$w_3 = \frac{(10{,}000 \times 0.0089) + (4000 \times 0.00062)}{14{,}000} = 0.00653 \text{ lb/lb dry air}$$

With these values the temperature of the mixture may be found from the psychrometric chart (Chapter 17, Fig. 1) to be 57.8° db. Since $w = 0.00653$ and w_3 at saturation $= 0.0102$, the degree of saturation of the mixture is $0.00653/0.0102 = 64$ per cent.

(*e*) *By-Passing.* In summer cooling the temperature of the saturated air leaving the apparatus may be too low for direct introduction into the conditioned space. In this event it is much less economical to raise its entering temperature by reheating than it is to pass a quantity of room air around the cooler and mix it with the air leaving the cooler before it enters the fan. By this mixing the air can be usually raised to a temperature satisfactory for introducing into the space. The quantity of room air by-passed should be approximately equal to the quantity processed, and the calculations for the conditioning of the recirculated air are not affected.

In winter the reheating load may be appreciably reduced by passing room air around the humidifier and mixing it with the processed air before entering the reheater.

(*f*) *Sensible Heat Factor* (SHF). The ratio of the sensible heat gain or loss to the total heat gain or loss is an important consideration in determining the requirements of the air conditioner. This ratio is called the sensible heat factor or the load ratio. It is defined by the equation

$$\text{SHF} = \frac{H_s}{H_T} \tag{5}$$

$$H_T = H_s + H_L \tag{6}$$

where H_s = the sensible, H_L = the latent, and H_T = the total heat gain or loss in Btu per hour.

In the process of cooling and dehumidifying the SHF is especially useful. To conserve the desired relationships in the conditioned space the proportion of the sensible heat to the total heat taken up per pound of air must equal the SHF of the entire conditioned space, or

$$\text{SHF} = \frac{0.24(t_r - t_a)}{h_r - h_a} \tag{7}$$

where t_r = room design temperature.
t_a = entering air temperature.
h_r = enthalpy of room air and moisture in Btu per pound of air.
h_a = enthalpy of entering air and moisture in Btu per pound of air.
0.24 = specific heat in Btu per pound of air.

(*g*) *Apparatus Dew Point.* To avoid reheating the air leaving the cooling apparatus to a proper temperature for mixing with the room air, the saturated air must leave the apparatus at the temperature and water content designed for the air entering the room. This correct apparatus dew point may be determined by first finding the SHF and then substituting values by trial for t_a and h_a in Equation 7 until the equation is satisfied.

Example 3. The sensible heat gain in a room = 90,000 Btu per hr, and the total heat gain 110,000 Btu per hr. The design conditions in the room are 80° db and 50 per cent saturation. Find the SHF and the apparatus dew point.

$$\text{SHF} = \frac{90{,}000}{110{,}000} = 0.78$$

with SHF = 0.78, $t_r = 80°$ and $h_r = 31.4$ Btu. Equation 7 becomes $0.78 = \dfrac{0.24(80 - t_a)}{31.4 - h_a}$. Substituting 62 and 27.85 for t_a and h_a, $\dfrac{0.24(80 - 62)}{31.4 - 27.8} = 1.2$ which is too high. Substituting 55 and 23.2, $\dfrac{0.24(80 - 55)}{31.4 - 23.2} = 0.73$, which is too low. Substituting 56.5 and 24.16, $\dfrac{0.24(80 - 56.5)}{31.4 - 24.16} = 0.78$, which is satisfactory.

56.5° is then the apparatus dew point.

The apparatus dew point may also be found directly on the psychrometric chart by drawing a line, called the condition line, from the point 0.78 on the sensible heat factor scale through the state point of 80° db and 50 per cent saturation. Extend this line to the left and its intersection with the saturation curve marks the apparatus dew point.

2. Cooling and dehumidifying. The method employed to determine the cooling load for an enclosure usually involves the following steps: (*a*) Calculate sensible and latent heat gains. (*b*) Find sensible heat factor and apparatus dew point by computation or by the use of the psychrometric chart with sensible heat factor index and condition line. (*c*) Calculate the effective air quantity required. (*d*) Find temperature of air leaving the fan and entering room.

Example 4 (Fig. 1). Outdoor air 95° db; 78° wb; $h = 41.5$; $w = 0.01685$. Indoor air 80° db, 50 per cent saturation, $h = 31.4$; $w = 0.0116$. Cooling load 62,000 Btu. Occupants, sensible load 10,000 Btu, latent load 23,000 Btu. Fan motor 8000 Btu.

$$\text{Sensible heat load} = 62{,}000 + 10{,}000 + 8000 = 80{,}000 \text{ Btu}$$

Total sensible and latent heat load = 80,000 + 23,000 = 103,000 Btu. SHF = 80,000/103,000 = 0.77. Intersection of 80° db line and 50 per cent saturation curve on the diagram Fig. 1 gives the design point of the indoor air. From 0.77 on the SHF index draw the condition line through the design point to its intersection with the saturation curve at 56.4°, which is the apparatus dew point.

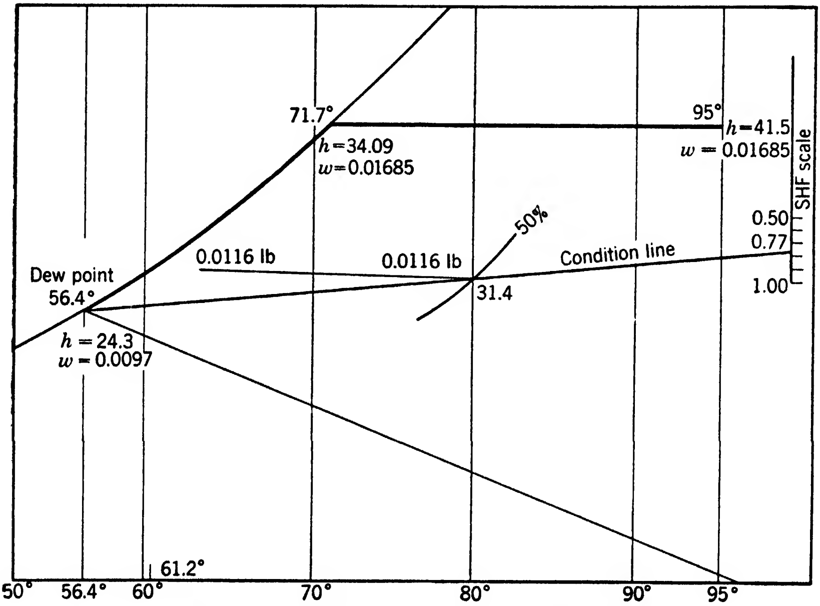

Fig. 1. Use of SHF scale and condition line.

Example 5. *Dancing school hall* in 40° N. latitude. *Outside temperature,* 95° dry bulb and 78° wet bulb in summer, 0° dry bulb and 80 per cent saturation in winter. *Inside temperature,* 80° dry bulb, 50 per cent saturation in summer, 70° dry bulb, 30 per cent saturation in winter. *Outside walls,* 12-in. brick, metal lath, plastered and furred; $U = 0.25$. *Partition,* wood stud plastered on wood lath; $U = 0.34$. *Roof,* 2-in. concrete flat slab, 4-ply felt and slag, with 1-in. insulating board in furred and plastered ceiling; U (summer) = 0.18, U (winter) = 0.19. *Floor,* double wood floor on wood joists, ceiling under, metal lath plastered; $U = 0.25$. *Lighting,* 8184

Btu. *Fan motor* will be outside hall. *Occupants,* 80 dancing. Outside air ventilation, 15 cu ft per min per occupant.

The basement below is at 75° dry bulb in summer and 60° dry bulb in winter. Adjoining rooms are at 80° dry bulb in summer and 70° dry bulb in winter. They will be separately heated by radiators. East and west walls each 60 X 15 = 900 sq ft. East and west windows set flush with outside wall, single sheet common glass, 3 X 7 X 5 = 105 sq ft. Net east and west walls each = 795 sq ft. South wall 40 X 15 = 600 sq ft. North partition 40 X 15 = 600 sq ft. Door 4 X 7 = 28 sq ft. Net north partition = 572 sq ft. Room 60 X 40 = 2400 sq ft. Floor 60 X 40 = 2400 sq ft. Conditioning equipment in part of building to north of hall. Windows have single common glass panes and inside Venetian blinds.

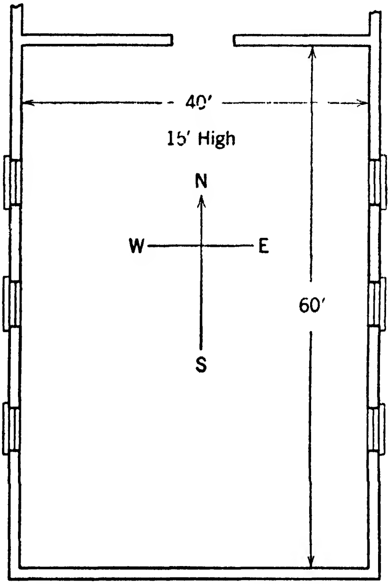

Fig. 2. Example 5. Plan of hall.

Solution. Summer Cooling.

(*a*) *Outdoor ventilation* will be 15 cu ft per min per occupant, 15 X 80 = 1200 cu ft per min and 72,000 cu ft per hr. Since the hall volume is 36,000 cu ft, the air changes per hour = 72,000 ÷ 36,000 = 2, which is sufficient because of the large hall volume per occupant, 450 cu ft.

(*b*) *Time of Maximum Cooling Load.* It is found by use of Equation 2, Chapter 18, because of the flat roof area, the large amount of glass on the west side of the room with high rates of heat gain in the afternoon, and the low illumination level at night, that the calculations should be made for 4:00 P.M. for the west wall.

(*c*) *Heat Gain.*

	Btu per Hour	
	Sensible	Latent
West wall:		
Temperature differential = 10; $10 \times 0.25 \times 795$	1,990	
Glass $[(205 \times 0.74) + 25 - 5] \times 105$	18,060	
205 = Solar gain; 25 = convection + radiation gain; 0.74 = Venetian blind; 0.25 = U; 5 = temperature correction		
East wall:		
Temperature differential = 12; $12 \times 0.25 \times 795$	2,385	
Glass $[(12 + 21) - 5] \times 105$	2,940	
South wall: Temperature differential = 6; $6 \times 0.25 \times 600$	900	
North partition and door: No temperature difference	0	
Roof: Temperature differential = 54; $54 \times 0.18 \times 2400$	23,328	
Floor: $0.25 \times (80 - 75) \times 2400$	3,000	
Occupants, dancing: Sensible, 80×245; latent, 80×605	19,600	48,400
Fan motor (Equation 7, Chapter 18): 6 hp $\times 1 \times 2544$	15,264	
Lighting (Equation 6, Chapter 18): 2400 watts $\times 1 \times 3.41$	8,184	
	95,650	48,400
	48,400	
Total hall load	144,050	
Outside ventilation load	19,440	33,105
Totals	163,490	81,505
Grand total sensible and latent	244,995	

(*d*) *Heat Gain from Outdoor Ventilation.* With rate of flow of 1200 cu ft per min the heat gains are as follows:

Sensible heat: $1200 \times 1.08(95 - 80) = 19{,}440$ Btu (Equation 4, Chapter 18)
Latent heat: $1200 \times 4840(0.0169 - 0.0112) = 33{,}105$ Btu (Equation 5, Chapter 18)

(*e*) *Heat Gain from Infiltration.* There is no infiltration because the windows are set fast and do not open.

(*f*) *Sensible Heat Factor.* SHF = 95,650/144,050 = 0.66, where 144,050 = 95,650 sensible + 48,400 latent heat. If 51.5° is assumed to be the apparatus dew point with enthalpy of 21.4 Btu, then SHF must equal

$$\frac{0.24(80 - 51.5)}{31.4 - 21.4} = 0.66$$

where 31.4 = enthalpy of air at 80° and 50 per cent saturation.

The apparatus dew point is 51.5°.

(*g*) *Effective Air Quantity.*

$$\frac{95{,}650}{1.08(80 - 51.5)} = 3108 \text{ cu ft/min}$$

$$3108 \times 60 = 186{,}480 \text{ cu ft/hr} \quad \frac{186{,}480}{13.84} = 13{,}474 \text{ lb/hr}$$

where 13.84 cu ft = specific volume of air at 80° and 50 per cent saturation.

The dry-bulb range through which the air will be cooled in the apparatus will be

$$80° - 51.5° = 28.5°$$

and the saturated air will leave the apparatus at 80° − 28.5° = 51.5°.

Since the fan motor is not within the hall its heat, although a load on the apparatus, does not affect the conditions within the hall. The dry-bulb temperature leaving the fan will then be

$$80 - \frac{95{,}650 - 15{,}264}{1.08 \times 3108} = 80 - \frac{80{,}386}{3357} = 80 - 24 = 56°$$

Air at 56° is too cool to be directly introduced into the hall and must be raised in temperature.

(*h*) *Efficiency of Apparatus.* In the foregoing calculations the cooler was assumed to be 100 per cent efficient. If its efficiency were 80 per cent, only 80 per cent of the air would be cooled and more air must be used than if the cooler were 100 per cent efficient. The equation for effective air quantity would become

$$\frac{95{,}650}{1.08(80 - 51.5) \times 0.80} = 3884 \text{ cu ft/min}$$

The dry-bulb range would then be (80 − 51.5)0.80 = 22.8, and the air would leave the apparatus at 80 − 22.8 = 57.2°. The dry-bulb temperature leaving the fan would be

$$80 - \frac{95{,}650 - 15{,}264}{1.08 \times 3884} = 80 - \frac{80{,}830}{4195} = 80 - 19.0 = 61.0°$$

With proper diffusion within the hall, this temperature should be satisfactory without producing draughts and further conditioning and reheating would be avoided. The additional air required by a moderate rate of inefficiency in the cooler is therefore sometimes advantageous.

(*i*) *By-Pass.* When the air leaving the fan is too cool to be introduced directly into the room, a quantity of room air, approximately equal to the processed air or 13,474 lb, will be by-passed around the apparatus and mixed with the processed air before it enters the fan. The calculations include 3 steps: (1) determination of state of the mixture of ventilating and recirculating air before entering the cooler; (2) determination of its state upon leaving the cooler; (3) determination of the state of the mixture of processed and by-passed air.

(1) The quantity of the outdoor ventilating air is 72,000 cu ft per hr. Its specific volume is 14.35 cu ft per lb, its enthalpy 41.4 Btu, and its water content 118 grains. Its quantity in pounds = 72,000/14.35 = 5017 lb per hr. The quantity of recirculated room air will be 13,474 – 5017 = 8457 lb. Its enthalpy is 31.4 Btu, its specific volume 13.84 cu ft, and its water content 77 grains. The enthalpy of the mixture will be

$$\frac{(5017 \times 41.4) + (8457 \times 31.4)}{13{,}474} = 35.1 \text{ Btu}$$

Its water content will be

$$\frac{(5017 \times 118) + (8457 \times 77)}{13{,}474} = 92.2 \text{ grains}$$

From the psychrometric chart the dry-bulb temperature of a mixture with these qualities is found to be 86°.

(2) This air leaves the apparatus saturated at 51.5° db with an enthalpy of 21.14 Btu and a specific volume of 13.046 cu ft. Its total volume will be

$$\frac{13{,}474 \times 13.04}{60} = 2928 \text{ cu ft/min}$$

(3) The total volume of the by-passed room air will be

$$\frac{13{,}474 \times 13.84}{60} = 3108 \text{ cu ft/min}$$

The enthalpy of the mixture is

$$\frac{(3108 \times 31.4) + (2928 \times 21.2)}{6036} = 26.4 \text{ Btu}$$

Its specific volume is

$$\frac{(3108 \times 13.84) + (2928 \times 13.04)}{6036} = 13.4 \text{ cu ft}$$

where 6036 = 3108 + 2928.

The dry-bulb temperature corresponding to these values is 63.5°, which is satisfactory for air entering the room, and reheating is avoided.

The fan and the duct system beyond the point of mixture of the processed and by-passed air is designed for 13,474 lb × 2 = 26,948 lb per hr at 13.4 cu ft specific volume, or

$$\frac{26{,}948 \times 13.4}{60} = 6018 \text{ cu ft/min}$$

3. Heating and humidifying. Three usual methods of humidification are (*a*) by adiabatic saturation; (*b*) by heated spray water; (*c*) with recirculation. They are described in Chapter 18, Art. 2, and are illustrated in the following examples. Adiabatic saturation is used whenever feasible to save the expense of heating the spray water.

(*a*) *Humidification by Adiabatic Saturation.*

Example 6. Outdoor air at 0° and 80 per cent R.H. is heated to 70° and 30 per cent saturated. Find the dew point of the conditioned air and the temperature of the outdoor air before entering the washer. Efficiency of conditioner 100 per cent. Use the psychrometric chart.

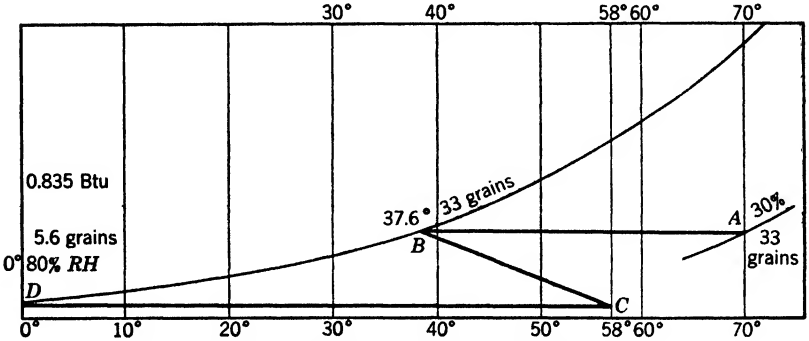

Fig. 3. Humidification by adiabatic saturation.

Solution. The air will be preheated, adiabatically saturated by recirculated spray water, and reheated. As shown on Fig. 3, at *A*, air at 70° and 30 per cent R.H. will have a dew-point temperature at saturation of 37.6° and a water content of 33 grains, as at *B*, the point of intersection of the horizontal line through *A* and the saturation curve; 37.6° will also be the dry- and wet-bulb temperatures of the completely saturated air when it leaves the spray. The dry-bulb temperature to which the outdoor air is preheated will, therefore, be on the wet-bulb line passing through *B*. Its value (58°) is determined by the point of intersection, *C*, of the horizontal line from *D* and the wet-bulb line. *D* denotes the position of the outdoor air at 0° and 80 per cent R.H. Thus the air is preheated to 58° dry bulb and 37.6° wet bulb and is saturated adiabatically by passing from *C* to *B* through an unheated but recirculated spray, during which process the dry-bulb temperature falls to coincide with the wet-bulb temperature of 37.6° and the spray assumes the same temperature. The air thus saturated will contain 33 grains of water vapor. It is then reheated to 70° and still contains 33 grains, which is 30 per cent of 110 grains, the saturation capacity at 70° dry bulb.

In this example all the air is taken from outdoors. It is delivered to the room at the desired room temperature and degree of saturation, the heat to compensate the heat losses from the room being furnished by direct radiators or convectors in the room (split system).

(*b*) *Humidification by Heated Spray Water.* When adiabatic saturation is not feasible, the air is saturated by passing through a heated and recirculated spray.

Example 7. With the same conditions as in Example 6, this method involves raising the temperature of the entering air above freezing point by the preheater and heating the spray water in the washer to a temperature such that the ensuing saturation will permit the air to leave the washer at 37.6° and contain 33 grains of moisture. It then passes through the reheater where it is warmed to 90° and carries 33 grains of moisture.

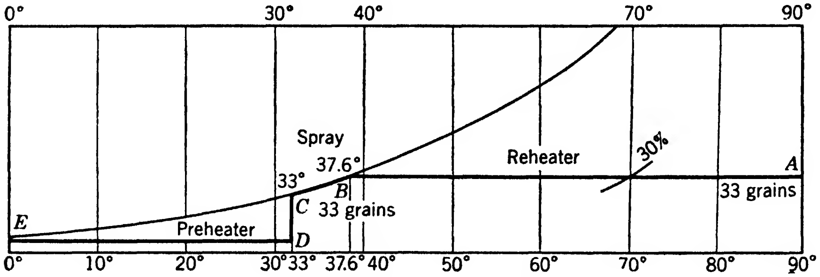

Fig. 4. Humidification by heated spray.

The air at 0° and 80 per cent saturation is warmed by the preheater to 33°, as shown on the line from *E* to *D* (Fig. 4). It is then saturated and warmed by the heated spray to 37.6° and contains 33 grains, as shown on the saturation curve from *D* to *C* and *C* to *B* and then is raised to 90° by the reheater as shown from *B* to *A*.

In this example the air is raised to 90° to compensate for the heat losses as well as to maintain the room at the desired temperature of 70°. The heat available to balance the losses will be 27 Btu − 22 Btu = 5 Btu per lb of dry air, which is the quantity assumed to be required here. The moisture continues to be 33 grains per lb of dry air, which at 70° gives the desired degree of saturation, 30 per cent.

(*c*) *Humidification with Recirculation.*

Example 8. A room is to be maintained at 70° temperature and 30 per cent saturation with outdoor temperature at 0° and 80 per cent saturation. The effective air quantity is 12,780 lb per hr, and the required outdoor ventilating air is 6212 lb per hr. The quantity of recirculated room air will then be 12,780 − 6212 = 6568 lb per hr. Find the preheating required and the dry-bulb temperature of the mixture before saturation. Point *A* (Fig. 5) represents the state point of the room air. A line through *A* extending horizontally to the left will cut the saturation curve at *B*, the dew point of the room air, 37.6°. Since the mixture of recirculated and ventilating air undergoes saturation at 37.6°, its temperature upon entering the spray must be somewhere on the 37.6° wet-bulb line *BC*.

By the method shown in Example 9 it may be computed that the outdoor ventilating air must be raised to 22° in the preheater before mixing with recirculated air. A line joining *D* and *A* will cut *BC* at *E* which marks the dry-bulb temperature of the mixture, 46.5°, upon entering the washer. $DE:EA = 6568:6212$.

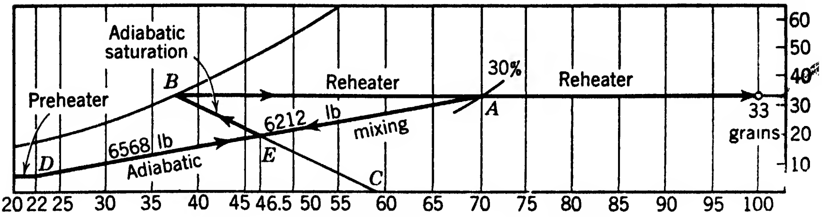

Fig. 5. Humidification with recirculation.

By use of the chart, point *D* is fixed by constructing the line *AD* which is cut by the wet-bulb line through *B* so that *AE*:*AD* = 6212:12,780.

Example 9. Use the same plan as in Example 5. Outdoor design temperature, 0° dry bulb and 80 per cent saturation. Indoor design temperature, 70° dry bulb and 30 per cent saturation. For additional winter conditions, see Example 5.

1. *Heat Losses*

	Btu per Hour	
	Sensible	Latent
West wall, 0.25 × 70 × 795	13,912	
East wall, 0.25 × 70 × 795	13,912	
South wall, 0.25 × 70 × 600	10,500	
North partition and door, no temperature difference	0	
Roof, 0.19 × 70 × 2400	31,920	
Floor, 0.25 × 10 × 2400	6,000	
Windows, 2 × 1.13 × 70 × 105	16,611	
Infiltration, none. Windows do not open.	0	
Total heat losses from hall (92,855)	93,000	
Ventilating outside air, 15 × 80 = 1200 cu ft/min, 72,000 cu ft/hr		
sensible, 1200 × 1.08(70 − 0) (Equation 4, Chapter 18)	90,720	
latent, 1200 × 4840(0.004746 − 0.000629) (Equation 5, Chapter 18)		23.892
Grand total losses	183,720	23.892

2. *Heat Gains in Hall*

Occupants, dancing, hall at 70°, 30 per cent R.H.		
sensible, 80 × 430	34,400	
latent, 80 × 420		33.600
Lighting, 2400 watts × 3.41	8,184	

Solution. Winter Heating. The sensible heat losses from the hall total 93,000 Btu per hr. The supply air entering the hall will be heated to 100° with an enthalpy of 29.276 Btu and water content of 0.00474 lb. The hall will be maintained at 70° with 30 per cent saturation, enthalpy of 22 Btu per lb, and water content of 0.00474 lb or 33 grains. The outdoor ventilating air is at 0° and 80 per cent saturation. Its enthalpy is 0.668 Btu, its specific volume 11.59 cu ft, and its water content 0.0006298 lb. The required total volume of ventilating air is 80 × 15 × 60 = 72,000 cu ft per hr. Heat gain from lights and occupants, being variable, will not be considered.

The outdoor air will be preheated and then mixed adiabatically with recirculated air from the hall. The mixture will then enter unheated spray water and be adiabatically saturated. It will contain the quantity of water, 0.00474 lb per lb of dry air, designed to be maintained in the hall. The mixture is then heated to 100° to counterbalance the heat losses and conserve the desired 70° temperature in the hall.

The saturation temperature or dew point of air at 70° db and 30 per cent saturation is 37.6° with enthalpy of 14.14 Btu and water content of 0.00474 lb. This is the state to be reached by the adiabatic saturation of the air mixture with the recirculated spray water.

The weight of the dry outdoor ventilating air = 72,000/11.59 = 6212 lb. The weight of the dry recirculated air = 93,000/(29.276 − 22) = 12,780 lb.

The weight of the hall air in the mixture of outdoor and recirculated air is 12,780 − 6212 = 6568 lb per hr.

The water content of the mixture per pound dry air will be

$$w = \frac{(6212 \times 0.0006298) + (6568 \times 0.00474)}{12{,}780} = 0.00274 \text{ lb}$$

Since the mixture is to undergo adiabatic saturation at a temperature of 37.6°, its wet-bulb temperature upon entering the spray must be such that its enthalpy will be

$$h = 14.14 - (0.00474 - 0.00274) \times 5.676 = 14.12 \text{ Btu}$$

where 5.676 Btu = enthalpy of condensed water at 37.6°.

In order that the mixture may have the enthalpy of 14.12 Btu, the outdoor ventilating air, before mixing with the recirculated air, must be preheated to the value

$$h = \frac{(12{,}780 \times 14.12) - (6568 \times 22)}{6212} = 5.78 \text{ Btu}$$

With $w = 0.0006298$ and $h = 5.78$, the temperature of the outdoor air on leaving the preheater is 22.2°. The enthalpy of the mixture upon entering the spray will be

$$\frac{(6212 \times 5.78) + (6568 \times 22)}{12{,}780} = 14.12 \text{ Btu}$$

as designed where 22 is the enthalpy of the recirculated room air in Btu per pound. With $w = 0.00474$ and $h = 14.12$ the dry- and wet-bulb temperatures will be 46.5° and 37.6°, respectively. The mixture will then be adiabatically saturated with the spray water and will leave the spray with a temperature of 37.6° and a water content of 0.00474 lb per lb of dry air.

The mixture is then raised to the temperature of 100° in the reheater and contains the same amount of water.

Quantity of Heat Required

	Btu
(1) Preheating ventilating air: $6212 \times (5.78 - 0.668)$	31,755
(2) Added to supply air in reheater to 100°. $12{,}780 \times (29.276 - 14.12)$	193,693
(3) Added by spray water: $12{,}780 \times 5.676(0.00474 - 0.00274)$	142
(4) Introduced with ventilating air into preheater: 6212×0.668	4,149
	229,739
Less heat carried out with inside air: 6212×22	136,664
Net total	93,075

which checks closely with sensible heat loss 93,000 Btu.

4. Central systems. In the preceding illustrative examples the requirements of the same room have, for simplicity, been considered for both summer and winter calculations. It is evident that in the majority of cases a number of rooms would be included in a building, each having its particular dimensions, demands, and exposure. If the duct lengths are not too great, a single conditioning system consisting of one apparatus with its coils, sprays, filters, and fans is a more economical installation than separate unit heaters in the several rooms. Individual ducts with their necessary dampers and controls then lead the air to each room in the quantity and at the temperature and moisture content desired in that room.

5. All-season air conditioning. A single central all-season system may be relied upon to accomplish the task of both summer and winter conditioning more economically than two systems, one for cooling and the other for heating. Most of the equipment, such as grilles, filters, fans, ducts, and dampers, is used in all seasons. The reheaters are necessary in winter and sometimes in summer. Water spraying is used for both humidifying and dehumidifying. Little equipment is, therefore, idle during any part of the year, and all duplication is avoided.

Since large volumes of air are often required for summer conditioning and it is generally considered advisable for the fan to handle the same volume of air in winter as in summer, certain adjustments may be required. A degree of saturation of over 30 per cent is seldom used in designing for winter comfort. A high efficiency in the spray dehumidifier which may be required in summer may furnish too much moisture in the humidified air for winter needs. A lower efficiency may then be produced by shutting off certain sprays in the humidifier. Other easily performed adjustments are also possible which transform the apparatus into a satisfactory system for any season.

PROBLEMS

1. What is meant by the following terms: (*a*) effective air quantity; (*b*) sensible heat factor; (*c*) apparatus dew point.

2. (*a*) What are the advantages of recirculating room air through the conditioner? (*b*) What is the effect of by-passing a portion of the room air around the conditioner and mixing it with the conditioned air before it enters the fan?

3. What are the steps involved in calculating the quantity and temperature of the conditioned air required to be introduced into a room to maintain certain desired conditions within that room during hot weather?

4. Discuss from a practical and economic point of view the use of central systems in air conditioning and the feasibility of all-season air conditioning.

5. Compute the heating requirements in winter for an isolated one-story school building 30 ft wide, 60 ft long, and 10 ft high in 40° N. latitude. Short side facing south has a 2-in. double door and vestibule 4 ft by 7 ft 6 in. high and a continuous fixed window 15 ft long and 6 ft high with sill 3 ft from floor. Long side facing west has two continuous fixed windows each 12 ft long by 6 ft high with sill 3 ft from floor. No infiltration. No openings in other walls. Flat roof 2-in. wood plank, built-up roofing, hung ceiling, 1-in. insulation. Walls 12-in. solid brick plastered and furred on inside. Double floor of yellow pine on wood joists with metal lath and plaster under. Outside temperature 4° and 65 per cent R.H.; inside temperature 72° db and 30 per cent R.H. Air-conditioning equipment and fan in basement. Assumed temperature of basement 61° db. Occupants, 44. Lights, 4000 watts. Outside ventilation, 15 cu ft per person. Supply air, 105°.

6. Compute the cooling requirements in summer for the school of Problem 5. Outside temperature, 95° db and 75° wb. Inside temperature, 80° db and 50 per cent R.H.; basement temperature, 75° db. Provide awnings. Same number of occupants. Apparatus, 85 per cent efficient.

7. What is the advantage of combining the heating and cooling functions into one system?

8. What is a split system?

9. Why does the heat to be removed from the ventilating air not affect the cooling load in the room?

10. What are the sources of the latent heat load as part of the (*a*) room cooling load, (*b*) ventilating-air cooling load?

Chapter 20

EQUIPMENT AND CONTROLS

1. Procedure. Figure 1 indicates the progress of air through an all-season conditioner. The outdoor ventilating air, usually predetermined at a minimum quantity, enters at *A*. If indoor air is also utilized it enters from the duct *C* and mixes with the outdoor air in *E*. The mixture then passes through the filters *F* and is purified. *B*, *D*, and *K* are dampers.

(*a*) *Winter Heating.* Air entering the humidifier must not be lower than 34 or 35° and may be required at a higher temperature for desired results at design dew points. The air is therefore warmed in the preheater *G* and enters the humidifier *H* where it is saturated. The spray may be heated to warm the air or be unheated if the process is adiabatic. The air then passes through the reheater *J*, to attain the design temperature for introduction to the room. The cooler *I* is not used.

(*b*) *Summer Cooling.* The preheater is not used. The air may enter the air washer *H* and be dehumidified by cold sprays at a design dew point, or *H* may not be used and the dehumidification performed by the cooling coil *I*. It may then be necessary to heat the air in the reheater *J* before entering the room. In both heating and cooling it is often economical to by-pass room air around the conditioner for mixing with the processed air.

(*c*) Air leaving the fan may be delivered to all parts of a building at the same temperature, or each room or zone may receive air at a particular temperature suited to its requirements. This differentiation is accomplished in several ways. In Fig. 1 a method is by means of a heating or a cooling coil *K* in each individual duct. In Fig. 2 a second method places the supply fan directly after the air washer which is not operated in hot weather. Coils heat or cool the air from the fan and deliver it to hot and cold pressure air chambers, respectively, *A* and *B*. From these chambers hot and cold air are drawn in proper proportions by mixing dampers in each supply duct. The dampers are interlocked so that as one opens the other closes and vice versa.

2. Air cleaning. The contaminating elements in air may consist of solid particles, such as dust, lint and smoke, droplets, such as mists and fogs, vapors and gases, such as gasoline and carbon monoxide, organisms, such as bacteria and pollen, and lastly odors and smells. Some dusts are valuable and are collected and re-used.

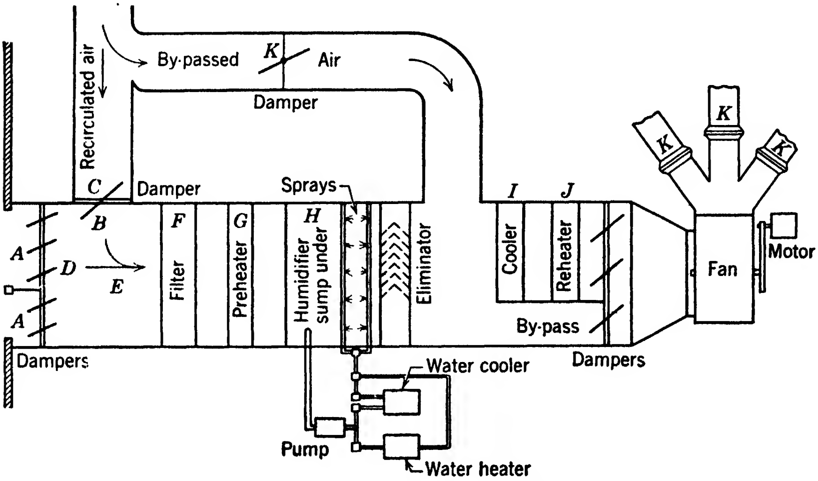

Fig. 1. All-season air conditioner.

3. Air filters are employed to remove the dust, lint, and other solid material. They are seldom intended to handle dust contents of more than 4 grains per 1000 cu ft of air. Periodic cleaning or replacement is required to avoid accumulation of dirt.

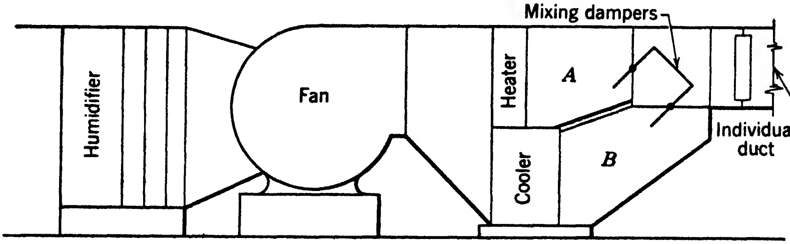

Fig. 2. Air conditioner with pressure chambers.

(*a*) *Dry Filters* consist of wire frames or panels enclosing felt, cotton batting, or cellulose pockets or V-shaped pleats through which the air is screened. They have high lint-holding properties but have not the general use of viscous filters. Accumulated dirt is removed by dry or vacuum cleaning.

(*b*) *Viscous Filters* consist of a series of metal deflecting plates or screens coated with viscous oil. Coming in contact with these surfaces the air flow is abruptly changed in direction, and the dust is trapped in the oil film and remains there. The space between the screens is filled with steel or glass wool or animal hair. Viscous filters may be cleaned by air, water, or steam jet or by dipping in kerosene or oil.

For both dry and viscous filters inexpensive panels with cardboard frames may be discarded when dirty and replaced with fresh panels.

(*c*) *Automatic Viscous Filters.* To insure more reliable and economical cleansing, viscous filters consist of two endless vertical filter curtains which move on wheels at the top and bottom of the housing.

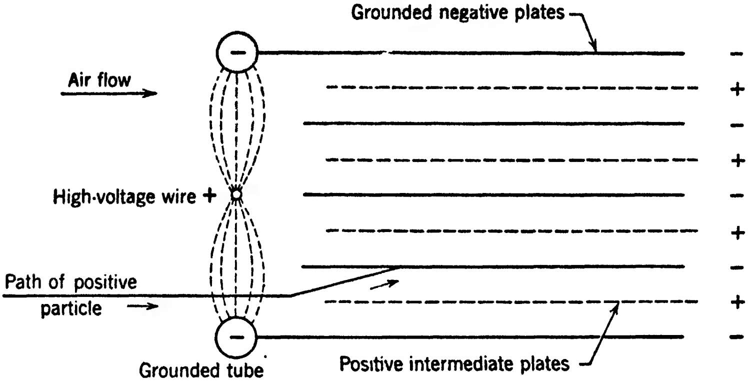

Fig. 3. Electrostatic precipitator.

The front curtain is the more dense and passes downward through an oil reservoir at the bottom of the container. The rear curtain does not pass through the bath but catches entrained oil in the air from the front curtain. The curtains consist of removable wire screens backed with layers of wire mesh and are moved by electrically driven devices set to revolve periodically.

(*d*) *Electric Precipitators* consisting of positive electric fields and negative grounded tubes remove from the air the fine dusts, mists, unburned particles in smoke and other matter which would pass through dry and viscous filters. The particles receive an electric charge in passing through the high-voltage fields and are then attracted to and precipitated upon plates of opposite polarity. Two sets of plates are used, one set attached to the negative tubes and the other positively charged from direct current terminals, the positive and negative plates alternating in parallel rows (Fig. 3).

The potential between the high-voltage wires and the grounded tubes, 12,000 volts, and that between the plates, 6000 volts, are generally derived from the alternating supply which is changed to direct current and transformed by electronic devices in the apparatus. The plates are commonly coated with light oil, and cleaning is done by flushing with water sprays. Automatic cleaning types are also made which are mounted on wheels and dip into an oil bath similarly to the automatic viscous filter.

4. Dust collectors are designed to handle the large quantities of contaminants arising from the fast-growing industrial developments which, if not controlled, would result in dangerous pollution not only of the industrial areas but of entire cities. The dust content may range from 100 to 20,000 grains per 1000 cu ft of air. The collectors may be classified as follows:

(*a*) *Electrostatic Precipitators.* Similar in principle to the electric air-filter type already described in Art. 3, electrostatic precipitators are designed for heavy duty and consist of an assembly of parallel collector electrodes in one or two stages. High potentials of 60,000 to 75,000 volts are used.

(*b*) *Dry Fabric Collectors.* Consisting generally of cotton cloth in the shape of envelopes or bags supported on steel frames, dry fabric collectors are highly efficient, but space requirements often necessitate outdoor installation. Low air velocities of 1 to 3 ft per min give best results.

(*c*) *Wet Collectors.* Bringing the contaminating substances into contact with water, especially for handling high-temperature and moisture-laden gases, wet collectors are of many designs representing various methods and special purposes.

5. Air washers, humidifiers, and dehumidifiers. (*a*) An *air washer* consists of a chamber supplied with rows or banks of atomizing nozzles generating a fine water mist which completely fills the compartment and through which the air must pass. This mist wets the smallest dust particles, increasing their weight so that they are readily separated from the air by the eliminating units. The direction of the spray may be either upstream or downstream with the air flow, and the number of banks of nozzles depends upon the duty to be performed. Diffusing plates or sheet-iron louvers are often furnished at the entrance of the compartment to retain the spray and to distribute the air uniformly through the chamber with the same velocity, usually from 250 to 500 ft per min. The spray banks are followed by the air scrubbers and the eliminators which baffle the air flow and catch the wet dust on their surfaces. They consist of corrugated galvanized iron or copper sheets spaced 1⅛ in. apart and deflecting the air flow at about 30°. The scrubber plates are constantly wet by water passing down over them; the eliminator plates are also wet for the most part and are provided with projecting lips to remove entrained water from the air. When it is desired to add very little humidity to the air, the spray nozzles may be closed and the flooded eliminator plates depended upon to clean the air. The spray water drains to a settling tank from which it is drawn through a strainer by a centrifugal pump and recirculated to the nozzles. Fresh water is supplied through a float valve as required.

For effective removal, dust must be completely wet; consequently some kinds, such as lamp black, fine ashes, and soot, are better eliminated by a viscous filter than by an air washer.

(*b*) *Water Sprays.* The following methods are general to reduce the water particles to a fine spray when issuing from the nozzles and to propel the spray through a sufficient area for proper distribution and evaporation (1) atomization, which employs a compressed air jet to form the spray and to project it from the nozzle; (2) impact, by which a jet of water under pressure impinges upon a fine metal point to generate the spray. The impact also induces a current of air which distributes the spray.

(*c*) *Humidification.* An air washer may humidify air in three ways (1) by the use of recirculated spray water in contact with the air, neither the air nor the water being preheated; (2) preheating the air and mixing it with recirculated spray water; (3) preheating the spray water.

In the first method the air is adiabatically saturated and the temperature of the spray water finally equals the wet-bulb temperature of the entering air. The saturation generally is not entirely complete, and the percentage of efficiency of the washer under this method may be seen from the following table:

1 bank, downstream	60–70
1 bank, upstream	65–75
2 banks, downstream	85–90
2 banks, 1 upstream and 1 downstream	90–95
2 banks, upstream	90–95

In the second method the wet- and dry-bulb temperatures of the entering air are increased, the degree of saturation is lowered, and the weight of water vapor per pound of dry air remains the same. More water can, therefore, be received in the washer per pound of dry air, and the effectiveness should be greater. The amount of preheating should be sufficient to raise the entering air to the wet-bulb temperature desired.

In the third method, by heating the spray water both the wet- and dry-bulb temperatures may be raised along with the humidification.

(*d*) *Dehumidification and Cooling.* Lowering of the temperature begins when the dry- and wet-bulb temperatures of the spray water are, respectively, below the dry- and wet-bulb temperatures of the entering air. The removal of moisture takes place when the spray water temperature is below the dew point of the entering air and condensation commences.

Air washers for dehumidifying are generally furnished with two banks of sprays which will cool the air to 1 or 2 degrees below the temperature of the leaving spray water. Washers are often equipped inside with direct expansion coils, and the spray water is entirely recirculated.

Both sensible and latent heat are removed during dehumidification, sensible heat during the entire process and latent heat when condensation begins.

(*e*) *Coils* are used for heating or cooling water and also for heating air or for cooling it either with or without dehumidification.

For heating, the medium may be steam or hot water. Usual conditions are (1) delivered air temperature, 72° for ventilation alone to 150° for complete heating; (2) steam pressure, 5 lb per sq in.; (3) water temperature, 150 to 225°. Selection depends upon dry-bulb temperature and sensible heat.

6. Heaters. The heaters employed in air conditioning may be classed as (*a*) tempering coils; (*b*) preheaters; (*c*) reheaters; (*d*) water heaters. The first three heaters generally consist of copper or aluminum tubes wound on the outside with a helical copper ribbon soldered in place, thus giving extended radiating surface. These tubes are firmly pressed into the tube plates of the heaters, which likewise carry the pipe tapping for the steam supply and water return. Water heaters if open inject steam directly into the water, or if closed heat the water by heat interchangers from steam supply.

(*a*) *Tempering Coils* are placed near the outdoor inlet and heat the entering air to about 35° so that the spray of the air washer will not freeze. Two or three sections may be separately controlled to act in accordance with outside conditions. They are not necessary when all the air is recirculated.

(*b*) *Preheaters* are used when it is desired to heat the air to a wet-bulb temperature such that it will become adiabatically saturated by passing through the unheated spray of the washer and emerge with a moisture content corresponding to the required dew point. Preheaters and tempering coils may be interchanged both in duty and name.

(*c*) *Reheaters* raise the air leaving the washer to the degree necessary to maintain the temperature desired in the rooms of the building. In the split system the air is raised to 70°, or a little above, by the reheaters.

7. Coils. For cooling and dehumidifying, coils are common instead of water sprays, or they may be combined with water sprays, depending upon the requirements and economics involved. Water sprays are generally designed for complete saturation of the air and can be simply controlled for dew-point temperature by a duct thermostat. They also produce a degree of air cleaning and odor absorption.

Coils, on the other hand, provide a simple closed water circuit without pumps and water level controls but are not quite so efficient. Cooled water is usually circulated in the coil. Sometimes a simplification is obtained with *direct expansion coils* in which the refrigerant itself is expanded into the coil directly from the refrigerating machine. In case of leakage these coils are dangerous and are not often used in comfort conditioning. When combined with spray water the coils are installed in the spray chamber.

When cooling alone is desired, sensible heat and dry-bulb temperature only are involved but for cooling combined with dehumidifying wet- and dry-bulb and dew-point temperatures and latent as well as sensible heat must be considered.

Usual conditions are (*a*) entering air, 60 to 100° dry bulb and 50 to 80° wet bulb; (*b*) refrigerant temperatures, 25 to 55°; (*c*) water temperatures 40 to 65°.

The construction of cooling coils for water is similar to those already described for heating. For both purposes the outside diameters of the tubes vary from ½ to 1 in., the fin spacing from 3 in. to 8 in., and the tube spacing from 1⅛ to 2½ in. on centers. The capacities of both heaters and coolers depend upon the face area of the coil and upon the number of rows of coils in depth.

8. Refrigeration. When the natural water supply is not capable of sufficiently cooling the spray of the dehumidifier a mechanical refrigerating machine must be employed to reduce the temperature.

Unit of Refrigeration. A ton of refrigeration is the cooling effect obtained when 1 ton of 32°F ice melts to water at 32°F. Since the latent heat of fusion of ice is 144 Btu per lb the cooling effect or rate of 1 ton of refrigeration (2000 lb) is taken as $144 \times 2000 = 288{,}000$ Btu per day of 24 hr or 12,000 Btu per hr. The requisite capacity of a refrigerating machine in tons may therefore be found by dividing the total heat gain in a building in Btu per hour by 12,000.

9. Mechanical. Mechanical refrigeration is based upon the alternate liquefying and evaporating of a volatile liquid with a low boiling point. A large amount of heat is required for the vaporization process, and this heat, called latent heat of vaporization, is withdrawn from the air, water, or other substances which surround the liquid during its evaporation.

The equipment consists of a compressor, a condenser, an expansion valve, and an evaporator (Fig. 4). The volatile liquid refrigerant is a vapor under normal temperatures and pressure. As a low-pressure saturated vapor it is subjected to high pressure in the compressor, which raises its boiling point and temperature. At this same high pressure the vapor is piped into the condenser coils where it is cooled by streams of water to a degree below its liquefaction point. It condenses into liquid state and still under high pressure passes through the expansion coils but maintains the high pressure on the condenser side. In the evaporator the pressure is relieved by the suction stroke of the compressor, the boiling point of the liquid drops, and evaporation into a vapor takes place. The air, water, or brine which surrounds the coils gives up its heat in causing the vaporization at low pressure, thus reducing its temperature to the temperature of the refrigerant. It can then be piped at this low temperature to any desired point. The refrigerant is sucked back into the compressor as a saturated vapor for re-use in a continuous closed cycle, the compressor acting as an exhaust pump on the suction stroke and as a compression pump on the pressure stroke. By changing the pressure reduction in the evaporator the boiling temperature of the refrigerant may be established as desired and the heat absorbed from the surrounding medium may be controlled.

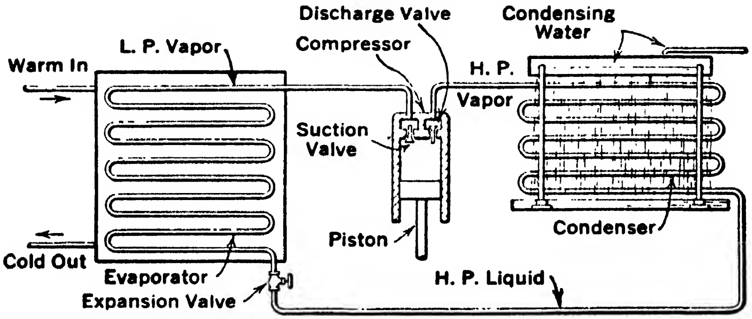

Fig. 4. Mechanical refrigeration.

In air-conditioning systems, water generally surrounds the evaporator coils and, when cold, passes to the dehumidifying sprays or to air coolers from which it is returned to the evaporator for recooling. In small installations, such as unit conditioners, air to be cooled may pass directly over evaporating coils in the cabinet.

10. Compressors are made in three types: reciprocal, centrifugal and rotary.

(*a*) *Reciprocal Piston Compressors* are the original type and are still very generally used. They consist of a vertical or horizontal cylinder with a piston and are made both single- and double-acting. Upon the suction stroke the suction valves open and the saturated vapor from the evaporator is drawn into the cylinder. Upon the reverse stroke the suction valves close, the vapor is compressed in the end of the cylinder, and, finally, when the discharge valves open, the vapor is forced into the condenser at a high pressure and temperature (Fig. 4). Compressors are usually driven by electric motors at speeds up to 3500 rpm. They may be either air- or water-cooled.

(*b*) *Centrifugal Compressors* are adapted to low-pressure refrigerants in quantities and act in a similar manner to centrifugal pumps described in Chapter 1, Art. 5. They occupy less than a quarter of the space of reciprocating machines and generally consist of two or more impellers or stages (Fig. 5).

(*c*) *Rotary Compressors* furnish the compressive force by an eccentric rotor turning in a sealed housing (Fig. 6). The suction inlet and the discharge outlet are separated by a thin sealing partition held in contact with the rotor by a spring. As the eccentric passes the partition the suction inlet is opened and vapor is sucked into the housing behind the rotor, the vapor ahead of the rotor being compressed against the partition. The eccentric then passes the partition and again frees the suction valve for the entrance of more vapor. These compressors are quiet in operation and are frequently applied to fractional tonnage operations.

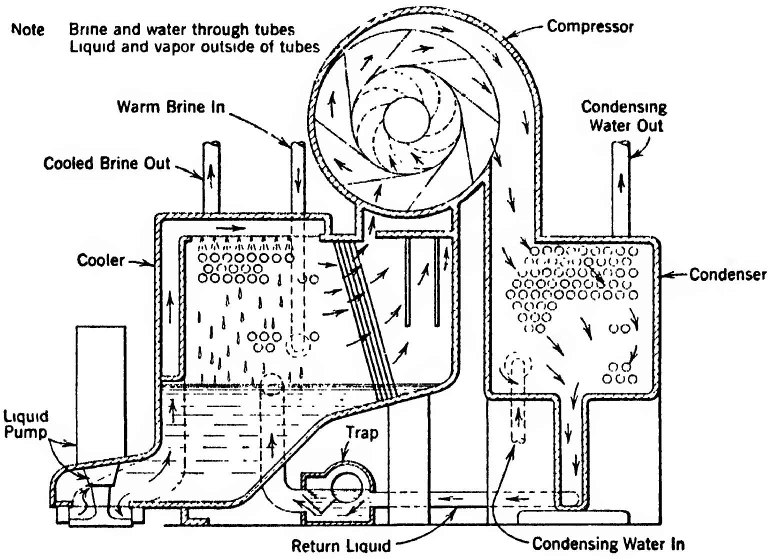

Fig. 5. Centrifugal compressor.

11. Condensers. For air conditioning the most used types of condensers are the double-pipe and the shell-and-tube.

(*a*) *The Double-Pipe Condenser* is made up of two pipes, one passing inside the other. The cooling water flows through the inner pipe, and the refrigerating vapor passes through and is condensed in the annular space between the pipes. The vapor enters at the top, passes through the coil, and discharges at the bottom in a liquid state to the evaporator or to a storage tank. The cooling water enters the inner

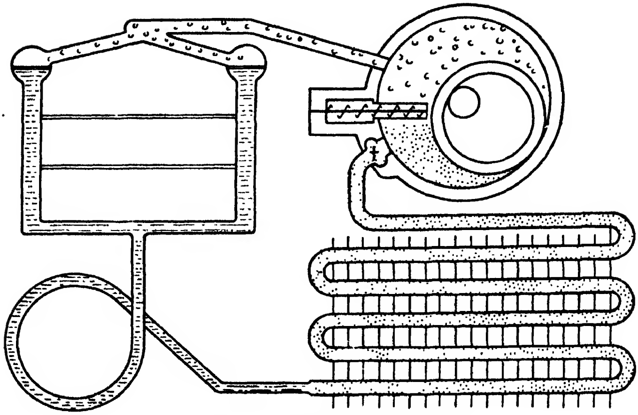

Fig. 6. Rotary compressor.

pipe at the bottom and passes upward, thus producing a counter flow to the refrigerant and maximum temperature differences. The inner pipe generally has a diameter of 1¼ in., and the outer pipe, 2 in. (Fig. 7).

(*b*) *The Shell-and-Tube Condenser* consists of an outer vertical shell with a heavy sheet fixed in the top into which a series of vertical steel tubes is welded. The cooling water enters a chamber above the tube sheet, flows down through the tubes, and is discharged into a container at the bottom. The refrigerant enters the shell as a vapor, is condensed by contact with the cold tubes, and passes out at the bottom in liquid state. The heat transference is very good, and the refrigerant is cooled to within 4 to 8° of the temperature of the water.

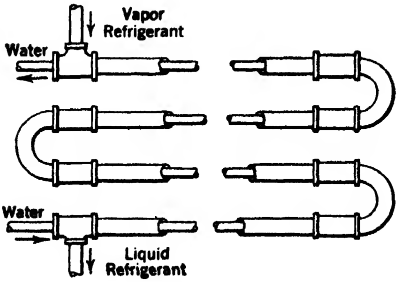

Fig. 7. Double-pipe condenser.

Since low-temperature condensing water is difficult to obtain, relatively large quantities are required to be used and disposed of for economical operation. To save this waste of water *evaporative condensers* (Fig. 8) have been developed which use only 3 to 5 per cent of the amount required if the condenser is entirely water-cooled. They consist of a condenser coil into which the gas refrigerant is led at high temperature and pressure from the compressor. Water is sprayed over the coil and is evaporated by heat extracted from the gas which changes its state to liquid. Air enters near the bottom of the machine, is drawn up over the wet coils, and is discharged by a fan at the top, taking heat and moisture with it. The water drips into a sump from where it is pumped again to the sprays. The liquid refrigerant, still under high pressure, is piped from the bottom of the coil into a receiver and from there circulates in the usual manner. Each pound of water extracts approximately 1000 Btu from the refrigerant in comparison with 20 Btu per lb as in the straight water-cooled condenser.

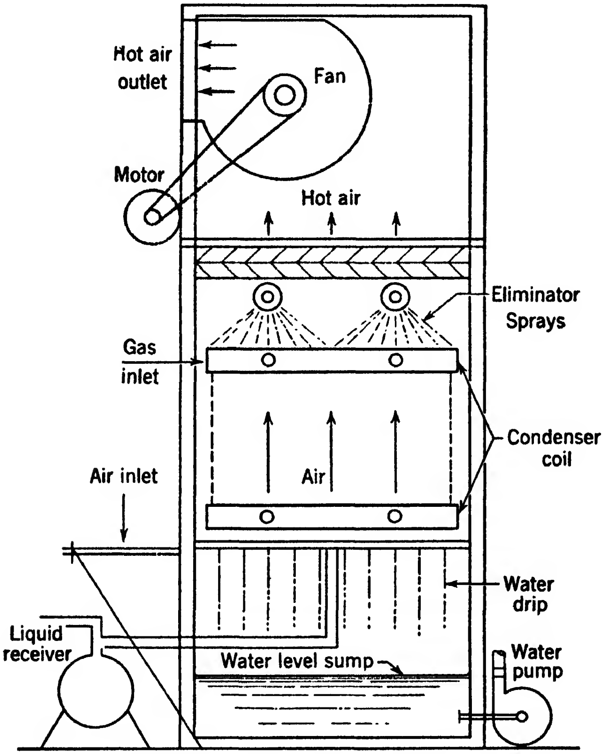

Fig. 8. Evaporative condenser.

12. Refrigerants. Of the materials tried out as refrigerating media, comparatively few combine economy, efficiency, and safety. Two of these in general use will be noted here.

(*a*) *Monofluorotrichloromethane* (CCl_3F) is also known as Freon 11. Its critical pressure is 535 lb per sq in., and its saturation temperature at this pressure is 388°. The boiling point at standard atmospheric pressure is 74.7°, and the freezing point is $-168°$. It is very slightly toxic and is not explosive or corrosive. This refrigerant has been largely used by the Carrier Corporation under the name of Carrene No. 2. It is well adapted to centrifugal machines.

(*b*) *Dichlorodifluoromethane* (CCl_2F_2) is also known as Freon 12. Its critical pressure is 582 lb per sq in., and its saturation temperature at this pressure is 232°. At standard atmospheric pressure the boiling and freezing points are, respectively, −21.6° and −247°. It is very slightly toxic and is not explosive or corrosive. It is satisfactory in all types of reciprocating compressors.

Ammonia has several desirable properties and has been used in the past, but, because it is explosive, corrosive and very toxic, leakage is highly dangerous and it is seldom employed at the present time.

13. Controls. (*a*) Heating, cooling, and air-conditioning design is of necessity based upon the most severe conditions that are likely to be met in the particular location. It is evident, however, that the temperature and humidity of outdoor air during many days may be very appreciably removed from the severest conditions. Therefore, to maintain human comfort and industrial demands within predetermined ranges as well as for economy of fuel and of individual attention, automatic control is necessary to supplement manual operation and to produce rapid, uniform, and safe response to changing conditions of temperature, moisture, or pressure.

(*b*) The manner of actuating the control may be two-position or modulated. By the first the damper or valve is completely shut or completely opened; by the second the movement of the device is controlled by small increments of travel in response to slight changes in the regulator.

(*c*) The regulators or actuating devices themselves are classed as thermostats, hygrostats, and pressure regulators.

14. Thermostats. The basis of automatic control is the thermostat, an instrument which responds to changes in temperature. These instruments consist of a sensitive element which expands and contracts according to the degree of heat. The element may be metal or a volatile fluid within a bellows. The metal type, by the movement of the element, may close or open a small port in a compressed air line [Fig. 9(*a*)] or may make or break an electric circuit. Two metal strips, one of brass with a high temperature coefficient and the other of an alloy of iron and nickel with a low coefficient, are usually brazed together. The element may be straight, spiral, or curved [Fig. 9(*c*)]. If only one end is fixed, the expansion or contraction of the metal will cause the free end to move to the right or left, making electric contacts to start motors which open and close valves and dampers or control oil and gas burners. The contacts may be adjusted to function at predetermined high and low temperatures, 70° and 65°, for example. By connection with a clock, action may be governed for stated hours. In the type with bellows, the volatile fluid by expanding raises the top of the diaphragm, which in turn actuates a lever arm controlling valves or other equipment [Fig. 9(*b*)]. Thermostats may be placed within rooms or spaces to be treated, or they may be inserted in ducts, boilers, sprays, or hot water tanks with the sensitive element within the area and the connections outside. *Direct-acting thermostats* actuate the controls directly by their own power through levers or compressed fluid tubes. *Indirect-acting thermostats* control a source of power, compressed air, or electric current, which in turn operates the valves or dampers. With the pneumatic system an air compressor at 15 to 20 lb and a reservoir must be provided. The electric system operates small motors. The indirect method with electric connections is generally more effective since the energy in the thermostat is seldom sufficient to move the valve or damper parts mechanically.

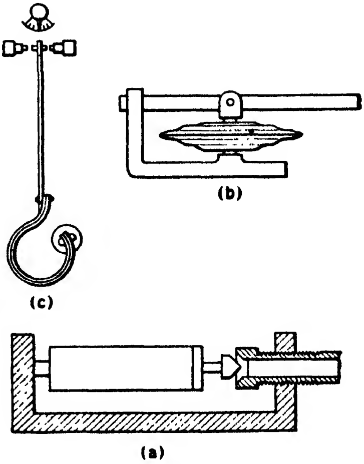

Fig. 9. Thermostats.

15. Hygrostats or humidistats are controllers sensitive to the degree of moisture in the air and are made for use in both rooms and ducts. They are often part of the equipment of unit air conditioners for single rooms. In industrial installations, or where the temperature is high and the controlled condition is to have very low or very high degree of saturation, they are essential.

16. Pressure regulators. These instruments are sensitive to changes in pressure. They may control a single pressure or a differential between two pressures. In air ducts the static pressure regulators are sensitive to changes of 0.01 in. of water. For steam they consist of a metal bellows responsive to boiler pressure.

17. Control valves. These valves are variable orifices which are moved by motors to present smaller or larger openings as directed by a thermostat. They may be normally open or closed, may be designed for tight or partial shut-off, or be 3-way valves for mixing or diverting two fluids.

18. Dampers. These control the flow of air or gases. Those with a single blade are difficult to operate in large sizes because of air pressure. Louvers or multiblade dampers are in more general use, the adjacent blades being arranged to move in the same or opposite directions. The opposed-blade type gives better direction and flow to the air.

19. Relays. Relays are devices that use electrical energy to amplify or convert the power of a thermostat or other controller so that the resultant force will be sufficient and adaptable to operate a valve or damper motor.

20. Residential controls. For an oil-burning plant the controls act as follows: (*a*) The room thermostat directs the starting and stopping of the burner through the relays. (*b*) The control relay starts the motor pumping oil and air to the burner. Automatic ignition is provided by an electric spark. (*c*) The combustion safety control in the relay shuts off the oil and air supply if it does not ignite after a chosen length of time. (*d*) The limit control relay stops the burner if the temperature or pressure in the furnace or boiler becomes excessive or if the combustion gases become too hot in the chimney. Otherwise the burner functions until stopped by the room thermostat through the control relay.

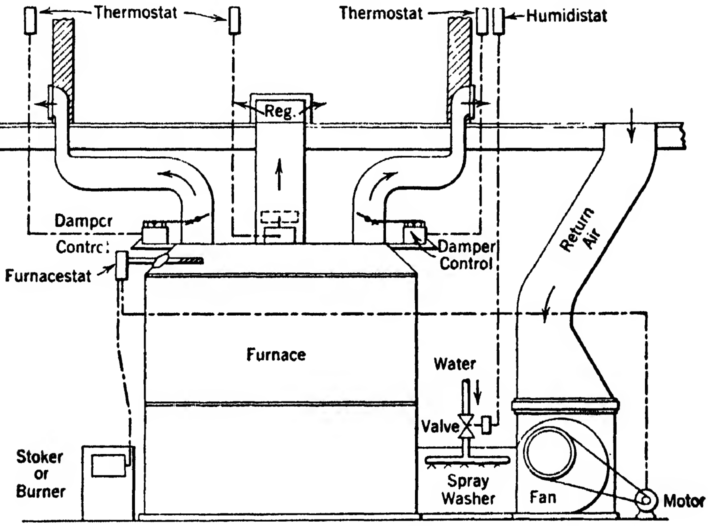

Fig. 10. Furnace control.

For a *gas-burning* plant the room thermostat opens the gas valve and the safety pilot ignites the gas in the burner. The limit control regulates the gas flame to maintain a desired temperature or pressure in the air, water, or steam or shuts off the gas valve in an emergency. The safety pilot closes the gas valve if the pilot light is accidentally extinguished.

A forced hot air furnace with fan and conditioner may be governed as shown in Fig. 10. Room thermostats control dampers in the corresponding ducts, and a humidistat opens or closes the supply valve to the water spray. An insert thermostat in the furnace stops and starts the burner according to the intensity of heat in the furnace bonnet.

21. Zone control. (*a*) *Small Buildings.* When of limited size an entire building may be considered as one zone. One properly placed thermostat may then control the central automatic heater.

(*b*) *Large Buildings.* For greater accuracy of control, to give various degrees of heat to distinct portions operating under differing conditions, buildings may be divided into zones, each with its separate control. The various conditions to be considered include (1) exposure to prevailing winds and solar radiation and the degree of shelter from surroundings; (2) occupancy depending upon the activities and hours of the occupants; (3) various methods of construction in different sections producing unequal heating requirements.

The function of the control is to maintain a desired indoor temperature in the zone, regardless of outdoor conditions, to reduce to an economically low temperature during periods of unoccupancy, and to reheat quickly after such periods. For efficient results the control should respond to outdoor temperature and to the influence of sun and wind—and be affected also by the indoor temperature of the zone.

The quantity of heat furnished to a zone as demanded by conditions is generally controlled by (1) shutting off or turning on the steam, (2) altering the steam pressure, (3) changing the flow of steam by the size of orifices in the valves, (4) varying the temperature of the water in hot water heating, and (5) changing the flow of hot water.

22. All-season air-conditioning control. Figure 11 represents a central air-conditioning plant with automatic changeover from heating to cooling. *T* indicates a thermostat, *V* a valve, *H* a hygrostat, and *D* a damper.

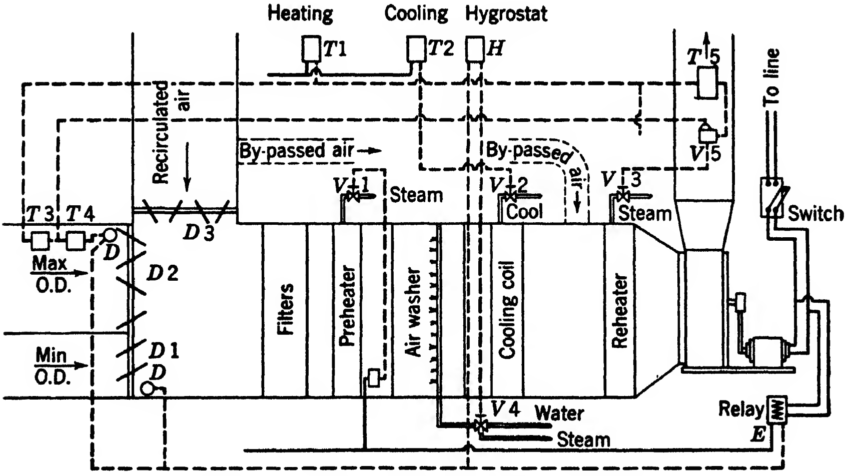

Fig. 11. Central all-season system controls.

Beginning with the heating season the fan motor starter sets the fan in motion and actuates the relay *E*, which opens the minimum outdoor air damper *D*-1, puts the hygrostat *H* in operation to control the 3-way mixing valve *V*-4, and permits the duct thermostats *T*-3 and *T*-4 to operate the maximum outdoor air and the recirculated air dampers *D*-2 and *D*-13, respectively. *H* is generally placed in the room or in the recirculated air duct and may control steam supply to the humidifier or to a mixing valve, which determines the temperature of the spray water. *D*-1, *D*-2, and *D*-3 govern the proportions of outdoor air and recirculated air to enter the room. The quantity of outdoor air is often fixed by the occupancy, the quantity of recirculated air depending upon the resulting demands of the design.

Heating is controlled in the preheater by *T*-6 in the duct through *V*-1 and in the reheater by *T*-1 situated in the room or in the recirculating air duct, acting through *V*-3 in conjunction with *T*-5, the low-limit discharge thermostat. This combination prevents delivery of air from the fan to the room at too low a temperature for proper mixing with room air.

23. Changeover from heating to cooling. As outdoor temperature rises *V*-1 and *V*-3 close in proportion. In rises from 30 to 65°, *T*-3 gradually moves *D*-2 and *D*-3 until, at 65°, *D*-2 is fully open and *D*-3 fully closed. Upon further rises in outdoor temperature *T*-3 directs *V*-5 so that, at 75°, *T*-5 is by-passed and *V*-3 is governed directly by *T*-1. During the rise from 65 to 75°, *T*-4 gradually closes *D*-2 and opens *D*-3.

Thermostats and hygrostats or dew-point thermostats control cooling and dehumidifying by regulating the mixing valves or dampers to hold air at the proper temperature and humidity for delivery to the room. The instruments may be in the fan duct or in the recirculating air. As the room temperature rises *T*-2 directs *V*-2 to deliver gradually increasing amounts of chilled water.

When the fan is switched off, no current passes to *E* and the outdoor dampers and *V*-4 automatically close.

PROBLEMS

1. (*a*) How may air be contaminated? (*b*) Describe the various types of filters and dust collectors, and how they function.

2. Describe fully an air washer, including the types of nozzles, the direction of the sprays, and the operation of the other equipment.

3. What are three methods of passing air through an air washer for the purpose of humidification, and how do they operate?

4. How and under what circumstances can air be cooled and dehumidified by passing through an air washer?

5. By what other method besides air washing can air be cooled and dehumidified? Describe the process.

6. Outline the sequence of processes in cooling spray water by mechanical refrigeration and the equipment involved.

7. (*a*) Describe two types of compressors. (*b*) How do condensers and evaporators function?

8. Describe two types of thermostats, and tell how they control valves, dampers, and electric motors.

9. In a residence what are the automatic controls on gas- and oil-burning plants, respectively?

10. Describe two methods of arranging the branch air ducts and the heating and cooling elements of a central system so that the condition of the air entering each room may be separately controlled.

Chapter 21

DISTRIBUTION AND APPLICATION

1. Air-duct design. The velocity of air through a duct should be sufficient to distribute the air through the room served without stratification. Excessive velocities, however, produce high friction losses, objectionable draughts upon occupants, and unpleasant noise in the ducts and registers. Table I sets forth desirable velocities in feet per minute.

Table I. Recommended and Maximum Duct Velocities *

	Recommended Velocities			Maximum Velocities		
Designation	Residences	Schools, Theaters, Public Buildings	Industrial Buildings	Residences	Schools, Theaters, Public Buildings	Industrial Buildings
Outside air intakes[a]	500	500	500	800	900	1200
Filters[a]	250	300	300	350	350	350
Heating coils[a]	450	500	600	500	600	700
Air washers	500	500	500	500	500	500
Suction connections	700	800	1000	900	1000	1400
Fan outlets	1000–1600	1300–2000	1600–2400	1700	1500–2200	1700–2800
Main ducts	700–900	1000–1300	1200–1800	800–1200	1100–1600	1300–2200
Branch ducts	600	600–900	800–1000	700–1000	800–1300	1000–1800
Branch risers	500	600–700	800	650–800	800–1200	1000–1600

[a] These velocities are for total face area, not the net free area; other velocities in table are for net free area.

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Where noise is not objectionable as in industrial buildings velocities of 2800 to 3000 ft per min are allowable in the main ducts; in department stores, 2000 to 2200 ft per min.

In ordinary air conditioning the density of the air is assumed to be constant throughout its travel. The formulae for the flow of air may then be based upon those for the flow of liquids.

The velocity head is the pressure required to produce the velocity of flow. It is generally expressed in inches of water.

$$V = 1096.5\sqrt{\frac{h}{0.075}} = 4005\sqrt{h} \quad h = \left(\frac{V}{4005}\right)^2 \text{ inches of water} \qquad (1)$$

The *static head* is the pressure necessary to overcome the frictional resistance of the duct. It may be considered a pressure outward against the sides of the duct and consequently may be measured directly by a tube in inches of water (Fig. 1).

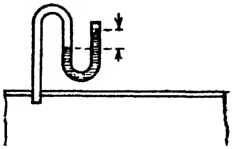

Fig. 1. Static head.

The initial pressure is reduced by friction of the air on the sides of the ducts, called *friction losses,* by elbows and other obstructions in the ducts, or by changes in velocity of air flow, called *dynamic losses.*

2. Friction losses. The resistance to air pressure through friction in a straight duct is affected by the roughness of the material, the type of joints, and the workmanship. Calculations are, however, based upon good standard conditions, and it is, therefore, advisable to select fans and motors of a size to permit a factor of safety. Dampers should also be provided in each branch outlet for better adjustment of flow.

Friction losses are calculated with the assistance of charts such as Fig. 2. The charts are constructed from the fluid flow equation for pressure loss in circular ducts and are based upon standard air, that is, dry air at 70° with a density of 0.075 lb per cu ft. They are sufficiently accurate without correction for conditioning work with any air temperature from 50 to 90°. For distinctly higher and lower temperatures the friction loss may be assumed to vary directly and the air volume inversely as the air density.

For example, if the friction loss at 70° with a density of 0.075 lb is 0.38 in., at 135° with a density of 0.066 lb the friction loss would be $(0.066/0.075) \times 0.38 = 0.34$ in. If the air volume at 70° were 2000 cu ft, the volume at 135° would be $(0.075/0.066) \times 2000 = 2240$ cu ft.

The values in Fig. 2 assume the air to be passing through average, clean, round, galvanized metal ducts with approximately 40 joints per 100 ft. For very rough ducts information and charts should be consulted which give corrections to be applied to the friction losses for average ducts.

If Fig. 2 is entered with a known air quantity passing through a duct of known diameter and length, the friction loss and air velocity may be found as follows: find the air quantity on the left-hand scale; pass horizontally to the right to the diagonal duct diameter line; the intersection at this point with the diagonal line sloping in the other direction gives the velocity in feet per minute. Directly below the intersection the friction in inches of water per 100 ft of circular duct is found on the scale at the bottom. This value has the same ratio to the required friction at 100 ft to the known length of pipe.

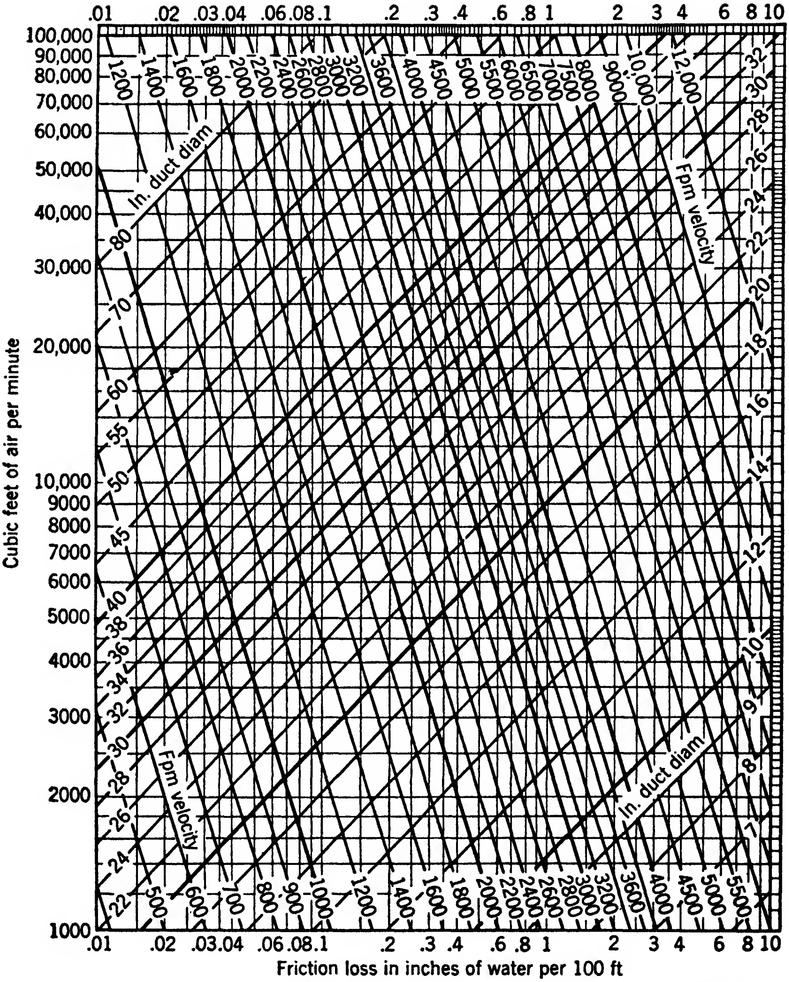

Fig. 2. Friction of air in straight ducts. For volumes of 1000 to 100,000 cfm. (Based on Standard Air of 0.075 lb per cu ft density flowing through average, clean, round, galvanized metal ducts having approximately 40 joints per 100 ft.) No safety factor included. Caution: Do not extrapolate below chart. Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide, 1953,* page 687.

3. Circular equivalents of rectangular ducts. If, for practical reasons, rectangular ducts are preferred, their sizes should provide air-carrying capacities equivalent to those of the round ducts selected from Fig. 2. The ratio of the widths of the sides should not exceed 8:1 to retain the same static friction pressure loss for equal lengths and velocities of flow. Table II gives the circular equivalents of rectangular ducts. Multiplying or dividing the round size of a duct by a constant is the same as multiplying or dividing the width of each side of an equivalent rectangular duct by the same constant. If the round size is 50 in. it may be divided by 2; the equivalent widths of sides for 25 in. are found to be 16 in. × 34 in., which, multiplied by 2, gives 32 in. × 68 in. as the equivalent widths for a 50-in. round size.

4. Dynamic losses. Dynamic or shock losses in ducts may be divided into two classes (*a*) losses due to changes in direction such as elbows; (*b*) losses due to changes in cross section, such as conduit transitions and discharges to atmosphere. These losses vary as the square of the air velocity and for standard air are expressed by

$$H = C(V/4005)^2 \tag{2}$$

where H = loss in inches of water; V = velocity of air in feet per minute; C = shock loss constant.

(*a*) *Losses in Elbows.* The dynamic and friction losses are, for convenience, expressed together as equivalent to the loss in a length, L, of similar straight duct. The radii are taken to the center line of the duct. A radius of 1.5 W is often found practical. Lengths of straight ducts between elbows are measured to the intersection of their center lines. Radius ratio = R/W; aspect ratio = H/W.

To find equivalent straight length from Fig. 3, pass from value of R/W on bottom line upward to sloping line denoting H/W value, then pass left to L (ft)/W (in.) value = l; then $L = l \times (W/12)$.

Example 1 (Fig. 4). For elbow 1, $R_1/W_1 = {}^{18}\!/_{24} = 0.75$; $H_1/W_1 = {}^{6}\!/_{24} = 0.25$. From Fig. 3, $l = L/W_1 = 11.5$ and $L_1 = 11.5 \times {}^{24}\!/_{12} = 23$ ft. For elbow 2, $R_2/W_2 = {}^{9}\!/_{6} = 1.5$; $H_2/W_2 = {}^{24}\!/_{6} = 4$; $L_2 = 6 \times {}^{6}\!/_{12} = 3$ ft.

$$\text{Total length} = 6 + 23 + 15 + 3 + 4 = 51 \text{ ft of duct } 6 \text{ in.} \times 24 \text{ in.}$$

From Table II the diameter of an equivalent circular duct is 12.4 in. At an air delivery rate 2000 cu ft per min, Fig. 3 gives a loss of 0.6 in. per 100 ft for a 12.4-in. duct. The total loss in the duct would then be $0.6 \times {}^{51}\!/_{100} = 0.306$ in. of water.

Turning vanes and concentric splitters in elbows greatly reduce the pressure losses and provide more uniform downstream velocities (Art. 13).

Table II. Circular Equivalents of Rectangular Ducts Measured in Inches *

Side Rectangular Duct	6	7	8	9	10	11	12	13	14	15	16	17	18	19
6	6.6													
7	7.1	7.7												
8	7.5	8.2	8.8											
9	8.0	8.6	9.3	9.9										
10	8.4	9.1	9.8	10.4	10.9									
11	8.8	9.5	10.2	10.8	11.4	12.0								
12	9.1	9.9	10.7	11.3	11.9	12.5	13.1							
13	9.5	10.3	11.1	11.8	12.4	13.0	13.6	14.2						
14	9.8	10.7	11.5	12.2	12.9	13.5	14.2	14.7	15.3					
15	10.1	11.0	11.8	12.6	13.3	14.0	14.6	15.3	15.8	16.4				
16	10.4	11.4	12.2	13.0	13.7	14.4	15.1	15.7	16.3	16.9	17.5			
17	10.7	11.7	12.5	13.4	14.1	14.9	15.5	16.1	16.8	17.4	18.0	18.6		
18	11.0	11.9	12.9	13.7	14.5	15.3	16.0	16.6	17.3	17.9	18.5	19.1	19.7	
19	11.2	12.2	13.2	14.1	14.9	15.6	16.4	17.1	17.8	18.4	19.0	19.6	20.2	20.8
20	11.5	12.5	13.5	14.4	15.2	15.9	16.8	17.5	18.2	18.8	19.5	20.1	20.7	21.3
22	12.0	13.1	14.1	15.0	15.9	16.7	17.6	18.3	19.1	19.7	20.4	21.0	21.7	22.3
24	12.4	13.6	14.6	15.6	16.6	17.5	18.3	19.1	19.8	20.6	21.3	21.9	22.6	23.2
26	12.8	14.1	15.2	16.2	17.2	18.1	19.0	19.8	20.6	21.4	22.1	22.8	23.5	24.1
28	13.2	14.5	15.6	16.7	17.7	18.7	19.6	20.5	21.3	22.1	22.9	23.6	24.4	25.0
30	13.6	14.9	16.1	17.2	18.3	19.3	20.2	21.1	22.0	22.9	23.7	24.4	25.2	25.9
32	14.0	15.3	16.5	17.7	18.8	19.8	20.8	21.8	22.7	23.6	24.4	25.2	26.0	26.7
34	14.4	15.7	17.0	18.2	19.3	20.4	21.4	22.4	23.3	24.2	25.1	25.9	26.7	27.5
36	14.7	16.1	17.4	18.6	19.8	20.9	21.9	23.0	23.9	24.8	25.8	26.6	27.4	28.3
38	15.0	16.4	17.8	19.0	20.3	21.4	22.5	23.5	24.5	25.4	26.4	27.3	28.1	29.0
40	15.3	16.8	18.2	19.4	20.7	21.9	23.0	24.0	25.1	26.0	27.0	27.9	28.8	29.7
42	15.6	17.1	18.5	19.8	21.1	22.3	23.4	24.5	25.6	26.6	27.6	28.5	29.4	30.4
44	15.9	17.5	18.9	20.2	21.5	22.7	23.9	25.0	26.1	27.2	28.2	29.1	30.0	31.0
46	16.2	17.8	19.2	20.6	21.9	23.2	24.3	25.5	26.7	27.7	28.7	29.7	30.6	31.6
48	16.5	18.1	19.6	20.9	22.3	23.6	24.8	26.0	27.2	28.2	29.2	30.2	31.2	32.2
50	16.8	18.4	19.9	21.3	22.7	24.0	25.2	26.4	27.6	28.7	29.8	30.8	31.8	32.8
52	17.0	18.7	20.2	21.6	23.1	24.4	25.6	26.8	28.1	29.2	30.3	31.4	32.4	33.4
54	17.3	19.0	20.5	22.0	23.4	24.8	26.1	27.3	28.5	29.7	30.8	31.9	32.9	33.9
56	17.6	19.3	20.9	22.4	23.8	25.2	26.5	27.7	28.9	30.1	31.2	32.4	33.4	34.5
58	17.8	19.5	21.1	22.7	24.2	25.5	26.9	28.2	29.3	30.5	31.7	32.9	33.9	35.0
60	18.1	19.8	21.4	23.0	24.5	25.8	27.3	28.7	29.8	31.0	32.2	33.4	34.5	35.5
62	18.3	20.1	21.7	23.3	24.8	26.2	27.6	29.0	30.2	31.4	32.6	33.8	35.0	36.0
64	18.6	20.3	22.0	23.6	25.2	26.5	27.9	29.3	30.6	31.8	33.1	34.2	35.5	36.5
66	18.8	20.6	22.3	23.9	25.5	26.9	28.3	29.7	31.0	32.2	33.5	34.7	35.9	37.0
68	19.0	20.8	22.5	23.2	25.8	27.3	28.7	30.1	31.4	32.6	33.9	35.1	36.3	37.5
70	19.2	21.1	22.8	23.5	26.1	27.6	29.1	30.4	31.8	33.1	34.3	35.6	36.8	37.9

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(*b*) *Losses Due to Changes in Cross Section.* Changes in areas of ducts are often necessitated by the design of the building or by volume changes in the air handled. Experiments show that losses in reductions of area are low and are generally neglected but the angle of convergence should not exceed 60°. Losses in sudden enlargements are, however, high. Abrupt enlargements should be avoided, and the angle of divergence should not exceed 20°.

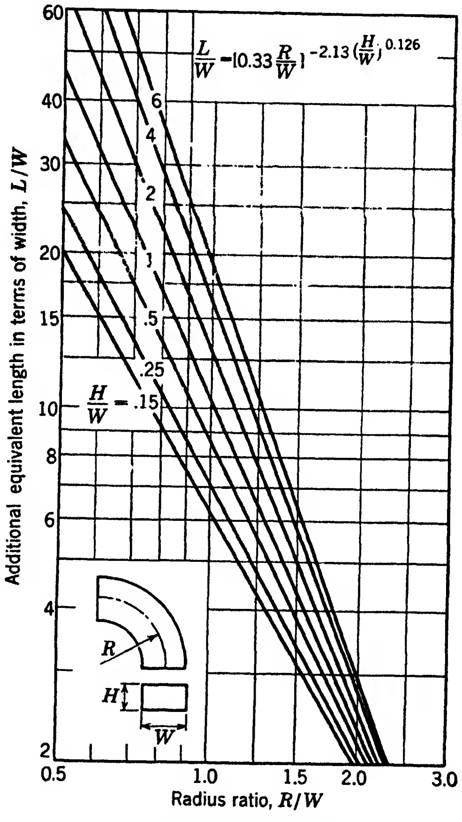


Fig. 3. Losses of pressure in rectangular 90° elbows. W = width; H = height; R = radius of elbow. Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide, 1953,* page 694.

For abrupt discharge from a duct to room atmosphere $C = 1.0$ in Equation 2.

The transition from one duct size to another should be made as smoothly as practicable by a gradual sloping of the sides of the duct.

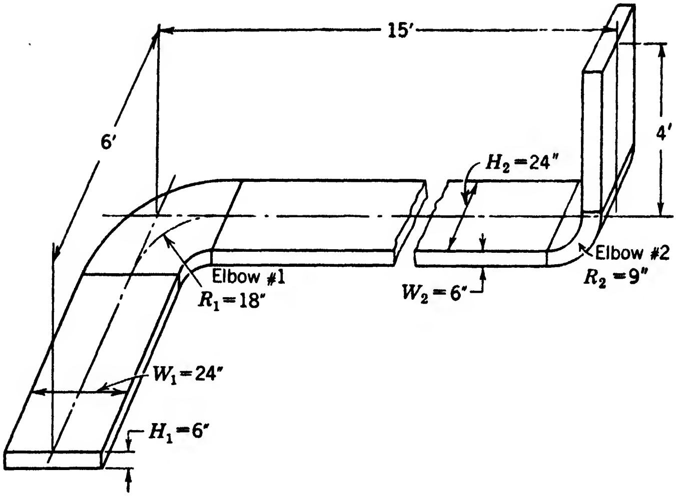


Fig. 4. Example 1.

For standard air, the pressure loss in inches of water due to gradual enlargement is

$$H = C\left(\frac{V_1 - V_2}{4005}\right)^2 \tag{3}$$

where V_1 = velocity in inlet duct feet per second, V_2 = velocity in outlet duct feet per second, C = coefficient depending upon angle of slope.

Table III. Values for *C* in Equation 3

Total Included Angle (degrees)	5	7	10	20	30	40	50	60
C	0.20	0.15	0.16	0.35	0.65	0.80	0.92	1.0

5. Procedure. The three methods of duct design are the velocity reduction method, the equal friction method, and the static regain method. The procedure for the equal friction method, at present generally used, may be outlined as follows:

(*a*) Lay out a convenient arrangement of ducts to furnish a suitable distribution of heat, with special reference to the building structure and to simplicity of design. The air should travel as directly as possible, and sharp bends and elbows should be avoided.

(*b*) Fix the position and size of each branch from the trunk upon the basis of the volume to be supplied and the velocity.

(*c*) Determine the sizes of the trunk sections based upon a selected air velocity and upon the volumes discharged at the branch outlets.

Determine the friction loss in the main section of trunk, and use this value as a constant loss for all sections of the trunk and ducts.

(*d*) Determine the friction and shock losses for the duct offering the greatest resistance, generally the longest duct, and add to it the resistance of the air-conditioning apparatus. The fan must deliver the required volume of air against this total resistance. The losses in the air-conditioning apparatus can be found in the manufacturers' catalogues. Outlets to branch ducts should have dampers to adjust the pressures.

Example 2 (Fig. 5). The fan delivers 4800 cu ft per min of air at 120° at the outlets. Trunk velocity is 1200 ft per min. Layout of ducts with lengths and quantity of air handled at each outlet are shown in Fig. 5. The velocity at outlets 1, 2, and 3 is 800 ft per min, and at outlet 4, 1300 ft per min. Friction losses in the conditioner and fan outlet are 0.42 in. of water. Determine sizes of ducts and total pressure loss.

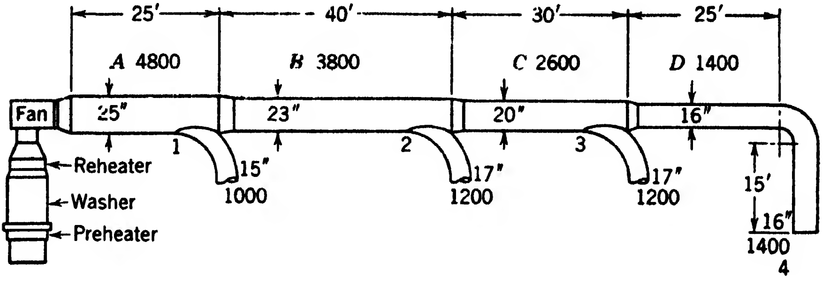


Fig. 5. Example 2.

Solution. Section *A* of trunk delivers 4800 cu ft per min at a velocity of 1400 ft per min. The area of the trunk will be (4800 × 144)/1400 = 494 sq in., and its diameter 25 in. From Fig. 2 it is seen that 4800 cu ft of air flowing in a 25-in. round duct has a friction loss of 0.10 in. of water per 100 ft of length. Using the same friction loss, the diameters of Sections *B*, *C*, and *D* may be found from Fig. 2 as shown in Table IV.

Table IV. Tabulations, Fig. 5

Section	Volume	Friction	Diameter	Velocity	Rectangular Duct
A	4800	0.10	25	1400	34 × 16
B	3800	0.10	23	1180	28 × 16
C	2600	0.10	20	1070	22 × 16
D	1400	0.10	16	1300	16 × 14

With an air velocity of 800 ft per min the size of outlet 1 is (1000 × 144)/800 = 180 sq in., diameter 15 in., rectangle 12 × 16 in. The size of the other outlets is found in a similar manner: oulet 2 is 216 sq in., outlet 3 is 216 sq in., outlet 4 is 155 sq in.

The longest run is to outlet 4 or 135 ft. The total pressure loss is the friction loss in 135 ft of duct with air at 120° temperature and density of 0.068 lb plus the loss in one elbow plus the loss at outlet 3. With the constant friction loss of 0.10 in. per 100 ft of duct for standard air the total friction loss in the longest run will be

$$\frac{0.10 \times 135}{100} \times \frac{0.068}{0.075} = \frac{13.5}{100} \times 0.9 = 0.122 \text{ in.}$$

From Fig. 3, loss in 1 elbow, $R/W = 0.75$	= 0.019
From Equation 2, loss at outlet 4, $C = 1$	= 0.105
Total pressure loss in duct	0.246 in.
Assumed pressure loss in air conditioner	0.42
Total load on fan	0.666 in.

6. Construction (Fig. 6). Ducts are built up in panels of aluminum or of galvanized sheet steel. Longitudinal seams of the grooved type are preferred, although standing seams are sometimes used.

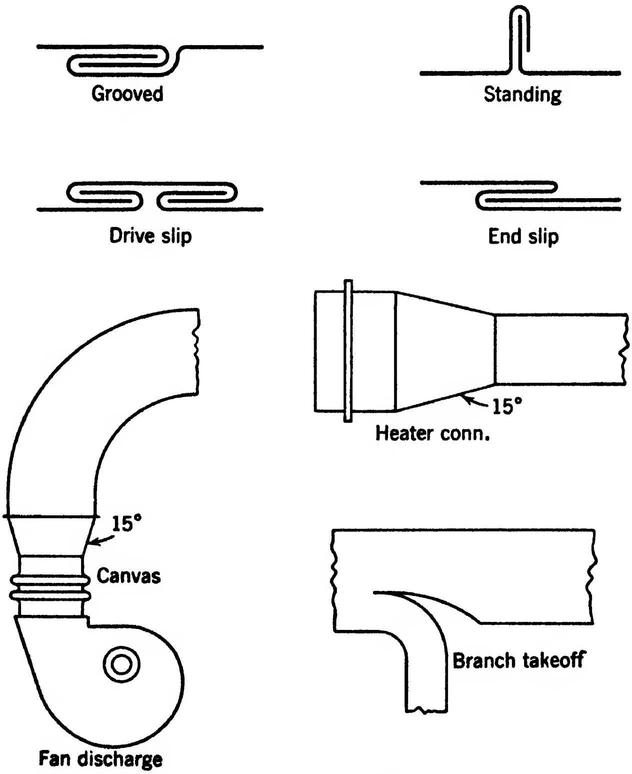


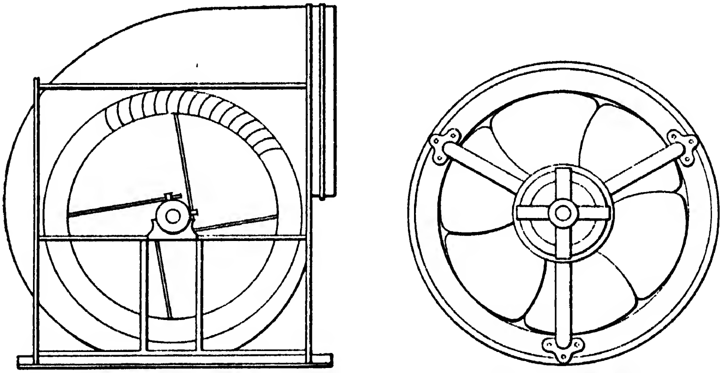
Fig. 6. Duct details.

Transverse or slip seams are of various types, of which the end slip and the drive slip are illustrated. Inlets and outlets of fans should have canvas connections.

Gauges of aluminum and steel sheets, respectively, are used for maximum sides of ducts as follows: 24 and 26 up to 12 in., 22 and 24 for 13 to 30 in., 20 and 22 for 31 to 60 in., 18 and 20 for 61 to 90 in., and 16 and 18 for 91 and over. Slip seams are generally 7 ft 10 in. on centers, and 1½ × 1½ angle iron braces should be used for sides more than 25 in. wide.

7. Fans. The fans used for ventilation are the centrifugal type and the propeller or disk type. In the *centrifugal* or radial type the air enters at the side near the axis of the wheel and is discharged radially through the outlet placed at a tangent to the wheel. The velocity can be controlled and partially converted into static pressure by the spiral shape of the fan housing. In the *propeller* or axial type the air enters at the rear of the fan and emerges at the front in a line parallel to the axis of rotation. The hub is sometimes enlarged in the shape of a disk to operate at higher pressures.

Radial or centrifugal fans are generally intended for moving air at comparatively high pressures and are in common use in duct systems. The blades may be curved at an angle, the forward curve producing higher velocity and requiring a lower rotative speed than the backward curve. The kind of motor drive, belt or direct connection, therefore, in some applications determines the blade design. Multiblade fans, often employed in ventilating, have a large number of short curved blades set near the periphery of the wheel and are of high efficiency (Figs. 7 and 8).



(a) Centrifugal Fan (b) Propeller Fan

Fig. 7. Fans.

Axial flow fans were originally confined to the open propeller or disk fan mounted within a plate or ring. They were intended for moving large quantities of air at low pressures, as in creating air movement in a room or in exhausting air directly out of doors. The blades may be flat, curved, or cambered [Fig. 7(*b*)].

Two types of axial flow fans, *tubeaxial* and *vaneaxial*, have been developed for use against higher resistances. They have large hubs and helical blades and are built for high capacities. The tubeaxial is mounted in a cylinder; the vaneaxial is also mounted within a cylinder with a set of air guide vanes either in front of or behind the wheel. A vaneaxial fan is more efficient and quieter than a tubeaxial but is more costly and often requires more space (Fig. 8).

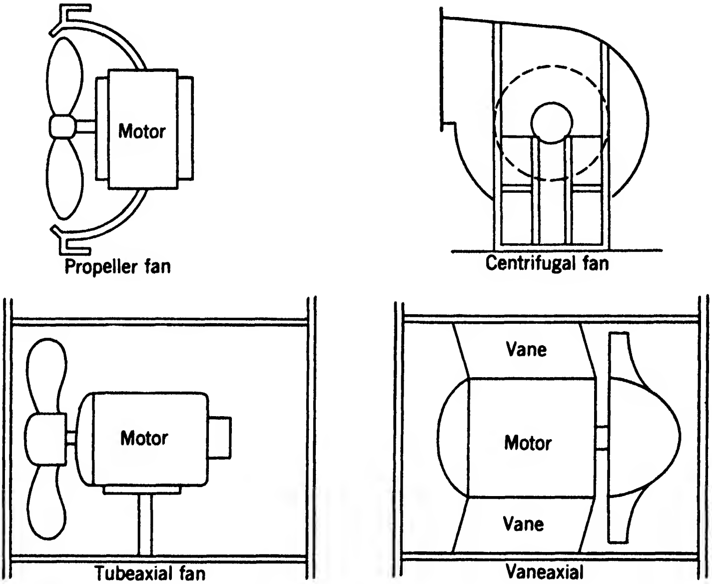


Fig. 8. Fans.

8. Fan selection. To select a fan for an air-conditioning system the following information is required: (*a*) volume of air in cubic feet per minute; (*b*) total static pressure; (*c*) air density; (*d*) type of service; (*e*) sound level and use of space; (*f*) nature of load; (*g*) motive power available. The manufacturers rate all their fans with respect to the first two of the above items and also with respect to revolutions per minute, horse power, tip speed, and outlet velocity. By comparisons the satisfactory fan may be selected.

The most satisfactory applications of type of fan to requirements are generally the following:

Air-conditioning central systems: Centrifugal for the supply fan and centrifugal or axial for the exhaust fan.

Exhausts: Wall exhaust fans are propeller type. Hood exhaust fans involving duct work are centrifugal. Without duct work axial and propeller fans are satisfactory.

Unit systems of heaters, coolers, and air conditioners are best equipped with centrifugal fans where there is considerable resistance or with propeller fans for the small suspended types.

Room circulating fans are of the propeller or disk type.

Kitchen fans for window or wall mounting are propeller fans.

Attic fans are of the propeller type and should have low velocities to minimize noise and vibration during sleeping hours.

9. Systems of ventilation. The various methods of heating and ventilation are described in Chapter 18, Art. 2. The placing and type of the air outlets require careful study to produce rapid mixing and diffusion and to avoid stratification and cold downdraughts at the windows.

These methods may likewise be used when summer cooling is combined with winter heating. A further study of the placing of inlets and outlets is necessary, however, so that the same ducts and registers may satisfactorily serve both heating and cooling requirements.

10. Distribution. With gravity circulation warm air is admitted to the rooms through an interior partition to avoid cooling by an outside wall. With mechanical circulation, such as is required in most all-season conditioning, warm air may be introduced through the exposed wall near the floor and exhausted on the opposite side of the room also near the floor. This method is not so satisfactory for cool air, however, since a current is formed along the floor from outlet to exhaust, the upper part of the room remaining warm. A more satisfactory distribution is obtained by admitting and discharging the air through the inner partition, the outlet being high and the return intake being near the floor. The air currents will be approximately the same in both summer and winter, as shown by the arrows in Fig. 9(*a*).

With the split system, air may be admitted and discharged in both seasons in the same manner [Fig. 9(*b*)], radiators under the windows providing the heat in winter. In rooms not over 400 sq ft in area, air may enter through a hung ceiling, the exhaust being in the center and the outlets surrounding it and turned to distribute the air laterally [Fig. 9(*c*)]. Radiators then supply the heat. Radiant heat panels are also now used in combination with conditioned air.

When necessary to counteract downdraughts at windows without the use of radiators, all heat being supplied by the conditioned air, the outlets may be separated, one being under the window and the other on the interior wall [Fig. 9(*d*)].

Unit air conditioners are generally placed under windows and in this position are satisfactory in both winter and summer.

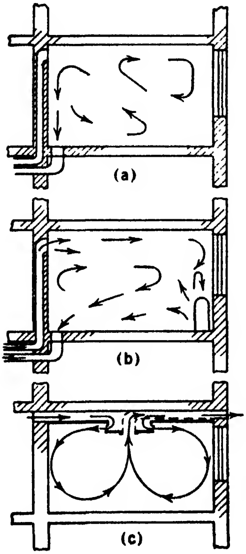


Fig. 9. Distribution.

11. Diffusion. Upon entering a room air should have such characteristics that it satisfactorily fills the following requirements:

(*a*) *Throw.* The projection or throw of the stream should be sufficient to avoid too rapid rise and stratification of heated air or too sudden drop of cold air, with resulting drafts, before a proper mixing with room air. The throw is considered to end at the point where the velocity is reduced to 55 ft per min. It should extend to 75 per cent of the distance to an exposed wall or window.

(*b*) *Drop.* The air stream at the end of the throw should be at least 5 or 6 ft above the floor. When necessary the proper drop may be obtained by an outlet low on the wall and a throw arching toward the ceiling.

(*c*) *Air Motion* in the room must not be so rapid as to cause draughts and discomfort. It should not exceed 30 ft per min in the vicinity of occupants.

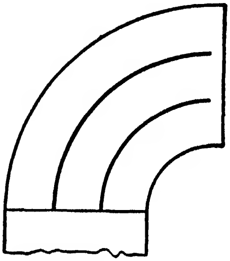
(*d*) *Temperature* differentials between room and supply air should be as large as possible since they influence the changes in room temperature in relation to changes in loads. The outlets should therefore so diffuse the air as to obtain rapid mixing.

12. Air outlets are made for two locations, wall and ceiling.

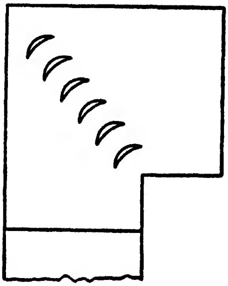
Wall outlets include the following: (*a*) *Perforated grilles* are nonadjustable and are used almost exclusively for return intakes. (*b*) *Vaned outlets* are furnished with adjustable vanes which may be either horizontal or vertical or both and may be set for a straight or a diverging stream. For a straight stream the angle included is 14°, and, for a maximum diverging stream, 60°. Diverging the stream reduces the throw and the quantity of air for a given pressure. Vanes should have a depth of one to two times the spacing between them. (*c*) *Registers* are perforated grilles or vaned outlets with dampers. They are used in house systems.

Ceiling outlets include the following: (*a*) *Plaques* consist of plates set parallel to the ceiling just beyond the outlet. They deflect the air horizontally and are satisfactory in some locations. (*b*) *Ceiling diffusers* deliver the air in many planes and layers, thereby increasing the quantity of entrained room air and the rapidity of mixing. (*c*) *Perforated panels* consist of finely perforated plates set in the ceiling. They are often backed by plenum chambers for even distribution of the air over the perforations. They are inconspicuous and lend themselves readily to sound insulation of the room.

13. Elbows. The elbow at the top of a vertical stack should deliver the air perpendicularly to the face of the outlet and at a uniform velocity throughout. This result is best attained by the use of splitters and turning vanes. Splitters in round elbows reduce to 74 per cent the 100 per cent energy required in plain round elbows, and vanes in square elbows reduce to 45 per cent the energy required in plain square elbows. Vanes have approximately 2-in. inner and 1-in. outer radii (Fig. 10).



Splitters



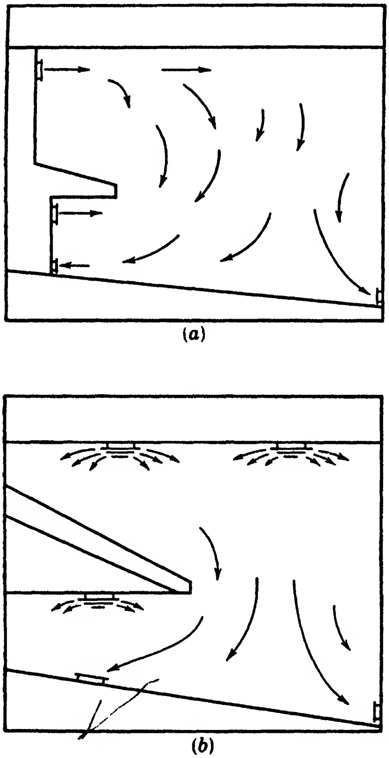
Vanes

Fig. 10. Elbows.

14. Application. The application of the principles of air conditioning varies somewhat according to the peculiar demands of the space to be served. Several general types will be considered.

15. Office buildings. Because the summer heating effect of the sun is so powerful, the amount of necessary cooling varies greatly with the exposure of the offices. It is consequently advisable to divide a building into sections or zones, each one with separate thermostatic control and often with separate fans and dehumidifiers. The north and east sides are often combined in one zone and the south and west in another.

Extensive open spaces such as banking rooms and large stores are usually heated by the conditioned air supply without the use of direct radiation. Owing to their high ceilings, air admitted to cool them in summer may be at lower temperature than would be comfortable in less lofty rooms. On the other hand, the split system is often employed on the office floors with radiators or enclosed convectors under the windows to counteract the downdraughts of air cooled by the glazed sash. Self-contained coolers may be provided for summer.


(a)

(b)

Fig. 11. Theaters.

16. Theaters. Because of the large number of occupants in proportion to floor area, air conditioning has been more widely applied to theaters and cinemas than to any other class of building and is now considered essential.

The auditoriums are usually treated entirely by the ventilating air, no direct radiation being employed during the heating season. The stage, lobbies, and vestibules, however, are often heated by radiators in winter and are not always artificially cooled in summer. Radiation should be calculated for the walls, roof, and skylight of the stage with an assumption of at least one air change each hour. Some large lobbies are heated and cooled by conditioned air, and in some a separate fan and humidifier are provided. Projection booths are separately ventilated by a fan with 60 air changes per hour drawn either from out of doors or from the auditorium. The outlets are generally near the floor, and the return inlets in the ceiling. A combination of three different systems is often used, one to ventilate the machines, one for general ventilation, and a third as a general exhaust.

Down-feed systems have proved most comfortable for the occupants of auditoriums. The air is delivered through outlets in the main ceiling and in the underside of the balconies. The exhausts, consisting of large grilles, may be placed in the standing rail, the proscenium arch, or the walls. Mushroom returns under seats are now seldom used. If the ceiling is high and the room spacious, cooling air may be delivered 15 to 20° below the desired room temperature without draughts. For smaller spaces the difference should not be more than 10°. The indoor temperature is maintained at 10 to 15° less than the outdoors. Thus, with an exterior heat of 90° the interior should be at about 80° and the cooling air delivered at from 60 to 70°.

The body heat of the occupants forms a large portion of the heating in summer and must be considered in the cooling calculations. It is not, however, generally included in winter heating design because of the necessity of warming up the auditorium before the occupants assemble. Lecture halls, assembly rooms, and court rooms may be treated in the same manner as theaters.

17. Schools. Because schoolrooms are planned with large windows in one exterior wall and with desks near these windows it becomes necessary to avoid cold downdraughts. This may be done by placing radiators under the windows and introducing air only for ventilation as in the split system [Fig. 9(*b*)] or by delivering the completely heated air at two points, under the windows and in the opposite wall [Fig. 9(*d*)]. The outlet in the interior wall should be high and the exhaust near the floor. A split system with inlet and outlet in the ceiling [Fig. 9(*c*)] may also be used in the smaller areas. Unit air conditioners are likewise often installed in each room, giving winter and summer service under individual control.

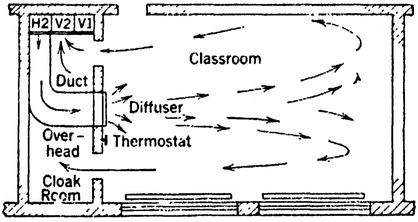


Fig. 12. Class room.

The supply and exhaust ducts are often brought up in the cloak rooms with the branch supplies extending across the cloak-room ceilings and discharging into the class rooms. The return air passes into the cloak rooms through louvers near the bottoms of the doors and so enters the exhaust ducts (Fig. 12).

18. Hospitals. Conditioning air in hospitals is very important, not only in the general wards and private rooms but especially in the operating rooms and nurseries. The usual method is to deliver conditioned air at sufficient temperature to offset all heat losses in the general wards. Private rooms may be treated in the same manner or by the split system with direct radiation. Anesthesia rooms should have a high relative humidity of 60 per cent or more, and operating rooms are often maintained at a temperature of 70 to 100°. Nurseries, particularly those for premature infants, must be kept at accurate degrees of temperature, generally from 75 to 100° with 65 per cent saturation.

19. Restaurants. Air conditioning of restaurants and public dining rooms often proves a profitable investment. Special consideration should be given to situation, proximity of kitchen, and the heat given off by food. Restaurants may possess little outside wall and no ceiling exposure, or they may have large glass windows and roofs with intense sun effect in summer and much heat loss in winter. When the kitchens are close by, air should be supplied to the dining rooms in somewhat greater quantity than it is exhausted in order that the pressure may be outward into the kitchen and the passage of heat, odors, and steam into the dining room prevented. For the same reason more air is exhausted from the kitchen than is supplied from ducts, the rest of the air being injected from the dining room. Steam tables, coffee urns, grilles, and ovens in restaurants should be separately ventilated to eliminate them as sources of heat.

20. Industries. Air conditioning for industrial plants has three purposes: (*a*) to improve the product; (*b*) to render the process of manufacturing independent of climatic conditions; (*c*) to procure comfort for the operatives, the removal of dust, lint, and odors being included. The required conditions vary so greatly in the many classes of industrial activity that a thorough understanding of the stages of manufacture is required in each industry before an air-conditioning scheme can be attempted. In general, humidifying is required in many processes and may be procured by indirect, direct, or combined systems.

The indirect system consists in introducing moistened air into the factory room and corresponds to the humidification used in nonindustrial buildings. It is most effective where high or low relative humidities together with cooling and air motion are desired. The direct system employs atomizing sprays projecting a fine mist directly into a space so that the moisture may be easily taken up by the warm, dry air. It is most useful when high humidities with little cooling or ventilation are necessary. Conditions which require high humidities and the absorption of a large quantity of heat from machinery are often best treated by a combination method, the indirect system caring for the ventilation and cooling and the direct atomized spray providing the moisture. Usually humidities below 40 per cent are considered dry and those above 80 per cent relatively damp.

21. Residences. A greatly increased interest has been shown in air conditioning of residences, and many types of equipment have been put on the market for more or less complete treatment in summer and winter. The chief impediment at the present time appears to be the expense since a thorough all-season conditioning of a dwelling may amount to an undue proportion of the total cost of the structure. For this reason partial conditioning may often be sufficient, that is, treatment during one season only, or simply of one portion of the house. Such a procedure is logical when, because of location or period of occupancy, one season is far more important than the other and also when, by conditioning the main rooms, comfortable quarters are provided without humidifying or cooling the entire residence.

The work may be done through a central equipment in the basement delivering conditioned air through ducts to the various rooms in the same manner as devised for larger buildings. This method with adequate thermostatic control is the most satisfactory and the least noisy. When a warm-air furnace and duct system have already been installed, only the air washer fan and refrigerating machine, with or without filters and eliminators, need be added. Here the cost will be less than if the original heating equipment consisted of steam boiler and piping. A single outlet in a central location without individual room ducts is also an inexpensive installation. For new houses very efficient complete equipment is manufactured usually with oil or gas as the fuel. The process is then entirely automatic and the results most satisfactory. Cold well water or mechanical refrigeration may be used for cooling. City water is generally too warm to be effective.

Self-contained cooling units are also made for installation in offices and living quarters. They combine in one cabinet all the air-cooling apparatus and require only electric connection. Two fans are sometimes employed, the first for air-cooling the condenser and the second for discharging the conditioned air into the room. The first fan may be equipped with a slinger blade which sprays the condensate over the cooling coil where it is vaporized. No drain is then needed. By means of dampers desired amounts of outdoor air may be introduced and room air recirculated or exhausted. The cabinets may be placed below windows or on window sills. A vent is arranged through the window for the discharge of heat.

22. Noise elimination. In all kinds of air-conditioning installations, except possibly in some types of industrial work, satisfactory performance is sometimes impaired by the noise produced during operation. Objectionable sounds may include the hum of the motor and fan, the breathing and roaring of the air, and the vibration and shuddering of the ducts. Such sounds are generally the result of faults in design, workmanship, or insulation. Noises of air flow result from too small pipes and too high velocities; fan humming is caused by excessive speed or insufficient capacity; and vibration of ducts may be charged to flimsy construction and sharp bends. Insulation of motors and fans from the structural frame and of machinery rooms from other portions of the building, as well as the interior lining of ducts with sound-absorbing material, is likewise important and should receive most careful study by the architect.

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2. *Modern Air Conditioning, Heating and Ventilating,* by Carrier, Cherne, and Grant, Pitman Publishing Corp.

3. *Heating, Ventilating and Air Conditioning,* 2nd Ed., Harding and Willard, John Wiley & Sons, New York, N. Y.

PROBLEMS

1. What is meant by static head in duct design?

2. (*a*) What are the acceptable velocities of air in the branch ducts of residences, public buildings, and industrial buildings? Why are excessive velocities objectionable? (*b*) On what basis are friction losses in straight ducts and in elbows computed?

3. Outline the procedure in duct design according to the equal friction method.

4. A system of air ducts consists of a main trunk with a 90° elbow 85 ft from the fan *A* and an additional run 40 ft long terminating in an outlet *C*. At a distance of 55 ft from *A* a branch duct is taken off from each side of the main duct at *B*. The fan delivers 2500 cu ft per min at a velocity of 1200 cu ft per min. Air to be delivered at $C = 1000$ cu ft per min, and at each branch at $B = 750$ cu ft per min. Velocities at *B* and $C = 600$ cu ft per min. Air temperature = 135°. Find duct sizes and total pressure loss.

5. (*a*) Describe centrifugal and propeller fans. What are vaneaxial and tubeaxial fans? (*b*) What kind of fan should be selected for the following cases: central air-conditioning system; exhausts; unit heaters, coolers, and air conditioners; room circulating; kitchens; attics?

6. Where should the air outlets and exhausts be placed for all-season use in (*a*) a room heated by radiators in the split system, and (*b*) a room where all heat is supplied by the conditioned air?

7. What is meant by throw and drop in connection with air diffusion in a room, and how may duct elbows be equipped to deliver air satisfactorily to a room?

8. What special air-conditioning methods are applicable to a residence, a theater, and a school?

9. Discuss the importance of noise elimination in the success of air conditioning.

10. What special conditions of humidity and temperature are necessary in hospital air conditioning?

SECTION V · ELECTRICAL EQUIPMENT

Chapter 22

ELECTRICITY AND ELECTRIC CIRCUITS

1. Electric generators and batteries. The common sources of electricity are alternating-current (a-c) generators, direct-current (d-c) generators, and storage batteries. Alternating-current generators, abbreviated to *alternators*, provide a majority of electrical energy used in all buildings. The d-c generator, however, furnishes energy in a few important building applications, including elevators, escalators, intercommunicating telephone systems, control of signal systems, clock systems, special business machines, and the recharging of storage batteries. The storage battery usually supplies emergency lighting circuits for hallways, stairways, exits, and exit signs; the operation of automatic switchgear and switchgear control devices, clocks, police and fire alarms, automatic locks, certain types of automatic calculating machines, and signal systems.

2. Electricity. Scientists now believe that all matter is made up principally of two kinds of extremely small particles of matter called electrons and protons. These particles are electricity. Electrons are negatively charged particles, and protons are positively charged particles of matter. Particles of unlike charge (+ and −) attract each other; like charges (+ and +) or (− and −) repel each other. Each *chemical element*, such as copper, tin, iron, hydrogen, and nitrogen, is composed of atoms made up of these two kinds of particles. For instance, a hydrogen atom [Fig. 1(*a*)] is made up of a nucleus of 1 proton about which 1 electron rotates. The atoms of other elements, such as copper [Fig. 1(*b*)], have various combinations of protons and electrons welded into a small particle, called the positive nucleus, about which a definite number of negative electrons, called planetary electrons, rotate. Molecules are closely related groups of these atoms. The outermost planetary electrons in some types of atoms are rather weakly attracted to the nucleus. Elements composed of these atoms therefore contain many electrons which are not bound to one atom but which move about continually from one to another. These are called free electrons. Although the free electrons constitute only a small percentage of the total number of electrons present in matter, still they are very numerous—a cubic centimeter of copper, for instance, contains about one sextillion free electrons (10^{21}) or 1,000,000,000,000,000,000,000 electrons. It is the motion of these electrons which constitutes an *electric current* in a solid conductor.

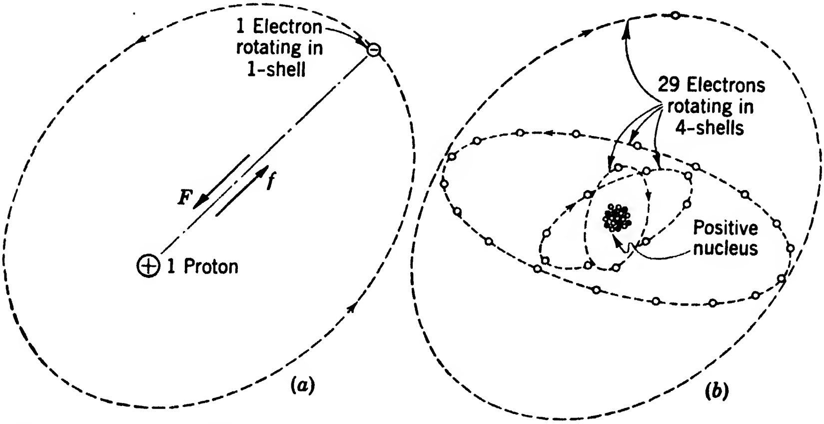


Fig. 1. In the hydrogen atom (*a*): centrifugal force (*f*), and the centripetal force (*F*) due to attraction between the charges on the proton (+) and on the electron (−) counterbalance each other. In the copper atom (*b*): this is a much more complicated atomic structure than the hydrogen atom. However, the same centrifugal and centripetal forces are reacting on the free electrons rotating in their orbits.

Figure 2(*a*) is a model of a round conductor in its normal state, not electrified, giving some idea of the uniform distribution of atoms and free electrons. Figure 2(*b*) shows the migration of charges to the ends of the conductor, due to the action of some external magnetic field, or to chemical reactions in a battery. When the switch *s* is closed a continuous flow of current (*I*) will take place, i.e., by convention the electrons will travel around the circuit in a clockwise direction from the positive battery terminal to the negative terminal.

3. Unit of current: the ampere. When electric current flows in a wire, a certain number of electrons pass through the cross section of the wire in 1 sec of time. The practical unit of measurement of this current is the ampere. One ampere (amp) of current flows in a conductor when 6.251×10^{18} electrons pass a given cross section in 1 sec. In the home and office, on 120-volt service, the ordinary 100-watt lamp filament carries about 0.833 amp; the motor for an office desk fan, about 1.00 amp.

Experiment shows that electric current travels with the speed of light, i.e., 186,000 mi per sec. For example, if the terminals of a battery (Fig. 3) should be connected by a switch *s* to a 2-wire line 186,000 mi in length, a current would be noted in an ammeter *A* in 1 sec after closing the switch. This rate of conduction of electric current may be considered instantaneous.

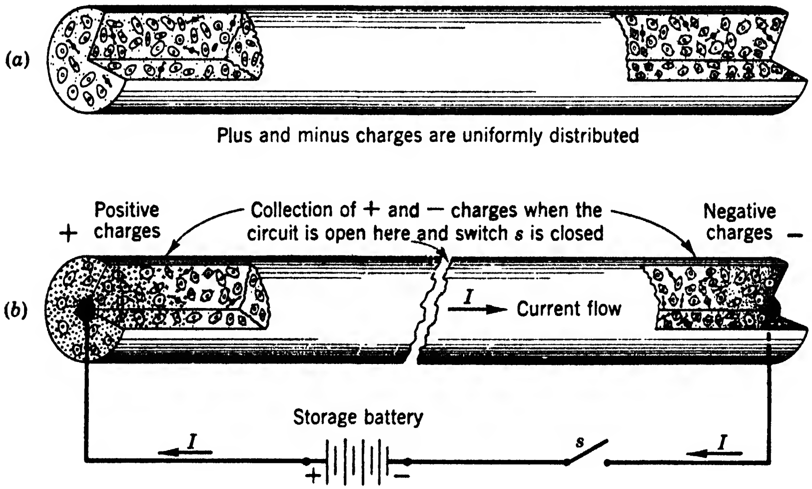


Fig. 2. (*a*) The relatively even distribution of atoms and electrons in a de-energized copper conductor. (*b*) The collection of positive charges at the left end and negative charges at the right end of the copper conductor due to the influence of the charged storage battery. Under such conditions when a circuit is completed from the left end to the right end and the switch *s* is closed, conventional current will flow as indicated. Note that the storage battery in the figure is being discharged since the current will flow in the direction from the plus (+) to the minus (−) terminal.

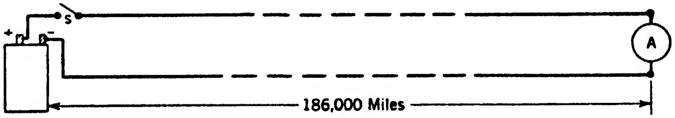


Fig. 3. Speed of propagation of electric current: 186,000 miles per second.

4. Unit of electrical potential: the volt. Free electrons are caused to move along a given conducting material, such as a wire, by creating a higher positive electric charge at one end than at the other. In the ordinary dry cell or the storage battery, chemical action causes positive charges (+) to collect on the positive terminal and electrons or negative charges (−) to collect on the negative terminal. It is here assumed that nothing is connected to the battery terminals. There is a definite force-attraction, or tendency to flow, between the electrified particles concentrated at the positive and negative terminals. *Potential difference* or *voltage* is the name given to this *electromotive* *force* (*emf*) which now exists between these two terminals. The symbol for the internal voltage "generated" or "induced" at the terminals of the battery or generator is the letter E. If a wire is connected to these terminals [Fig. 4(*a*)] electric current (I) will flow.

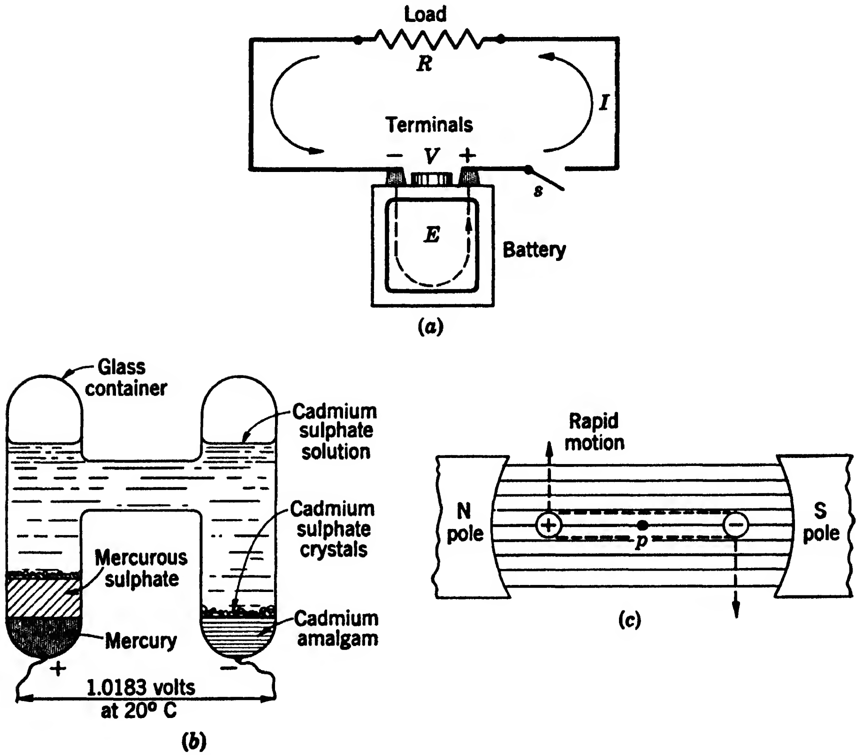


Fig. 4. (*a*) Flow of conventional electric current around a conducting circuit, electrons flowing as the result of the emf of the battery. (*b*) Weston standard cell used as the international standard for the measurement of volts. This standard is easily reproduced in the testing laboratory. (*c*) A coil rapidly revolving in a clockwise direction (about point p) and at the same time cutting a magnetic field extending from the N-pole to the S-pole. This rapid cutting of the lines of magnetic force induces voltage in the coil in the directions shown by the + and − signs. A + sign indicates an inward induced voltage. A − sign indicates an outward induced voltage. When 10^8 lines are cut in 1 sec by 1 conductor, 1 volt is induced.

The direction of this current is arbitrarily and by convention taken as from the positive to the negative terminals.

The letter V is used to identify the *voltage* at the terminals of a generator, a battery, or a load when the current is flowing. Since voltage is "dropped" in the internal resistance of the source (generator or battery) when delivering current, the internal drop is the *difference* between E and V; V being less than E. For example: If the internal resistance of the battery, between terminals, is 0.1 ohm, and the battery is delivering 25 amperes, then the voltage "dropped" within the battery is $0.1 \times 25 = 2.5$ volts. Hence the battery when switch s is closed will have a terminal voltage of 12 volts. When s is opened the "open circuit voltage" of the battery will be $12 + 2.5$ or 14.5 volts. Also study Ohm's law, Art. 7.

For convenience of reference and standardization, the *volt* is measured quantitatively by a Weston standard cell [Fig. 4(*b*)] which produces 1.0183 volts potential difference between its terminals at 20°C. The voltmeter which indicates the voltage, or electrical pressures between any two points, is calibrated by comparison with such a standard cell.

5. Unit of resistance: the ohm. Whenever free electrons move they must necessarily take a devious path through the nebulae of atomic and molecular structure of the conducting material. *Conductors* such as copper, aluminum, gold, and other metals allow relatively free travel of electric current. *Insulators* such as glass, mica, rubber, synthetic compounds, varnish, and oils practically prevent such movement. Hence, conductors and insulators are characterized by their relative resistances to the flow of electrons. Even in metals there is considerable difference in electrical resistance. The unit of specific resistance is given in *ohms per mil-foot*. A round copper wire $\frac{1}{1000}$ in. in diameter and 1 ft long is a *mil-foot,* and its approximate resistance at 0°C is 9.56 ohms. The symbol is the Greek letter rho (ρ).

The international *standard ohm* is defined as that resistance which will allow 1 amp to flow when 1 volt is impressed across it. A column of pure mercury 106.30 cm long, of uniform cross section and weighing 14.4521 grams at 0°C has exactly 1-ohm resistance. The resistance of practically all conductors changes slightly with temperature. The temperature *coefficient of resistance* for any conducting metal is the change of resistance per degree centigrade temperature rise or drop. The symbol is the Greek letter alpha (α). Average temperature coefficients are given in Table I. The equation which relates the change in resistance to change in temperature is given by:

$$R_t = R_0(1 + \alpha t) \tag{1}$$

where R_0 is the resistance at 0°C and R_t is the resistance at a higher temperature t.

Example 1. A 100-ft length of copper wire one mil in diameter at 0°C has a resistance of 956 ohms. What is its resistance at 20°C?

Solution. $R_{20°} = 956(1 + 0.0039 \times 20°) = 1032$ ohms.

In electrical engineering all temperatures are usually expressed in degrees centigrade. The relation between centigrade and Fahrenheit degrees is:

$$°C = \tfrac{5}{9}(F° - 32°) \qquad (2)$$

or

$$°F = \tfrac{9}{5}C° + 32 \qquad (3)$$

Example 2. Convert 40°C to degrees Fahrenheit.
Solution. $°F = \tfrac{9}{5} \times 40°C + 32 = 104°F$.
Example 3. Convert 100°F to degrees centigrade.
Solution. $°C = \tfrac{5}{9}(100°F - 32°) = 37.8°C$.

6. Resistance of conductors. If a given emf is applied to the terminals of wires of several different metals, each of the same diameter and length, the relative values of electric current that will flow in the wires will depend upon their *specific resistances* or resistivities. Table I indicates approximate *resistivities* of several metals and of typical chemical solutions. Practically all wires, cables, and bars used in electric machinery, electrical devices, and transmission and distribution circuits are of uniform cross section; round, rectangular, oval, or of some odd section like a trolley wire. The cross section of a railroad rail, used as a conductor on electric railway systems, is another example

Table I. Approximate Specific Resistances and Temperature Coefficients of Resistance for Some Metals and Solutions

Metals at 0°C			Chemical solutions at 18°C			
	Ohms per mil-ft	Average temperature coefficient *		Ohms per mil-ft		Average temperature coefficient †
				5% solution	10% solution	
Aluminum	15.75	0.0042	Nitric acid (HNO_3)	23.45	13.12	0.015
Copper	9.56	0.0039	Hydrochloric acid (HCl)	14.23	9.58	0.016
Gold	13.23	0.0037	Sulphuric acid (H_2SO_4)	28.85	15.35	0.012
Iron	67.48	0.0042	Caustic potash (KOH)	35.13	19.20	0.019
Lead	119.10	0.0041	Zinc sulphate ($ZnSO_4$)	314.70	187.80	0.022
Mercury	565.00	0.0009	Copper sulphate ($CuSO_4$)	319.00	188.40	0.021
Nickel	41.66	0.0062	Sodium sulphate (Na_2SO_4)	146.90	87.90	0.024
Silver	8.85	0.0040	Soda ash (Na_2CO_3)	133.50	85.60	0.026
Tin	63.20	0.0047	Table salt ($NaCl$)	89.70	49.70	0.022
Tungsten	26.30	0.0051	Ammonium chloride (NH_4Cl)	65.65	33.90	0.020

* Average temperature coefficient from 0° to 100°C.
† Average temperature coefficient at 18°C.

of an odd shape. The *resistance* of any conductor of uniform cross section is

$$R = \rho(L/A) \tag{4}$$

where R is the resistance in ohms; L is the length in feet; A is the area in circular mils, and the Greek letter rho, ρ, is the resistance of a circular mil-foot of the substance of which the conductor is made. A circular mil-foot of copper wire is a round wire 1/1000 in. in diameter and 1 ft long. This wire has a resistance of approximately 9.56 ohms at 0°C as given in Table I.

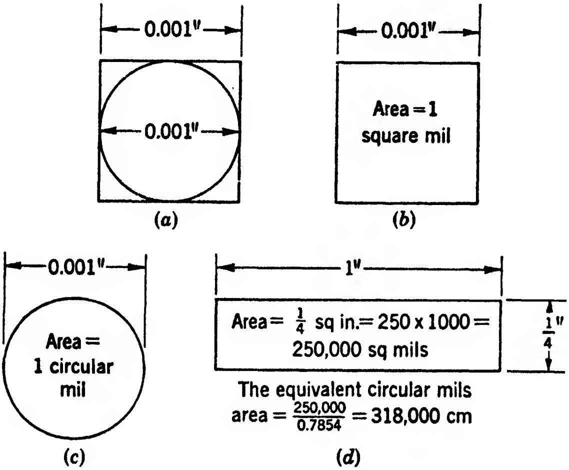


Fig. 5. The relative cross-sectional area of a square inch and of a circle 1 inch in diameter are compared: (*a*), (*b*), and (*c*). The area of the circle is only 0.7854 of the area of the square mil. (*d*) shows the computation for the circular mil area of a round wire which has an area equivalent to the square mils of a rectangular copper bar.

The *circular mil* is defined as the area of a circle 1/1000 in. in diameter. Since the area of a circle ($\pi d^2/4$) is directly proportional to the square of the diameter, d, it is apparent that the area of a round wire in circular mils is simply the square of the diameter in mils. (See Fig. 5.)

Example 4. What length of No. 10 copper wire at 0°C is needed so that the wire will have a resistance of 1 ohm? The resistance of a circular mil foot of copper is 9.56 ohms at 0°C. No. 10 wire is 10,380 circular mils in cross section.

Solution. The resistance is $R = \rho(L/A)$; therefore,

$$L = \frac{RA}{\rho} = \frac{1 \times 10{,}380}{9.56} = 1086 \text{ ft}$$

Wires and cable are usually round in cross section, and this cross section is expressed in circular mils. The standard American wire gauge (abbreviated awg or AWG) identifies various standard sizes and gives their cross-sectional areas in circular mils. Table I, Chapter 23, p. 334, gives the gauge numbers, areas in circular mils, resistance in ohms per 1000 ft at 65°C, and the safe current-carrying capacities specified by the National Electrical Code (NEC) for each size and type of insulation. The student should become thoroughly familiar with the use of this table.

It is frequently necessary to know the circular mils of a conductor of rectangular cross section. Such conductors or *bars* are made of solid copper rectangular in cross section, such as $\frac{1}{4}$ by 2 in. and $\frac{3}{8}$ by 4 in. Figure 5 shows the comparison between a circular mil (0.001 in. in diameter) and a square mil (0.001 in. square). The cross section of the circular mil is only 0.7854 times the area of the square mil. Thus to convert a rectangular area to the equivalent circular mils, divide the rectangular area in square mils by 0.7854, i.e.,

$$\text{Circular mils} = \frac{\text{Area in square mils}}{0.7854} \tag{5}$$

Conversely, an area in circular mils may be converted to a rectangular cross section in square mils by the equation

$$\text{Area in square mils} = \text{Area in circular mils} \times 0.7854 \tag{6}$$

Example 5. A round copper wire of AWG Size 2, of 66,370 cm, is to be replaced by a copper conductor with a square cross section. What is (*a*) the measure of its cross section in square mils; and (*b*) the measure of one side of the square in inches?

Solution. The cross section in square mils (sq mil) is

$$\text{Sq mil} = \text{cm} \times 0.7854 = 66{,}370 \times 0.7854 = 52{,}200 \text{ sq mil}$$

The length of one side of the square is

$$\sqrt{52{,}200} = 228.4 \text{ mils or } 0.2284 \text{ in.}$$

7. Ohm's law. The current I which will flow through a given resistance R is directly proportional to the voltage V impressed on it. This is known as *Ohm's law.* It is expressed by the equation

$$I = V/R \tag{7}$$

where I is the current in amperes, V the voltage drop in volts, and R the resistance in ohms. The letter V is used to indicate the voltage at the terminals of the resistance (R) or the power-consuming device. Usually V differs numerically from the induced voltage E when current is flowing in the closed circuit. A few examples will illustrate the practical application of Eq. 7.

Example 6. An incandescent lamp having a hot resistance of 66 ohms is put into a socket which is connected to a 115-volt supply. What is the current?

Solution. $I = V/R = {}^{115}\!/\!_{66} = 1.74$ amp.

It is apparent that if any two factors of the formula are given the third factor may be determined.

Example 7. A bathroom heating unit draws 10 amp at 115 volts. What is its hot resistance?

Solution. $R = V/I = {}^{115}\!/\!_{10} = 11.5$ ohms.

Example 8. If a fuse is protecting the circuit of a 15-ohm percolator, and it is designed to blow out at a current of 10 amp, what is the maximum voltage that should be applied across the terminals of the percolator?

Solution. $V = RI = 15 \times 10 = 150$ volts.

In the above examples, 6 to 8, it should be remembered that most resistances are higher when they are hot, i.e., at normal operating temperatures. When cold, at room temperatures, their resistances are lower. Clear evidence of this is the fact that when a tungsten filament lamp (cold) is first turned on it takes, for a fraction of a second, perhaps 10 to 15 times the current that flows when the filament is hot.

8. Power and energy. The unit of electric power is the *watt* (w). A larger unit is 1000 watts, called the *kilowatt* (kw). The power input in watts to any electrical heating device in which the element has a resistance R and in which the current is I is given by the equation:

$$W = RI^2 \tag{8}$$

But by Ohm's law $V = RI$; hence

$$W = VI \tag{9}$$

where W is in watts, R in ohms, I in amperes, and V in volts.

Example 9. An electric ironer is rated as 1000 watts. (*a*) What is its resistance, and (*b*) what is the current through it if it is connected to a 115-volt outlet?

Solution. $W = RI^2$ or $W = VI$. Therefore,

$$I = W/V = 1000/115 = 8.7 \text{ amp}$$

$$R = W/I^2 = 1000/(8.7)^2 = 13.2 \text{ ohms}$$

The energy delivered is equal to the power input times the time. This is usually expressed in watthours or in kilowatthours. A *watthour* (whr) is 1 watt delivered for 1 hr; a *kilowatthour* (kwh) is 1000 watts delivered for 1 hr.

The *national averages* of costs per kilowatt hour for these classifications of customers of public utilities in the United States are approximately as follows:

For residences, 2.74 cents per kwh
For small commercials, 2.52 cents per kwh
For industrials, 0.75 cents to 2.5 cents per kwh

The variation from these would depend upon: variations in cost of coal or water power; density of business, industrial and domestic population; variations in load factors (hours of use); changes in kw demands; changes in load power factors. (This information is indicated by reports of the Edison Electric Institute, June, 1954.)

Thus, when t is the time in hours,

$$Wh = RI^2t \text{ watthours} \tag{10}$$

$$Wh = VIt \text{ watthours} \tag{11}$$

and

$$Wh = (RI^2t)/1000 = \text{kilowatthours} \tag{12}$$

$$Wh = (VIt)/1000 = \text{kilowatthours} \tag{13}$$

Most electrical devices used in the home, office, and factory are required by the National Board of Fire Underwriters (NBFU) and by the National Electrical Code (NEC) to be marked with *name plates* which identify the electrical rating in volts, amperes, and watts. Such *ratings* are necessary in order to aid in the determination of the electrical capacity of the service and the sizes of circuit breakers, fuses, cables, wires, switchboards, and panelboards. The name plates of rotating electrical machinery also include the speed in rpm, type of design, the allowable temperature rise in degrees centigrade at rated horsepower or kilowatts output, and the manufacturer and the manufacturer's type and serial number. These name plates are also helpful to NEC inspectors who may be engaged to approve and certify the safety of all installations, as specified by the NEC. The National Board of Fire Underwriters furnishes a book of *Inspected Electrical Equipment,* which identifies tested and approved equipment for installation under the NEC.

9. Direct current and alternating current (abbreviated a-c and d-c). Whenever the flow of electric current takes place at a constant time rate, practically unvarying and in the same direction around the circuit, it is called *direct current.* The curve (straight line) of Fig. 6(a) indicates such a current of 10 amperes.

Whenever the flow of current is periodically varying in time rate and in direction, as indicated by the symmetrical positive and negative loops or sine waves in Fig. 6(b), it is called an *alternating current.* The distance along the time axis spanned by a positive and a negative a-c loop is called 1 cycle of time. Present-day a-c systems are usually of 60-cycle or of 25-cycle frequencies. This means that current at 60 or 25 *cycles per second* (cps) is delivered to the consumer. The d-c generator, the dry battery, and the storage battery produce direct voltages and currents. The a-c generator delivers alternating voltages and currents.

10. Effective value of an alternating current. It is seen [Fig. 6(*b*)] that the instantaneous value of an alternating current is continuously varying with time. Starting at the zero point of curve (*b*) the current rises in ¼ cycle to its maximum value in a positive direction, decreases to zero at the 180° point, and then repeats these corresponding values in a negative or reverse direction from 180 to 360°. This 360° cycle known as the *sine wave* of currents, is produced by an a-c generator. Any constant (direct-current, d-c) value of electric current, as shown in Fig. 6(*a*) will deliver heat energy into a heating device such as a toaster or iron at a uniform rate.

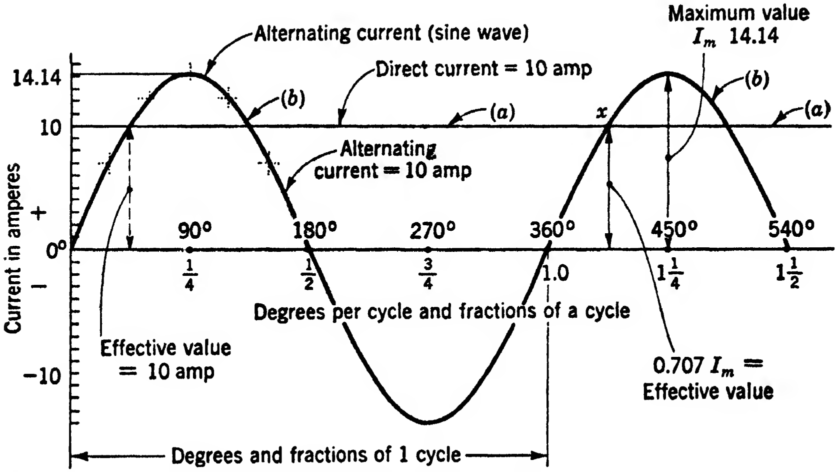


Fig. 6. (*a*) Direct current (*b*) alternating current. The ordinate of the d-c amperes will produce the same heating effect in a given resistor as will the effective flow of alternating current in the same resistor. Because this is so, effective flow of alternating current equals 0.707 times the maximum value I_m. This flow of alternating current is indicated at point x on the right-hand loop of the a-c curve.

The average heating effect or effective value of an alternating current (sine wave, Fig. 6) is the square root of the sum of all the *ordinates squared* over one-half cycle of the wave. This may be proved by calculus. It may also be proved by scaling the lengths of about 20 equally spaced ordinates, then taking the square root of the *sum of these ordinates squared.* The result will show that the effective value is $0.707 \times I_m = 0.707I_m$. Thus 1 amp of direct current and 1 amp of alternating current (i.e., the effective values thereof) are directly comparable and produce the same energy in electrical equipment and devices.

Example 10. The effective value (I) of a given alternating current is 50 amp. What is its maximum value (I_m)?

Solution. $I_m = 50/0.707 = 70.7$ amp.

Example 11. Fifteen amperes (d-c) are required to heat a flat iron. What is the maximum value (I) of the alternating current required to operate this iron?

Solution. $I_m = 15/0.707 = 21.2$ amp.

A sine wave of a-c current in any pure resistance circuit is produced by and is at every instant proportional to a corresponding sine wave of impressed a-c voltage. Hence the voltage also has an effective value of 0.707 times the maximum value of the sine wave.

11. Simple d-c series circuits. In general an *electric circuit* may be defined as a complete conducting path carrying current from a source of electricity to and through some electrical device (or load) and back to the source. A current can never flow unless there is such a complete circuit. The simple *series circuit* is represented by the wiring diagram (Fig. 7), in which all separate parts of the circuit are carrying the same current. In any series circuit the total resistance R is the sum of all the resistances around the circuit. The general equation for resistances in series is

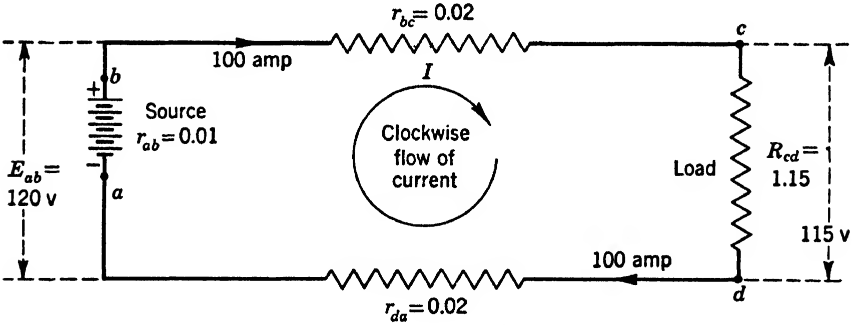


Fig. 7. A series circuit with current flowing clockwise out of the source.

$$\text{Total resistance} = R = r_{ab} + r_{bc} + R_{cd} + r_{da} \qquad (14)$$

where $r_{ab} + r_{bc} + R_{cd} + r_{da}$ are the resistances of each part of the series circuit. Hence the total circuit resistance is

$$0.01 + 0.02 + 1.15 + 0.02 = 1.20 \text{ ohms}$$

It is customary to refer to certain connection points on such wiring diagrams by letters a, b, c, d, $\cdots$. Then the battery voltage may be called $E_{ab} = 120$ V; the voltage across the load resistance, $V_{cd} = 115$ V; the resistance of the two wires $r_{bc} + r_{da} = 0.04$ ohm. The positive and negative terminals of the battery are shown.

Example 12. The battery in Fig. 7 is rated at 120 volts, the line resistance (both wires) is 0.04 ohm, the battery internal resistance is 0.01 ohm; and the load resistance 1.15 ohms. Determine: (a) current flowing in the circuit; (b) the power loss in the line; (c) power input to the load; (d) the voltage across the load (v_{bc}).

Solution. The current flowing is

$$(a)\quad I = \frac{E}{R} = \frac{E_{ab}}{r_{ab} + r_{bc} + r_{cd} + r_{da}} = \frac{120}{0.01 + 0.02 + 1.15 + 0.02} = 100 \text{ amp}$$

The total line loss is

$$(b)\qquad W = rI^2 = (r_{ab} + r_{cd})I^2 = 0.04 \times (100)^2 = 400 \text{ watts}$$

The power input to the load is

$$(c)\quad W = RI^2 = R_{bc}I^2 = 1.15 \times (100)^2 = 11{,}500 \text{ watts or } 11.5 \text{ kilowatts}$$

The voltage drop across the load is

$$(d)\qquad V_{cd} = R_{cd}I = 1.15 \times 100 = 115 \text{ volts}$$

An example of the use of the series circuit is a simple battery-operated door bell (Fig. 8), in which the battery supplies current over the resistance of the wires to and through the resistance of the bell.

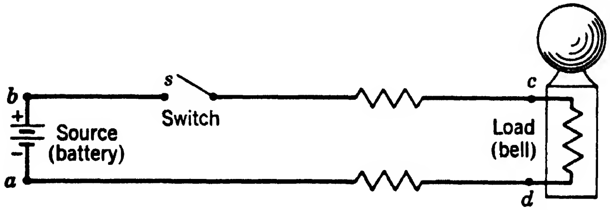


Fig. 8. This series circuit, similar to Fig. 7, indicates its connection to the coil for the operation of a bell when the switch s is closed.

12. Simple d-c parallel circuits. When more than one branch of the circuit is connected between the same two points, such as resistances r_{ef}, r_{gh}, and r_{km} in Fig. 9, they are said to be *connected in parallel.* A current I_{bc} flowing through the line bc will divide at c and pass through the three branch circuits ef, gh, and km. The same voltage V_{cd} is impressed across all three of these branches. The current passing through each branch is inversely proportional to the resistance of each branch. The current in wires bc and da is simply the sum of the currents in the three branch circuits.

When resistances are connected in parallel, the combined resistance of all the paths is equal to the reciprocal of the sum of the reciprocals,

$$R = \frac{1}{1/r_1 + 1/r_2 + 1/r_3 + \cdots} \tag{15}$$

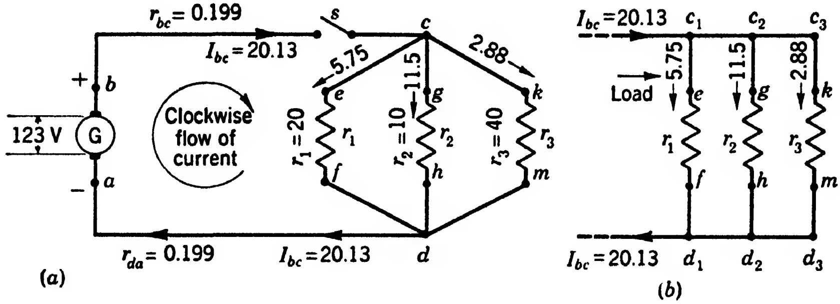


Fig. 9. (*a*) A typical parallel connection of three resistances r_1, r_2, r_3 between the points *c* and *d*. These resistances are said to be connected in parallel between points *c* and *d*. When the switch *s* is closed, each of the three resistors carries its own amount of current in accordance with Ohm's law. Each of these currents flows into the point *d* and therefore turns the total current clockwise in the return conductor *da*. (*b*) This is the usual way that the resistors r_1, r_2, and r_3 would be connected rather than at a point as in (*a*).

Example 13. Referring to Fig. 9(*b*), the generator delivers 123 volts to the line terminals *a* and *b*. The resistances in ohms of the line wires and of each branch of the parallel circuit are indicated on the figure. Determine: (*a*) the effective resistance of the load from *c* to *d*; (*b*) the total effective resistance around the entire circuit from *b* to *a*; (*c*) the total current from *c* to *d*; (*e*) the currents I_{ef}, I_{gh}, and I_{km}.

Solution. (*a*) The effective resistance of the parallel group *cd* is

$$R_{cd} = \frac{1}{\frac{1}{20} + \frac{1}{10} + \frac{1}{40}} = \frac{1}{0.05 + 0.10 + 0.025} = 5.71 \text{ ohms}$$

(*b*) The total circuit resistance from *b* clockwise to *a* is

$$R_{bcda} = (r_{bc} + R_{cd} + r_{da}) = 0.199 + 5.72 + 0.199 = 6.108 \text{ ohms}$$

(*c*) The total current is

$$I_{ab} = \frac{E_{ab}}{R_{bcda}} = \frac{123}{6.108} = 20.13 \text{ amp}$$

(*d*) The voltage impressed at the terminals of the parallel circuit *c* to *d* is the generator voltage (123*V*) minus the voltage line drop, or

$$E_{ba} - (r_{bc}I_{bc} + r_{da}I_{da}) = 123 - 2(0.199 \times 20.10) = 115 \text{ volts}$$

(*e*) The currents I_{ef}, I_{gh}, and I_{km} are, respectively,

$$I_{ef} = 115/20 = 5.75 \text{ amp}$$

$$I_{gh} = 115/10 = 11.5 \text{ amp}$$

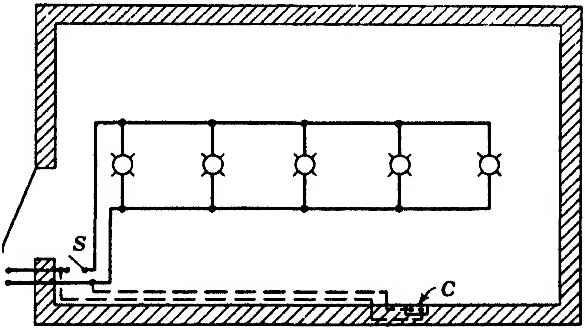
$$I_{km} = 115/40 = 2.88 \text{ amp}$$

Note that the total current I_{bc} is the sum of the three branch currents, i.e.,

$$I_{bc} = 5.75 + 11.5 + 2.88 = 20.13 \text{ amp}$$

This, of course, checks the value calculated in solution (*c*) above.

Lamps, resistors, and other electrical loads are usually connected in parallel, as shown in Fig. 9(*a*) and (*b*). Figure 9(*b*) shows the same devices as in (*a*) in a more practical way of making connections. The very small resistances between connections of each device (at c_1, c_2, c_3, etc.) are negligible.



Plan of room

Fig. 10. Schematic wiring plan of a single circuit to supply lamps in parallel, and connections to a plug outlet. Switch *S* controls the lamps. The plug outlet *C* is energized at all times.

A very common application of the parallel circuit is given in Fig. 10, showing the wiring diagram for a lamp circuit in a long room. There are five lamps connected in parallel across a given local circuit operated by a switch at the door. If each lamp takes 1 amp, the total current in the local branch circuit will be 5 amp. It is quite probable that another connection, shown by the dotted lines, would be run to a convenience outlet near the baseboard. If a toaster taking 7 amp should be plugged in, the branch circuit supplying the room would carry 5 + 7 = 12 amp. The convenience outlet would at all times be alive, but the lamps in this room would be controlled by one switch. Note that the lamps are in parallel with one another and that the convenience outlet (toaster) is in parallel with this group of lamps. The panelboard (Fig. 11) and its connections for a number of such circuits (as above) are all connected in parallel to the panelboard bus.

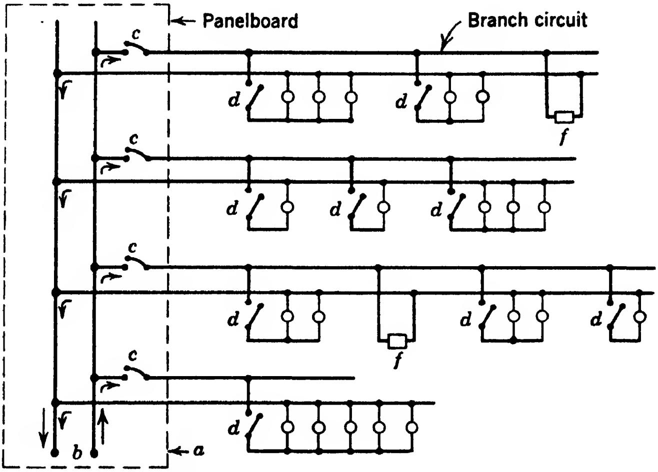


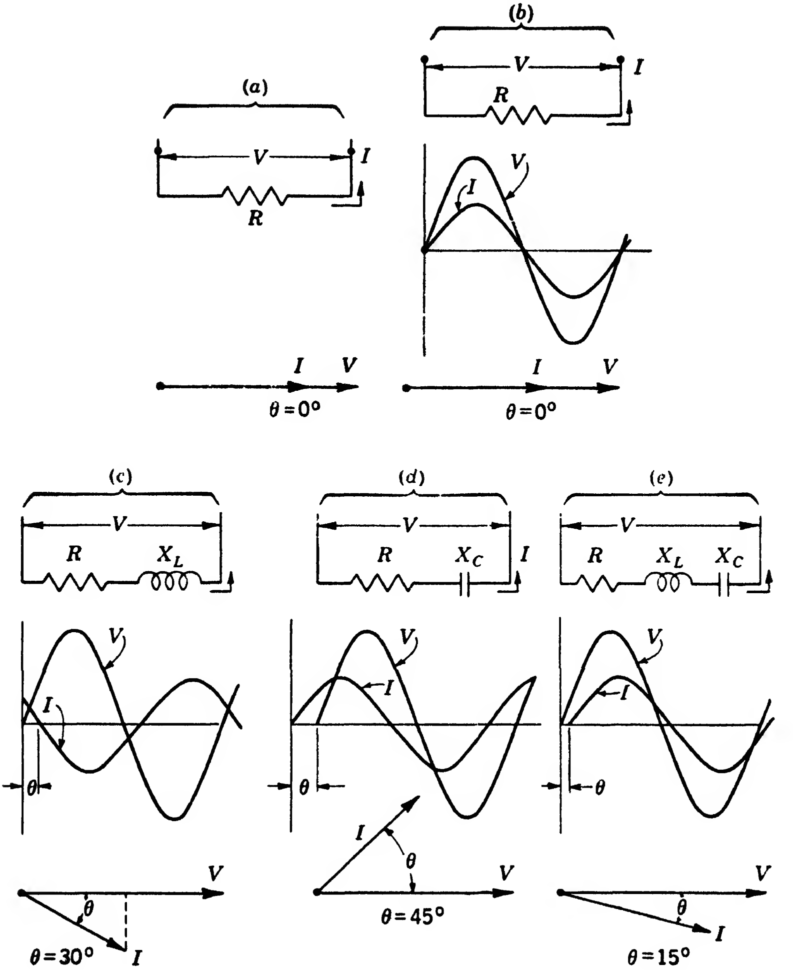
Fig. 11. Schematic d-c or a-c 2-wire panelboard (usually made of insulating asbestos or slate) on which are mounted the bus bars (*b*) and the single-pole overload trip switches (*c*). The four circuits shown (*d*) indicate the 2-wire branch circuits being supplied from the panelboard bus bars when the switches are closed. The switches (*d*) indicate local switches near the respective loads on the branch circuits. Plug outlets are designated by (*f*) and all lamps by circles.

13. Resistance, inductance, and capacitance. The relationships between voltage, current, and power in d-c circuits [Fig. 12(*a*)] has already been described in Art. 7 and Art. 8. The voltage and current vectors are in phase, and $W = VI$. However, in a-c circuits, which are the more commonly used, several new concepts must be introduced.

In an a-c circuit containing only resistance [Fig. 12(*b*)], the voltage and current rise and fall together and are said to be in phase. Here again, $W = VI$. In a circuit which has the property of inductance [Fig. 12(*c*)], the voltage and current are no longer in phase. The peak of current comes after (later than) the peak of voltage, and the current is said to *lag* the voltage. $W = VI \cos \theta$. These relationships may be represented by sine waves, by vectors, and by phase angles (θ), as shown in the figures.

Electrical appliances such as incandescent lamps, irons, or toasters may be considered as resistors. Such circuits may be treated in the same way as d-c circuits provided the effective values of voltage and current are used as described in Art. 10.

A-c motors and other a-c loads usually contain both resistance (R)



General a-c circuit equations for above circuits *a,b,c,d,e*

$$I = \frac{V}{Z} = \frac{V}{\sqrt{R^2+(X_L-X_C)^2}}$$

$$W = VI\cos\theta \qquad Z = \sqrt{R^2+(X_L-X_C)^2}$$

$$\cos\theta = \frac{W}{VI} \qquad \cos\theta = \frac{R}{Z}$$

Fig. 12. (*a*) A d-c circuit containing resistance R with the vectors V and I in phase: $W = VI = RI^2$. (*b*) An a-c circuit containing only resistance (R) with vectors V and I in phase: $W = VI = RI^2$. (*c*) An a-c circuit containing resistance (R) and inductive reactance (X_L), the latter causing I to lag V by an angle θ: $W = VI\cos\theta = RI^2$, $\cos\theta = W/VI$. (*d*) An a-c circuit containing resistance (R) and capacitative reactance (X_C), causing I to lead the voltage V by θ degrees:

and inductance [Fig. 12(*c*)]. The inductive reactance is represented by the symbol X_L and is expressed in ohms. In such a circuit the current lags the voltage by an angle θ, which depends on the relative magnitudes of the resistance and inductance in ohms.

A resistance and a capacitor load in series is represented in Fig. 12(*d*) with leading current. A typical series circuit containing R, X_L, and X_C as in (*e*) will have a power factor lagging the voltage or leading the voltage, depending upon the relative values of X_L and X_C. The capacitive reactance (X_C) is expressed in ohms. If X_L and X_C are equal in ohmic value the power factor is unity; if X_L is greater than X_C, then the current will lag; if X_C is greater than X_L, the current will lead. The working equations for these types of a-c series circuits are given in Fig. 12.

The term cos θ is known as the power factor (pf). It may vary from zero to 1.0. The usual power factors of such loads run from 0.75 to 0.95.[1]

Table II. Table of Trigonometric Functions *

A	*B*	*C*	*D*	*E*	*F*	*G*	*H*
$\theta°$	Sin	Cos	Tan	$\theta°$	Sin	Cos	Tan
0	0.000	1.000	0.000	50	0.766	0.643	1.192
5	0.087	0.996	0.087	55	0.819	0.574	1.428
10	0.174	0.985	0.176	60	0.866	0.500	1.732
15	0.259	0.966	0.268	65	0.906	0.423	2.145
20	0.342	0.940	0.364	70	0.940	0.342	2.748
25	0.423	0.906	0.466	75	0.966	0.259	3.732
30	0.500	0.866	0.577	80	0.985	0.174	5.671
35	0.574	0.819	0.700	85	0.996	0.087	11.430
40	0.643	0.766	0.839	90	1.000	0.000	......
45	0.707	0.707	1.000				

* Complete trigonometric functions may be obtained from any textbook on trigonometry.

$W = VI \cos\theta = RI^2$, $\cos\theta = W/VI$. (*e*) A circuit containing R, X_L, and X_C in which X_L is greater than X_C, thus causing vector I to lag V by θ degrees ···. All the sine waves of I and V have the same phase displacements (θ) as the vectors shown in (*a*, *b*, *c*, *d*, *e*) ···. The resultant impedance (Z) of any such a-c circuits as the above is always:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

from which it can be shown that

$$\cos\theta = R/Z$$

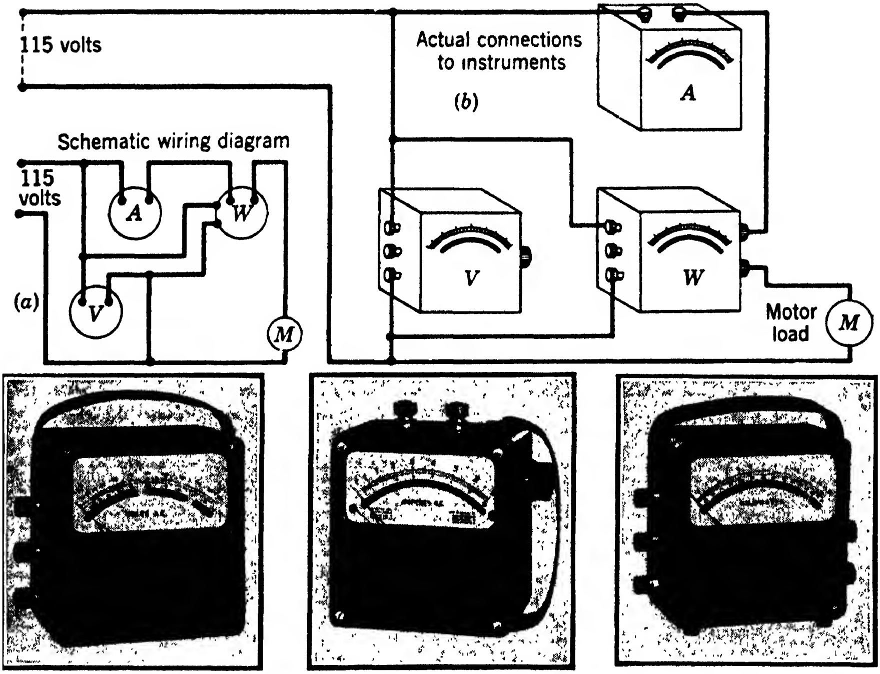
The values of R, X_L, X_C, and Z are expressed in ohms.

---

[1] Table II gives the values of cos θ, sin θ, and tan θ for values of θ from 0° to 90°.

It is most desirable that electrical equipment on a-c circuits operate at high power factors (0.85 to 0.95) for the following reasons: (Referring to equation $W = VI \cos \theta$) the desired watts input for the product $VI \cos \theta$ requires a high current if $\cos \theta$ is low; hence the larger current requires larger cables and generally increases the voltage drop in the cables. Also the conductors within a-c electrical machinery operating at low power factors (pf) cannot deliver the rated output in horsepower if the power factor is below that for which the motors are designed.

14. Measurement of circuit: volts, amperes, watts, and power factors. These a-c load readings may be measured by portable or switchboard instruments; the proper connections for the voltmeter, ammeter, and wattmeter are shown in Fig. 13. The load volts, amperes,



(c) (d) (e)

Fig. 13. Instruments and connections for measuring input (A, V, W, and $\cos \theta$) to an a-c (or d-c) motor: (*a*) the schematic diagram; (*b*) proper connections to the instruments; (*c*), (*d*), and (*e*) are reproductions of the instruments. The voltmeter (*c*) has two scales (150 and 300 volts); ammeter (*d*) two scales (5 and 10 amps); the wattmeter (*e*) two current (5 and 10 amps) and two potential scales (150 and 300 volts). Instrument accuracies are about one-half of 1 per cent of full-scale deflections.

and watts may be read directly from the instrument scales. For d-c circuits, similar instruments are available. For a-c circuits the power factor of the load is obtained by the simple equation

$$\text{Power factor} = \frac{\text{Watts}}{\text{Volts} \times \text{Amperes}} = \frac{W_L}{V_L I_L} \tag{16}$$

the subscripts (L) referring to the load.

Remember that cos θ is always unity (1) for d-c circuits. For a-c circuits the current may be in phase with the voltage, or lag or lead it. A load is called an inductive load if the current lags; a capacitive load if the current leads the voltage. Theoretically the power-factor angle (θ) may vary from 0 to 90°, lagging or leading.

15. Grounding for safety. For safety to life and property from damage which might develop through the breakdown of electrical insulation, certain parts of the electrical conducting system are grounded.

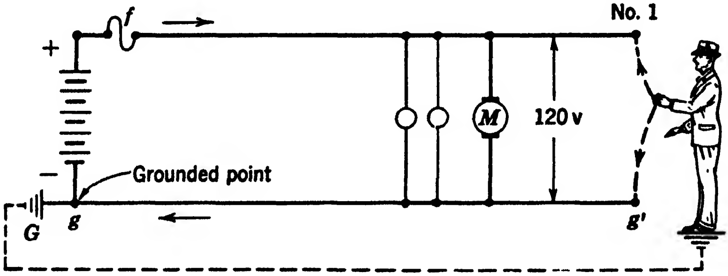


Fig. 14. When a 2-wire system is grounded at G, it is safe for a person in contact with the ground to touch wire g' but unsafe to touch wire No. 1.

The grounding of a system means the connection of a given conductor to another conductor which is in contact with the earth or ground. Such ground connections are frequently made to water and steam pipes, or to plates, rods, or pipes of copper buried or driven deep into the moist ground. In Fig. 14 a 2-wire system, receiving its voltage from a battery, the point g is connected to ground as shown by the symbol G. The wire g to g' will always be at ground potential, meaning that there will be no voltage between this wire and ground. In other words, if a person should be standing on the ground and should touch the wire g', he would receive no shock. Likewise there is no voltage strain across the insulation of this wire tending to make current flow to ground. If this system were not grounded it would be entirely possible for a person in contact with the ground to receive an electrical shock if he should touch either wire g' or wire 1. From wire 1 he would receive a shock of 120 volts even though the system were grounded. Likewise the insulation on this wire is under a strain of 120 volts. It should be noted, therefore, that the grounding of a system gives an added factor of safety, but it does not insure completely against electric shock, or against flow of current through breakdown of insulation.

Figure 15 shows a 3-wire system (Chapter 23, Art. 8) in which the middle or neutral wire *N* is grounded at point *G*. Between the two outside wires, 1 and 2, there is a potential of 240 volts, and between the neutral wire and each outside wire there is a potential of 120 volts. In this case a person standing on the ground would not receive a shock if he should touch the neutral wire at any point, such as *g′*. However, if he should touch either of the outside wires, 1 or 2, he would receive a shock of 120 volts. Likewise potential strains of 120 volts to ground are put on the insulation of wires 1 and 2, but there is no potential strain on the insulation of the neutral wire which is grounded. Now if an accidental ground, such as shown at *G′*, should occur on wire 2, owing to the breakdown of insulation on that wire, current would flow from *G* to *G′*. Likewise current would flow if any point of wire 1 should be grounded. No current would flow if any part of the neutral wire should become accidentally grounded. If a current flowing through an accidental ground is large enough to open the fuses (*f*) or circuit breakers in wires 1 or 2, these protective devices would open the grounded wire and thus protect the system. The opening of such a fuse would also prevent shock to anyone who should touch the grounded wire while this ground still exists.

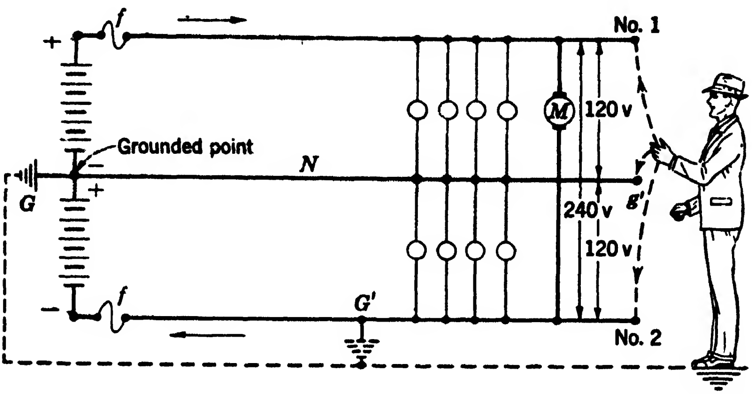


Fig. 15. When a 3-wire system is grounded at *G*, it is safe for a person in contact with the ground to touch wire *g′*, but unsafe to touch either wire No. 1 or No. 2.

Conduits, panelboard cabinets, and switchboard framework are all connected by copper wire to permanent grounds. If the conductor insulation should fail, allowing a nongrounded conductor to touch any of these grounded metal parts, as at *x*, Fig. 16, a circuit through the conduit to ground is established. Then a protective fuse (*f*) or circuit breaker is opened and the circuit becomes deenergized. If the conduit should not be grounded, any grounded person touching it would be subjected to shock. It is for this reason that the NEC requires the grounding of all such metal parts. Another protection afforded is that any high-voltage wire which might accidentally come in contact with a conduit system (or other grounded parts) would automatically discharge its current to ground.

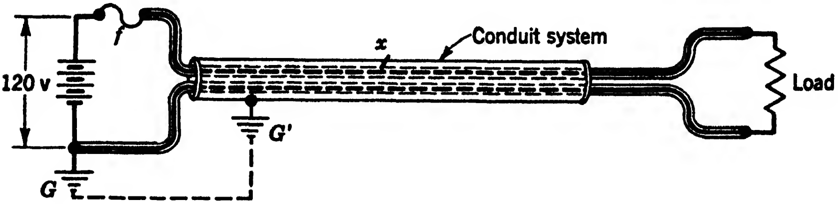


Fig. 16. Insulated electric wires are usually carried in metal conduits. These conduits are normally grounded (*G'*). If one of the wires is grounded (*G*) and another nongrounded wire has a break in the insulation (*x*) causing contact with the conduit, an abnormal current will flow from this wire to ground.

NEC CODE AND SUPPLEMENTARY TEXT REFERENCES

Appendix A NEC Items: A5, A6, A7, A8, A9, A10, A11, A73.
Appendix B Text Items: B1, B3.

PROBLEMS

1. (*a*) What is electricity? (*b*) What causes it to flow? (*c*) What will cause it to stop flowing? (*d*) How fast does it travel?

2. Define (*a*) volt; (*b*) ampere; (*c*) ohm. These are the three common units in d-c circuits.

3. Explain why the resistance of copper and many other metals increases as the temperature rises. Hint: The electrons move more rapidly, etc.?

4. Refer to Table I, p. 308. A No. 6, type RH, copper wire is 100 ft long and operating at 60°C with a current of 65 amp flowing. Determine (*a*) its resistance in ohms; (*b*) the voltage lost (called voltage drop) within the 100-ft length.

5. A 115-volt (d-c) hot water heater has a resistance of 5.75 ohms. (*a*) What current will it take at rated voltage? (*b*) If the voltage should be 5 per cent high (i.e., 1.05 × 115 volts), what current will then be required?

6. What power in watts (d-c) is necessary to operate the following devices whose resistances and currents are given: (*a*) a lamp of 44.2-ohms resistance requiring 2.6 amp; (*b*) a roasting oven of 7.67-ohms resistance requiring 15 amp?

7. A typical 6-room home may require the following usage of electrical equipment in 1 month: two 25-watt lamps for 115 hr; four 100-watt lamps for 120 hr; 350-watt refrigerator motor for 20 hr; 600-watt flatiron for 30 hr; and a 380-watt washing machine motor for 20 hr. Determine: (*a*) the total energy used for that month; (*b*) the monthly bill for electricity at 4.5 cents per kilowatt hour. Assume all loads are operating at unity power factor.

8. A 2-wire a-c motor draws from a 230-volt line 58 amp at a power factor of 0.866. Determine (*a*) the kw input; (*b*) the power-factor angle; and (*c*) show the vector diagram.

9. Convert (*a*) the circular mil area of a No. 0000 copper cable to the sq mil area of a copper strap one side of which is 3/16 in. wide.

10. Draw a diagram similar to Fig. 9 with $r_1 = 20$, $r_2 = 20$; $r_3 = 40$ ohms, and assume 120-volts between *c* and *d*, with r_{bc} and r_{da} each equal to 0.199 ohm. Determine (*a*) the voltage V_{ab} at the generator; (*b*) the total line current.

11. Referring to Fig. 6, the maximum value I_m of an a-c current is 17 amp. Determine: (*a*) the effective value *I*; (*b*) equivalent value of direct current?

12. Referring to Tables I and II (Chapter 23, pp. 334 and 335), tabulate the sizes of wire and sizes of conduit required for various circuits where appropriate current capacities, types of insulation, and of number of wires per conduit are given:

			Sizes for Problem 12		Sizes for Problem 13	
Current	Insulation	No.	Wire	Conduit	Wire	Conduit
215	R	3	....	....	....	....
45	RH	3	....	....	....	....
20	RH	5	....	....	....	....
270	AVB	3	....	....	....	....

13. The wires in Problem 12 are assumed to be operating in room temperatures of 20°C. If the room temperatures should average 40°C, how would you adjust the selections for Problem 12.

14. For the five a-c wiring diagrams of Fig. 13, assume that all values of $R = 5$ ohms, of $X_L = 5$ ohms, of $X_C = 5$ ohms; and that $V = 100$ volts. Determine (*a*) the currents; (*b*) the power factors ($\cos \theta$); and (*c*) draw the vector diagrams for each of the types of load.

15. Draw a schematic wiring diagram for measuring the volts, amperes, and watts of a two-wire a-c circuit, including proper connections for the instruments. (*a*) If the readings are $V = 120$, $I = 20$, and $W = 2400$, draw the vector diagram of *V* and *I* and state the power factor. (*b*) If the readings are $V = 120$, $I = 23.1$, and $W = 2400$, draw the vector diagram and state the power factor (assuming the load has both resistance and inductive reactance).

Chapter 23

DESIGN OF THE WIRING SYSTEM

1. Factors influencing the choice of a wiring system. The approximate nominal system voltages delivered at the service entrance for practically all interior and exterior use in domestic, public, commercial, and industrial buildings are 125, 240, 480, 600, 2400, 4160, and 13,800 volts. The corresponding nominal utilization equipment voltages are 120, 220, 440, 550, 2200, 4000, and 13,200 volts. When the utility voltages are nominally 2400, 4160, or 13,800 volts, step-down transformers are installed to reduce them to the lower values used in the building.

These voltages (125, 240, 480, 600, and 2400) are frequently referred to as secondary voltages since they are usually obtained from the secondary windings of utility companies' transformers. This standardization of utility service voltages enables manufacturers to design and mass-produce completely interchangeable electrical devices, such as lamps, household appliances, small and large motors, and standard heating elements for electric ranges.

Many factors should be considered prior to the selection of an appropriate wiring system. Some important considerations include:

(*a*) Analysis of the connected load.

(*b*) Probable future increases of connected load.

(*c*) Adoption of the most economical sizes of wire and cable.

(*d*) Selection of the proper types of insulation [see (*f*) below].

(*e*) Limitation of heat losses in the conductors.

(*f*) Local physical conditions (vibration, heat, cold, atmosphere, salt or acid conditions, wet or dry locations, excessive airborne materials) which may cause physical or chemical deterioration of the conduit, conduit fittings, insulation, and terminal contacts. These considerations, plus the circuit voltage, determine the type of insulation on conductors.

(*g*) Economic designs of the conduit or other wire race ways which enclose the conductors and appurtenances.

(*h*) Design and installation of the selected system in accord with the NEC and/or other federal, state, municipal, local, or utility requirements.

(*i*) Voltage drop on feeders from the main bus bars to the panelboards; and on branch circuits from panelboards to lamps, motors, and other loads (*j*) Accessibility of all electrical equipment for inspection, maintenance, and repair.

(*k*) Reservation of space for future locations of feeders, branch circuits, feeder breakers, panelboards, feeder conduits, connection boxes, etc.

(*l*) Enlargement of vertical wire shafts, space for horizontal runs of conduits, busways, and other wireways should be left for future electrical machinery, lighting, or other loads.

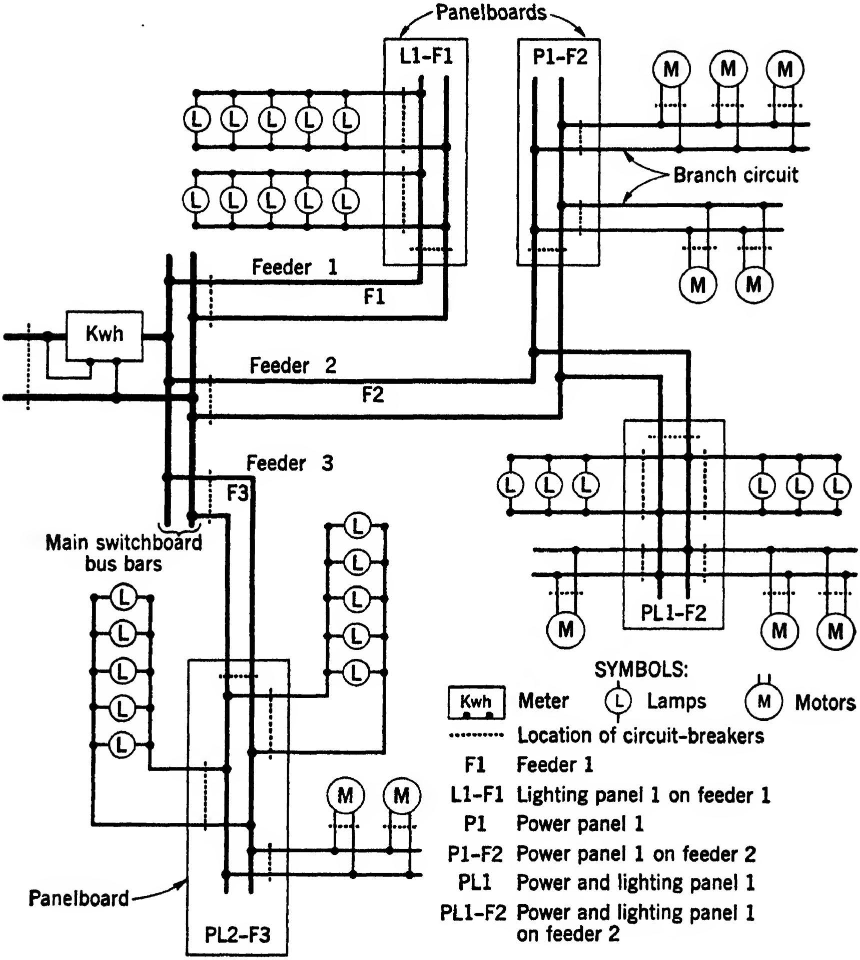
2. A complete 2-wire system. Figure 1 is a schematic diagram of the two conductors from the service entrance to various centers of electrical loads (lamps, motors, etc.). It is assumed that the service entrance cable and bus bars of the main switchboard are usually of the same current capacity; the outgoing feeder cables are selected of a smaller size to carry the estimated percentage of total current required for their average loads; the branch circuits likewise have still lower current capacity. In all 2-wire systems a reasonable degree of excess current ratings are allowed in all conductors to provide for future increases in load. The percentage increase might vary from 15 to 40 per cent.

3. Probability of future electrical loads. Present utility statistics indicate that total annual consumption is being doubled every 10 years. Although many factors influence the probability of increases above the present electrical load demands, the following percentages may be within reason up to a 10-year period from the present time:

Auditoria (convention halls, public halls, etc.)	30–60
Churches and other houses of worship	10–30
Clubs, lodge rooms, game rooms	30–60
Depots, waiting rooms, ticket offices	30–60
Domestic lighting and apartment lighting	30–80
Hospitals and other medical centers	20–80
Industrial buildings and industries	100–200
Libraries, reading rooms, drafting rooms	30–40
Night clubs and bars	20–50
Post offices	50–150
Public buildings (offices, clerical, general)	40–80
Railway stations, airports, and loading platforms	40–80
Schools and other places of study	40–80
Stores and commercial areas (first class)	50–100
Stores and commercial areas (second class)	20–50
Theaters, motion picture, and television auditoria	30–60

The above estimates include all applications: lighting, heating, motor loads, elevators, escalators, air conditioning, electrified business machines, assortments of new and improved plug-outlet devices, etc.

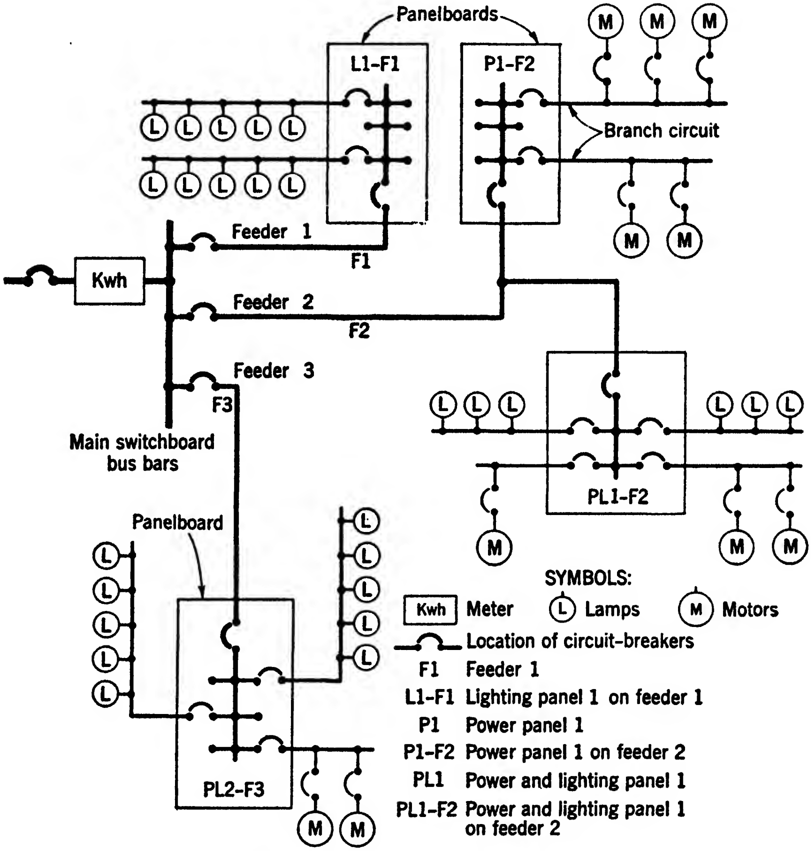
Provision for anticipated increases in power-consuming equipment must be provided for by reasonable increases in the initial sizes of feeders, subfeeders, and branch circuits, and by leaving space throughout the buildings for additional service transformers, switchgear, controlboards, panelboards, wire shafts, ducts, conduits, pull and connec-



Note: Circuit breakers (or fuses) progressively decrease in ampere rating as the wire sizes decrease

Fig. 1. A 2-wire system (d-c or a-c) is shown. The sizes of conductors and circuit breakers (or fuses) of typical feeders and branch circuits progressively decrease as the corresponding currents demanded by the loads decrease. The locations of these circuit breakers or fuses are shown by dotted lines ....

tion boxes, and underfloor duct systems. It is obvious that accurate forecasting of such matters cannot be achieved. It is considered reasonable and prudent, however, to allow 15 to 40 per cent extra space for feeder breakers at the service bus location, and also 15 to 40 per cent of spare space for panelboard branch circuit breakers or fuses. Panelboards are so designed that future breakers may be purchased and in-



Note: Circuit breakers (or fuses) progressively decrease in ampere rating as the wire sizes decrease

Fig. 2. A simplified diagram called a single-line diagram, of the above 2-wire system. Such a single-line diagram is used for any 2-wire, 3-wire, or 4-wire system. Such single-line wiring plans save a large proportion of drafting time and expense.

stalled as needed, but the bus bars and future breaker terminals must be ordered with the original panel and panelboard cabinet. Provision can readily be made in the initial specifications for adding future feeder breaker units to the main service bus bars. Considerable attention should be given to these future load questions when architects, engineers, and their clients are concerned with the planning and design of the project.

When a well-designed wiring system, for the above conditions, is first installed, the voltage drops in all conductors will be well under 5 per cent. Later, when allowable full-load currents have been reached for the various conductors and breakers, new circuits must be designed and installed.

4. Higher voltages for large buildings. For practically all domestic uses, apparatus ratings are limited to 120 volts, except for electric ranges and some air-conditioning equipment, which frequently requires 240 volts. For large buildings the voltage rating of all lamps, convenience outlets, and other devices available to the occupant or general public is 120 to 240 volts, but for operation of mechanical equipment such as elevators, pumps, fans, and escalators, the wiring systems are usually designed to deliver at the load terminals either 220 or 440 volts. It is customary to refer to the *rated terminal voltages* of lamps, motors, and other loads as 120 v, 220 v, 440 v, 2200 v, etc. It should be understood that these vary from these rated values owing to variations in voltage drop as the loads change or when loads are connected or disconnected from the branch circuits.

When exceptionally large buildings are under design it is desirable to consider the advantages of voltages higher than 440, if large blocks of power must be transmitted to electrical load centers distant from the point where electric service enters, or if the generating equipment is to be located in the building. With utilization voltages of 220, 440, and higher, exceptional care must be taken to protect operators and building workers from the danger of shock due to contact with exposed parts or failure of insulation. Such safeguards take the form of fireproofed ducts and conduits, locks on all transformer rooms, high-voltage switch enclosures, wire shafts, and metal screens around starting equipment. High-voltage motors (440 to 4160 v) are usually controlled by remote-control circuits excited at only 120 volts. High-voltage apparatus and wiring present no unusual problems or hazards since adequate engineering design, materials, methods, and NEC rules of installation provide against risks to experienced operators and maintenance men.

5. Elements of a simple wiring system. A *wiring system* for a building embraces all electrical conducting channels (wires), with all necessary auxiliaries from the point of service, or source, to every power-consuming device installed. (See Fig. 1, p. 328.) When a public utility furnishes power, the point of delivery is called the *service entrance*. Here the main service wires connect to the service switch and metering equipment, and then continue to the main switchboard. At this location the service wires terminate on heavy conductors, called bus bars, which usually run the full length of the switchboard. A number of heavy wire circuits, called *feeder circuits* or feeders, are connected to the bus bars through circuit breakers on the front of the switchboard. These feeders carry large blocks of power to various centers of electrical load. At these load centers the feeder terminates at a panelboard. The *panelboard* is really a lower-capacity switchboard from which a group of other *subfeeders* of smaller wire further subdivide or distribute the power from the main feeder to still smaller local panelboards. These are designated as subpanelboards. Both panelboards and subpanelboards, through small-capacity wires, called *local branch circuits* or local branches, deliver energy directly to motors and lamps. In many respects the system may be likened to a large tree with its trunk, limbs, and branches. In small buildings, such as homes, Fig. 3, there may be only the entrance switch, the meter, and one feeder to a local panelboard from which only four to six branches radiate to the lamp outlets and plug outlets. Accessory equipment for the wiring system is described in Chapter 24.

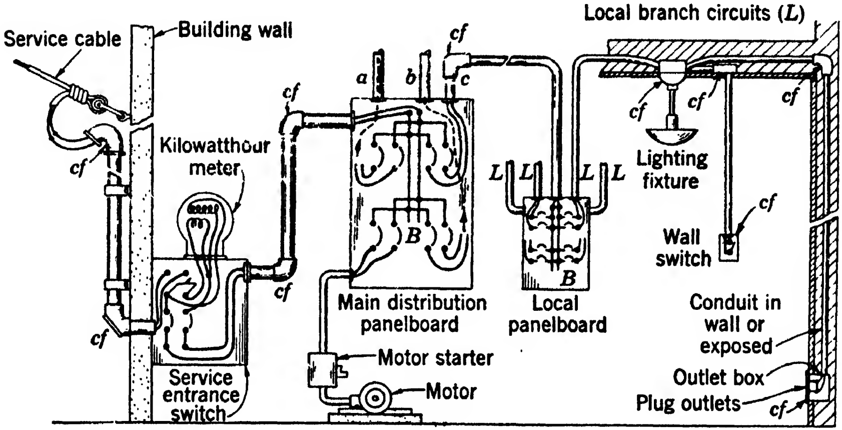


Fig. 3. Schematic wiring diagram of a typical small home 2-wire system: *cf* indicates conduit fittings; *abc*, conduits for outgoing feeders; *L*, conduits for outgoing local branch circuits; *B*, bus bars of the main distribution and local panelboards.

A typical 2-wire system (d-c or a-c) was illustrated in Fig. 1. The arrangements shown are partially schematic with the principal parts and conductors properly connected. Articles 8 and 9 describe and compare eight commonly used electrical systems of distribution. It will be seen that these systems require either 2-, 3-, or 4-wire conductors. It is common practice to draw single-line diagrams (Fig. 2) for any one of these systems. For example, an a-c 3-wire single-phase $^{120}/_{240}$-volt feeder or branch circuit would be identified by a single line on the wiring diagram. The simplification of drafting and drafting expense is obvious.

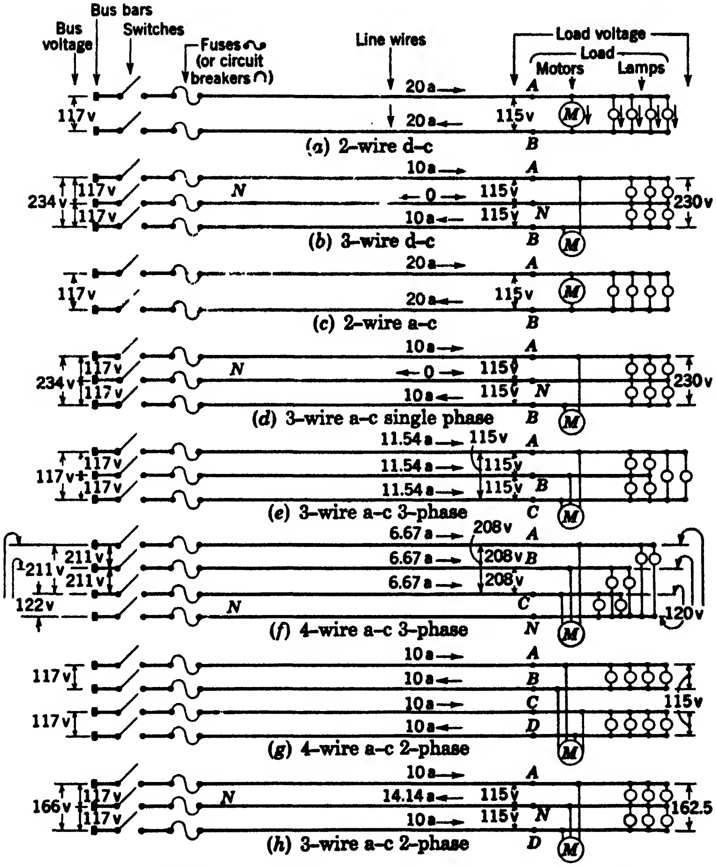
The size, or cross section, of any conductor (solid wires, cables, or bus bars) is always determined by the current to be carried by it under the estimated sustained maximum loads (referred to as the maximum demand) with conductor temperatures limited to the allowable NEC values. Likewise the accessory equipment, such as circuit breakers, fuses, switches, and even the lugs and terminals, are selected at current and voltage ratings equal to or greater than that of the circuit conductors.

6. Wire tables. Table I gives the safe current-carrying capacity of insulated conductors for various insulations based on room temperatures of 30°C (86°F), and other wire data. Table II gives the sizes of conduits rated to carry a given number of conductors of code size. These data are reproduced and amplified in NEC. The indicated correction factors must be used for ambient temperatures over 30°C (86°F).

7. Alternating-current vs. direct-current distribution. Probably 95 per cent of all electrical power is transmitted and distributed in this country by a-c systems. The reasons for this are that a-c power may be economically transmitted at high voltages; the voltages may be raised or lowered through transformers at either or both ends of the line; a-c is much cheaper and more rugged than d-c machinery, and the wiring systems available are more flexible for the proper balancing of load between respective wires of the system. Direct-current generation, distribution, and use are confined largely to certain variable-speed motor applications, to industrial chemical processes, and to municipal street railways and a few main-line railways. It is seldom used in domestic, office, or commercial buildings, although a certain section of New York City is still using d-c service. In all high-class passenger elevator installations direct current is used to operate the motor-driven elevator machines because of ease of control, smooth acceleration, and retardation, and availability of all speeds from zero to the maximum elevator rating.

Several methods are available for changing or converting a-c into d-c energy. The common methods are by motor-generator (m-g) sets, by synchronous converters, and by mercury-arc, vacuum-tube, and oxide-film rectifiers. It is not within the scope of this book to explain this apparatus. In buildings the most common application of such units is in motor-generator sets for elevator operation, for large business machines, and for charging storage batteries. (See Chapter 29 on elevators and Chapter 25, Art. 7, on storage batteries.)

D-c systems are not in common use in building installations above 240 to 500 volts. Hence, wherever direct current is used it will, in all probability, be about 115 volts or 230 volts. On the other hand, alternating currents at 120, 208, and 440 volts are commonly used. The 208-volt system is usually a 4-wire 3-phase a-c system as shown in (*f*) of Fig. 4. It supplies 120 volts single-phase between any outside wire (such as *A*, *B*, or *C*) and the neutral wire (*N*); 208 volts single-phase



(*a*) 2-wire d-c

(*b*) 3-wire d-c

(*c*) 2-wire a-c

(*d*) 3-wire a-c single phase

(*e*) 3-wire a-c 3-phase

(*f*) 4-wire a-c 3-phase

(*g*) 4-wire a-c 2-phase

(*h*) 3-wire a-c 2-phase

Fig. 4. Schematic diagrams of distribution systems for commercial, industrial, office, public, private, government and residential buildings. The neutral wire (*N*), always grounded, is usually installed without a fuse or circuit breaker and loads balanced between phase wires *A*, *B*, *C*, *D* and neutral.

between any two of the outside wires, i.e., between *A* and *B*, *B* and *C*, and *C* and *A*; and 208 volts, three-phase, between *A*, *B*, and *C*.

The higher voltages, with attendant lower currents, require much less expenditure for all electrical equipment, especially for conductors, switches, circuit breakers, conduits, and fittings. Installation labor and maintenance expense is obviously less costly. The flexibility of load balancing also lowers costs for materials and labor.

Table I. Allowable Current-Carrying Capacities of Insulated Conductors in Amperes (1953 National Electrical Code)

Not More Than Three Conductors in Raceway or Cable or Direct Burial
[Based on Room Temperature of 30°C (86°F)]

A	*B*	*C* *	*D* *	*E*	*F*	*G*	*H*	*I*	*J*	*K* *
Wire Size, American Standard Wire Gauge	Area (circular mils)	Resistance per Conductor in Code Size Conduit in ohms per 1000 ft at 60°C (140°F) (ohms)	Reactance per Conductor in Code Size Conduit in ohms per 1000 ft at 60 cycles per second (ohms)	Rubber Type R Type RW Type RU Type RUW (14-2) Thermoplastic Type T Type TW Type RH-RW	Rubber Type RH Type RH-RW Type RHW	Paper Thermoplastic Asbestos Type TA Var-Cam Type V Asbestos Var-Cam Type AVB MI Cable	Asbestos Var-Cam Type AVA Type AVL	Impregnated Asbestos Type AI (14-8) Type AIA	Asbestos Type A (14-8) Type AA	Approximate Correction Factors for Conductors in Free Air (Multiply by:)
14	4,107	2.92	......	15	15	25	30	30	30	1.20
12	6,530	1.83	......	20	20	30	35	40	40	1.40
10	10,380	1.16	......	30	30	40	45	50	55	1.40
8	16,510	0.725	0.0358	40	45	50	60	65	70	1.45
6	26,250	0.465	0.0336	55	65	70	80	85	95	1.50
4	41,740	0.292	0.0318	70	85	90	105	115	120	1.55
3	52,630	0.232	0.0305	80	100	105	120	130	145	1.55
2	66,370	0.184	0.0299	95	115	120	135	145	165	1.55
1	83,690	0.146	0.0305	110	130	140	160	170	190	1.55
0	105,500	0.1158	0.0297	125	150	155	190	200	225	1.55
00	133,100	0.0918	0.0290	145	175	185	215	230	250	1.55
000	167,800	0.0728	0.0281	165	200	210	245	265	285	1.55
0000	211,600	0.0577	0.0276	195	230	235	275	310	340	1.55
	250,000	0.0489	0.0282	215	255	270	315	335	...	1.55
	300,000	0.0407	0.0276	240	285	300	345	380	...	1.55
	350,000	0.0349	0.0271	260	310	325	390	420	...	1.55
	400,000	0.0305	0.0269	280	335	360	420	450	...	1.60
	500,000	0.0244	0.0264	320	380	405	470	500	...	1.60
	600,000	0.0203	0.0268	355	420	455	525	545	...	1.60
	700,000	0.0175	0.0264	385	460	490	560	600	...	1.60
	750,000	0.0163	0.0263	400	475	500	580	620	...	1.65
	800,000	0.0153	0.0262	410	490	515	600	640	...	1.65
	900,000	0.0135	0.0258	435	520	555	...	...	...	1.65
	1,000,000	0.0122	0.0262	455	545	585	680	730	...	1.70
	1,250,000	0.00976	0.0258	495	590	645	...	...	...	1.70
	1,500,000	0.00814	0.0255	520	625	700	785	...	...	1.85
	1,750,000	0.00697	0.0252	545	650	735	...	...	...	1.85
	2,000,000	0.00610	0.0250	560	665	775	840	...	...	2.05

Correction Factor for Room Temperatures over 30°C (86°F) for All Currents in Columns *E*, *F*, *G*, *H*, *I*, *J*

C°	F°	*E*	*F*	*G*	*H*	*I*	*J*
40	104	0.82	0.88	0.90	0.94	0.95	....
45	113	0.71	0.82	0.85	0.90	0.92	....
50	122	0.58	0.75	0.80	0.87	0.89	....
55	131	0.41	0.67	0.74	0.83	0.86	....
60	140	....	0.58	0.67	0.79	0.83	0.91
70	158	....	0.35	0.52	0.71	0.76	0.87
75	167	....	....	0.43	0.66	0.72	0.86
80	176	....	....	0.30	0.61	0.69	0.84
90	194	....	....	....	0.50	0.61	0.80
100	212	....	....	....	....	0.51	0.77
120	248	....	....	....	....	....	0.69
140	284	....	....	....	....	....	0.59

* Columns *C* and *D* are added by the author for convenience of voltage-drop calculations, and *K* for approximate calculations of higher current capacities for conductors in free air.

Table II. Number of Conductors in Conduit or Tubing (1953 NEC)
Rubber Covered, Types RF-2, RFH-2, R, RH, RW, RH-RW, RU, RUH, and RUW. Thermoplastic, Types TF, T and TW One to Nine Conductors
For more than nine conductors see NEC, Table 9.
(See sections 3013, 3466, and 3486)

Size, AWG MCM	Number of Conductors in One Conduit or Tubing								
	1	2	3	4	5	6	7	8	9
18	½	½	½	½	½	½	½	¾	¾
16	½	½	½	½	½	½	¾	¾	¾
14	½	½	½	½	¾	¾	1	1	1
12	½	½	½	¾	¾	1	1	1	1¼
10	½	¾	¾	¾	1	1	1	1¼	1¼
8	½	¾	¾	1	1¼	1¼	1¼	1½	1½
6	½	1	1	1¼	1½	1½	2	2	2
4	½	1¼	1¼	1½	1½	2	2	2	2½
3	¾	1¼	1¼	1½	2	2	2	2½	2½
2	¾	1¼	1¼	2	2	2	2½	2½	2½
1	¾	1½	1½	2	2½	2½	2½	3	3
0	1	1½	2	2	2½	2½	3	3	3
00	1	2	2	2½	2½	3	3	3	3½
000	1	2	2	2½	3	3	3	3½	3½
0000	1¼	2	2½	3	3	3	3½	3½	4
250	1¼	2½	2½	3	3	3½	4	4	5
300	1¼	2½	2½	3	3½	4	4	5	5
350	1¼	3	3	3½	3½	4	5	5	5
400	1½	3	3	3½	4	4	5	5	5
500	1½	3	3	3½	4	5	5	5	6
600	2	3½	3½	4	5	5	6	6	6
700	2	3½	3½	5	5	5	6	6	...
750	2	3½	3½	5	5	6	6	6	...
800	2	3½	4	5	5	6	6	...	...
900	2	4	4	5	6	6	6	...	...
1000	2	4	4	5	6	6	...	...	...
1250	2½	5	5	6	6	...	...	...	...
1500	3	5	5	6	...	...	...	...	...
1750	3	5	6	6	...	...	...	...	...
2000	3	6	6	...	...	...	...	...	...

8. Outline of systems. Eight systems of wiring largely cover the entire field of d-c and a-c distribution within buildings. The basic wiring diagram for each system is shown in Fig. 4. The systems are designated as follows:

(*a*) 2-wire system	for d-c service
(*b*) 3-wire system (sometimes called "Edison")	for d-c service
(*c*) 2-wire system	for a-c service
(*d*) 3-wire single-phase system	for a-c service
(*e*) 3-wire 3-phase system	for a-c service
(*f*) 4-wire 3-phase system	for a-c service
(*g*) 4-wire 2-phase system	for a-c service
(*h*) 3-wire 2-phase system	for a-c service

Residences, bungalows, stores, and other small domestic or commercial loads are usually served by systems (*a*), (*b*), (*c*), or (*d*). Systems (*e*) and (*f*) are frequently chosen for large stores, public buildings, office buildings, and factories. In communities where two-phase power is used (these are becoming less common), systems (*g*) and (*h*) are adopted for large commercial installations. It is common practice to utilize one system in one portion of a given building wiring scheme and to branch out from this system with another. Figure 5 shows system (*b*) on a feeder and system (*a*) on two branch circuits.

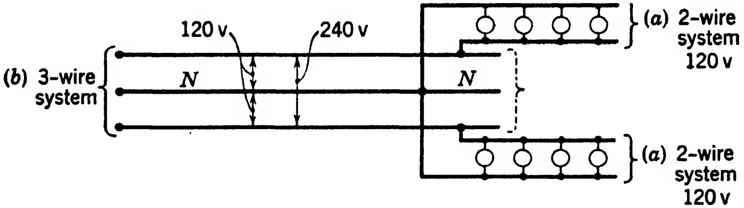


Fig. 5. Typical 3-wire 120/240-volt system (*b*) supplying two 2-wire 120-volt branch circuits (*a*).

Figure 6 shows a wiring plan using a 4-wire 3-phase (*f*) system; a 2-wire 1-phase branch (*c*) system; a 3-wire 1-phase branch (*d*) system; and a 3-wire 3-phase branch (*e*) system. The 4-wire system (*f*) is a favorite wiring scheme for large modern offices and public buildings. The feeders are usually designed (*f*), the power branches (*e*), heavily loaded lighting branches (*d*), and lightly loaded branches (*c*). Any number of such branches may be tapped off the 4-wire feeder, until its current capacity is reached. The average balanced-current loads on the three live wires (*A*, *B*, and *C*) should be attained in practice. It should be realized that short-time unbalance of loads on any system are to be expected, but the average degree of unbalance in a given feeder will not be a large portion of the total load if the designer has properly proportioned the connected devices (lamps, motors, heating equipment, etc.).

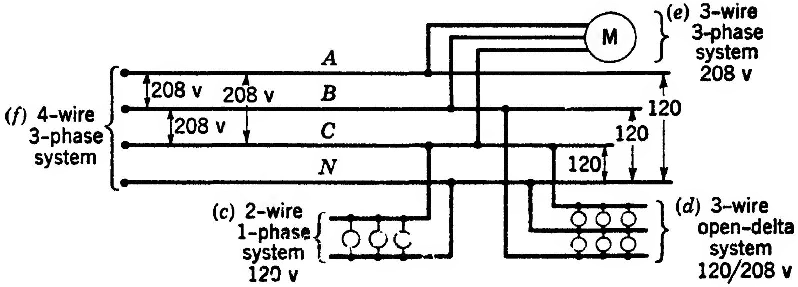


Fig. 6. A 4-wire, 3-phase system (*f*) supplying single-phase (*c*), 3-phase (*e*) branch circuits, and 3-wire open-delta system (*d*).

9. Comparison of wiring systems. For any given load and for a constant percentage loss in the line wires, the size of copper required for any system of distribution varies inversely as the squares of the system voltage. For example, any system operating at 230 volts (for a given power and line loss) will require only one-fourth the cross section of wire necessary for the same system operating at 115 volts. This may be expressed

$$\frac{\text{Required weight of copper at } V_1}{\text{Required weight of copper at } V_2} = \frac{V_2^2}{V_1^2}$$

when V_2 is greater than V_1. This formula justifies the use of high-voltage installations where other factors are not of greater importance.

The two-wire circuits of Fig. 4(*a*) and (*c*) are the most elementary of all systems. Practically all lamp outlets, plug outlets, and small motor loads are served by two-wire circuits. Two-wire branches, therefore, radiate from the panelboards of nearly all systems, irrespective of the number of wires feeding the panelboards. In very small buildings, such as small homes, the two-wire system alone is justified, since the economies of three-wire and four-wire systems depend upon larger electrical loads requiring heavier conductors (feeders) and longer distances to points of distribution. The power delivered to the load is

$$W = VI, \text{ for d-c} \quad \text{and} \quad W = VI \cos \theta, \text{ for a-c} \qquad (1)$$

where V is the voltage from A to B, and cos θ is the power factor of the a-c load. [See Chapter 22, p. 320, and Fig. 13, p. 321.]

The three-wire systems of Fig. 3(*b*) and (*d*) are exactly similar for d-c and for a-c single-phase distribution. These systems are said to be balanced when they are loaded with equal electrical loads (in amperes) between the outer wire A and neutral wire N, and between outer wire B and neutral wire N. When so balanced, no current will flow in the neutral N. Hence, for a given total balanced load, the entire power is distributed at double the rated voltage of the connected devices, thus requiring wire of one-quarter the size of the two-wire system. The neutral wire carries no current. If the load becomes unbalanced, some current will flow in the neutral wire, but the voltage across each part of the load will remain practically the same. In practice the loads are so connected that, by virtue of the expectation of their coincident use, they will be closely balanced. Since three wires of equal size are required, the saving in copper is not in the ratio of 1 to 4 over the two-wire lower-voltage system, but instead

$$\frac{1}{4} \times \frac{3}{2} = \frac{3}{8} = \frac{0.375}{1}$$

The power delivered to the load of a three-wire single-phase balanced system is

$$W = VI,\ \text{for d-c} \quad \text{and} \quad W = VI \cos \theta,\ \text{for a-c single-phase}$$

where V is the voltage from A to B, and $\cos \theta$ is the power factor of the a-c load.

The 3-wire 3-phase system of Fig. 4(e) is an a-c circuit having equal voltages between any two of the line wires, A, B, C. The load should be carefully balanced so that equal power is delivered to the total of all devices connected between any two wires A, B, C; i.e., the three respective loads should be equal in wattage. It is not difficult to approximate this in practice. All devices must have the same voltage rating. The power delivered to the load is

$$W = 1.73 VI \cos \theta \tag{2}$$

where V is the voltage between any two line wires, and $\cos \theta$ is the power factor of the load. Lamps may be connected across any two wires; motors are usually rated for 3-phase operation and connected to all three wires.

The 4-wire 3-phase a-c system of Fig. 4(f) is similar to the 3-wire system in that the loads are balanced, the voltages between any two wires A, B, C are equal, and the power equation is the same.

$$W = 1.73 VI \cos \theta \tag{3}$$

However, the voltages between any wire and the neutral, such as voltages A to N, B to N, and C to N, are equal to each other, and are less than the line-to-line voltage V by the ratio

$$\frac{V_{AN}}{V_{AB}} = \frac{1}{1.73} = \frac{0.577}{1}$$

For example, for the system shown in (f), if the voltages A to B,

Table III. Current and Wattage Relations for Various Types of Circuits (Assuming Balanced Loads); Also the Applicable Formulae

Amperes for voltages indicated. (All a-c loads assumed at unity power factor) *

Watts Load per Circuit (All a-c loads assumed at unity power factor)	D-C 2-Wire		D-C † 3-Wire	A-C 2-Wire 1-Phase		A-C † 3-Wire 1-Phase	A-C 3-Wire 3-Phase		A-C † 4-Wire 3-Phase		A-C 4-Wire 2-Phase		A-C ‡ 3-Wire 2-Phase	
	System (*a*)		(*b*)	(*c*)		(*d*)	(*e*)		(*f*)		(*g*)		(*h*)	
	115 v	230 v	115–230 v	115 v	230 v	115–230 v	115 v	230 v	115 v	230 v	115 v	230 v	115 v	230 v
100	0.87	0.435	0.44	0.87	0.435	0.44	0.50	0.25	0.50	0.25	0.435	0.22	0.435	0.22
200	1.74	0.87	0.87	1.74	0.87	0.87	1.00	0.50	1.00	0.50	0.87	0.43	0.87	0.43
500	4.35	2.17	2.17	4.35	2.17	2.17	2.5	1.25	2.5	1.25	2.17	1.09	2.17	1.09
1,000	8.7	4.35	4.35	8.7	4.35	4.35	5.0	2.5	5.0	2.5	4.35	2.17	4.35	2.17
2,000	17.4	8.7	8.70	17.4	8.7	8.70	10.0	5.0	10.0	5.0	8.7	4.3	8.7	4.3
5,000	43.5	21.7	21.70	43.5	21.7	21.70	25.0	12.5	25.0	12.5	21.7	10.9	21.7	10.9
10,000	87.0	43.5	43.50	87.0	43.5	43.50	50.0	25.0	50.0	25.0	43.5	21.7	43.5	21.7
20,000	174.0	87.0	87.00	174.0	87.0	87.00	100.0	50.0	100.0	50.0	87.0	43.5	87.0	43.5
50,000	435.0	217.5	217.50	435.0	217.5	217.50	250.0	125.0	250.0	125.0	217.5	109.0	217.5	109.0
100,000	870.0	435.0	435.00	870.0	435.0	435.00	500.0	250.0	500.0	250.0	435.0	217.0	435.0	217.0
Line current	$I = \frac{W}{V}$		$I = \frac{W}{2V}$	$I = \frac{W}{V}$		$I = \frac{W}{2V}$	$I = \frac{W}{1.73V}$		$I = \frac{W}{1.73V}$		$I = \frac{W}{2V}$		$I = \frac{W}{2V}$	
Line drop in volts	$v = 2rI$		$v = 2rI$	$v = 2rI$ §		$v = 2rI$ §	$v = 1.73rI$ §		$v = 1.73rI$ §		$v = 2rI$ §		$v = 1.7rI$ §	
Watt loss in all line wires	$w = 2rI^2$		$w = 2rI^2$ §	$w = 2rI^2$		$w = 2rI^2$	$w = 3rI^2$ §		$w = 3rI^2$ §		$w = 4rI^2$		$w = 4rI^2$	

* For a power factor lower than 1.0 increase the amperes above by dividing the given values by the power factor expressed as a decimal fraction. *Example:* Under system (*e*) for 1000 watts at 0.8 pf, 230 v, $I = 2.5/0.8 = 3.125$ amperes.

† The current in the neutral wire is zero for balanced loads.

‡ To obtain the current in the center or neutral wire, multiply these table values by 1.41.

§ These are approximate formulae for the sake of simplicity.

r = ohms total resistance of one wire carrying current, V = volts at the load, v = volts line drop, W = watts at the load, w = watts line loss, I = line amperes.

B to *C*, and *C* to *A* are 208 volts, the voltages *A* to *N*, *B* to *N*, and *C* to *N* will be

$$0.577 \times 208 = 120 \text{ volts}$$

For this reason it is referred to as a 120/208-volt 4-wire 3-phase circuit. The neutral wire *N* is effective in maintaining practically balanced voltages across the loads if the loads become unbalanced. The neutral also provides facility for connecting devices of two different standard voltage ratings: for example, 120-volt lamps and 208-volt 3-phase motors. The latter are connected across the three outside wires *A*, *B*, *C*.

The 4-wire a-c 2-phase system of distribution of Fig. 4(*g*) really is closely related in design and use to two 2-wire single-phase systems. Lamp loads are balanced on phase *AB* and phase *CD*, and 2-phase motors are connected by four wires to line wires *AB* and *CD*. The system provides only one nominal voltage to both lamps and motors. It requires four wires of equal size. It is not in common use, although a few large cities are still receiving such service. The power input to a balanced load is

$$W = 2VI \cos \theta \tag{4}$$

where *V* is the voltage across *AB* and across *CD*.

The 3-wire 2-phase a-c system of Fig. 4(*h*) is obtained merely by combining wires *B* and *C* of system (*g*), above, into one conductor of a size equal to 1.43 times the size of the outer wires *A* and *D*. The (larger) center wire is called the neutral *N*. The loads between *AN* and *DN* are balanced, and lamps and motors are connected as shown. The voltages *AN* and *DN* are equal; and the voltage ratings of both lamps and motors are equal. This system, like system (*g*), is seldom used.

The amperes per line wire for each of these systems, for a given balanced load and at various voltages, are shown in Table III. From this table it is a simple matter to make comparisons between the systems.

For example, compare the currents required if 1000 watts is to be distributed at 230 volts by the a-c 2-wire system (*c*) or by the a-c 3-wire 3-phase system (*e*). System (*c*) requires 4.35 amp, system (*e*) 2.5 amp, per line wire. Now in transmitting this same load at 115 volts, by the same systems, each current would be twice its former value: 8.7 and 5.0 amp, respectively. After the system voltage, *V* is selected, the line current *I* can be calculated for a given load in watts. Then, allowing a reasonable line drop in volts *v*, the line wire resistance *r* may be calculated. All the formulae for these calculations are summarized at the bottom of the table.

10. Wiring symbols and diagrams. On the plans for a given electrical installation, the wiring diagram should give complete informa-

Table IV

Ceiling	Wall	General Outlets *
○	-○	Outlet
Ⓑ	-Ⓑ	Blanked outlet
Ⓓ		Drop cord
Ⓔ	-Ⓔ	Electric outlet; for use only when circle used alone might be confused with columns, plumbing symbols, etc.
Ⓕ	-Ⓕ	Fan outlet
Ⓙ	-Ⓙ	Junction box
Ⓛ	-Ⓛ	Lamp holder
Ⓛ$_{PS}$	-Ⓛ$_{PS}$	Lamp holder with pull switch
Ⓢ	-Ⓢ	Pull switch
Ⓥ	-Ⓥ	Outlet for vapor discharge lamp
Ⓧ	-Ⓧ	Exit light outlet
Ⓒ	-Ⓒ	Clock outlet (specify voltage)

	Convenience Outlets
=⊖	Duplex convenience outlet
=⊖$_{1,3}$	Convenience outlet other than duplex. 1 = single, 3 = triplex etc.
=⊖$_{WP}$	Weatherproof convenience outlet
≡⊖$_{R}$	Range outlet
=⊖$_{S}$	Switch and convenience outlet
=⊖-🅁	Radio and convenience outlet
▲	Special purpose outlet *
⊙	Floor outlet

	Switch Outlets
S	Single-pole switch
S_2	Double-pole switch
S_3	Three-way switch
S_4	Four-way switch
S_D	Automatic door switch
S_E	Electrolier switch
S_K	Key-operated switch
S_P	Switch and pilot lamp
S_{CB}	Circuit breaker
S_{WCB}	Weatherproof circuit breaker
S_{MC}	Momentary contact switch
S_{RC}	Remote control switch
S_{WP}	Weatherproof switch
S_F	Fused switch
S_{WF}	Weatherproof fused switch

	Special Outlets *
○$_{a,b,c,etc}$ =⊖$_{a,b,c,etc}$ $S_{a,b,c,etc}$	Any standard symbol as given above with the addition of a lower case subscript letter may be used to designate some special variation of standard equipment of particular interest in a specific set of architectural plans. When used they must be listed in the key of symbols on each drawing and if necessary further described in the specifications.

Table IV (Continued)

Symbols	Panels, Circuits, and Miscellaneous
■	Lighting panel
▨	Power panel
——	Branch circuit; concealed in ceiling or wall
— —	Branch circuit; concealed in floor
- - - -	Branch circuit; exposed
—►—	Home run to panelboard. Indicate number of circuits by number of arrows. *Note:* Any circuit without further designation indicates a 2-wire circuit. For a greater number of wires indicate as follows: -⫻- (3 wires) -⫻-⫻- (4 wires), etc.
━━	Feeders. *Note:* Use heavy lines and designate by number corresponding to listing in feeder schedule.
≡□≡	Underfloor duct and junction box. Triple system. *Note:* For double or single systems eliminate one or two lines. This symbol is equally adaptable to auxiliary system layouts.
Ⓖ	Generator
Ⓜ	Motor
Ⓘ	Instrument
Ⓣ	Power transformer (or draw to scale)
⊠	Controller
□ʼ	Isolating switch
	Auxiliary Systems
⊡	Pushbutton
□/	Buzzer
□ᐅ	Bell
◇	Annunciator
|◀	Outside telephone
|◁	Interconnecting telephone
[|◁	Telephone switchboard
Ⓣ	Bell-ringing transformer
[D]	Electric door opener
[F]ᐅ	Fire alarm bell
[F]	Fire alarm station
☒	City fire alarm station
[FA]	Fire alarm central station
[FS]	Automatic fire alarm device
[W]	Watchman's station
[[W]]	Watchman's central station
[H]	Horn
[N]	Nurse's signal plug
[M]	Maid's signal plug
[R]	Radio outlet
[[SC]]	Signal central station
□	Interconnection box
╫╫╫	Battery
—·—	Auxiliary system circuits. *Note:* Any line without further designation indicates a 2-wire system. For a greater number of wires designate with numerals in manner similar to —·— 12-No. 18W-¾″C, or designate by number corresponding to listing in schedule.
$\square_{a,b,c}$	Special auxiliary outlets. Subscript letters refer to notes on plans or detailed description in specifications.

tion regarding the systems to be used, the connections and interconnections, the wire and conduit sizes, and tabular matter showing total connected lamp and motor loads, feeder, subfeeder, and branch circuit loads. The common devices to be installed in rooms, hallways, closets, and other locations are represented on the drawings by symbols, Table IV. These are placed on the floor plans close to the desired locations, as in Fig. 7. The elevations above floor level for typical devices are usually given in the written specifications, or in tabular form on the plans.

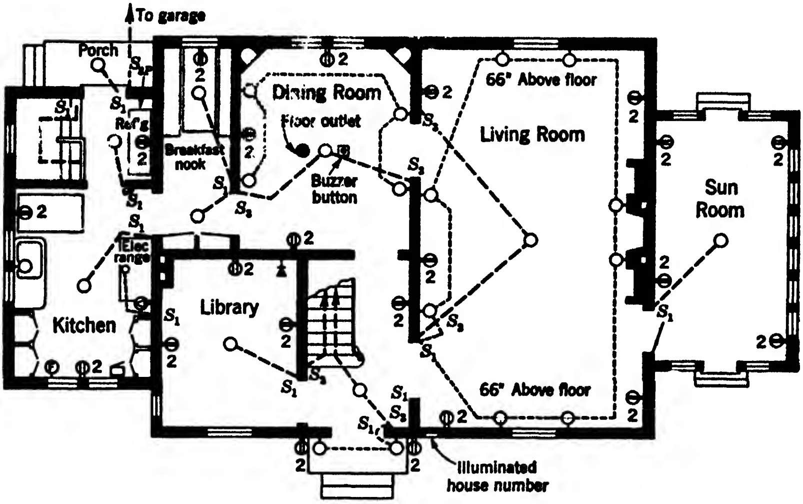


Fig. 7. Typical plan layout of symbols for residential wiring system. See Table IV for symbols.

It is customary on the wiring plans to present only such information and data as may be essential to the electrical contractor for the purpose of purchasing and installation. It is not necessary to show on such plans every wire and its connections. For instance, if a 3-wire 3-phase a-c system is to be used for power and lighting purposes throughout the building, a *schematic single-line diagram* is sufficient. The architect, the engineer, and the electrical contractor will then understand that any single line really represents three wires, and that the accessory equipment, such as bus bars, switches, and circuit breakers, are really of 3-pole construction. A typical single-line diagram is shown in Fig. 8. This may represent any one of the systems reviewed in Art. 3,

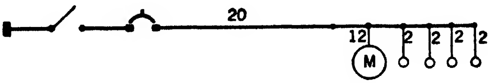


Fig. 8. Conventional single-line wiring diagram.

Fig. 4. For a large building it is necessary to divide the wiring plans into a number of different diagrams. For example, one schematic single-line diagram will cover the connections for the service entrance, service switches, transformers, main switchboard, and feeders. Another will start with a given feeder and include wiring to all connected panelboards and the branches from them. Still other detailed wiring diagrams may give unusual or special connections required in motor starting boxes or control equipment. Figure 9 shows a schematic single-line diagram for a transformer vault switchboard control room and feeders for a large modern office building.

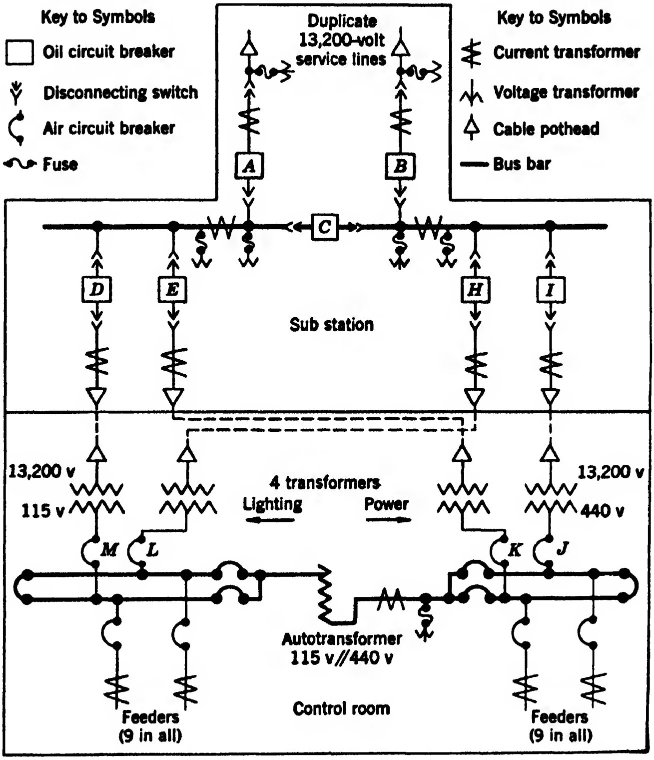


Fig. 9. Application of a single-line diagram to an office building for a large substation. Large motor loads operate at 440 volts, 3-wire, 3-phase; all lighting loads at 115 volts, 4-wire, 3-phase.

A service entrance switch, with connections to meter and panelboard, is shown in Fig. 10. This is for a 3-wire single-phase 115-230-volt service. The dashed lines on the panelboard indicate typical 2-wire branches. Note that the neutral wire is carried straight through the system without being fused. Also note that one wire of each 2-wire branch circuit is connected to the neutral bar of the panelboard and is not fused. The neutral wire in any 3-wire d-c or single-phase a-c circuit should never be fused.

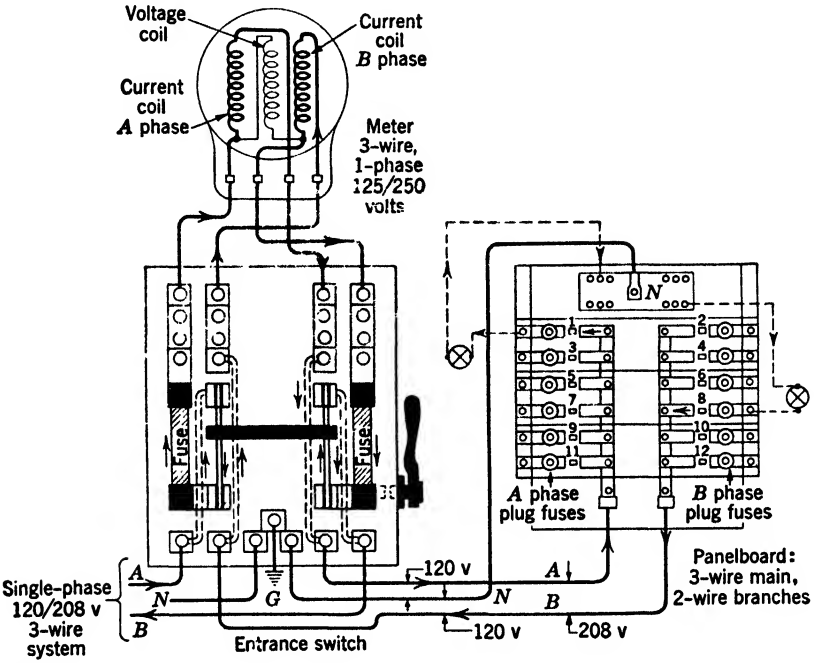


Fig. 10. Service entrance switch, panelboard, and wiring. The arrowheads indicate direction of flow of load currents in the two outside wires *A* and *B*, under balanced load. On balanced load no current flows in the neutral wire *N*.

In large apartment buildings the tenants are sometimes required to pay the management for electrical energy consumed. Likewise hotels or office buildings may be wired to measure the energy consumed in various areas. For this purpose *submetering panelboards* (not shown) may be used.

11. Estimating electrical loads. In the layout of any electrical work it is necessary to estimate the probable connected load and the periods of time at which all or part of the individual devices will be consuming energy. The *connected load* is the total load actually connected and ready for operation. This is the sum of the kilowatts of all electrical equipment presumed to be operating at their rated loads. The operating load is that part of the load which is in operation at any time of day. The *maximum demand* is the maximum load in kilowatts taken by all connected electrical equipment when the sum of the coincident loads is at a maximum.

The architect or engineer must visualize the needs for lamps, motors, and heating devices. If in doubt about the required horsepower (hp) of motors and the required sizes and numbers of lamps or other power-consuming equipment, he must either calculate requirements or secure the information from the manufacturers. Table V indicates the method of calculating the watts and amperes input if the horsepower required to drive a given machine is known. For these calculations the efficiencies (and power factors for a-c motors) must be known. These are readily obtainable from any sales office of electrical manufacturers.

Table V. Relation between Input Watts, Volts, Amperes, and Power Factors for D-c and A-c Motors Operating at Full Load

$$\text{Watts input} = \frac{HP \times 746}{\text{efficiency}} = W$$

Motors D-c and A-c Types	Watt Input (W) in Terms of Line Volts (V), Line Amperes (I), and Power Factor ($\cos\theta$)	Example: for a 25-hp motor at voltages indicated, having full load efficiency of 87% at power factor of 86%			
		W	V	I *	Cos θ †
D-c 2-wire	$W = VI$	21,420	230	93.3	(1.00)
A-c 1-phase 2-wire	$W = VI \cos\theta$	21,420	230	108.4	0.86
A-c 2-phase 4-wire	$W = 2VI \cos\theta$	21,420	230	54.2	0.86
A-c 3-phase 3-wire	$W = 1.73VI \cos\theta$	21,420	230	62.5	0.86
A-c 3-phase 4-wire (with balanced load)	$W = 1.73VI \cos\theta$	21,420	208	69.1	0.86

* Line current for the types of motors indicated.

† Cos θ = power factor.

Table VI shows estimated connected loads, their electrical characteristics, and time of use for a country golf club building. In Fig. 11 the component load curves, and the resultant total demand curve in kilowatts, show the power requirements at any time in a typical day. If

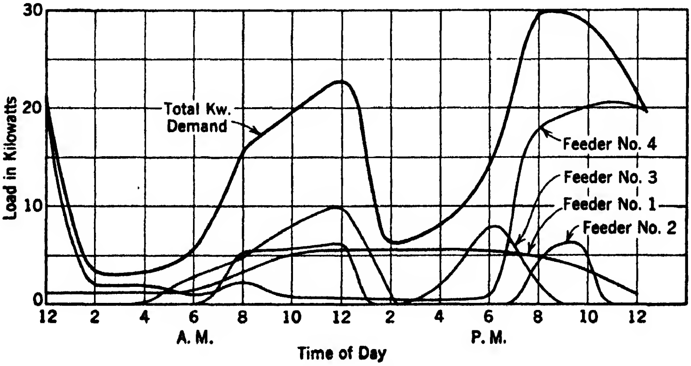


Fig. 11. Load demand curves of a large country club.

Table VI. Estimated Connected Loads and Load-Curve Data for a Country Golf Club Building

Connected Load			Rated Current at *		Estimated 24-hr Load (kilowatts)												Feeder †		
					A.M.						P.M.								
Purpose	Hp	Rated Input (kw)	230 Volts	115 Volts	12	2	4	6	8	10	12	2	4	6	8	10	No.	Amp	Wire Size
A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	*L*	*M*	*N*	*O*	*P*	*Q*	*R*	*S*	*T*
Fan	1	1.2	5.2	...	...	...	...	...	0.6	1.2	1.2	1.2	1.2	1.2	1.2	...	1	24.8	10
Fan	1.5	1.7	7.4	...	...	...	...	...	0.9	1.7	1.7	1.7	1.7	1.7	1.7	1.7			
Refrigerator	3.0	2.8	12.2	...	1.0	1.1	1.1	1.2	1.9	2.2	2.8	2.8	2.8	2.6	2.0	1.8			
Pump	5.0	4.4	19.2	...	...	...	...	...	4.0	4.0	5.0	...	...	...	5.0	5.0	2	28.3	8
Pump	2.0	2.1	9.1	...	...	...	...	...	1.5	1.5	1.5	...	...	...	...	...			
Range	...	8.0	34.8	...	...	...	...	2.0	4.0	6.0	8.0	...	2.0	8.0	2.0	...	3	52.2	5
Range	...	4.0	17.4	...	...	...	...	1.0	1.0	2.0	2.0	...	...	...	...	...			
Furnace	0.5	0.7	...	6.1	...	...	...	...	...	...	...	...	...	...	...	...	4	27.0	8
Radio	...	0.1	...	0.9	0.1	...	...	...	...	0.1	0.1	0.1	0.1	0.1	0.1	0.1			
Radio	...	0.1	...	0.9	...	...	...	...	...	...	...	...	...	...	...	...			
Lamps	...	22.0	...	19.1	20.0	2.0	2.0	1.0	2.0	0.4	0.6	0.4	0.4	0.8	18.0	20.0			
Plug outlets	...	2.0	...	...	...	...	...	...	0.1	0.3	0.1	...	...	...	...	...			
Totals	13.0	49.1	105.3	27.0	21.1	3.1	3.1	5.2	16.0	19.4	23.0	6.2	8.2	14.4	30.0	28.6	..	132.3	..

* Rated current $= \dfrac{kw \times 1000}{V}$.

† Select wire size corresponding to total operating load connected to each feeder.

summer and winter daily loads are widely different, the extremes should be studied after estimating the curves. An analysis of such curves forms the basis upon which contracts are made with public-service electric companies. The feeder wiring diagram, feeder and branch wire sizes, fuses, panelboards, and conduit size are based on the information shown in Table VI and Fig. 11.

The connected load for a large completely air-conditioned office building is shown herewith.

Total connected motor load (exclusive of spare units)		3,620 hp
Elevator load	1,046 hp	
Air-conditioning load	2,310 hp	
Domestic water system	121 hp	
Heating system (for condensate, etc.)	41 hp	
Miscellaneous applications	102 hp	
Total connected motor load (approximately)		3,100 kw
Total connected lighting load		1,676 kw
Grand total connected light and power load		4,776 kw
Total overall volume of building		7,977,000 cu ft
Total overall floor space		562,680 sq ft
Space occupied by owners	62,900 sq ft	
Office space, rentable area	328,510 sq ft	
Store space, rentable area	35,140 sq ft	
Nonrentable area (service areas, halls)	136,130 sq ft	

In a project of this magnitude, anticipated load curves should be drawn for days in the year which have widely divergent operating demands such as a typical day in June, in October, and in January. Sometimes Saturday, Sunday, and holiday load curves are drawn in order to study these loads conditions. By means of these typical daily load curves, drawn with the abscissae scaled in hours and the ordinates scaled in kilowatts, the sustained power requirements and the energy in kilowatthours are approximated. In this way the total energy consumption per month and per year may be estimated.

The specifications for the main service circuit breakers, the main transformers, and the main switchboards are determined from the information on these 24-hr load curves. These curves are, of course, made up of component curves which show the 24-hr operating cycles of other major loads in the building, such as lighting, motors, refrigerating, and elevators. These component curves are useful in determining the ampere ratings of feeders, subfeeders, switches, circuit breakers, panelboards, and branch circuits.

12. Branch-circuit wire size. All branch circuits connected to lamps and plug outlets should be selected of sufficient size to provide close to rated voltage at the outlets. Usually standard 115-volt or 120-volt lamps are selected. Table VII indicates the wire sizes neces-

Table VII. Branch-Circuit Wire Sizes Required to Restrict Voltage Loss to 2 Volts

(2-wire 115-volt circuits)

Length of Circuit (ft) *†	Watts per Circuit									
	100	200	300	500	750	1000	1500	1725	2000	3000
	Amperes per Circuit									
	0.87	1.7	2.6	4.4	6.5	8.7	13.1	15 ‡	17.4	26.1
A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*
10	14	14	14	14	14	14	14	14	14 §	14 §
20	14	14	14	14	14	14	14	14	12	12 §
30	14	14	14	14	14	14	12	12	12	10
50	14	14	14	14	14	12	10	10	8	8
100	14	14	14	12	10	8	8	6	6	4
150	14	14	12	10	8	8	6	4	4	2
200	14	12	12	8	8	6	4	4	2	2

* The length of wire is twice the length of the circuit. The length of circuit is the distance between the panel box and the farthest outlet.

† All voltage drops are computed for wires at 65°C (149°F). Assume wire insulation to be RW.

‡ Fifteen amperes is the allowable current capacity of No. 14 wire as set forth in the NEC. However, wire not smaller than No. 12 is recommended for all branch circuits.

§ Not in accordance with code requirements.

sary for given watts load for various lengths of branches. It has been calculated by means of Ohm's law ($I = E/R$), and the closest wire sizes and conduits have been selected from Tables I and II, pp. 334 and 335.

13. Solution of a feeder problem; three-wire system (d-c or a-c). In this system three wires extend from the source to the point of distribution, at which point the individual devices may be connected to two-wire branches or to three-wire branches. Also devices of a given voltage, or double that voltage, may be operated. Figure 12 illustrates the system. G_1 and G_2 are identical d-c generators, each rated at 120 volts and connected in series from *a* to *c*. Hence the voltage from *b* to *a* is 120, from *c* to *b* is 120, and from *c* to *a* is 240 volts. The transmission wires out to the distribution point (*d*, *e*, *f*) carry these voltages to the 115-volt lamps and to the 230-volt motors connected to the distribution circuits, totaling 5520 watts. The line wires are selected to carry the required current with a limited line drop to provide rated voltage at the loads.

To illustrate the distribution of current in the various parts of the system, assume that each lamp requires 2 amp at 115 volts, and each motor 7 amp at 230 volts. The arrows on the diagram give the current in the generators, the line wires, and the branch-circuit wires. Note that there are equal currents in the two outside wires *cd* and *af*, and zero current in the neutral wire *be*. Under these conditions the load and the entire system are said to be balanced. The neutral wire would be unnecessary if the load could always be balanced; but this balance cannot be maintained since any part of the load must be subject to use as needed.

The balanced condition is indicated by the equations

$$I_{cd} = I_{eb} + I_{fa}$$

$$24 = 0 + 24$$

Five volts are lost in each outside line wire, and, of course, none are lost in the neutral for there is zero current in it. Hence the voltages at *d*, *e*, *f* are

$$V_{df} = V_{de} + V_{ef}$$

$$230 = 115 + 115$$

When the load is unbalanced, as when the lamps of branch *B* are turned off (4 amp), the neutral wire will carry 4 amp inward toward the source. There will be 24 amp in wire *cd* and 20 amp in wire *fa*. These conditions can be stated by

$$I_{cd} = I_{eb} + I_{fa}$$

$$24 = 4 + 20$$

It will be seen that when the system is balanced both the voltages V_{de} and V_{ef} are balanced at 115 volts. When the system is unbalanced a slight difference in voltage will exist across each section of the load. With the unbalance of 4 amp indicated in the preceding paragraph the load voltages will be

$$V_{de} = 114.17 \qquad \text{and} \qquad V_{ef} = 116.66$$

The *RI* drop in each line wire is the resistance of each wire times the current in it; hence

$$V_{cd} = 5 \quad V_{eb} = 0.83 \quad V_{fa} = 4.17$$

The voltages across the loads in a properly designed 3-wire system are sufficiently close to give high efficiency under any normal expectation of unbalance. In general, the maximum unbalance does not exceed 15 to 20 per cent. The connected load on each branch circuit is balanced on the two sides of the system so that the expectation of total load at any time will produce minimum unbalance.

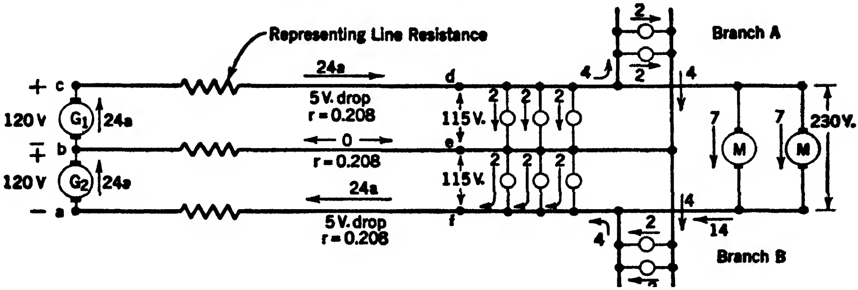


FIG. 12. Three-wire system supplying combined 115-volt lamps and 230-volt power load.

The expected unbalance of the system is expressed in terms of the balanced load current in the outer wires; i.e., for the example given above, the unbalance would be $\frac{4}{24} = 0.167$, or 16.7 per cent. The middle wire could be smaller than the two outside wires, depending upon the expected unbalance. As a rule, however, all three wires are of the same size.

It will be noted that the full power in a 3-wire system (at no unbalance) is transmitted at 230 volts instead of 115 volts, although all connected load may be rated at 115 volts. Hence the relative copper required for the two outside wires is only, by Art. 4,

$$\frac{115^2}{230^2} = 0.25 \text{ or } 25 \text{ per cent}$$

But, since three wires are needed instead of two, in order to take care of some unbalanced current, the actual ratio of copper becomes

$$\frac{3 \times 115^2}{2 \times 230^2} = 0.375 \text{ or } 37.5 \text{ per cent}$$

The total power delivered to the load is

$$W_L = V_L I_L = 230 \times 24 = 5520 \text{ watts}$$

The total power input to the line, at the generators, is

$$W_G = V_G I_G = 240 \times 24 = 5760 \text{ watts}$$

This indicates a line loss of $5760 - 5520 = 240$ watts; and the line efficiency is

$$\frac{\text{Line output}}{\text{Line input}} = \frac{5520}{5760} = 95.7 \text{ per cent}$$

NEC CODE AND SUPPLEMENTARY TEXT REFERENCES

Appendix A	NEC Code Items:	A5, A6, A7, A8, A9, A10, A11, A65, A66, A67, A68, A69, A70, A72, A73.
Appendix B	Text Items:	B1, B2, B3.

PROBLEMS

1. What functions are provided by a service entrance switch and its accessory equipment?

2. What are some of the important factors that must be considered when one selects a certain conductor (wires or cables) for a given application?

3. Consideration is being given to the operation of a group of motors rated from 3 to 10 horsepower (hp), at either 220 or 440 volts. What would be the approximate ratio of size of copper conductors required for these two voltages?

4. In what ways do 440-volt switches, circuit breakers, bus bars, and insulations or conductors differ in their ratings from those for 220-volt systems?

5. Explain why a 3-wire system is generally more economical than a 2-wire system?

6. Draw a schematic wiring diagram of a 2-wire 115-volt branch circuit with a load of ten 300-watt lamps and a small motor rated at 1 hp, 115 volts, 81 per cent efficiency. Determine: (*a*) the amperes per wire, (*b*) the proper wire size, (*c*) the conduit size.

7. By means of a wiring diagram show how 120-volt lamps and 208-volt motors may be connected to a 4-wire 3-phase a-c system.

8. Assume that a total a-c load of 15 kw operating at 0.70 pf must be supplied at either 115 volts or 230 volts over a 2-wire system. Determine the current if supplied at: (*a*) 115 volts; (*b*) 230 volts. (*c*) What would be the ratio of the required weights of copper wire? (Both lamps and motors are operating at 0.70 pf.)

9. Draw the floor plan of a typical 6-room bungalow, and indicate the outlets and general wiring plans. You may design an original floor plan. Refer to Fig. 7, p. 343.

10. Compare the advantages, if any, of a 4-wire 3-phase 120/208-volt system over a 3-wire 3 phase 220-volt system. Where would one be used in preference to the other.

11. A 3-wire 3-phase 440-volt feeder delivers 60 kw, at 0.866 pf lagging, to the a-c motor operating an elevator. Determine (*a*) the current in the feeder conductors, and (*b*) select the proper size of type RW conductors.

12. Draw a schematic single-line diagram of the four-wire system illustrated in Fig. 6, p. 337. Would this single-line diagram be changed in any way if the system were of 3-wire 3-phase design?

13. Estimate the maximum demand in the main building in which you do most of your daily work. (Consult with the electrical maintenance man if necessary.)

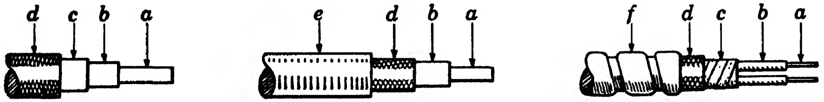
Chapter 24

ELECTRICAL MATERIALS AND METHODS OF INSTALLATION

1. Components of electrical systems. Electric wiring of buildings requires a varied assortment of equipment and auxiliaries for adequate, safe, and efficient operation. These may be classified according to the functions that they perform: the service switch, for main service control, protection, and metering; the main switchboard, for control, protection, and metering of main feeders; the panelboards (near the load end of feeders) for control and protection of branch circuits; the outlets, for local connections to lamps, motors, and other devices; the starting switches and/or control devices for power-consuming equipment; and the conduit and wiring system which interconnects all the preceding apparatus. Each of these parts must be carefully designed to operate safely and economically under normal and abnormal conditions. It is the work of the engineer and architect to anticipate the type of electric services desired or needed, then to provide the necessary plans and specifications covering the proper equipment. The qualities of electrical products and the effectiveness, economy, and efficiency of the various systems that may be specified vary widely. Experience in electrical applications and design is therefore essential to adequate planning.

2. National electrical code. The National Electrical Code of the National Board of Fire Underwriters defines the fundamental safety measures which must be followed in the selection, construction, and installation of all electrical equipment. This code is used by all electrical designers, engineers, contractors, and the operating personnel charged with responsibility for safe operation. The reader of this book should obtain and review the latest edition of the NEC, from the National Board of Fire Underwriters, in any large city, or at 85 John Street, New York 38, N. Y. Frequent references will be made to this code. In Appendix A, following Chapter 31, is a condensed summary of the articles of the latest NEC. This will be of assistance when the design, selection, and installation of electrical equipment is being considered. For example, when engineering work is being done on utility *services,* the Code reference will be found under that name in Appendix A.

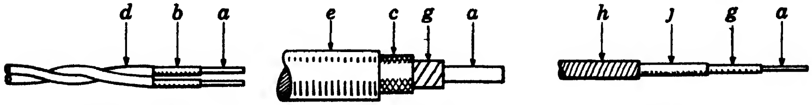
3. Insulated electrical conductors. Each appliance, lamp, or motor in an electrical system requires at least two (sometimes more) conductors to carry the current to such power-consuming equipment



Rubber

Lead covered

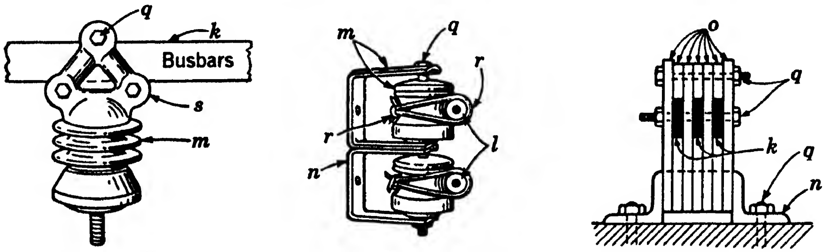
Armored



Dublex rubber

Lead covered

Fire proof (cambric)



Busbar with clamp and insulator

Cable support bracket and insulator

Busbar and support (3 bars in parallel)

Fig. 1. Insulated wire: (*a*), copper wire; (*b*), rubber insulation; (*c*), insulating tape; (*d*), protective braid; (*e*), lead sheath; (*f*), flexible steel armor; (*g*), cambric insulating tape; (*h*), flame-resisting cotton braid; (*j*), felted asbestos and compound; (*k*), busbars; (*l*), large weatherproof covered or insulated cable; (*m*), porcelain insulators; (*n*), insulator brackets; (*o*), rigid insulating sheets of Bakelite used as separators and supports; (*q*), bolts; (*r*), insulated tie wire; (*s*), steel busbar clamp.

and to return the current to the generator for recirculation. Hence wires, cables, and bars are used for such electric circuits. Conductors are usually of copper or aluminum. Each conductor must be insulated so that it will not come in contact with another conductor of the same or another circuit. Thus insulations are made of various tapes, varnishes, extruded rubber, or plastic and asbestos compounds. (See Chapter 23, p. 334.) When the conductors are made of bars, usually referred to as bus bars, they may be supported and insulated by rigid porcelain insulators or rigid sheets of high-voltage insulation (Textolite, Micarta, etc.) with or without insulation applied around the conductors. Figure 1 shows a few typical insulated conductors.

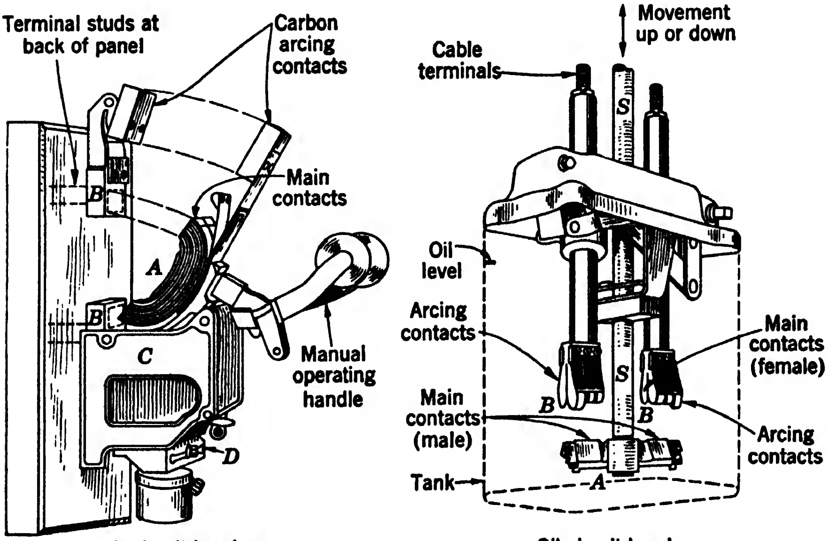
4. Switchboards and circuit breakers. Switchboards may be classified as live-front, dead-front, and metalclad type. Owing to the hazards of operating switchboards with energized bare copper on the front thereof, *live-front switchboards* should never be used today in modern buildings, designed for public or private use or for commercial or industrial purposes. Certain laboratory facilities may require the use of open copper switches, contacts, etc. When replacements are to be made to open-front switchboards the new panels should be of the dead-front type.

Dead-front switchboards (Figs. 3, 4, 5) are those that have all circuit breakers (commonly referred to as breakers) and all other live parts installed back of the panels. The operator controls switches, circuit breakers, and other devices by means of insulated handles extending through holes in the front panel. Main service, main *distribution switchboards* and *load-center switchboards* should be of the dead-front metalclad type, i.e., totally enclosed with steel plates on the top and all sides of the structures and with important units within them (circuit breakers, fuses, instrument transformers, bus bars, and cable entrance terminals) enclosed in separate metal compartments. When a load-center switchboard has circuit breakers with bayonet-type contacts mounted in a movable drawer (like the drawers of a standard letter file), these are designated as switchboards of the *draw-out type.* This drawnout arrangement facilitates emergency replacements, inspection, and repairs.

Load-center switchboards (Fig. 7, panels G and H), p. 363, are usually supplied by feeders from the major main switchboard in the building. They are located at approximate centers of load distribution. For example, closely located groups of motors and furnaces, lighting loads, welding machines, large office accounting machines, etc., would be economically served by a load-center metalclad switchboard of several panels. The individual panels are approximately 90 in. high and 20 to 36 in. wide. Depending upon the equipment enclosed, the depth is about 3 to 7 ft. Aisle space of 6 to 8 ft should be left in front of the rows of panels and about 3 ft in back for inspection and maintenance. The front aisles provide for the removal and replacement of heavy truck-type breakers.

5. The service entrance switch. Any small buildings or group of buildings supplied by a utility service feeder must have a *service switch* close to the point where the feeder enters the building. This switch, with its accessories, affords means of connecting or disconnecting the entire service, of metering the energy, and of automatic protection against severe overloads and short circuits. (See Fig. 3, Chapter 23.) The terms switch and circuit breaker are frequently used interchangeably. The switch properly consists of movable blades whose contacts make and break the circuit when closed or opened. If the contacts are opened under overloads by automatic overload "tripping" devices, it then is properly called a circuit breaker.

In large buildings, or in buildings having large power requirements, usually at high voltage, the service circuit breaker and often the main switchboard feeder breakers must be very rugged in order to withstand electrical and mechanical strains set up by automatic opening (tripping) under overloads or short circuits. Here the breakers usually take the form of heavy copper (or silver) contacts surrounded by air or oil in a metal tank (Fig. 2). These switches are closed by hand, by motor, by compressed air, or by solenoid. They are opened automatically by various types of overload relays when excessive currents flow in the circuits. The metering equipment for this type of switch usually requires instrument transformers to reduce the current and voltage to measurable low values for the meter and relay coils. The switchboard indicating instruments, recording chart instruments, and manual control handles are usually mounted on the front panel; the protective relays, meters, and other electrical controls on the rear panels. Figures



Air circuit breaker (open)

Oil circuit breaker (open)

Fig. 2. Air and oil circuit breakers. Circuit is closed when moving contact *A* presses against fixed contact *B*. A solenoid magnet enclosed in frame *C* will automatically trip open the air breaker when the coil current exceeds a preset limit (adjustable by lever *D*). The solenoid closing and overload "trip" mechanisms for the oil or air type of breaker is contained within the housing of large truck-mounted breakers (see Fig. 5).

3, 4, and 5 should be carefully studied to learn the general details and arrangements of switchboards and circuit breakers.

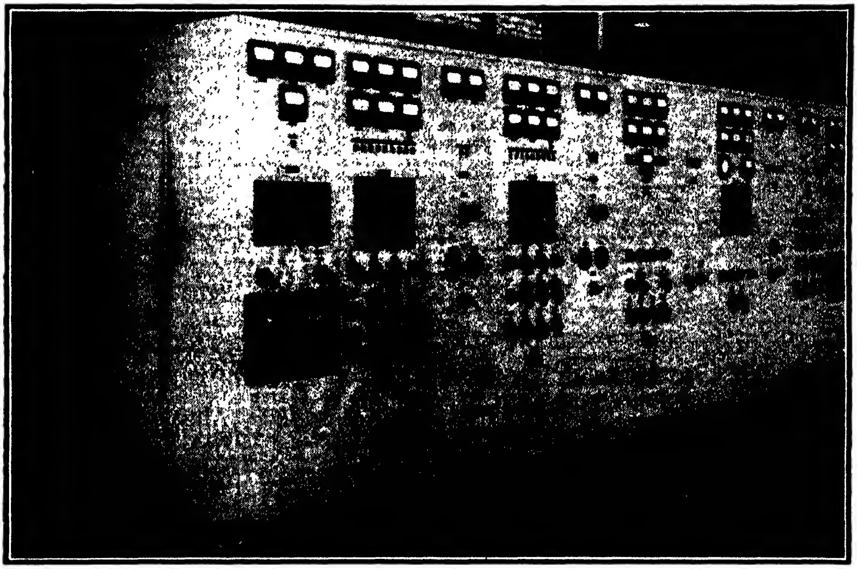


Fig. 3. Portion of a typical duplex metalclad controlboard. On this are contained manually and automatically operated controls and instrument circuits for large utility service breakers and feeder breakers. The large breakers themselves are located in a separate metalclad switchboard similar to that shown in Fig. 5. Indicating ammeters, wattmeters, voltmeters, power-factor meters, etc., are located at the top three rows (with white dials). Recording meters (kwh, etc.) are shown at the botton on the first and eleventh panels from the left end. All manual control circuits for feeders, etc., are shown on all panels; ten, for example, on panel 2. The small round handles (two on panel 1) are for manual adjustments on various instruments, rheostats, etc. (Some of the instruments can be transferred to read the amperes in various phases or circuits merely by being connected to the circuits by the small round tansfer switches.) Indicating lamps red (on) and green (off) show whether the breakers are closed or open. On the back panels of this "duplex" board are mounted various relays, recording wattmeters, and other devices not frequently in need of adjustment of observation by the switchboard operator. The doors (one at each end) give access to all back-of-board accessories and wiring for easy inspection and maintenance. *Dimensions:* Panels generally 20" to 30" wide, 90" high, depth to face of back panel 60" to 80". Minimum front clearance 4', back 3'.

6. Large air circuit breakers and oil circuit breakers. When the building requirements for electric power are very large, the modern service circuit breakers with their closing and tripping mechanisms, known as *metalclad switchgear,* are each contained on portable metal frames mounted on 4-wheel trucks. These "breakers," Fig. 5, are

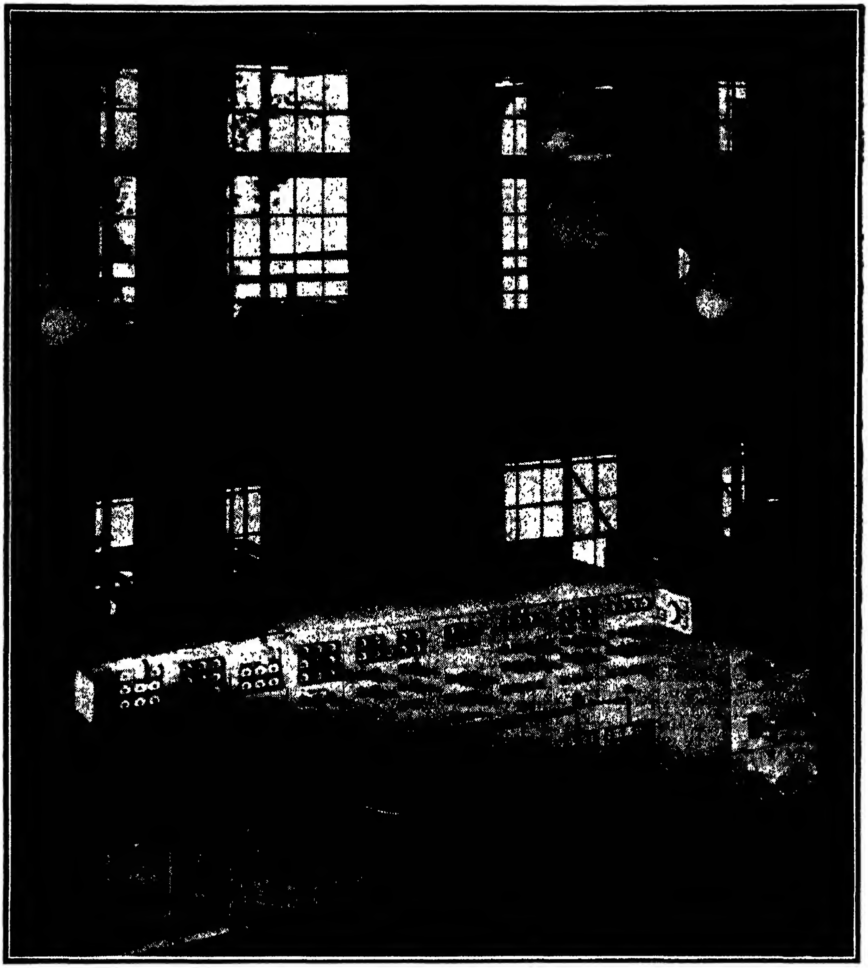


Fig. 4. Another duplex metalclad controlboard, with a typical feeder load center of eight breakers at the right end. The nine panels containing instruments and controls, starting at the column on the left, are the fronts of the duplex controlboard. Above, on the right end of the mezzanine floor, are the beginning of a row of metalclad drawout breakers which are controlled by the duplex board below. The general types of the front of the duplex boards agree with details described on Fig. 3. However, a schematic single-line diagram (or bus) of all main power circuits (simulating the metalclad circuit breakers thereon) is diagrammed to and between the operating breaker handles shown at the terminals of the bus. This aids the operator since the breaker's indicating lamps call attention to existing conditions (open or closed) of each breaker. This knowledge facilitates quick emergency operations. Note that the duplex controlboard is metal enclosed on top and all sides. It fits neatly between two columns. Two blank panels cover the unsightly brick columns, thus providing means of exten-

shoved into the metal-encased enclosures called metalclad switchgear, and, when in operating position, their terminals make contact with the heavy conductors of the incoming service cables and with the bus bars

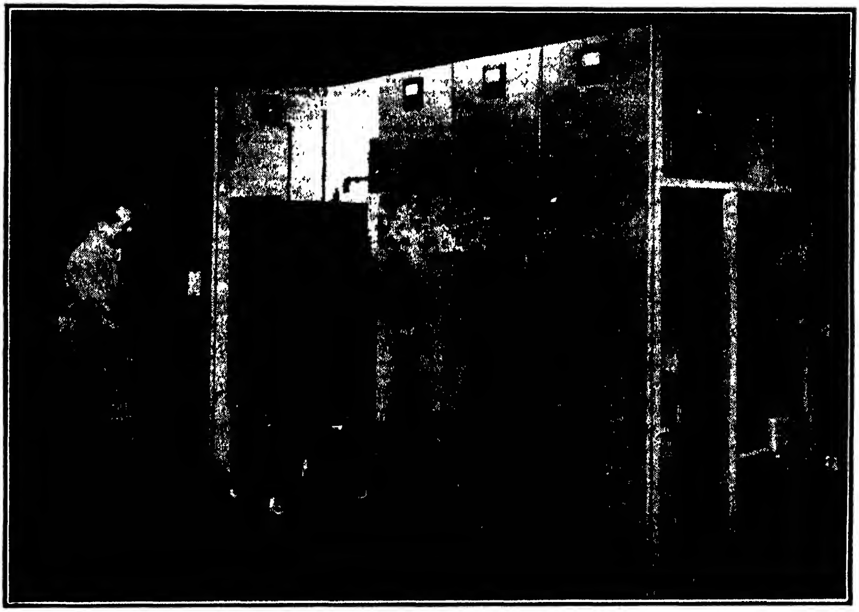


Fig. 5. This metalclad switchboard of four circuit-breaker panels (being assembled in the factory) shows a breaker and its truck. The truck facilitates the quick removable and replacement of any defective breaker. Spare breakers are always available. The electrical equipment on the doors, from top to bottom include an ammeter (*a*), a phase-transfer ammeter switch (*b*), the emergency manual control handle, and two lights just above (*c*), and three overcurrent relays (*d*) (one in each phase). Two door handles (*e*) appear at the right side of each door. *Dimensions:* Panels 20″ to 36″ wide, 90″ high, depth to face of back panel 50″ to 96″. Minimum front clearance for truck manipulation about 6′, back clearance 3′.

to which similar feeder circuit breakers will be connected. These latter breakers and feeders deliver current to local panelboards which, in turn, have local branch circuits to various motors and lamps throughout the building. Each movable breaker, its metal enclosure, the contacts, bus bars, meters, instruments, relays, and other operating auxiliaries form one self-contained metalclad unit. The required number of these

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sion of future panels beyond the columns. On top of the duplex board, note the long horizontal conduit connection box with many conduits extending upward. These carry the relay control and instrument wiring for the main metalclad breakers on the mezzanine floor, these breakers being generally similar to those shown in Fig. 5. *Dimensions:* Same as in Fig. 3 and Fig. 5.

metalclad units or panels constitute the main service and distribution switchboard in a large building.

Metalclad switchgear of large capacity frequently is placed at considerable distance from the control and instrument equipment associated therewith. For example, the breakers for very large turbine generators, or for large-capacity feeders, are frequently grouped 50 to 200 ft from the duplex control board. Figure 4 illustrates this arrangement. The term *duplex controlboard* comes from the fact that the front of the control panels contain small manual control switches indicating instruments, pilot lights (red and green to show closed or open positions of the main switches), and some recording meters; whereas on the back panels are mounted the automatic control relays, instrument-testing terminals, and other devices not requiring the constant attention of the operator. A walkway between the back and front panels gives freedom for workmen to inspect and to maintain all equipment and auxiliaries.

Such main metalclad switchgear and their duplex controlboards for commercial, industrial, and public buildings are almost invariably located in the basement, and housed in separate fireproof rooms, well ventilated. Access to such rooms must provide for the entrance and exit of an individual removable section of the metalclad switchgear or duplex controlboard which can be lifted by a truck crane on the street, skidded within the building, and lowered in the building by a fixed-position crane or chain-hoist mounted over the hatchway to floors below (or above). The designer will realize that adequate lifting hooks, exits, hallways, and hatches should always be provided for the entrance and exit of the equipment of largest dimensions and/or weight to be moved. Therefore, the specifications for switchgear and controlboards should state the maximum number and overall maximum dimensions of operating panels to be bolted together as one portable section. Two, three, or four panels form the usual practical section. These sections may vary in length from about 8 to 12 ft.

7. Panelboards and cabinets. A *panelboard* is an insulating panel on which are mounted, usually with some degree of symmetry, various switches and circuit breakers. (See Fig. 6.) The circuit protection may be either by automatic circuit breakers or fuses. One terminal of each switch is connected to the bus bars of the panelboard; the other terminal of the switch is connected to the protective device, which in turn is connected to an outgoing branch circuit. The bus bars of the panelboard are energized by a feeder or subfeeder which brings service to the panel from some main switchboard or *loadcenter* in another part of the building.

Panelboards may be classified as flush type or surface type. Flush-type panelboards used in most buildings are those which have the trim and doors practically flush with the finished surface of the wall. Surface-type panelboards project into the room, the cabinets being bolted to wall surfaces or columns. The latter type is frequently used in industrial plants. A further classification of panelboards has to do with the number of wires in the feeder and branch-circuit systems (Fig. 4, Chapter 23, p. 333). For instance, if a 3-wire feeder serves a number of 2-wire branch circuits, the panelboard will be classified as having

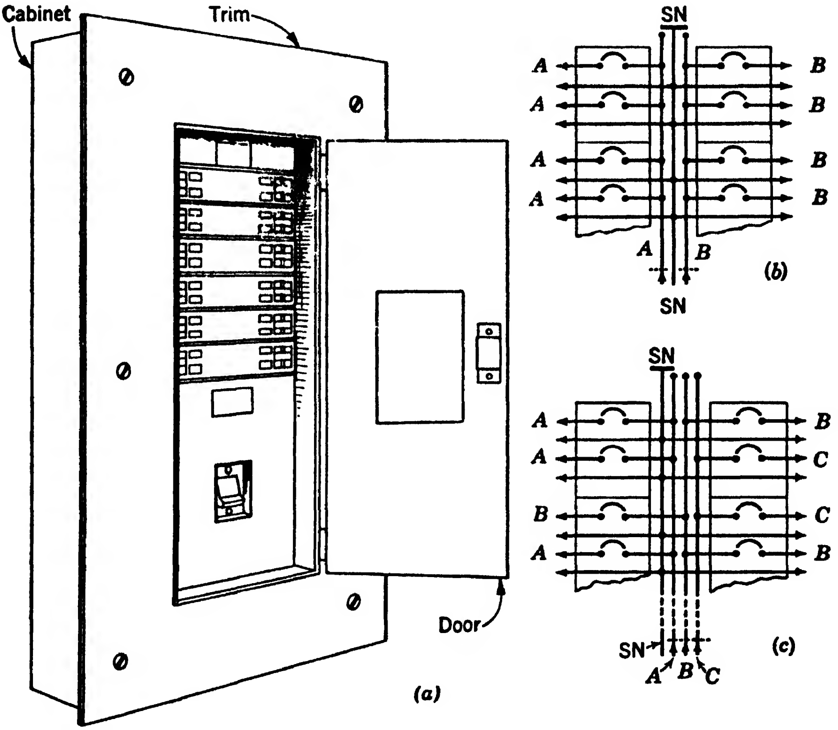


Fig. 6. A typical lighting panelboard from which branch circuits radiate to nearby lamp loads. (*a*) is a flush-type cabinet and 12-circuit enclosed panelboard with main circuit breaker, the flush front frame and cover forms the "finish" practically flush with the plastered surface. (*b*) shows a portion of the wiring for a 2-wire main with circuit breaker and 2-wire branch cabinet. (*c*) a portion of a 4-wire 3-phase grounded neutral main feeder with circuit breaker with 2-wire single-phase branches. Study Fig. 4, p. 333. A feeder circuit breaker is shown at the bottom of (*a*), but these are sometimes omitted. The wiring diagrams would have main breakers at the dotted line locations if they were so ordered. *Dimension:* Such panelboards vary in dimensions, depending upon numbers of circuits, whether a main breaker is required, and whether special features may exist. Approximate dimensions (shown) are face to back of cabinet 5", width 24", height 38". The trim is 6" from edge of door to edge of trim. The phase wires (above neutral voltage) are identified by the letters A, B, C. The solid neutral conductor is always grounded.

"3-wire mains and 2-wire branches." Such specifications as these depend upon the types of wiring systems adopted for the building, as described in Chapter 23.

Panelboards may be designed to serve branch circuits to lamps, motors, heating devices, or other electrical equipment. In general, however, a panelboard is designed to serve a group of somewhat similar branch circuits, feeding the same type of power-consuming devices. They are then designated as *lighting panelboards*, motor or *power panelboards*, etc. Therefore it is common practice to install in large buildings, as separate units, lighting panelboards and power panelboards. Deadfront panelboards (with insulated manually operated main and branch breaker handles) should always be used for safety reasons. Such panelboards are enclosed in metal boxes, with hinged covers, called *panelboard cabinets*. The cabinets are set in the walls and connected to the conduit system before the panelboards and trims are installed. The panelboards are then bolted into place in the cabinets, and the wires are pulled in through the conduits to make connections to the terminals of the panelboard bus bars and the outgoing branch circuits. The space between the edges of the panelboard and the sides, top, and bottom of the cabinet is called the wire gutter. *Wire gutters* must provide adequate space between the cabinet and the panelboard for making connections to branch circuits, the feeder, and the bus bars, for pulling in additional wires, or for replacement of defective wires.

On architects' and engineers' drawings the power and lighting panelboards are numbered systematically. For example, P1-F3 means power panelboard number 1 fed from feeder 3; L2-F4 means lighting panelboard number 2 fed from feeder 4; etc. A combination panelboard might be numbered PL1-F3, meaning power and lighting panelboard number 1 on feeder 3. Some engineering drawings include a numbering to identify the floor location; thus L1-F3-3F means lighting panelboard number 1 on feeder 3 on third floor. Such code numbers aid operators, electricians, and maintenance men in checking and maintaining defective circuits and equipment. These code numbers should be lettered on the outside of panelboard doors.

8. Unit substations and load centers. Unit substations indoors or outdoors form a compact operating unit containing the transformers, primary service circuit breakers, secondary bus bars, secondary feeder breakers, and the associated operating switches and instruments as shown in Fig. 7. Load centers are compact arrangements of draw-out-type breakers, each of which energizes a single motor or group of small motors or energizes a bus of a near-by panelboard with lighting or small motor outlets connected to its branch circuits. (See Fig. 7.)

9. Wires and cables (see NEC, Art. 240). Solid wires or twisted strands of solid wire forming cables are generally used as conductors for electric current. Rectangular bars, round bars, and tubes

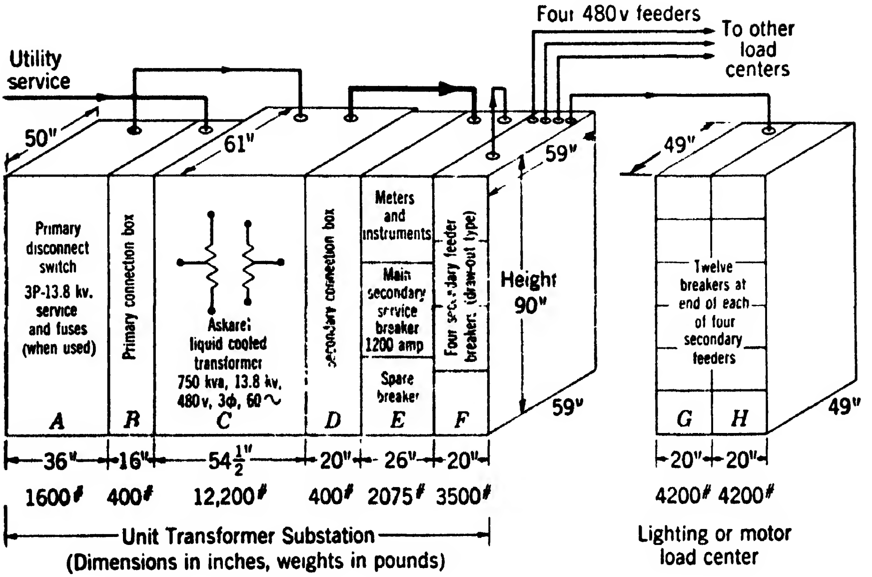


Fig. 7. Approximate sizes and weights of typical metalclad switchgear in a modern building which has a maximum motor demand of 750 kw, 13,800/480 volts, 3-phase, 60-cycles. The primary and secondary service breakers and feeders are arranged in a group called a unit substation. This unit substation may have a capacity sufficiently great in kva to carry additional lighting or motor loads for much larger buildings. The following description identifies the parts and connections of the metalclad switchgear: service cables will enter the enclosure at the bottom of *A* and *B* and be connected to the utility side of the primary disconnect switch, leaving that switch to enter the primary side at 13,800 volts and leave the secondary side of the transformer (*C*) at 480 volts. Leaving the secondary side of the transformer the cables will at connection box (*D*) make connection to the main secondary service breaker (*E*). The main circuit breaker (*E*) will energize the bus bars in section F which contains four feeder circuit breakers. Each one of these four feeders would then leave section *F* and energize the bus bars of a typical lighting or motor load center typified by the load center marked *GH*. This particular load center should be thought of as operating a group of 12 motors at 480 volts, 3-phase. It would be possible in this same building to energize all 120-volt lighting equipment with the use of a load center having a number of circuit breakers similar to those shown in *GH*, assuming also that a lighting transformer (rated at 480//120/216 v) would be connected to a 480-volt feeder. The secondary of each such transformer would be designed to give 120/216 volts to the bus bars of a typical load center containing the required number of breakers for the 4-wire system. Of course, the load would be balanced on each breaker.

are sometimes used as conductors for very high currents. These bars or tubes are usually referred to as bus bars. The material used is copper, aluminum, aluminumclad steel or copperclad steel. Copper conductors are used in the majority of buildings. All wires, cables, and bus bars, as well as all other conducting parts, are insulated from one another and from the adjacent nonconducting equipment and structural elements of the building. All building structural elements (beams, columns, and pipe systems) as well as frames of electric motors, transformers, and all switchboard pipe framework should be grounded. (See NEC, Rule 2521.) The types and bases of selection of conductor insulations is given in this chapter.

The insulation confines the current to the proper conducting paths or circuits. Failure of insulation would cause current leakage and might result in tripping of various breakers, blowing of fuses, consequent shutdown of lighting and power circuits, and possibly to fire damage if breakers should fail to operate. Except for the very large conductors, such as bus bars, all wires and cables are insulated with rubber, varnished cambric, paper, asbestos compounds, or other insulating envelopes resistant to electrical and mechanical breakdown. Bus bars are usually bare and are carried on porcelain insulators, slate, asbestos composition, or other nonconducting supports. Electrical breakdown may result from failure of the insulation caused by mechanical injury, by moisture or chemical reactions, by excessive temperatures, or by abnormal voltage rises in the system. It should be emphasized that insulation is manufactured to meet varying services and that there is a wide range of qualities. Careful consideration must be given to this factor in selecting the most suitable insulated wire and cable. The more common types of insulated wires used in buildings are described below.

10. Wire capacity and size (see wire table herein, Art. 6, Chapter 23, and NEC Art. 310 to Art. 344). The size, or cross-section, of wire to be chosen for a feeder, subfeeder, or branch circuit depends upon the current to be carried.

Example 1. A single large lighting fixture housing a 500-watt lamp requires about 4.35 amp, and the fixture wire (type RW) is No. 18, about 0.040 in. in diameter. The branch circuit serving 5 such lamps would carry 5 × 4.35 = 21.75 amp, and the wire is No. 10, about 0.102 in. in diameter. A subfeeder which delivers current to a panelboard with 10 such branch circuits would carry 10 × 21.75 = 217.5 amp, and the wire size is No. 0000, called four naught, about 0.528 in. in diameter. The safe temperature reached in each of these cables would be approximately equal when they are carrying the current loads indicated. In order to determine the proper wire, the conductor current and the type of insulation must be decided. When these are known, reference to (NEC) Table 1, Chapter 23, p. 334, showing allowable capacities of wires, will give the proper sizes.

It should be emphasized that, if the voltage drop in any wires or cables is sufficient to cause the terminal voltage of operating equipment to vary from the rated value by plus or minus about 5 per cent, then the wire size should be increased or the lengths should be shortened; or both.

In Example 1 above the actual sizes of branch circuit wires and of the feeder to the panelboard would usually be selected of larger sizes of wire to provide for some future expansion of load. Also some spare branch breakers would be provided.

11. Rubber-insulated conductors. The major part of all building wiring systems utilizes rubber-insulated conductors. Such conductors resist moisture, are flexible, have long life, and are economical. The standard grades of such insulation are named code, water-resistant, heat-resisting, and corona-resisting. In general, code wire is a minimum quality specified by the National Electrical Code. It contains about 20 per cent pure rubber in the compound forming the sheath. Corona-resisting insulation is a very high grade rubber compound especially prepared for cables subjected to voltages of 2500 or more volts. Many types and grades of insulation for special applications are tabulated in Chapter 23, p. 334. Also see NEC Art. 310.

Such cables as the following are selected for systems operating at approximately 125, 216, 240, 480, and 600 volts. Corona-resisting insulations are used on systems of 2300, 4000, 6600, 13,800 volts and higher. The maximum safe operating temperature of rubber insulations varies from 50°C (122°F) to 75°C (167°F), depending upon the grade of rubber used. Rubber-insulated conductors should not be located so close to steam and hot water pipes, radiators, or boilers that their heat combined with that of the current in the conductor will injure the insulation. *Electrical connection and pull boxes, raceways, and underfloor ducts should never be located near very hot or very cold pipes or ducts. Excessive heating above the allowable maximum temperatures may damage insulation. Excessive cold locations frequently cause condensation within the conduits and ducts, causing insulation failure.*

12. Varnished-cambric insulated conductors. This insulation is put on the wires in the form of spirally wound layers of varnished cambric. The winding is done in a bath of heavy oil compound. Over this are wound a tape and braid to hold the varnished cambric in position and to afford mechanical protection. The oil compound fills all spaces and thus provides better insulation and lower corona discharges on high-voltage cables. Varnished cambric is safe in temperatures of about 85°C (185°F) but is not so flexible as rubber and therefore requires more careful handling. It resists moisture but not so well as rubber. Good rubber insulation may be subjected alternately to wet and dry conditions, and even immersed occasionally, but varnished cambric must never be used where such conditions may prevail, unless it is covered with a lead sheath. Varnished-cambric insulation has a much higher electrical strength than rubber and is less damaged by corona at high voltages. It is usually selected for systems operating at 4160, 6900, 13,800 volts and higher. For systems operating at 135, 216, 240, 480, and 600 volts with heavy conductors where the operating temperature will be above, say, 75°C (167°F), this insulation should be used in preference to rubber. A smaller conductor with varnished-cambric insulation operating at temperatures up to 85°C (185°F) is usually cheaper than a larger conductor with rubber insulation which must be limited to a temperature of 75°C (167°F).

13. Paper-insulated cables. In this type the principal insulation is of oiled paper tape put on and protected in the same way as varnished cambric. The paper-insulated cables can operate safely up to a maximum of about 85°C (185°F). They are less flexible than either rubber or varnished cambric. They require more care in installation, and they must always be encased in a lead or other absolutely waterproof sheath. These cables are equal to varnished cambric in electrical strength and corona resistance. They are operated on systems reaching voltages as high as 75 kv. A kilovolt is 1000 volts. Cables for voltages higher than 2500 or 4160 v are rarely used for feeders within buildings, although in a few very large buildings installations up to 13,800 volts have been made.

14. Armored wire and cable. In this type the wires (usually insulated with rubber) are bound together with a braid or tape and then wrapped with a spiral-wound interlocking strip of steel tape. The wire and the interlocking armor are installed as a unit, usually by simple U-clamps or staples holding it against beams, walls, ceilings, and columns. This type of installation is frequently used in inexpensive homes, summer cottages, garages, and barns. It finds frequent application in wiring or rewiring existing buildings where the tearing up of floor, wall, or ceiling surfaces would for any reason be costly or objectionable. Such armored cable can be pulled into place through existing spaces back of plastered surfaces, under floor joists, or behind studding in the walls. Special couplings, box connectors, and other fittings are made to complete such armored cable installations or to interconnect them with rigid conduit systems. A similar type of armored cable, oval instead of round in cross section, is available for installation under plaster, or where the round armored cable would be too thick for the space.

15. Conduits and raceways. In order to save the insulation from mechanical harm and to avoid the risk of fire or shock, NEC requires that all conductors be enclosed in a metal sheath or otherwise adequately protected. Rigid and flexible steel conduits are employed in general construction, and steel conduit or raceways of round, rectangular, and oval sections have been developed for underfloor concrete work. Round and oval fiber raceways are also used in concrete floor slabs.

Figure 8 shows a number of types of conduits and raceways. By far the major portion of all well-designed wiring systems is carried in rigid steel conduits. This conduit may be supported in exposed locations or within structural walls, and may be carried in or across the flanges of steel columns and beams, or embedded in slabs, columns, or beams of concrete. Figure 9 illustrates some typical methods of installing conduits and raceways. Other forms of cable-protective enclosures and coverings are shown in Fig. 10. Table II, Chapter 23, shows the required size of conduit for any number of specified sizes of conductors.

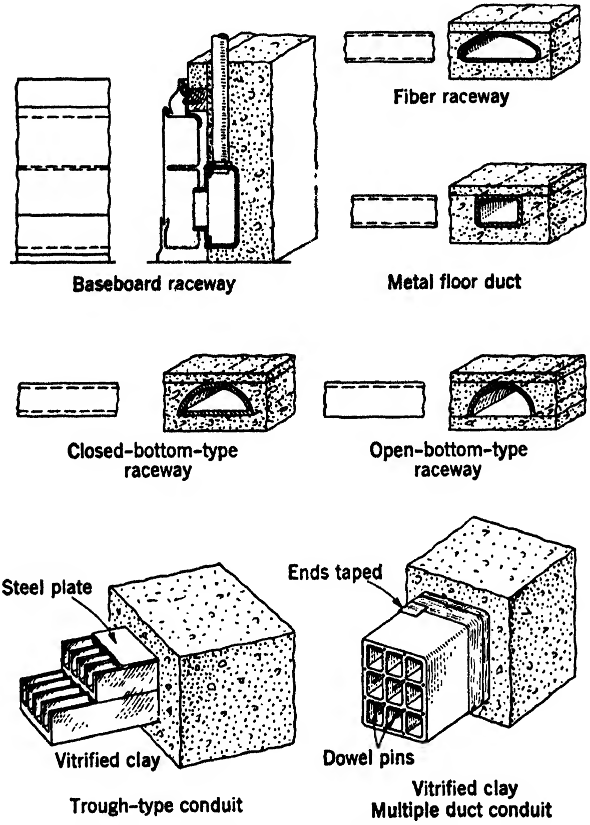


Fig. 8. Some types of raceways cast in concrete or plaster walls. All adjoining ends are covered and taped to exclude drippings from wet concrete or plaster.

The flexible steel conduit is used where it is difficult to install rigid steel conduit or where, for some reason, a flexible protective sheath is needed.

For all the conduit systems, rigid, flexible, etc., the range of conduit fittings is wide. Such fittings include straight and angle couplings, elbows, T- and cross-connections, and many forms of outlet boxes. A number of these fittings and outlet boxes for the rigid steel conduit system are shown in Fig. 11.

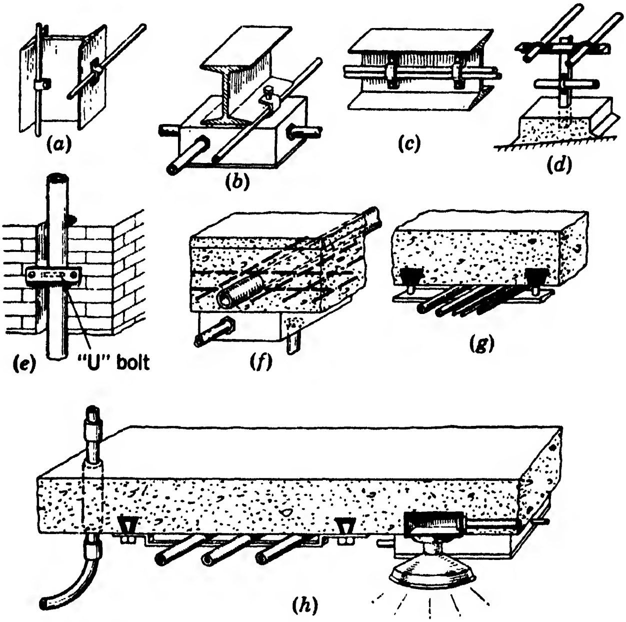


Fig. 9. Typical conduit supports. The letters identify standard types. Blank or special covers are available for each type. All standard conduits are threaded at both ends. Conduit installations: (*a*), (*b*), and (*c*) mounted on structural-steel members; (*d*) angle bracket supported by a concrete block and supporting brackets holding conduits (held in position by friction and weight); (*e*) in wall chase; (*f*) cast in concrete slab with conduits entering the pull box under the slab; (*g*) supported by steel strap and inserts; (*h*) miscellaneous slab details showing support of conduits, luminaire outlet box and pull box beneath the slab.

16. Selection of conduits. A rigid *electrical conduit* is merely a round metal pipe carefully manufactured to insure strength, to provide internal and external smoothness, and to resist corrosion and formation of rust. A good conduit should be ductile and should not split, break, or splinter when sharply bent. Rustproofing and lacquer should not break under the bending done in installation. The fittings, such as couplings, elbows, and small cast boxes giving access to the pipe (usually called *conduit fittings*), should be equally smooth, strong, and resistant to rust and corrosion. The conduit and corresponding fittings are procurable in stock sizes with approximate inside diameters

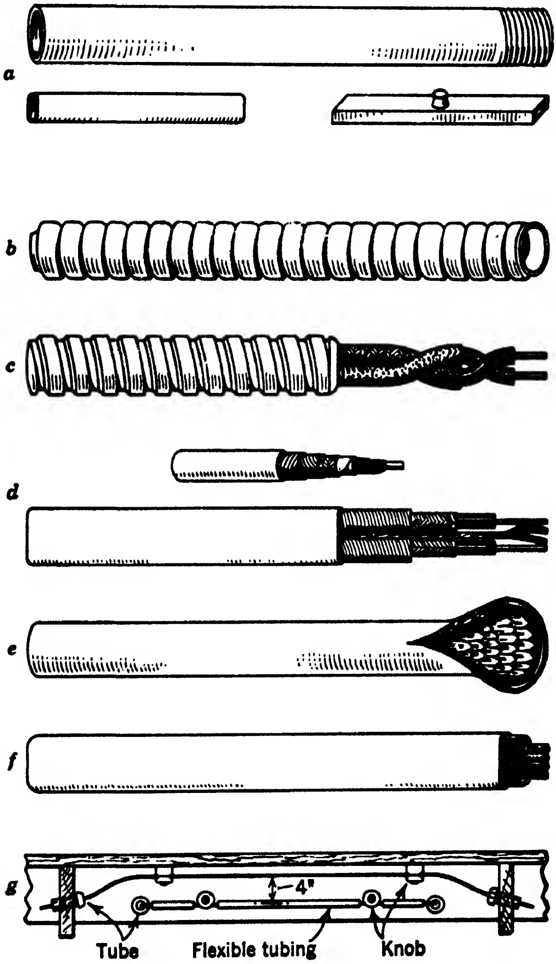


Fig. 10. Conduits and raceways: (*a*) rigid steel conduit, oval steel raceway, and square steel raceway; (*b*) flexible steel conduit; (*c*) flexible armored duplex wire or "B-X"; (*d*) 1-conductor and 2-conductor lead sheath cables; (*e*) flexible lume (nonmetallic, fire-resisting); (*f*) clip-type raceway or "wire-moulding"; (*g*) knob-and-tube wire system.

of ½, ¾, 1, 1¼, 1½, 2, 2½, 3, 3½, and 4 in. Five- and six-in. conduits are occasionally used.

The selection of size depends upon the number and diameter of the wires which may be drawn into the conduit without undue abrasion or cutting of the insulation, and without stretching the wire. (See NEC, Art. 346 for details of installation of conduits.) The number and radius of bends in the conduit, as well as the total length, affect the degree of abrasion to insulation when the wire is pulled in. Also there should not be more than two 90° bends or more than three 45° bends in any continuous run. Long straight pulls may be made through as much as 150 to 200 ft of continuous conduit without bends. The above comments represent conservative practice, but many field conditions arise to alter practical rules of this kind.

To exceed a total of six or eight conductors in a given conduit is not good practice. In general the service requirements in any one portion of a building are such that only circuits of say two or three conductors are installed in one conduit. In running branch circuits from the panel board to local lamp or plug outlets, three or four circuits (six or eight wires) may run in one large conduit to a given pull box in the system, then branch off in smaller conduits to the final outlet points.

The NEC states that no wire shall be spliced, connected, or tapped and then drawn into the conduit so that the connection is within the conduit itself. All such splices, connections, and taps shall be made within connection or pull boxes. Also no wires should be installed in the conduit system until it has been inspected and approved by the National Board of Fire Underwriters (NBFU).

When conduits are to be cast in concrete slabs the boxes and conduits (prior to pouring) are connected and held in position by blocks and iron wire fastened to the reinforcing bars. The concrete is then poured and tamped. For structural reasons these runs of conduit are usually close to the bottom surface or near the central portion of a floor slab. If a great number of conduits must be embedded it may be necessary to increase the slab thickness. In any event the top of any conduit should be at least 1 in. below the finished floor surface in order to prevent possible cracking. When heavy trucking is to be expected this allowance should be increased to 1½ in. or 2 in.

17. Knob and tube system. In small, low-cost installations the wire may be supported on porcelain knobs and tubes, shown in Fig. 10. The most common applications are in frame buildings. Some city building codes prohibit the use of this system. Some disadvantages, as compared to rigid metallic conduit, are that conductors are not protected from mechanical injury; burning insulation may ignite timbers; warping or settling of the building structure may slacken the wires; porcelain tubes or insulators may break or loosen owing to vibration, and replacement or change of wires is difficult. Flexible, nonmetallic, fire-resisting tubing known as loom must be placed around adjacent wires if they are closer together than 5 in. on centers. Wherever it enters an outlet box each wire must have this additional tubing.

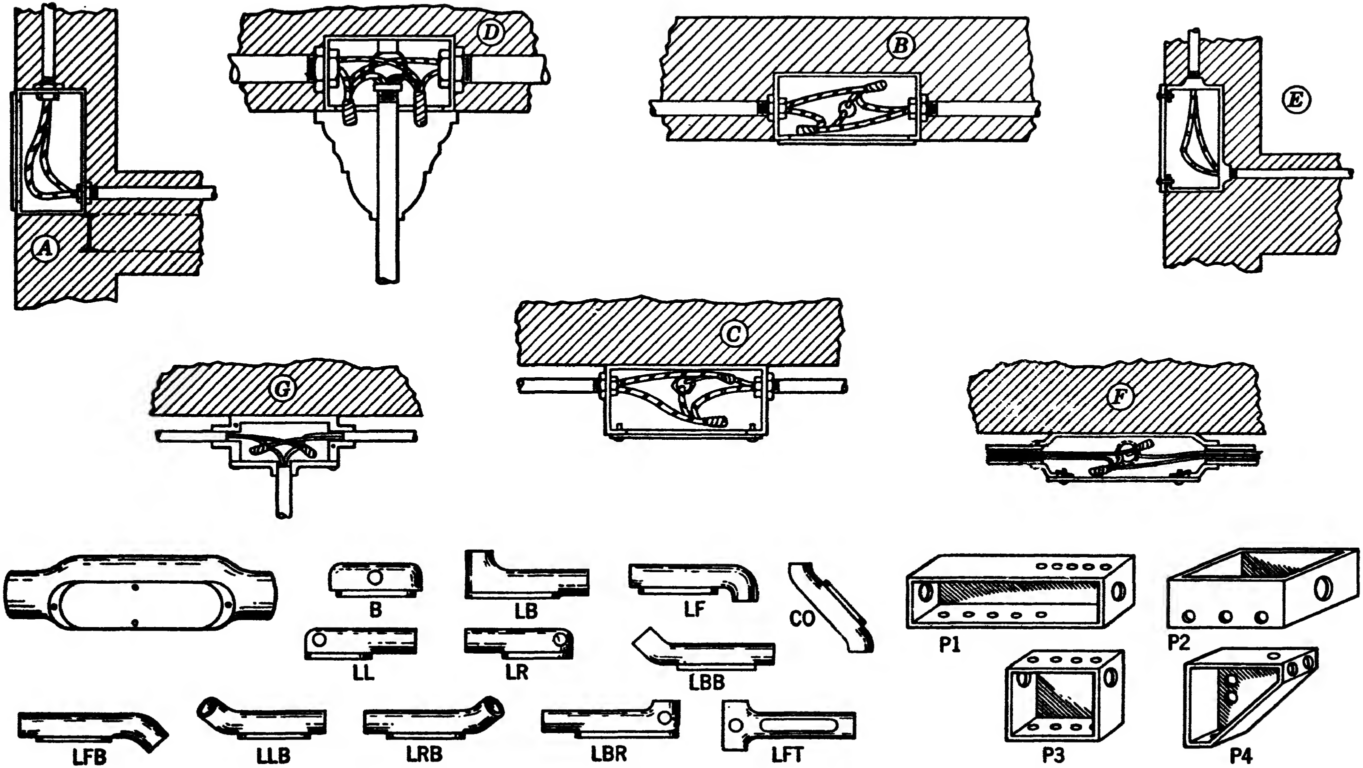


Fig. 11. Standard pull boxes and connection boxes *A*, *B*, *C*, *D*, *E*, and *F* and wiring details. Designs of typical sheet metal pull and junction boxes (*P*1, *P*2, *P*3, and *P*4) in a variety of sizes (with covers not shown) and to fit any number of conduit connections and conduit sizes. The holes represent the desired locations and sizes. Many types of standard conduit fittings are shown with their symbols (types B to LFT). (See NEC Art. 93521 to Art. 93704, and Art. 370.)

18. Pull boxes, connection boxes, and outlet boxes (see NEC, Art. 370). In order to provide access to the conduits for installing the necessary wires and for making connections to them, the continuous conduit runs are interrupted at frequent intervals by sheet-metal or cast-metal boxes. These boxes are usually of a rectangular, octagon, or round form having punched or knock-out holes to fit the conduits which terminate in them. "*Knockouts*" are *partially* punched holes that are easily knocked out with a hammer. The threaded ends of the conduit are held rigid in the holes by means of a bushing on the inside and a locknut on the outside of the box. The bushing is tapered and rounded to provide a smooth entrance to the inside of the conduit. On certain sizes of conduit the NEC requires bushings covered with or made of solid insulation. This reduces the possibility of abrasion of conductor insulation where the conductor leaves the end of the conduit. Such pull, connection, and outlet boxes are manufactured in a number of small standard sizes punched with holes for ½-, ¾-, and 1-in. conduits. The holes are located on the sides and in the bottom at positions which provide easy manipulation of the wrenches in tightening the locknuts and bushings. Figure 11 shows a few typical standard fittings and boxes.

In many conduit systems the number and size of conduits terminating at a given location require boxes much larger and, in many systems, much different in design from any standard box. Such boxes may be rectangular, L-shaped, or T-shaped, or may have rounded sections or other odd contours to fit into corners of the building structure or to avoid interference with other electrical or mechanical equipment. All boxes, whether standard or specially designed, are fitted with removable or hinged covers which are usually screwed on after the wires are pulled in and the connections are made. Boxes are rigidly fastened in position by screws or bolts through holes provided in the box or drilled on the job. When they are fastened to concrete, stone, or brick, expansion bolts or inserts are used.

19. Fuses (see NEC, Art. 240). In order to protect insulation, circuit wires, bus bars, switches, and other apparatus from overload and short-circuit currents it is necessary to provide automatic means for opening the circuit. The simplest device of this kind is the ordinary *fuse*, consisting of an alloy link or wire of relatively low melting temperature enclosed in an insulating fiber tube and called a cartridge fuse, or in a porcelain cup and known as a *plug fuse*. Figure 12 shows common types of fuses. Plug fuses, such as those normally used in a dwelling, are obtainable in capacities of 5 to 30 amp. *Cartridge fuses* with ferrule contacts are made in sizes from approximately 5 to 60 amp, and with *knife-blade contacts* from 60 to 600 amp. In general, a wire rated to carry a definite number of amperes should be protected by a fuse of similar rating. Table I, Chapter 23, p. 334, shows allowable carrying capacities in amperes of each size of wire. This table may be used, therefore, to identify safe fuse capacities for such wires.

When a fuse is subjected to an excess current the energy loss in the link (RI^2 loss) generates heat and eventually melts it. In cases of very high current, such as those which result from short circuits, the melting of the fuse is followed by the creation of a large volume of vapor, which in turn creates pressure within the fuse housing. These explosive pressures must be temporarily sustained within the tube by the excellence of its mechanical construction. Small holes

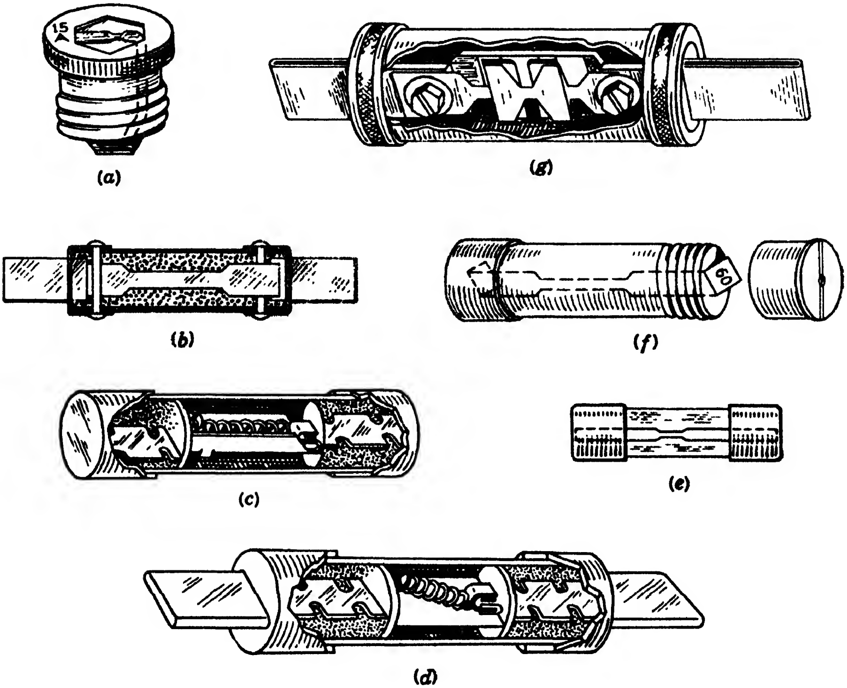


Fig. 12. Standard types of fuses: (*a*) nonrenewable plug; (*b*) nonrenewable knife blade; (*c*) one-time "fusetron" cartridge; (*d*) renewable "fusetron" knife blade; (*e*) one-time miniature nonrenewable (for radio and instruments); (*f*) renewable knife-blade cartridge; (*g*) renewable superlag knife blade. With the exception of types (*e*, *f*), these are available in standard ratings from about 0.2 to 600 amperes in all standard voltages up to 600 volts. (See NEC Art. 240.) Superlag fuses have a greater time lag (in seconds) at 150 to 300 per cent of rated current than the ordinary fuses which have very small time lags on overcurrents. Thus temporary surges of high current will not "blow" the superlag type. Fusetrons have very long time lags on overcurrents and therefore cause much less blowing of the fuses on starting currents and short-time overloads.

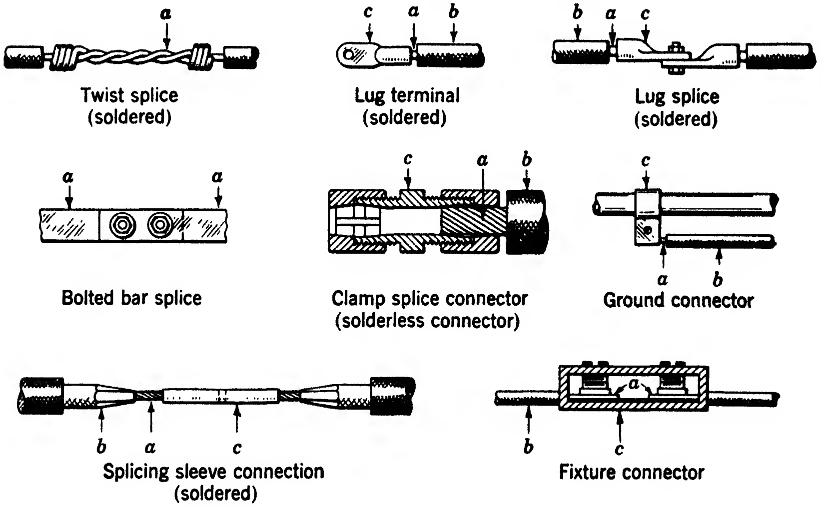
are placed in the ends of the fuse to allow the pressure to be released gradually and without the expulsion of flames.

The two principal types are the *renewable link fuse* (Fig. 12, *f* and *g*, p. 373) and the *one-time fuse* (Fig. 12, *a*, *b*, *c*, *d*, *e*). As the name implies, the renewable fuse may be disassembled and a new fuse link put in to replace the one blown. In the one-time fuse the *fuse link* is permanently soldered to the contacts at each end of the fuse, and this link is then surrounded by an arc-quenching powder. By far the greater number of fuses used at present are the renewable type. The NEC specifies the exact rating of fuses which should be used for the protection of each type of motor or lamp circuit. It also states the exact ratings for fuses which may be used in the main feeder, subfeeders, and branch circuits. When fuses are being specified this code should always be consulted.

20. Circuit breakers (see NEC, Art. 240). The fuse is the cheapest type of timed automatic circuit-opening device, but air and oil circuit breakers have almost unlimited life, are more accurately timed, and are more dependable. This is especially true for circuits of high current and high voltage. They are designed to open the circuit upon any desired degree of overload current and to perform this operation within any desired limit of time, from approximately 0.1 to 10 sec or longer. The time-setting device is adjustable. In selecting a circuit breaker of either the air or the oil type (Fig. 2, p. 356), it is necessary to include the following electrical specifications: the voltage of the circuit; the number of poles; the expected normal load in amperes; the maximum load in amperes, together with the number of hours that this load will probably exist; the low and high limits of excess current at which it may be desired to trip the breaker under overload or short-circuit conditions; and the maximum limits of generating capacity in kilovolt-amperes which this circuit-breaker will be required to interrupt at the time of tripping. In addition to these electrical specifications, it is, of course, necessary to designate the particular mechanical design of the circuit breaker and to indicate on the plans the outline dimensions and the methods of connecting the main feeders and control wiring.

Oil and air circuit breakers some years ago were usually mounted on the back of switchboard panels on special brackets, or separately supported on pipe framework, and operated by bell crank mechanisms connected to manually operated switch handles on the front of the panel. Such pipe-mounted switchboards (without sheet-metal side and top enclosures) are now obsolete and should never be installed in new buildings. They are dangerous and, in the long run, equally expensive, owing to labor costs in installation. Oil and air circuit breakers of heavy current capacity (500 to 10,000 amp) are usually closed by solenoids or by motors. These closing devices force the breaker contacts together against the compression of a spring which, at the time of opening, functions to make the contacts separate rapidly. The spring and tripping (opening) mechanism is released by a trigger, or "*dog*," which is moved by electrical remote control. Either the closing or opening operations, or both, may be performed automatically by relays. The *automatic tripping features* may be specified to operate under such conditions as overcurrent, overvoltage, undervoltage, line failure, reversed power flow, phase reversal, definite times of day, and many other desired conditions. Most electrical machinery, including motors, generators, transformers, and motor-starting and control apparatus, is limited in its capacity by the *maximum safe temperatures* which its insulation can stand without deterioration. Hence practically all such apparatus has some form of protective *thermal relays* which are actuated at dangerously high currents to disconnect the circuit.

21. Connections. In the installation of electrical conductors it is necessary to make *joints, splices,* and branch-circuit connections or *taps.* Such electrical conducting connections must be made on round wire, on rectangular bus bars, and on bus bars made of pipes. Figure 13 shows a few of the most common methods and materials for making such connections.



Twist splice (soldered)

Lug terminal (soldered)

Lug splice (soldered)

Bolted bar splice

Clamp splice connector (solderless connector)

Ground connector

Splicing sleeve connection (soldered)

Fixture connector

Fig. 13. Connections and splices: (*a*) conductor; (*b*) insulation; (*c*) conducting lug or connector.

With reference to this figure, the twist splice is used in practically all connections of small solid wires of the same size. This splice usually is then soldered over its entire length. The lug terminal is another common method of producing a splice which may be used on either solid wires or cables. The method of connecting or extending bus bars is shown by the bolted bar splice. The *solderless connector* is designed to secure contact to the end of the wires or cables by a tapered sleeve wedged into the conductor by means of a threaded nut. Connectors such as these may be obtained for joining wires of different sizes, for making taps from a wire of one size to a wire of another size, and for making connections between cables and bus bars. A common type of ground connector is shown, in which a brass or bronze ring is clamped over a water pipe and at the same time connected to a ground wire. A cylindrical splicing sleeve, with a small slot cut lengthwise in it, slipped over the two ends of wires to be spliced and then filled with solder, forms a *splicing-sleeve* connection. In order to provide a cheap and rapid means of connecting lighting fixtures to the branch circuits, a small insulated fixture connector containing two binding screws is frequently used. In any type of connection, large or small, the resistance of the connection should be not greater than a corresponding length of the adjacent smallest conductor.

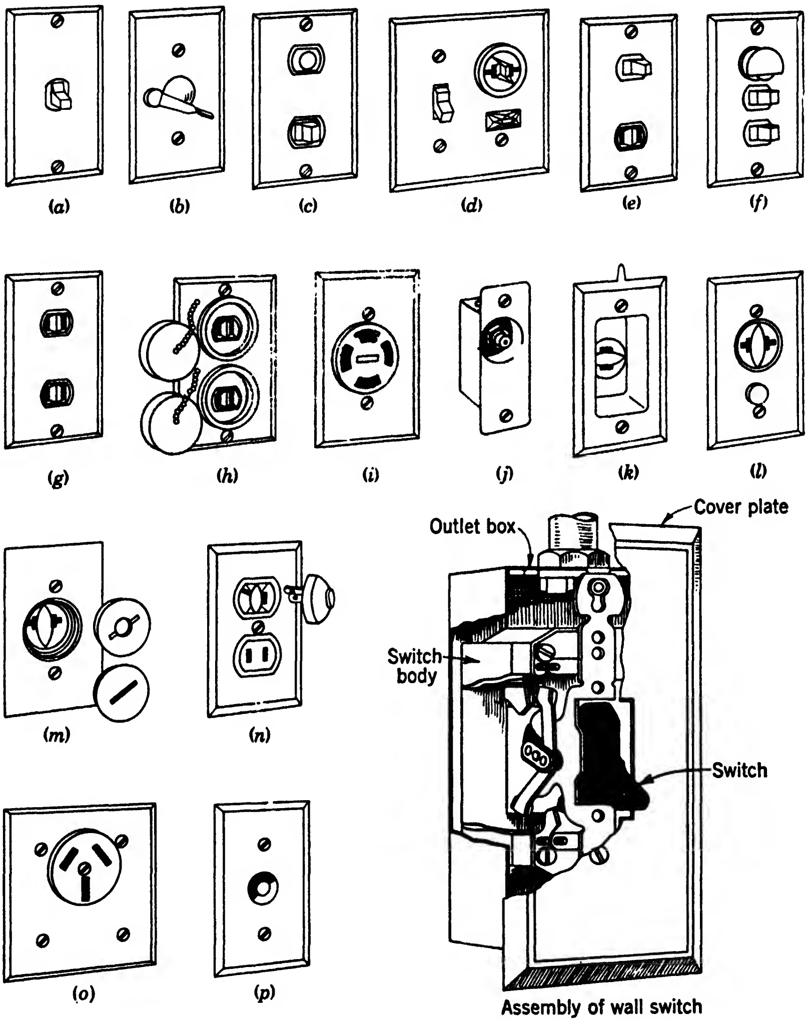
Whenever an insulated conductor is spliced, tapped, or connected by any of these types of joints to another insulated conductor the connection should be covered with insulation and protective wrappings which are in all respects equal in electrical and mechanical characteristics to the insulation on the conductors themselves. In order to provide such adequate insulation and protection, various types of adhesive-rubber, varnished-cambric, and friction tapes, and insulating compounds and varnishes are available.

Whenever connections are made to *lead-sheath cables* the connection and insulation must first be made as indicated above, and then a lead *wiping sleeve* (of larger diameter) must be slipped back over the joint and soldered to the lead sheath on either side of the joint. Skilled wiremen are required to wipe-on such lead sleeves.

On large uninsulated rectangular or tubular bus bars the connections are usually made with bolts and locknuts and with threaded or clamp-joint connectors, somewhat similar in design to the solderless connector shown in Fig. 13. The portions of the bars held in contact by the bolts are usually *silver-plated* to provide permanent low-resistance *contacts*.

22. Wall plates. *Wall plates* are commonly used on the plaster or finished surface of a room in a residence, office, or factory. Such plates may contain the ordinary toggle or push-button switch, single- or double-plug outlets, pilot lamps or radio outlets. Some standard types and sizes of conventional wall plates are shown in Fig. 14.

A one-gang plate is one of standard size (2¾ in. by 4½ in.), which is mounted on a one-gang outlet box containing a single device such as a switch for controlling the lamp circuit in a room. *Two-gang,*



Assembly of wall switch and plate

Fig. 14. Typical switches and outlets: (*a*) standard wall switch; (*b*) weatherproof switches; (*c*) switch and pilot light; (*d*) switch pilot light and outlet; (*e*) switch and outlet; (*f*) night light; (*g*) duplex outlet; (*h*) weatherproof convenience; (*i*) grounded 4-wire outlet; (*j*) door switch; (*k*) clock hanger; (*l*) fan hanger; (*m*) floor outlet with cover; (*n*) radio outlet; (*o*) range outlet; (*p*) telephone outlet.

three-gang plates, etc., are available for several switches, plug outlets, pilot lamps, or other combinations.

Wall plates are made of metal, rigid insulated compound, or glass, in many plain and ornamental designs. Some of the common finishes include brass, silver, gold, wood veneer, celluloid in various colors, colored enamels, and mother-of-pearl. The most common standard finish is polished or brushed brass and black or brown shades of compound (Bakelite, Micarta, Textolite, etc.).

The height of the center of switch plates is usually specified as 48 or 54 in. above floor level. The former is, and the latter is not, accessible to very small children. The location of plug outlets is largely dependent upon the use to which the connected device will probably be put. The common location in homes and office is either in the baseboard or a few inches above. However, in many offices and in some dwellings the height of the center of the plug outlets is about 32 in. above the floor level, providing easy accessibility for devices on tables or shelves. Fan and clock outlets are frequently placed from 7 to 8 ft above the floor.

23. Underfloor duct systems. This method of providing preset inserts for outlets for lamps and appliances, for telephones, and for low-voltage signal systems is widely used. Study carefully Fig. 15 and Fig. 16 and their legends. The junction boxes are shown at the intersections of all ducts. The removable tops of these boxes are flush with the floor and finished with the same material as the floor. For example, a linoleum floor covering would be matched by the circular piece of linoleum set in the groove provided in the cover. The boxes and ducts are placed in the concrete subfloor or forms and leveled with vertical adjusting clamps. Then the top pouring of concrete comes almost level with the top of the box rim, lacking only the thickness of the linoleum or other floor covering. These systems may likewise be installed in monolithic or steel deck floors.

One-, two-, or three-duct systems are available using, respectively, the junction boxes shown in Fig. 16. Two sizes of ducts may be used:

No. 1, with outside dimensions 1⅞ in. by 1¼ in.; inside area 1.926 sq in.

No. 2, with outside dimensions 3⅛ in. by 1¼ in.; inside area 3.313 sq in.

The present trend is towards the use of only the larger size.

Standard duct of the above sizes comes in lengths of 5 ft, 0 in.; 6 ft, 8 in.; 7 ft, 6 in.; full length, 10 ft, 0 in. In general, it is desirable to use the larger duct (No. 2).

With desks averaging 48 to 60 in. in width a convenient spacing of duct runs should be from 6 to 8 ft on centers. The inside walls should be 3 to 4 ft from the center lines of the adjacent parallel duct run. The inserts (for the attachment of service fittings) along each duct are spaced on 24-in. centers. They may be spaced at other intervals on special order.

These duct runs are usually set $5\frac{1}{2}$ to 7 ft apart (on centers), and cross-connecting ducts may be centered 6 to 8 ft apart. The electric services enter these *junction boxes* at the corners and from these make connections (*"home runs"*) through standard round conduit to the electric panelboards, telephone terminal cabinets, etc.

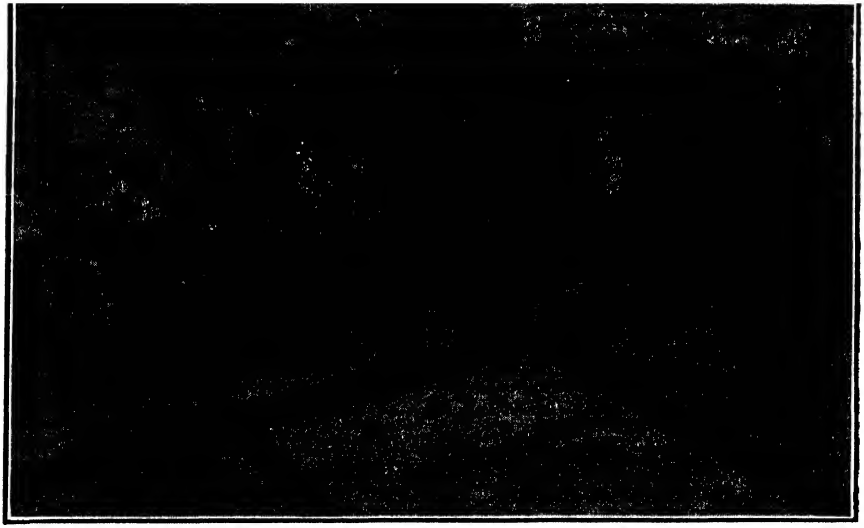
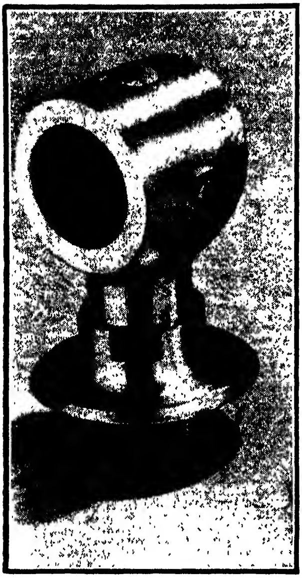


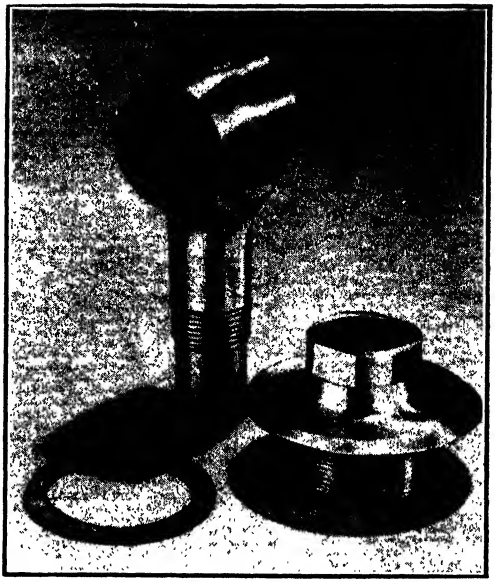
Fig. 15. A typical layout of the Walker underfloor duct system: (*a*) three separate ducts; (*b*) with preset inserts for outlet fittings spaced 24 in. apart; (*c*) a 3-duct junction box; (*d*) a typical duct spacing of 7 ft on centers (can be varied); (*e*) duct inserts (spacing changed on special order), exact center location of each of which can be identified by a magnetic pointer instrument; (*f*) locations of special floor outlets for telephone and signal circuits, for 115/230-volt appliances, and for desk machines (dictaphones, electric typewriters, and comptometers).

A typical layout of the *underfloor duct system* is shown in Fig. 17 for a rather large office area. Many fittings are available for connecting underfloor ducts of the two standard sizes to the junction boxes; or for connecting any size conduit (up to 2 in.) to the corners of the junction boxes.

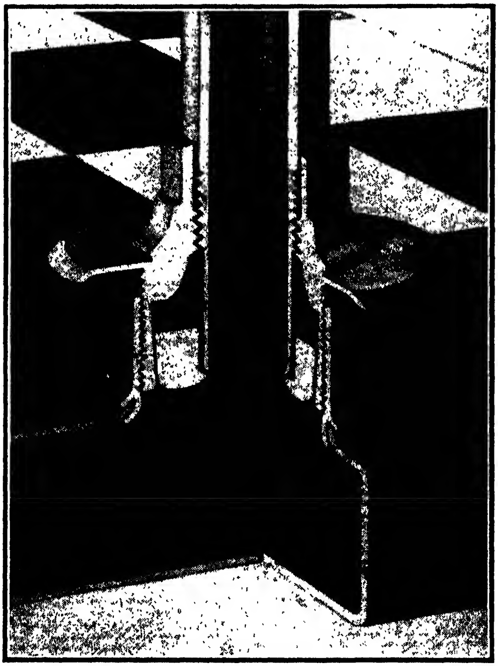
24. Q-floor duct system. A typical portion of this *duct system* is shown in Fig. 18. The methods of laying the 24-in. sections of *Q-floor* on the main beams, extending the header ducts at right angles



(*a*)



(*b*)



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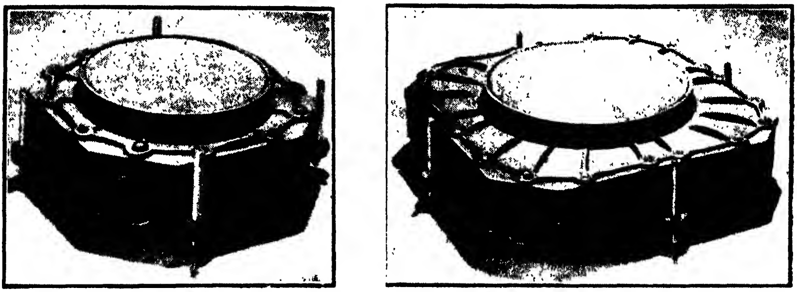
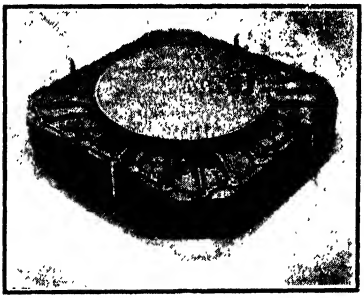


(*d*) (*e*)



(*f*)

Fig. 16. Typical junction boxes and outlet fittings for Walker underfloor duct system: (*a*) 3-wire outlet; (*b*) for round cable outlet, (*c*) enlarged view of installation details for typical base of standard outlet fittings for power, telephone, and signal systems; (*d*), (*e*), and (*f*) typical junction boxes for 3-, 2-, and 1-duct systems. The overall dimensions of the junction boxes (for size 2 duct) are (*d*) 3-duct, 15¼ by 15¼ by 3⅜ in. high; (*e*) 2-duct, 11¾ by 11¾ by 3⅜ in. high; (*f*) 1-duct, 8¼ by 8¼ by 3⅜ in. high. The various types of outlet fittings average 3½ to 5 in. high above floor finish.

to the duct-cells and upward to wall mounted distribution panels, and the installation of conductors and floor outlets on branch circuits are generally similar to those mentioned in Art. 23, p. 378. A careful study of the figures and their captions should be made and compared with those for the Walker duct system, Fig. 15, p. 379.

All *Q-floor cell sections* and the crosswise header ducts (for feeder and branch circuits) are tack-welded to the main floor beams and to each other. These welds insure electrical grounding of the raceways. The safety rules and regulations for this system are covered in NEC, Art. 354. (Also see Art. 100, definition of raceways, wireways, busways, etc.) The three following types of wiring systems must run in separate Q-floor cells and header ducts: general lighting and appliances; telephones; and low-voltage signal systems. A complete range of outlets and fittings is available, together with installation tools and accessories.

Several other excellent underfloor duct systems are available. One by the General Electric Company consists of impregnated fiber duct conduits connecting all the cast-steel junction boxes. The junction boxes, conduit fittings, various types of outlet fittings, etc., are quite similar to those previously mentioned and shown.

The methods of installation for all the above underfloor systems are quite similar. In general the procedure for installing an outlet (where one does not exist) is to cut away the floor finish and the surface thickness of concrete or wood floor until the desired duct is exposed. Then the conduit (fiber or metal) is cut and threaded to fit the threads of the desired outlet fitting. Patching cement and pieces of the linoleum or other floor covering are then applied. One, two, or three ducts may be installed in any of the systems mentioned. Special tools and instruments are provided by underfloor duct manufacturers to facilitate installation and operation. Among these are junction-box and conduit leveling screws; a magnetic instrument for locating the centers of junction boxes and separate conduit runs; braces, drills, and threading tools for inserting additional outlet fittings at any place along any of the ducts.

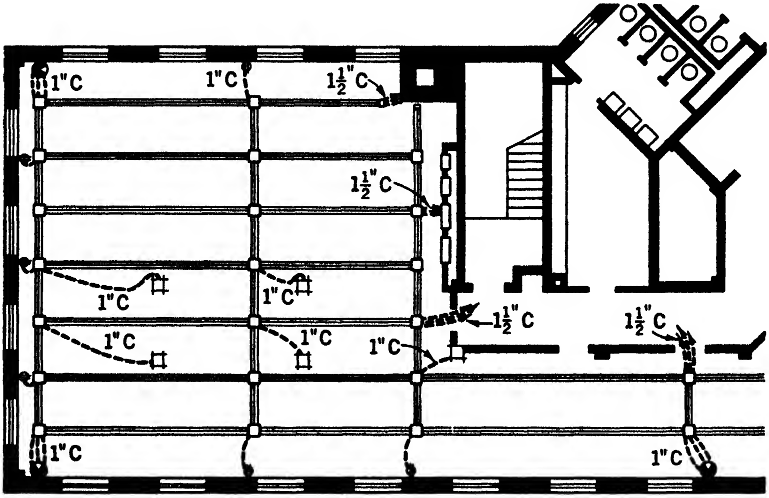


Fig. 17. A typcial layout of connection boxes and rectangular raceways for a 3-duct Walker underfloor system. Note the round-conduit connections (dashed lines) for wall and column outlets and for home-run connections to sources of supply in panelboards, etc.

NEC CODE AND SUPPLEMENTARY TEXT REFERENCES

Appendix A NEC Items: A13, A14, A15, A16, A21, A22, A24, A25, A26, A27, A28, A30, A31, A33.

Appendix B Text Items: B1, B2.

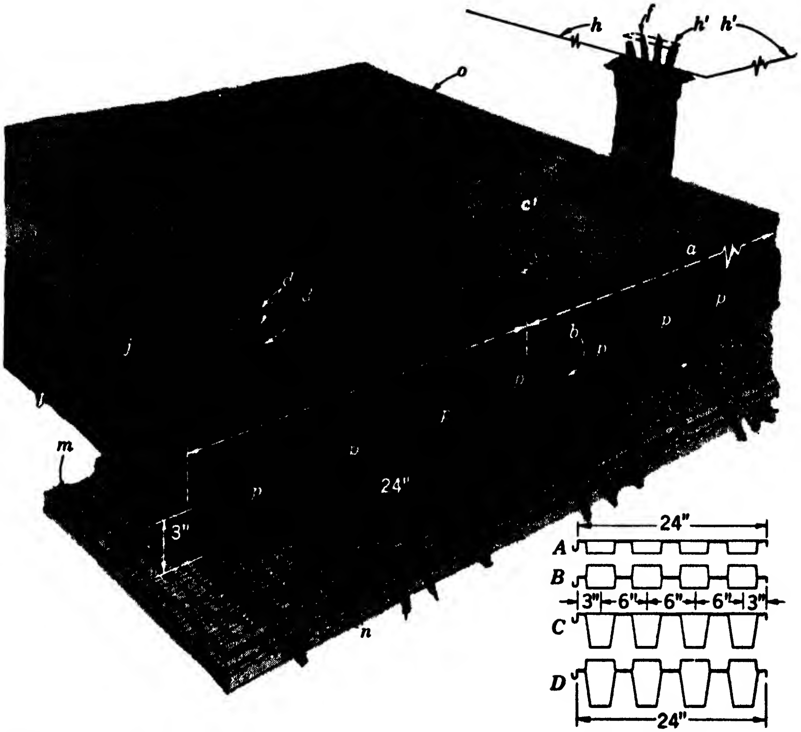


Fig. 18. Typical B-section view of the Q-floor Robertson duct system: (*a*) 24-in. sections; (*b*) interlocking joint of sections; (*c* and *c'*) floor outlets; (*d* and *d'*) box leveling screw; (*e*) linoleum filler on outlet cover to match the floor covering; (*f*) cables carried in crossheaders; (*g*) elbow from crossheader to bottom of wall cabinet or panelboard; (*h* and *h'*) bottom of cabinet; (*j*) crossheader; (*k*) concrete floor; (*l*) linoleum covering; (*m*) upper side of hung ceiling; (*n*) details of hung-ceiling hangers, steel supports, metal lath, and acoustical plaster; (*o*) typical floor outlet (duplex type); (*p*) natural metal ducts for wire runs to crossheaders. Any separate ducts or crossheaders may be used for power, telephone connections, or signal circuits, but not in the same ducts. Four available cross sections of typical Q-floor ducts are identified in the lower right corner of the figure. (See NEC Art. 356.)

PROBLEMS

1. (*a*) What is the purpose of the NEC? (*b*) Does its use necessarily secure an efficient electrical system? Mention about 10 major sections, and give a one-sentence outline of what each of these sections covers.

2. Refer to the wire table (Table I, Chapter 23, p. 334). What sizes of RH Wire would be selected to carry 20, 75, 100, and 400 amperes?

3. Refer to Table I, Chapter 23, p. 334. Determine the conduit sizes for the following combinations of conductor sizes and number of conductors: two No. 12; six No. 10; three No. 2; three 400,000.

4. Assuming that 100 amp flow continuously in a given circuit, what sizes of wire would be suitable if the insulations were types R, RH, V? If the table does not indicate the actual current, select the wire size for the next higher current.

5. What types of service and feeder switchgear would be used for very large and high office buildings? Sketch an approximate layout with overall dimensions and weights of the service breaker, four feeder breakers, and the duplex controlboard for the 13,800-volt service. This assignment covers two separate fireproof rooms.

6. Make a sketch showing conduit fittings types LB, CO, and LR (Fig. 11) connected in a typical conduit system.

7. Sketch an exposed conduit system passing through a room where use is made of typical conduit fittings, say types LL, TB, and E or others.

8. What types of fuses may be selected for protection of conductors whose current must be limited to: (*a*) 20 amp, (*b*) 45 amp, (*c*) 250 amp? Could circuit breakers be used instead of fuses?

9. What types of splice would be desirable for connecting: (*a*) a wire to a motor terminal; (*b*) two large cables; (*c*) two copper bars 2 by ¼ in.; (*d*) two small wires? Identify these splices by name. Sketch part (*c*).

10. Make a schematic wiring diagram for (*a*) a 10-circuit 2-wire lighting panelboard (refer to Fig. 6, p. 361); (*b*) for a 3-wire single-phase panelboard; (*c*) for a 4-wire 3-phase panelboard connected to a grounded-wye feeder.

11. For a 4-wire grounded-neutral lighting panelboard (*a*) show the complete panelboard diagram, and (*b*) indicate the proper location of main and branch circuit breakers. Under what conditions may the main-line circuit breaker at the panelboard be left out? (Refer to NEC for proper rules.) (Refer to Fig. 6, p. 361.)

12. Discuss the design and operations of the several types of fuses.

13. What design features of circuit breakers differ from those of fuses?

14. What should be the locations (height above floor) of several types of wall plates?

15. Lay out a complete underfloor duct system for an office desk area 30 ft by 40 ft. List approximate quantities of duct accessories. Write a brief specification for duct materials.

Chapter 25

PRINCIPLES AND APPLICATIONS OF D-C MACHINERY

1. General. The design and operation of electrical machinery is based on well-established principles of electricity and magnetism. A few of these principles will be given in the following articles and their applications indicated. Mechanical equipment, such as fans, pumps, compressors, and valves, are usually driven by a-c motors. The d-c motor is used where variations in speed over wide ranges are needed as in its application to elevators. (See Chapter 29.)

2. Magnetic circuit for a d-c generator or motor. The magnetic circuit of a generator or motor (Fig. 1) includes the iron and steel through which the magnetic flux (Φ) passes. For a d-c generator this includes the portions of the frame, the poles, the armature and the two air-gaps. This flux is produced by the two field windings marked f. The number of turns *times* the amperes in these windings is referred to as the *field ampere-turns* (NI) or *magnetomotive force* (mmf). It is the mmf which causes the magnetic flux to be set up.

Relative *permeability* (μ) refers to the ease with which magnetic flux passes through iron or steel as compared to the permeability of air. In air the *permeability* (μ) is 3.192. In annealed iron, such as the iron laminations used in electric motors, generators, and transformers, the *flux density* (β) set up by the ampere-turns (NI) in the coils is measured in total lines per square inch. If the iron paths were replaced with nonmagnetic materials (such as wood, cement, or even air), then the equation for flux per square inch (β) would be

$$\beta = \frac{3.192NI}{l} \quad \text{or} \quad NI = 0.3133\beta l \qquad (1)$$

where l is the length of the magnetic path in inches.

If the paths are of special grades of iron, as used in electrical machinery, then 0.3133 does not remain a constant but varies with the flux densities existing in the magnetic materials of these machines under various conditions of operation. This constant which thus becomes a variable for magnetic materials is designated as the *permeability* by the Greek letter mu (μ).

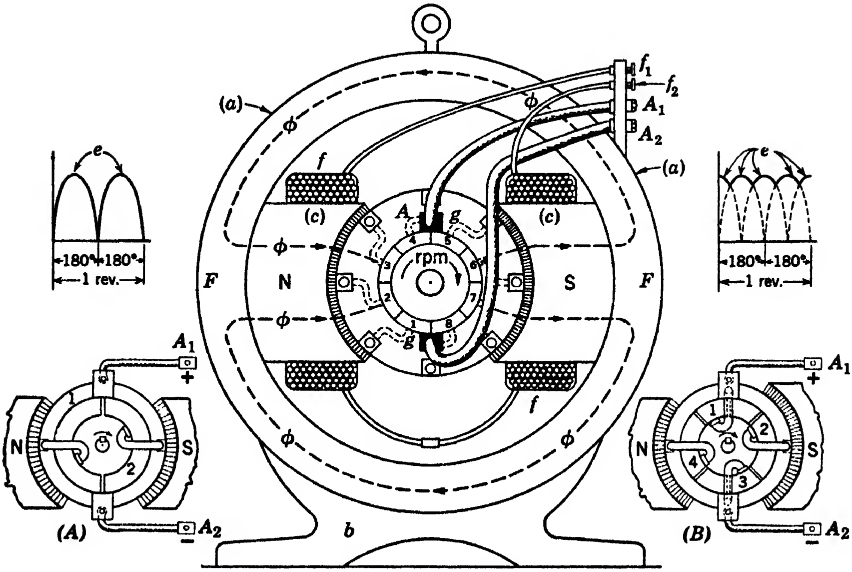


Fig. 1. Elementary cross section of a d-c generator. The parts include: F, the exterior frame; (b) the base; (c) the two poles, N and S; A, the revolving armature; (f) 2 field coils with terminals f_1 and f_2; 8 conductors (o) in slots on the armature; 8 commutator bars (numbered 1 to 8) insulated from one another; (g) 2 brushes bearing on the commutator; and the armature leads from these brushes to the armature terminals. The 2 conductors of armature (A) are so connected to the 2 commutator bars that a d-c voltage similar to e' with 2 surges in 1 revolution is induced. With 4 bars and 4 conductors as in (B) the pattern of voltage surges becomes much nearer to a constant value of direct voltage (4 surges, e''). The brushes on the commutators thus "pick-off" the induced voltages of the coils at more frequent periods with a greater number of commutator bars. In modern d-c generators with many bars and conductors the surges become mere "ripples" or a nearly constant direct voltage. In the a-c generator, or *alternator*, there is no commutator. A group of armature conductors are connected in series to 2 *slip-rings* on the shaft. Brushes bear on the slip-rings and deliver the typical a-c sine wave to the armature terminals. See a-c generators, p. 397.

Equation (1) then changes to

$$\beta = \frac{\mu NI}{l} \qquad \text{or} \qquad NI = \frac{\beta l}{\mu} \tag{2}$$

Magnetic paths in electrical machinery usually have μ-values from about 2000 μ_0 to 13,000 μ_0; and β-values from about 3000 to 80,000 lines per sq in.

The *total flux* (ϕ) which passes through any cross section of the flux path A, such as out of the face of a N or S pole, is equal to the area of the pole face in square inches (A) times the flux density (β); hence

$$\phi = A \times \beta \tag{3}$$

This total flux ϕ will appear in the next equation (Art. 3).

The flux in a d-c generator or motor operating at a given speed is dependent upon the number of turns on the field poles and the d-c current in those turns. It can be shown that the speed of a d-c motor when connected to a constant d-c source of supply (such as 110 or 220 volts) will vary inversely as the field flux. Hence a rheostat in series with field circuit can control the speed. When the armature or rotor of a d-c generator is driven at a constant speed, the induced emf in the armature is directly proportional to the flux from the poles due to the field current, I_f. Hence this voltage may be varied by the use of a field rheostat.

3. Generator action or induced electromotive force. Figure 2 represents a magnetic flux in the air gap between two iron pole pieces,

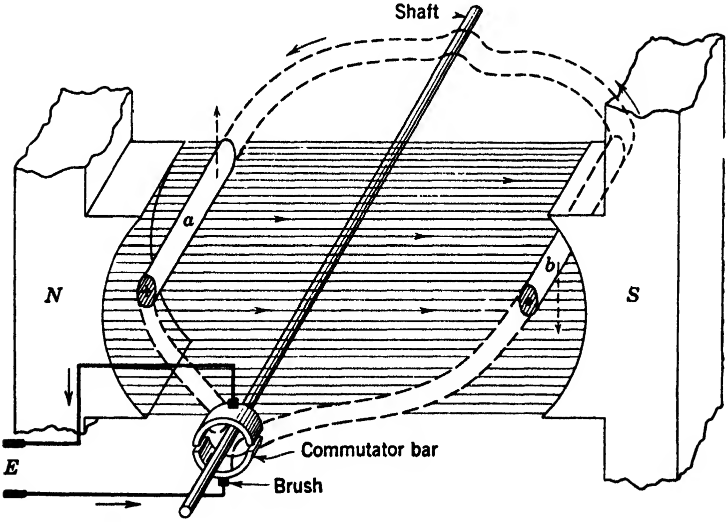


Fig. 2. A single loop coil consisting of two sides (a) and (b) moving through a field of magnetic flux. Rotation of the shaft and coil is clockwise. An inflowing emf is induced in (a) and an outflowing emf is induced in (b).

with the coil side (*a*) moving transversely upward to cut the flux lines from the N pole. This cutting induces a voltage (emf) *inward* into (+) the wire. The other side of the coil (*b*) is moving downward across the flux at the S pole at the same time that (*a*) moves upward, inducing an *outward* voltage (•). Therefore the two emf's add to give a voltage between the terminals of the coil. Thus high voltages may be obtained: by having a large flux, by increasing the rate of the cutting (i.e., the speed), or by adding to the number of turns per rotating coil. The armature of a modern, high-voltage generator is so wound that a great many conductors in series cut large fluxes at high speed. The formula below gives the output voltage of a generator for P number of poles, with ϕ flux per pole, Z armature conductors, n revolutions per second, and p the number of parallel paths.

$$E = \frac{P\phi Zn}{10^8 p} \text{ volts} \tag{4}$$

All modern generators should be driven at constant rated speed by their prime movers: steam turbines, water wheels, or electric motors. Therefore, the voltage induced in conductors or *"armature windings"* of these machines is constant as long as the field flux cut by the conductors remains constant. A generator voltage regulator is used to adjust the field rheostat automatically to maintain a constant desired voltage at the terminals of the generator. It may be so adjusted that it will gradually raise the terminal voltage as the load on the generator increases, thus compensating for losses of voltage (RI drop), in the circuit conductors. Thus an essentially constant voltage may be delivered to the terminals of the operating electrical equipment. The armature of a d-c generator is the revolving element containing slots within which are coils whose conductors (Z) are typical of those just mentioned. The armature windings are so arranged that several exactly similar paths are connected in parallel; each path having induced in it exactly equal emfs. Each path is also of the same size wire as other paths; hence, when the generator is under load the total armature current I_A delivered at the two terminals of the machine is equal to the current per path times the number of paths, or

$$I_A = I_p \times N_p \tag{5}$$

The total output of the armature in watts would therefore be

$$V_A \times I_A = W_A \tag{6}$$

4. Motor action or torque produced. It can be proved experimentally that a wire carrying current in a magnetic field is acted upon by a force which tends to move (push) the wire out of the field. The actual force acting on each unit length of the wire depends on the number of amperes in the wire and the strength of the flux transverse to the wire. The formula for the force in pounds is:

$$F = 0.885\beta li \times 10^{-7} \tag{7}$$

where β is the flux per square inch, l the length of the wire in inches, and i the current in amperes.

Figure 3 illustrates the N and S poles of a horseshoe magnet, each pole face being 1 sq in. in cross section. The magnetic field or flux extends from the N pole to the S pole through the air gap and then completes its path through the magnet. The flux density is assumed to be 40,000 lines per sq in. The wire a is 1 in. in length at right angles (transverse) to the flux in the air gap and is to carry a current of 50 amp. Under these conditions the force on the wire is

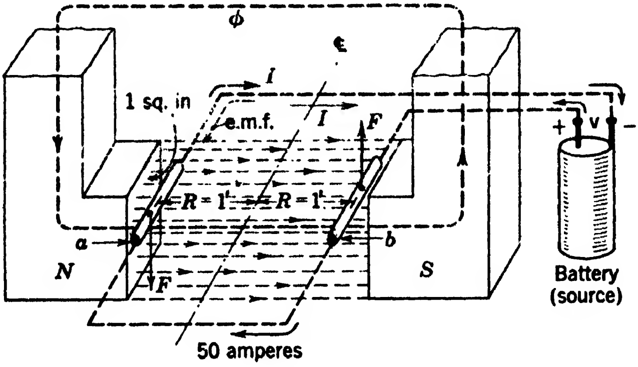


Fig. 3. Generator action of an armature turn. A loop of wire consisting of two sides (a) and (b), lying in a magnetic field and through which an electric current is being forced from a battery, is subjected to a rotational force on the two conductors as indicated by arrows FF.

$$F = 0.885 \times 40{,}000 \times 1 \times 50 \times 10^{-7} = 0.177 \text{ lb}$$

The force on the other wire b is the same. Therefore the force on the two sides of the coil, tending to rotate it, would be $2 \times 0.177 = 0.354$ lb. Torque is defined as the turning force exerted at the end of a given radius from the center of rotation. For example, if the distance (radius) from the center of the shaft to the center of the conductor a were 1 ft the torque, in foot-pounds (ft-lb), exerted on the shaft by the force on this conductor would be

$$T = F \times r = 0.177 \times 1 = 0.177$$

This is the fundamental theory on which torque is produced in all d-c and a-c motors.

5. Direct-current generator. The conductors which cut across the flux from the poles of a generator are supported by slots cut parallel to the shaft in the face of a cylinder of iron revolving with the shaft. This cylinder together with the conductors is called the armature. Narrow air gaps, sufficient to allow freedom of rotation, separate the armature from the pole faces. The conductors on the face of the armature are so connected to a commutator that the induced emf's add to give the desired terminal voltage. The commutator is a cylindrical arrangement of copper segments insulated from one another and rotating concentrically with the shaft. Brushes of carbon or graphite are pressed down by springs upon the surface of the revolving commutator, and these brushes are connected to the terminal posts (terminals) of the machine. The purpose of the commutator is to provide means of conducting the current from the moving conductors to the stationary terminals and to commutate the alternating emf's and currents which flow in the conductors as they alternately pass N and S poles.

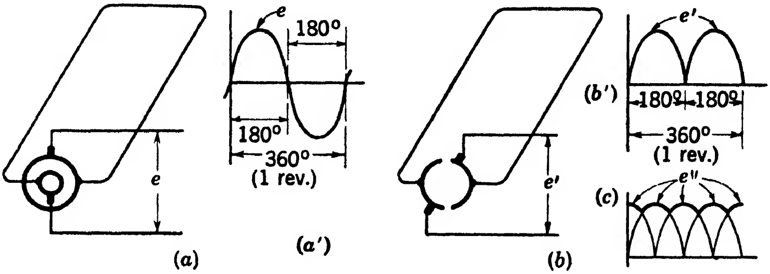


Fig. 4. Motor action, torque produced by conductors carrying current in a magnetic field. A loop of wire when connected to continuous slip-rings (*a*) when rotating in a magnetic field produces in one revolution an alternating voltage consisting of a positive and a negative loop (*a'*). A similar coil (*b*) with ends connected to 2 half-circle segments (commutator) as indicated, when rotating in a magnetic field, produces in one revolution two positive loops of direct voltage (*b'*). In (*c*) four quarter-circle segments with two loops of wire 90° apart (not shown) produce almost a constant direct current having four minor pulses (*e''*).

The elementary principle of commutation may be learned by a study of Fig. 4. The emf generated in each conductor has a positive and a negative value (alternating) as it passes the N and the S pole. The "commutator" reverses the negative half, thus approaching the formation of a unidirectional emf, i.e., a direct voltage tending to make current flow in the same direction at all times. However the two pulses of emf and current (as at *e'*) in 1 revolution can be less severe if the commutator should have 4 bars and an ***additional coil*** (not shown) and be displaced 90° from coil 1. The pulses now are approaching ripples. Thus the brushes "pick-off" only the maximum values of the voltages induced in each coil, as shown in (*c*) at *e''*.

The induced emf, and also any current flowing in any conductor (a or b), reverses in direction through that conductor as it passes the point of zero flux between each adjacent pair of poles. If, for example, each end of the one-turn coil in Fig. 4(a) were connected to a smooth ring revolving concentrically, then brushes rubbing on these two rings would impress an alternating voltage on the external circuit. In this case the machine would be an a-c generator. If, however, each end of the one coil is connected in a half-circle segment, as shown in Fig. 4(b), p. 390, and if each of the two segments is insulated from the other, then the emf is rectified or commutated (by contact with the carbon brushes) with respect to the external connections. This machine would be a d-c generator.

If the radial flux in the air gap is dense at the center of the pole and tapers off according to a sine-wave law ($\phi = \phi' \sin \theta$) to zero midway between the poles, then the induced emf in the conductor will vary from maximum at the pole center to zero at the midposition between poles, and will have a sine-wave shape during each half-revolution or 180°, as in curve (a) Most generators are so designed that the induced emf at the terminals of all conductors connected in series has this sine-wave form. Thus the two slip rings, Fig. 4(a), give an alternating (a-c) sine-wave emf at the terminals; and the two insulated commutator segments, Fig. 4(b), give a rectified or commutated (d-c) sine-wave emf. These two sketches represent the only fundamental difference in construction between a-c and d-c generators: the former has slip rings, the latter has a commutator. The a-c generator applies alternating emf's, and the d-c generator applies direct emf's, to any connected external circuit. In order to smooth out the sine-wave humps indicated in the emf wave of Fig. 4(b), a large number of coils are distributed around the armature and are connected to many commutator segments or bars, as in Fig. 1(B).

The voltage at the terminals of a d-c generator decreases as the kilowatt output increases, owing to RI drop in the armature conductors and to armature reactions which reduce the magnetic flux from the field poles. To compensate for such voltage drop the current in the field circuit is increased, either by hand or by automatic control of a field rheostat in the field circuit. A shunt generator has many turns of small wire around each pole, the circuit being excited at the terminals (in shunt) with the armature. A compound generator has another winding (series field) of large wire making several turns around each pole, and connected in series with the armature circuit to the terminals. As the current output to the load increases, the additional mmf added to that of the shunt field by the series field *ampere-turns* (NI) raises the flux and thus compensates automatically for voltage drop. Figure 5(a, b, c) illustrates the schematic connections of the shunt, series, and compound generators.

The shunt generator is used in buildings for elevator control, charging storage batteries, operation of large calculating machines, and a few rare applications requiring variable speeds. If direct current at a constant or rising voltage should be desired with increasing load, the compound generator would be selected. When a-c service is supplied to the building, all d-c service is usually obtained by an a-c motor driving a d-c generator, the combination being referred to as a motor-generator (m-g) set.

6. Direct-current motors. The shunt, series, and the compound motor, Fig. 5(*d*, *e*, *f*), are three common types of d-c motors. The shunt motor is constructed electrically and mechanically like the shunt generator. The series motor takes its name from the fact that its field flux is set up by heavy wire field coils which are excited in series with the armature and the line. The compound motor which has a few special applications is similar in construction to the compound generator.

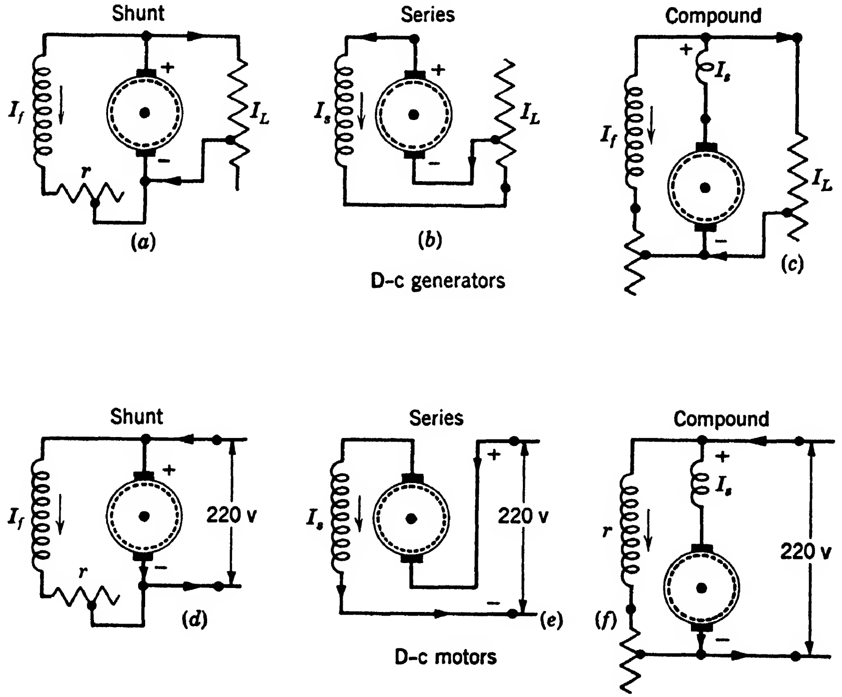


Fig. 5. Elementary d-c generators and motors. These show the schematic wiring diagrams for the above generators and motors.

The armature conductors of the motor have electromotive forces (emf) induced in them, because of their rotation through the field flux. This emf is *opposite* (backwards) to that of the impressed voltage at the terminals of the motor and always less than this *back emf.* The current which flows into the motor armature is dependent on the difference between the impressed emf and the back emf (E_b), and is limited by the resistance of the armature windings. This may be expressed by

$$I = \frac{\text{Impressed voltage} - \text{Back emf}}{R} = \frac{V - E_b}{R} \tag{8}$$

or

$$V = E_b + RI \tag{9}$$

where R is the resistance, in ohms, of the armature circuit.

I is the current, in amperes, in the armature.

The motor current is forced through the armature from the positive to the negative line terminals, i.e., in the same direction as the applied terminal voltage V, but opposite to E_b. The numerical value of the E_b of a motor and the induced emf (E) of a generator is expressed by the same equation:

$$E_b = E = \frac{P\phi Zn}{10^8 p} \quad \text{as developed in Article 3, p. 387.}$$

For any given motor the quantity $PZ/10^8 p$ in the above equation is a constant k, hence the equation may be written

$$E_b = k\phi n \tag{10}$$

or, substituting in the above equation for I and solving for n,

$$n = \frac{V - RI}{k\phi} = K\frac{E_b}{\phi} \text{ rev per sec} \tag{11}$$

where $(V - RI) = E_b$. The last equation shows that the speed varies inversely as the field flux ϕ and directly as the back emf. This means that a d-c motor at a given load (torque) will increase in speed if the field current is reduced, and vice versa. These are the fundamental equations of the d-c motor.

The current flowing in the armature conductors reacts with the field flux to produce torque as explained in Art. 5, p. 389. This torque drives the armature and shaft, overcomes bearing friction and windage, and may be made to carry an additional mechanical load.

The speed regulation vs. horsepower output for the several types of d-c motors from zero to full-load conditions may be derived from a study of the above speed equation. As the load on the motor is increased the armature tends to slow down. Thus the back emf is slightly reduced and more current flows into the armature, producing a greater RI drop. As the current increases, armature reaction flux (which is set up by the armature in opposition to the main field flux) is increased and cuts down the resultant field flux, tending to increase the speed and to counteract the additional load torque. The *shunt motor,* therefore, runs at fairly constant speed at all loads.

For a given load on the *series motor* the same current passes through the series field coil and the armature. At light loads the current decreases. As it decreases, the field flux ϕ also decreases and the *RI* drop becomes less. Both of these effect an increase in speed; and if the load becomes too light the motor will run away. *For this reason a series motor must always have a connected load sufficient to prevent destructive speeding.* As the load is increased the flux quickly builds up, the *RI* drop increases, and the speed falls at a rapid rate. A compound motor, having characteristics depending upon both shunt and series field phenomena as explained above, has a greater drop in speed with increase of load than the shunt motor, but not so great as the series motor.

A standard shunt motor is usually designed to produce from 1 to 2 times full-load torque at starting; it rises rapidly to full speed, carries a variable load at practically constant speed, and can be varied from 100 per cent down to about 75 per cent of rated speed. Under special designs the speed range may be made to vary from 30 to 100 per cent.

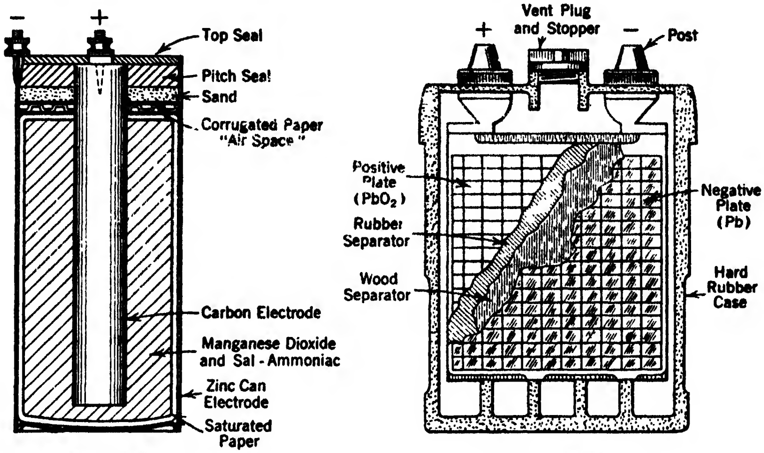
The characteristics of the *compound motor* combine certain features of both the shunt and the series motor. The degree to which it resembles one or the other depends upon the relative ampere-turns in the shunt field and in the series field coils. It has a greater starting torque and more variable speed under changing loads than the shunt motor, but less than the series motor.

A series motor (seldom used for building service) has a very high starting torque ranging from 100 to 500 per cent of rated full-load torque; it rapidly accelerates to full speed, and the speed varies greatly with change in load. A typical application is the closing of a heavy-oil circuit breaker, the complete operation requiring a very heavy starting torque and a rapid acceleration. The operation is started, completed, and the motor disconnected in about 1 sec.

7. Storage batteries and primary cells. In general the word cell refers to a single element which produces an emf by chemical action. The term battery is applied to a number of such cells connected together in series to obtain a greater voltage or a greater current than would be furnished by one cell. Figure 6 shows a typical storage battery and a typical primary dry cell.

The emf, or potential, of a dry cell or of a storage battery is produced through chemical reactions; that of an electric generator through induction, that is, mechanical motion of conductors in a magnetic field. The effect of applying equal emf's to a given circuit, generated either by chemical reaction or by induction, is identical. Ohm's law is applicable for either emf.

Storage batteries are used in large buildings for fire alarms, paging, signal and intercommunicating telephone systems. Emergency lighting circuits are frequently supplied from storage batteries, such circuits being controlled to light a few lamps in hallways, at exits, and other locations through which occupants must be guided in case of failure of normal lighting. The automatic and remote-control equipment (relays, solenoid-operated switches, pilot lights, and protective devices on large switchboards) is usually energized by storage batteries.



(a) Dry Cell (b) Storage Battery

Fig. 6. General materials and details of construction of a dry cell (*a*), and of a storage battery (*b*).

Primary batteries are very infrequently used in modern buildings. The small transformer for operation on a-c house circuits has largely displaced the dry cell for ringing bells. Occasionally a small intercommunicating telephone system is operated by primary cells, although a storage-battery installation, with a vacuum-tube rectifier for charging it from the a-c circuit, is preferable.

Storage batteries are normally charged by automatically operated motor-generator sets. A relay is adjusted to cause slow charging (*trickle charging*) whenever the battery voltage is slightly below normal. When the battery is subjected to steady or emergency discharges, the m-g set again recharges it. Electronic converters are also used to charge the batteries from an a-c source.

8. Direct-current requirements. In large buildings direct current is seldom used to supply the major power requirements. The a-c system has practically displaced it. Equipment requiring direct current for operation usually demands very little energy; hence a small motor-generator set, a storage battery, or a vacuum-tube rectifier is sufficient for the purpose. In the majority of cases it is no longer necessary to depend upon d-c motors for variable-speed drives since a-c motors with variable-speed characteristics are available. However, in high-class passenger elevator installations in large buildings direct current is invariably used. The wide adoption of alternating current as a standard for electric service has led manufacturers of motor-driven mechanical equipment (fans, pumps, compressors, and other machinery) in many cases to alter the design so that variable loads may be carried at high efficiencies at constant speeds.

NEC CODE AND SUPPLEMENTARY TEXT REFERENCES

Appendix A NEC Items: A10, A73.
Appendix B Text Items: B1, B2, B3.

PROBLEMS

1. Very briefly outline what is meant by (*a*) the magnetic circuit of a generator or motor; (*b*) the electric circuits of a generator or motor.

2. Define the words: (*a*) ampere-turns; (*b*) flux, flux density. In general in a given d-c electrical machine does the flux remain essentially constant?

3. Describe the several physical principles which seem to justify the equation for the induced emf (e) in a d-c generator, i.e.,

$$E = \frac{P\phi Zn}{10^8 p} \text{ volts}$$

4. An electromagnet 8 sq in. in cross section has a flux density of 15,000 lines. What is the total flux?

5. What flux would be produced by a coil of 2000 turns carrying 10 amp in a ring of annealed sheet steel (a ring formed like a doughnut) with the turns wound around it, with a cross section of 5 sq in. and an average diameter of 16 in., assuming a permeability of 40,000?

6. There are 6 poles, 240 conductors in series between terminals, and a flux of 5,000,000 lines per pole in a certain d-c generator. The rotating coils revolve at 1800 rpm (30 rps). (*a*) What voltage is generated? (*b*) What voltage would be generated if the flux was increased 20 per cent? Note: The generated voltage varies in direct proportion to the speed and to the flux.

7. (*a*) What current would flow in a motor armature of 0.25-ohm resistance if the impressed voltage was 120 and the back emf was 115 volts? (*b*) Assuming that the speed under the above condition was 1200 rpm, and that the applied voltage and flux remain constant, what current would flow into the armature at 1000 rpm?

8. (*a*) For what purposes are storage batteries frequently used in office buildings? (*b*) How are they recharged?

Chapter 26

PRINCIPLES AND APPLICATIONS OF A-C MACHINERY

1. A-c generators. The a-c generator or alternator impresses an alternating wave of emf on the external circuit. The proper number of armature conductors are connected in series to produce the desired voltage at the machine terminals. All modern alternators have a pole flux distribution and a spacing of the active conductors in such relation that the induced emf between slip rings (or armature terminals) is practically a true alternating sine wave. The equation for the instantaneous values, e, of a sine wave in terms of the maximum induced emf, E_m, is

$$e = E_m \sin \theta \tag{1}$$

The instantaneous values of the induced sine wave of emf may be represented by the projection on the vertical of any rotating vector equal in length to the maximum value of emf, E_m, or to the corresponding ordinates of the sine wave, as in Fig. 1(*a*). When the point *p*, Fig. 1(*b*), on the slip ring is opposite the fixed point *fp*, the conductors are cutting minimum flux and the instantaneous value of e is zero. When point *p* has moved 90°, maximum flux is being cut and the value of e is E_m. The amplitude of the a-c emf wave depends upon the field flux set up by a d-c field winding, upon the number of armature conductors in series between the terminals, and upon the speed. In a 2-pole machine one revolution of the armature will form a complete

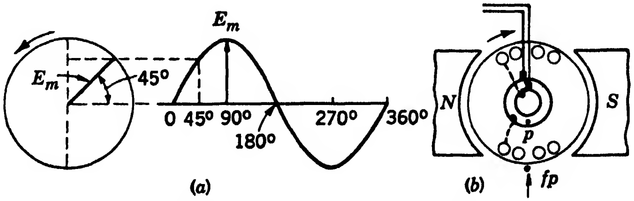


Fig. 1. The induced sine wave (*a*) is generated in one revolution of the armature of a 2-pole generator (*b*).

positive and negative sine wave or cycle, Fig. 1(*a*). The number of cycles per second is called the frequency. The majority of the power generated in the United States is at a frequency of 60 cycles per sec. For alternators having 4, 6, and 8 poles the number of complete cycles for each revolution of the armature would be, respectively, 2, 3, and 4. For each pair of poles there is one cycle per revolution. From this consideration, the number of revolutions per second (n) times the number of pairs of poles $P/2$ gives the frequency (f) in cycles per second

$$f = \frac{Pn}{2} \tag{2}$$

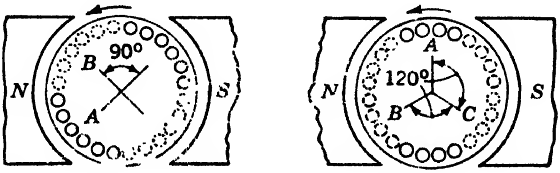
or, if the speed be expressed in revolutions per minute (N), the equation becomes

$$f = \frac{PN}{120} \tag{3}$$

The speeds of 60-cycle and 25-cycle alternators having various numbers of poles may be obtained from this equation. For example, a 4-pole 60-cycle a-c generator would run at 1800 rpm.

In general, large 60-cycle steam turbine generators (from about 25,000 to 200,000 kw) in central stations are 2-pole machines operating at 3600 rpm. Smaller steam turbine generators (say, from 2000 to 25,000 kw) frequently are 4-pole machines and operate at 1800 rpm. Small reciprocating steam-engine-driven 60-cycle alternators in small isolated plants may run at speeds of 60 to 120 rpm. Much care is taken in central-station practice to maintain a constant frequency by holding the average speed of the generator absolutely constant. Absolutely uniform speed is essential because such devices as clocks and radio sets will not perform properly at variable frequencies. Motors operate most efficiently when supplied at their rated frequency.

Any alternator having more than one set of armature conductors, in each of which are generated the same values of emf applicable separately to an external circuit, is called a polyphase alternator. The 3-phase alternator is used more than any other type because of economies in design and production and high efficiencies in distribution and utilization. The 2-phase alternator, however, is used in a few central stations. Figure 2(*a*) and (*b*) shows the locations of the sets or bands of conductors for 2- and 3-phase alternators. Each set of conductors is referred to as phase *A*, phase *B*, etc. The three vectors *A*, *B*, *C*, drawn at angles of 120°, Fig. 2(*b*), represent the centers of the bands of conductors (windings) of each of the phases. At the instant shown in Fig. 2(*b*), corresponding to time t_0 in Fig. 3, phase *A* has zero induced emf since it is in the field of zero flux; phases *B* and *C* are symmetrically located in equal fields of flux and therefore have equal instantaneous values of induced emf. One-quarter of a revolution later, phase *A* will be at the center of the poles (field of maximum flux) and will have maximum induced emf while phases *B* and *C* will be symmetrically located in fields of equal flux and will have equal induced emf's. The instantaneous induced values of emf for each phase, *A*, *B*, and *C*, for this last position of the coils, is shown by the dotted line (at time t_1) across the sine waves of Fig. 3. The vertical projections of the three corresponding rotating vectors of this figure show these same instantaneous values.



(*a*) (*b*)

Fig. 2. The symmetrical 2-phase generator (*a*) has 2 windings, the 3-phase generator (*b*) has 3 symmetrical windings (*b*).

It is important to note that, as time elapses, maximum values of induced emf's are first generated in phase *A*, then in phase *B*, then in phase *C*, the time interval being that necessary for the centers of the respective coils to pass through 120 electrical degrees. These 120° intervals are marked on the sine waves in Fig. 3.

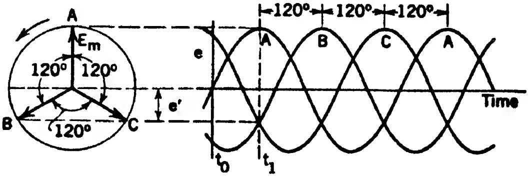


Fig. 3. The three vectors (*A*, *B*, *C*) are in proper phase positions to represent the instantaneous values of induced emf on the sine waves at time t_1: $A_{t1} = 100\% E$; $B_{t1} = -50\% E$; $C_{t1} = -50\% E$.

Whenever lamps and motors are connected to polyphase machines it is the general and economic practice to balance the load between phases. In order to balance a 3-phase 3-wire, or a 3-phase 4-wire, system the individual loads must be so connected that the current in each line wire (not including the neutral) shall be practically equal. (Review these systems and load connections in Chapter 25.) In this way each phase of the alternator carries the same current, has the same voltage drops, delivers the same power, and supplies an equal voltage to the terminals. A 3-phase generator, under balanced load, delivers successive and equal pulses of electric power just as a multicylinder gasoline engine delivers pulses of mechanical power.

A 3-phase a-c motor likewise receives balanced pulses of electric current from the a-c service wires and delivers successive and equal pulses of mechanical power to the shaft-connected load (such as pumps, fans, etc.).

2. The transformer. The transformer receives energy at one voltage and transforms it to another. A *step-up transformer* raises the voltage; a *step-down transformer* lowers it. The principle of operation is dependent upon the phenomenon that, when magnetic flux changes direction in an iron core, an emf is induced in any coil wound around this core. The magnitude of emf induced for a given rate of change of flux is directly proportional to the number of turns in the coil (or coils) on the core. Figure 4(a) shows a core of laminated iron, around which are N_1 turns of wire, carrying an alternating current I_e, producing a flux ϕ. This flux alternates through the core in phase with the corresponding alternations of the current. The flux (as well as the exciting current I_e), therefore, alternately has points of zero, maximum positive, zero, maximum negative, zero, etc. An emf is thus induced in each turn of the coil of N_2 turns. This emf is a sine wave and is proportional to the number of turns, N_2, of the coil. The relationship of the voltage V_1 impressed on coil N_1 to the voltage V_2 at the terminals of coil N_2, for all practical purposes, equals the ratio of turns; that is,

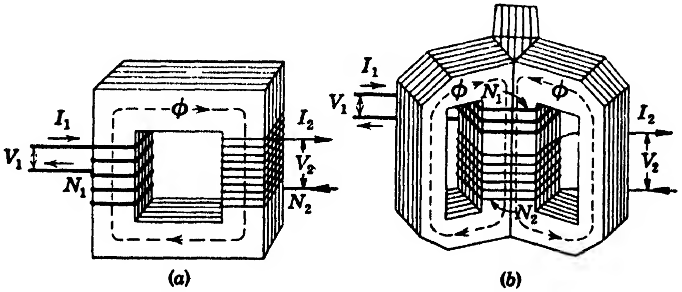


Fig. 4. The core and coils of a single-phase transformer (a) have voltages induced in direct proportion to their respective number of turns. Transformer (b) also has two coils but the magnetic circuit is more efficient since the flux has a greater area of iron core than in (a).

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \tag{4}$$

When a load is connected to the secondary coil, a current I_2 flows and a corresponding current I_1 must enter the primary coil from the service line. These two load currents are so related to each other that

$$N_1I_1 = N_2I_2 \tag{5}$$

Hence

$$I_1 = \frac{N_2}{N_1} I_2;\ \text{and}\ I_2 = \frac{N_1}{N_2} I_1 \tag{6}$$

The value of the exciting current I_e is relatively so low that it can be neglected in practical applications.

Transformer efficiencies are of the order of 97 to 99 per cent. This implies very low internal losses, and, for purposes of estimating transformer capacities, currents, and voltages, the efficiency may be assumed to be 100 per cent. On this assumption, the primary power (1) input equals the secondary power (2) output, or

$$V_1I_1 \cos\theta_1 = V_2I_2 \cos\theta_2 \tag{7}$$

where the subscript 1 indicates the input or primary values, and subscript 2 indicates the output or secondary values of voltage, current, and power factor, respectively. For all practical purposes the input and output power factors are equal; hence the primary and secondary volt-amperes are, respectively,

$$V_1I_1 = V_2I_2 \qquad \text{or} \qquad \frac{V_1}{V_2} = \frac{I_2}{I_1} \tag{8}$$

or, since

$$N_1I_1 = N_2I_2 \tag{9}$$

it follows that

$$\frac{N_1}{N_2} = \frac{I_2}{I_1} \tag{10}$$

The currents in primary and secondary coils are, therefore, inversely proportional to the number of turns in these coils.

Figure 4(*b*) shows another commercial form of laminated iron core which provides flux paths, or magnetic circuits, for the transformer. Figure 5 is a phantom view, showing the principal parts. All transformers so far discussed are single-phase units.

A 3-phase transformer is one that has three magnetic cores, each of which contains its primary and secondary core and coils. Each primary coil is connected to one phase (two wires) of a 3-phase power system, the secondary coils of each core having corresponding connections to the secondary 3-phase power system. The coils of both primary and secondary may have various internal interconnections. By special coil design, two single-phase transformers may be connected to transform energy from 2-phase to 3-phase. Figure 6(*a*) shows some schematic connections of common 1-phase types; (*b*) and (*c*), of 3-phase; (*d*), of 2-phase; and (*e*), of 3-phase to 2-phase types. Table I lists some standard voltage ratings of single-phase transformers.

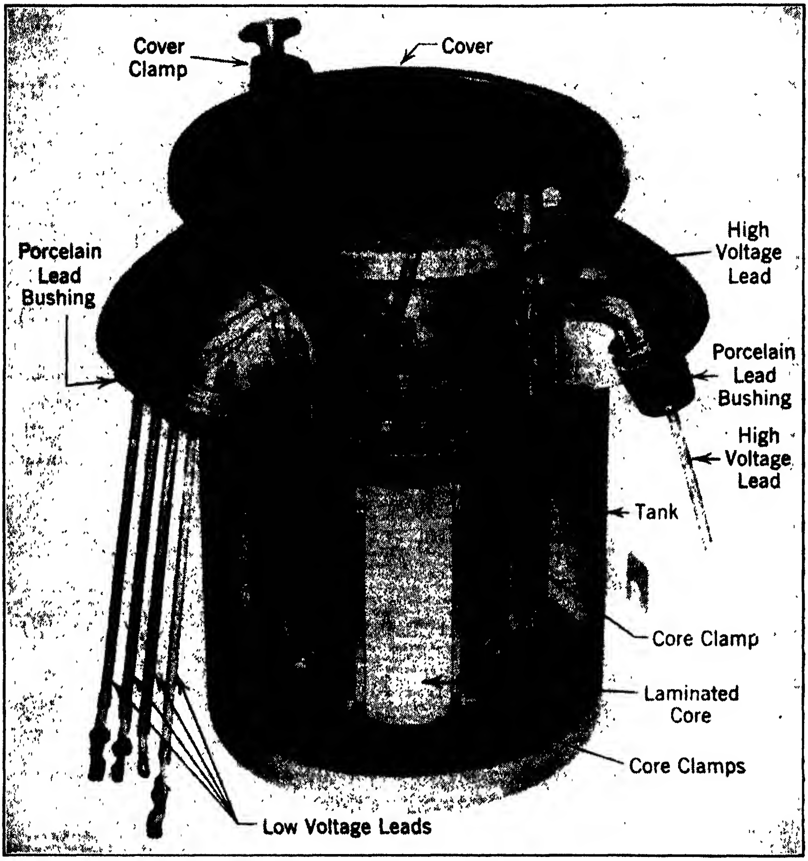


Fig. 5. This phantom view affords opportunity to identify the principal parts of a standard pole-type single-phase transformer. It contains the three magnetic paths [as in Fig. 4 (*b*)].

Transformers are further classified according to the method of dissipating internal RI^2 and core losses, as self oil-cooled, water-cooled, and radiator- or air-cooled. The self oil-cooled type is contained in a smooth or corrugated tank, filled with a light insulating oil which circulates by gravity, owing to the difference in weight between the cooler oil at the top and the warmer oil at the bottom. The water-cooled units have coils of copper tubing near the top of the tank

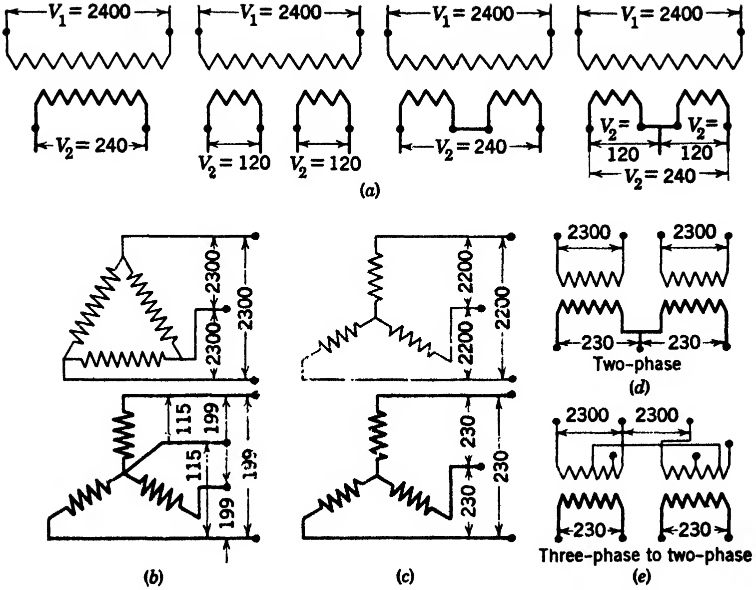


Fig. 6. Schematic connections of 1-phase, 2-phase, and 3-phase transformers. The high-voltage windings are shown in light lines, the low-voltage windings in heavy lines.

Table I. Some Typical Transformer Ratings *

Kv-a: 1.5–2.5–3–5–7.5–15–25–37.5–50–75–100–150–200–250–333–500

Voltage Ratings

High-Voltage Winding	Low-Voltage Winding	High-Voltage Winding	Low-Voltage Winding
2,400	120/240	22,000	120/240
2,400	240/480	22,000	240/480
6,900	115/230	33,000	120/240
6,900	240/480	33,000	240/480
11,500	115/230	44,000	120/240
11,500	230/460	44,000	240/480
13,200	120,240	66,000	120/240
13,200	240/480	66,000	240/480

* Standard ratings are also made in a considerable number of additional capacities, voltages, and coil ratios. Taps on any of the standard coils for additional voltages may be obtained at low cost. Special sizes and voltages are obtainable. The above ratings (and many others) may be specified in indoor, outdoor, or subway types, and in the self-cooled, water-cooled, or air-cooled designs. These ratings are stated for both 60-cycle and 25-cycle types.

through which cold water (sometimes oil) is pumped to reduce oil temperatures. The warm water is discharged to the drain or recirculated after cooling. The radiator-cooled types have special projecting pipes or tubes, connected at the top and bottom of the tanks, through which the oil circulates by gravity. The air around these projecting tubes is effective in dissipating more heat than could be carried away from surfaces of smooth or corrugated tanks.

Transformers are installed in vaults or rooms which must be properly fireproofed, ventilated, and supplied with French-drains for discharging transformer oil in case of tank failure. The doors must be fireproof and have emergency (safety) handles for opening from the inside. The NEC (Art. 450) gives much information regarding approved methods of application and installation of transformers. The primary leads are brought to the transformer in conduit from the service switch. The secondary leads are extended to the main switchboard in conduit or on bare copper bus bars. Review of Fig. 9, Chapter 23, will show the connections to transformers for a large building.

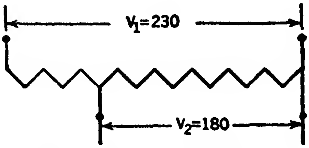


Fig. 7. Schematic diagram of a 1-phase autotransformer.

An *autotransformer* is one in which the primary and secondary coils are electrically connected together (wire-to-wire) to form one winding, Fig. 7. The primary and secondary voltage and current relations, with respect to the turns between the primary leads and the secondary leads, are the same as in the standard transformer:

$$\frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2} \tag{10}$$

The autotransformer is generally used where the voltage ratios are low, for example, 1 to 1, 1 to 1.2, or 1 to 1.45. If a high-ratio autotransformer were used, such as 2300 volts to 115 volts (ratio 20 to 1), there would be danger of a shock of 2300 volts to anyone touching the low-voltage conductors; or 230-volt insulation might be strained by this potential. The NEC therefore limits the use of autotransformers to certain low-voltage low-ratio applications, such as those installed in starters for induction motors, for vacuum-tube rectifiers, and for bell-ringing transformers. (See NEC sections 2003, 5225c, and 94,302, concerning the limitations of use of autotransformers.)

Transformers and autotransformers are selected according to the kilovolt-ampere (kva) capacity required, the primary and secondary voltages, the frequency, the temperature rise under normal load, and the method of cooling. A typical name plate would read: 30 kva, 2300 to 230/115 volts, 1-phase, 60-cycle, 50°C, self oil-cooled. This transformer would have one 2300-volt coil and two 115-volt coils. Its temperature rise (above room temperature) at full-load current would be about 50°C or less. If a 3-phase transformer was required, the rating would be exactly the same except that "3-phase" would appear on the name plate. If three single-phase units were required to furnish 30 kva, after being interconnected, Fig. 6(*b* or *c*), each unit would be rated 10 kva.

3. The static capacitor. The static *capacitor* or *condenser* is an electrical device which may be used to draw a leading current from the line. If connected in parallel with a machine drawing lagging current, the two currents combine to produce a line current which is more nearly in phase with the line voltage, as explained in Chapter 22, Art. 13. Figure 8(*a*) shows the elementary construction of the interior, and (*b*) an assembly view of a standard capacitor. The diagram of connections for power-factor correction on a feeder to a 3-phase induction motor is shown in Fig. 9.

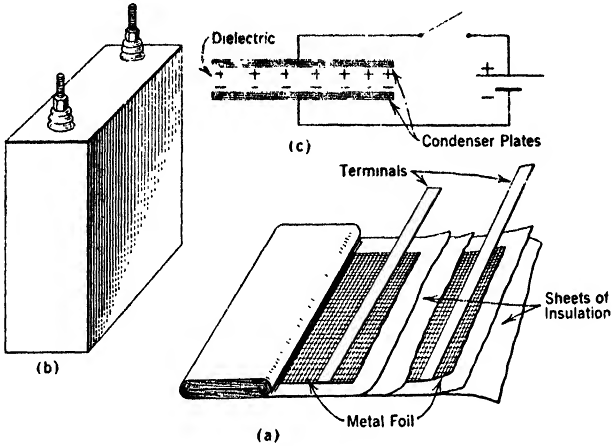


Fig. 8. Interior construction (*a*), assembly view (*b*), and schematic wiring diagram (*c*) of a static condenser.

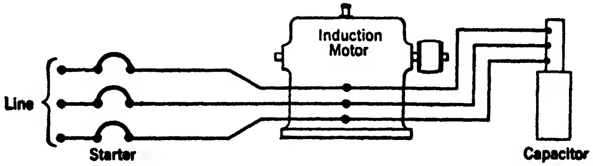


Fig. 9. The lower power factor of the induction motor is raised by connecting a static capacitor to its terminals.

The static capacitor consists merely of two conducting plates, or groups of plates, separated by insulation. Referring to Fig. 10, if a battery is connected to the terminals + and −, a current (of charged particles, electrons and positrons) will flow from the battery to the plates. Positive charges will collect on the positive plate, and negative on the negative plate. The current is maximum when the switch is first closed, then it quickly decreases to zero as the condenser plates become fully charged. The electrons and positrons cannot pass through the insulation between plates; they can accumulate only on the plates, to a maximum charge which is limited by the emf of the battery. A battery of 220 volts would cause an average current flow of twice that produced by a potential of 110 volts. If an alternating voltage is impressed on a capacitor, the current rises and falls, alternately positive and negative, following a sine wave. The sine wave of current leads the voltage by practically 90 deg.

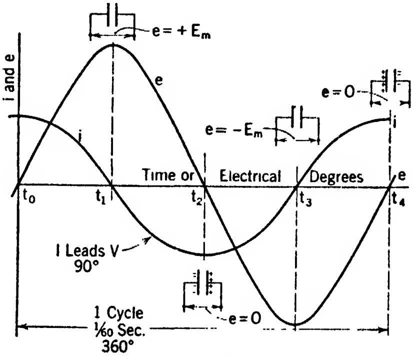


Fig. 10. The sine wave of current *i* taken by static capacitor leads the sine wave of impressed voltage *e* by 90 deg. The schematic wiring diagrams on the center lines t_1, t_2, t_3, and t_4 indicate the charges on the condenser plates at these time intervals.

In a 3-phase condenser, three single-phase units have their terminals interconnected and terminating in three wires. Each of the single-phase units must be rated for the voltage to be impressed on it. Also the kva rating is equally divided among the three units. The nameplate rating of any condenser must indicate the following quantities: kilovolt-amperes, volts, amperes, number of phases, and frequency.

4. The induction motor. In number and diversity of applications the 3-phase induction motor leads all other types. Figure 11 shows the cross section of a typical 3-phase induction motor. Three exactly similar windings or phases are placed on the stator or outside frame of the motor. One of the phases is identified by the letters $A+A-$, another by $B+B-$, and another by $C+C-$. It will be noticed that these windings are spaced symmetrically, 120° apart.

When three alternating voltages are impressed on these three stationary windings from a 3-phase source, 3-phase currents in these windings produce a rotating field of magnetic flux across the air gap between the stator and the rotor. The rotor is shown in Fig. 11 to have a number of copper bars projecting from slots in the rotor iron and identified by the numerals 1, 2, 3, 4, etc. These copper bars are short-circuited at each end of the rotor by circular copper end-rings (R_1) which are welded to the ends of the rotor bar. The copper end-ring is shown cross-hatched. By magnetic induction, currents are induced in the bars of the rotor by the revolving magnetic field. These currents react with the rotating flux to produce torque on the shaft and to bring the motor and its connected load up to speed.

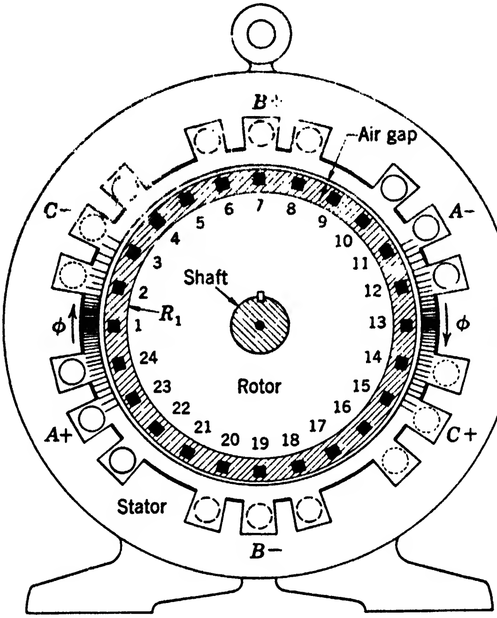


Fig. 11. Cross section of the stator and rotor windings of a 3-phase squirrel-cage induction motor. The combination of currents in the 3-phase currents in the stator produces a concentration of flux across the air gap as shown near the arrows. This flux revolves at synchronous speed (i.e., 3600 rpm for a motor having 2 poles per phase). The above motor has 2 poles per phase.

The revolving magnetic field rotates at a constant speed (called *synchronous speed*), but the rotor (and shaft) revolves at 3 to 5 per cent lower speed with full load on the motor. The difference in rpm between synchronous and actual speed at any load is expressed in per cent of synchronous rpm or in rpm. Thus an 1800-rpm motor with a load producing 1728 rpm would have a "*slip*" of 72 rpm or 72/1800 = 0.04, or 4 per cent slip. At no load the speed of the shaft practically equals the speed of the revolving flux, "slip" being only about 0.01 or 1 per cent of 1800 = 18 rpm. Induction motors are available for many synchronous speeds, such as 3600, 1800, 1200, 900, 720, and 600 rpm, when connected to a 60-cycle source.

Such motors are used to drive fans, blowers, pumps, escalators, air compressors, and refrigerating equipment. When a very high starting torque (2 to 3 times normal) is required the squirrel-cage motor cannot be used. For this high-torque application, the rotor is designed with windings which may be connected through slip-rings to external variable resistances which are gradually cut out of the rotor circuit as the speed increases to normal. This type is called a wound-rotor induction motor.

Two-phase induction motors operate on the same principle as the 3-phase machine. Single-phase induction motors must be wound with two stator windings for starting purposes; then these windings are parallel during the running period. For such motors special types of starting devices, both internal and external to the motor, are available. In general the 3-phase and 2-phase types are much more rugged and dependable. In fractional-horsepower single-phase induction motors (approximately $\frac{1}{100}$ to $\frac{3}{4}$ hp) there are many serviceable designs. These comprise the ordinary types used on household sewing machines, fans, refrigerators, and automatic furnace mechanisms; and office accessories, such as adding machines, water coolers, and air conditioners.

NEC CODE AND SUPPLEMENTARY TEXT REFERENCES

Appendix A NEC Items: A10, A13, A44, A45, A46, A47, A48, A49, A50, A72, A73.
Appendix B Text Items: B5, B3.

PROBLEMS

1. Why is most electrical energy generated by a-c generators instead of d-c generators?

2. Give the speeds at which 2-, 6-, and 8-pole 60-cycle a-c generators must operate.

3. What equation expresses the relation between the instantaneous value of voltage (or current) and the maximum value, assuming that a sine wave of voltage is generated? Sketch one cycle of a 115-volt 60-cycle sine wave.

4. What is the difference in the arrangement of armature conductors for a single-phase generator and for a 3-phase generator? (*a*) Show by sketches. (*b*) What is the most common number of phases used?

5. Discuss concisely the functions of a transformer, and why such apparatus is so frequently used.

6. What are the mathematical relations between primary and secondary *voltages*, *currents*, and *number-of-turns*.

7. A typical transformer is rated at 100 kva, 2500-v primary, 250-v secondary. What currents will flow in (*a*) the primary coil, and (*b*) the secondary coil at full load?

8. The transformer of Problem 7 is carrying a load at full kva, but the load has a power factor of 0.80. What is the kilowatt output of the transformer?

9. Draw the coil diagrams of three single-phase transformers connected delta primary and grounded-wye secondary, each transformer being rated at 100 kva, 2500 volts/250 volts, 60 cycles. (*a*) What is the rated current in each transformer primary and secondary winding at full current load; and (*b*) the currents in the primary- and secondary-line wires? Assume a balanced load.

10. An induction motor draws 40 amp at a power factor of 0.866 from a 220-volt a-c line. (*a*) What is the volt-ampere (va) capacity of a 220-volt condenser required (when connected in parallel with the motor) to cause the line current to have unity power factor?

11. (*a*) What are the general principles upon which the operation of an induction motor depends? (*b*) What kinds of machinery are frequently driven by induction motors in large buildings?

Chapter 27

LIGHTING

THEORY AND FUNDAMENTALS

1. Functions of lighting equipment. Lamps and light-control equipment are placed in interior spaces for two principal purposes: first, to afford visibility of objects, and second, to secure pleasing and decorative effects. The human eye sees an object because that object reflects light from its surfaces towards the eye. A white object in a completely dark room could not be seen. A single small candle 10 ft from that object would illuminate it to an intensity of approximately one-one hundredth ($\frac{1}{100}$) of the brightness of the flame itself; but, being white, it can be seen. If the object were completely black (nonreflecting) it would not be visible. Therefore, color, over the complete range of colors from white to black, will reflect various wide percentages of the light which strikes a given colored object. Walls, ceilings, floors, columns, beams, etc., are, of course, made visible in the same way.

Lighting is conceived as an integral part of the architectural design, an element of the structure. The character and intention of the building thus create problems in the purpose, detail, requirements, and decorative importance of lights. The solutions, in terms of brilliancy, intensity, uniformity, mystery, and color, are presented by intelligent use of reflection, refraction, diffusion, and direction, rather than by the haphazard spotting of luminous points upon an otherwise completed blueprint. The true significance of modern lighting lies in employing the inherent qualities of the incandescent and fluorescent electric lamps and luminaires to their fullest extent without the handicap of traditional and outmoded forms based upon candles, oil, or gas.

Lighting should conform with and express the architectural spirit. Modern methods of lighting are very desirable when in harmony with this spirit, but discrimination must always be exercised to reconcile the illumination with the demands of consistency and taste.

Good lighting is attainable by everyone. The guaranteed life of lamps and reductions in power costs per kilowatthour in recent years are shown by the following approximate data:

	1924	1934	1944	1954
Lumens per watt:	6	10	14	18.5
Average energy cost per kilowatthour:	11 cents	5.3 cents	4.0 cents	2.75 cents
Life of lamp:	270 hr *	1000 hr †	1000 hr †	7500 hr ‡

Notes: * Indefinite. † Guaranteed. ‡ Average life.

The above costs refer to approximate overall use of both incandescent and fluorescent lamps, and are based on an estimated light output per kilowatthour for lamps only in the decades mentioned. The costs per kilowatthour in decades ending in 1924, 1934, and 1944 are probably close to the overall costs of all power and lighting load. In the decade ending in 1954, the fluorescent lamp has been widely used. It is for this reason that the 1954 estimate of 2.75 cents is allocated with special reference to lamp loads alone.

2. Modern lamps. The major portion of all interior illumination is provided by various designs and sizes of fluorescent and incandescent lamps, and corresponding well-designed and efficient luminaires to control the light from these lamps. Figures 1 and 2 identify the principal design, parts, and materials of both of these light sources. These characteristics shown in Figs. 1 and 2 have been obtained owing to

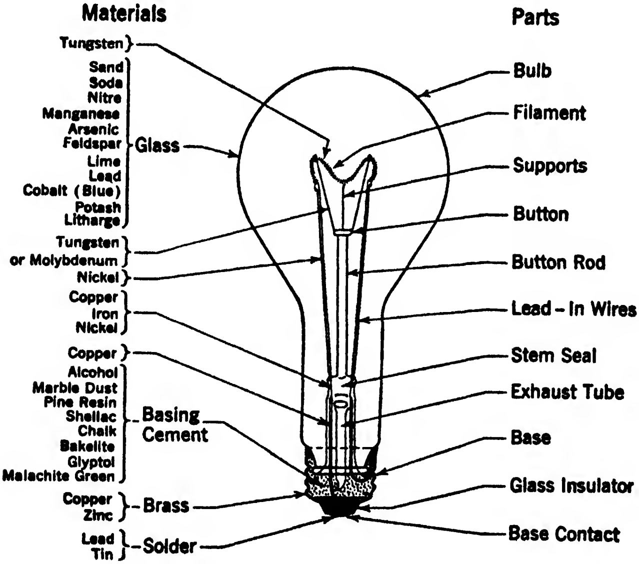


Fig. 1. Diagram of a standard general-service incandescent lamp, showing parts and materials.

excellent research facilities, standardization of sizes and ratings, and by the application of recommended codes of practice issued by the Illuminating Engineering Society, IES. The major manufacturers of lamps and luminaires have cooperated with the IES; National Bureau of Standards, NBS; with the American Standards Association, ASA; and other national societies and commercial laboratories interested in various aspects of illumination. Both professional societies and principal lamp and fixture manufacturers have advanced the field of illuminating engineering by the circulation of innumerable technical papers and design information.

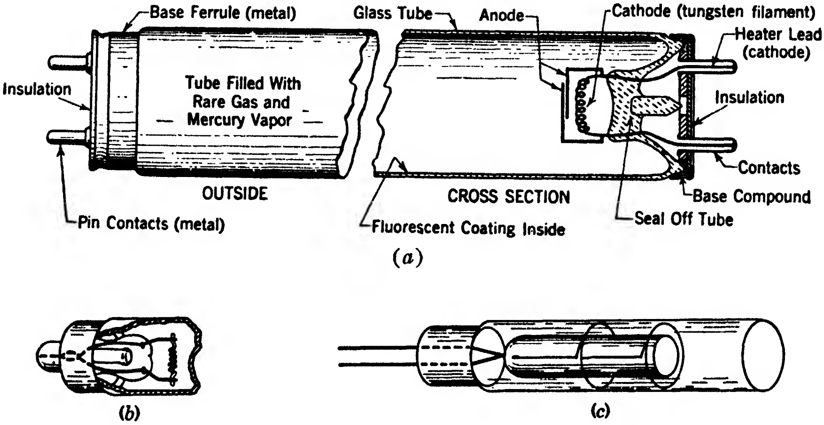


Fig. 2. Details of constructions of standard fluorescent lamps. The two ends of the lamp are of identical construction. Type (*a*) hot-cathode for pre-heat-starting, (*b*) hot-cathode for instant starting, (*c*) cold-cathode for instant starting. See *IES Lighting Handbook* for details.

Other types of lamps, luminaires, and accessories are available for special illumination purposes, including those used for picture projection, photography, signs, show windows, radiant heating, etc. These fields, however, are not covered in this book.

3. Fluorescent lamps. The fluorescent lamp has assumed a place of major importance in the lighting field. Luminaires utilizing fluorescent lamps are now made in both the direct and indirect types. Table I and Table VI, Chapter 28, give some types of fluorescent fixtures for commercial and industrial interiors. Fluorescent lamps are usually operated in pairs with auxiliary equipment, or ballasts, designed to stabilize the arc and to decrease light fluctuations. Characteristic curves of typical pairs of lamps operating with a two-lamp ballast are given in Fig. 3. The total watts, lumens, line current, and overall efficiency may be compared with those of the incandescent lamp given in Fig. 4.

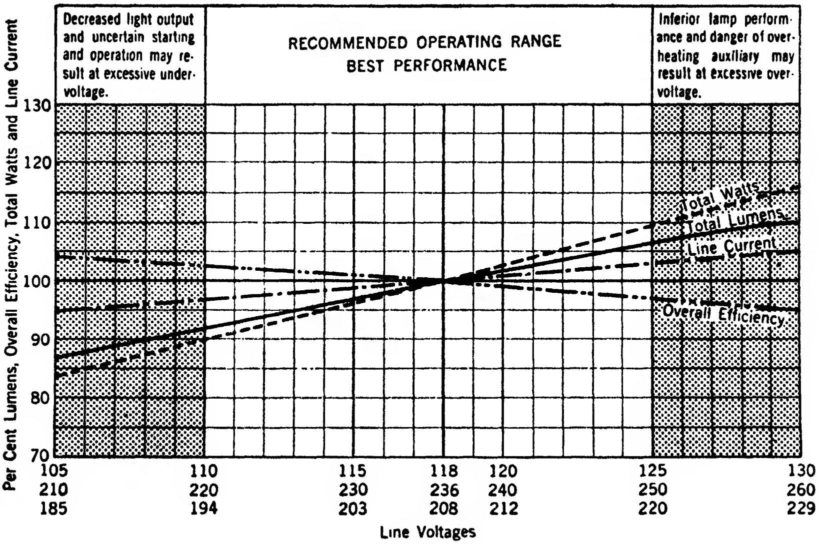


Fig. 3. Recommended operating ranges of circuit voltages for most satisfactory operation. The curves indicate the percentage changes in output lumens, efficiency, total watts, and current for line-voltage changes from the ideal 118-volt value. These curves refer to fluorescent lamps.

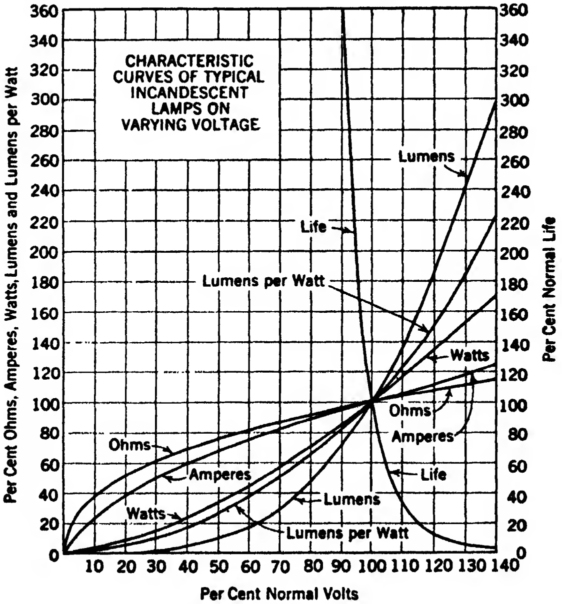


Fig. 4. Curves identify the per cent changes in ohms, amperes, watts, lumens, and lumens per watt for per cent variations in line voltage from the ideal value (100% of normal rated voltage). These curves refer to incandescent lamps.

Table I. Fluorescent Lamp Data

General Line Lamps

Nominal Lamp Watts	8	13	14	15 (T-8)	15 (T-12)	20	25	30	40 (T-12)	40 (T-17)	90	100
Nom. length *	12"	21"	15"	18"	18"	24"	33"	36"	48"	60"	60"	60"
Diameter	⅝"	⅝"	1½"	1"	1½"	1½"	1½"	1"	1½"	2⅛"	2⅛"	2⅛"
Bulb	T-5	T-5	T-12	T-8	T-12	T-12	T-12	T-8	T-12	T-17	T-17	T-17
Av. lp. watts	7.9	13.0	14.0	15.0	14.1	19.2	24.5	30.0	39.0	41	89	99
Av. lp. amps	0.16	0.16	0.39	0.30	0 33	0.37	0.52	0.355	0.43	0 425	1.57	1.52
Av. lp. volts	58	99	37.5	55	45.5	57	52	98	99	103	61	70
Standard Cool White												
Lumens †	310	600	520	690	615	915	1380	1700	2350	2350	4850	4850
Lumens/Watt ‡	39	46	37	46	43	48	56	57	60	57	54	49
Brightness												
Foot-Lamberts	2750	2750	1500	2350	1400	1450	1550	2600	1800	1050	2150	2150
Candles/sq in.	6.1	6.1	3.3	5.2	3.1	3.2	3.5	5.8	4.0	2.3	4.7	4.7
Standard Warm White												
Lumens †	330	610	550	730	640	950	1420	1800	2500	2500	5150	5150
Lumens/Watt ‡	42	47	39	49	45	49	58	60	64	61	58	52
Brightness												
Foot-Lamberts	2950	2800	1600	2450	1450	1500	1600	2800	1900	1100	2250	2250
Candles/sq in.	6.5	6.2	3.5	5.5	3.2	3.3	3.6	6.1	4.2	2.4	5.0	5.0

Slimline Lamp Data

Lamp Designation			Nominal Lamp Current (Ma)	Average Lamp Watts	Average Lamp Volts	Rec. Min. Starting Voltage	Foot-Lamberts and (Candles/sq in.)		Lumens † and (LPW) ‡	
Bulb	Nominal Length (in.) *	Diam. (in.)					Standard Cool White	Standard Warm White and White	Standard Cool White	Standard Warm White and White
T-6	42	¾	120	17.5	168	450	1900(4.2)	1950(4.3)	1010(58)	1060(61)
			200	25.0	145		2700(6.0)	2800(6.2)	1450(58)	1520(61)
			300	32.5	125		3250(7.2)	3300(7.3)	1750(54)	1840(57)
	64	¾	120	25.5	265	600	1900(4.2)	1950(4.3)	1610(63)	1680(66)
			200	37.0	225		2700(6.0)	2800(6.2)	2300(62)	2400(65)
			300	48.0	195		3250(7.2)	3300(7.3)	2800(58)	2900(60)
T-8	72	1	120	24.5	240	600	1200(2.7)	1250(2.8)	1590(65)	1650(67)
			200	36.5	210		1800(4.0)	1850(4.1)	2350(64)	2450(67)
			.300	48.5	190		2350(5.2)	2450(5.4)	3050(63)	3200(66)
	96	1	120	32.0	320	750	1200(2.7)	1250(2.8)	2250(70)	2350(73)
			200	49.0	285		1800(4.0)	1850(4.1)	3300(67)	3450(70)
			300	65.0	255		2350(5.2)	2450(5.4)	4300(66)	4500(69)
T-12	48	1½	425	38.0	97	430	1750(3.9)	1850(4.1)	2200(58)	2350(62)
	72		425	55.0	145	525	1750(3.9)	1850(4.1)	3400(62)	3550(65)
	96		425	74.0	190	625	1800(4.0)	1850(4.1)	4950(67)	5100(69)

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* Nominal length includes the lamp and two standard lampholders. The overall length is 49⅛ in. when turret lampholders are employed with 40-watt lamps.

† White (3500°) lamps have the same lumen outputs as corresponding sizes of Standard Warm White lamps.

‡ Lumens-per-watt values are computed on the basis of average lamp wattage.

Table I. Fluorescent Lamp Data (Continued)

Circline Lamp Data

Electrical data and dimensions have been established for circular fluorescent lamps of 8¼- and 12-in. diameters. Circline lamps have 4-pin bases set at an angle of 45° to the plane of the lamp. FS-2 and FS-20 starters, for the 8¼-in. size, and FS-12 starters, for the 12-in. size, may be used. If manual starting switches are employed, a 0.006-mfd capacitor should be connected in multiple to facilitate starting and to reduce radio interference.

Nominal Lamp Size	8¼″	12″
Nominal lamp watts	22	32
Bulb diameter	1⅛″	1¼″
Bulb designation	T-9	T-10
Avg. lamp watts	21	31.5
Lamp amperes	0.390 *	0.435
Lamp volts	60	82
Circuit volts	110–125	110–125
Lumens		
Standard cool	930	1550
Standard warm	...	1600

* This lamp may also be operated at higher currents up to 4.3 ampere.

One of the outstanding advantages of the fluorescent over the incandescent lamp is that the former has a life of 7500 hr versus 1000 hr for the incandescent; and the average lumen output per watt input to the luminaire auxiliaries and the lamps varies from about 200 per cent to 400 per cent higher than the incandescent. The longer life of the fluorescent lamps means lower replacement labor cost. In general, all fluorescent luminaires may be designed for standard lamps of 18, 24, 48, and 96 in. in length.

4. Operating principles of fluorescent lamps. A fluorescent lamp consists of a glass tube containing a small drop of mercury and a small amount of argon or krypton gas to facilitate starting the arc. After the arc is started the mercury vapor emits ultraviolet radiation, most of which is at 2537 Angstroms wavelength. This radiation is invisible and does not pass through the glass. However, it activates the phosphor powders with which the inner wall of the tube has been coated, and these phosphors absorb and reradiate the energy at visible wavelengths. By mixtures of various phosphors a wide range of visible light is produced.

The two ends of the lamp are of identical construction. Figure 5 shows a preheat-starting lamp and its operating auxiliaries. The glow-switch contacts *f* are open when the lamp is off. To start the lamp, switch *a* is closed. The voltage across the starter is sufficient to produce corona or glow discharge between the bimetal and the center electrode at *f*. The heat of this discharge causes the bimetal to expand and to close the contacts *f*, thus completing the series circuit through the lamp cathodes at both ends of the lamp. Because the glow discharge is shorted out, the bimetal strip cools and the contacts open; at which time the inductive kick of the ballast starts the arc and normal lamp operation continues. The voltage at the starter contacts *f* is insufficient thereafter to cause the contacts to close (while the lamp is in operation). The glow starter, therefore, consumes no energy in normal operation. The glow starter is self-contained in a small tubular jacket (outer jacket not shown in Fig. 5) with terminals to provide easy replacement in case of failure.

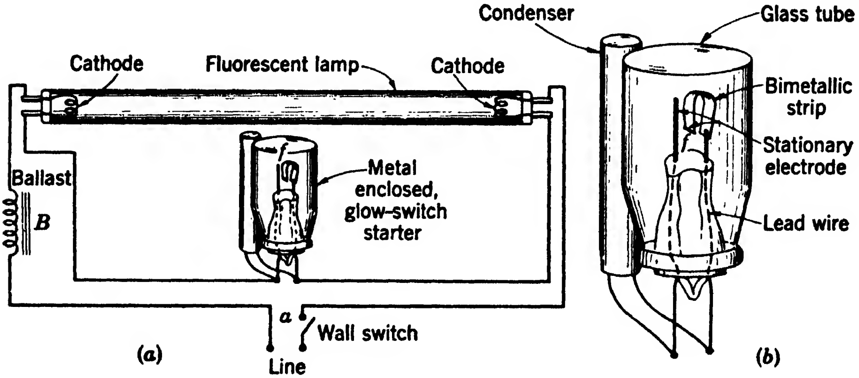


Fig. 5. Fluorescent lamp, operating auxiliaries and circuit connections (*a*). Enlarged details of the glow-switch starter (*b*).

As indicated by the above description, when preheat-starting lamps are used, there is a short time delay, perhaps 1 to 5 sec, between the time the switch is thrown and the lamp lights. Instant-starting lamps are designed so that they light with practically no time delay. They therefore do not require starters. However, they need a high starting voltage, and this is provided by a transformer. The life of hot-cathode lamps is materially affected by the number of starts since a small amount of the electron-emitting material on the cathode is lost during each start. Cold-cathode lamps have a large cathode area [see Fig. 2(*c*)], and the emitting material is not dislodged by starting. These lamps therefore have a long life which is not materially affected by the number of starts. Hot-cathode lamps may be dimmed only slightly, because the voltage soon becomes too low to maintain the arc. Cold-cathode lamps are easily dimmed. Since the cold-cathode lamps have a high voltage drop at the cathode, their overall operating efficiency is less than that of hot-cathode types.

Fluorescent lamps operate at highest efficiency in normal room temperatures of 70 to 80°F, with glass tube temperatures of 100 to 120°F.

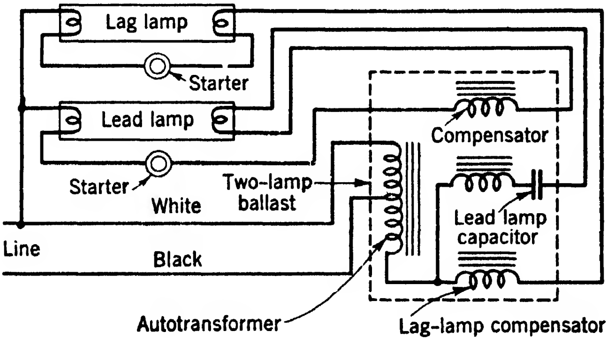


Fig. 6. Wiring for a two-lamp high-power-factor, lead-lag, luminaire. The two-lamp ballast contains the line autotransformer, the lag lamp compensator, the lead-lamp compensator, and the lead-lamp capacitor and compensator.

Figure 6 is similar to Fig. 5 except for the fact that Fig. 6 is a two-lamp circuit. This lead-lag ballast is designed to eliminate the excessive blinking effect given by one-lamp circuits. The capacitor in one mesh or section of the circuit keeps that section out of phase with the other (it leads the other), thereby having one lamp blinking on while the other is off. This gives a more uniform light output without the stroboscopic effect.

5. Incandescent lamps. These consist of hollow glass bulbs (Fig. 1) mounted on brass bases which screw into standardized outlet sockets, thereby forming an electric contact. The bulb contains a looped tungsten filament connected at its ends to the contact area in the base, thereby completing an electric circuit. The threadlike filament offers high resistance to the current passing through it and is consequently heated to a bright incandescent glow.

There are two classes of filament lamps: vacuum or B, and gas-filled or C lamps. For lamps of the first class, air is withdrawn to create a partial vacuum inside the bulb, thereby raising the melting point of the tungsten filament. Evaporation of the tungsten takes place at the high filament temperatures with a consequent loss of cathode material and blackening of the bulb. This places a limitation on the operating temperature and affects the light intensity and life of the lamp. Practically all present-day lamps above 40 watts are filled with a mixture of argon and nitrogen which retards the evaporation of the filament and allows higher operating temperatures. The gas pressure within the

Table II. Incandescent Lamp Data

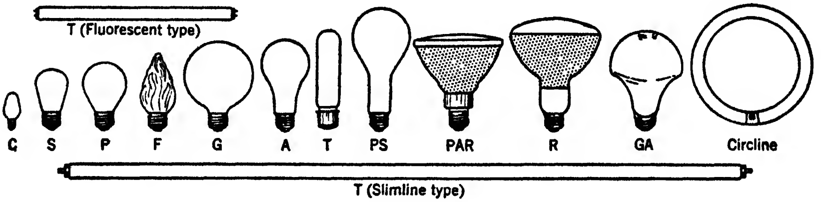
(Listing a few of many sizes and types of 115-, 120-, and 125-volt lamps)

Watts and Life		Lumens			Types of	
Lamp (1) Watts	Av'g Rated Life (hr)	Initial Lumens	Lumens per Watt	Mean Lumens	Shape (2) of Bulb	Base
60 A	1000	835	13.9	790	A-19	Med
60 A/W	1000	835	13.9	780	A-19	Med
75 A	750	1,150	15.4	1,090	A-19	Med
100 A	750	1,630	16.3	1,530	A-21	Med
100 A/W	750	1,630	16.3	1,520	A-21	Med
100 A/SB	750	......	....	......	A-23	Med
150 A	750	2,650	17.6	2,450	A-23	Med
150/SB	1000	......	....	......	PS-25	Med
200 *	750	3,700	18.4	3,300	PS-30	Med
200/IF	750	3,700	18.4	3,300	PS-30	Med
200/SBIF	1000	......	....	......	PS-30	Med
300 *	1000	5,650	18.9	5,050	PS-35	Mog
300/SBIF	1000	......	....	......	PS-35	Mog
500/IF	1000	9,900	19.8	8,800	PS-40	Mog
500/SBIF	1000	......	....	......	PS-40	Mog
750/IF	1000	15,600	20.8	13,700	PS-52	Mog
1000 *	1000	21,500	21.6	18,000	PS-52	Mog
1000/IF	1000	21,500	21.6	18,000	PS-52	Mog
1500 *	1000	33,000	21.9	26,500	PS-52	Mog

Notes: (1) Figures in this column designate the input watts, and the letters identify the treatment of the glass bulb; thus: 60 A means 60 watts, A means inside frosted. The other letters have these meanings: A/W, inside frosted, white; A/SB, inside frosted, silver bowl; *, clear bulb; SBIF, silver bowl, inside frosted; SB, silver bowl; IF, inside frosted; M/IF, clear, inside frosted.

(2) Bulb Designations. Bulb designations consist of a letter to indicate its shape and a figure to indicate the approximate diameter in eighths of an inch. Overall length is measured from top of bulb to bottom of base. (Lengths are not given herein.)

Complete data on all shapes and sizes of incandescent and fluorescent lamps may be obtained from representatives of prominent lamp manufacturers. Owing to research and development, lamp characteristics are occasionally changed.



bulb is about 80 per cent of atmospheric pressure when the bulb is cold and approximately at atmospheric pressure when it is hot. Since the greater part of the electrical energy is consumed in maintaining the filament at a high temperature, only a small proportion is converted into visible light, the efficiency ranging from 6 to 9 per cent for vacuum lamps and 7 to 12 per cent for the large gas-filled lamps. The light is rich in red and orange radiation, and the general color sensation is a soft cream white. The visible output of light is measured in lumens as explained in Art. 8, Chapter 28.

Incandescent lamps are made in a variety of shapes, sizes, and light outputs. The principal standard bulbs and bases are shown in Fig. 7, and also Table II, the letters referring to the following shapes: A, standard; G, globular; S, straight; T, tubular; PS, pear-shape. Diameters are given in eighths of an inch. A PS-30 lamp, therefore, refers to a pear-shape bulb with $^{30}/_{8}$- or $3\frac{3}{4}$-in. diameter. The bases are designed to fit standard sockets and are designated as medium, intermediate, mogul, miniature, bayonet (single contact), mogul bipost, and candelabra. The glass bulb may be clear or frosted upon the inside. The frosting diffuses the light and minimizes the glare yet reduces the efficiency by only 1 per cent. A new type of coating has been developed which is composed of tiny particles of pure silica. It gives better diffusion and a whiter appearance with little decrease in efficiency. It is the standard finish for all sizes from 15 to 200 watts and may be obtained for higher ratings. Clear blue glass is used to absorb the excess of red and orange rays and produce the effect of daylight when desired. Colored lamps are available in red, blue, green, and orange. Any clear-bulb standard lamp may be changed to any desired color by means of a standard lamp dye. The method of using these dyes is to immerse a cold lamp in them, and then to turn on the lamp to dry the dye. A dye of good quality will retain its color throughout the life of the lamp.

Table II gives the properties and ratings of 19 standard types of incandescent lamps. The light output, wattage consumption, and total life shown are dependent upon operation at the voltage etched on the lamps. Hence, to obtain economical efficiency in lamps, the wiring and control equipment should be designed to maintain rated lamp voltage at the terminals. The results of departures from rated voltage are shown by the curves in Fig. 4. Most sizes of standard incandescent lamps are made for operation at 110, 115, and 120 volts.

6. Neon-vapor lamps. Neon-vapor lamps consist of exhausted glass tubes filled with neon gas which is ionized and conducts an electric current through the tube. A high voltage is required because of the large voltage drop at the cathode, and consequently a transformer is a necessary part of the equipment. A step up from 115 to 6000 or 10,000 volts may be required. Neon light has a pink to dark red color, depending upon the gas pressure. The tubes are commonly used in street and window signs as well as indoor signs. Different colors

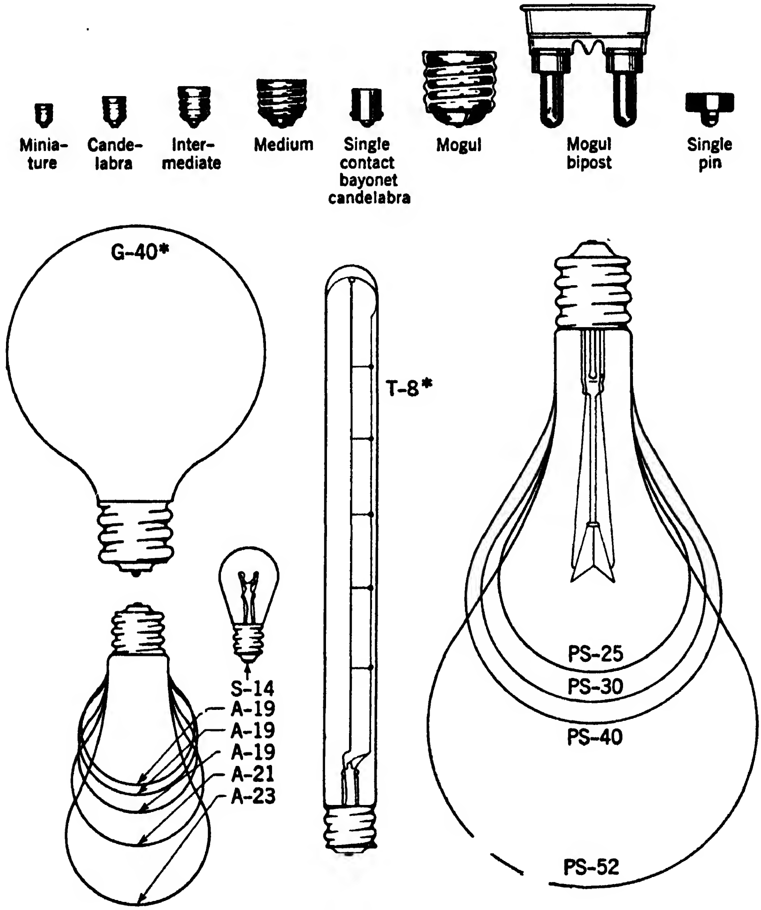


Fig. 7. Standard shapes of incandescent lamps and lamp terminals. The maximum diameters (in eighths of an inch) are indicated by the numbers on the lamps, i.e., A-21 is 21/8 = 1⅝ in.

may be obtained by the use of helium gas instead of neon or mixtures of the two, as well as by colored glass tubing.

Mercury- and sodium-vapor lamps are mainly used in industrial and street lighting applications and are therefore not discussed in this book.

7. Selection of fluorescent or incandescent lamps. The design and operating characteristics of these two types of lamps, luminaires, and their control devices are so radically different that a choice should be made on the basis of rather complete and comparable information.

The operating auxiliaries and circuit connections of one fluorescent lamp per luminaire and of two lamps per luminaire are shown and described in Art. 4.

Data on present standard fluorescent lamps are given in Table I, p. 414, and electrical characteristics and efficiencies are given in the curves of Fig. 3. Corresponding data are given on the standard incandescent lamps in Fig. 4.

Comparisons and analysis of the corresponding lamp characteristics will aid the architect and engineer in making a choice. Such comparisons will show, in general, the facts apparent in Table III with reference to a standard luminaire with two 40-watt fluorescent lamps (2-40F) vs. a 100-watt incandescent lamp. The reader should not jump to conclusions as to which type of lamp and luminaire is more desirable for a given application. The various cost data and operating characteristics must first be more exactly obtained from vendors and contractors and then analyzed in detail. Unless the reader is an expert in the field, he should secure the services of a capable illuminating engineer. Assuming that each lamp is operated at its rated voltage and in the same type of room, under the same designed illumination and physical conditions, some important comparisons may be made.

Many years of research and application have perfected manufacturing and commercial standards for incandescent lamps and luminaires. The fluorescent lamp first became available for general application in 1935. Soon afterwards many disturbing characteristics developed. Intensive research has eliminated or greatly reduced these unfavorable factors. It is probable that fluorescent illumination may be specified for most installations in the near future, especially in large buildings and industrial plants.

Solutions of typical illumination designs and applications of fluorescent and incandescent lamps and luminaires are given in Chapter 28.

8. Measurement of light. The measurement of light is today a highly specialized field known as the science of photometry. Extensive tables and charts of photometric data simplify and determine many details of lighting design. As a background for an understanding of this material it is necessary to become familiar with some commonly used terms.

The unit of luminous intensity in the United States is called the candle (c). The standard candle was newly defined in 1937 and is based on the assignment of 60 candles per square centimeter as the brightness of a blackbody at the temperature of freezing platinum. Since the intensity of any actual light source is not usually the same when the light is viewed from different directions, it is customary to define a mean horizontal candlepower and a mean spherical candlepower. The mean horizontal candlepower is the average of all the

Table III. Some Comparative Characteristics of Fluorescent (F) and Incandescent (I) Lamps and Luminaires, Comparing Two 40-Watt Fluorescent Lamps with One 100-Watt Incandescent Lamp *

Item	Characteristics of 2—40w—F vs. 1—100w—I Lamps		*C*	*D*
			Favorable + Unfavorable −	
A	*B*	Footnotes	Fluorescent 2—40w—F	Incandescent 1—100w—I
1	Expected life of the lamp	*	+	−
2	Cost of the lamp itself		−	+
3	Cost of the entire group of lamps		−	+
4	Cost of lamp lumen-hr per watt, including fixtures and auxiliaries	(1)	+	−
5	Cost of luminaire per lumen-hr	(1)	+	?
6	Cost of required number of luminaires		−	+
7	Cost of maintenance per luminaire per lumen-hr		+	−
8	Investment cost for all luminaires	(2)	−	+
9	Initial lamp lumens per watt (average: F = 45; I = 16)	(3)	+	−
10	Cost of cleaning luminaire reflectors		−	+
11	Relative luminaire efficiency	(4)	−	+
12	Lamp efficiency at overrated voltage (+10%)	(5)	−	+
13	Lamp efficiency at underrated voltage (−10%)		+	−
14	Starting conditions	(6)	−	+
15	Rated life lowered by frequent starting		−	+
16	Replacement costs for starters, ballasts, contacts	(7)	−	+
17	Losses due to dirty reflecting surfaces		−	+
18	Instant starting	(8)	−	+
19	Flicker, arc-rolling, hesitant starting	(9)	−	+
20	Obsolescence of luminaire	(10)	−	+
21	Unsatisfactory operation due to temperature changes		−	+
22	Use of 2 or more lamps in one luminaire	(11)	−	

Notes: * The two outstanding factors of major importance are: the fluorescent lamp produces about double the lumens per watt; and its average life is from about eight to ten times the life of the incandescent lamp. (1) For rated lamp life. (2) Cost of complete luminaires, installing and connecting. (3) Approximate values at 100 hr burning. (4) Most F luminaires of same ratios of photometric light distribution as I luminaires are less efficient. (5) Efficiency in lumens per watt (but life is shortened). (6) Starting affected by temperatures and low voltage. (7) There are no auxiliaries for I lamps. (8) Slimline F lamps start instantly. (9) Due to aging, faulty starter or ballasts, low-voltage, undue temperature variations. (10) Favorable to I luminaires since F luminaires are changing more frequently. (11) A luminaire decreases in efficiency with additional lamps, usually decreasing about 2 per cent for each added lamp over two.

candlepowers taken in a horizontal plane around a source; the mean spherical candlepower is the average of all the candlepowers in all directions about a source. (See Fig. 8.)

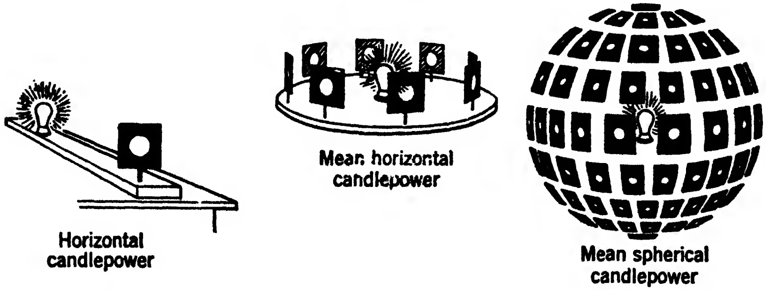


Fig. 8. Illustrating the definitions of horizontal, mean horizontal, and mean spherical candlepower from a fixed source of light.

If a light source of 1 standard candle, whose light is concentrated at a point, is assumed to be placed at the center of a hollow sphere of 1-foot radius, the illumination at any point on the sphere will be 1 foot-candle (ft-c). (See Fig. 9.) The lumen (L) is the unit of luminous flux. When 1 L of flux is uniformly distributed over 1 sq ft of area, the illumination at any point on that area is then 1 foot-candle. Referring to Fig. 9, since the sphere of 1-foot radius has a total surface

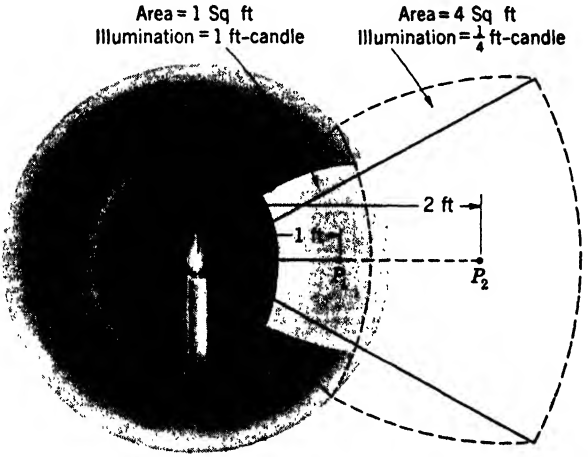


Fig. 9. Relations between candles, lumens, and foot-candles defined with reference to a standard light source of 1 candlepower located at the center of a sphere.

area (A) of 12.57 sq ft ($A = 4\pi r^2$) and there is 1 L falling on each square foot of surface, a 1-candlepower source therefore provides a total of 12.57 L of luminous flux.

Since the illumination E in foot-candles is defined as $E = F/A$ where F is the flux in lumens and A is the area in square feet, for the sphere described above this may be written $E = F/4\pi r^2 = I/r^2$ or I/D^2 where I is the candlepower of the source and D is the distance from the source in feet. This indicates that the illumination varies inversely as the square of the distance from the source. This is known as the "inverse square law."

Hence, as indicated in Fig. 9, since the illumination at 1 ft is 1 ft-c the illumination at 2 ft is ¼ ft-c. It should be noted that we have assumed above a point source of light. The inverse square law, with an actual light source, will hold with good accuracy only where the distance from the source to the surface is five or more times the maximum dimension of the light source.

Example 1. What will be the illumination on a surface which is 12 ft from a lamp of 80 cp?

$$E = I/D^2 = 80/12^2 = 0.555 \text{ ft-c}$$

9. Brightness. The brightness of an object is a measure of the amount of light which leaves the surface of the object toward the observer. The source of brightness may be a self-luminous object such as a lamp bulb, a translucent object such as a white glass globe, or a reflecting surface such as a wall. Two units of brightness are in use: the foot-Lambert (ft-L) which is used for comparatively low brightness surfaces; and the candlepower per square inch (cp per sq in.) for high-brightness light sources. They are related by the fact that 1 cp per sq in. equals 452 ft-L.

If a spherical luminaire is considered and the candlepower of the lamp inside is known, the brightness of this source is given by

$$\text{Brightness} = \frac{\text{Candlepower} \times \text{Efficiency}}{(\text{Globe radius})^2} \qquad (1)$$

where the brightness is in foot-Lamberts when the globe radius is in feet.

Example 2. What is the brightness of a ¼-ft radius, uniform bright globe of 80 per cent transmission efficiency containing a 50-cp lamp?

Solution.

$$\text{Brightness} = \frac{50 \times 0.80}{(\frac{1}{4})^2} = 640 \text{ ft-L}$$

$$= {}^{640}\!/\!_{452} = 1.415 \text{ cp/sq in.}$$

The brightness in foot-Lamberts of a surface such as a wall is related to the average foot-candles of illumination upon it by the equation:

$$\text{Foot-Lamberts} = \text{Foot-candles} \times \text{Reflection factor of the wall finish} \qquad (2)$$

Example 3. What is the brightness of a surface having a 0.55 reflection factor when the surface is uniformly illuminated to an intensity of 25 ft-c?

Solution. Brightness = 25 × 0.55 = 13.8 ft-c.

10. Physical principles of light. In Art. 8 it was shown that the level of illumination from a source varies as the square of the distance from the source. Figure 10 illustrates a number of other physical characteristics which are of importance in the field of illumination design. These phenomena are utilized in the design of both lamps and luminaires and in their application to specific illumination problems. In Fig. 10:

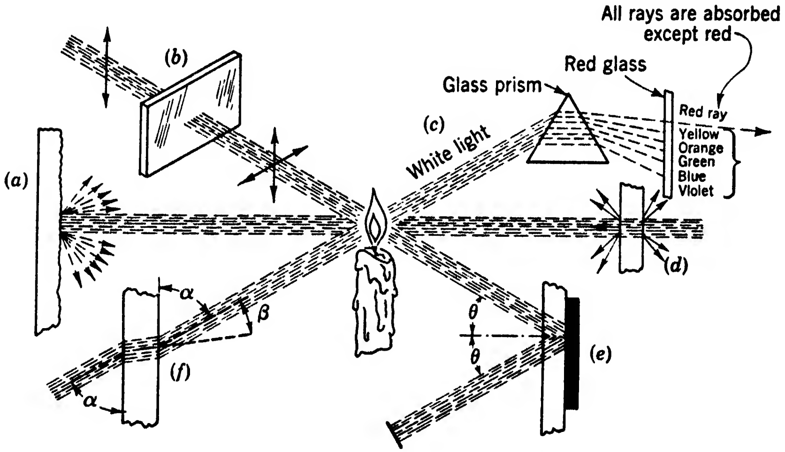


Fig. 10. The successive figures illustrate the following phenomena of light rays and their control: (*a*) diffusion; (*b*) polarization; (*c*) color absorption; (*d*) transmission; (*e*) reflection; (*f*) refraction. In (*c*) all colors except red are absorbed within the transparent red glass, red *only* being passed through.

(*a*) *Diffusion.* The light rays leaving the source strike a rough opaque surface, at which point they are diffused and reflected back towards the source.

(*b*) *Polarization.* Here the light rays strike what is known as a polarized glass which causes the horizontally polarized light rays to be eliminated but allows the vertically polarized rays to penetrate the glass.

(*c*) *Color Absorption.* Rays from the source strike a highly polished glass prism, are refracted at the surface to almost horizontal paths, and then again refracted as they leave the prism. The prism has the characteristic of separating the red, yellow, orange, green, blue, and violet rays. These rays, having been separated, then strike a transparent red glass. This red glass permits the red rays to continue through and beyond it, but absorbs all the other colors mentioned.

(*d*) *Transmission.* When the rays from the source strike a plain transparent glass some of the rays pass to proceed further, while other rays are reflected backwards toward the source. There is some diffusion at each surface.

(*e*) *Reflection.* In this case the rays from the source pass through a plate glass (perpendicular to the rays) to a silvered surface on the far side of the glass, from which surface they are reflected back through the glass with practically no diffusion. The angle of incidence is equal to the angle of reflection, as shown at θ on either side of the dotted line.

(*f*) *Refraction.* The light from the source is projected against a clear plate glass placed at an angle (α) with respect to these rays. The rays within the glass are deflected at an angle (β) within the glass, and then continue at the angle (α) on the far side of the glass.

11. Reflection of light. Reflection of light by various colored surfaces is given in Table IV. White surfaces when clean may reflect from 80 to 90 per cent of all incident rays. The reflection of light from polished surfaces may cause discomfort to those who are in direct reflected or transmitted rays of high intensity. Uncomfortable reflections are usually referred to as glare.

Table IV. Approximate Reflection Factors, Percentage

(For medium light colors)

White	83	Tan	50–30
Gray	70–44	Brown	40–20
French gray	40	Green	55–20
Dark gray	19	Olive green	20
Ivory white	80	Azure blue	55
Caen stone	78	Sky blue	37
Ivory	71–63	Shell pink	54
Pearl gray	72	Pink	70–50
Buff	70–40	Cardinal red	20
Buff stone	20	Red	40–15

Figure 11 shows such disturbing rays being transmitted through plate glass and other rays reflected from ceilings and walls of highly polished surfaces of gloss paint, polished plate glass, and highly polished marble walls in a large bank building. All such discomforts were anticipated and prevented by matte finished ceilings, etched portions of the glass, and sandblasting of specified areas of the marble.

12. Candlepower distribution curve. A graphic representation of the distribution of light intensity of a luminaire is given by the candlepower distribution curve. Such curves are given for each luminaire of Tables II and V, Chapter 28. They are a valuable aid in the selection of suitable lighting equipment for various applications.

In order to make use of the candlepower distribution curves it is necessary to know how they are obtained. The candlepower in a given direction from a light source has already been shown in Art. 8 to be equal to the illumination in foot-candles at a given distance from the source times this distance squared ($I = ED^2$). In making measurements a distance of 10 ft or 25 ft is usually chosen.

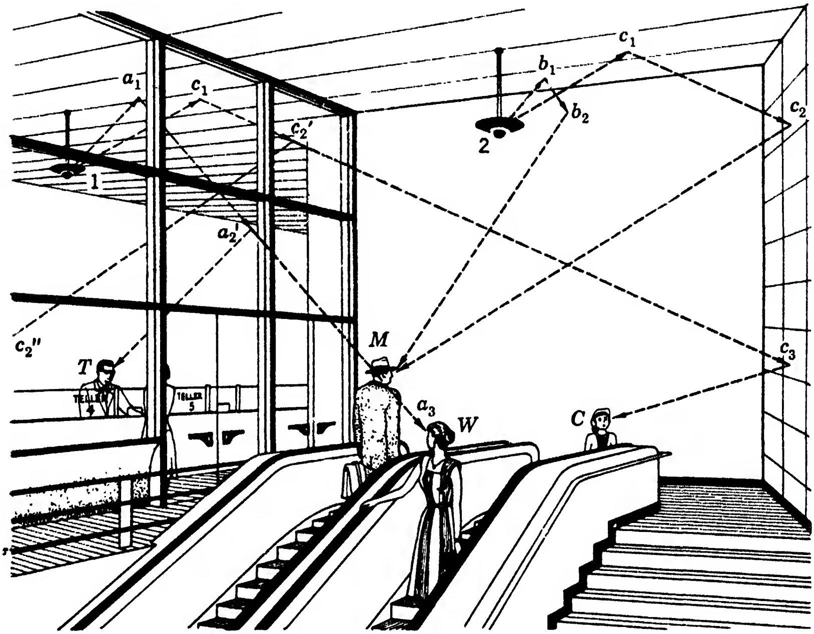


Fig. 11. Direct rays from light sources which are reflected from highly polished or mirror surfaces frequently require analysis and corrective treatment. The direct rays from 2 silver bowl lamps (No. 1 and No. 2) are projected to the ceiling, then to the polished surfaces of marble walls and plate glass partitions in the lobby of a second-floor bank building. Glare from lamp No. 1 disturbs the woman (W) through reflections at points a_1 and a_2'. The teller (T) is disturbed by reflections at a_2'. The man (M) at the top of the escalator is made uncomfortable by rays from points b_1, b_2, c_1' and c_2. The child (C) entering the escalator is hindered by rays from points c_1, c_2' and c_3.

Referring to Fig. 12(a) it may be seen that if a band having 1 sq ft of area is drawn on the unit sphere it will intercept 1 L. If the sphere is now divided into bands or zones of 10° each [see Fig. 12(b)], the number of lumens in each zone is equal to 1 candlepower times the area of the zone in square feet. Note that zones near the 90° positions have a larger area than those near the 0° and 180° positions which become very small. The value of these areas may be calculated by geometry. Thus for a 1-candlepower source the 0 to 10° zone has 0.10 sq ft of area and therefore receives 0.10 L while the 80 to 90° zone has 1.09 sq ft of area and therefore receives 1.09 L (*c*). For an actual source the lumens in each zone would be equal to the above values times the candlepower of this source. This, then, gives a method for obtaining the curves shown in Fig. 12(*d*). It should be noted that the area of the curve is not a measure of the lumens output since a source which gives high candlepower near the vertical has its lumens in this direction spread over only a small area.

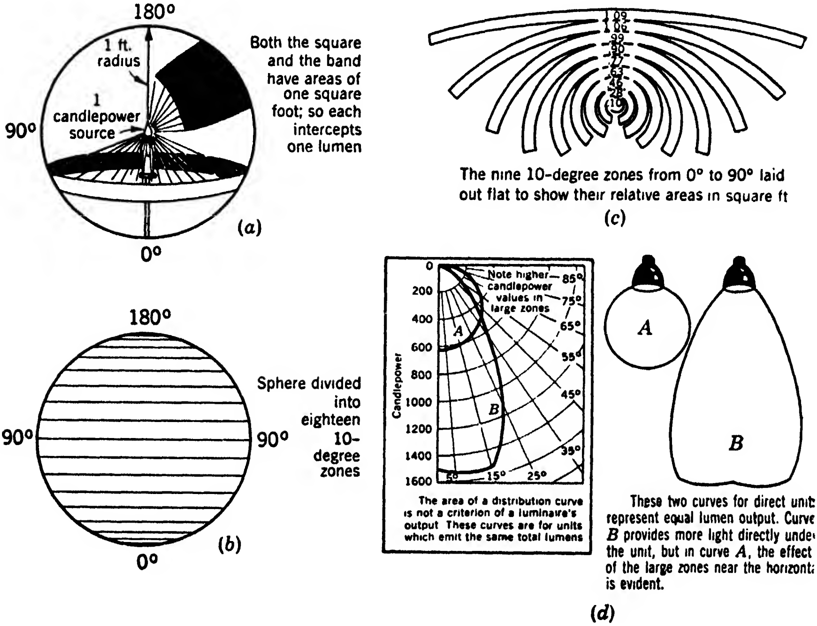


Fig. 12. Standard method of dividing 1-ft sphere to get candlepower distribution curves.

In making candlepower distribution curves of a nonsymmetrical source such as a fluorescent luminaire, it is necessary to choose specific planes in which the values will be taken. It is standard practice to choose three planes—a normal, a parallel, and 45° plane (see Fig. 13).

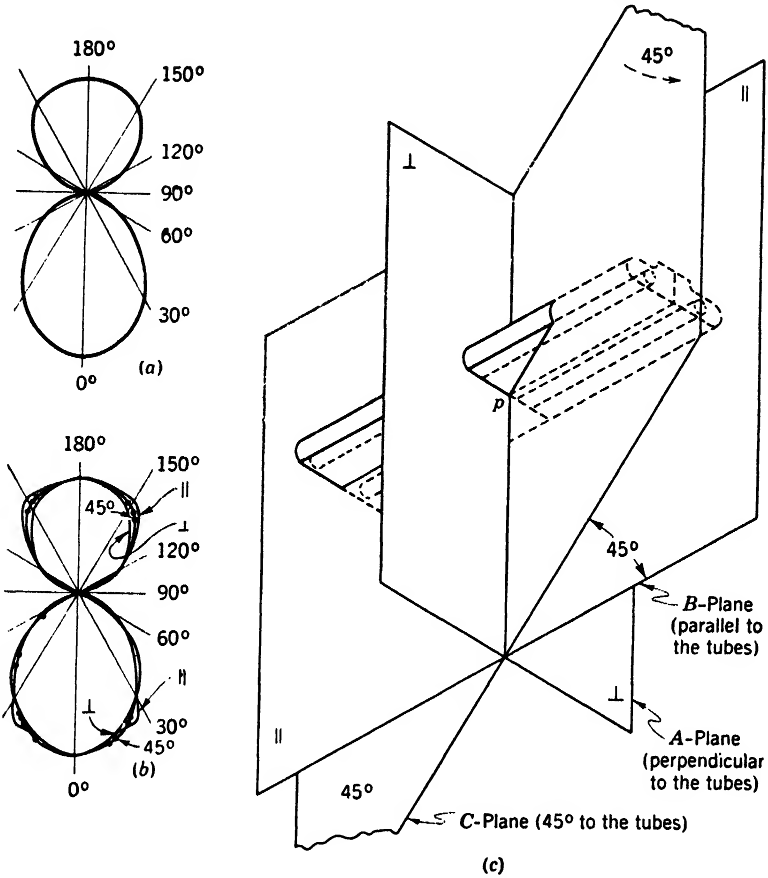


Fig. 13. Three planes for a given luminaire within each of which a candlepower distribution curve is measured and plotted at a given uniform distance from the common central point (p) of plane intersection. The three resulting curves are then plotted as shown in (b). The curves are referred to as: the foot-candle distribution within the plane perpendicular to the center of the lamps (⊥), a plane parallel to the center between the lamps (||), and a plane through the center (p) at 45° from the other two planes.

NEC CODE AND SUPPLEMENTARY TEXT REFERENCES

Appendix A NEC Items: A3, A6, A5, A7, A42, A43, A53, A65.
Appendix B Text Items: B6, B7, B10.

PROBLEMS

1. Briefly summarize your impressions of the various ways in which *light* is of importance to the architect and interior designers.

2. In your personal experiences, what constitutes quality of light? Try to explain what *kinds* of light you prefer for several different utilitarian or decorative purposes.

3. Give a general description of the construction of a standard incandescent lamp.

4. Give a general description of the construction of a standard fluorescent lamp.

5. Referring to Fig. 4, determine the percentages of amperes, watts, lumens, and lumens per watt for a 500-watt 115-volt incandescent lamp: (*a*) when operating at 115 volts; (*b*) when operating at 10 per cent undervoltage; and (*c*) when operating at 10 per cent overvoltage.

6. Tabulate the lumens output and lumens per watt for the following 115-volt standard incandescent lamps: 60, 100, 300, 500, and 1000 watts.

7. What is the illumination in foot-candles at a point (*a*) 1 ft; (*b*) 5 ft; (*c*) 10 ft; (*d*) 20 ft from a source of 200 cp?

8. What are the approximate reflection factors of surfaces of the following colors: (*a*) white; (*b*) ivory white; (*c*) very light buff; (*d*) sky blue; (*e*) very light pink?

9. What is meant by: (*a*) intensity of light; (*b*) quality of light?

10. It is understood that the most economical operation of an incandescent lamp may be expected when it is energized at its rated voltage. Consider a 300-watt 114-volt lamp, and determine the average lumens per watt at: (*a*) rated voltage; (*b*) 110 per cent voltage. Determine the life of the lamp in hours at: (*c*) rated voltage; (*d*) 110 per cent rated voltage.

11. Define the following terms used in the art and science of lighting: (*a*) lumen; (*b*) foot-candle; (*c*) intensity; (*d*) glare; (*e*) quality; (*f*) diffusion; (*g*) luminaire; (*h*) semi-indirect unit; (*i*) foot-candle meter; (*j*) standard candle.

12. Define *brightness,* and give several examples supporting the definition.

13. Give several practical applications involving polarization of light?

14. Sketch a small elevator lobby providing entrance to three elevators, a main door from the street, and a door to a snack bar. Utilize wall, door, and window materials which would produce glare. Then provide vertical and horizontal cove lighting to produce good illumination for this area with no glare. Consider this as a problem involving modern design, with little interest in the foot-candle levels.

15. (*a*) In what respects do fluorescent lamps excell incandescent lamps? (*b*) In what ways do incandescent lamps excel fluorescent lamps? Confine answers to five important factors for (*a*) and for (*b*).

***Table I. Recommended Standards of Illumination for Commercial and Public Interiors (Continued)**

		Foot-Candles
Hotels		
lobby		20
dining rooms		5–10
kitchen		20-40
guestrooms		15-30
corridors		5–10
writing rooms		30
Libraries		
reading room		30–40
stack room		10
Moving-picture theaters (*See* Theaters)		
Museums		
general		10
special displays	B	50
Night clubs and bars		5–10
Office buildings		
bookkeeping, typing, and accounting		40
business machines, power-driven (transcribing and tabulating)—calculators, key punch, bookkeeping	B	40
conference room		
general meetings		20
corridors and stairways		5–8
desk work		
intermittent reading and writing		30–40
prolonged close work, studying, designing, etc.	C	40–60
reading blueprints and plans		40–60
drafting		
prolonged draft- and designing		50–100
lobby		20
mail sorting		30
reception rooms		20
stenographic work		30–50
vaults		20

		Foot-Candles
Post offices		
lobby		20
sorting, mailing, etc.		50
storage		10
offices—private and general		30–40
file room and vault		25
corridors and stairways		5
Professional offices		
waiting rooms		20
consultation rooms		30
general offices		30–50
dental chairs		200
Restaurants, lunch rooms, and cafeterias		
dining area		10
food displays	B	50
Schools		
auditoriums		10
class and study rooms—desks, blackboards		40 ●○
corridors and stairways		5
drawing room		50–75
gymnasium		20–50
laboratories and general		30
close work, laboratories	C	50
close work, manual training	B	40
lecture rooms		20
special exhibits, demonstrations	B	30
library and offices		30–50
sewing room	B	60
blackboards		30
Service space		
corridors		5
elevators—freight and passenger		10

* Refer to footnotes at bottom of Table I, p. 434.

***Table I. Recommended Standards of Illumination for Commercial and Public Interiors (Continued)**

		Foot-Candles
Service space (Continued)		
halls and stairways		5
lobby		10
storage		5
toilets and wash rooms		15–30
Telephone exchanges		
operating rooms		10–50
terminal rooms		20
cable vaults		5
Theaters and motion-picture houses		
auditoriums (intermission)		5
foyer		10
lobby		20
Transportation		
cars		
baggage, day coach, dining, Pullman, mail		30
Transportation (Continued)		
mail		
bag racks and letter cases		30–40
storage		5
street railway, trolley, bus, and subway		30
motor bus		30
depots		
waiting rooms	C	20–30
ticket offices		
general		20
ticket rack and counters	B	50
rest rooms, smoking rooms		20
baggage checking office		20
storage		5
concourse		10
platforms		20–30

* Refer to footnotes at bottom of p. 434.

and by the use of suitable reflectors, shades, or diffusing media incorporated in them. Uniformity also depends on the reflection factors of near-by walls, ceilings, floors, and furniture.

Diffusion refers to the number of directions and angles from which illuminating rays proceed. Good diffusion is obtained when light falls upon a mat or satin surface from a variety of directions, thus eliminating shadows and streaks of brilliancy. Light reflected from a white area, for example a wall or ceiling, is spread out in many directions, as is light passed through a diffusing glass. Poor diffusion results from illumination from one direction only, thus causing visual confusion because of distorted high lights and shadows.

Glare is usually produced by great differences in intensity of direct or reflected light emanating from adjacent objects in the field of vision, for example bright lamps, brilliant ornaments, glass desk tops, or glossy paper surrounded by a lower degree of illumination. The results of glare are lessened visual acuteness, slow observation, eye strain, and fatigue. Premature aging and permanent injury of eyes are frequent consequences. The iris and pupil either become adjusted to the lower general levels of illumination, and the glaring light dazzles and strains the eye; or they adapt themselves to the higher levels and surrounding less bright objects become obscure or invisible. Bare lamps or brilliant fixture globes should, therefore, never be in the line of sight from any point in a room. An angle of 25° between the horizontal line of sight and the line from the lamp to the eye is generally accepted as the greatest permissible angle. In Fig. 2 lamp *C* is not objectionable to an observer at the point *P*, lamp *B* is allowable, and lamp *A* would prove disagreeable.

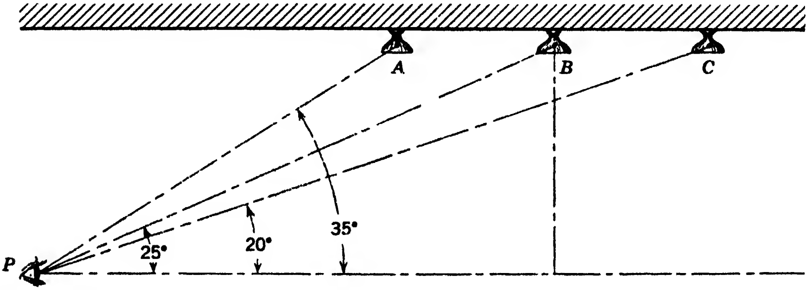


Fig. 2. Method of reducing direct glare when direct-lighting units are used. Direct rays from lamps *A* and *B* produce discomfort at 35° and 25°, but glare is eliminated from lamp *C* at 20° and at all lower angles for the more distant lamps.

The material and diameter of diffusing globes, when within the line of vision, should be carefully selected to avoid undue brilliancy. The glass should have uniform diffusing qualities to reduce the transmitted light, and the diameter should be such that the surface brightness is not more than 3 to 5 cp per sq in. The diffusing quality of modern lighting glassware is obtained by using globes of opal glass, alabaster, china, cellulose compounds, and other materials, by molding a film of opal glass on the outside of a body of clear glass, by casting prismatic surfaces on the glass, and by placing interposed surfaces of diffusing glass or plastic between the light source and the clear glass. The lamp bulb itself is usually lightly frosted (inside) to provide better diffusion.

The color of an object depends largely upon the color of the light which illuminates it. Since the eye has developed under the influence of the white light of the sun, true colors are assumed to be those perceived by white light. Although the light from an incandescent lamp is not white it is sufficiently near to white to be quite acceptable in a majority of installations. However, blue glass bulbs, specially treated enclosing globes, and glass color screens have been developed for department stores, florists' shops, and art galleries to give light which approaches the daylight spectrum. For close observation of detail, as in the inspection of small machine parts and for drafting and photographing when color is not a consideration, the mercury-vapor lamp with its greenish blue hue is very effective. Units have been devised combining mercury-vapor and incandescent lamps, in proportionate wattages of $\frac{2}{3}$ to $\frac{1}{3}$, to give a color quality closely approximating north sky daylight conditions. Fluorescent lamps in white, "daylight," and various colors are frequently used in industrial installations for many varied seeing tasks.

5. Luminaires. A device or fixture which supports the source or sources of electric light and redirects or helps to control the rays from the source is called a luminaire. Control of the rays is usually necessary to secure even distribution, to avoid glare, to cut off direct rays from the eye, to eliminate disturbing reflection of the rays from polished surfaces, etc. Luminaires for incandescent and fluorescent lamps of many typical types are shown in Table 11, p. 441. Luminaires are frequently referred to as fixtures, reflectors, lighting units, or merely units. The design of the frame, exterior contours, ornamentation, and the reflecting or deflecting surfaces cover a wide variety of types. Selections may therefore be made with some assurance that their appearance will be in harmony with the architectural and functional environment. Likewise, if properly designed and maintained, the reflectors and deflectors (or louvers) will have high efficiency in using a maximum of the total light emitted by the lamps. Types of luminaires with respect to the five patterns of direction of light flux, as in Art. 1, p. 431, are designed to operate at overall light-flux efficiencies from about 47 to 87 per cent.

6. Types of luminaires. As outlined in Art. 1, objects may be lighted by the following means:

Direct-lighting units, by emitting the majority of light rays straight toward their object, furnish the highest illumination (Fig. 3). They are, however, likely to create glare and unpleasant visual conditions unless carefully selected and installed with particular attention to surrounding conditions and the locations of the users. The intensity distribution curve for the luminaire should be studied with respect to its hanging height and to the eyes of the occupants. High intensities do not always mean good seeing conditions, and this is particularly true in reference to direct lighting. Glare may be diminished by means of partially opaque globes or by concealing the lamps in panels or troughs covered with diffusing glass. Ordinary paper and cloth shades soften light by absorbing it and thus very materially reduce glare. Direct lighting lends itself fairly well to the design of wall brackets and chandeliers in the traditional styles of past periods.

Indirect-lighting units (Fig. 4) transmit lower intensities than direct and semi-indirect units because a part of the light is absorbed by the upper reflecting surfaces of the walls and ceiling. Far better and more comfortable seeing conditions with practically no glare are, however,

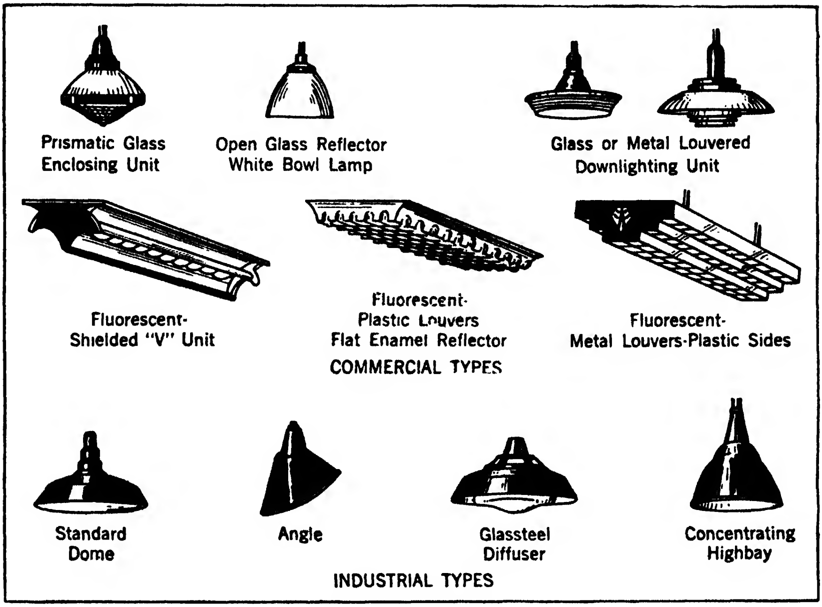


Fig. 3. Various types of direct-lighting units.

provided. In well-designed indirect systems the ceiling should be mat white of an extremely light tint of color; and the side walls should be very light in mat white or light tints of color for a distance of 3 to 4 feet below the ceiling. In general, the light cut-off line on the wall from the indirect luminaires should identify the lighter and the darker wall tints. An indirect luminaire furnishing 10 ft-c may frequently provide more satisfactory vision than a direct luminaire providing 20 ft-c. Generally, to attain the same levels of illumination, the indirect system will require from 50 to 70 per cent more wattage than the direct

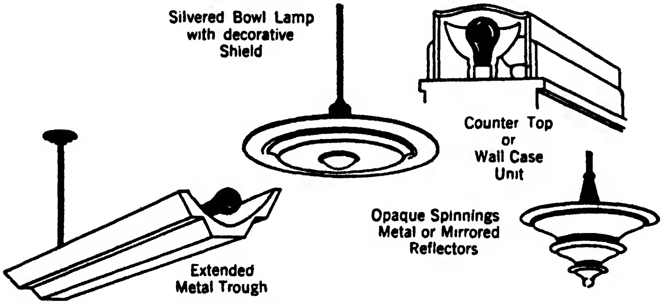


Fig. 4. Commercial types of indirect-lighting units.

system. Wall brackets act upon the indirect principle when reflectors in front of or surrounding the lamp throw light against walls and ceilings.

Table II shows a number of typical incandescent and fluorescent *direct and indirect luminaires* having light outputs distributed above and below the horizontal.

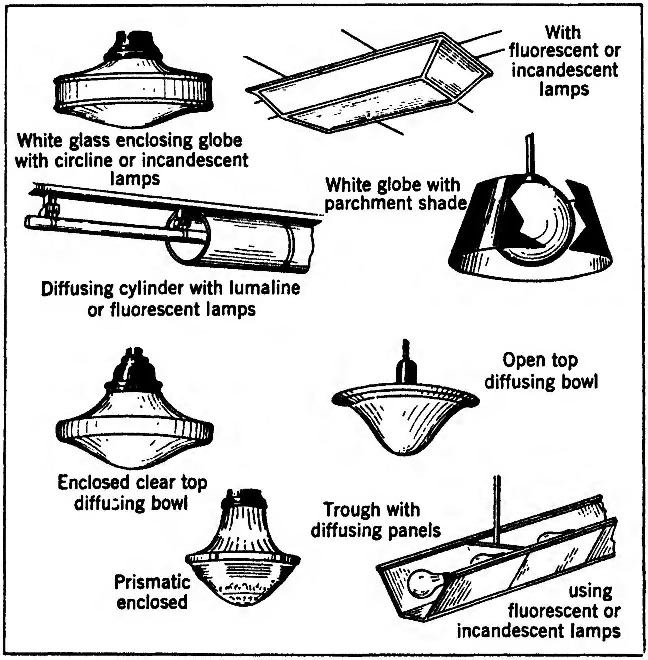


Fig. 5. Semi-indirect-lighting units.

Semi-indirect-lighting units (Fig. 5) provide conditions midway between those of the direct and indirect types. The light is softer and less glaring than the unmodified rays from direct luminaires and possesses greater intensity than that from indirect units of like power. For the same level of illumination semi-indirect lighting may require from 20 to 40 per cent more wattage than the direct system. The bowls of the fixtures combine upward reflection with downward diffusion and should be of such density that they are no brighter than the ceiling. In general, more than 10 and less than 50 per cent of the light is projected downward. To avoid glare a dense opal or flashed glass rather than a thin frosted glass should be used. The exterior may be etched or carved as desired, but the interior should be smooth, white, and of high reflecting power.

Table II

COEFFICIENTS OF UTILIZATION

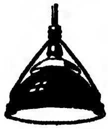
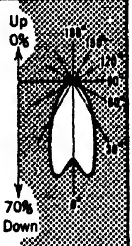
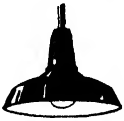
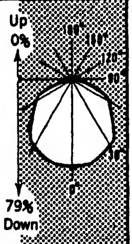
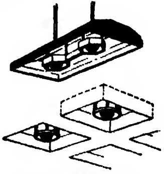
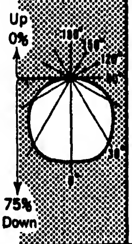
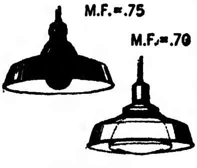
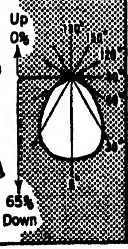
FIXTURES FOR INCANDESCENT LUMINAIRES		PER CENT REFLECTION FACTORS								
		Ceiling	75%			50%			30%	
Pictorial Views Descriptions Maintenance Factors (M.F.)	Candlepower Distribution Curves	Walls	50%	30%	10%	50%	30%	10%	30%	10%
		Room Index	COEFFICIENTS OF UTILIZATION							
I-1 M.F.=.70  High Bay Units Prismatic Glass Mirrored Glass Specular Metal		J	.40	.38	.36	.39	.38	.36	.38	.36
		I	.48	.46	.46	.47	.46	.46	.45	.43
		H	.51	.51	.50	.50	.50	.49	.50	.48
		G	.55	.54	.54	.54	.52	.52	.52	.51
		F	.58	.56	.55	.55	.55	.54	.55	.53
		E	.60	.59	.58	.59	.58	.57	.57	.56
		D	.64	.61	.60	.62	.60	.60	.60	.59
		C	.65	.63	.61	.63	.62	.60	.60	.60
		B	.65	.64	.63	.64	.62	.62	.62	.61
		A	.66	.65	.64	.64	.63	.62	.62	.62
I-2 M.F.=.75  Inside Frosted Lamp R.L.M. Dome Coefficients apply for white-bowl lamp		J	.37	.32	.28	.37	.32	.28	.31	.28
		I	.46	.41	.38	.45	.40	.37	.40	.37
		H	.50	.46	.43	.49	.46	.43	.45	.43
		G	.54	.50	.47	.53	.50	.47	.48	.47
		F	.58	.54	.50	.56	.52	.50	.52	.50
		E	.62	.59	.56	.61	.58	.56	.57	.56
		D	.67	.64	.60	.65	.63	.60	.62	.60
		C	.69	.66	.63	.67	.64	.63	.64	.62
		B	.72	.69	.67	.70	.68	.66	.67	.65
		A	.74	.71	.69	.72	.69	.68	.68	.67
I-3 M.F.=.75  Silvered Bowl Lamp Trough and Coffer		J	.35	.30	.26	.34	.30	.26	.29	.26
		I	.44	.39	.36	.43	.38	.35	.38	.35
		H	.48	.44	.41	.46	.44	.40	.43	.40
		G	.51	.48	.45	.50	.47	.44	.46	.44
		F	.54	.51	.48	.52	.50	.47	.49	.47
		E	.59	.56	.53	.58	.55	.52	.54	.52
		D	.63	.60	.57	.62	.59	.57	.68	.57
		C	.65	.62	.59	.63	.61	.59	.60	.58
		B	.68	.65	.63	.66	.64	.62	.63	.62
		A	.69	.67	.65	.68	.65	.64	.64	.63
I-4 M.F.=.75 M.F.=.70  Silvered Bowl Lamp and Glassteel Diffusers		J	.34	.31	.29	.34	.31	.29	.31	.29
		I	.42	.39	.38	.41	.38	.37	.38	.36
		H	.45	.43	.42	.44	.42	.41	.42	.41
		G	.48	.46	.45	.47	.46	44	.45	.44
		F	.51	.49	.46	.49	.47	.46	.47	.46
		E	.54	.52	.50	.53	.51	.49	.51	.49
		D	.57	.55	.53	.56	.54	.53	.53	.53
		C	.59	.57	.54	.57	.55	.54	.55	.53
		B	.60	.58	.57	.58	.57	.56	.56	.55
		A	.61	.59	.58	.60	.58	.57	.57	.56

Table II (Continued)

COEFFICIENTS OF UTILIZATION

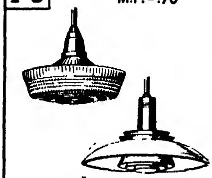
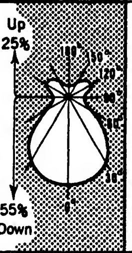
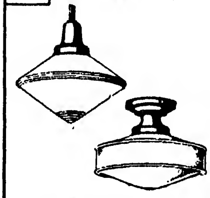
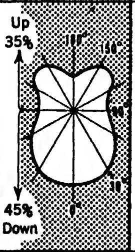
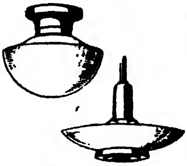
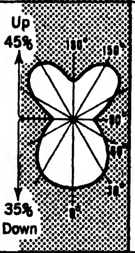
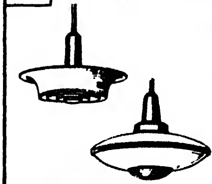
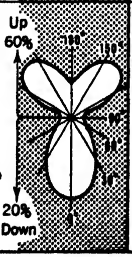
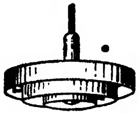
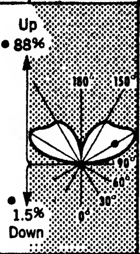
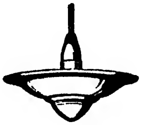
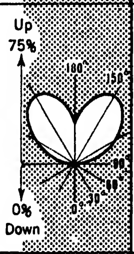
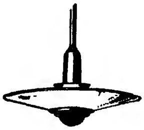
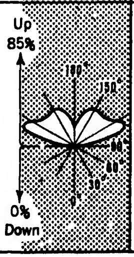
FIXTURES FOR INCANDESCENT LUMINAIRES			PER CENT REFLECTION FACTORS							
		Ceiling	75%			50%			30%	
Pictorial Views Descriptions Maintenance Factors (M.F.)	Candlepower Distribution Curves	Walls	50%	30%	10%	50%	30%	10%	30%	10%
		Room Index	COEFFICIENTS OF UTILIZATION							
I-5 M.F.=.70  Downlighting Unit Glass or Metal Louvered		J	.33	.32	.28	.31	.27	.26	.27	.25
		I	.40	.37	.35	.38	.35	.33	.33	.31
		H	.44	.41	.39	.41	.39	.37	.37	.35
		G	.47	.45	.43	.44	.41	.40	.40	.38
		F	.51	.48	.45	.46	.44	.42	.42	.40
		E	.54	.51	.49	.50	.48	.45	.45	.43
		D	.58	.54	.51	.53	.50	.48	.48	.46
		C	.60	.57	.53	.55	.52	.49	.48	.47
		B	.62	.59	.57	.57	.54	.53	.51	.49
		A	.64	.61	.58	.59	.56	.54	.52	.51
I-6 M.F.=.70  Glass Enclosing Units		J	.23	.19	.16	.21	.17	.15	.16	.14
		I	.29	.24	.22	.26	.22	.19	.21	.18
		H	.33	.28	.25	.29	.26	.23	.23	.21
		G	.37	.32	.28	.32	.28	.26	.26	.23
		F	.40	.35	.32	.35	.31	.28	.28	.26
		E	.44	.40	.36	.39	.35	.32	.32	.29
		D	.48	.43	.39	.42	.38	.35	.35	.32
		C	.51	.46	.42	.44	.40	.37	.37	.34
		B	.55	.50	.46	.48	.44	.41	.39	.37
		A	.57	.53	.49	.50	.46	.43	.41	.39
I-7 M.F.=.70  Glass Enclosing or Metal Louvered Unit		J	.24	.20	.17	.21	.17	.15	.15	.14
		I	.29	.25	.23	.26	.22	.20	.20	.18
		H	.33	.29	.26	.28	.26	.23	.22	.20
		G	.37	.33	.30	.32	.28	.26	.24	.23
		F	.40	.35	.32	.34	.30	.28	.26	.23
		E	.44	.40	.36	.37	.34	.31	.29	.27
		D	.47	.43	.40	.40	.37	.34	.32	.30
		C	.50	.46	.42	.42	.39	.36	.33	.31
		B	.53	.50	.47	.44	.42	.40	.35	.34
		A	.56	.51	.49	.47	.44	.41	.37	.35
I-8 M.F.=.70  Glass Enclosing or Metal Louvered Unit		J	.21	.17	.15	.16	.14	.12	.12	.09
		I	.26	.22	.20	.21	.18	.16	.15	.13
		H	.29	.26	.23	.23	.20	.19	.17	.15
		G	.33	.27	.26	.26	.23	.21	.18	.17
		F	.36	.32	.28	.28	.25	.23	.20	.20
		E	.39	.36	.32	.31	.28	.26	.22	.20
		D	.43	.38	.36	.33	.30	.28	.24	.22
		C	.45	.41	.38	.35	.32	.30	.25	.24
		B	.49	.46	.42	.37	.35	.34	.27	.26
		A	.51	.48	.45	.40	.37	.35	.28	.27

Table II (Continued)

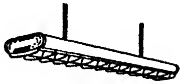
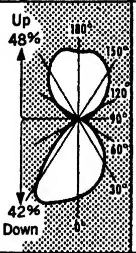
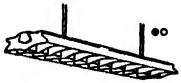
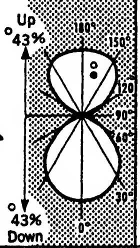
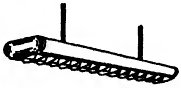
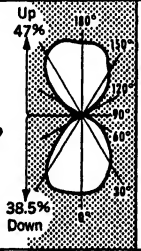
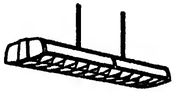
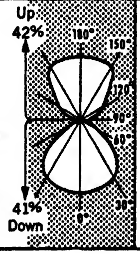
COEFFICIENTS OF UTILIZATION

FIXTURES FOR INCANDESCENT LUMINAIRES		PER CENT REFLECTION FACTORS								
		Ceiling	75%			50%			30%	
Pictorial Views Descriptions Maintenance Factors (M.F.)	Candlepower Distribution Curves	Walls	50%	30%	10%	50%	30%	10%	30%	10%
		Room Index	COEFFICIENTS OF UTILIZATION							
I-9 • M.F.= .70 •  Silver Bowl Lamp Three Reflector Rings		J	.19	.17	.15	.14	13	10	.07	.06
		I	.23	.18	.17	.17	.15	12	.09	.08
		H	.26	.23	.20	.19	.17	14	.10	.09
		G	.29	.27	.24	.22	.19	.17	.13	.12
		F	.33	.30	.27	.24	.21	.20	.14	.13
		E	.36	.32	.29	.26	.24	.23	.15	.14
		D •	.39•	.36	.33	.27	.26	.25	.16	.15
		C	.42	.38	.35	.29	.28	.27	.17	.16
		B	.45	.43	.39	.33	.31	.29	.18	.17
		A	.47	.45	.42	.36	.33	.31	.20	.18
I-10 M.F.= .60  Dense Glass or Metal Indirect Unit		J	.15	.12	.10	.10	.08	.07	.04	.04
		I	.19	.15	.14	.13	.10	.09	.06	.05
		H	.22	.18	.16	.14	.12	.10	.08	.06
		G	.25	.21	.18	.17	.14	.13	.08	.08
		F	.27	.24	.21	.19	.16	.14	.09	.08
		E	.31	.27	.25	.21	.18	.16	.10	.10
		D	.34	.30	.28	.22	.20	.19	.12	.11
		C	.36	.33	.30	.24	.22	.20	.13	.12
		B	.40	.37	.34	.26	.25	.23	.14	.14
		A	.42	.39	.37	.28	.26	.25	.16	.14
I-11 M.F.= .75  Shallow Shield Unit Silvered Bowl Lamp		J	.17	.13	.11	.11	.09	.08	.05	.04
		I	.21	.17	.15	.14	.12	.10	.07	.06
		H	.25	.21	.18	.16	.14	.12	.08	.07
		G	.28	.24	.21	.20	.16	.14	.09	.08
		F	.31	.27	.23	.21	.18	.16	.10	.09
		E	.35	.31	.28	.24	.20	.19	.12	.11
		D	.39	.34	.31	.26	.23	.21	.14	.13
		C	.41	.37	.34	.27	.25	.23	.14	.14
		B	.46	.42	.39	.30	.28	.26	.16	.15
		A	.48	.44	.42	.32	.30	.28	.18	.16

• Identifies data used in sample calculations

Table II (Continued)

COEFFICIENTS OF UTILIZATION

FIXTURES FOR FLUORESCENT LUMINAIRES		PER CENT REFLECTION FACTORS								
		Ceiling	75% ●			50%			30%	
		Walls	50%	30%	10%	50%	30%	10%	30%	10%
Pictorial Views Descriptions Maintenance Factors (M.F.)	Candlepower Distribution Curves	Room Index	COEFFICIENTS OF UTILIZATION							
F-12 M.F. .70  Metal V-Reflector, and Projecting Metal Louvers Plastic Side Panels		J	.31	.27	.25	.27	.25	.23	.22	.21
		I	.37	.34	.32	.33	.30	.28	.27	.26
		H	.41	.38	.36	.36	.34	.32	.31	.29
		G	.46	.42	.39	.40	.37	.35	.33	.31
		F	.49	.45	.42	.42	.39	.37	.35	.33
		E	.53	.49	.47	.46	.43	.41	.38	.36
		D	.57	.53	.50	.49	.46	.44	.40	.39
		C	.60	.56	.53	.51	.48	.45	.42	.40
		B	.63	.60	.57	.53	.50	.48	.44	.42
		A	.64	.62	.59	.56	.52	.50	.45	.43
F-13 ● M.F. .75 ●○  Metal V-Louver and Crosswise Louvers		J	.32	.29	.24	.29	.26	.25		
		I	.39	.36	.34	.33	.32	.31		
		H	.44	.40	.38	.38	.36	.34		
		G	.47	.44	.42	.42	.39	.37		
		F	.50	.47	.44	.44	.41	.40		
		E	.54	.51	.48	.47	.45	.43		
		D ●○	.58●○	.54	.52	.50	.48	.46		
		C	.60	.57	.54	.52	.50	.48		
		B	.63	.60	.58	.54	.52	.50		
		A	.64	.62	.59	.56	.54	.52		
F-14 M.F 70  Metal V-Reflector; Projecting Crosswise Louvers; Plastic Side Panels		J	.29	.26	.23	.25	.23	.21	.21	.19
		I	.35	.32	.30	.31	.28	.27	.26	.22
		H	.39	.36	.34	.34	.32	.30	.29	.27
		G	.43	.40	.37	.37	.34	.32	.31	.29
		F	.46	.42	.39	.40	.37	.35	.33	.31
		E	.50	.47	.44	.43	.40	.38	.35	.34
		D	.54	.50	.47	.46	.43	.41	.38	.36
		C	.56	.53	.49	.48	.45	.43	.39	.37
		B	.59	.56	.53	.50	.48	.46	.41	.40
		A	.60	.58	.55	.52	.49	.48	.42	.41
F-15 M.F 75  V-Lengthwise Louver and Crosswise Louvers, Glass Panels		J	.29	.25	.23	.26	.23	.21	21	19
		I	.35	.32	.30	.32	.29	.27	26	.24
		H	.39	.36	.34	.35	.32	.30	.29	.27
		G	.43	.39	.37	.38	.35	.33	.32	30
		F	.46	.42	.40	.40	.37	35	34	.32
		E	.50	47	44	.44	41	39	36	.35
		D	.54	.50	47	.46	44	42	.39	.38
		C	.56	.53	.49	48	46	44	40	39
		B	.59	.56	.53	51	48	46	42	41
		A	61	.58	55	52	50	48	44	42

●● Identifies data used in sample calculations

Table II (Continued)

COEFFICIENTS OF UTILIZATION

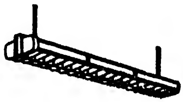
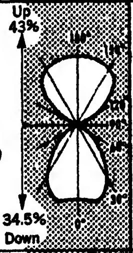
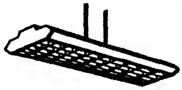
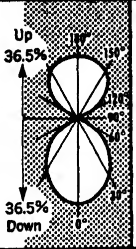
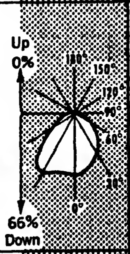
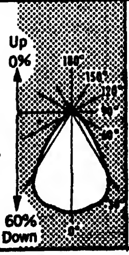
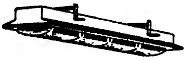
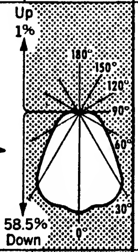
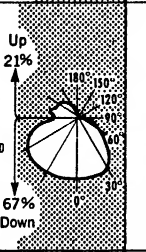
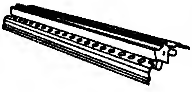
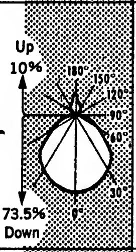
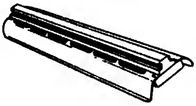
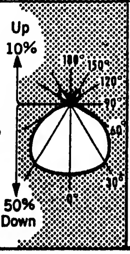
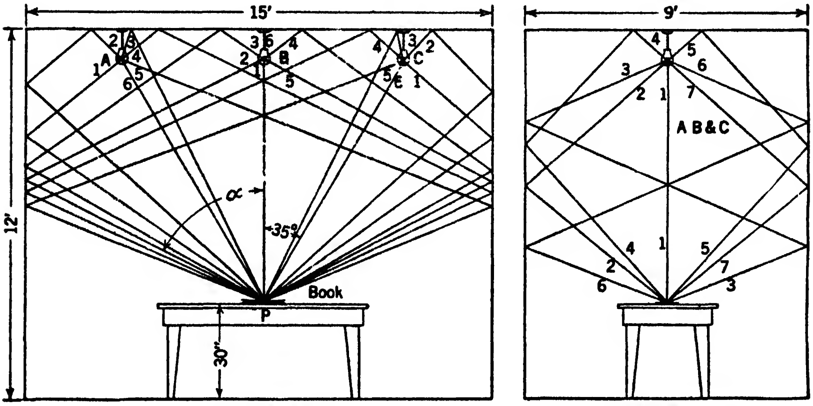
FIXTURES FOR FLUORESCENT LUMINAIRES		PER CENT REFLECTION FACTORS								
		Ceiling	75%			50%			30%	
Pictorial Views Descriptions Maintenance Factors (M.F.)	Candlepower Distribution Curves	Walls	50%	30%	10%	50%	30%	10%	30%	10%
		Room Index	COEFFICIENTS OF UTILIZATION							
F-16 M.F .75  Plastic Side Panels; Slightly Projecting Metal Louvers		J	.26	.22	.21	.23	.20	.19	.19	.17
		I	.32	.28	.27	.28	.25	.24	.23	.21
		H	.35	.32	.30	.31	.28	.27	.26	.24
		G	.39	.36	.34	.34	.31	.30	.28	.26
		F	.41	.38	.36	.36	.33	.32	.29	.28
		E	.45	.42	.39	.39	.36	.34	.32	.30
		D	.49	.45	.42	.41	.39	.37	.34	.33
		C	.51	.48	.45	.43	.41	.39	.35	.34
		B	.54	.51	.49	.45	.43	.42	.37	.36
		A	.55	.53	.50	.47	.45	.43	.38	.37
F-17 M.F. .75  Egg-Crate Louvers Crosswise and Lengthwise		J	.26	.24	.21	.24	.22	.20		
		I	.32	.29	.28	.29	.27	.25		
		H	.35	.33	.31	.31	.30	.28		
		G	.39	.36	.34	.35	.32	.31		
		F	.41	.39	.36	.36	.34	.33		
		E	.44	.42	.40	.39	.37	.35		
		D	.48	.44	.42	.41	.39	.38		
		C	.50	.47	.44	.43	.41	.39		
		B	.52	.49	.48	.45	.43	.42		
		A	.54	.51	.49	.46	.44	.43		
F-18 M.F. .70  Troffer Type with Projecting Lense or Ribbed Glass		J	.33	.29	.27	.32	.29	.27		
		I	.39	.37	.36	.38	.36	.35		
		H	.43	.40	.39	.42	.40	.38		
		G	.46	.43	.42	.45	.43	.41		
		F	.49	.48	.43	.48	.45	.43		
		E	.51	.50	.47	.50	.49	.47		
		D	.55	.52	.51	.54	.52	.50		
		C	.57	.54	.52	.55	.53	.52		
		B	.58	.56	.55	.57	.54	.53		
		A	.60	.57	.56	.58	.56	.54		
F-19 M.F. .75  Troffer Type with Stepped or Ribbed Flush Glass Panel		J	.33	.30	.29	.32	.31	.29		
		I	.39	.37	.37	.38	.37	.36		
		H	.42	.41	.40	.41	.40	.40		
		G	.45	.43	.43	.44	.43	.42		
		F	.47	.46	.44	.45	.45	.44		
		E	.50	.49	.47	.49	.48	.46		
		D	.53	.50	.49	.52	.50	.50		
		C	.54	.52	.50	.53	.52	.51		
		B	.55	.53	.51	.54	.53	.52		
		A	.56	.54	.53	.55	.54	.53		

Table II (Continued)

COEFFICIENTS OF UTILIZATION

FIXTURES FOR FLUORESCENT LUMINAIRES		PER CENT REFLECTION FACTORS								
		Ceiling	75%			50%			30%	
Pictorial Views Descriptions Maintenance Factors (M.F.)	Candlepower Distribution Curves	Walls	50%	30%	10%	50%	30%	10%	30%	10%
		Room Index	COEFFICIENTS OF UTILIZATION							
F-20 M.F .70  Troffer Type with Curved Lense Below Ceiling		J	.29	.26	.24	.29	.26	.24	.26	.24
		I	.35	.32	.31	.35	.32	.30	.32	.30
		H	.39	.36	.34	.38	.36	.34	.35	.34
		G	.41	.39	.38	.40	.38	.37	.38	.37
		F	.44	.42	.39	.42	.40	.39	.40	.39
		E	.46	.45	.42	.46	.44	.42	.43	.42
		D	.50	.47	.45	.49	.46	.45	.46	.45
		C	.51	.49	.46	.50	.48	.46	.47	.46
		B	.53	.51	.49	.52	.49	.48	.49	.48
		A	.54	.52	.51	.53	.51	.49	.50	.49
F-21 M.F. .70  Porcelain Enamel V-Reflector; No Cross Louvers		J	.33	.27	.23	.31	.25	.22		
		I	.41	.35	.31	.38	.33	.29		
		H	.45	.40	.36	.42	.38	.34		
		G	.50	.44	.40	.46	.42	.38		
		F	.53	.48	.43	.49	.45	.41		
		E	.59	.54	.49	.55	.50	.47		
		D	.64	.59	.54	.59	.55	.52		
		C	.67	.62	.59	.61	.57	.54		
		B	.71	.67	.63	.65	.62	.59		
		A	.74	.70	.65	.68	.64	.61		
F-22  Bare Lamp Fixture with Metal Top Frame		J	.35	.30	.26	.34	.29	.26	.28	.25
		I	.43	.38	.35	.42	.37	.34	.37	.34
		H	.47	.43	.40	.45	.42	.39	.41	.39
		G	.51	.47	.44	.49	.46	.43	.44	.42
		F	.54	.50	.47	.52	.48	.46	.47	.45
		E	.59	.55	.52	.57	.54	.51	.52	.50
		D	.63	.60	.57	.60	.58	.56	.56	.55
		C	.65	.62	.59	.62	.60	.58	.58	.56
		B	.68	.65	.63	.65	.63	.61	.61	.59
		A	.70	.67	.65	.67	.64	.63	.62	.61
F-23 M.F. .65  Typical Unshielded Industrial; Two Side Reflectors with Slotted Tops		J	.37	.31	.27	.36	.31	.27		
		I	.46	.40	.38	.44	.39	.36		
		H	.50	.46	.42	.48	.45	.41		
		G	.54	.49	.46	.52	.49	.45		
		F	.57	.53	.50	.54	.51	.49		
		E	.62	.58	.55	.60	.57	.54		
		D	.67	.63	.60	.64	.61	.59		
		C	.69	.66	.63	.65	.63	.61		
		B	.72	.69	.67	.69	.66	.65		
		A	.74	.71	.69	.70	.68	.66		

7. Determination of illumination in foot-candles. If a room having two long and two short sides were lighted by three bare incandescent lamps as shown in Fig. 6, a book lying on a table would be illuminated by the sum of all the rays reaching the book from all sources. These rays would consist of direct rays from the lamps, reflected rays from the ceiling and from each side and end wall, and doubly reflected rays from both ceiling and walls. If the intensities of the lamps in all directions and the reflecting values of the walls and ceiling were known, light upon the book could be calculated in foot-candles by means of formulae involving the sines and cosines of the inclination angles of the rays. This process, known as the point-by-point method, is slow and laborious.



Long Elevation
(a)

Short Elevation
(b)

Fig. 6. Side elevation (*a*), and end elevation (*b*), showing direct and reflected light from sources *A*, *B*, and *C*. Certain typical rays numbered 1, 2, 3, 4, 5, 6 leave the lamps and, after reflection from ceilings, walls, etc., finally illuminate the object on the table. Thus both direct and reflected rays add to the total light on the book. The average intensity in foot-candles is the sum of all rays emitted by the lighting unit *reduced* by the inverse-square of the distance and by the reflection factors of the ceiling and walls.

A portable instrument (Fig. 7) called an illumination meter or illuminometer indicates directly in foot-candles the *intensity* of light falling upon a surface. With the help of this meter a large series of experiments were made in model rooms of different proportions and wall and ceiling coloring and with a wide variety of fluorescent and incandescent lighting fixtures, spacings, and hanging heights. The deductions from these experiments have been tabulated, and factors, constants, and guiding principles of great assistance in the design of interior lighting have been determined.

The methods of interior illumination design are described in Arts. 9 and 10, inclusive. The entire field of illumination design may be found in the current edition of the *IES Lighting Handbook,* published by the Illuminating Engineering Society, 1860 Broadway, New York 23, N. Y.

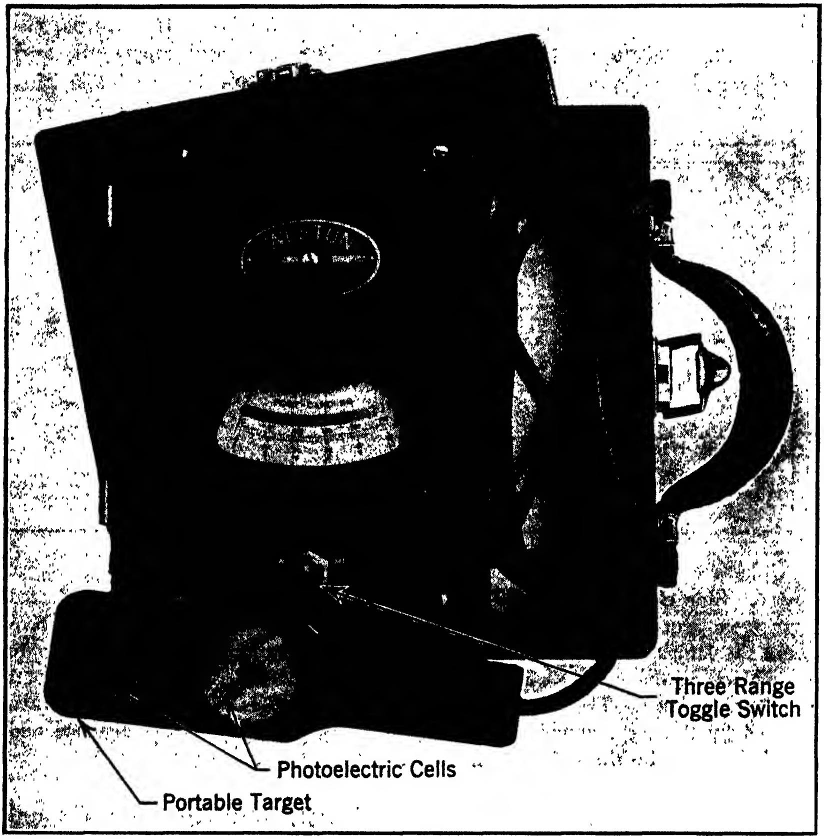


Fig. 7. Foot-candle meter or light-flux meter. This instrument indicates illumination in foot-candles.

8. Some design features. Consideration of the following principles is essential for a satisfactory and efficient lighting installation:

(*a*) The maintenance factor of the equipment depends upon the dust-catching properties of the luminaire, the prevalence of dust and smoke, and the frequency of cleaning.

(*b*) The spacing in both directions between overhead luminaires should be from about 0.8 to 1.0 times the mounting height and in no case greater than 1.3 times the mounting height.

$$\frac{124{,}000}{32} = 3875 \text{ lumens per unit}$$

H. The luminaire chosen contains two 40-watt fluorescent lamps. Referring to Table I, Chapter 27, it is seen that a 40-watt, standard cool white fluorescent lamp gives 2350 l. The total per luminaire is therefore 4700 l. The actual foot-candles will be

$$\frac{4700 \times 32 \times 0.58 \times 0.75}{30 \times 45} = 48.5 \text{ ft-c}$$

This is therefore a satisfactory alternate installation.

11. Supplementary lighting. It is frequently desirable to design illumination for a general low-level intensity over the entire area, and then to provide supplementary lighting for high intensities for more critical seeing tasks. For example, a large library or business-machine room may have general lighting at 10 ft-c with supplementary reading lamps averaging 25 ft-c on the tables. An airplane assembly plant may have 25 ft-c of general lighting on the open floor, with portable supplementary floodlights or reflectors (Fig. 10) to secure desired intensities of 25 to 50 ft-c for working operations under the wings or within the fuselage. Machinists often use an adjustable fixture mounted directly above the working points of machine tools.

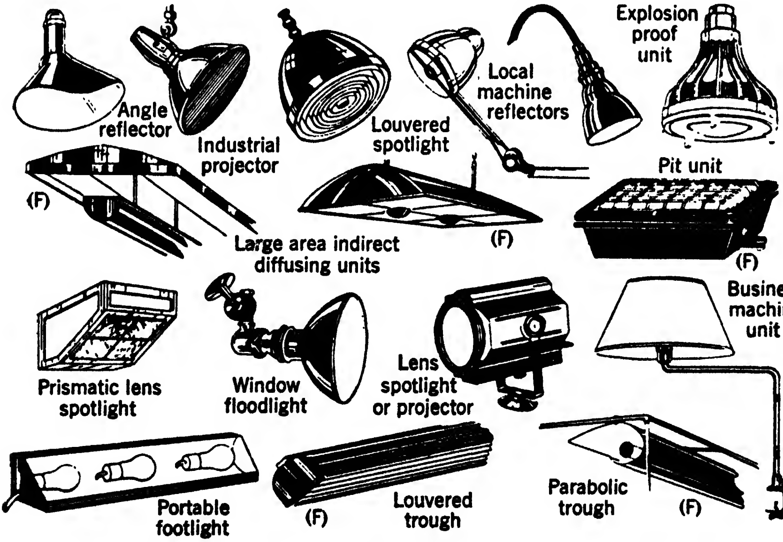


Fig. 10. Typical supplementary lighting units: for both incandescent and fluorescent lamps. (F for fluorescent lamps.)

12. Cove lighting and panel lighting. Many unusual and dignified lighting effects are obtainable by the use of well-designed cove or panel illumination. This is especially effective in long hallways, lobbies, and meeting rooms where intensities of from 5 ft-c to 20 ft-c are sufficient. The lighting units are concealed in coves, or directly facing towards diffusing glass or glass lenses.

Figure 11(*a*), (*c*), and (*d*) illustrates the cross sections of three typical coves of this kind. Figure 11(*b*) shows a ceiling panel with a reflector directing light downward to a painting on the wall of an art gallery. Figure 11(*a*) consists of a long reflector of a highly polished metal or mirrored glass in which the lamps are usually placed with their axes horizontal and relatively close together for uniform illumination on the reflecting surface. Figure 11(*c*) and (*d*) illustrates the use of individual reflectors spaced along a cornice or cove at the proper angles to project the light upon the ceiling. Every part of the reflector and of the lighting equipment should be sufficiently low in the cove to prevent observation from any normal location in the room. Lines of sight should be projected on the working drawings from every point

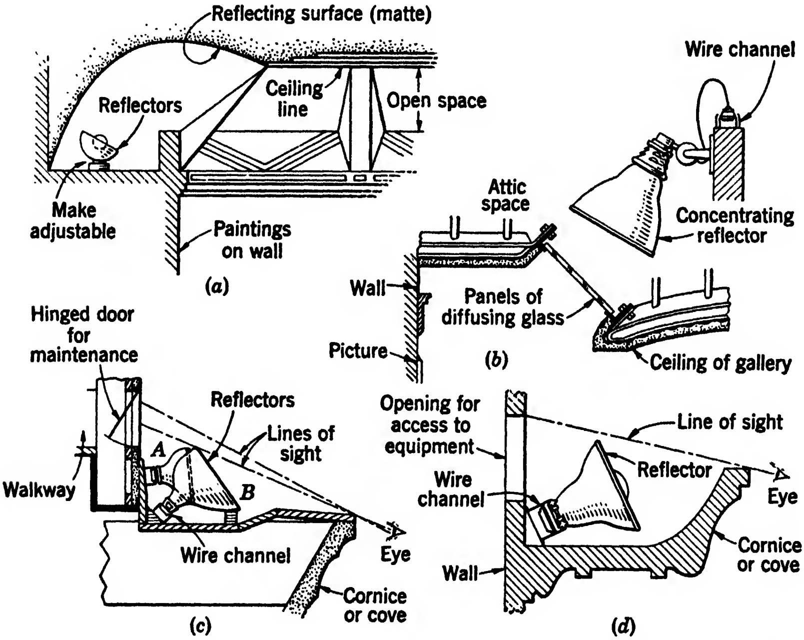


Fig. 11. Typical arrangements of equipment for cove lighting and panel lighting. All wire channels and individual lamp sockets should be made adjustable for ease in obtaining final focus.

where the angle of vision toward the cove might bring the lighting equipment into view. Access to the luminaires for cleaning, relamping, and repairs should be provided by means of catwalks, hinged doors, or open spaces just back of the lighting equipment and below the lines of sight. The reflecting curves of coves and ceilings require careful study to procure effective directional angles for the light rays.

13. Shop and display lighting. Rapid adoption of the fluorescent lamp has revolutionized both large department stores and smaller stores and shops. General illumination provides a soft, dignified, and pleasing overall illumination. Where "sparkle" is desired on the merchandise the direct rays from lowered fluorescent and incandescent spot- and floodlights are very effective. Where jewelry is arranged in showcases for eye appeal, the direct incandescent or fluorescent tubular lamps are generally placed in the show cases and always out of the direct lines of sight.

14. Show-window lighting. Show-window lighting is usually by the direct method consisting of small lamps and reflectors from 12 to 18 in. apart concealed overhead or at the sides of the window. Downlights of concentrating types are often placed above the ceiling level. The intensity, 30 to 300 ft-c, depends upon the light or dark color of the goods on display and upon the competing brilliancy of neighboring shop windows. Head and foot panels with flat prismatic lenses are often placed near the plate glass windows with rays directed as required. Where colored materials are on display, care should be taken in the selection of lamps with favorable color characteristics.

15. Schoolroom lighting. Schoolrooms demand a diffused uniform illumination, 40 to 100 ft-c of artificial light, without glare in order that eye strain may be reduced to a minimum. This result may be obtained by direct, indirect, or semi-indirect luminaires if the lighting is well designed. The indirect and semi-indirect methods produce more effective uniform light but at more expense and with more frequent cleaning of the open or partially enclosed lamps and fixtures. The major portion of the light is directed downward, but a sufficient amount is transmitted upward to present a cheerful ceiling. Auditoriums may be lighted by the same arrangements or by indirect cove or panel lighting.

16. Hospitals. Wards require four lighting divisions: (*a*) general illumination in the evening. Direct, indirect, or semi-indirect methods may be used but the light must be well diffused and the luminaires of low brilliancy to insure comfort to the patients. (*b*) Night lighting of about 0.1 ft-c. This may be provided by low-wattage lamps in the fixtures for general illumination wired on a separate circuit; or preferably by baseboard or portable lamps placed close to the floor. (*c*) Local portable fixtures at the beds, usually with brackets, and with the lamp and a convenience receptacle combined in the lamp base. (*d*) The nurse's desk is provided with an outlet for a portable desk lamp, and the chart rack requires a suitable wall bracket.

Private rooms are lighted uniformly by one of the indirect systems with direct fixtures at the beds. Signal lights with switch at the bed may be installed outside the door to enable the patient to summon the nurse. Night baseboard lights are common in both private rooms and corridors.

Operating rooms require shadowless diffusion and very high local illumination. These conditions may be attained by rows of lamps with reflectors and prismatic glass plates recessed in the ceiling. The lamps surround the operating table and provide illumination from all directions without glare. Portable floor lamps with storage-battery connection provide for emergencies upon failure of the normal circuits. Less costly installations consist of lamps with concentrating reflectors equally spaced on a circular frame suspended horizontally over the operating table. Lamps with reflectors are also fitted under a large metal hood above the table and provide adequate illumination for the less exacting operations and maternity work. Portable lamps are sometimes added to direct light on vertical surfaces. The reflectors for all these types are usually of mirrored glass, and screens of blue glass are often employed to simulate the color values of daylight.

17. Theater auditoriums. Rather radical changes of public interest in entertainment at the theater, including motion-picture houses, are having their influence on illumination design problems. Television is noticeably decreasing attendance at the local and in-town movies. Acoustical design and increasing use of air conditioning equipment are factors which affect the location of luminaires, special service and emergency lighting fixtures. Television auditoriums require a foreground of low-intensity, well-diffused light to insure eye comfort during the viewing of the screen. Acoustic treatment of side-wall soffits and ceiling contours gives rise to a new floodlight treatment from lamps in concealed coves at the top of the soffits or behind shields halfway up the soffits.

Elaborate ceilings and domes offer many possibilities for diffused direct and indirect lighting from concealed lamps. When suitable, central crystal chandeliers are extremely decorative and may contain concealed indirect equipment to project light upon the ceiling, the crystals themselves being illuminated by floodlights. Luminous ceilings with fluorescent lamps in the plenum chamber above them offer a new field to the illuminating engineer in the lighting of auditoriums, drafting rooms, and offices. Cornices, coves, domes, and the sides of beams may be utilized for masking lamps with mirrored glass reflectors. Indirect overhead luminaires and cove lighting are satisfactory in less elaborate auditoriums.

In cinema theaters lamps set in the aisle side of end seats and in the risers of steps project sufficient light across the floor for service while the auditorium is darkened. Means should always be furnished for instantly flooding a theater with light. To this end the fixtures are in series with dimmers or variable resistors manipulated manually or by remote control. In cheaper installations. two circuits to lamps of low and high wattage in the same fixtures may be installed. The full brilliancy, turned on instantly, could cause a blinding effect with consequent eye strain.

18. Lighting in homes and apartments. The fixtures of homes decorated in traditional period style should possess style, character, and suitability, and the illumination should be gracious, sympathetic, and becoming. Local lighting, whether direct or indirect, is here a welcome relief because of its variety and change. The glow from a few table lamps or wall brackets and the mysterious grades of light and shadow intervening transmit livable and desirable qualities. Ceiling outlets frequently may be omitted and wall outlets and baseboard receptacles installed. The wall outlets should not be placed in the center of wall spaces but should be symmetrically arranged with respect to fireplaces, windows, and doors. The receptacles conveniently serve desks and tables or electric appliances. A reading lamp of 40 to 100 ft-c with fine diffusion, wide-range uniformity, and low surface brilliancy is of great importance. The 3-level incandescent lamp is quite popular. Bedrooms require concentrated light from brackets or table lamps at dressing mirrors and the bed.

The kitchen and working spaces may have soft uniformly diffused lighting from the ceiling luminaires with or without concentration at special points.

The modern kitchen should have indirect or shielded lighting over the work tables, sink, stove, and cupboards. This illumination is usually obtained by placing tubular lumaline or fluorescent lamps under the cabinets (above the level of stove, sink, work table, etc.) in such positions that the lower frame of the cabinet conceals the lamps. Convenient local switches control these lamps. Kitchens require a number of wall outlets for refrigerators, heating appliances, mixers, etc.

19. Floodlighting. Floodlighting is used for many important purposes such as the illumination of nighttime sports; the illumination of buildings, bridges, and monuments; the illumination of runways and other areas of airfields; floodlighting of parking areas; the emergency lighting of yards of penal institutions, of strategic defense areas, and of rescue operations at sea. The armed services have many important applications of floodlamps on land, sea, and in the air.

20. Scope of floodlighting. Extensive use of outdoor floodlamps for illuminating the exteriors of well-designed commercial, public, and governmental buildings is a common practice. Other areas that are frequently floodlighted include athletic fields, playing floors of gymnasiums, dock and ferry landings, airports, monuments, bridges, prison yards, construction sites, churches, and military applications. The principles of design for such systems are essentially the same as for interior illumination.

The *intensity* of illumination on the object will be

$$\frac{\text{Beam candlepower}}{\text{Square of the distance}} = \frac{I_b}{d^2} = \text{ft-c}$$

In this equation I_b is the beam candlepower in a given direction from the source, d is the distance in feet to the object illuminated, and ft-c is the foot-candle *intensity* of light.

It is assumed that the candlepower is uniform over the entire area of the beam at the floodlamp. If all the light is projected into the beam (i.e., 100 per cent beam efficiency), the maximum possible intensity will be secured on the wall. Owing to the imperfections of mirrors, the absorption of light in the reflectors, the absorption and diffusion of light in the cover glasses of lenses, and the impossibility of making an incandescent filament into a true point source of light, the beam efficiencies of floodlamps vary from about 15 to 45 per cent. The "spilled light" is that which is not directly in the beam. A considerable portion of the light is not confined to the beam but spills in other directions; hence the total output of the floodlamp includes the lumens in the beam plus the lumens scattered outside the rated angle of beam spread. The efficiency of floodlamps, including the beam light and the spilled light, varies from 55 to 75 per cent. Usually the spilled light is helpful in obtaining a smooth overlap of circular patterns on the wall and uniform intensities. When a single small stationary object is to be lighted from a distance by one lamp it is important to have a high beam efficiency, for spilled light, in this case, will detract from the effect.

When the center line of the beam is projected at right angles to the surface illuminated, the surface reflects the maximum amount of light. A divergence of 10 to 15° from this position, however, will not materially affect the efficiency of reflection from the ordinary structural materials. In many instances it is impracticable to locate the floodlamps so that the light will strike nearly perpendicularly to the surfaces illuminated. In fact, many installations require beam projection angles of 50 to 75°. Figure 12(*a*) and (*b*) shows typical examples of beam projection where high surface reflection may be expected; (*c*) and (*d*) are examples of low surface reflection due to wide divergence of beam angle. In (*c*) and (*d*) the light reflected back into the observer's eye is much less; hence the wattage required is considerably greater.

The elevation (*e*) suggests various locations of projectors in the overhung floors or in the walls of building for floodlighting near-by areas of the same building. Note that the light which strikes the undersides of the overhung portions will immediately be deflected and diffused to create *soft illumination*, contrasting with lighter or darker areas near-by.

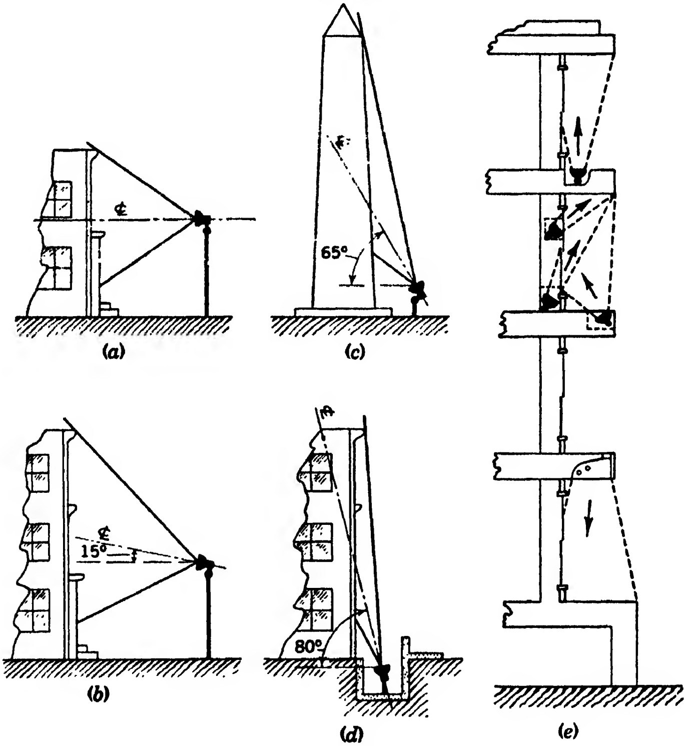


Fig. 12. Typical arrangements and locations of outdoor floodlamps (*a*, *b*, *c*, *d*); and suggested arrangements (*e*) of incandescent or fluorescent lamps for lighting the exterior surfaces and cantilever floor extensions.

The pattern of a circular beam is round if the beam center line is perpendicular to the wall (Fig. 13). The pattern becomes elliptical if the beam center line is raised or lowered from this perpendicular position (*b*). The lengths of the long and short axes of the ellipse depend upon the angle of divergence from the perpendicular. The approximate dimensions of the beam pattern axes may easily be measured from plan and elevation drawings made to scale.

21. Floodlamps. The light from floodlamps is generally directed within narrow beam spreads, say from 10 to 50°, the concentration and pattern (round or oval) of the light flux being secured by an incandescent lamp and a reflector of the proper shape. The lamp is usually placed at the focal point of the reflector in order to secure the rated beam spread and maximum efficiency of projection. By efficiency of projection is meant the maximum ratio of light output in lumens to the total bare lamp lumens.

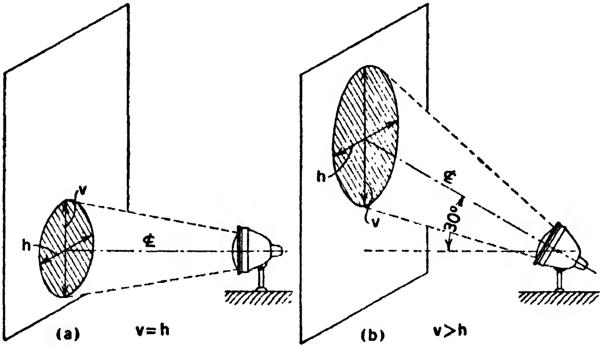


Fig. 13. Typical locations of floodlamps with respect to vertical walls, showing the circular to elliptical patterns for projected beams.

Floodlamps are classified as enclosed or open types for outdoor use. For indoor applications a floodlamp usually consists only of a reflector and a lamp respectively supported in proper focal position and without the housing and elaborate details required for the outdoor types.

22. Beam patterns. Practically all floodlamps have reflectors which produce circular beam patterns as illustrated at *A*, *B*, and *C*, Fig. 14(*b*). An elliptical beam pattern may be obtained by the use of ribbed glass cover lenses mounted on the front of the reflector housings, the ribs taking a vertical position when a horizontal elliptical beam pattern is desired, as in *D*, Fig. 14(*b*). Turning the glass ribs 90° will produce the vertical beam pattern *E*, Fig. 14(*b*).

In order to overcome irregular intensities on the illuminated surfaces and to give a desired soft quality to the light, stippled lenses or reflectors are frequently used instead of plain lenses. These irregularities are due to the fact that a true point source of light cannot be provided at the focal point of the reflector and are emphasized by imperfections in the reflector surface and in the cover lenses and plates.

The general direction of the center line of the beam may be changed by adjustment of the floodlamp on its trunnions or on its swivel base. Means are provided for locking the lamp in the desired position.

The curves of Fig. 15 give the circular areas illuminated by beams of 10 to 70° spread, projected perpendicular to the surface lighted

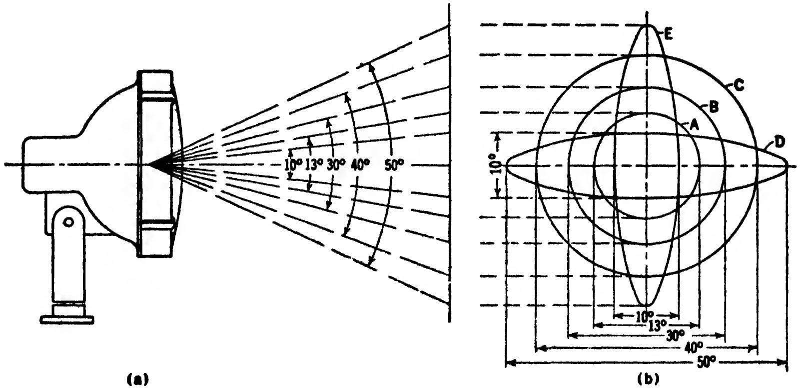


Fig. 14. Measurements of beam angles and typical corresponding patterns of projected beams.

with the lamps located at various distances. Certain manufacturers provide lamps of intermediate beam spreads. For these the curves may be interpolated.

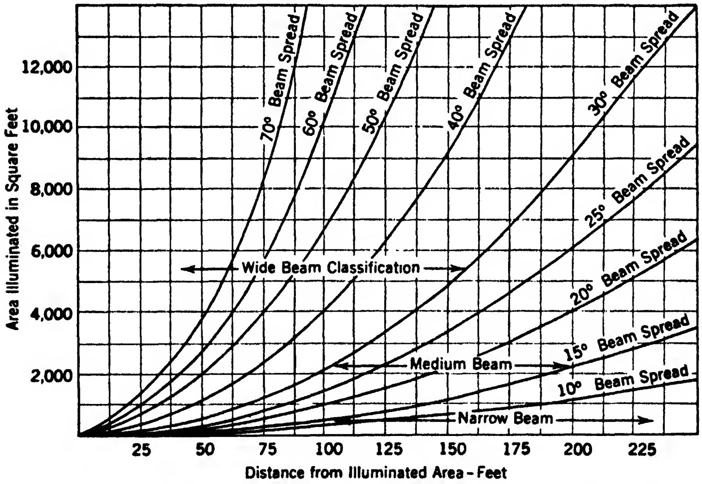


Fig. 15. Curves showing areas illuminated in square feet vs. the distance from illuminated areas.

23. Flood lighting intensities. Table V gives recommended *intensities* for floodlighting installations. If the surface to be illuminated is in a location where the surrounding surfaces are also brightly lighted, the intensity must be much greater to produce the desired contrast.

Table V. Desirable Intensities for Display Lighting of Outdoor Surfaces

	Foot-Candle Intensity	
	Minimum	Maximum
Building materials		
Brick: smooth, buff, gray	10	15
Brick: gray, darkfield; red, common; tan, common; Brownstone	15	30
Limestone, Bedford: buff, gray, light, gray, medium	10	15
Marble: light	5	10
Sandstone (Briar Hill)	10	20
Terra cotta: cream, white, gardens, flower	5	10
Gasoline service stations	5	10
Monuments and statues, depending on material used (*see* Building materials, above); signs, billboards, etc.	10	30
Stacks; water tanks	8	12

The color and reflection characteristics of various building materials have a marked influence on the wattages required. For example, a white terra-cotta surface may require 5 to 10 watts per sq ft to produce a given intensity, whereas common tan brick may require 15 to 30 watts per sq ft to produce the same intensity.

24. Location of floodlamps. In new installations the exact positions of floodlamps with respect to the surfaces illuminated should be determined during the period of design. In general, it is desirable to hide the source. On large buildings in business districts the locations are usually on the building itself, behind parapet walls, on the outer edges of setbacks, on the edges of cornices, or behind ornamental friezes. If the floodlamps can be placed on adjacent buildings the beams may be projected nearly perpendicular to the surfaces to be illuminated, insuring a higher efficiency and a less expensive installation. When building surfaces are lighted from the ground, lamps may be conveniently concealed in shrubbery, on mountings in trees, within specially designed pylons, or from light wells adjacent to the building. Occasionally certain portions of buildings are lighted from points within the building itself by projecting the beams through windows. Figure 16 shows in side elevation a number of typical methods of mounting floodlamps. The lamps are usually set in rows, but for large surfaces it may be desirable to divide the lamps in groups to project the light from several different points; this arrangement softens the shadows and adds to the harmony of the architecture.

25. Calculation of a typical floodlight installation. The plan and elevation of the front of a school building are shown in Fig. 17(*a*)

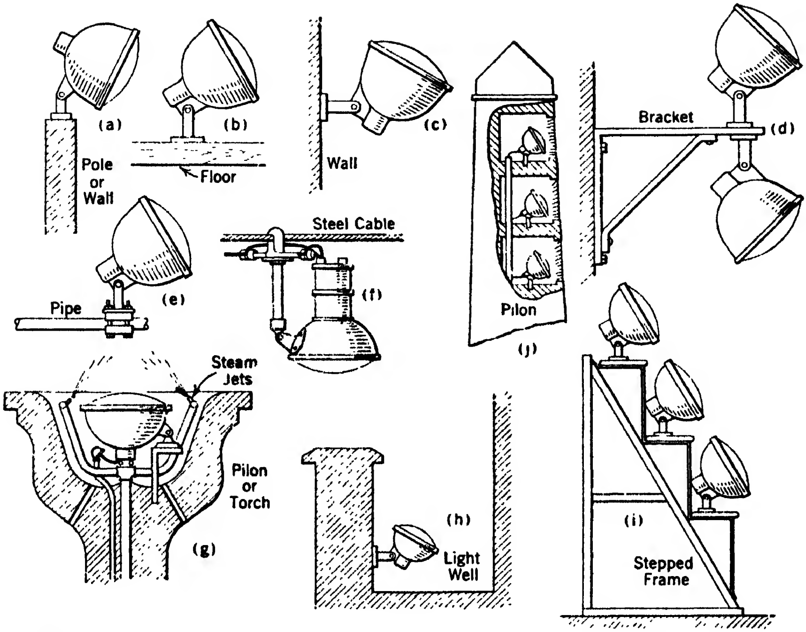
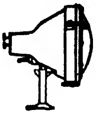


Fig. 16. Some convenient methods of supporting exterior floodlamps.

and (*b*). The building is of light gray limestone and is to be floodlighted to an approximate intensity of 6 ft-c. The yard in front of the building extends 100 ft forward to the sidewalk. A wall extends around the schoolyard with trees and shrubbery just inside it. The quality of the light is to be obtained with clear glass covers.

In the practical solution it seems obvious to place the floodlamps directly in front of the building and partially concealed by the shrubbery. Since there is a U-shaped driveway to the front entrance, it is desirable to divide the lamps into two groups, one on each side of the driveway. Assume that 8 floodlamps will be used, 4 in each group, situated approximately 80 ft in front of the building. A protractor [placed on Fig. 17(*b*)] shows that a beam spread of 40° will be wasteful of light because of the overshoot of the beam at the top. A 30° spread, on the other hand, will approximately cover the entire front of the building in a vertical direction, lacking a strip near the ground line. However, since the driveway and the 6-ft sidewalk are of light-colored concrete, the reflecting characteristics of this material will assist in building up the intensity upon the uncovered area. Referring to the plan [Fig. 17(*a*)] it is seen that each group of 4 lamps must have a horizontal beam spread of 30° in order to cover the entire front of the building. The wastage of light due to a slight overshoot at the

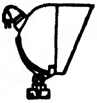
Table VIA. Design Data for Enclosed-Type Floodlights



These data apply to enclosed-type floodlights with silver glass reflectors and plain, stippled, or spreading lenses. Ample allowance has been made for depreciation so that with reasonable care these foot-candle values can be maintained.

Area per Floodlight (sq ft)	Average Foot-Candles						
	200 watt	300 watt	500 watt	750 watt	1000 watt	1500 watt	2000 watt
500–750	1.6–2.4	2.3–3.4	4.0–6.1	5.4–8.1	7.6–11.4	12.9–19.4	19.3–29.0
750–1000	1.2–1.6	1.7–2.3	3.0–4.0	4.0–5.4	5.7–7.6	9.7–12.9	14.5–19.3
1000–1250	.95–1.2	1.4–1.7	2.4–3.0	3.2–4.0	4.6–5.7	7.8–9.7	11.6–14.5
1250–1500		1.1–1.4	2.0–2.4	2.7–3.2	3.8–4.6	6.5–7.8	9.7–11.6
1500–1750			1.7–2.0	2.3–2.7	3.3–3.8	5.5–6.5	8.3–9.7
1750–2000			1.5–1.7	2.0–2.3	2.9–3.3	4.9–5.5	7.3–8.3
2000–2250			1.3–1.5	1.8–2.0	2.5–2.9	4.3–4.9	6.5–7.3
2250–2500			1.2–1.3	1.6–1.8	2.3–2.5	3.9–4.3	5.8–6.5
2500–2750			1.1–1.2	1.5–1.6	2.1–2.3	3.5–3.9	5.3–5.8
2750–3000			1.0–1.1	1.4–1.5	1.9–2.1	3.2–3.5	4.8–5.3
3000–3250				1.3–1.4	1.8–1.9	3.0–3.2	4.5–4.8
3250–3500				1.2–1.3	1.6–1.8	2.8–3.0	4.2–4.5
3500–3750				1.1–1.2	1.5–1.6	2.6–2.8	3.9–4.2
3750–4000					1.4–1.5	2.4–2.6	3.6–3.9
4000–4250					1.3–1.4	2.3–2.4	3.4–3.6
4250–4500					1.2–1.3	2.2–2.3	3.2–3.4
4500–4750					1.1–1.2	2.1–2.2	3.1–3.2
4750–5000						2.0–2.1	2.9–3.1
5000–5250						1.9–2.0	2.8–2.9
5250–5500						1.8–1.9	2.6–2.8
5500–5750						1.7–1.8	2.5–2.6
5750–6000						1.6–1.7	2.4–2.5

Table VIB. Design Data for Open-Type Floodlights

Area per Floodlight (sq ft)	 These data apply to open-type floodlights with porcelain enamel or aluminum reflecting surfaces. Ample allowance has been made for depreciation so that with reasonable care these foot-candle values can be maintained.						
	Average Foot-Candles						
	200 watt	300 watt	500 watt	750 watt	1000 watt	1500 watt	2000 watt
500–750	1.4–2.0	2.0–2.9	3.4–5.0	4.6–6.9	6.5–9.7	11.0–16.5	16.5–25.0
750–1000	1.0–1.4	1.4–2.0	2.6–3.4	3.4–4.6	4.9–6.5	8.3–11.0	12.5–16.5
1000–1250	0.8–1.0	1.2–1.4	2.0–2.6	2.7–3.4	3.9–4.9	6.6–8.3	10.0–12.5
1250–1500		0.9–1.2	1.7–2.0	2.3–2.7	3.2–3.9	5.5–6.6	8–10
1500–1750			1.4–1.7	2.0–2.3	2.8–3.2	4.7–5.5	7–8
1750–2000			1.3–1.4	1.7–2.0	2.5–2.8	4.2–4.7	6–7
2000–2250			1.1–1.3	1.5–1.7	2.1–2.5	3.7–4.2	5.5–6.0
2250–2500			1.0–1.1	1.4–1.5	2.0–2.1	3.3–3.7	5.0–5.5
2500–2750			0.9–1.0	1.3–1.4	1.8–2.0	3.0–3.3	4.5–5.0
2750–3000			0.8–0.9	1.2–1.3	1.6–1.8	2.7–3.0	4.0–4.5
3000–3250				1.1–1.2	1.5–1.6	2.6–2.7	3.8–4.0
3250–3500				1.0–1.1	1.4–1.5	2.4–2.6	3.6–3.8
3500–3750				0.9–1.0	1.3–1.4	2.2–2.4	3.3–3.6
3750–4000					1.2–1.3	2.0–2.2	3.1–3.3
4000–4250					1.1–1.2	1.95–2.0	2.9–3.1
4250–4500					1.0–1.1	1.9–1.95	2.7–2.9
4500–4750					0.9–1.0	1.8–1.9	2.6–2.7
4750–5000						1.7–1.8	2.5–2.6
5000–5250						1.6–1.7	2.4–2.5
5250–5500						1.5–1.6	2.2–2.4
5500–5750						1.4–1.5	2.1–2.2
5750–6000						1.3–1.4	2.0–2.1

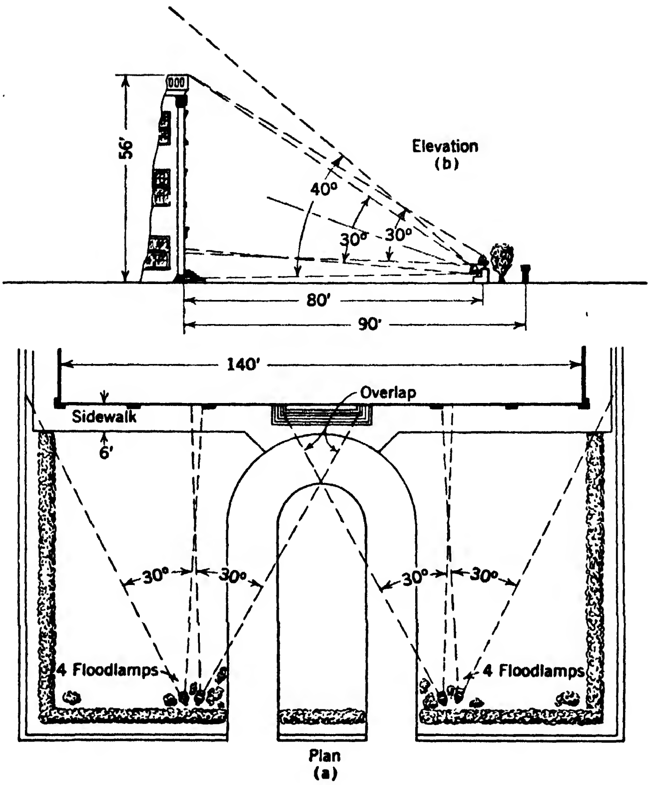


Fig. 17. Plan and front elevation of a typical building, showing locations of proposed floodlamps and patterns of beam spread.

ends may be eliminated in the final adjustment of the beam directions and at the same time will slightly increase the desired illumination of 6 ft-c. In order to get a uniform spread and a soft quality of light over the entire area, stippled cover plates are used. From Table VII, G-bulb floodlight lamps give a beam spread of 30° by 30°, and PS-bulb lamps have a 35° by 35° spread. In the latter case, there will be a slight

Table VII. Beam Spreads of Typical Floodlights *

	Enclosed Type					
	Plain Lens	Lightly Stippled Lens	Heavily Stippled Lens	Horizontal Spread Lens	Vertical Spread Lens	Open Type
PS-bulb general-service lamps	25° X 25°	35° X 35°	50° X 50°	50° X 20°	50° X 20°	90° X 90°
G-bulb flood-lighting lamps	13° X 13°	30° X 30°	40° X 40°	50° X 10°	50° X 10°	

* For more exact data on beam spreads refer to manufacturers' catalogues.

overshooting of the beams at both the top and sides of the building, but again this can be corrected in the final directional adjustment of the beams. The beam overlap at the center (see plan) will build up an agreeable higher intensity emphasizing the entrance doorway. Since it is desirable to lower the cost of maintenance and upkeep, the PS-bulb general-service lamps will be used in the 35° by 35° units.

In order to determine the wattage, first find the area covered per lamp, or

$$\frac{\text{Width} \times \text{Height}}{\text{Number of floodlamps}} = \frac{140 \text{ ft} \times 56 \text{ ft}}{8} = 980 \text{ sq ft}$$

Referring to Table VIA, in the left-hand column under 980 sq ft (750–1000) and in the column of 6 ft-c (5.7–7.6), it will be noted that a 1000-watt lamp is required. Hence, it will be necessary to provide a total of eight 1000-watt floodlamps, 4 in each group. These may be conveniently located on a stepped rack (Fig. 16).

As a check on the above solution the problem is solved with reference to the number of lumens of light flux which issue from the 8 floodlamps. Each lamp (PS-bulb, general service, Table II, Chapter 27) has an initial output of 21,500 l. The average output of such a lamp, over its entire life of 1000 hr, is 84 per cent of this value, i.e., 18,000 lumens. A floodlamp of the type selected will have a beam efficiency of approximately 35 per cent. This means that 35 per cent of the average lumens from the PS-bulb will be projected into the beam, or 6000 l. The total light flux required to illuminate the entire area to an intensity of 6 ft-c is the product of the area and the foot-candle intensity:

$$7840 \text{ sq ft} \times 6 \text{ ft-c} = 47{,}040 \text{ l}$$

Dividing this total (47,040) by the effective output per lamp (6000), the quotient is 7.8 lamps. The eight 1000-watt floodlamps will, therefore, give the desired illumination.

NEC CODE AND SUPPLEMENTARY TEXT REFERENCES

Appendix A NEC Items: A43, A42, A56, A65, A69, A72.
Appendix B Text Items: B6, B10, B7.

PROBLEMS

1. Express an opinion regarding which type of luminaires might well be used in: (*a*) a low-ceiling (10-ft) library; (*b*) a high-ceiling (14-ft) library; (*c*) a high-ceiling (14-ft) class room; (*d*) a high official's office (11-ft ceiling). (This is purposely asked before the reader has had opportunity to study the whole chapter.)

2. What is your idea of an ideal lighting design for reading in bed?

3. Concisely outline what is meant by (*a*) quality of illumination; (*b*) diffusion; (*c*) glare; (*d*) color.

4. Discuss the advantages and disadvantages of printed matter on mat paper vs. glossy paper.

5. Outline how a survey of foot-candle levels should be made in a library, using a meter as shown in Fig. 7.

6. A rectangular college lecture room with a seating capacity of 100 students is 45 ft long, 30 ft wide, with a flat hung ceiling 14 ft high. Determine the proper number, size spacing, and hanging height (above floor) of the necessary incandescent lighting units to produce 40 ft-c on the working plane (30 in. above the floor), assuming the units to be (*a*) of the direct, (*b*) indirect, (*c*) semi-indirect types, respectively. The walls are very light gray, the ceiling white, and all surfaces are finished with flat mat surface paint. Very light shades or Venetian blinds may be pulled over the windows on one side of the room. It is suggested that luminaires F-19 be used for (*a*), F-14 for (*b*), Table II. For each solution sketch the positions of all luminaires.

7. For the room conditions of Problem 6, determine the number and spacing of incandescent lighting units similar to unit F-6.

Chapter 29

VERTICAL TRANSPORTATION—ELEVATORS

1. Vertical transportation. Elevators and escalators provide the major facilities for vertical transportation of men and materials. In general the passenger elevator is depended upon to carry the up and down traffic in buildings where several peak periods occur each day. In a typical office building such peaks might occur, for periods of 15 to 30 minutes each, the maximum traffic conditions occurring near 8:00 A.M., 12:00 Noon, 1:00 P.M., and 5:00 P.M. (See Fig. 1.)

Escalators (Chapter 30) are selected where large numbers of people are scattered throughout a given area and on a number of floors, these people being interested in moving almost constantly to various locations for short periods of time. Thus traffic is constantly on the move both up and down and usually has a rather uniform "base load" with only occasional "peaks." The escalator is, therefore, most appropriate for large department stores, for basement and first-floor areas of the Woolworth-type and supermarket stores, and for feeders to adjacent floor levels in subways, railways, bus terminals, and stations. Many buildings utilize escalators to carry passengers from subway, basement, or mezzanine floor levels to and from the main floors.

The freight elevator is commonly used to carry heavy loads of all kinds to various levels. In large tall buildings with restaurants on upper floors the freight elevator may extend upward to those levels. Wherever frequent vertical movements of furniture, safes, heavy supplies, maintenance equipment, loaded trucks, movable beds, and tables are expected, then freight elevators may be needed.

Dumb-waiters, moving belts, and moving platforms are of many types to solve material handling problems, but these are not covered herein.

Ideal passenger service from an elevator installation provides immediate access to cars at any floor level, rapid transportation, comfort during the acceleration, steady speed and deceleration periods, rapid entrance and exit without discomfort. The rapid and quiet operation of the doors; visual floor indicators and floor-stop buttons; smooth, quiet, and safe operation of all elevator safety equipment; comfortable and adequate lighting; and courtesy of the car operator and all pas-

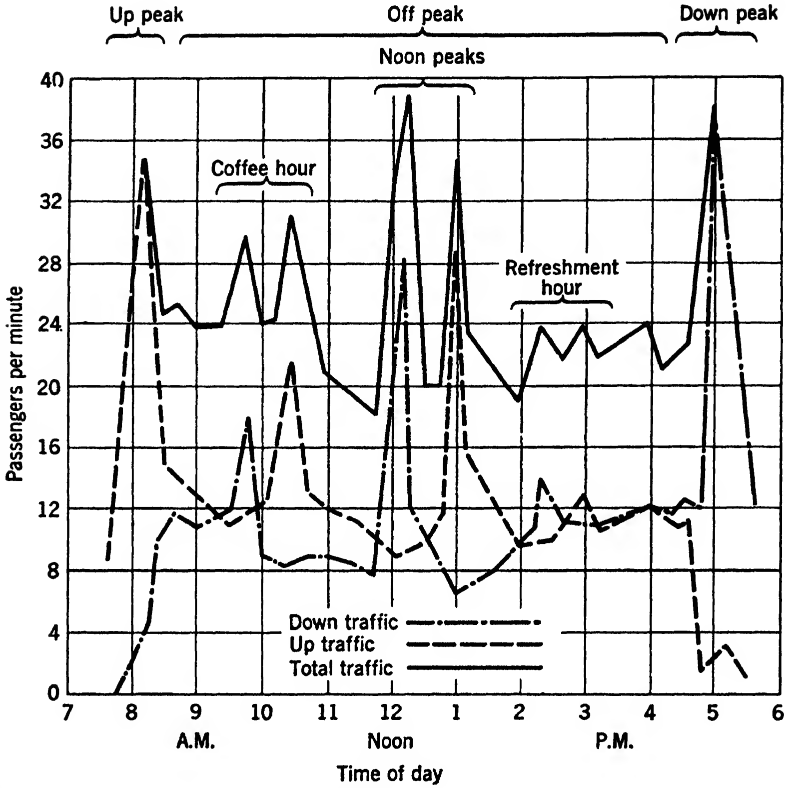


Fig. 1. These curves show the difference in peak loads on elevators in typical office buildings. In general the two maximum peaks occur in the morning and afternoon. In some highly populated buildings the morning peak may exceed the evening peak.

sengers in the car are important factors. Emphasis is placed on the design, specifications, operation, and maintenance to insure complete safety to passengers and operators.

2. Elevators under electronic group supervisory collective dispatching and control. From about 1931 to 1951 elevator passengers have become familiar with the facilities offered by passenger elevators of two general types: those controlled by starters at the lower terminal and with car operators in each car; and those in small or large apartment buildings without starters or car operators. Such elevators give a large measure of rapid, safe, and satisfactory vertical transportation. From 1936 to 1952 intensive research and gradual development resulted in dependable semiautomatic peak period control for elevators operating up to 500 fpm with a starter and car operators.

However, since 1952 complete automatic auxiliaries and control (without starter or car operators) have now become available. These deliver more passengers per elevator; open and close the doors at all terminals and at hall signals and car signals registered by the passengers; they prevent closing of doors against a passenger standing in the doorway; they permit the starting-up and shutting-down of elevators not needed; they provide the selective loading of all waiting down-passengers who will be picked up by a down-car in order downward, so that their weight will require less electrical energy by the elevator motors; and, finally, no starter or car operators are needed at any time. The entire group or bank of cars in a given group of elevators is in automatic operation at periods of up or down peak load; automatically they shut down successively as the number of passengers becomes very low; also successively they return to service as the passengers again increase to a high peak. At night, when only the building maintenance forces use the elevator, only one car or none may be in use; it, too, is operated automatically. If not used in a period of 15 min, it shuts down until the next floor call puts it again into operation. Thus variations of available passengers (*up, down,* or the *sum of instantaneous up and down*) are automatically "known" by the electronic control relays, and these relays control the equipment in the most economical way. The electronic control system actually "hears" all signals, "memorizes" them, "weighs" the passengers for most economic car dispatching (80 per cent of rated load), causes the car and its auxiliaries to operate correctly at the times and periods "memorized." The car loading and all movements of car, doors, and signals are performed at the "commands" of the electronic "master."

A number of the latest elevator installations, varying from two to six or eight automatic elevators under group control, are in successful operation. The Otis Elevator Company and the Elevator Division of the Westinghouse Electric Corporation have been the pioneers in research and development of these group supervisory collective dispatching and control systems. The Otis system is referred to as *Autotronic Elevatoring;* the Westinghouse as the *Selectomatic Elevator System.*

The approximate cost of the electronic supervisory group-controlled systems is about 8 to 11 per cent higher than that of a similar nonautomatic system of elevators providing similar rapid vertical transportation but using a ground-floor dispatcher and car operators. In general, one may expect to need approximately the same number of automatic as nonautomatic elevators to provide service.

3. Elevator specifications. Elevator specifications may be prepared after an analysis of the traffic is made and due consideration is given to the available standard types of machinery and control. The various types may be classified according to several schemes, including mechanical arrangement of cables and sheaves, mechanical arrangement of gears and motor drive, ratio of drum speed to motor speed, d-c or a-c motor drive, electrical service and feeders, control of hoist motor, automatic or manual control, and penthouse or basement machinery location.

The details of structural design of the building, space allotments, power supply, characteristics and requirements of the expected traffic, considerations of first cost, and cost of maintenance and operation are factors that influence the selection of types and the designation of mechanical and electrical details. It is not possible to present here a detailed analysis of these types, but each major classification and the principal influencing factors will be outlined.

4. Location of elevators and elevator lobbies. The elevator lobbies and shafts form one of the major space factors with which the architect is concerned. The elevator lobby on each floor is the focal point from which the corridors radiate for access to all rooms, stairways, service rooms, etc. Such lobbies must naturally be located one above the other, since the elevator shafts rise vertically. All passengers enter or leave the cars from these lobbies. Obviously, the ground-floor elevator lobby must be conveniently located with respect to main entrances; the modern equipment within or closely adjacent to this area should include public telephones, building directory, elevator starter service, and elevator indicator and control panels.

All lobbies should be adequate in area for the peak-load gathering of passengers to insure rapid and comfortable service to all. The number of people per floor contributing to the period of peak load, say within a 15- to 20-min peak, determines the required lobby area on the floor.

Approximately 4 sq ft of floor space per person should be provided at peak periods for waiting passengers at a given elevator or bank of elevators. The number of hallways leading to such lobbies should also provide about 4 sq ft per person approaching the lobby. This requires a check on human traffic through all approaches to elevator facilities. An ideal installation would provide a car "always waiting" at a given landing. Actually, excellent design provides an expected waiting period or interval of from 20 to 30 sec at any landing.

The ground-floor lobby (frequently called the *lower terminal*) usually provides access to stairways and corridor doors, and probably entrances or counter space for commercial establishments. Finally, the entire architectural design and treatment of the main elevator lobby should be in keeping with the modern design of both the interior and exterior of the building. Growing popularity of the completely automatic elevators, without operators, is influencing many features of elevator design and control. (See Fig. 2.)

The main lower terminal of elevator banks is usually on the street-floor level, although some buildings may place this terminal on the basement level or second-floor level. The upper terminal is usually the top floor of the building. In certain step-back types of very tall buildings the lower zones (stories) are served by local elevators; the next zone by another bank of elevators which travel express through the lower zone, then local through the second zone, etc.

Occasionally, it is necessary in tall buildings (without step-backs) to consider what number of elevators shall be installed to give local service to a zone of say half the floors above the street level; and what number

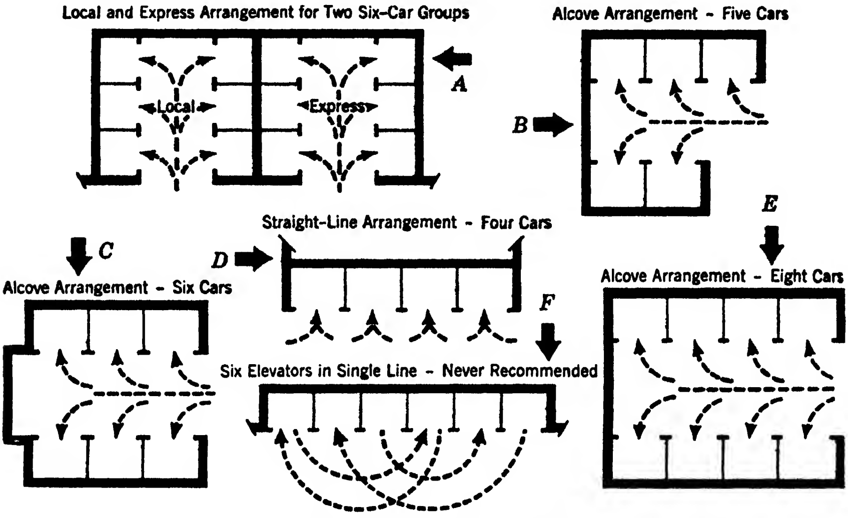


Fig. 2. The free flow of traffic into and out of elevators at the lower lobby is facilitated by the arrangements *A*, *B*, *C*, *D*, and *E*. Arrangement *F* is never used since cross traffic hinders entrance and exit of passengers.

shall be installed to give initial express service to the first floor of the upper-local-zone with local service thereafter to the top floor. This consideration poses the question whether all elevator shafts should be designed to continue to the top floor, or whether the lower local-service elevator shafts should be terminated just above the last floor of that zone.

In general it is desirable to establish future maximum traffic conditions to all upper floors and extend shaftways according to these expected demands. It is also possible that escalators between certain upper floors might be anticipated for future local zone traffic, instead of extending elevator shafts.

Of course, the penthouse floor and secondary level floor (respectively, containing the elevator traction machine and control panels and the secondary sheave and selector tape drive) are located above the shaft of each elevator and need approximately two stories of additional height above the top of the support beam of a given elevator when it is standing at its top-floor location. The actual floor area required by the elevator traction machine, its motor-generator set, and control panels is roughly about 2.0 times the area of the elevator shaft itself. The required area of the floor of the secondary level is no larger than the elevator shaft it serves. See Table I for approximate dimensional details and Fig. 3 for one of several possible arrangements of machinery in the penthouse and on the secondary floor levels.

5. Elevator equipment. The principal apparatus and major parts in any elevator installation include the car, the cables, the elevator machine, the control equipment, the counterweights, the shaft or hoistway, the rails, the penthouse, and the pit. Some elementary ideas of the function of these major items and auxiliaries are essential. Figure 3 shows these major parts and other auxiliaries.

The cars with their equipment for safety, convenience, and comfort, and their furnishings and finish, are an important unit in the system —the only one with which the average passenger is familiar. Much of the prestige of the architect and engineer depends on proper design of the car. Essentially it is a cage of light metal supported on a structural frame, to the top member of which the cables are fastened. By means of rail shoes on the side members the car is fixed in its vertical travel in the shaft. The car is provided with safety doors, operating control equipment, floor level indicators, illumination, emergency exit ports, ventilation, kick plates, and hand rails. It is designed for long life, quiet operation, and low maintenance.

The cables lift and lower the car. Usually three to eight cables are placed in parallel, and the weight of the car is equally distributed over them. The cables are fastened to the top of the car by cable sockets which provide secure clamping. These cables then pass over a motor-driven cylindrical sheave (grooved for the cables) and pass downward to the counterweight to which they are fastened with cable sockets. Replacement of cables is one of the major costs in elevator operation and maintenance.

The elevator machine turns the sheave and lifts or lowers the car. It consists of a heavy structural frame on which are mounted the sheave and driving motor, the gears (if any), the brakes, the magnetic safety brake, and certain other auxiliaries. The governor which limits the car to safe speeds is mounted on or near the elevator machine. In most modern installations the elevator driving motor receives its energy from a separate motor-generator set (m-g set) which is in operation during the period that the particular elevator is available for handling traffic. This m-g set is properly considered a part of the elevator machine, although it may be located some distance from it.

The control equipment, in a general sense, is the combination of push buttons, contacts, relays, cams, and devices which are operated manu-

Table I. Some Approximate Dimensions of Gearless Elevator Equipment *

Duty		Main Controller			Electronic Relay Panel			Selector			M-G Set		
Live Weight (lb)	FPM	*W*	*D*	*H*	*W*	*D*	*H*	*W*	*D*	*H*	*W*	*D*	*H*
3000 at	400	52	17	75	31	14	80	21	23	75	18	46	46
2500	500												
3000	500												
4000	400	52	17	86	31	14	80	21	23	75	18	46	46
3500	500												
4000	500												
3000	600	36	27	80	42	14	80	38	29	†	36	70	70
3500	600												
2500	700												
2500	800												
3000	800	36	27	80	42	14	80	38	29	†	44	75	75
3500	700												

* This table gives approximate dimensions in inches of the indicated equipment: *W* = width, *D* = depth, *H* = height.

Notes. (1) The motor-generator set has a height of approximately the same dimensions as the length.

(2) If additional I-beams or a foundation is laid for the m-g set above the penthouse floor, then the height of the m-g set must be increased by the elevation of the extra foundation.

(3) The secondary level should have headroom of approximately 5 ft below the main elevator machine beams. The secondary level floor is designed and erected by others than the elevator manufacturing company.

(4) The double-wrap (secondary) sheave for gearless elevators is supported by the main elevator beams.

(5) The selector tape drive and the speed governor are normally supported on the secondary level, but occasionally are mounted to the penthouse floor.

(6) The penthouse floor and the secondary level floor must have removable trap doors and door supports if it is intended to raise and lower the main elevator machine through the elevator shaft.

† Height of selector depends on floors served since each floor adds one selector mechanism to the total height of the selector stack.

ally or automatically to initiate door operation, starting, acceleration, retardation, leveling, and stopping of the car. In reality these auxiliaries are interrelated in such a way that the major apparatus functions to produce the maximum of safety, comfort, and convenience. Electrical limit switches automatically stop the car from overrunning at the top and bottom of the hoistway. The well-known floor indicators, floor

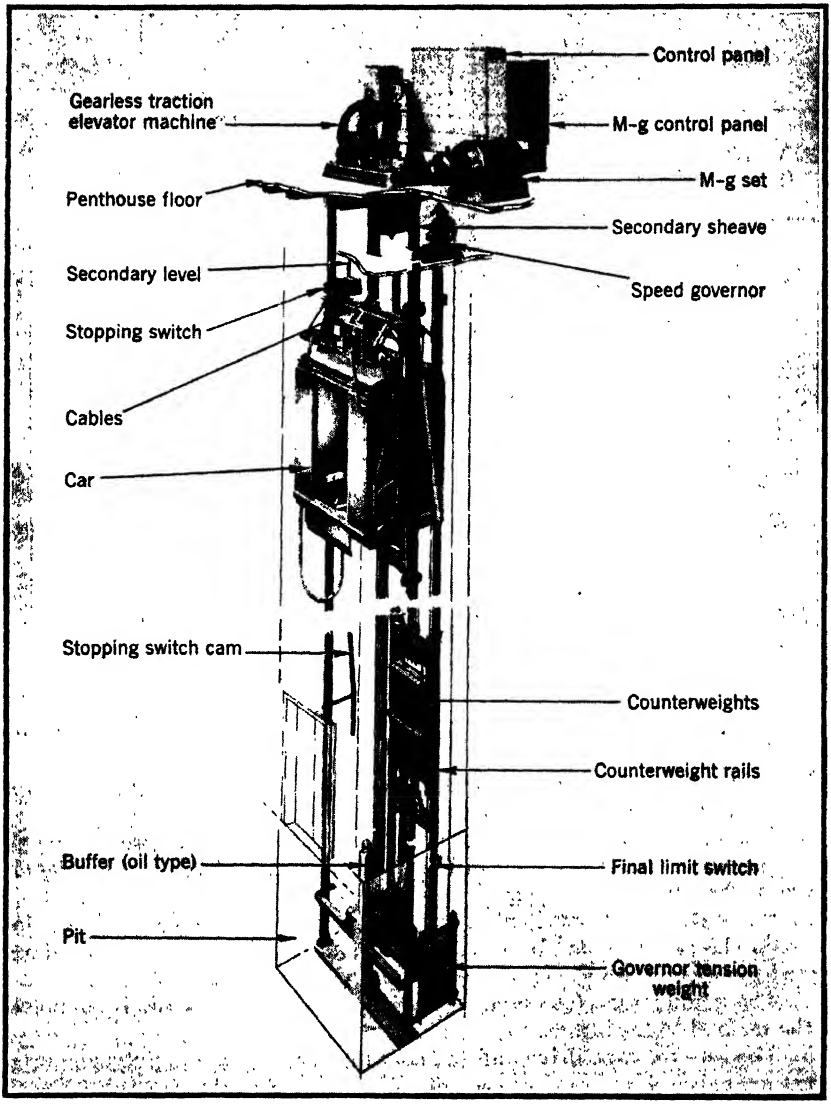


Fig. 3. Principal equipment and parts for a gearless traction elevator installation.

pilot lights, preset stop panels in the car, call buttons at floor levels, floor leveling devices, and up and down indicating lamps are all parts of the coordinated control equipment.

The counterweights are rectangular blocks of cast iron stacked in one frame which is supported at the opposite ends of the cables to which the car is fastened. The counterweight is related to the weight of the car and its load so that the required energy input to the elevator machine (which moves the car) is relatively low. In fact the energy required is large only during the periods of car acceleration and retardation. The counterweight is guided in its travel up and down the shaft by two guide rails at the back of the shaft. Obviously the counterweight travels in the reverse direction to that of the car.

The shaft is the vertical passageway for the car and counterweights. On its side walls are the guide rails, door frames, and certain mechanical and electrical auxiliaries of the control apparatus. At the bottom of the shaft are the car bumpers. At the top is the structural platform on which the elevator machine rests.

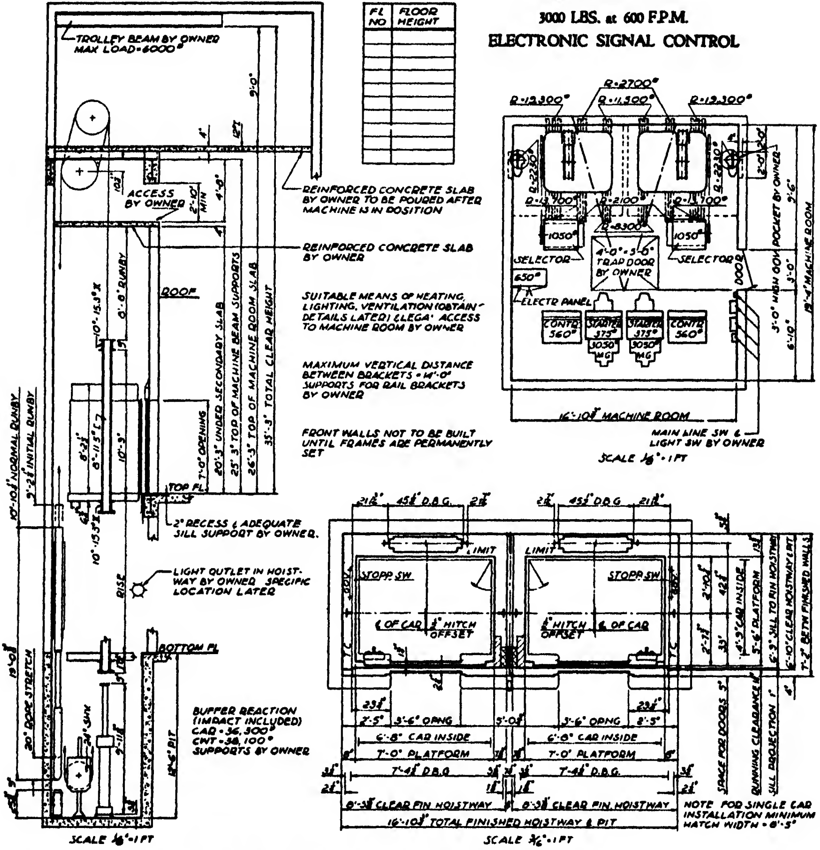
The guide rails are the vertical tracks that guide the car and the counterweights. They are of heavy machined steel, dovetailed at the joints and carefully aligned to insure smooth operation. The guide shoes on the side frames of the car are slotted to fit the projecting web of the guide rail. The rail has a T cross section. The counterweight rails are somewhat similar in construction but smaller. All guide rails are bolted to the structural steelwork of the building, which is especially designed in elevator shafts to accommodate these rails. Rails of modern elevators are not lubricated since rubber roller guide shoes are used.

The penthouse is the room directly above the hoistway in which the elevator machine is housed. It contains the m-g set which supplies energy to the elevator machine, the controlboard, and other control equipment. All electrical contactors and other possible sources of noise from machinery and control equipment are designed for quiet operation.

Figure 4 shows a typical elevator hoistway and machinery room layout. It gives approximate dimensions for a weight of 3000 lb and speed of 600 fpm. A 3000-lb elevator would have an average at peak-load periods of 80 per cent of full load (0.8 × 19 passengers plus 1 operator = 0.8 × 20 × 150 = a 2400-lb live load). Elevator capacity is based on an average of 150-lb per person.

A 3000-lb electronic controlled automatic elevator is rated for 20 × 150 = 3000 lb, instead of 19 × 150 = 2850 lb, i.e., 20 passengers instead of 19, since an operator is not needed. Any standard passenger elevator may be loaded approximately 20 to 25 per cent in excess of its rated capacity in pounds, although the most rapid transportation of the greatest number of people will occur at about 80 per cent of rated

PASSENGER - U.M.V. - M.M.M.
GEARLESS - D.W.T.
3000 LBS. at 600 F.P.M.
ELECTRONIC SIGNAL CONTROL



IMPORTANT: DO NOT CHANGE ANY DIMENSIONS WITHOUT CONSULTING AN OTIS REPRESENTATIVE AS SUCH CHANGE MAY SERIOUSLY AFFECT THE ENTIRE LAYOUT

REACTIONS GIVEN INCLUDE ALLOWANCE FOR IMPACT. DIMENSIONS SHOWN FOR PIT AND OVERHEAD HEIGHT COMPLY WITH A.S.E. CODE; THE SPAN OF ANY SUPPORTING BEAM SHOULD NOT EXCEED 10 TIMES ITS DEPTH. HOISTWAY JAMB CONSTRUCTION AS PER CONTRACT.

LAYOUT APPROVED:-
HOISTWAY GUARANTEED:-

RECOMMENDED STRESS
STEEL 18000# PER SQ. IN.

BUILDING:-
LOCATION:-
OWNER:- DATE:-

GENERAL CONTRACTOR:-
ARCHITECT - ENGINEER:-

OTIS ELEVATOR COMPANY

FORM 2608A (4-1-53)

Fig. 4. Typical elevator hoistway and machinery room layout. A general dimensional layout of a hoistway and machinery room for a passenger, multivoltage (U.M.V.) main motor microleveling (M.M.M.), gearless, single-wrap traction (S.W.T.), 3000-lb, 600-fpm, electronic signal control elevator. Also see Fig. 15, p. 509.

car capacity in pounds. With automatic control elevators the doors close and car starts at this 80 per cent loading, this action being initiated by the fact that the elevator floor is the surface of a platform scales.

6. Arrangements of elevator machines, sheaves, and ropes. The simplest method of arranging vertical travel of a car would be to pass a rope over a pulley and to counterbalance the weight of the car by a counterweight. Then, by rotating the pulley, the car would move up or down and require very little energy to move it. This is essentially the scheme which is used on a majority of high-speed passenger elevators and is illustrated in Fig. 5(*a*). The pulley referred to above is made in the form of a cylindrical sheave containing grooves for the several ropes which support the weight of the car.

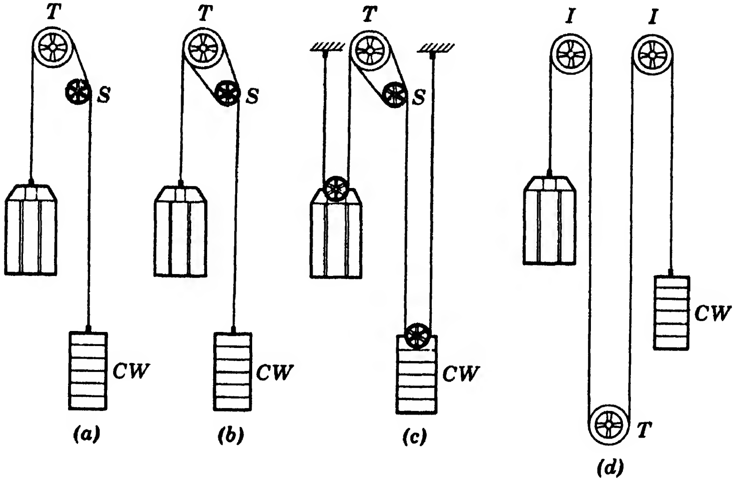
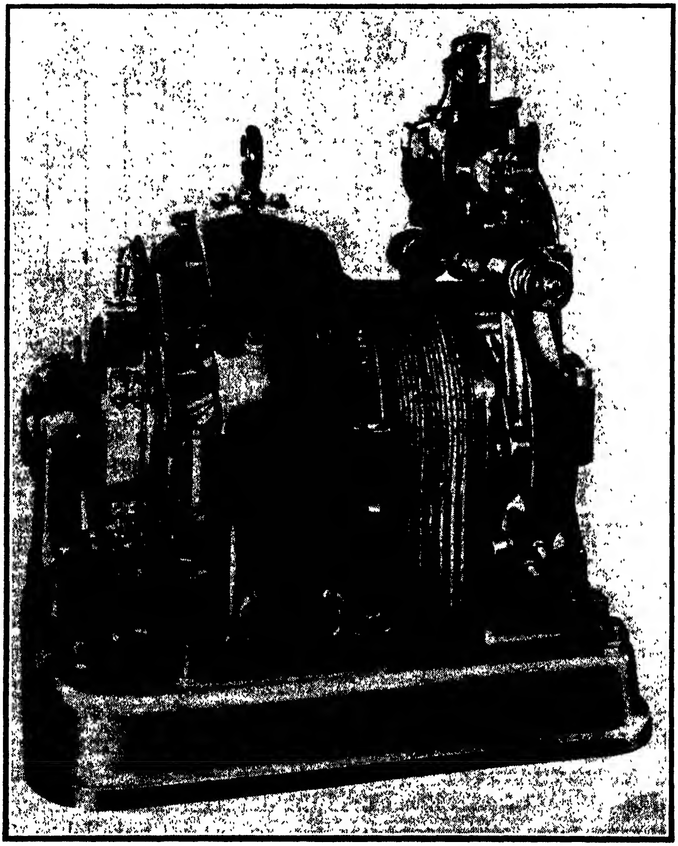


Fig. 5. Typical elevator rope and sheave arrangements, (*a*), (*b*), and (*c*) for machine installed above hoistway, (*d*) for machine installed at the bottom of hoistway.

When the supporting ropes merely pass over the sheave (in the grooves) and connect directly to the counterweights, the lifting power is exerted by the sheave through the pinching effect or traction of the ropes in the grooves. This system is referred to as the single-wrap traction elevator machine. The function of sheave *S* is merely that of a guide pulley; usually it is called the deflector sheave. Each of the three or more supporting ropes lies in a groove cut parallel to all other grooves on the sheave.

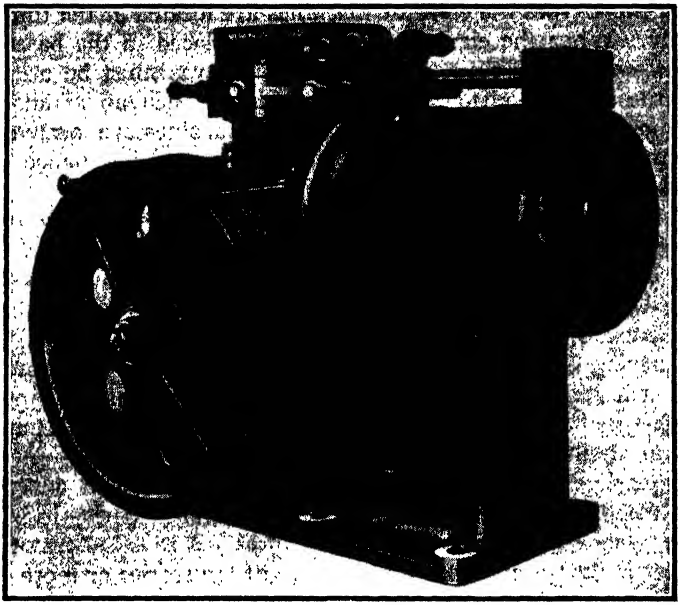
In Fig. 5(*b*) the ropes from the car are first wrapped over the traction sheave *T*, then around the secondary or idler sheave *S*, once more around sheave *T*, and back over *S* to the counterweights. This arrangement is characteristic of the one-to-one, double-wrap traction machine. It provides greater traction than the single-wrap machine.

In the arrangement of Fig. 5(*c*) the peripheral speed of the sheave is double the vertical speed of the car; the car travels more slowly for a given sheave speed, thus providing the economic advantage of higher-speed motors. This scheme gives to the elevator machine the name double-wrap traction, two-to-one type. Its principal application is on very heavy, short-travel passenger or freight elevators. Its use is generally limited to elevators rated at speeds not greater than 500 fpm or to freight elevators with heavy loads at speeds less than 500 fpm.

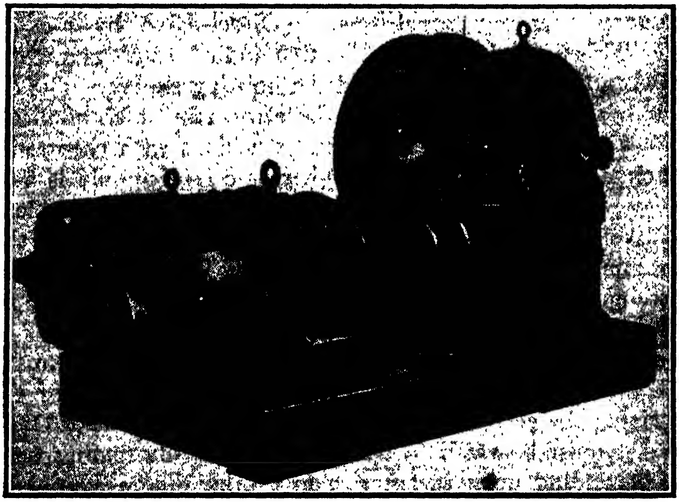


(*a*)

Fig. 6. Typical elevator machines: (*a*) gearless d-c traction machine, (*b*) geared a-c traction machine, (*c*) geared d-c traction machine.



(*b*)



(*c*)

Fig. 6 (Continued)

In all these types the elevator machines are located at the top of the hoistway. When the elevator machines are placed in the basement a very different arrangement of cables and sheaves must be utilized to secure the same results. Figure 5(*d*) shows such an arrangement. Much more rope is required when elevator machines are located in the basement, and consequently the problems of rope maintenance are increased.

7. Gearless traction machines. A gearless traction machine, Fig. 6(*a*), consists of a d-c motor whose shaft is directly connected to the driving sheave. The elevator hoist ropes are placed around this sheave, traction being obtained by friction between the ropes and the sheave. The absence of gears means that the motor must run at the same speed as the driving sheave. Since it is not practical to build d-c motors for operation at very low speeds, this type of machine is limited to medium- and high-speed elevators, that is, for speeds from 400 to 1200 fpm. The motors are built in ranges from 20 to 150 hp.

The gearless traction machine is generally considered superior to geared machines. Since there are fewer moving parts, it is more efficient, gives quieter operation, and requires less replacement of parts. For office buildings and apartment houses of ten stories or more, where high speeds and smooth high-quality operation are desired, the gearless traction machine is usually chosen.

8. Geared traction machines. (Direct-drive by a-c or d-c motors.) This type of machine, Fig. 6(*b* and *c*), employs a worm and gear between the driving motor and the hoisting sheave. The driving motor with rheostatic control may therefore run at economical high speeds from 600 to 1800 rpm. Geared machines with rheostatic control use either a-c or d-c motors. Where a-c service only is available and car speeds greater than 100 fpm are desired, it is preferable to use unit multivoltage control, permitting a d-c driving motor on the elevator machine. The geared traction machine is used on both freight and passenger elevators. The horsepower ratings of these motors range from about 3 to 100 hp.

9. Variable-voltage elevator systems. A motor-generator (m-g) set is required to provide variable voltage for operation of the d-c motor driving the elevator machine. The motor and motor starter of the m-g set must be rated to operate on either alternating or direct current, depending upon the service to the building. The generator of the m-g set must be provided with an exciter (another small generator on the same shaft) if the set is driven from an a-c building service.

A single m-g set serves for each elevator. Whenever an elevator is to be put in or removed from service the supervisor starts the m-g set by a remote-control start or stop button (Fig. 7). The sequence of operations of the elevator m-g set is as follows: the dispatcher presses the start button which initiates first the closing of the 3-pole contactor *A* which connects the motor of the m-g set to the line through two sets of series starting resistors. These resistors absorb energy temporarily, and the motor starts slowly. In a few seconds the 3-pole contactor *B* is automatically closed, cutting out or short-circuiting the series resistor *B* and increasing the speed; shortly afterwards the 3-pole contactor *C* automatically closes, cutting out the remaining resistor *C*, thus impressing full-line voltage on the motor which then quickly reaches full speed. As the motor comes up to speed the exciter builds up its voltage and is ready to excite the generator field when called upon to do so by the car operator or by the control relays of the automatic elevators. The exciter maintains a constant terminal voltage across the field of the elevator traction motor.

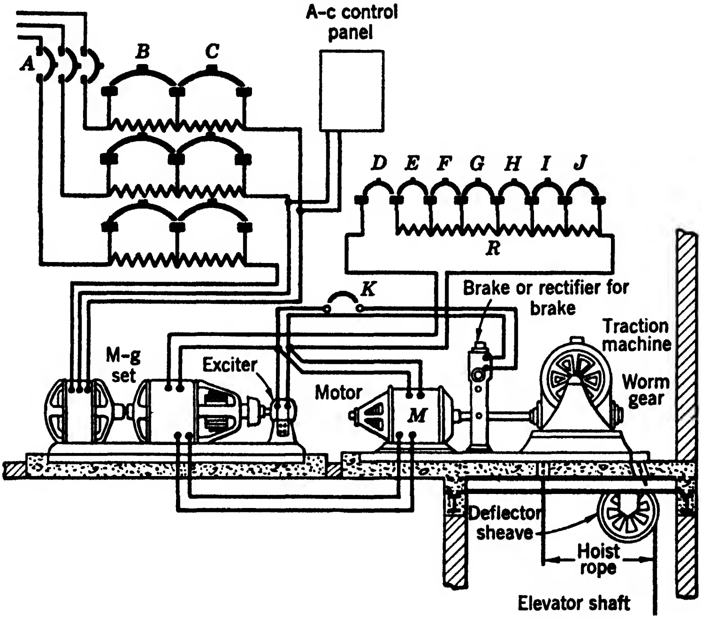


Fig. 7. Schematic diagram of the control and power wiring of an elevator system, using an m-g set for supplying variable voltage to a geared traction elevator machine. In a gearless traction machine the shaft of the motor would be directly connected to the shaft of the traction machine.

If the elevator system is arranged for automatic car operation initiated by manual control, the car operator may now move the master controller in the car to the up or down position. This initiates the automatic sequence of operations for accelerating. The various relays and contactors on the control panel perform as follows: the brake magnet is energized by the closing of the contactor *K*, thus releasing the brake shoes from the drum. Contactor *D* closes the generator field circuit, which is in series with the full resistance of the exciter field rheostat *R*, furnishing low field excitation to the main generator. The generator at this low excitation impresses a low voltage on the armature of motor *M*, slowly starting the elevator machine.

Shortly after contactor *D* closes, the other contactors *E*, *F*, *G*, *H*, *I*, and *J* close at short intervals, thus smoothly raising the voltage of the generator and accelerating the elevator motor. The elevator is now running at full speed in the desired direction. When the operator (or automatic elevator) wishes to stop the car, the handle is moved to the stop position and the control switchboard automatically sets up a timed sequence of operation which opens the field contactors in the reverse order *J*, *I*, *H*, *G*, *F*, *E*, *D*, thus decelerating the car. When the car stops, the brake magnet contactor *K* opens, allowing the spring to force the brake band against the brake drum and hold the sheave and elevator stationary.

A signal-control elevator is very largely controlled automatically by a relay panel or selector device which makes the necessary electrical contacts to register the corridor and car stop, and actuates the various signals in the lobby, corridors, and car. This automatic equipment allows the waiting passenger to initiate a stop at his floor by means of the "up" or "down" button. This signal-control machine contains sets of vertical contacts over which small contact brushes move up or down in synchronism with the corresponding car movements in the shaft. The brushes are moved by mechanical reduction gearing driven by control cables fastened to the car, or by electric motors rotating in synchronism with the car travel. The main controller determines the direction of car travel, the starting acceleration, running, leading and stopping, and opening and closing of the doors.

10. Rheostatic system of control. In installations where the owner cannot afford the variable-voltage control or where low speeds (150 to 300 fpm) and traffic conditions do not justify the better and more costly features, the traction machine may be driven either by d-c or a-c motors whose speeds are controlled by rheostats (variable resistances). Such elevators are usually controlled by an operator's hand wheel or lever in the car. Figure 8(*a*) is a schematic wiring diagram of the rheostatic connections for an a-c 3-phase induction motor for a geared traction elevator; and (*b*) for a d-c compound-wound motor on a gearless traction elevator. In (*a*) the contactors (solenoid-operated switches) *A*, *B*, *C*, *D*, and *E* are successively closed as the motor starts and accelerates to full speed. They are opened in the reverse order, *E*, *D*, *C*, *B*, *A*, when the speed is retarded. The opening and closing are automatically timed by relays which are energized by the controller in the car. Within the control panel is a switch (not shown) which changes the internal connections of the motor so that two definite speed ranges may be obtained in addition to the intermediate speed steps due to the rheostatic control.

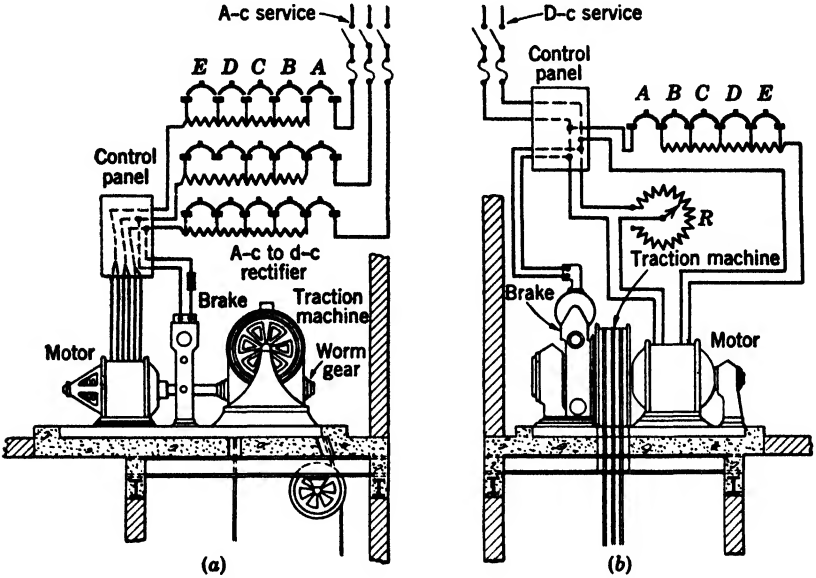
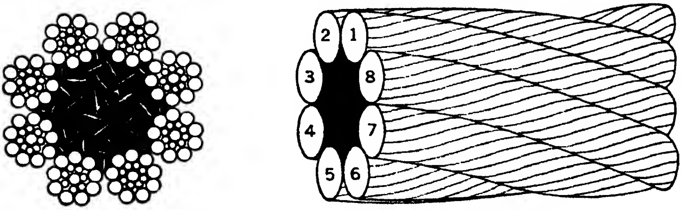


Fig. 8. Schematic diagram of two different types of elevator drive, (*a*) 3-phase induction motor, (*b*) d-c compound wound motor. The speed of these elevators is varied by rheostatic control. Rheostatic systems are usually associated with geared elevator machines.

In Fig. 8(*b*) the d-c motor is accelerated and adjusted in speed by the resistances *A*, *B*, *C*, *D*, *E*, which are controlled in the same manner as in the a-c rheostatic drive. Intermediate steps of speed control are obtained by the field rheostat *R*, which is driven automatically by a small motor. Acceleration, retardation, and constant running speeds are initiated in all rheostatic systems by the car operator, but usually he has no control of the rate of acceleration or retardation.

11. Hoisting ropes. The ropes which are connected to the crosshead (top beam of the elevator) and which carry the weight of the car and its live load are made of groups of wires of traction steel wire especially designed for this application. All cables have a hemp core which serves as a support for the strands. Figure 9 shows the general construction of an elevator cable.

The ability of a wire rope to withstand bending and to give the longest life depends largely on the type of construction. The 8-by-19 construction is generally used by several manufacturers as standard for main hoisting ropes, governor ropes, and counterbalance ropes on traction elevators. A 6-by-19 cable construction is also used. The 8-by-19 rope is more pliable and has a longer life than the 6-by-19 rope. The ASE Code covers details of selection of the proper number and sizes of cables. The factor of safety is usually taken as 7-to-1 for passenger and 12-to-1 for freight elevators, that is, the total number of cables used will not break unless 7-to-1 (or 12-to-1) times the normal working stress is applied to them.



Rope Lay, 8x19 Rope

Fig. 9. General construction of typical elevator hoisting rope. The black section represents the hemp core.

Considerable power is required to accelerate or decelerate the weight of cables. Frequent inspection of elevator cable is important. Inspection will indicate when it is necessary to shorten the rope because of its natural stretch, to equalize the tension in parallel ropes, to remove the twist from ropes, and finally to replace them. Wire ropes should be properly lubricated at all times.

Refer to ASE Code for detailed rope specifications for elevator service. These also specify the required types of rope for elevator control equipment.

12. Safety devices. The main brake of an elevator is mounted directly on the shaft of the elevator machine, Fig. 6. It controls the brake shoes which are forced against the brake drum by springs. The brake is released by the action of a d-c electromagnet and is set by the springs when the magnet is deenergized. When d-c machines are used, the elevator is first slowed down by dynamic braking action of the motor and the brake then operates to clamp the brake drum holding the car still at the floor.

A *safety* is designed to stop an elevator car automatically before the car's speed becomes excessive. The action of this device is controlled by a centrifugal fly ball or fly weight governor, Fig. 10(*e*), which is independent of the other elevator machinery. At normal speeds the safety system has no effect on the operation of the elevator.

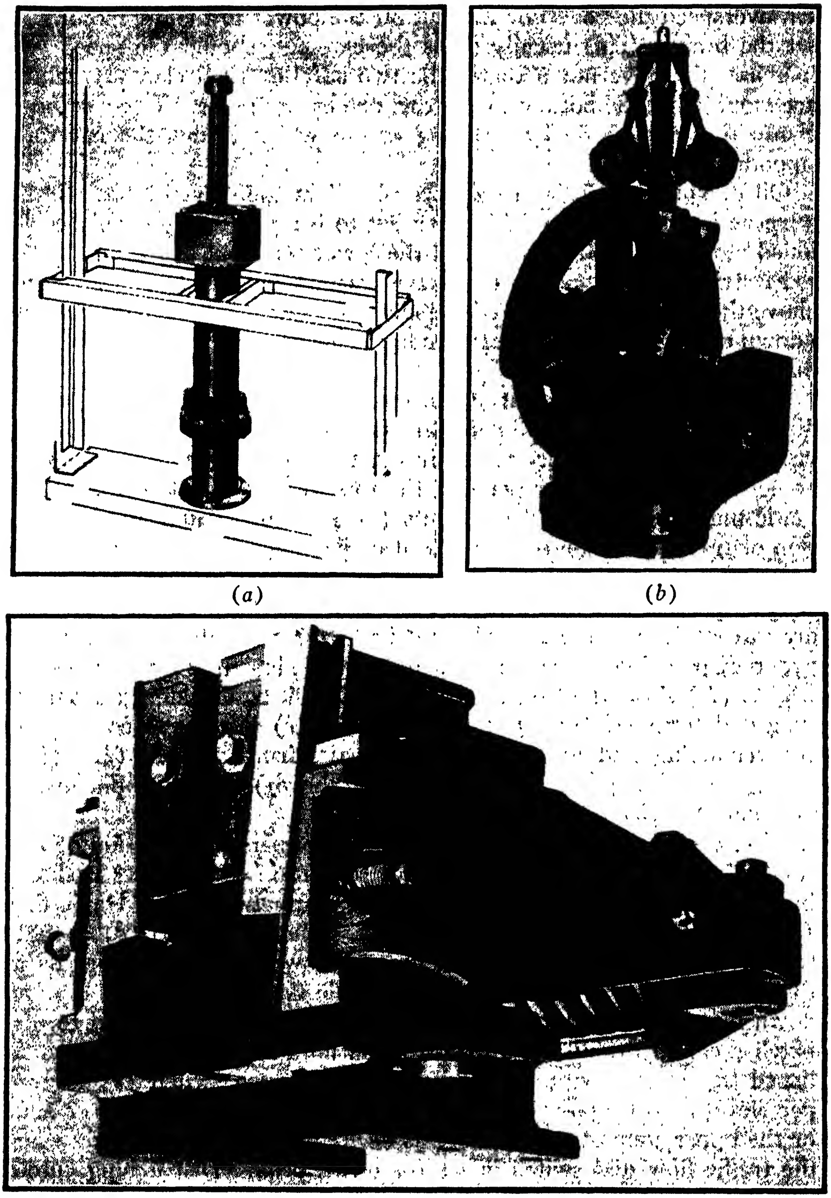
On overspeed the governor will cut off the power to the d-c motor and set the brake. This usually stops the car, but, should the speed still increase, the governor actuates the two safeties (rail clamps), which are mounted at the bottom of the car, one on each side. These safeties clamp the guide rails by wedging action which brings the car to a smooth stop.

Oil or spring buffers are always placed in the elevator pit. Their purpose is not to stop a falling car but to bring it to a partially cushioned stop if it should overtravel the lower terminal.

Electrical final-limit switches are located a few feet below and above the safe travel limits of the elevator car. If the car overtravels (down or up), these switches deenergize the traction motor and set the main brake.

13. Features of indicator, control, and car panels. A signal indicator panel and a control panel are furnished with each group of elevators. They are usually placed in flush panelboards and mounted together with the indicator panel at the top. Figure 11 shows the automatic indicator panel. These lights (*A*, *B* arrows) indicate the position or travel direction of each car at or passing a hall landing. Other lights (*C*) show direction and location of hall calls (up or down) for waiting passengers. Nonstop lights (*D*) indicate that certain elevators are purposely by-passing registered hall calls. Lights (*E*) indicate a group dispatching signal for a car to leave the lower or upper terminal. Lights (*F*) show the particular car which will be dispatched from the indicated terminal (up or down). Lock (*G*) opens the cover plate for relamping and inspection of internal wiring. Clock (*H*) gives correct time. Night lock switches (not shown) manually put out of automatic service all elevators and controls.

Figure 11 also shows the automatic control panel. Direction of major traffic flow (*a*) (up or down) for the group of elevators is shown by arrows. Dial switch (*b*) provides for manual control of traffic flow (when automatic control is not desired). The dial switch (*c*) changes the dispatching interval between up and down dispatching signals at the terminals for any position of the traffic flow dial switch. Up and down manual dispatching buttons (*d*, *d′*) are used if required to dispatch a car in the up or down direction ahead of the schedule established by the automatic timing device. One zone switch (*e*) is used per elevator to transfer cars individually to operate in the lower zone or the upper zone of the building as desired and is effective only when the traffic flow dial switch is set for down peak. Dispatching cutout switches (*f*) are furnished for each car and used to disconnect individual cars from dispatch systems in the event it is desired to take any car out of service. Signal buttons (*g*) are for prearranged signaling to car operators by prearranged code. Motor-generator pilot lights (*h*) indicate when each motor-generator set and its corresponding car

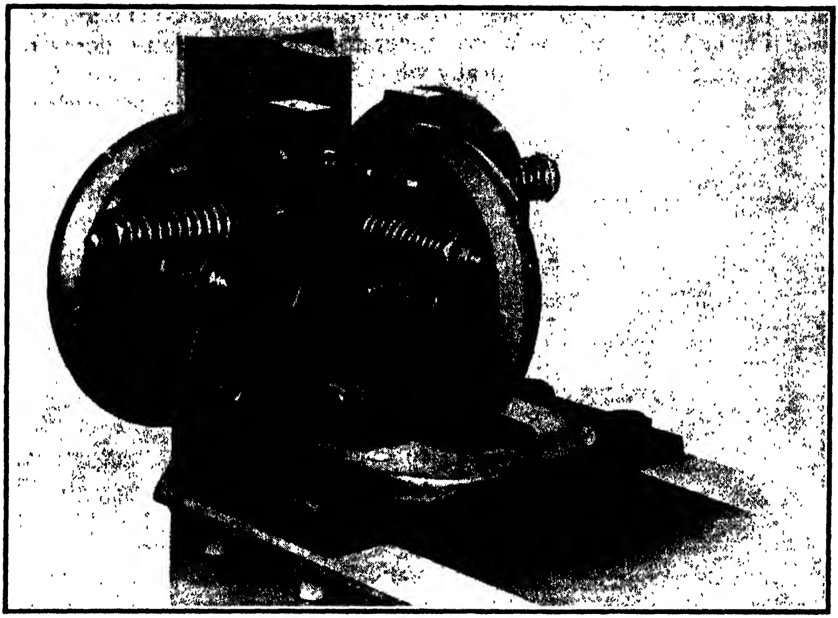


(a)

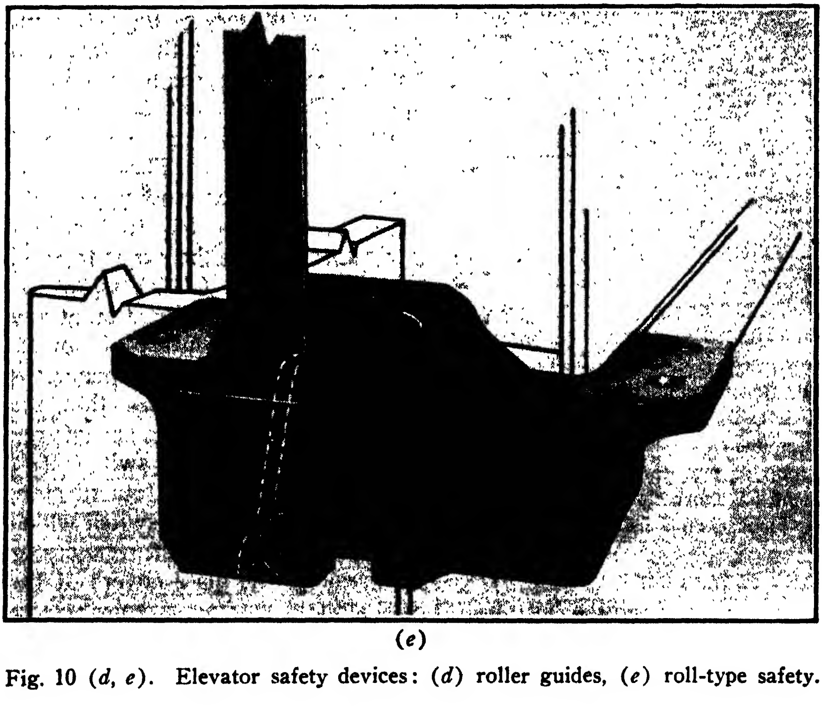
(b)

(c)

Fig. 10 (*a*, *b*, *c*). Elevator safety devices: (*a*) oil buffer, (*b*) fly ball speed governor, (*c*) flexible guide clamp safety.



(*d*)



(*e*)

Fig. 10 (*d*, *e*). Elevator safety devices: (*d*) roller guides, (*e*) roll-type safety.

are in or out of operation. Motor-generator switches (*i*) are for starting and stopping the motor generators, and they cause doors of parked cars to open automatically when the car is put in service. The lock (*j*) controls the doors back of which are the connections to the various switches, lamps, etc.

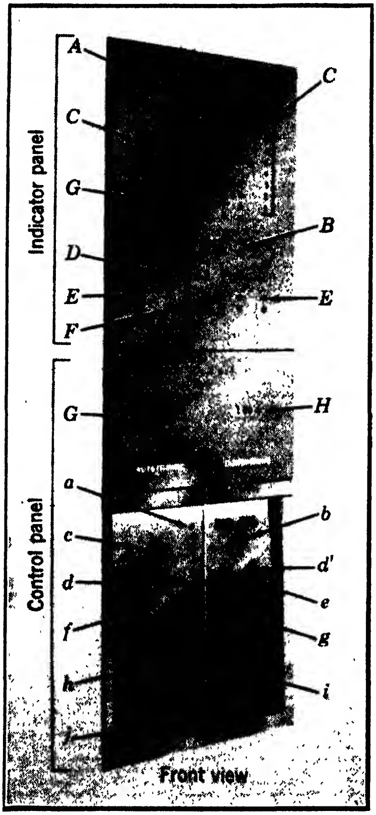


Fig. 11. The starter's control and indicator panels may be mounted separately if desired. They are usually located on the lower terminal floor in the elevator lobby. Separate equipment is furnished for each group of elevators, although equipment for more than one group may be incorporated in a single fixture.

In the electronic automatic features of the most modern elevator, provision has been made for cutting out all the "without attendant features," making it possible for the car attendants to operate the entire system. With this automatic and/or manual control a car operating panel is mounted in each car. (See Fig. 12.) The highest call return light (*a*) remains illuminated until the elevator stops at the highest registered call. The car will automatically reverse and start down when the operating lever (*m*) is next moved to the start position. The basement service light (*b*) informs the attendant that there is a landing call registered at this lower floor. The basement floor button must be pressed before the car will respond to this call. The floor buttons (*c*) (one per landing served) register car calls for the various landings at which the car is to stop. Reversal buttons (*d*, *e*) allow the attendant to reverse direction at any landing, independently of unanswered calls. The motor-generator pilot light (*f*) indicates that the motor-generator set is operating. The motor-generator switch (*g*) has a three-position (start, stop, neutral) operating key switch which starts and stops the motor-generator set. A hammer (*h*) is provided for breaking the glass covers of the door and gate release buttons. The door and gate emergency release buttons (*i, j*) are located behind break-glass covers, and are used for emergency purposes only. The elevator can be operated with the hoistway doors open while the door release button is being pressed and, similarly, can be operated with the car door open while the gate release button is being pressed. The nonstop switch (*k*) when pressed causes the car to become an express elevator and by-pass all registered landing calls. The car will, however, continue to respond to calls registered on its own operating panel. This feature is used by attendants when their cars are filled, or in case of emergency. When a call is by-passed, it automatically transfers to the next available car. The buzzer cutout switch, marked "Night—Day," (*l*) is furnished on all signal control installations except those equipped with electronic touch-button landing fixtures. When it is in the night position, the buzzer will sound each time a landing button is pressed. The buzzer [located behind the operating panel] (*m*) will sound when the corresponding call-back button is pressed. When the elevator is on night service, the buzzer sounds whenever a landing button call should be answered. The operating lever (*n*) when moved to the start position closes the doors and starts the elevator. If the operating lever is moved to the intermediate position, doors will close but the car will not start. When a car is standing at a landing with its doors closed, movement of the lever in the opposite direction, away from start, will cause the doors to re-open. The light switch (*o*) operates the elevator car light. The emergency stop switch (*p*) may be used to stop the car. As long as the switch remains in this position the elevator will not operate. The highest call return cutout switch (*q*) is furnished on all signal control installations except those equipped with an automatic supervisory system. When it is in the off position the highest call return feature is modified so that the elevator, on each up trip, travels to the top terminal or some other predetermined upper landing before reversing. The red down schedule light (*s*), the green up schedule light (*t*), and the white loading light (*u*) are also of help

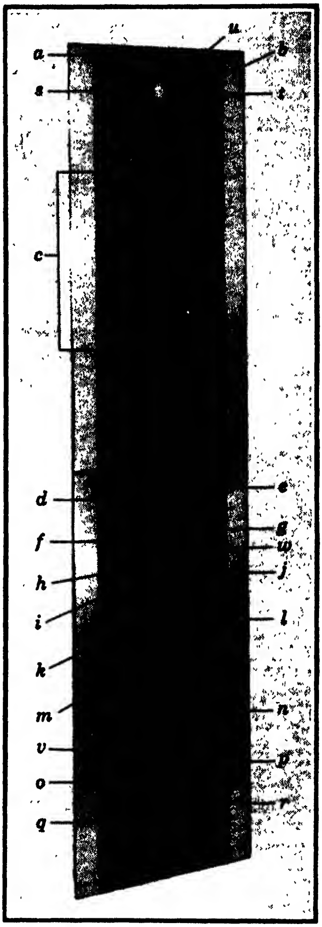


Fig. 12. Car operating panel.

to the attendant. The fan switch (v) and the key for the emergency exit (w) are standard equipment. The inspection switch (r) is used when the elevator is to be operated manually for inspection and maintenance purposes. When it is turned to inspection slow, and the proper machine room setting has been made, the car can be operated at a slow speed as a manually controlled elevator by moving the operating lever to the start position. Under these circumstances, the direction of travel is controlled by the D and U reversal buttons.

14. Traffic and service requirements. In selecting the capacity and number of elevators and the type of elevator system for a given building, the building characteristics and the up and down travel requirements of its population must be known or estimated. The class of work of the occupants and the type of building provide a basis for estimating the building population. Thus banks, large business offices, subdivided offices, department stores, apartment houses, and hospitals all suggest different traffic requirements.

Population estimates for office buildings are based on the available floor area, for apartment houses on the number of bedrooms and for hospitals on the number of beds. Table II gives some typical values of floor area per person.

In the central business district in large cities the service competition of similar types of buildings in the area must be considered. People should not be conscious of delays in elevator service. In first-class elevator installations the waiting period or interval should be from 20 to 30 sec. The "waiting time" or "interval" (I_w) is defined as the time (in seconds) between cars leaving a terminal floor. Mathematically, for a given bank of elevators, it is the average round-trip time of an elevator divided by the number of elevators in the bank which are operating. An interval as high as 40 sec is permissible in some installations.

Another measure of the quality of the elevator installation is the passenger-carrying capacity. This is generally expressed as the percentage of the building population that can be carried one way in 5 min. In high-class installations this is approximately 13 per cent. Traffic studies are generally based on the morning up-peak period as this is the time of greatest demand on the elevator system.

In making a traffic study, building characteristics such as the number of floors, the floor heights, and the travel distance are generally known. The building population must be estimated as indicated above. If a particular type of elevator is then assumed, the average round-trip time, the waiting interval, and the number of elevators required may be determined. The following tables (II to VIII) include many of the terms and definitions commonly used in traffic studies:

Table II. Population of Typical Buildings for Estimating Elevator and Escalator Requirements

Office buildings	Sq ft per person
Diversified:	
Large lower floors	90 to 100
Upper floors	100 to 125
Average use	100
Single purpose	75 to 110
Hotels	Persons per sleeping room
Normal use	1.3
Conventions	1.9
Hospitals	Visitors per bed
General private	1.5
General public (large wards)	3 to 4
Apartment houses	Persons per apartment
One or two small bedrooms	2.0
One or two rooms "efficiency"	2.0
High rental; one or two bedrooms	2.0 to 3.0
Moderate rental housing	2.8
Low cost housing	4.0

Table III. Passengers per Trip

A Elevator Capacity (lb)	*B*[2] Passenger Capacity[1]	*C*[2] Passengers per Trip (Normal Peak)
1200	7	6
2000	12	10
2500	16	13
● 3000	19	● 15
3500	22	19
○ 4000	26	○ 21

[1] Not including the operator. On completely automatic control, without operator, Column *B* capacities may be increased by 1. At peak loads faster movement of passengers results if car doors are closed when car is 80 per cent loaded. This occurs automatically on cars under full electronic control without operator since the elevator floor (operating as a platform scale) initials the door-closing mechanism.

[2] In the larger elevators passengers may safely exceed the normal capacity if loading is not in excess of about $1/10$ the rated number.

A. Rated capacity of an elevator is a function of its platform area as specified in the American Standard Safety Code for Elevators, commonly spoken of as the ASE code.

B. Rated or contract speeds vary from 100 fpm or lower to as high as 1200fpm. Various combinations of capacities and speeds are available.

C. Passengers per trip are the number of passengers which a loaded elevator will normally carry. The passenger capacity is first determined by dividing the rated capacity by 150 lb and subtracting 1 for the operator. Passengers per trip is then taken as 80 per cent of the passenger capacity. (See Table III.)

Table IV. Average Number of Probable Stops *

A	*B*	*C*	*D*	*E*	*F*	*G*
No. of Possible Floors Served	Passengers per Trip					
	6	10	13	◖ 16	18	21 ○
5	3.73	4.47	4.92	4.98	5	5
6	3.92	4.96	5.57	5.98	5.36	5.90
7	4.26	5.50	6.12	6.48	6.62	6.76
8	4.40	5.90	6.90	7.25	7.40	7.70
9	4.56	6.23	7.40	7.85	8.10	8.41
10	4.73	6.5	7.5	8.2	8.5	9.0
11	4.77	6.6	7.8	8.6	9.0	9.6
12	4.92	7.0	8.09	8.99	9.5	10.1
13	4.97	7.2	8.4	9.4	9.9	10.6
● ○ 14	5.03	7.35	8.7	◖9.7	10.3	○ 11.0
15	5.16	7.5	8.9	10.0	10.7	11.6
16	5.18	7.6	9.1	10.3	11.0	11.9
17	5.19	7.75	9.3	10.6	11.3	12.2
18	5.23	7.87	9.4	10.9	11.6	12.7
19	5.27	7.94	9.6	11.0	11.8	13.0
20	5.32	8.0	9.7	11.2	12.1	13.2
21	5.33	8.13	9.87	11.4	12.3	13.3
22	5.33	8.19	10.0	11.5	12.5	13.5

* These statistics result from data gathered on many installations. Columns *B, C, D, E, F, G* give the *average number of stops* made by each car, depending upon the number of passengers per trip. Example: A car serving 17 local floors carrying a starting load of 16 passengers will probably average 10.6 stops. ● ○ These symbols identify the values used in the problem solution; ◖ and ᑕ refer to cases where interpolations are necessary.

D. Openings or floors served are the number of local floors served above the main terminal floor.

E. The number of *local stops* is an average value which depends on the number of passengers per trip and the number of openings served. (See Table IV.)

F. The number of *full-speed stops* (in a round trip) is two if there is an express zone and one if there is not.

G. Average jump is the distance in feet traveled at local speed divided by the number of local stops.

H. The speed attained in the local zone is usually less than the rated speed since the distance traveled between stops is usually too small to permit the car to accelerate to full speed. Thus it depends on the average jump. (See Table V.)

Table V. Maximum Attained Speed for Passenger Elevators in Average Office Buildings

A Average Jump (ft)	*B* Maximum Attained Speed (fpm)	*A* Average Jump (ft)	*B* Maximum Attained Speed (fpm)
8	240	20	520
9	270	22	560
10	300	24	595
11	325	26	625
12	350	28	650
13	375	30	675
14	398	35	725
15	420	40	765
16	440	50	827
18	480		

I. The local running time in seconds, or running time in the local zone, is the distance traveled in the local zone divided by the rated maximum speed in *feet per second* attained in the local zone.

J. The express running time in seconds is the distance in feet traveled at express or rated speed in *feet per second* divided by the rated speed.

K. The accelerating time in seconds, which is the additional time required for the combined accelerating and retarding period at each stop, increases for increasing values of attained speed. It may be kept to a minimum by automatic control devices which give a smooth stop and start. The total of accelerating and retarding time is obtained by multiplying by the number of stops. (See Table VI.)

L. The leveling time in seconds is practically zero for modern automatic leveling elevators. It may vary from 1.5 to 4 sec for manual operation.

M. The door time in seconds considered for automatic control elevators is only the time required for closing. The opening of the doors consumes no additional operating time. The doors start to open as the elevator approaches a landing and are fully open by the time the elevator stops. The

Table VI. Combined Accelerating and Retarding Time

A Attained Speed (fpm)	*B* Additional Time for One-Stop (seconds)	*A* Attained Speed (fpm)	*B* Additional Time for One-Stop (seconds)
200	1.25	600 ●	2.8 ●
250	1.4	650	3.0
300	1.65	700 ○	3.2 ○
350	1.8	750	3.4
400	1.93	800	3.6
450	2.2	1000	4.25
500	2.4	1200	6.25
550	2.6		

door-opening period and the retarding period of the car are coincident. The door-closing time depends on the width of opening and the type of door. It may be 4 to 6 sec for manual operation. The total door-operating time is obtained by multiplying by the number of stops in a given trip. (See Table VII.)

Table VII. Time for Power Door Operation with Attendant Operation

A	*B*	*C*	*D*
	High-Speed Operator		
Width of Opening	Two-Speed Side Opening	Center Opening (Preferred)	Two-Speed Center Opening
36	2.4	1.9	
38	2.4	1.9	
40	2.5	2.0	
42 ●	2.5	2.0 ●	
44	2.6	2.1	
46 ○	2.6	2.1 ○	
48	2.7	2.2	
54	2.9	2.4	
60			2.4
66			2.6
72			2.7

N. The total passenger time in seconds is the time required for the passengers to get on or off and depends on the width of the door opening. The total time is obtained by multiplying by the passengers per trip. (See Table VIII.)

Table VIII. Loading and Unloading Time per Passenger in Seconds

A	*B*	*C*	*D*	*E*
Door opening, in.	36	42	54	60
Loading time	1.1	1.0	0.9	0.8
Unloading time	1.4	1.3	1.2	1.1
Total time	2.5	● 2.3	c 2.1	1.9

O. The lost time in seconds, due to false stops and waiting at the first floor may be assumed zero for most installations during the peak periods.

P. Other lost time is a factor which is included as a small correction. It is 0.2 sec times the number of local stops.

The above terms and definitions will now be applied to an analysis of a typical elevator problem.

Example 1. An office building for which the following round-trip-time analysis is typical contains 28 rentable floors. The distance from the ground floor to the second-floor level is 18 ft and the distance between all other floor levels is 12 ft. In this building the express zone is from the ground to the fourteenth floor, the local zone extending from the fourteenth to the twenty-eighth floor. The system is to have automatic leveling, power-operated doors, and employ an elevator operator. The estimated building population distributed in the upper zone is 1500 people. The maximum waiting interval is to be 30 sec and the required passenger capacity is 13 per cent of population in 5 min. The solutions are to be based on the selection of elevators for the maximum 5 P.M. peak of outgoing traffic.

(*a*) Determine the round trip time for a 3000-lb capacity gearless traction elevator with a rated speed of 600 ft per min and 3-ft-6-in. center-opening doors. (*b*) How many express elevators would be required, and what would be the waiting interval? (*c*) What would the above values be for a 4000-pound, 700-ft-per-minute elevator with 3-ft-10-in. center-opening doors?

Solution. To determine the round-trip time it is convenient to set down the data in tabular form. The letters preceding each heading refer to the previously given list of terms. The calculations for the 3000-lb (*a*) and 4000-lb (*b*) elevators are given in adjacent columns.

	Elevators	
	(*a*)	**(*b*)**
A. Rated capacity	**3000 lb**	**4000 lb**
B. Rated speed	**600 fpm**	**700 fpm**
C. Probable passengers per trip (Table III)	**15**	**21**
D. Openings served (14th to 28th floor)	**14**	**14**
E. Probable local stops (Table IV)	**9.4 ***	**11.0**

	Elevators	
	(*a*)	(*b*)
F. Full speed stops (28th and 1st floors)	2	2
Total stops (= sum of E and F)	11.4	13.0
Distance, local zone (12 ft × 14)	168 ft	168 ft
Distance, express zone (2 × 18) + (12 × 12) + (26 × 12)	492 ft	492 ft
G. Average jump (local zone)		
168 ÷ 9.4	17.7 ft	
168 ÷ 11		15.3 ft
H. Speed obtained in local zone (Table V)	474 fpm	426 fpm
Time Calculations		
I. Local running time (in seconds)		
(168 ft ÷ 474 fpm) × 60 =	21.3	
(168 ft ÷ 426 fpm) × 60 =		23.7
J. Express running time (in seconds)		
(492 ft ÷ 600 fpm) × 60 =	49.2	
(492 ft ÷ 700 fpm) × 60 =		42.2
K. Combined accelerating and retarding time (in seconds) (local stops) (Table VI)		
(9.4 × 2.26)	21.2	
(11.0 × 2.07)		22.8
K. Accelerating time in seconds (express stops) (Table VI)		
(2 × 2.8)	5.6	
(2 × 3.2)		6.4
L. Total leveling time in seconds	0.0	0.0
M. Door time in seconds (Table VII)		
(11.4 × 2)	22.8	
(13.0 × 2.1)		27.3
N. Total passenger loading and unloading (in seconds) (Table VIII)		
(15 × 2.3)	34.5	
(21 × 2.2)		46.2
O. Lost time in seconds (false stops)	0	0
O. Lost time in seconds (first floor)	0	0
P. Other lost time in seconds		
(0.2 × 9.4)	1.9	
(0.2 × 11.0)		2.2
Total round trip time in seconds	156.5 sec	170.8 sec

* When a desired figure is not in the table, calculations for this figure are found by interpolation. Where the figures require *interpolation*, these are identified by the symbols ◖ and ☾.

To determine the number of cars required:

$$\text{Passenger capacity per car in 5 min} = \frac{60 \times 5 \times \text{Passengers per trip}}{\text{Round-trip time in seconds}}$$

$$= \frac{60 \times 5 \times 16}{161.9} = 29.6 \text{ people}$$

$$\text{Total number of people to be carried in 5 min} = \text{Passenger-carrying capacity in per cent} \times \text{Total population}$$

$$= 0.13 \times 1500 = 195 \text{ people}$$

$$\text{Cars required} = \frac{\text{Total to be carried in 5 min}}{\text{Passenger capacity per car in 5 min}}$$

$$= \frac{195}{29.6} = 6.6 = 7 \text{ cars}$$

$$\text{Waiting interval} = \frac{\text{Round-trip time}}{\text{Number of cars}} = \frac{161.9}{7} = 23.1 \text{ sec}$$

This value is less than the maximum specified waiting time of 30 sec, and the system would therefore be acceptable. It is greater than the sum of the passenger-loading time plus the door time at the first floor (16 + 2 = 18 sec) which is the smallest allowable interval.

The round-trip time for the 4000-lb elevator has been arrived at above. Now going through the same calculations as for the 3000-lb elevator, it is found that

Passenger capacity per car in 5 min = 36.4 people

Cars required = 5.3 = 5 or 6

Checking the waiting interval for 5 cars, it is found to be 34.7 sec which is too great. Therefore 6 cars will be used, and it is seen that the waiting interval = 28.9 sec.

Thus it appears that there are at least two acceptable elevator systems which may be used in this building; seven 3000-lb 600-fpm elevators with an interval of 23.1 sec; or six 4000-lb 700-fpm elevators with a waiting interval of 28.9 sec. Other possibilities may also be considered and checked in the same way. A decision may then be made based on consideration of initial cost, maintenance, space required, and service.

15. Similarity of waiting time for automatic vs. nonautomatic elevators. It has been found that the round-trip time of an elevator with starter and car-operator control is approximately equal to that of the electronic full automatic elevator. Hence a typical round trip in seconds and the resulting waiting period in seconds at any landing may be calculated by the method given in Example 1. It should be remembered, however, that the first cost, operating economies, and rapid amortization of investment favor the electronic controlled cars.

16. Noise reduction. All elevator apparatus is carefully aligned; ball bearings are liberally used, and all rotating armatures, sheaves, gears, and shafts are balanced. Control switches and contactors are cushioned. Laminated magnetic parts including the armatures and field cores of relays and breakers are most carefully assembled and riveted together under great pressure. The geared elevator machine, m-g set, and unit-assembled control panels are placed on rubber-padded foundations.

17. Apartment elevators. The geared traction machine provides moderate speeds with smooth operation. The advantage of direct connection to the driving motor is retained as in the gearless traction elevator machine, but a worm and gear transmit power from motor shaft to the cable sheave. The brake is applied to the brake sheave which is mounted directly on the motor shaft. The general design of the brake is similar to that described in Art. 12. Since smooth application of brakes is best secured by a d-c brake magnet, a metallic rectifier is used to secure the direct current from the a-c source.

The geared traction machine is usually driven by an a-c motor; hence its accelerating and decelerating periods are likely to be less smooth than if it were driven by a d-c motor. In order to minimize the discomfort which might otherwise be felt when the elevator is starting, the control is adjusted to provide an exceptionally slow start, which is further cushioned by the gear reduction of the machine. The rail guide shoes on the car frame are also provided with shock-absorbing cushions to insure smooth and quiet operation.

Since these cars are designed for control by the passenger, a very simple and obvious system must be provided. A single-call push-button control provides a plate with one button and an in-use light in the corridor; the car panel contains a stop button and a call button for each floor served. Pressure on any corridor call button will call the car to that level, except when the car is in use and therefore traveling under the direction of another passenger or prospective passenger.

18. Motor horsepower requirements. Modern elevators are always operated by d-c or a-c motors. The motor horsepower required is found to be at the maximum when the elevator is traveling at full rate speed in the "up" direction and carrying its rated live load. If the rated capacity were 3000 lb the car could carry a maximum live load of 3000/150 lb = 20 people, one of whom would be the operator. The average weight per person is usually considered 150 lb. Thus the maximum number of passengers in this car, when an operator is used, is 20 − 1 = 19 passengers. If the elevator should be completely automatic and without an operator, the live load could be 20 passengers.

It is standard practice to counterweight all the dead weight of the car, cables, and 40 per cent of the live load. The effective passenger weight to be lifted is, therefore, 60 per cent × rated capacity in pounds. This practice (40 per cent) strikes an economic balance between the various factors influencing operating costs, that is, average loading, average speeds, average number of stops per mile, energy for acceleration and retardation, maintenance, and first cost of equipment.

The mechanical efficiency of the gearless traction elevator varies from 78 to 88 per cent; the geared type from 40 per cent for slow speed to 70 per cent for speeds up to 350 ft per min. Speeds of modern elevators may vary from approximately 100 to 1200 ft per min. In a few very high buildings the speeds have reached 1400 ft per min.

The corresponding capacity of the m-g set must be such that the d-c generator will deliver the kilowatts required by the motor; and the a-c motor will draw from the building feeder (serving this elevator machine room) the necessary kilowatts to drive the generator. When the overall efficiency of the m-g set is known, the required kilowatt input is easily calculated.

Example 2. A 4000-lb elevator is rated to carry 27 people, including the operator. Find the weight (W) to be moved by the cable when the 27 people are in the car.

Solution.

$$\text{Weight in pounds} = W = (1 - 0.40) \times (27 \times 150) = 2430 \text{ lb}$$

Example 3. Twenty people are in a 3000-lb 700-fpm d-c gearless traction elevator with 90 per cent mechanical efficiency (of the loaded car, cables, rail friction, and counterweights), 80 per cent efficiency for the m-g set, and 87 per cent efficiency for the traction machine motor. Determine (*a*) the horsepower rating of the traction machine motor; (*b*) the input in kilowatts to the m-g set.

Solution. The effective weight to be lifted is

$$\text{Pounds} = (1 - 0.40) \times \text{rated capacity}$$

$$= 0.60 \times 3000 = 1800 \text{ lb}$$

$$\text{Horsepower} = \frac{\text{Weight lifted in pounds} \times \text{Speed in feet per minute}}{33{,}000 \times \text{Efficiency}}$$

$$\text{Horsepower} = \frac{1800 \times 700}{33{,}000 \times 0.90} = 42.4 \text{ hp input to the traction machine shaft}$$

$$\text{Input horsepower to m-g set} = \frac{42.4}{0.87 \times 0.80} = 60.9 \text{ hp}$$

Since 1 hp equals 0.746 kilowatt:

$$\text{Kilowatt input} = 60.9 \times 0.746 = 45.4 \text{ kw}$$

If a-c service is furnished to the building, the m-g set would require an a-c squirrel-cage motor.

This power (45.4 kw) must be delivered over an elevator feeder to the starting panel of the m-g set. Since the usual feeder would be a 3-phase 230-volt 60-cycle circuit, the feeder can now be selected. Under usual practice this feeder would be installed in a rear corner of the hoistway (or shaft), rising from the main distribution center to the penthouse.

Example 4. Determine the specifications for the above elevator feeder.

Solution. Refer to Chapter 24, for types of conductor insulation; and to the wire table Chapter 23, Table I. Since the elevator shaft is here assumed to be an outside wall, there is probability of condensation on this wall and within the conduit, owing to the higher humidity of the warm air in the shaft when the warm air rises over the colder surface of the outside wall. Therefore, select RW insulation. The line current required (I) for each conductor of the 3-phase feeder is from Table II, Chapter 23, p. 335.

$$I = \frac{W}{1.73 V \cos\theta} = \frac{45{,}400}{1.73 \times 230 \times 0.866} = 131.7 \text{ amp}$$

The kilowatthours (kwhr) required per car mile for three types and ratings of elevators and for various stops per mile of car travel are shown in Fig. 13. For any given installation an analysis of the expected operating conditions would be made before the type and ratings of elevators and the corresponding energy curves could be drawn. Statistical data for all classes of occupancy and types and ratings of elevators to meet the needs are available. During acceleration the power input to the m-g set is very

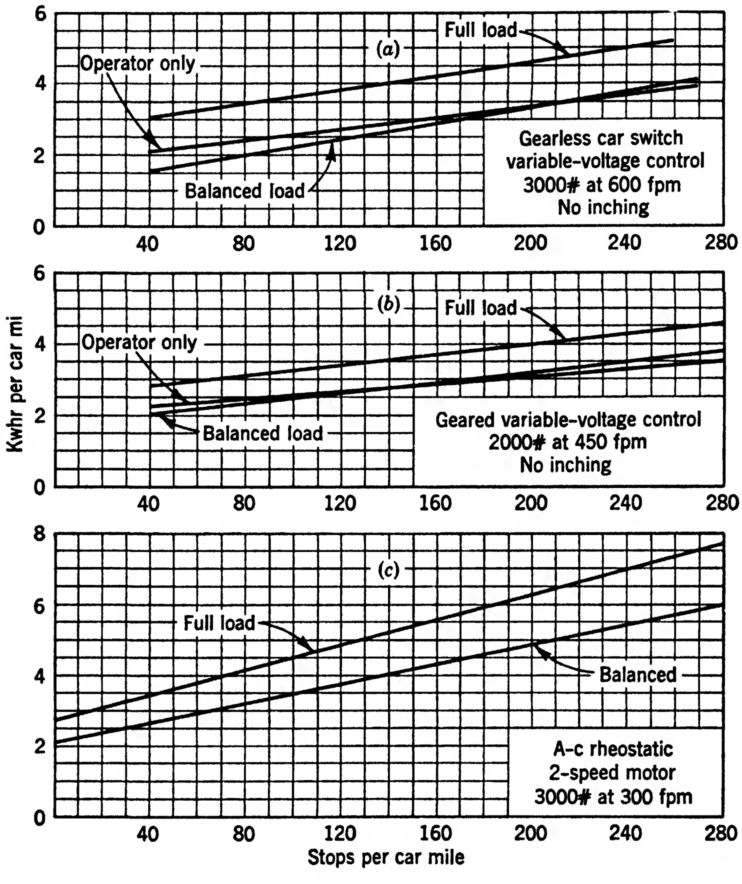


Fig. 13. Energy consumption (kwh) required by several types of elevators when loaded to full capacity, when loaded to balanced weight, and when occupied by the operator only. A "balanced load" is defined as a car which is carrying rated capacity plus 40% of the rated capacity, thus balancing the counterweights.

high in proportion to the speed, since the torque required to overcome the inertia is so great. The maximum current drawn by the elevator motor when accelerating at full load is of the order of 200 to 225 per cent of that required at constant rated speed. Thus heavy cars and equipment, with consequent high inertia, directly increase power capacity and energy consumption. High-speed cars necessarily add to the energy requirements since higher accelerating speeds are necessary to maintain the traffic schedules.

With variable-voltage control the motor of the m-g set may be smaller in capacity than the generator or the traction (elevator) motor, for, although the acceleration may require a very high current, the terminal voltage may be low over most of the accelerating period. For this reason, the size of the motor of the m-g set is determined by computing the average power required over the peak-load hour of operation. These estimates may be made from curves similar to Fig. 13, for elevators of given types and speeds. Figure 14 shows the corresponding elevator car speeds for the kilowatt input curve of (*b*). A study of these two curves for corresponding time intervals, such as t_0–t_1, t_1–t_2, · · ·, shows the very high kilowatt inputs required during acceleration, the steady input required during constant rated speed, and the low consumption of power during retardation. In the period 11–13 sec, on curve (*b*), the m-g set actually returns power to the line (called regenerative action). This regenerative action is effective in adding braking power (called regenerative braking) during the retarding period. A high number of stops per car mile requires increased energy consumption, owing to the more frequent number of accelerating periods. This indicates that a high-level elevator during its travel in the express zone (at constant speed) may consume less energy per car mile than might be required after it reaches the local zone. These

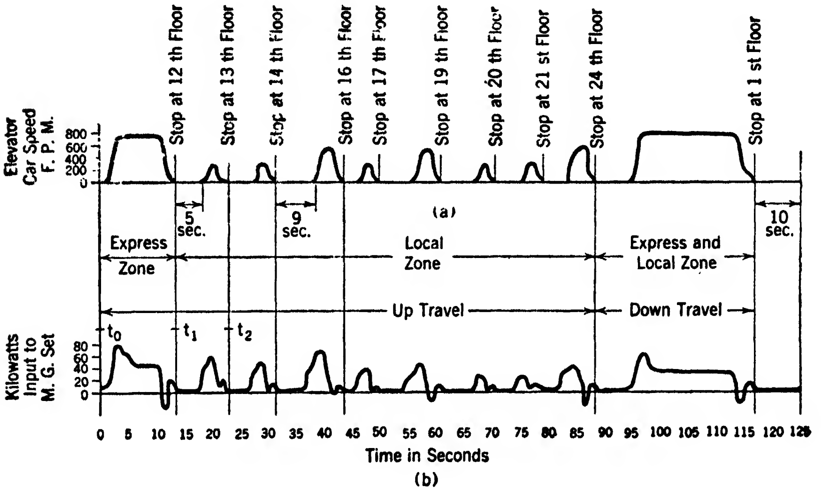


Fig. 14. Power input and car speed, illustrating the typical operation during periods of acceleration, constant speed of travel, and retardation.

curves also show the stop intervals at floor levels; for example, 5 sec at 12th floor, 9 sec at 14th floor, ···. At the end of the trip there is a loading period of about 10 sec at the first floor before a new trip is started.

19. Elevator operating data. In order to provide for the maximum satisfactory service and for minimum cost for maintenance and operation, it is essential that the building management be familiar with every operating detail that affects these objectives. For this purpose a number of testing instruments should be provided in any large installation to secure the necessary data. Among these are the car-mile recorder, the start and stop recorder, the kilowatthour meter for energy input, an instrument designed to record on charts the time of acceleration, time of deceleration, time of uniform running periods, total time of round trips, runs, and number of starts and stops per round trip.

It is obvious that analysis of such data for each elevator, with reference to the operations of a group of elevators, will indicate important factors affecting operating costs and accuracy of automatic controls.

20. Maximum structural stresses. For purposes of structural design it is necessary to know the foot-pounds of kinetic energy which must be supported by the foundations, structural columns extending upward to the penthouse, and the main beams which support the penthouse floor and subfloor. This kinetic energy is given for several typical elevators in Table IX. The weights given (in columns *D*, *E*, *F*, *G*, and *H*) include the actual dead weights of equipment when the elevator is not in motion plus the added weight caused by the momentum of all

Table IX. Analysis of Kinetic Energy of Typical Elevators

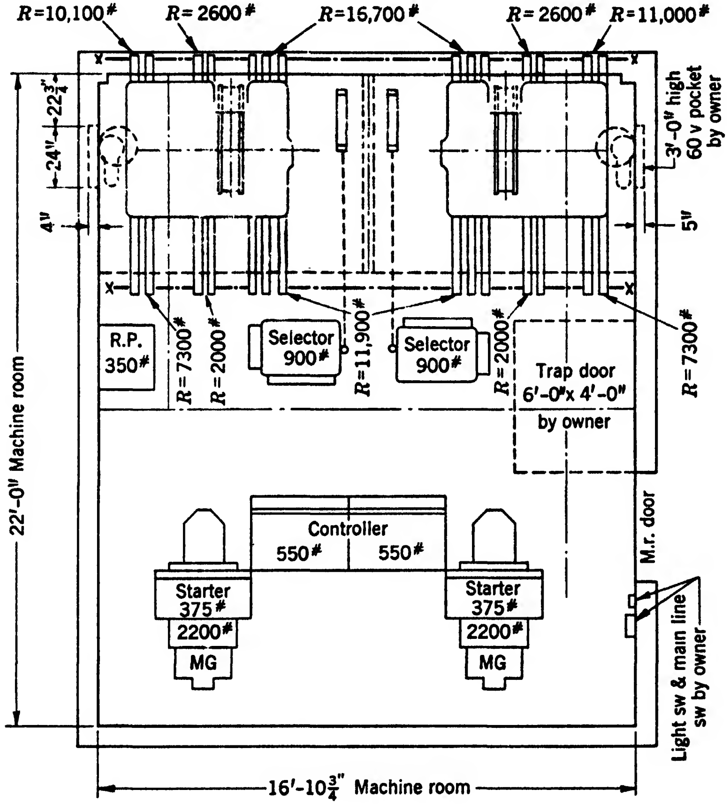
(Kinetic energy at rated load and speed in foot-pounds)

A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*
Traction-Machine Type, Hoist Motor and Control	Rated Duty	Rise in Ft	Machine	Car	Counter-weight	Ropes	Live Load	Total Col. *D*, *E*, *F*, *G*, *H*
Gearless 1:1 d-c motor, voltage control	2500 lb at 800 fpm	435	4180	15,250	18,200	10,000	6900	54,530
Gearless 2:1 d-c motor, voltage control	3000 lb at 500 fpm	200	2900	6,750	8,050	3,900	3250	24,850
Worm gear 1:1 d-c motor, voltage control	3500 lb at 250 fpm	125	6200	1,500	1,880	160	950	10,590
Worm gear 1:1 a-c motor, 1-speed rheostatic control	2500 lb at 150 fpm	100	2450	460	560	50	245	3,765

Adapted from *Standard Handbook for Electrical Engineers*, p. 1631, Table 17–69.

moving parts and passengers when the elevator is at top speed and is suddenly caused to stop rapidly by the safety devices.

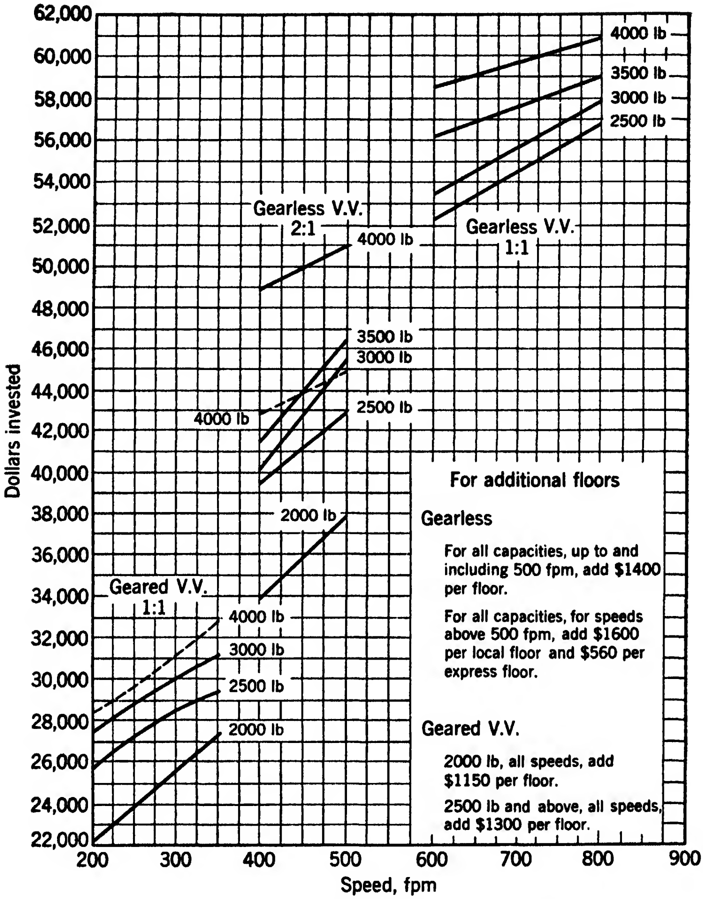
21. Dimensions and weights of elevators. A set of standard dimensions for elevators has been agreed upon by the National Elevator Manufacturers Industry (NEMI). Typical layouts for elevators with



Suitable means of heating, lighting, ventilating and legal access to machine room by owner

Fig. 15. Typical machinery room layout for 2500-lb, 500-fpm passenger elevator using gearless machines. Note supporting beams under elevator machines and the reaction loads (R) on various supporting beams (also see Fig. 4).

gearless machines, capacities from 2000 to 4000 lb and speeds of 400 and 500 fpm is shown in Fig. 4 with the accepted dimensions and weights. Other layouts are available for different values of capacity



For additional floors

Gearless

For all capacities, up to and including 500 fpm, add $1400 per floor.

For all capacities, for speeds above 500 fpm, add $1600 per local floor and $560 per express floor.

Geared V.V.

2000 lb, all speeds, add $1150 per floor.

2500 lb and above, all speeds, add $1300 per floor.

Fig. 16. Cost data of geared and gearless variable-voltage passenger elevators for use in office buildings, general-purpose buildings, hospitals, hotels, and industrial buildings with speeds of 200 to 800 fpm and with elevator passenger capacities from 2000 to 4000 lb. These curves are based on 6 floors (floor heights of 12′ 0″) or more. The cost data presented include cost of the complete elevator and its operating auxiliaries and control including cab, entrances, and installation costs. Expert elevator mechanics are available in all large cities to install and to maintain all installations. These crews work under the direction of the architect, architectural engineers, and under the supervision of experts assigned by the elevator manufacturer. Figures 4 and 15 show general plans for typical elevator penthouse and shaftway installations. These form a part of the complete installation specifications and drawings furnished by the manufacturers. It is emphasized that these cost data are for budget purposes only. Representatives of the manufacturers should be asked for specific quotations to be based on adequate specifications for a given proposed installation.

and speed and for geared machines. Figure 15 is a typical machinery room layout for two elevators.

As may be seen from Fig. 4, it is necessary, in providing for an elevator installation, to consider such factors as the depth of the pit, the dimensions of the hoistway, the clearance from the top of the hoistway to the floor of the penthouse, the size of the penthouse, and the loads which must be carried by the supporting beams. It should be noted that it may be necessary to deviate from the standard locations of penthouse equipment. In that event it will be necessary to seek space allocations in the vicinity of the penthouse areas. Space variations may also arise because of special provisions of the local elevator code.

22. Cost data for elevators. It is general practice for architects and architectural engineers to prepare elevator specifications in collaboration with a representative of the elevator manufacturers during the period of building design. A very wide range of weights and speeds of the cab and of the auxiliaries required naturally result in a wide range of installed costs. An example of the cost data shown in Fig. 16 covers the gearless and the variable-voltage NV geared types for the most popular types of elevators for modern buildings.

NEC CODE AND SUPPLEMENTARY TEXT REFERENCES

Appendix A NEC Items: A58, A10.
Appendix B Text Items: B12, B13, B11.

PROBLEMS

1. An office building in the central district of a large city has 28 floors with rental area of 20,000 ft per floor. The first floor houses a bank; the next 10 floors are leased by banking firms and corporations; the next 17 floors are subdivided into small offices. Determine the probable population on each floor. State the general type of elevator service that would fit the needs of the occupants.

2. Explain briefly what time factors must be given consideration in the determination of the round-trip time of an elevator.

3. What is the range of speeds of modern passenger elevators, and under what general conditions would slow and fast speeds be selected?

4. What are the principal pieces of machinery and apparatus in an elevator installation?

5. Describe briefly (*a*) the variable-voltage control system; (*b*) the rheostatic control system. (*c*) What conditions favor the use of each?

6. Variable-voltage 500-ft-per-min 18-passenger gearless traction elevators are operating with automatic acceleration and retardation, automatic floor leveling and door operation, and preset stop and call system. These elevators are to travel from the ground floor (first floor) to the fifteenth floor as expresses, then to 15 floors above as locals. Assume that these elevators are to operate at 5 P.M. to discharge passengers as rapidly as possible from the upper floors to the ground-level lobby. Estimate: (*a*) the round-trip time, the elevators starting empty at the ground level; (*b*) the number of passengers discharged from this upper local zone in 15 min.

7. Referring to Figs. 1 and 2 lay out a typical elevator lobby floor plan to scale ⅛ in. equals 1 ft. Assume the elevator lower terminal to be at the street-floor corner of an office building with two 6-car alcoves, a drugstore, a coffee shop, and six public telephone booths. Show street entrance doors. The answer will naturally be influenced by the judgment of the designer in analyzing required comfortable passage space for all pedestrians in these areas. Indicate with arrows the general flow of traffic in all hallways, corridors, and elevator lobbies. The time of day is assumed to be at the morning up-peak from about 8:00 to 8:30 A.M. One 30-passenger car is always ready at the lower terminal with sign *"next car up."* All twelve cars are in operation with a waiting period or interval of 30 sec.

Chapter 30

MOVING STAIRWAYS

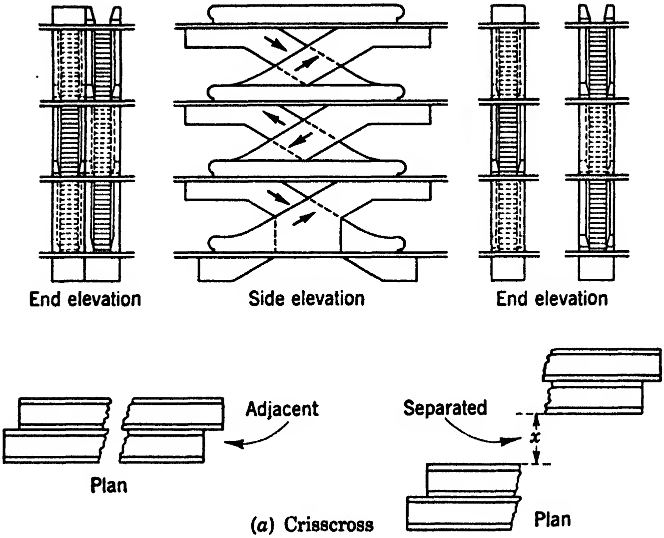
1. Moving stairways. The moving stairway is frequently referred to as an escalator, or as an electric stairway. Throughout this section all three names will be used. It was first operated at the Paris Exposition in 1900. In this country moving stairways now provide comfortable and rapid vertical transportation for many millions. Some of the conditions which favor the application of escalators rather than elevators were mentioned in Chapter 29, p. 473. These should be reviewed.

The escalator not only delivers passengers comfortably, rapidly, and safely, but also it continuously receives and discharges its live load at a constant speed with practically no waiting periods at any landing. The many seconds of time which are lost by elevators are not present on traveling stairways. For example, time is not lost by acceleration, retardation, leveling, door operation, operator's reactions; nor by pressing hall buttons, by passenger interferences in getting in or out of the cars, etc. One seldom sees a waiting passenger or congestion of passengers at the lighted comb plate of an escalator.

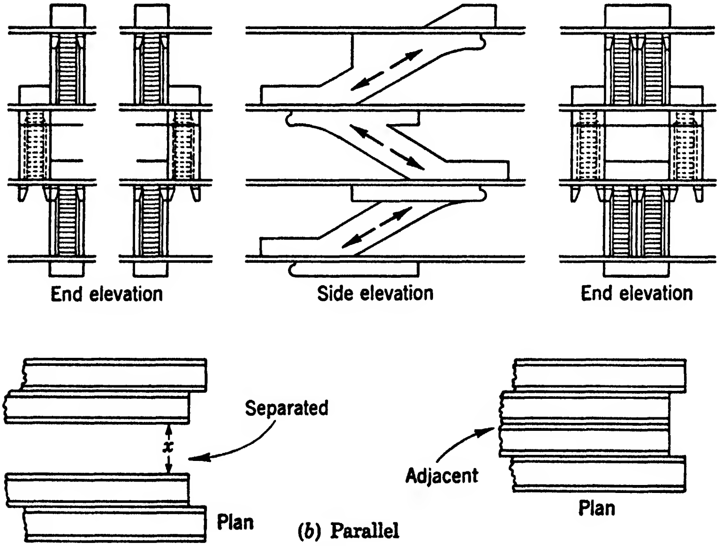
Instead of formal lobbies and hallways leading to a bank of elevators on each floor, the electric stairway is always in motion and inviting passengers to "take a ride." The corridors, aisles, and other passageways in existing buildings usually provide space for floor openings adequate for the installation of escalators. In contrast, it would in most cases be almost impossible to install an adequate bank of elevators in an existing building to meet the growing needs for vertical transportation. The elevator hoistways would have to be vertical from bottom to top floors; an escalator installation could be "staggered" at various appropriate locations. (See Fig. 1.)

Figure 2 shows side views of a modern moving stairway. The outside balustrade is cut away at the lower and upper ends to show the general arrangement of the major parts and appurtenances.

The stairway is prepared for shipment by dividing the structural truss into three sections. The upper section of the truss is separated from the middle section at the locations near the arrows 22 and 8. A similar lower section is likewise separated at a closely corresponding line (hidden by the balustrade) near the arrow 23. The middle straight

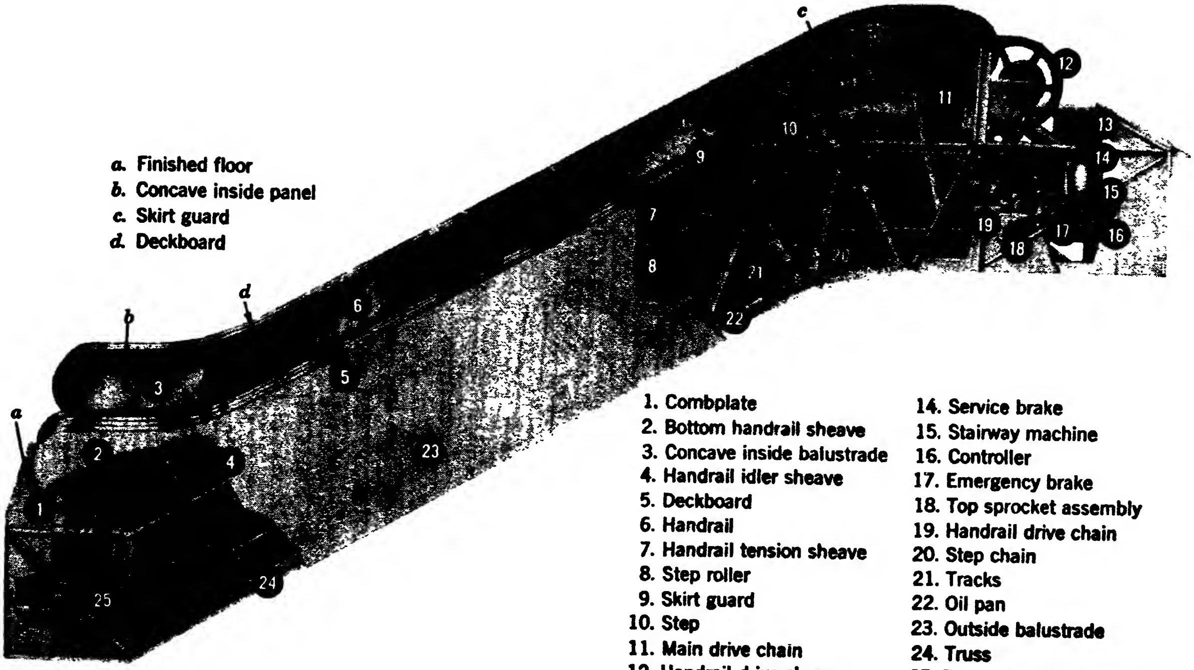


(a) Crisscross



(b) Parallel

Fig. 1. End and side elevations, showing various details of criss-cross and parallel stairways. Distance x may be chosen to suit architectural plans in new or existing buildings.



a. **Finished floor**
b. **Concave inside panel**
c. **Skirt guard**
d. **Deckboard**

1. Combplate
2. Bottom handrail sheave
3. Concave inside balustrade
4. Handrail idler sheave
5. Deckboard
6. Handrail
7. Handrail tension sheave
8. Step roller
9. Skirt guard
10. Step
11. Main drive chain
12. Handrail drive sheave
13. Governor
14. Service brake
15. Stairway machine
16. Controller
17. Emergency brake
18. Top sprocket assembly
19. Handrail drive chain
20. Step chain
21. Tracks
22. Oil pan
23. Outside balustrade
24. Truss
25. Bottom sprocket assembly

Fig. 2. Typical end and side views of a modern escalator.

section may be any desired length to provide rises for floor heights of from say 10 to 23 ft. When the rise is over 20 ft an intermediate support is located between the two end supports of the stairway. Generally, the upper corners of the bottom and top ends of the truss, after assembly, carry the complete weight of the stairway mechanism and its live load. See the two large beams on which the truss rests.

Figure 3(*a*, *b*, *c*, *d*, *e*, *f*) illustrates various arrangements and views of the entrances of escalators.

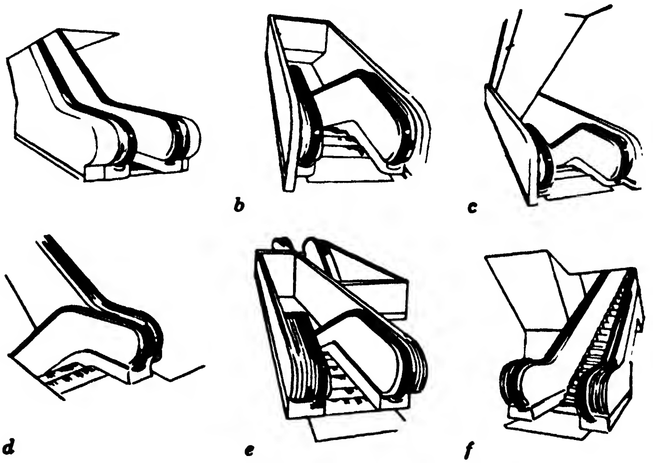


Fig. 3. Typical views of stairway landings, floor openings, and trims for escalators.

2. Parallel and crisscross installations. Escalators may be installed so that the up-stairway and down-stairway crisscross each other as in Fig. 1(*a*); or arranged in parallel as in (*b*). The arrangements also may be such that the center lines of the pairs of stairways are close together (or adjacent); or that the center lines are far apart (or separated). These are clearly shown in the figure. Any up and down set of escalators may, in fact, be separated by many feet. This permits the sometimes desirable plan of forcing passengers to travel on a given floor (as in a department store) in order to display merchandise to create purchases.

3. Safety features. Protection to passengers during normal operation is insured by a number of safety features associated with moving stairways:

(*a*) Handrails and steps travel at exactly the same speed (90 or 120 ft per min) to insure steadiness and balance on the up or down travel and to aid naturally in stepping on or off the combplates.

(*b*) The steps are large, steady, and prevent slipping.

(*c*) Step design and their leveling with the combplates at each landing insure against tripping as one enters or leaves the escalator.

(*d*) The balustrade includes all the enclosures as furnished by the escalator manufacturers, as shown in Figs. 1, 2, and 3, including the deckboards, concave inside panels, skirt guards, handrail guards, handrails, and combplates. Details of these parts are designed to prevent catching of clothing and of packages being carried by passengers. Close clearances provide safety features near the combplates and step treads.

(*e*) Automatic controls of a service brake bring the stairway to a smooth stop if electric power or mechanical parts should fail. Passengers would then walk the steps as they would any stationary stairway.

(*f*) In case of overspeed or underspeed an automatic governor shuts down the escalator and prevents reversal of direction (up or down) and operates the service brake.

(*g*) Adequate illumination is provided at all landings at the combplates and completely down all stairways.

(*h*) An emergency stop switch is located near the combplate or in some unobtrusive location. Building employees and adult passengers may operate the switch to stop the escalator. A key-operated up-starting switch and another down-operating key-operated switch is available near the emergency stop switch. The electric controls also are arranged to shut down the stairway if by some accident it is caused to reverse its direction.

4. Fire protection. Four methods of affording protection in case of fire near escalators are available: the rolling shutter; the smoke guard; the spray-nozzle curtain; and the sprinkler vent.

Figure 4 quite clearly illustrates how the wellway at a given floor level may be entirely closed off by the fire shutter, thus preventing draft and spread of the fire upward through escalator wells. The movement is actuated by temperature and smoke relays which automatically start the operation of the motor-driven shutters. The shutter in Fig. 4 is shown at the third-floor level, but other shutters may be installed at the tops of all horizontal wellway openings at any floor.

The smoke-guard method of protection, Fig. 5, consists of fireproof baffles surrounding the wellway and extending downward about 20 in. below the ceiling level. Smoke and flames rising upward to the escalator floor opening meet a curtain of water automatically released from the usual type of sprinkler heads shown at the ceiling level. The baffle is a smoke and flame deflector. The vertical shields between adjacent sprinklers insure that the spray from one will not cool the near-by thermal fuses and prevent the opening of adjacent sprinklers.

The spray-nozzle curtain of water (not shown) is quite similar to the above smoke-guard protection. Here closely spaced high-velocity water nozzles form a compact water curtain to prevent smoke and flame rising through the wellways. Automatic thermal or smoke relays open all nozzles simultaneously.

The sprinkler-vent fire control is shown in Fig. 6. Here the fresh air intake (*A*) housed on the roof contains a blower to drive air downward through escalator floor openings while the exhaust fan on the roof creates a strong draft upward through an exhaust duct; this duct in turn draws air from the separate ducts just under the ceiling of each moving stairway floor opening. Three such separate wellway ducts are shown. Each duct has a number of smoke-pickup relays which automatically start the fresh air fans. The usual spray nozzles on the ceiling near the stairways aid in quenching the fire.

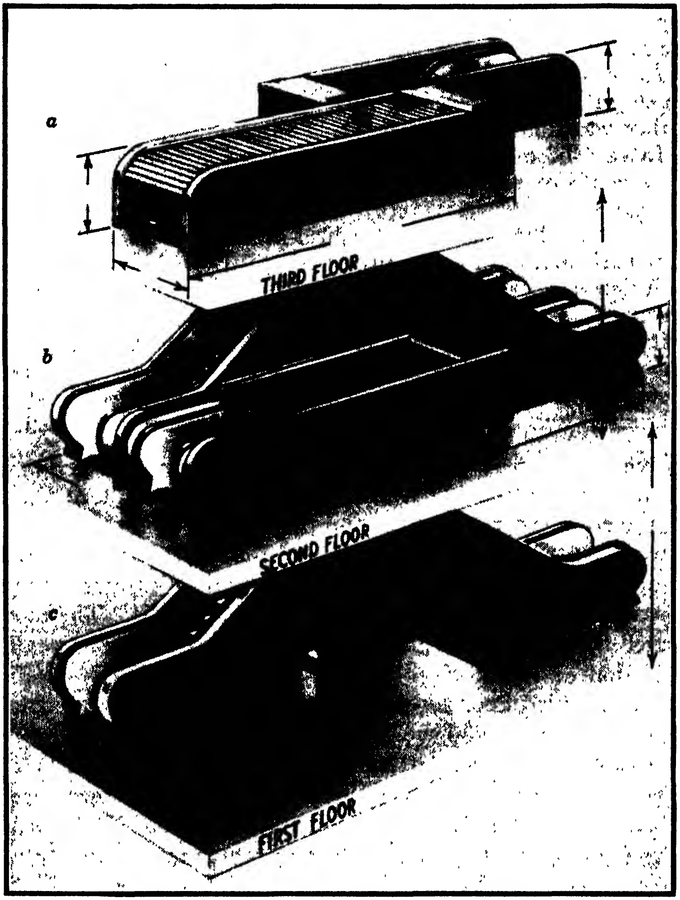


Fig. 4. Rolling-shutter method of wellway fire protection.

Wellways and the entire escalator equipment may be well protected against fire by totally enclosing them between fireproof walls from floor to ceiling. The approaches to the stairs at each level are provided with lobbies which have fireproofed swinging doors. These doors are self-closing, and are held open by fusible links. Hot gases, smoke, or fire near these enclosures melt the fuses and allow the door springs to close the doors. The area of the enclosed lobbies should provide 3 sq ft per person.

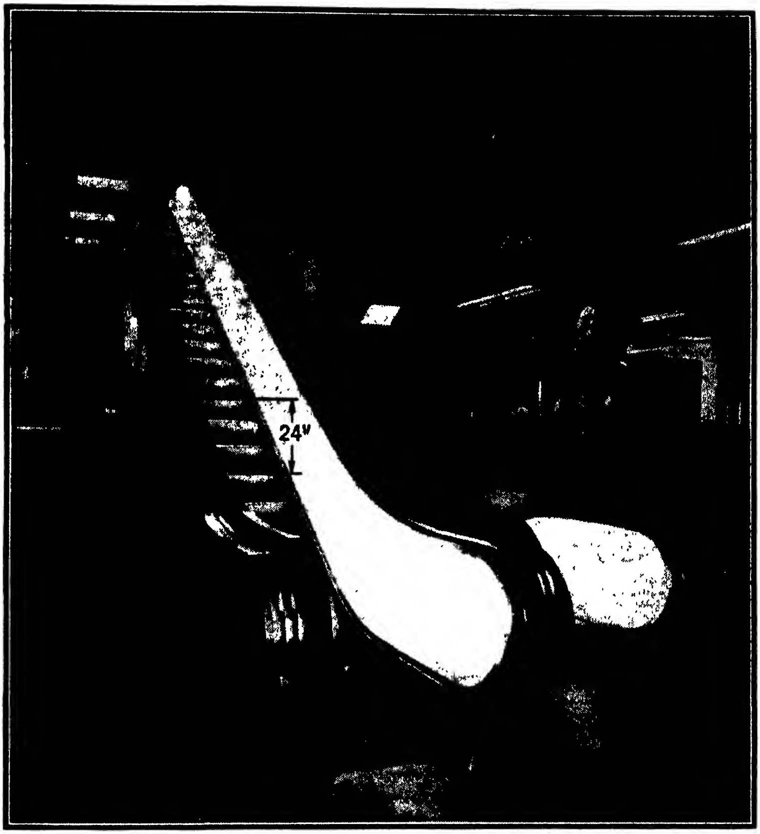


Fig. 5. Smoke-guard method of fire protection for a 32-inch moving stairway, criss-cross type. Main baffle and typical stairway enclosures contain approximate dimensions. The escalator floor opening (per floor) is approximately 4′ 4″ by 14′ 6″. (See Fig. 7.)

With the exception of the total-enclosure method, last mentioned, the operating floor areas near all escalators are not burdened with any apparatus connected with the protective equipment.

5. Horsepower requirements for escalators. The live or contract load of an escalator in pounds is specified by the American Standard Safety Code for Elevators as

$$\text{Contract load} = 4.6WA \tag{1}$$

where *W* is the nominal width of the escalator in inches and *A* the horizontal projection of the length of the exposed treads in feet. *A* for a 30° incline is equal to $\sqrt{3}H$, where *H* is the vertical rise of the esca-

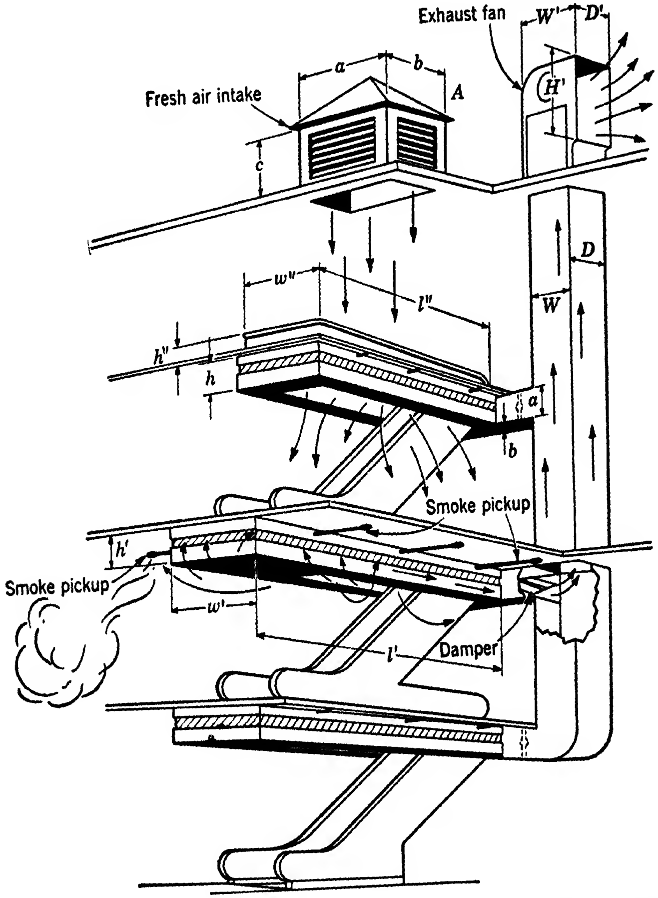


Fig. 6. Sprinkler-vent method of wellway fire protection for a typical escalator, single flight, reversible.

lator in feet (floor to floor height). All escalators are designed for installation on a 30° incline. The nominal width (*W*) is measured between the ballustrading at a vertical height of 24 in. above the nose-line of the treads. The standard nominal widths (*W*) are 32 in. and 48 in. See Fig. 5, dimension *W*.

$$\text{Horsepower} = \frac{\dfrac{4.6W \times \sqrt{3}\,H \times S \sin 30^\circ}{33{,}000} + \text{hp}_e}{E} \tag{2}$$

$$= \frac{(0.000121 \times W \times H \times S) + \text{hp}_e}{E} \tag{3}$$

where S is the speed in feet per minute, hp_e is the horsepower required to drive the empty escalator, and E is the per cent efficiency. The efficiencies of escalator equipment range from approximately 69 to 85 per cent. The horsepower required to drive the empty stairway may be closely estimated to be from 1 to 2 hp for a 32-in. machine and from 1.25 to 2.25 hp for a 48-in. machine for rises of 10 to 23 ft.

Example 1. Determine the horsepower required to drive a 32-in. wide loaded escalator with a vertical rise of 20 ft, assuming the standard 30° incline and standard speed of 90 ft per min. The efficiency of the loaded escalator is 80 per cent. If the efficiency of the motor is 85 per cent at full load, what is the full-load power required in kilowatts? 1.5 hp is required to drive the empty escalator. If the motor efficiencies are 82 per cent at ½ load and 50 per cent at no load (without passengers), what are the kw requirements at each of these loads?

Solution. The required horsepower of the motor is based on the full-load condition. Therefore from Equation 3

$$\text{Horsepower} = \frac{(0.000121 \times 32 \times 20 \times 90) + 1.5}{0.80} = 10.6\ \text{hp}$$

$$\text{Power (kw) required at full load} = \frac{10.6 \times 0.746}{0.85} = 9.33\ \text{kw}$$

At half load:

$$\text{Horsepower} = \frac{(0.000121 \times 32 \times 20 \times 90 \times 0.5) + 1.5}{0.80} = 6.23\ \text{hp}$$

$$\text{Power required} = \frac{6.23 \times 0.746}{0.82} = 5.67\ \text{kw}$$

At no load:

$$\text{Horsepower} = \frac{1.5}{0.80} = 1.88\ \text{hp}$$

$$\text{Power required} = \frac{1.88 \times 0.746}{0.50} = 2.80\ \text{kw}$$

The power required at half load is 64.5 per cent of the full-load power, whereas at no load it is 14.3 per cent.

Example 2. If the escalator of the previous example uses an average of 8 kw during a 10-hour day and the cost of electricity is 1 cent per kilowatt-hour, what would be the daily cost of electric energy?

Solution.

$$\text{Cost} = 8 \times 10 \times 0.01 = \$0.80$$

The energy cost for an escalator installation is usually quite low.

6. Typical escalator traffic problems. In addition to the preceding comments on escalators one should consider the following traffic conditions affecting operating efficiencies:

(*a*) All escalators are furnished with controls for reversible operation, up or down as desired, merely by pressing a control button. This provides for one-way movement of large groups of people in either direction, such as during the opening or closing times of large stores.

(*b*) When operating at rush periods in one direction as in (*a*), a few stairways may be operated in the reverse direction to enable employees and others to have both up and down facilities.

(*c*) In emergencies, such as during fire or panic in a local portion of the building, escalators in other portions may effectively be operated. The stairways in the danger zones could be automatically closed by the fire protection equipment. Foot traffic would be directed by the organized emergency monitors of a given building.

(*d*) It should be obvious that electric stairways could not effectively be used as a single means of transportation in a very tall building, say one of 30 to 80 stories. It is left to the reader to work out a trial problem, based on the maximum peak travel and population, alternately by traveling stairways or elevators. Comparisons of times for completed movements of all occupants will be indicative.

(*e*) On the other hand, the escalator finds its most important application in effective transfer of passengers in buildings of relatively few floors. This is especially true where the number of users is rather constant in flow, whether small or large.

(*f*) It is often indicated that a combination of escalators and elevators provides not only the best service but also the most satisfactory service in first cost, and in the cost of operation and maintenance.

In the analysis of all transportation problems, the time elements in seconds are of great importance. Elevator problems have emphasized this, as in Art. 14, Chapter 29. The time analysis for escalators is extremely simple since the rates of travel are specifically given for the standard sizes, rises, and speed. Standard speeds of escalators at this time are 90 fpm and 120 fpm. Standard sizes are 32 in. and 48 in. The vertical height from tread to tread is 8 in. The passengers per step may vary, depending upon whether adults or children are considered. In general 1 adult and 2 children or 2 adults may easily stand on the 32-in. tread; 3 adults may easily stand on a 48-in. tread.

Table I gives some characteristics and dimensional information of standard moving stairways.

Table I. Characteristics of Standard Moving Stairways

(For rises of 10 to 23 ft)

A	*B*	*C*	*D*	*E*	*F*	*G*
Step Width [1] (in.)	Passengers per Hour at 90′ per Min	Passengers per Hour at 120′ per Min	Approximate Floor Opening		Landings	
			Length	Width	Length	Width
32	5000	6,670	20 to 25′	4′ 4″	6′ 0″	4′ 4″
48	8000	10,670	20 to 25′	6′ 0″	6′ 0″	6′ 0″

[1] The steps are 16 in. deep and the vertical distance between step levels is 8 in.

7. Structural design and installation data. The architect and his engineers must design the floor openings, stairway supports and other structural work, and finishes. A typical moving stairway drawing, arranged for the information of the architect and the trained stairway erectors is shown in Fig. 7. A careful review of all the details shown on these plans and indicated specifications picture the coordination necessary between the architect, engineer, and erection superintendent.

Outlined on these plans are the details for which the architect-engineers are responsible, including structural, mechanical, and electrical features. It will be seen that two "working points" are identified, between which a very strong steel wire is tightly stretched. From these two points all other measurements are made: to locate the center line of the truss sections; to place the lower and upper landing truss support beams, etc. Such plans as this one (Fig. 7*A*) are available from all escalator manufacturers for any standard type of stairway.

8. Cost data on escalators. The cost of an escalator includes the cost of the associated mechanical and electrical equipment plus the shipping installation charges. The manufacturer provides expert engineering and a union field erector who supervises the installation which is done by unionized elevator and escalator mechanics.

The 32-in. and the 48-in. electric stairways are considered standard production models. These may be furnished from a 10-ft rise to a

23-ft rise, operating at 90 fpm or 120 fpm. On special orders other rises and speeds may be obtained.

Approximate costs of escalators for various rises in feet are shown in Fig. 8. These are average figures for machines furnished and installed at various distances from the factories and under varied local union wage rates. The installation work furnished with the machine is mentioned in the specifications and dimensional information shown in Fig. *7B*.

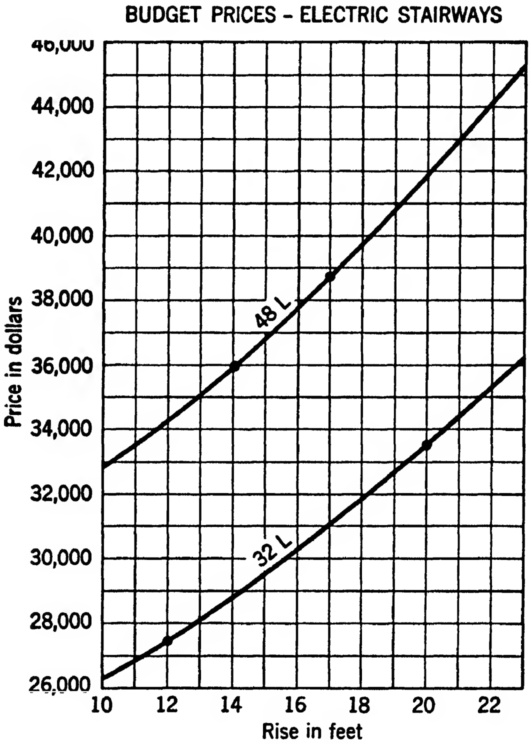


Fig. 8. Price curves for 32L and 48L electric stairways.

In reference to Fig. 8, the curves show the following costs for a single stairway, erected:

Size (in.)	Rise (ft)	Cost per Stairway	Size (in.)	Rise (ft)	Cost per Stairway
32	12	$27,000	32	20	$33,550
48	14	$36,000	48	17	$38,800

A general average rule-of-thumb for quick estimating of costs for a 32-in. electric stairway, installed, is $26,000 for the first 10 ft of rise and $750 for each additional foot; the corresponding figure for a 48-in. stairway is $32,000 and $1000 for each additional foot. It is especially important that the assistance of experts in vertical transportation be employed in the engineering analysis, specifications, installation, and costs involved on all projects.

NEC CODE AND SUPPLEMENTARY TEXT REFERENCES

Appendix A NEC Items: A58, A10.
Appendix B Text Items: B12. B13, B11.

PROBLEMS

1. A 32 in. escalator operates with a vertical lift of 20 ft and standard speed of 90 ft per minute. What is its maximum passenger capacity (*a*) per minute, (*b*) per hour, (*c*) per 8-hr day.

2. For the escalator of Problem 1, (*a*) what are the approximate dimensions of the floor opening at the upper level, (*b*) the dimensions of the floor opening at the lower level. Refer to Fig. 7, Art. 7.

3. For a nominal 32-in. electric stairway what is (*a*) the width from center-to-center of the hand rails, (*b*) the riser height from step to step, (*c*) the width of the tread?

4. State the safe average number of adult passengers per tread carried by escalators of widths (*a*) 23 in., (*b*) 32 in., (*c*) 36 in., (*d*) 48 in. In general what adjustment of tread loading and total number of people delivered would result if about one-third of the passengers were children (6 to 10 yr) for stairway widths of (*a'*) 24 in., (*b'*) 32 in., (*c'*) 36 in., (*d'*) 48 in.? Assume average adult weight at 150 lb and children at 75 lb. (Answers may vary, depending upon your analysis.)

5. A 10-story store (1st to 10th floors) is assumed to have 200 adult shoppers per floor at a given closing period. The 48-in. moving stairways are arranged in crisscross close-parallel design from top to bottom floors. How long will it take for *all* shoppers to reach the first floor? Assume that the average loading time (on and off) is 1.0 sec, and unloading time 1 sec, walking to next "down" stairway 13 sec. The distance between all floor levels is 15 ft.

6. By actual tests, determine the time in seconds for people (*a*) to step on and (*b*) to step off escalators. For (*a*) and (*b*) state the type of service rendered by the escalator. For example, do most of the passengers regularly get on and off at about the same time, as a morning crowd of workers from incoming subway trains, etc.?

SECTION VI · ACOUSTICS

Chapter 31

ACOUSTICS OF BUILDINGS

Acoustical treatment of buildings is needed where there is an excess of objectionable noise, which interferes with the functions of the occupants. Noise may be variously defined as sounds which prove to the auditor to be objectionable, annoying, physically distressing, etc. Loudness and discordant frequency characteristics may contribute to unwanted sounds. The sources of such disagreeable sounds may be in adjacent rooms or areas, these sounds being transmissible through walls, lobbies, or corridors throughout the building. Acoustical treatment is applied to reduce the disagreeable sounds. If the treatment is overdone, a deadening effect is produced which is almost as objectionable as the noise. It is therefore necessary to analyze the space and conditions which exist or are under design and then to solve the acoustical problem.

Acoustical treatments and results may be exactly right for one type of occupancy and equally wrong for another:

(*a*) Classrooms, auditoria, theaters, and music halls are places demanding proper acoustical design.

(*b*) Restaurants may be made more comfortable by such treatment, but the proprietor may lose profit by having encouraged customers to linger to enjoy the atmosphere.

(*c*) Wherever a group of typewriters and/or other business machines is in operation the noise must be radically reduced to insure high morale and efficiency of the working force. Acoustical materials may be used effectively.

(*d*) A separately built home needs little special sound-absorbing material. Interior furnishings usually provide sufficient sound absorption.

(*e*) Hospital bedrooms should be well insulated from the noises of kitchens, toilets, elevators, etc. Acoustical treatment of surgical wards and operating rooms must be accomplished with nonabsorbent insulating materials. Contamination may be carried by air currents or aspirators. Thin solid-sheet metal coverings with enclosed nonabsorbent acoustical materials should be used.

(*f*) In large apartments or flats sound insulation may be necessary, especially in long corridors, soffits of stairways, and combined stairway and fire-escape towers.

(*g*) Industrial areas are frequently soundproofed by appropriate sound-absorbing and sound-insulating materials, especially when executive and clerical rooms are near-by. It may be necessary also to add sound-absorbing material in these latter spaces.

(*h*) Department stores have such varied merchandising problems that acoustical treatment likewise covers a wide range: special rooms prepared for listening to radio and television programs or for reproduction of phonograph records; small assembly rooms for customer programs, such as fashion shows; noises from the toy department must be eliminated from certain adjacent merchandising areas, etc.

1. Origin and propagation of sound. Before discussing the practical acoustical problems in buildings, it is desirable first to get some general idea of what sound is and how it acts. Sound originates in a vibration of some sort—the buzz of a bee's wings, the pulsation of the air columns in a cornet, the agitation of violin strings, the human voice, etc. These vibrations set up compressions and rarefactions in the surrounding air. As a rather artificial example, imagine that the air pressure inside a rubber balloon is regularly increased and diminished through the pipe *P*, Fig. 1. As the pressure increases, the balloon expands, and the resulting compression of the air around the balloon is propagated out in spheres with the balloon as the center. In the same way, the diminished pressure sets up a slight collapse of the balloon, resulting in a rarefaction on the outside air which follows the compression. A regular series of these compressions and rarefactions constitutes a train of sound waves. Each particle of air in the path of the waves is vibrated back and forth—quivered—with a regular simple harmonic motion, the average motion being very small, only about $^1/_{2500}$ of an inch. On entering the ear, these waves push and pull on the eardrum, setting the hearing mechanism into vibration; the vibrations enter the inner ear and stimulate the nerve endings, causing nerve impulses which travel to the brain and elicit the sensation of hearing. Sound waves travel much faster than is commonly supposed, going about as fast in air as a rifle bullet, 1120 ft per sec at 60°F. The velocity depends on the elasticity and density of the medium, being greater in water and steel than in air: 4400 ft per sec in water, and 17,000 ft per sec in steel.

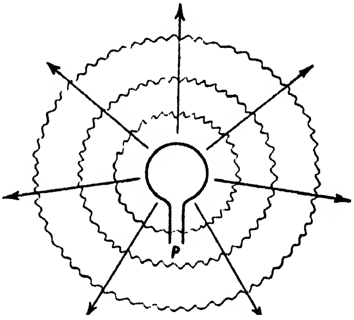


Fig. 1. Sound waves created when the pressure of air in the rubber balloon is regularly increased and diminished. (After Saunders.)

2. Characteristics of sound. Acoustical treatment in buildings is made for the comfort of the occupants. To be effective these changes should take into account the phenomena of hearing as well as the objective phenomena of sound. The three fundamental subjective characteristics of sound are loudness, pitch, and quality. Loudness is a measure of the magnitude of the sound; it is related primarily to the intensity or rate of flow of sound energy per second, but secondarily to the frequency and the tone structure. The pitch is a measure of the highness or lowness of the sound; it is related primarily to the frequency (the number of vibrations per second), but secondarily to the intensity and tone structure. The quality is self-explanatory; it depends on the relative intensity and frequency of the components of sound, and, for example, distinguishes the differences in the sounds of a piano and a violin.

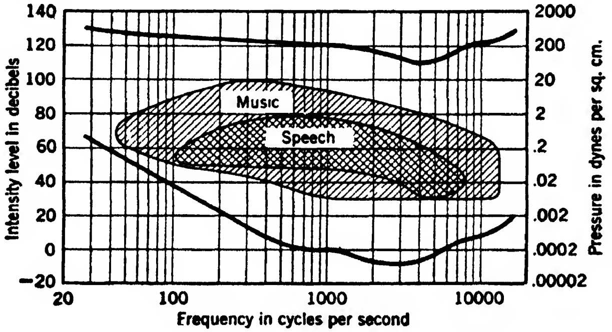


Fig. 2. Diagram showing the sounds that can be heard by the human ear. (From *Bell Laboratories Record*, June, 1932.)

Figure 2 pictures the sounds that can be perceived by the human ear. The lower curve indicates the threshold of hearing, that is, the faintest sounds at various frequencies that can be heard by persons with normal hearing; the upper curve gives values of the loudest sounds that the ear can endure. The maximum separation of these curves is approximately 120 decibels (units explained later) and occurs in the region of 1000 cycles. The shaded portions show the frequency and intensity ranges of speech and music in relation to the total range of audible sounds for the normal-hearing ear. The hard-of-hearing ear does not have as great a range, the amount and kind of limitation depending on the type and extent of the impairment.

3. The decibel scale of intensities. The range of sound pressures as indicated on the curves of Fig. 2 is from about 2×10^{-4} dynes per sq cm to about 10^6 times as great. If any value of sound pressure in this range is selected as the unit for measurement, then, to indicate all pressures of interest, either exceedingly large or exceedingly small numbers will be involved.

Any device which will enable one to work with numbers not too far from unity will be greatly welcomed. If, instead of the sound pressures, their logarithms are used, the range of interest will be from log 1 to log 10^6 or from 0 to 6. The decibel scale described below causes a compression of the range similar to this, but not so severe.

Table 1 gives the intensity, or relative energy, and the decibels above this zero level for various typical sounds.

Table I. Intensities of Common Sounds with the Corresponding Decibel Values

(After Waterfall)

(A)	(B)	(C)
Intensity—Amount of Energy in the Sound	Decibels	Type of Noise
1,000,000,000,000	120	
100,000,000,000	110	Airplane engine
10,000,000,000	100	
1,000,000,000	90	Heavy traffic, pneumatic drill
100,000,000	80	
10,000,000	70	Noisy office, telephone conversation, ordinary traffic
1,000,000	60	
100,000	50	Average office
10,000	40	Ordinary conversation
1,000	30	Quiet home, quiet conversation
100	20	" " " "
10	10	Rustle of leaves, whisper
1	0	Inaudible

If two values of acoustical power w_2 and w_1 are to be compared, the power w_2 is x decibels above the power w_1 where x is given by the formula

$$x = 10 \log_{10} \frac{w_2}{w_1}$$

If w_2 is less than w_1, then x will be negative and the same formula still applies, the negative signs changing the sense from "above" to "below."

If the elements in which the powers w_2 and w_1 appear are of the same impedance, then the powers will be proportional to the squares of the sound pressures P. In this case the decibels can be determined from the equation:

$$x = 10 \log_{10} \frac{w_2}{w_1} = 10 \log_{10} \frac{P_2^2}{P_1^2} = 20 \log_{10} \frac{P_2}{P_1}$$

This concept can be used directly to describe the gain in an amplifier, and the efficiency of a microphone or loud-speaker. In discussing the effectiveness of soundproofing materials, the transmission loss is expressed in decibels.

Although the decibel originally is defined to compare two quantities (by using their ratio), it can be used to indicate a pressure or voltage, etc., if a zero level is first agreed upon. This zero level, of course, must not itself be zero.

If the pressure of 2×10^{-4} dynes per sq cm is selected as zero level, then any pressure P will exceed zero level by

$$x = 20 \log_{10} \frac{P}{2 \times 10^{-4}} \text{ decibels}$$

Note that a change of 3 decibels doubles or halves the power for

$$\text{db} = 10 \log_{10} \frac{2w}{w} = 10 \log_{10} 2 = 3.01$$

and likewise a change of 6 decibels doubles or halves the pressure, as

$$\text{db} = 20 \log_{10} \frac{2p}{p} = 20 \log_{10} 2 = 6.02$$

Generally any sound with level greater than 70 db (decibels) is objectionable. It may be shown that a reduction of 9 db in the intensity level of a sound makes it seem approximately half as loud. The human ear accepts the decibel scale as a natural scale; that is, a constant decibel increment can be judged much more readily than an increment of say 2 dynes per sq cm.

4. Types of acoustical problems. The practical acoustical problems encountered in buildings and the analysis required for their solution are the following:

A. The control of sound in rooms.
  - *a.* A study of the *shape* to control echoes and to secure the best distribution of sound.
  - *b.* An estimation of the amount of *sound-absorbing material* needed to cause sound to die out in the optimal reverberation time and a consideration of the conditions of the room to determine where the material should be placed for the best effect.

B. The insulation of sound. A survey of information about the *sound-insulating* values of walls, partitions, doors, and windows, and a study of ventilating systems, to provide a basis for reduction of the transfer of sound from one room to another.

C. The isolation of machines. An analysis of how to reduce machine disturbances and to isolate them from the building structure.

5. Shape of room. The acoustical adjustment of a room involves a study of the size and shape of the room, a calculation of the amount of sound-absorbing material required and a decision about where it should be installed. In small rooms, such as offices, the chief consideration is reduction of noise, which is brought about by the introduction of a suitable amount of absorbing material; but, with large rooms, the problem is more complicated, as will appear presently. If the room has concave walls, the reflected sound will be focused by them so as to produce undesirable echoes or concentrations. If the reflected sound reaches an auditor about $\frac{1}{15}$ sec or more later than the direct sound, an echo will be perceived. This means that the difference in path between the direct and reflected sound will be about 75 ft, since sound will travel that distance in $\frac{1}{15}$ sec. Figure 3 presents a diagram indicating what may happen with concave walls. Figure 4 illustrates how convex sections in a concave wall will diverge sound and reduce focusing.

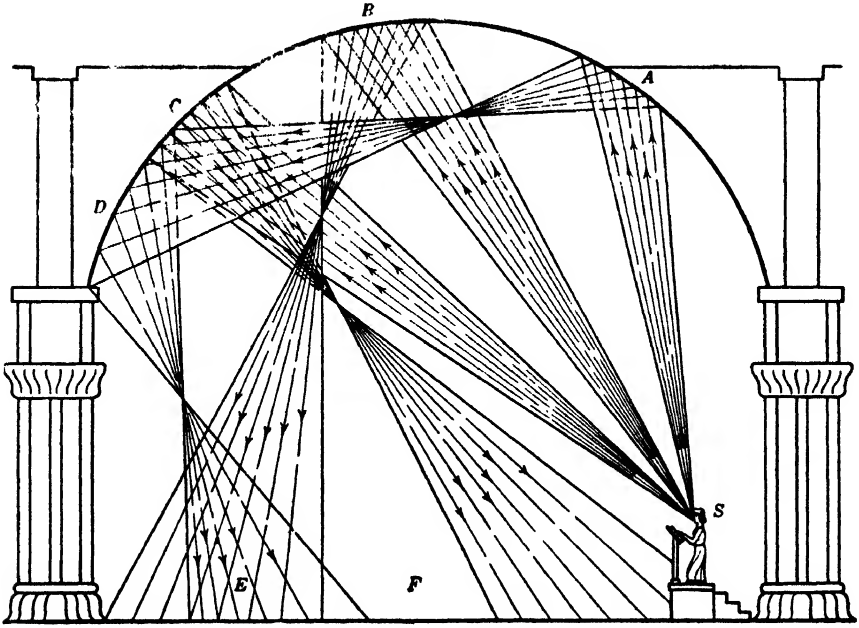


Fig. 3. Diagram showing objectionable reflection and concentration of sound by a dome surface. (From Watson's *Acoustics of Buildings.*)

Various other arrangements may be employed to minimize objectionable reflections and thereby increase diffusion. Strips of absorbing

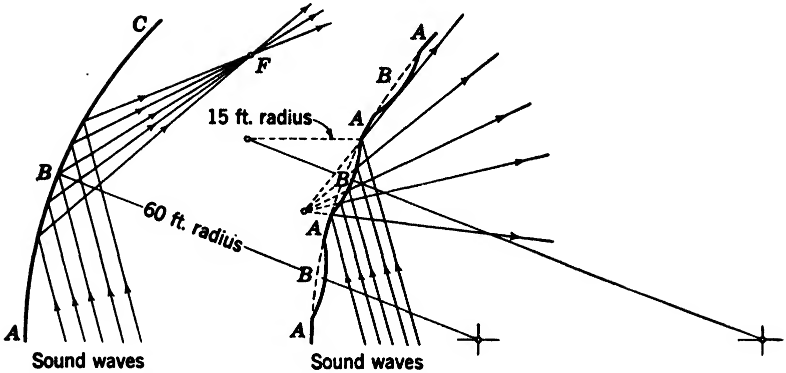


Fig. 4. Convex segments in a wall break regular reflections and focusing. (From Watson's *Acoustics of Buildings.*)

material on the walls tend to disturb regular reflections of sound. Practically no sound at all is reflected from organ grilles or ventilation openings. A combination of these devices is frequently used to increase diffusion. Figure 5 shows an example of sound control utilizing convex surfaces and strips of absorbing material.

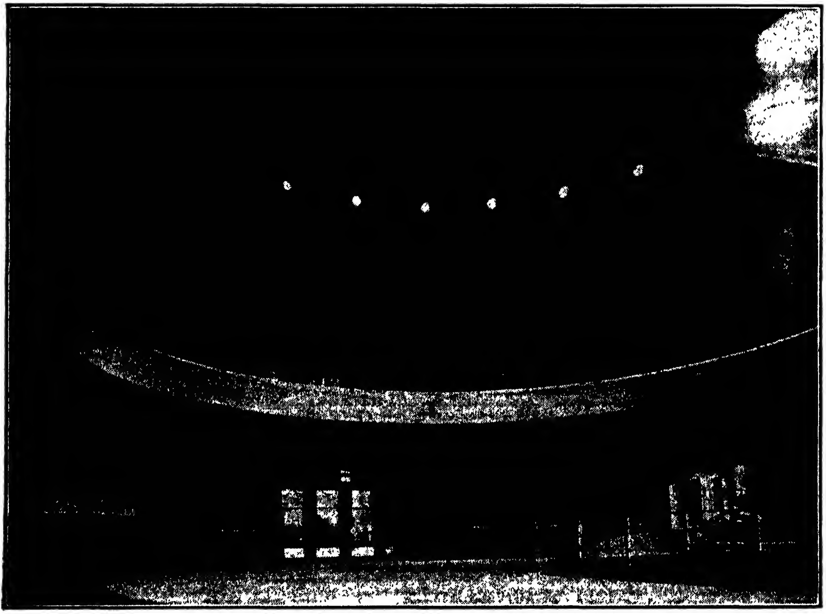


Fig. 5. Voder Room, New York World's Fair. Acoustically adjusted by convex walls with suitable absorbing materials. (Photograph by John Mills. Potwin and Maxfield, *J. Acous. Soc. Amer.*, Vol. 11, p. 48, 1939.)

$$as = 0.05 \times \frac{80{,}800}{1.3} = 3100 \text{ units}$$

Since the room with an average audience of 200 people has 1364 units, the absorption to be added is thus 3100 − 1364 = 1736 units. The times of reverberation with the 1736 units added are as in Table III.

Table III. Times of Reverberation for a Corrected Room

t (sec)	Audience
$0.05 \times 80{,}800/2300 = 1.8$	None
$0.05 \times 80{,}800/3100 = 1.3$	200 (optimum)
$0.05 \times 80{,}800/3900 = 1.0$	400
$0.05 \times 80{,}800/4500 = 0.90$	550 (capacity)

Figure 7 gives a graphical picture of the results for both the uncorrected and the corrected room, showing that the room when corrected is practically independent of the audience.

The efficiency of the material used to treat a room is affected by its location. Generally the absorptive material should be distributed over the surfaces rather than concentrated. Part of the material should go on the room ends (or one side), and part on the floor and/or ceiling.

Material placed near the edge where the ceiling meets a wall is about twice as effective as material near the center of a wall. Material placed in the corner of the ceiling is about three times as effective as material near the center of a wall. Considerable saving can be achieved by careful positioning of the acoustic material. This procedure may influence the decorative and lighting problems, and all three should be coordinated during the design period.

8. Public-address system. A very important development in the acoustics of rooms has been brought about by the use of sound-amplifying systems. Such a system consists of a microphone that picks up the sound and converts it into an alternating electric current, an amplifying system that amplifies and controls the current, and a loud-speaker system that converts the amplified electric currents back into sound much louder than the original sound entering the microphone. It is necessary to design and arrange the system so that it coordinates with the speaker's voice to give as uniform distribution of sound as possible throughout the audience. Auditors in the rear seats should get as much sound as the auditors near the stage; the sound level should be adjusted to approximately 60 db in all parts of the room.

These sound-amplifying systems introduce new problems in the acoustic adjustment of auditoriums. Although the larger part of the sound from the loud-speakers strikes the area of seats occupied by the audience where it is absorbed by the clothing and seats, it is necessary to make drastic reduction of the reflection from the rear walls if echoes and other concentrations are to be avoided. This control is approximated by breaking the rear wall by convex segments, strips of effective absorbing materials, grilles, etc.

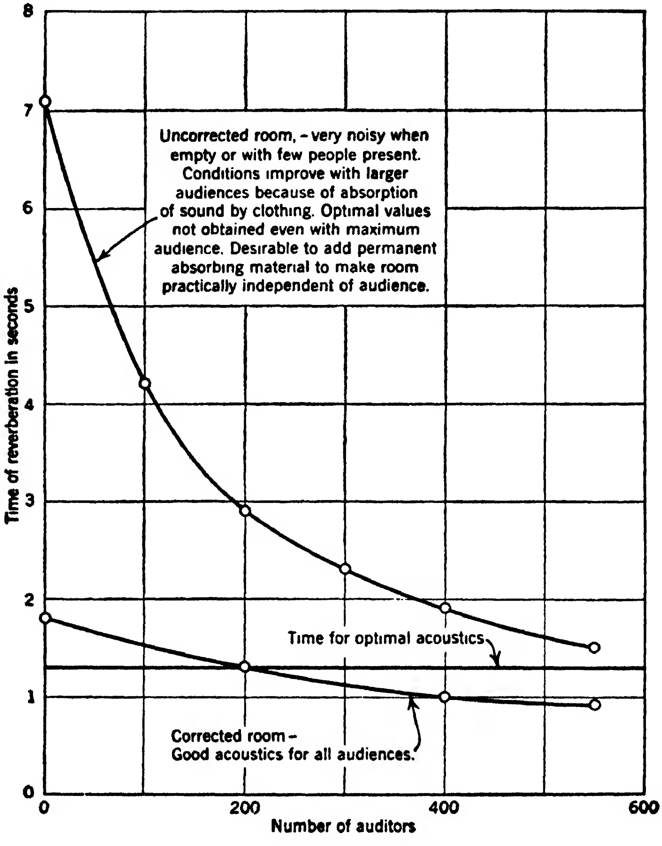


Fig. 7. Graphical representation of the absorbing effect of an audience in an auditorium before and after correction. Note that the corrected room is practically independent of the audience. (From Watson's *Acoustics of Buildings.*)

9. Broadcasting rooms. In order to produce a realistic effect the echoes in a broadcasting studio must be carefully controlled. If the program is intended to suggest a large hall, cathedral, etc., echoes must be added to the program with the proper time delay. The natural echoes of a small studio may be inappropriate. In this case the studio itself must be deadened. Padding the room heavily with absorbing materials reduces the reflection, but it may make the room too dead for the performer to speak or to sing easily. All normal people are accustomed to some echo and feel very uncomfortable talking or singing in a room that is too dead.

Various compromises have been made to get the best results. Plywood bent into the shape of half cylinders and attached to the walls with an air space enclosed diverges the reflected sound and reduces the annoying resonances set up by reflections between parallel walls.[2] Nonparallel walls have been used, but these do not seem as effective as the convex cylinders. Another device to increase the liveness of sound is "shutters" of absorbing material that are installed so that they can be turned when desired so as to present highly reflecting surfaces. Reflecting screens are also useful in adjusting the acoustic conditions.

10. Treatment of small rooms. The largest amount of acoustical correction in buildings is made in offices. The problem here is noise reduction rather than control of reverberation. Sound-absorbing materials installed on the walls and ceiling bring about a number of improvements: the noise is reduced; the time of reverberation is decreased; certain high frequency sounds that annoy people are absorbed more or less, thus creating a "comfort" factor.

As a result of these improvements, the occupants of the corrected offices find the conditions congenial; they work with less nerve strain and with greater efficiency.

11. Sound-absorbing materials. The absorption of sound is a vital consideration in securing good acoustics. Irregularities in the shape of the walls, columns, coffering, and similar devices break up the regular reflection and make the sound more diffuse, but absorption must take place to remove the sound energy from the room. Any device which removes sound energy from a room is an absorber. An open window which reflects none of the incident sound is taken as having an absorption of 100 per cent. Other absorbers act by converting some of the sound energy into heat. If a wall is porous, sound enters the pores and loses considerable energy in friction in the narrow channels. The absorption may be as much as 90 per cent or more, depending on the nature of the material and the frequency of the sound. Figure 8 shows data for a typical absorbing material, indicating that the amount of absorption is less at the low than at the high frequencies. Thicker materials absorb more than thin ones, but the increase in absorption is not in proportion to the thickness. An audience is a very efficient absorber of sound because of the clothing worn. Absorption at low frequencies has been obtained by thin vibrating panels backed by an air space, as, for example, the convex plywood panels mentioned earlier.

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[2] Volkmann, "Polycylindrical Diffusers in Room Acoustic Design," *J. Acous. Soc. Am.*, 13:234, 1942. Boner, "Performance of Broadcast Studios Designed with Convex Surfaces of Plywood," *J. Acous. Soc Am.*, 13:244, 1942.

Figure 9 shows a number of types of materials chosen from manufacturers' technical bulletins.[8] Table IV gives absorbing coefficients for materials in common use. Inspection of Table V shows that

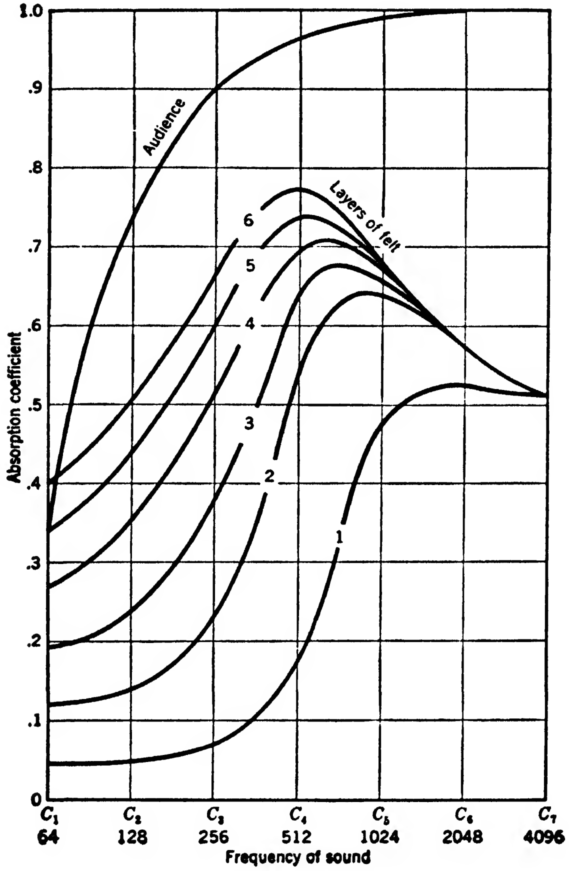
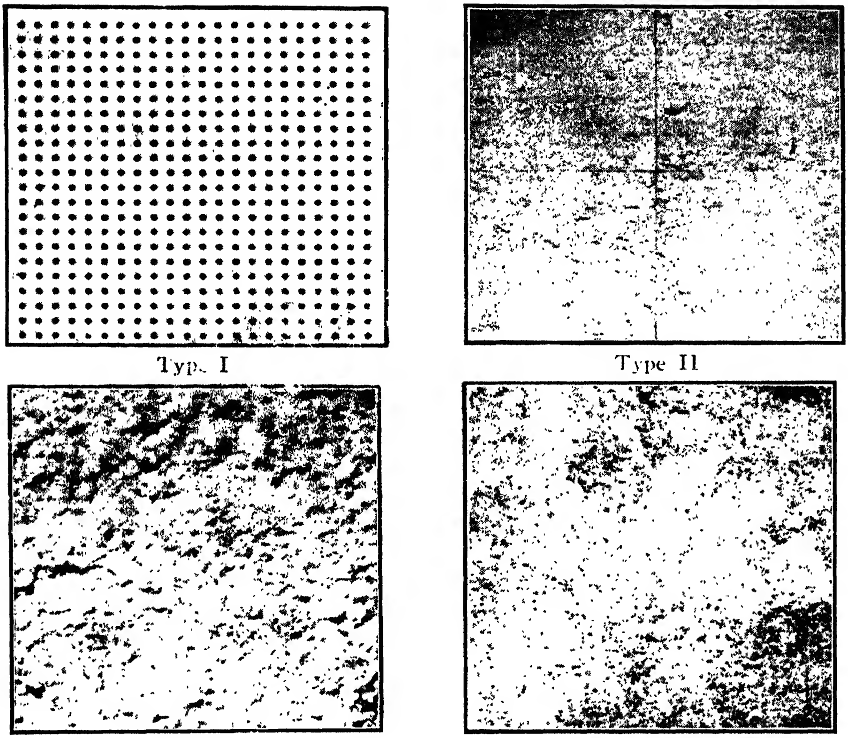


Fig. 8. Graph showing how the sound-absorbing efficiency of a material depends on the frequency of the incident sound and on the thickness of the material. An audience is an efficient absorber because of the clothing worn. (W. C. Sabine.)

coefficients are given for three frequencies—128, 512, and 2048 cycles per sec. These data are useful for calculations for some rooms where the control of sound is necessary for a wide range of frequencies, as, for example, in broadcasting rooms.

[8] It is suggested that the reader should apply to the Acoustical Society of America for a list of its members who are manufacturers of most of the acoustical materials. The association and representative manufacturers have a number of technical bulletins quite thoroughly covering specific acoustical characteristics and methods of installation.



Type I

Type II

Type III

Type IV

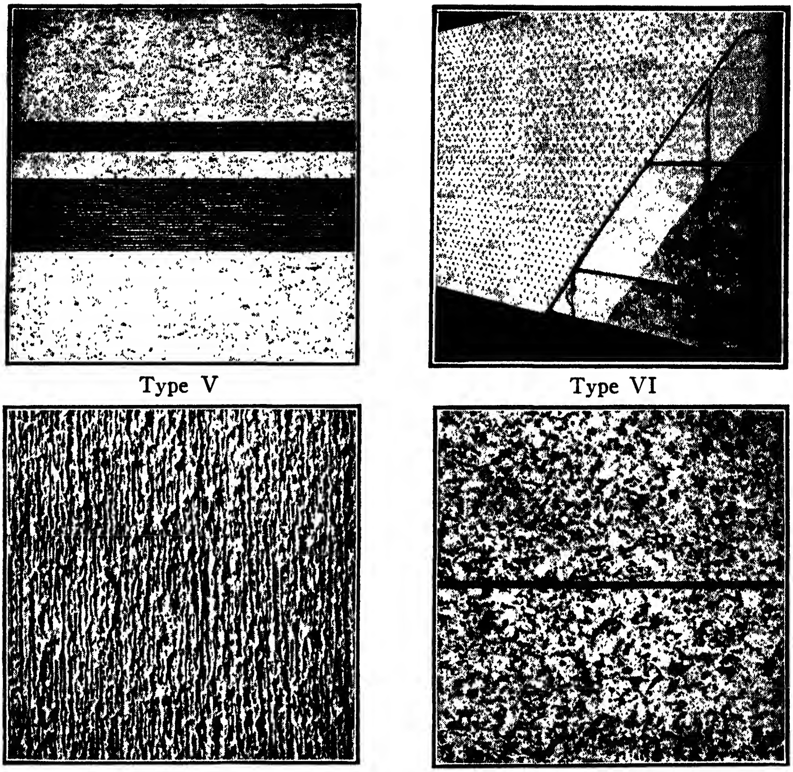
Type I. Rigid wood-fiber or glass-fiber tile with 482 per sq ft drilled holes. Surface factory finished with white fire-resistant paint. Additional brush painting does not reduce sound absorption. Painted wood-fiber tiles usually classified as slow-burning. Not recommended where excessive moisture is present. Deeper holes provide increasing absorption with greater tile depth. (Certain-Teed Products Corp., Simpson Logging Co., Wood Fibre Division, National Gypsum Co., Armstrong Cork Co.)

Type II. Mineral wool tile with a fissured surface resembling travertine marble. Finished with travertine white tesin-emulsion paint. May be brush or spray repainted without loss of sound absorption. Incombustible. Not recommended where exposed to steam or constant high humidity or where it will be subjected to impact or abrasion. (National Gypsum Co., Armstrong Cork Co., United States Gypsum Co.)

Type III. Mineral fibers mixed with binder and sprayed on ceiling surfaces with air gun or blower to any desired thickness. Surface to which it is applied is prepared with a coating of asphalt emulsion. Can be painted without destroying acoustical properties. Incombustible and rotproof. Also acts as a thermal insulating material. Surface is likely to be broken if placed within reach of people. (National Gypsum Co.)

Type IV. Inorganic "Fiberglas" fiber tile with textured surface. May be spray-painted with water base paint without affecting acoustical properties. Incombustible. Moisture resistant. (Certain-Teed Products Corp.)

Fig. 9. Sound-absorbing materials.



Type V

Type VI

Type VII

Type VIII

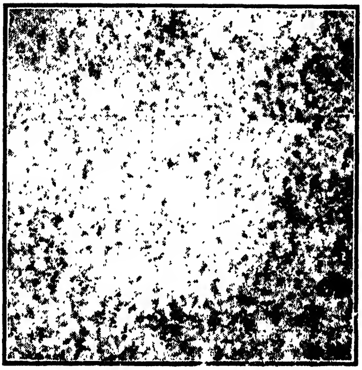
Type V. Same material as Type II above except embossed with a series of grooves. Tiles may be arranged in various combinations for decorative effect. (Armstrong Cork Co.)

Type VI. Perforated metal pan containing a sound-absorbing mineral wool pad. Metal surface is finished with baked-on white enamel. May be washed or repainted without loss of acoustical efficiency. Incombustible. High mechanical strength. Space is maintained between pad and surface of pan for better sound absorption. 1105 holes per square foot is standard spacing. (National Gypsum Co., Armstrong Cork Co., Detroit Steel Products Co. (Fenestra).)

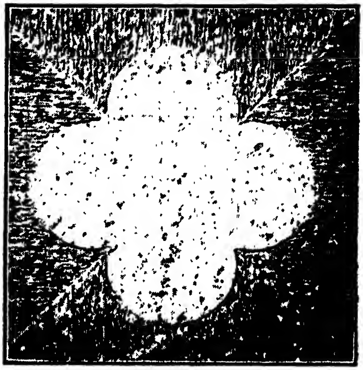
Type VII. Same material and physical characteristics as Type II except that surface is "etched" producing a shade contrast due to the heavier shadows. Decorative effects may be produced by designs etched into individual tiles or merely by the arrangement of light and dark shades of tiles. Produces small loss in light reflection efficiency. (United States Gypsum Co.)

Type VIII. Fissured cork acoustical tile. Painted with white resin-emulsion paint. Slow burning. Recommended for use where problems of excess moisture and high humidity exist. Good thermal insulating properties. Made from cork particles baked under heat and pressure. May be bent slightly to fit curved surfaces. (Armstrong Cork Co.)

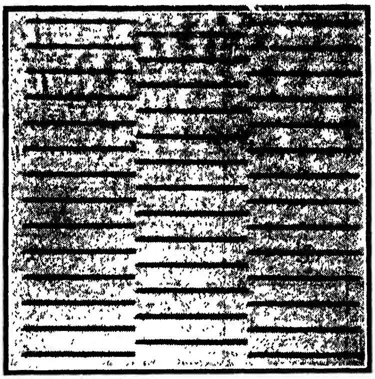
Fig. 9 (Continued)



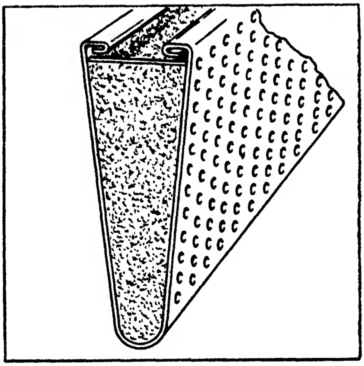
Type IX



Type X



Type XI



Type XII

Type IX. Wood-fiber tile. Factory-coated with white paint. May be spray-painted with a light coat of casein or oil paint but brush painting is not recommended. Combustible. Made from finely shredded fibers of southern woods. (National Gypsum Co., Armstrong Cork Co., Certain-Teed Products Corp.)

Type X. Mineral wool tile with a fissured surface resembling travertine marble. Finished with travertine white resin-emulsion paint. May be brush- or spray-repainted without loss of sound absorption. Incombustible. Not recommended where exposed to steam or constant high humidity or where it will be subjected to impact or abrasion. It is embossed with clover-leaf or other special designs. Tiles may be arranged in various combinations for decorative effect. (United States Gypsum Co.)

Type XI. Slotted wood-fiber tile. Factory-painted with white paint. May be brush- or spray-painted with oil or resin-emulsion paint. Combustible. Not recommended where it will be exposed to steam or high humidity or where it will be subjected to impact or abrasion. Slotted surface gives possibility of various design effects. (United States Gypsum Co.)

Type XII. Perforated wedge-shaped metal baffle filled with inorganic fiber. Used in connection with luminous ceilings. Run length of ceiling at spaced intervals. White baked-on enamel finish. Incombustible. (Wakefield Brass Co.)

Fig. 9 (Continued)

Table IV. Respective Types of Acoustical Materials in Fig. 9 and Fig. 10

Type No.	Standard Thickness (in.)	Noise Reduction Coefficient		Light Reflection Coefficient
		Cemented to Plaster	Nailed to Furring	
I	½	0.55	0.60	0.78
	¾	0.65	0.70	
	1	0.70	0.75	
II	¹¹⁄₁₆	0.65		0.80
	¹³⁄₁₆	0.65		
III	½		0.80 *	
	¾		0.85 *	
IV	¾	0.65	0.80	0.75
	1	0.75	0.85	
V	¹¹⁄₁₆	0.65		0.80
	¹³⁄₁₆	0.65		
VI	1⅜		0.85 †	0.76
VII	¹¹⁄₁₆	0.65		0.78
	¹³⁄₁₆	0.65		
VIII	1½	0.45	0.45	0.80
IX	½	0.55		0.77
X	¹¹⁄₁₆	0.65		0.78
	¹³⁄₁₆	0.65		
XI	¾	0.65	0.65	0.78
	1	0.70	0.70	
XII			0.30 †	

* On metal lath, with air space behind lath.

† Mechanically supported.

Table V. Coefficients of Absorption for Common Materials *

Material		Coefficients	
Frequency (cps):	128	512	2048
Brick wall, painted	0.012	0.017	0.023
unpainted	0.024	0.03	0.049
Carpet, unlined	0.09	0.20	0.27
felt lined	0.11	0.37	0.27
Fabrics, hung straight			
light, 10 oz per sq yd	0.04	0.11	0.30
medium, 14 oz per sq yd	0.06	0.13	0.40
heavy, draped, 18 oz per sq yd	0.10	0.50	0.82
Floors			
concrete or terrazzo	0.01	0.015	0.02
wood	0.05	0.03	0.03
linoleum, asphalt, rubber or cork tile on concrete		0.03–0.08	
Glass	0.035	0.027	0.02
Marble or glazed tile	0.01	0.01	0.015
Openings			
stage, depending on furnishings		0.25–0.75	
deep balcony, upholstered seats		0.50–1.00	
grilles, ventilating		0.15–0.50	
Plaster, gypsum or lime, smooth finish on tile or brick	0.013	0.025	0.04
same on lath	0.02	0.03	0.04
Plaster, gypsum or lime, rough finish on lath	0.039	0.06	0.054
Wood paneling	0.08	0.06	0.06
Absorption of Seats and Audience			
Audience, seated, units per person, depending on type of seats, etc.	1.0-2.0	3.0–4.3	3.5–6.0
Chairs, metal or wood	0.15	0.17	0.20
Pew cushions	0.75-1.1	1.45-1.90	1.4–1.7
Theater and auditorium chairs			
wood veneer seat and back		0.25	
upholstered in leatherette		1.6	
heavily upholstered in plush or mohair		2.6–3.0	
Wood pews		0.40	

* From Watson's *Acoustics of Buildings.*

12. Transmission of sound from room to room. An important requirement in securing good acoustics in buildings is to control the transfer of sound from one room to another. A grave source of confusion and difficulty in this field results from the fact that the material placed on a wall to reduce the echoes in a room may do so by increasing the transmission through the wall. Similarly a solid steel wall is quite soundproof, but it is an excellent reflector. The problem of reduction of either echoes or transmission is fairly simple, but when both corrective effects are required the problem becomes much more difficult.

Transmission takes place most easily through air passages, as evidenced by the effectiveness of speaking tubes. Sound is also transmitted by partitions or other solid constructions. Sound waves on one side push and pull on the partition, causing it to vibrate and set up waves on the farther side. Two types of sound transmission should be considered in the problem of insulation. For example, suppose that a person walks across a wood floor and talks at the same time. The sound of his voice reaches the walls through the air, and the resulting vibration of the wall may be sufficient to enable the sound to be heard in the next room. On the other hand the impact of his heels vibrates the floor directly and the sound is therefore much more efficiently transmitted to neighboring rooms. A similar situation occurs when a singer is accompanied by a piano. The piano legs provide an efficient sound path to the frame of the building. For these reasons the noise of a motor bolted to the floor is much more difficult to isolate than that of a motor on a resilient support.

Unless air passages, such as ventilation ducts, are arranged to reduce sound, it is useless to consider making the walls soundproof. Sound may be absorbed in ducts by lining the ducts with sound-absorbing material, which should be fireproof to avoid costly fires. Sound traps are sometimes needed for wide ducts. These consist of parallel sheets of sound-absorbing material that cause the sound to pass in the narrow channels between the sheets where the absorption takes place. Doors and windows are not so effective in stopping sound as partitions, partly because they do not close tightly and sound escapes through the cracks, and partly because they are thinner than partitions and thus vibrate more easily. Double windows transmit less sound than single ones; the air space between windows should be 4 in. or more to be effective.

Table VI presents insulation data for a few typical constructions.[4] Doors and windows have insulating values of 20–30 db, depending on the type and tightness of closing; partitions have from 30 to 50 db, depending on the construction. A reduction of 9 db will make the sound appear approximately one-half as loud.

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[4] Knudsen, "Architectural Acoustics," *National Bureau of Standards, Report BMS 17,* "Sound Insulation of Wall and Floor Constructions"; also *Supplement to Report BMS 17* (for sale by the Superintendent of Documents, Washington, D. C.

Table VI. Sound-Insulation Data *

Floor and Ceiling Partitions

Description of Panel	Weight in Pounds per Square Foot	Reduction Factors in Decibels					Authority	Probable Average Value of Transmission Loss in Decibels	Probable Average Value of Transmissivity
		128	256	512	1024	2048			
		Cycles per Second							
Airplane fabric, doped and varnished	0.055	.	3.6	3.0	5.9	10.1	Bureau of Standards	..	....
Fiber board 0.5 in. thick	0.75	...	15.5	19.0	29.0	...	Davis and Littler	19	0.013
Hairfelt, 0.58 in	[illegible]	...	6.7	6.1	6.3	....	"	..	....
Birch veneer door, light, four panel	...	13.0	16.1	20.4	22.8	22.0	P. E. Sabine	22	0.0063
Oak, solid, 1¾ in., with cracks as ordinarily hung	..	11.5	15.1	20.4	22.0	16.2	"	20	0.01
Steel, solid ¼ in.	...	25.1	26.7	31.1	36.4	31.5	"	35	0.00032
Glass, ⅛ in., 12 panels	...	16.9	18.3	21.5	25.8	23.6	"	25	0.0032
Brick panel, Mississippi, 8 in.; plastered both sides gypsum brown coat, smooth white finish; good workmanship	0.87	....	50.2	47.6	55.5	63.5	Bureau of Standards	50	0.000010
Tile, clay, 3-cell 3 in. by 12 in. by 12 in., plastered both sides gypsum scratchcoat, very thin smooth-finish coat	......	....	39.1	....	35.7	59.3	"	41	0.000080
Wood studs, 4-paper plaster board, 3-coat smooth finish gypsum plaster	.....	....	52.1	....	52.3	57.0	"	50	0.000010
Wood studs, metal lath, scratch and brown coats plaster (1 part sand to 1 part gypsum wood-fibered plaster)	.....	....	43.4	....	43.7	55.0	"	44	0.000040
Concrete flat slab floor construction, reinforced. Floating floor consisting of nailing strips, rough and finish flooring. Insulite furred out and applied as ceiling	58.1	58.9	57.0	55.4	67.6	65.2	"	57	0.0000020
Tile, 3-cell partition, 4 in. by 12 in. by 12 in. Ceiling finished with furring strips, ½-in. Insulite plaster	69.8	56.5	56.6	55.8	57.7	58.8	"	53	0.0000050
Wood joists. Lower side plastered on wood lath; upper side, subflooring, and ⅜-in. finish flooring	......	47.9	46.8	40.7	50.1	48.8	"	43	0.000050

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* From Watson's *Acoustics of Buildings.*

13. Isolation of machines. The first consideration in reducing disturbance is to secure machines that run smoothly. Vibrations that are set up may be minimized before reaching the floor by mounting the machine on a heavy base resting on a resilient support such as springs, rubber, or cork. It is a mistake to assume generally that a sheet of cork under the machine will solve the problem if the machine is unbalanced or has loose parts which may vibrate. If the machine has a slow velocity of turning, or if it exerts sudden, low-frequency shocks, the insulating support may contain a combination of cork for the continuous noise and springs for the shocks that result from sudden changes in load or speed.

14. Conclusion. The condensed treatment in the preceding discussion sets forth some of the essential ideas that should be considered in securing satisfactory acoustics in buildings. Simple problems may be solved by following the suggestions given; more detailed information can be obtained from the references already noted, and from various books on acoustics.[5]

NEC CODE AND SUPPLEMENTARY TEXT REFERENCES

Appendix A NEC Items: A60, A61.
Appendix B Text Items: B9, B8, B7.

PROBLEMS

1. From Table I, show that a sound of 70 db has an energy intensity of 10,000,000 threshold units. (*a*) Such a sound has a pressure intensity of how many threshold units? (*b*) Calculate the number of decibels in a sound that has an energy intensity of 20,000 threshold units.

2. A person stands on the floor where he is at the center of the curve of a dome ceiling. Draw a diagram showing that if he claps his hands he will get a marked reinforcement of sound by reflection from the ceiling. How would you change the shape of the dome ceiling to reduce this reinforcement? What distance should there be between the dome ceiling and the person in order that he get a noticeable echo from the reflected sound?

3. Draw plan and section of a broadcasting room that will give diffuse sound.

4. (*a*) Calculate the number of absorption units in a room 30 ft by 30 ft by 15 ft high, if it has plaster walls and ceiling and a wood floor. *Ans.* 116 units. (*b*) Calculate the time of reverberation for the room in (*a*). *Ans.* 5.8 sec. (*c*) Show that 334 units of absorption must be added to the room of (*a*) to reduce the time of reverberation to 1.5 sec. (*d*) How may the 334 units be added to reduce the time of reverberation?

[5] F. R. Watson, *Acoustics of Buildings,* Wiley, 1941; Vern O. Knudsen and Cyril M. Harris, *Acoustical Designing in Architecture,* Wiley, 1950.

5. A sound of 70 db in one room is reduced 27 db in passing through a wall to an adjoining room. What type of partition will give this reduction? See Table VI. Show that the final sound will be one-eighth as loud as the original sound, assuming that a reduction of 9 db will make a sound appear about half as loud.

6. The dimensions of a classroom seating 100 persons in wood armchairs, facing the lecture platform are 30 ft by 45 ft. A lengthwise ceiling support beam is 8 in. wide and 24 in. in depth below the ceiling. The center cross beam is 22 in. by 20 in. deep. The ceiling is 14 ft high. Each of two windows (on one side of the room) are 11½ ft wide, 8½ ft high, and the window sills are 3 ft above the floor. The materials are: all inner walls of smooth plaster on tile; beams, floors, and ceiling are of painted concrete, doors of wood except glass 30 in. by 40 in. in an upper panel of each door. A slate blackboard 30 ft by 5 ft high is located along the front end of the room. Assume a lecturer stands at the center of the wooden platform (1 ft high). (*a*) and (*b*) Show crosswise and longitudinal cross sections of the room and illustrate the travel and reflections of sound waves. (*c*) Plan acoustical treatment using 1-ft-sq acoustical materials illustrated in Fig. 10, type 1. Record the type of material used, and the locations which will give effective sound control as well as good appearance. (*d*) Compare the times of reverberation for the uncorrected and corrected rooms, assuming no audience and an audience of 100 people. The source of sound is 5 ft above the geometrical center of the platform.

APPENDIX A

Articles of the National Electrical Code

Throughout Chapters 22 to 30 inclusive, in Section V of this text on Electrical Equipment, important references are made to the National Electrical Code. The electrical features covered by each article are summarized as indicated below. Specific item references to any article in the NEC are indicated in the text (at the end of Chapters 22 to 30 inclusive) by numbers A1, A2, A3, etc. The rules and regulations governing selection, installation, operation, and maintenance must be applied in all installations, except for local municipal or state variations, which may slightly change or emphasize a few of the many articles. The NEC is the basis of all state board examinations for architects and engineers.

Those who study this textbook should obtain a copy of the 1953 Code at about 20 to 25 cents, from the National Board of Fire Underwriters, 85 John Street, New York 38, N. Y., or from the local office of this organization in any large city.

The following tabulation identifies the *article* numbers and general subject matter covered by these articles. The first column *item* numbers of special application to a given chapter are given at the end of each chapter. A study of such identified articles will aid materially an understanding of safety requirements.

Items	*Articles*
A1	Contents of NEC (Page 5)
A2	Introduction to NEC (Page 9)

Chapter 1. General

Items	*Articles*	
A3	100	Definitions
A4	1101–1120	General

Chapter 2. Wiring Design and Protection

Items	*Articles*	
A5	2001–2009	Polarity Identification of Systems and Circuits
A6	2101–2127	Branch Circuits
A7	2201–2205	Feeders
A8	2301–2392	Services
A9	2401–2481	Overcurrent Protection
A10	2501–2599	Grounding
A11	2611–2632	Grounding Conductor Connections
A12	2801–2826	Lightning Arresters

Chapter 3. Wiring Methods and Materials

Items	*Articles*	
A13	3001–3020	General Requirements for Wiring Methods
A14	3101–3106	Conductors
A15	3201–3215	Open Wiring on Insulators
A16	3241–3248	Concealed Knob-and-Tube Work
A17	3281–3287	Bare-Conductor Feeders
A18	3301–3309	Mineral Insulated Metal Sheathed Cable
A19	3341–3348	Armored Cable
A20	3361–3370	Non-Metallic Sheathed Cable
A21	3381–3383	Service-Entrance Cable
A22	3391–3392	Underground Feeder and Branch Circuit Cable

Items	*Articles*	
A23	3401–3409	Non-Metallic Waterproof Wiring
A24	3421–3429	Non-Metallic Surface Extensions
A25	3441–3444	Underplaster Extensions
A26	3461–3471	Rigid Metal Conduit
A27	3481–3490	Electrical Metallic Tubing
A28	3501–3503	Flexible Metal Conduit
A29	3511–3515	Liquid-Tight Flexible Metal Conduit
A30	3521–3526	Surface Metal Raceways
A31	3531–3532	Multi-Outlet Assembly
A32	3541–3556	Underfloor Raceways
A33	3561–3570	Cellular Metal Floor Raceways
A34	3621–3630	Wireways
A35	3641–3653	Busways
A36	3701–3719	Outlet, Switch and Junction Boxes, and Fittings
A37	3731–3738	Cabinets and Cutout Boxes
A38	3741–3749	Auxiliary Gutters
A39	3801–3814	Switches
A40	3841–3886	Switchboards and Panelboards
A41	3901–3903	Prefabricated Buildings

Chapter 4. Equipment for General Use

Items	*Articles*	
A42	4001–4010	Flexible Cords
A43	4101–4216	Lighting Fixtures, Lampholders, Lamps, Receptacles and Rosettes
A44	4221–4286	Appliances
A45	4301–4439	Motors and Motor Controllers
A46	4451–4458	Generators
A47	4501–4548	Transformers and Transformer Vaultac
A48	4601–4611	Capacitors
A49	4701–4706	Resistors and Restors
A50	4801–4807	Storage Batteries

Chapter 5. Special Occupancies

Items	*Articles*	
A51	5001–5087	Hazardous Locations
A52	5101–5135	Specific Occupancies
A53	5201–5293	Theaters and Assembly Halls
A54	5301–5320	Motion Picture Studios and Similar Locations
A55	5401–5432	Motion Picture Projectors

Chapter 6. Special Equipment

Items	*Articles*	
A56	6001–6037	Signs and Outline Lighting
A57	6101–6144	Cranes and Hoists
A58	6201–6277	Elevators, Dumbwaiters, and Escalators
A59	6301–6334	Electric Welders
A60	6401–6407	Sound Recording and Similar Equipment
A61	6501–6506	Organs
A62	6601–6634	X-Ray Equipment
A63	6651–6671	Induction and Dielectric Heat Generating Equipment
A64	6701–6753	Machine Tools

Chapter 7. Special Conditions

Items	*Articles*	
A65	7001–7061	Emergency Systems
A66	7101–7125	Circuits and Equipment Operating at More than 600 Volts between Conductors
A67	7201–7210	Circuits and Equipment Operating at Less than 50 Volts
A68	7251–7293	Remote-Control, Low-Energy Power, Low-Voltage Power and Signal Circuits
A69	7301–7362	Outside Wiring

Chapter 8. Communication Systems

Items	*Articles*	
A70	8001–8041	Communication Circuits
A71	8101–8192	Radio and Television Equipment

Chapter 9. Construction Specifications

Items	*Articles*	
A72	92401–94702	Construction Specifications

Chapter 10. Tables, Diagrams, Examples

Items		*Articles*
A73	Pages 288–333	Tables, Diagrams, Examples

Index

A74	Pages 334–356	Index

Appendix

A75	Pages 357–363	Rules of Procedure

APPENDIX B

Supplementary Textbook References

Those who wish to study further the elementary theory and practical aspects of the applications of electrical equipment for buildings will find the following textbooks helpful. At the end of certain chapters these special book references are identified by the item number (B1, B2, B3, etc.).

Item

B1 *Elements of Electrical Engineering*, by Cook and Carr, John Wiley & Sons, 440 Fourth Ave., New York 16, N. Y.

B2 *Principles of Electrical Engineering*, by Timbie and Bush, John Wiley & Sons, 440 Fourth Ave., New York 16, N. Y.

B3 *Electrical Engineering Theory and Practice*, by Erickson and Bryant, John Wiley & Sons, 440 Fourth Ave., New York 16, N. Y.

B4 *Electrical Engineering* (Vol. I), by Dawes, McGraw-Hill Book Company, 330 West Forty-second St., New York 36, N. Y.

B5 *Electrical Engineering* (Vol. II), by Dawes, McGraw-Hill Book Company, 330 West Forty-second St., New York 36, N. Y.

B6 *The IES Lighting Handbook*, by The Illuminating Engineering Society, 1860 Broadway, New York 23, N. Y.

B7 *Introduction to Lighting*, by Sharp, Prentice-Hall, Inc., 70 Fifth Ave., New York, N. Y.

B8 *Acoustical Designing in Architecture*, by Knudsen and Harris, John Wiley & Sons, 440 Fourth Ave., New York 16, N. Y.

B9 *Acoustics of Buildings*, by Watson, John Wiley & Sons, 440 Fourth Ave., New York 16, N. Y.

B10 *Electric Illumination*, by Kraehenbuehl, John Wiley & Sons, 440 Fourth Ave., New York 16, N. Y.

B11 *American Standard Safety Code for Elevators, Dumbwaiters and Escalators* (reprinted in 1945 with 1942 changes), American Standards Association, 29 West Thirty-ninth St., New York 18, N. Y.

B12 *Technical Bulletins on Elevators and Escalators*, by Otis Elevator Company, 260 Eleventh Ave., New York 1, N. Y.

B13 *Technical Bulletins on Elevators and Escalators*, by the Elevator Division, Westinghouse Electric Corporation, 150 Pacific Ave., Jersey City, N. J.

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