Section 12

Building Construction and Equipment

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12.1 INDUSTRIAL PLANTS

by Vincent M. Altamuro

REFERENCES: Hodson, ''Maynard's Industrial Engineering Handbook,'' 4th ed., McGraw-Hill. Cedarleaf, ''Plant Layout and Flow Improvement,'' McGraw-Hill. Immer, ''Materials Handling,'' McGraw-Hill. Rosaler, ''Standard Handbook of Plant Engineering,'' 2d ed., McGraw-Hill. Merritt and Ricketts, ''Building Design and Construction Handbook,'' McGraw-Hill.

PURPOSES

Industrial plants serve many **functions**. They can:

1. Protect people, products, and equipment from the weather.
2. Preserve and conserve energy.
3. Condition the inside environment to be suitable for the processes, products, and people engaged therein.
4. Protect the outside environment from any fumes, dust, noise, or other contaminants their processes produce.
5. Provide physical security for their contents.
6. Block access, visual and/or physical, of those not authorized to see inside or enter them.
7. Provide the stable, strong, and smooth platform or surface required for operations.
8. Be the frameworks for the distribution networks of the services needed—electric power, lights, fuels, compressed air, gases, steam, air conditioning, fire protection, water, drainage piping, communications.
9. Support the cranes, hoists, racks, and other lifting and holding equipment attached to their superstructures.
10. Be integral parts of equipment (such as drying ovens) by having one or more walls serve as sides of them, and the like.
11. Be safe, pleasant, and efficient places to work for employees, impress visitors, and reflect positively on the company.
12. Fit the surroundings, blend in, be aesthetically attractive, make architectural statements.

This list of design criteria can be expanded to include functions other than those cited and which may be specific to a given proposed plant.

After a plant's expected present and future activities and contents are defined, it is designed to provide the desired functions, and then built to provide spaces for operating personnel and to house equipment and services. An existing plant considered for purchase or lease must be selected so that it will provide its user a competitive advantage. Generally, the decision to own or rent a plant depends on factors such as the expected life of the project, prudent use of capital, the possible need for early occupancy, the availability of a rentable building that matches the requirements, and the possibility of either a very rapid growth or complete failure of the enterprise. Some **commercial real estate** developers will erect a building to meet the specifications of the future operators of the industrial plant and then lease it to them under a long-term contract, often with an option to buy it at the end of the lease. A new structure to be designed and built must have its specifications clearly established so that it will serve its intended use and fit its surroundings.

The creation of an **industrial plant** involves the commitment of sizable resources for many years. The plant is therefore a valuable asset, both present and future. Its design and construction must be timely and within budget, and once undertaken, the project must, at most, be subject to minor modifications only, and preferably none. Once the structure is in place, it is very difficult or not economically feasible to move or change the plant. Even if not truly irreversible, design decisions can be corrected or changed only with great difficulty and added expense. There is often little difference in the cost of designing a plant and configuring its equipment and services layout one way versus another. The difference arises in the operating expenses and efficiencies, i.e., the wrong way versus the best way.

When designing a plant, one should estimate how long it is expected to last—both economically and physically. When making this determination, one accounts for the expected lives of the products manufactured, the processes and manufacturing methods used, the machines used, and the extant technology, as well as the duration of the market, the supply of labor, and so forth. Plant life and production life should coincide to the maximum extent possible. Major difficulties arise when a plant becomes obsolete and may warrant either abandonment or, at best, major modification for conversion. Often the manufacturing methods employed in production have so far outgrown the original methods that the conversion of an existing plant can not be justified at all.

Obsolescence can be deferred by making the factory versatile, adaptable, and flexible. Possible changes in conditions can be anticipated and the ability to alter the plant can be included in the original design. An industrial plant is said to be *versatile* if it can do more than one thing, if its equipment can switch over and make more than one variation of the product, or if its output can be raised or lowered easily to match demand. It is said to be *adaptable* if it can make other related products with only programming and tooling changes to its equipment, without the need to alter their layout. It has *flexibility* to the degree that it is easy to move its services, machines, and other equipment to change the layout and flow paths, and thereby accommodate different products and changing product mixes. Such a building will have a minimum of permanent walls, barriers, and other fixed features. A plant can be made to be general-purpose or special-purpose, or more one than the other. A general-purpose plant is more generic and can be used for a wide variety of purposes. It is usually easier and less expensive to design, build, and convert to new use and is more salable when no longer needed. A special-purpose plant is designed for a specific task. It is more efficient and can make a lower-cost product, as long as the specifications stay within narrow limits. With modular machines, quick-change tooling, and programmable automation, such as robots, it is possible to gain the advantages of both general- and special-purpose construction in one plant. It can be built with the versatility, adaptability, and flexibility to be configured one way for one set of requirements, then reconfigured when conditions change. This enables the manufacturer to produce the wide variety of products that consumers want, and still make them with the lower per unit costs of a special-purpose plant. Both economy of scale and economy of scope are possible in the same facility.

There are trends in the design of some products which are causing plants to be constructed differently, in addition to the demand for the benefits of versatility, adaptability, and flexibility cited above. Some products are getting smaller: computers, electronic circuits, TV cameras, and the like. For other products, greater manufacturing precision and freedom from processing contamination require the establishment of ultraclean facilities such as clean rooms. These and other trends are causing some plants to be built with the ratio of manufacturing space to administrative space different from that in the past. In some plants with large engineering, design, test, quality control, research and development, documentation, clerical, and other departments, the prior ratios have been reversed, so that manufacturing and warehousing spaces constitute a rather small percent of the total plant.

In addition to the basic building structure and its supporting services, an industrial plant comprises people, raw materials, piece parts, work in process, finished products, warehouse stock, machines and supporting equipment, systems and services, office furniture and files, computers, supplies, and a host of other things. While each is an individual entity, the plant must be designed so that all can work together in an **integrated and balanced system**. For a new facility, the best way to achieve this end is to design it in a progressive manner, going from the general to the specific, with each step based on prior decisions, until a set of detailed specifications is established. The sequence of design decisions is not linear, wherein one is finalized before the next one starts. Rather, it is more like a series of loops, with the output of one feeding back and possibly modifying prior decisions. For example, plant size could influence the site chosen, which then could influence the amount of air conditioning and other services needed, all of which, in turn, require space that could change the prior estimate of plant size. Almost all decisions have an impact on one or more interrelated plant specifications. The design of the product influences the degree of automation, which sets in motion a chain of decisions, starting with the number of employees required, down through the number of toilets, the size of the cafeteria, medical department, parking lot, personnel department, etc., and ultimately even placement of emergency exit doors.

PLANT DESIGN

An industrial plant must fulfill its intended functions efficiently and economically. Its design must consider and account for the basic operating conditions to be served. A detailed discussion along those lines follows.

Prerequisite Data, Decisions, and Documentation

The decision to build or buy an individual plant is made by the company's senior executives. It involves the commitment of large sums of money and is properly based on major considerations: need for additional production capacity; introduction of a new product; entering new markets; availability of new and/or better technology and machinery; building a new plant to replace an existing inefficient one or refurbishing and tailoring the existing plant for new production processes and cycles; relocation to a different area, especially if closer proximity to markets and availability of specialized labor are involved; making products in house which were previously bought for resale. Studies, analyses and projections provide input data to help determine the proper site, size, shape, and specifications of a plant. Economic analyses, technological forecasts, and market surveys are used to justify the investment in a plant and to calculate the approximate amount of money required, break-even point, payback period, and profitability. Detailed product design and engineering documentation includes drawings, parts lists, test points, inspection standards, and specifications. Product variations, models, sizes, and options are defined. Sales forecast data addresses expected unit volumes, seasonality, peaks and valleys, growth projections, and other patterns. In addition to projections, constraints on the plant must also be understood at the outset. These may include location restrictions, budgetary limitations, timing deadlines, degree of mechanization, the type of building and its appearance, limits on its effluents, exhaust fumes, and noise, and other effects on the neighborhood and environment.

Activities and Contents

The determination of the activities and contents of a plant is facilitated by a series of analyses and management decisions. Make/buy decisions determine which items or component piece parts are to be made in the plant and which are to be purchased and stored until needed. Some purchased items are used as received, others need work, (painting, plating, cutting to size). Parts purchased on a just-in-time basis will reduce the amount of in-process storage space required.

Processes are classified as **continuous** (refineries, distilleries, paper mills, chemical and plastic resin production); **repetitive** (automobiles, air conditioners, appliances, computers, telephones, toys); or **intermittent,** custom job shop, or to order (elevators, ships, airliners). Some plants include combinations of these processes when they make several types of products. In such mixed, or **hybrid,** situations, one product and processing method usually dominates, but there are cases where a plant set up for mass production work has a special-order shop to make small quantities of variations of the basic product, such as a vending machine that accepts only foreign coins. The manufacturing methods used in these processes may include casting, shearing, bending, drawing, forming, welding, machining, assembly, etc. (see Sec. 13). **Engineering documentation** used to facilitate manufacturing analysis includes operations analyses, flow process charts, precedence diagrams, ''gozinto'' charts, bills of materials, and exploded views of subassemblies and final assemblies. With computer-aided design (CAD) and other graphics, these documents can often be constructed, updated, and stored in a common database.

These documents help define the operations, their sequence and interrelationships, inspection points, storage points, and the points in the process where materials and parts join others to form subassemblies and the finished product. (See Hodson, ''Maynard's Industrial Engineering Handbook.'') Special characteristics of the operations may be noted on these documents, such as ''Very noisy operation,'' ''Piece parts can be stacked, but after assembly, they cannot,'' and the like. Product movement is determined. People/tools/things must move in an industrial plant. Workers and their tools go to the stationary work in process, as in shipbuilding; the worker and the work go to stationary tools, as in a general machine shop; the work in process goes to the workers and the tools, as in an assembly line. Other combinations of the relative movement of workers, tools, and work in progress are used. (See Cederleaf, ''Plant Layout and Flow Improvement.'')

An industrial plant should be designed to facilitate, not hamper, the **smooth movement of people, material, and information**. The efficiency of flow is also influenced by the layout of the equipment and other contents of the building. A multilevel building implies movement between the levels, which usually takes more time, energy, and expense than having the same activities on one level. Some operations are performed better in high structures, where raw material is elevated and then gravity-fed down through the lower levels as it evolves into a finished product. A plant built into the side of a hill receives material directly into an upper level without the need to elevate it. In most cases, a single-level plant affords the opportunity for the most efficient flow of materials and product. Even a single-level plant should have all its floor at the same elevation so that material moving from one area to another need not go up or down steps, ramps, or inclines. Features of the building such as toilets and utilities should be located where they will not interfere with the most efficient plant layout, and will not have to be moved in relayouts or expansions.

To the maximum extent possible, the **material flow** through an industrial plant should be smooth, straight, unidirectional, and coupled (the output of one machine should be the input to another, without a large cushion of inventory between them); require the least rehandling; be at constant speed over the shortest direct route, with the least energy and expense; and be always directed toward the shipping dock. Raw materials and piece parts should move continuously through the plant as they are converted progressively by a combination of people and equipment into finished products of the desired quantity and quality. Materials must flow with few interruptions, side excursions, or stops, so that they are in the plant for the shortest time possible and thereby facilitate expeditious product completion. Where possible, movements should be combined with operations, such as having a mobile robot or an automatic guided vehicle (AGV) work on (inspect, sort, mark, pack) the item while transporting it. An analysis of the plant's activities, including a list of its contents and an analysis of their relative movements, results in a rational determination of how they must flow through it. This must be done for materials (raw materials, purchased parts, work in process, finished goods, scrap, and supplies), people, data, and services.

Space and Size Calculations

Annual sales forecasts plotted by the month sometimes show peaks and valleys due to **seasonal variations** in demand. A plant with the capacity to produce the highest month's demand has much of its capacity idle or underutilized in the other months. The ideal plant would have a constant output every month, with long production runs of each item to minimize tool changes and setup times. This is not always practicable, for either very high inventory buildups or shortages could result. The compromise is the calculation of a production schedule that is more level than the sales forecast, builds as little inventory as possible without risking shortages, and allows for rejects, equipment breakdowns, vacations, bad weather, and other interruptions and inefficiencies. This will result in a plant with less production equipment and space but with more inventory space (and associated material handling equipment) to accumulate finished product to meet shipping demands in response to sales. Obviously, the warehouse and other storage areas must accommodate the maximum amount of inventory expected to be stored.

The proper size of a plant is determined by **calculating the total space required** (immediate and future) by all its contents: material at all stages of production, people (employees and visitors), equipment (production, materials handling, support, and services) and the ancilliary spaces required (working room, aisles, lobbies). At first, only the **general types of equipment are specified** (spot welders, overhead chain conveyors, forklift trucks, etc.). Later, **specific items are selected** and listed by manufacturer, model number, capacity, speed, size, weight, power, and other requirements. (See Sec. 10.) Finally, one model may be substituted for another to gain a particular advantage. A simplified typical equipment selection calculation follows:

1. Define the operation: Joining.
2. Decide the method: Welding.
3. Note personnel available: Semiskilled.
4. Determine general machine type: Spot welder.
5. Calculate required production output:

Spot Welds Required

	Product			
	A	B	C	Total
Number of spots	120	60	80	
Units per year	10,000	40,000	20,000	
Spots per year, millions	1.2	2.4	1.6	5.2
Spots per day 250 days/year)				20,800
Spots per hour (8 h/day)				2,600
Spots per minute (60 min/h)				44

6. Select a particular candidate machine, considering type of metal, thickness of metal, diameter of spot. From catalog, choose manufacturer (Hobart) and model (series 1500 rocker arm SW-V).
7. Calculate capacity of one machine in minutes per spot.

Operating time	0.03
Material handling time	0.06
Setup time allocated	0.01
Minutes per spot	0.10

8. Calculate the number of machines needed.

$$N = \frac{TP}{60\ HU}$$

where N = number of machines required; T = standard time to perform the operation, minutes; P = production needed per day, operations; H = standard working hours per day; U = use factor—up-time of the machine, its utilization (percent of time it is producing), or its efficiency. Example:

$$N = \frac{0.10 \times 20{,}800}{60 \times 8 \times 0.80} = 5.4 \text{ machines}$$

9. Round off to next higher number: 5.4 becomes 6 machines.
10. Alternatively, return to catalog to see of there is a faster model. If so, 5.4 could become 5 of a different model machine.
11. Record specifications of selected machine on an equipment card or in a computer file. Appropriate notations should be made therein, such as:

Crane must go over this machine.
Must be near outside wall for venting.
Will require supplemental lighting.
Requires a special foundation.
Requires a drain for water.
Allow room on side for gear changes.
Allow room for largest-size sheet-metal parts.

12. Use data for all machines needed to help establish specifications for equippage of the plant:

Sum of space required (including space for workers, material, aisles, services) becomes size of that department or function

Sum of utilities and supplies (electricity, water, steam, compressed air, oxygen, nitrogen, acetylene, coolants, lubricants, air conditioning) addresses requirements for them.

Sum of weights affects floor loading capacities and specifications. For some parameters, the extreme value is important in establishing the building specifications; i.e., the height of the tallest machine may set the required clear height inside the plant, locally or throughout. Equipment mounted on columns or roof beams will influence their size. Specific equipment may require special foundations or subfloor access pits.

Sums of the prices of the machines and the required tooling, the number of workers, their required skills, and their wages and benefits provide information regarding the investment and operating expenses for the plant.

The same procedure is used to determine the **material handling equipment,** its required space, and its influence on the plant's specifications. (See Immer, ''Materials Handling.'') Equipment may be capable of moving materials horizontally, vertically, or in both directions; some have a fixed path of travel, while the paths of others can be varied. The general types of equipment that move materials horizontally in a fixed path include conveyors, monorails, and carts pulled by trucks, dragged by chains in floor troughs, or that follow buried wires. Conveyors are overhead or floor-level type. Overhead conveyors clear the floors of some congestion but add to the loads carried by the building's columns and beams. Other types of conveyors are installed at floor level or at working height, and include belt conveyors and powered or unpowered roller conveyors. The general types of material handling equipment that travel in variable horizontal paths include hand trucks, powered trucks, pallet trucks and automatic guided vehicles. Those that travel in fixed vertical paths include elevators, skip hoists, chutes, and lift tables. Those that travel in both horizontal and vertical fixed paths include traveling bridge cranes, gantry cranes, jib cranes, and pneumatic tubes. Those that travel in both horizontal and vertical variable paths include robots and forklift trucks. Forklift trucks may be powered by either battery, gasoline, or liquefied petroleum (LP) gas. Those powered by batteries will require the installation of charging facilities within the plant, and those with internal combustion engines will require safe fuel-storage space.

The installation of each of the above-listed material handling equipment types will influence the plant's specifications in some way. In computing loads on the building's structural members, all static and dynamic loads arising from material handling equipment must be factored into their design, as applicable.

With respect to **raw material,** its form, weight, size, temperature, ruggedness, and other qualities are considered, as are the expected distances to be moved, speed of transit, number of trips, and amount carried per trip. For **warehouses,** the important considerations are cubic space and density of use for various package sizes, weights, and stacking patterns.

The same basic approach is used for **support functions** and **plant services**. The space required for people can be estimated by listing them by functions, jobs, and categories (male versus female, plant versus office, department, location, shift), then allocating space to each. For example, office floor space allocation in ft^2 (m^2) per person may be: plant manager, from 150 to 300 (13.9 to 27.9) depending on size and type of plant; assistant plant manager, 125 to 250 (11.6 to 23.2); department heads, 100 to 200 (9.3 to 18.6); section heads, engineers, specialists, 100 to 150 (9.3 to 13.9); general personnel, 50 to 100 (4.6 to 9.3). When accounting for all employees in an industrial plant, the space per person can range from about 200 to 4,000 ft^2 (18.6 to 370 m^2), depending on the type of industry and the degree of automation employed. An estimate of the male/female ratio often must be made early in the planning stage, for many localities will issue a building permit only if adequate sanitary and rest facilities are included for each gender.

The space required for each department and function is compiled and added to show the approximate total plant size. See Fig. 12.1.1, which also shows the percent of the total plant floor space allotted to functional subtotals. The size of the plant should not be deemed final without including the manner in which to allow for anticipated growth and/or plant expansion. Anticipated growth, if realistic, must enter into the decisions reached as to the initial size of the plant to be built. When dealing with the initial plant size vis-à-vis any anticipated future expansion, some questions usually posed are: Should it be large enough to accommodate expected growth, knowing that it will be too big initially? Should it meet only present needs, then be expanded as and if required? Should a midsize compromise be made? A plant too big for present needs will cost more to build and operate and may place the firm in an uncompetitive position. Expenses for taxes, insurance, heating, air conditioning, etc. for a partially vacant plant are almost the same as for one fully occupied. On the other hand, a plant built just to satisfy present requirements of a growing business can quickly become cramped and inefficient and may lead to rental of external storage and warehouse space, with all the added expense and loss of control entailed thereby. Any future expansion of the original plant will not only be disruptive to operations, but also will cost significantly more than building it bigger in the first place. The correct choice is made by analyzing all options and comparing expected costs and profits and the realistic probability of growth.

If a building is to be expanded or upgraded easily and economically after it is built, that capability must be included at the outset. This is done by deciding in advance the direction and degree of possible future expansion, knowing that if the business grows, not all sections of the plant may have to be expanded to the same degree. After the basic form of the building shape and envelope have been addressed, attention is then directed to other matters: location of the building on the property; materials of construction for internal walls that may have to be rearranged; location of spaces and equipment that will be difficult or impossible to move in the future, such as toilets, shipping/receiving docks, transformers, heavy machinery, and bridge cranes.

Superstructure members, pipes, monorails, ducts, and so on can be terminated at the proposed expansion side of the plant, with suitable end caps or terminations which may be removed easily and activated quickly when required. Installations of major utilities are prudently sized to handle future expansion. If the initial design strategy includes anticipation of vertical expansion via mezzanines, balconies, or additional stories, foundations, footings, superstructure, and other structural elements must be designed with that expansion in mind. To accommodate that requirement at some later date will prove to be prohibitively expensive and will disrupt ongoing operations to a degree unimaginable. By the same token, if future operations require a contraction of active space in the proposed plant, space would be available, at worst, for sublease to others. Regardless of whether possible expansion or contraction is contemplated, the initial plant design should consider both possibilities and seek to have either occur with minimum disruption of production.

Department or function	Area, ft²	Area, m²
Main receiving	5,700	530
Incoming inspection	900	84
Main stockroom	9,600	892
Large-component storage	6,000	557
Coil steel storage	1,840	171
Steel coil line	2,360	219
Sheet metal fabrication	18,000	1,672
Welding	3,000	279
Sheet-steel storage	13,800	1,282
Copper tubing storage	600	56
Tubing fabrication	1,200	111
Cleaning and painting	9,600	892
Insulating	1,200	111
Electrical subassembly	1,200	111
Final assembly	33,600	3,121
Finished goods storage	40,200	3,735
Wood storage and fabrication	2,400	222
Shipping	9,600	892
Maintenance and tool room	600	56
Print shop	600	56
Plant offices	1,200	111
Engineering laboratory	12,000	1,115
Reproduction room	420	39
Canteen/eating area	3,600	334
Medical/first aid	330	31
Offices and lobby	21,600	2,007
Toilets	1,650	154
Total	202,800	18,840

Function	% of total plant	ft²	m²
All receiving, incoming inspection, storage, and shipping	44.2	89,440	8,309
All production	35.3	71,360	6,629
Engineering lab and repro	6.2	12,420	1,154
Support areas: Maintenance and tool, print, first aid, canteen, toilets, plant offices	4.0	7,980	741
General offices and lobby	10.3	21,600	2,007
Total	100.0	202,800	18,840

Fig. 12.1.1 Space required by department, subtotals by function, and for the entire facility for a plant designed and built to manufacture roof-mounted commercial air conditions. *(Source: VMA, Inc.)*

Plant Emplacement and Site Selection

The emplacement of a plant is defined by its geographical location, site, position, and orientation, in that order. Geographical location is determined by the country, region, area, state, county, city, and municipality in which the plant is situated. The site is that particular plot of land which can be identified by street address or block and lot numbers in that geographical location. The position and orientation speak to the exact placement and compass heading of the building on the site.

Typical considerations entering each stage of the placement decision, from broad to specific, follow.

Location: Political and economic environment. Stability of currency and government. Market potential. Raw materials supply. Availability and cost of labor. Construction or rental costs. Environmental regulations. Climate. Applicable laws within the governing jurisdiction. Port, river, rail, highway, airport quality. Utilities and their relative costs. Taxes. Incentives offered. Local commercial services. Housing, schools, hospitals, shops, libraries, and other community attractions. Crime rate, police and fire protection. General ambiance of the locality.

Site: Availability. Price. Incentives offered. Building and zoning codes. Near highway entrance/exit, on railroad spur, waterway, and major road. Public transportation for employees. Availability of water, sewer, and other utilities. Topography, elevation, soil properties, subsurface conditions, drainage, flood risk, earthquake faults. Neighbors. Visibility.

Position: Placement for possible expansion with sides of building that may be extended facing an open area or parking lot and the sides not to be extended close to the property line. Proximity to railroad tracks, road, utilities or other fixed features. Positions of buildings on neighboring property.

Orientation: Turned toward or away from winter's wind and summer's sun, as desired, considering the frequently open large shipping and receiving doors. Needs for heating, air conditioning, natural light, color matching, and the like that would be affected by compass heading.

Proximity to competitors may be desirable if the locale has developed into a well-recognized center for that industry, where are found skilled people, and a wide variety of suppliers and supporting services (testing laboratories, local centers of higher learning with faculty available for consultation on an ad hoc basis). Without these conditions, and especially if the product is heavy and expensive to ship, it is desirable to locate close to market areas and distant from competitors.

The amount of land required depends on plant size, the number of employees and their need for parking space, the probability of storing some raw materials and finished goods outdoors, the need to turn large trucks around on the property, the possibility of future expansion of the plant, zoning, and the possible desire to create an open park-like ambiance. Total land area of from 4 to 8 times the plant size is usually adequate; the lower end of the range applies in built-up areas, and the higher end applies in suburban areas. In some locations the land can cost more than the plant.

Before placement of a plant becomes final, all conditions and extremes should be simulated, including winter storms, rainy seasons, floods, several consecutive days of 100°F heat, power outages, labor disruptions, and the like. It is unlikely that the perfect site will be found, thus sought-after attributes must be ranked in order of importance. As an incentive to get new industry, some governments will build roads and schools and reroute buses if necessary. Test borings are often taken at a candidate site before a commitment is made to buy or lease it to ensure that it is suitable. A plot plan (see Fig. 12.1.2) can be made with an approximation of the planned plant on the candidate site indicating land size, topography, drainage, position on the plot, anticipated expansion, compass orientation, location of power lines, railroad tracks, roads, rivers, open fields, neighbors, etc.

Configuration

The configuration of a plant is determined ideally by the optimum layout of its contents. Compromises are usually made, however, often resulting in a conventionally shaped building. A building with several extended branches is very expensive. For a given floor area, a square building requires less total wall length than other quadrilateral shapes, but rectangular buildings are the most common compromise between cost and efficiency. For the lease or purchase of an existing building, the best approach is to design the best layout and then seek an existing building within the desired area in which that layout may be accommodated. For a new building, the layout is set down before the location is selected and then adjusted for the particular features of the site. A layout prepared after the site has been selected can be tailored to fit the site, all the while maintaining the desired features of that layout.

Before the configuration and layout become final, certain broad and tentative choices about the type of building should be made. These include general-purpose versus special-purpose, multilevel versus single level, use of mezzanines and balconies, with windows or windowless, etc. Setting aside considerations of material flow, a multilevel building enjoys the advantages, on a unit floor area basis, of using less land and costing less to build. The columns, however, will generally be spaced closer together, thereby presenting an impediment to desired flow paths and a reduction in options for overall layout. A single-level building, on the other hand, can more easily support heavier floor loads by virtue of its concrete slab on grade floor construction.

The matter of shipping/receiving floor level vis-à-vis truck bed level must be resolved satisfactorily, keeping in mind that loading and unloading ought to be effected with small hoists or forklifts for maximum efficiency. To that end, loading floor level can be built to be flush with

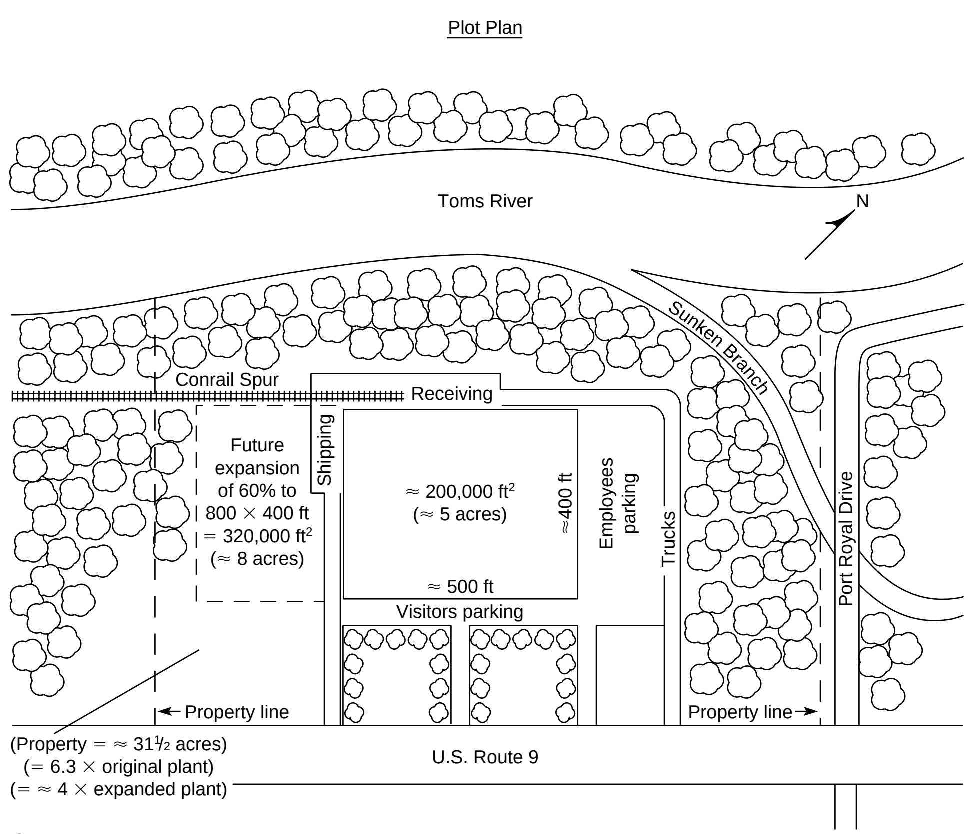


Fig. 12.1.2 Plot plan of an industrial plant. *(Source: VMA, Inc.)*

the bed height of most of the anticipated truck traffic, or the truck parking apron can be inclined downward to align the two. If those cases when trucks with other bed heights have to be accommodated, small demountable ramps can be employed, the same being built sufficiently rigid to permit forklift traverse.

Balconies and mezzanines may be added to gain more storage space, to locate offices with a view of the production areas below, for raw materials or subassembly work that can be gravity-fed and drop-delivered to the operations below, and for the placement of service equipment (hot-water tanks, compressors, air conditioners, and the like). Basements may be included for the placement of heavy equipment, pumps, compressors, furnaces, the lower portion of very tall machines, supplies, and employee parking.

Windows in an industrial plant lower lighting bills, permit truer color matching in natural light, aid cooling and ventilation when opened, may provide a means of egress in case of fire, and may lower fire insurance rates. The advantages of a windowless plant are easy control of the intensity and direction of light (elimination of glare, contrasts, shadows, diffusion, and changing direction); (sometimes) less expensive construction; and less heat transfer, dust and dirt infiltration, maintenance expense to wash and repair glass, and worker distraction; better security; lower theft insurance rates. It is generally easier and more economical to design a windowless building. The absence of fenestration allows more flexibility in interior layouts by virtue of uninterrupted wall space. The absence of low windows, in particular, obviates the need for blinds or drapes to keep the interior private from the passing viewer. Elimination of an enticing target to vandals is not to be dismissed lightly; often damage to machinery and equipment, as well as injury to personnel, results from flying missiles launched at and through windows.

The relative positions and detailed layouts of each department's machines, support equipment, services, and offices are based on analyses of their functions, contents, activities, operations, flow, relationships, and frequency of contacts. The layouts may be product- or process-oriented, or a combination of the two. In a product-oriented layout, machines are arranged in the sequence that the production process requires. This permits the product to advance in a direct path, such as on an assembly line, and with smooth material flow. In a process-oriented layout, the machines are grouped by type, such as a welding or drilling. This requires that the products requiring those operations be brought to that area. It is used where products vary and the output of each is low, such as in a job shop, and allows production to continue even when a machine breaks down.

Another early decision involves the preferred placement of the receiving and shipping departments and the related basic pattern of material flow through the plant. If it is preferred to have the material enter at one end of the plant and exit at the other (Fig. 12.1.3*a* and *b*), then separate receiving and shipping facilities, equipment, and personnel will be required. Capital investment and operating economies ensue from combining these functions, with shared personnel, equipment, supervision, and space, but then the basic material flow will loop back to allow the finished product to exit from the same location where raw materials entered (Fig. 12.1.3*c*).

The drawing showing the size, shape and position of each department or area of an industrial plant is called a **block diagram**. It is developed by constructing a series of **analysis documents**. These include the frequency of relationship chart, proximity preference matrix, relative position block arrangement, sized block arrangement, initial block diagram, refined block diagram, and final block diagram (or simply block diagram). The **frequency of relationship chart** (also called a **from/to chart**) is constructed from an analysis of the engineering and manufacturing documentation and the activities of the plant. It shows the frequency and magnitude of movement, flow, and contacts between the entries. It may be weighted to include the importance of high-priority factors. The **proximity preference matrix** (also called a **relationship chart**) is constructed the same way. It shows (Fig. 12.1.4) which functions, departments, equipment and people should be close to each other, how close, and why, and which should be away from which other and why. It is constructed with a diamond-shaped box at the intersection of every two

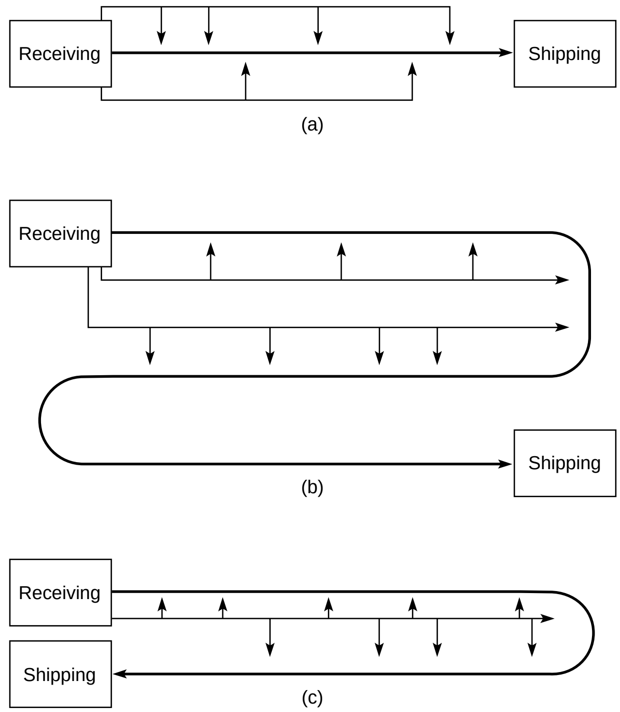


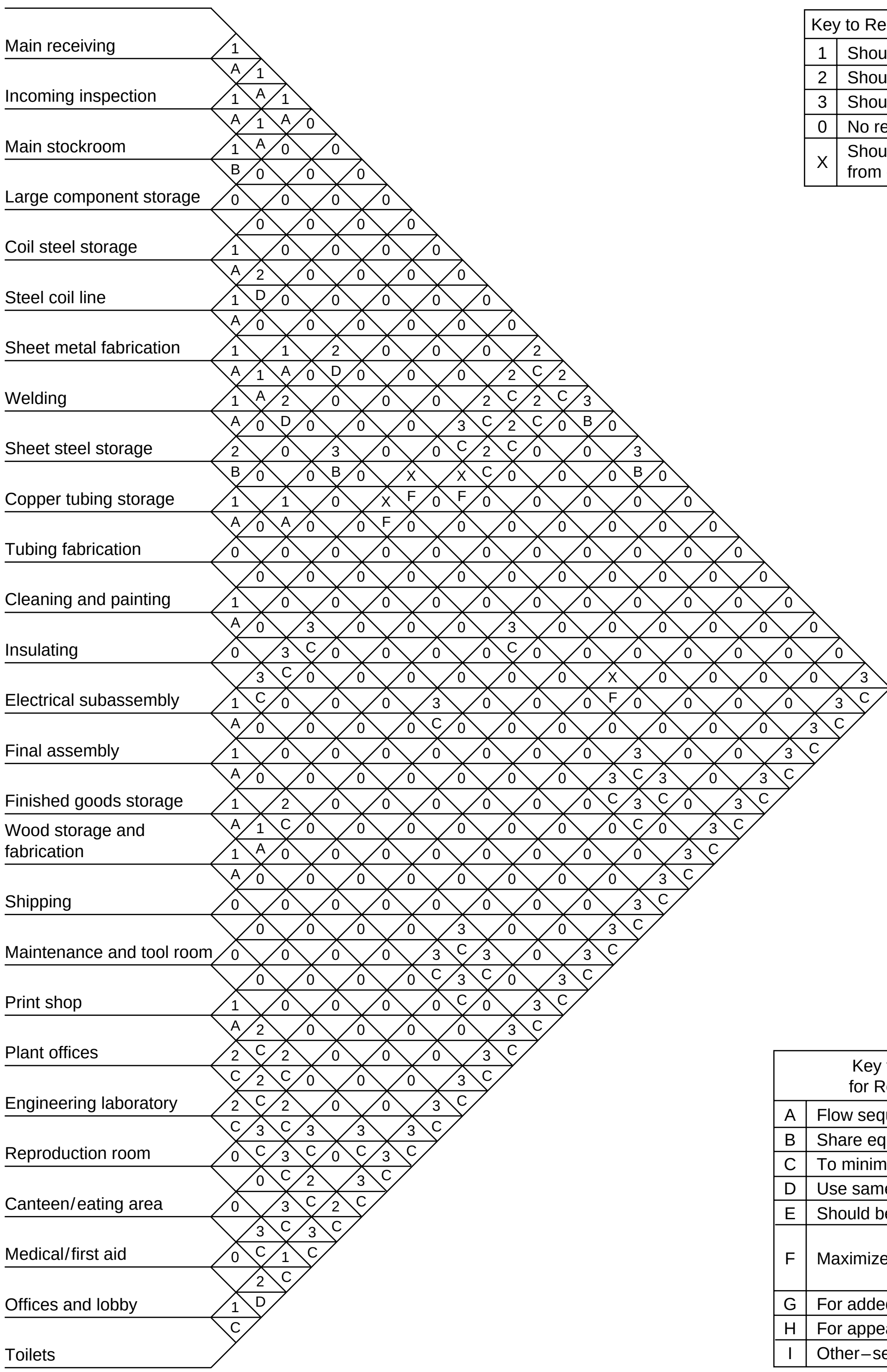
Fig. 12.1.3 Three different relative positions of a plant's receiving and shipping areas. *(Source: VMA, Inc.)*

entries. The notations made in each box show the importance of their need to be either close or separated by a number or code. The reasons can also be shown by entering a code in the lower half of the box, as shown in Fig. 12.1.4. The matrix may be made at the function or department level and, later, at the individual machine or person level. The objective of the matrix and chart is to lay out the plant so that things are as close to (or as far from) other things to satisfy the criteria established, and ensure that those with the highest number of contacts are so located to minimize the time, distance, and energy required.

When this is done, a **relative position block arrangement** (Fig. 12.1.5) may be made; this shows the various arrangements possible by shifting around pieces representing the departments. The arrangement selected is the one that best satisfies the relationships (in decreasing order of importance) and degrees of contacts, as previously determined. The size of each model (or computer graphic representation) is the same because only the relative positions of the departments or areas is of interest at this stage of the design. Assigning a different color or background pattern to each adds to clarity and, when carried through to final and detailed drawings, helps visualize quickly the totals of separated areas; e.g., the total of inventory storage areas spread throughout the plant can be understood quickly if all are shaded the same color on the drawings. The **sized block arrangement diagram** (Fig. 12.1.6) is the relative position block arrangement with the size of each area scaled (but still square) to represent its square footage as determined by its expected contents and room for expansion (unless the expansion is to be handled by extending the building, in which case the department should be placed where expansion is proposed. The **initial block diagram** converts the square representation of each department into a shape that is more suitable for its contents and activities, but of the same square footage. The **refined block diagram** (Fig. 12.1.7) adjusts the initial shapes to effect a compromise between the advantages of having them be the best operational shape and those of fitting them in an economical rectangular building. L-, T-, U-, H-, and E-shaped buildings are often the result of such configuration compromises.

After the main aisles are drawn, as straight as possible, to serve as

Key to Relationship Rating	
1	Should be contiguous
2	Should be very close
3	Should be close
0	No relationship
X	Should be far away from each other



Key to Reasons for Relationships	
A	Flow sequence
B	Share equipment/personnel
C	To minimize travel distance
D	Use same services/utilities
E	Should be on outside wall
F	Maximize distance – noise – vibration – fumes
G	For added safety/security
H	For appearance/image
I	Other–see notes

Fig. 12.1.4 A proximity preference matrix listing the departments, functions, and areas, and ranking how near or far each should be relative to the others, and why. *(Source: VMA, Inc.)*

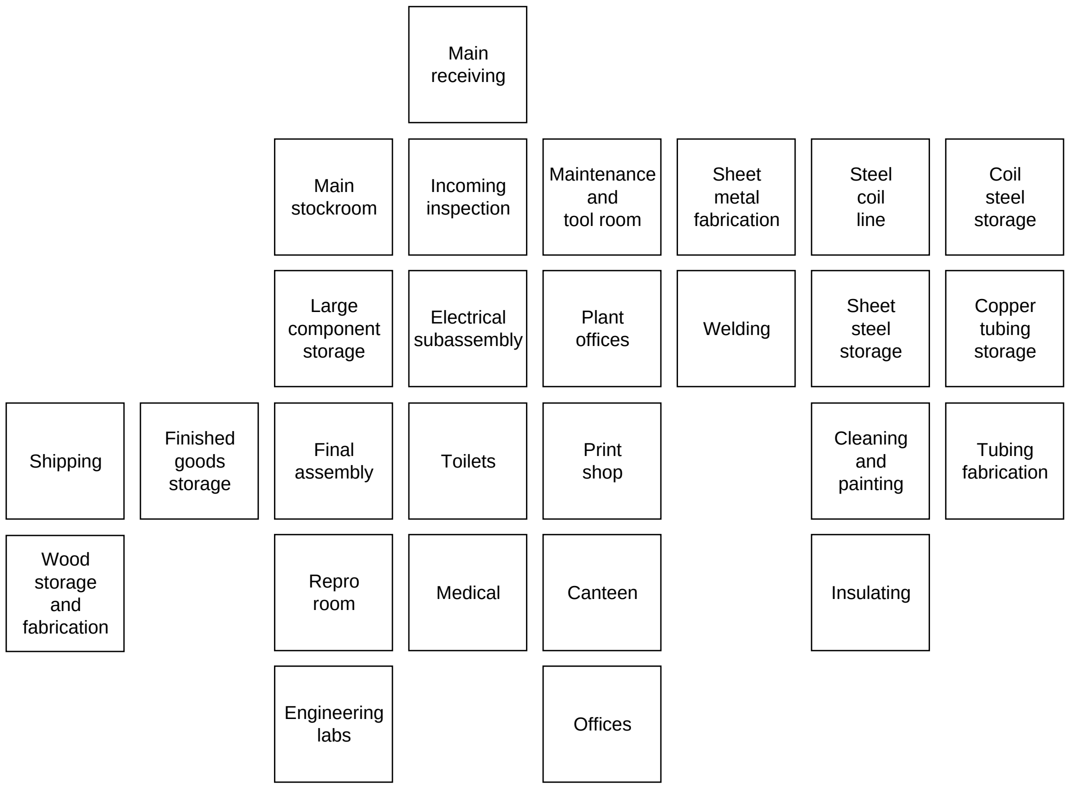


Fig. 12.1.5 A relative position block arrangement that attempts to satisfy and optimize the dictates of the prior proximity preference matrix. *(Source: VMA, Inc.)*

dividers between departments, the size and shape of each area can be fine-tuned, and a **final block diagram,** or simply **block diagram,** is drawn, keeping the same color code scheme used throughout. Detailed layouts are constructed for each department and function to fit within the spaces allocated in the block diagram. When assembled onto one drawing, the block diagrams become the detailed layout for the entire plant.

There are several aids to constructing both block diagrams and detailed layouts. These range from scaled templates to three-dimensional models of machines and equipment. They are available as plain blocks and as highly detailed plastic or cast-metal models. Computer-based optimization programs are also available. Some computer-aided design packages contain libraries of plant components and equipment that can be selected, positioned, rotated, and moved on the screen until a satisfactory layout is achieved. See Figs. 12.1.8 and 12.1.9 for two- and three-dimensional, respectively, computer-generated detailed layout drawings. Arrows are added to these diagrams to show flow paths. Copies of these drawings can be annotated with dimensions and machinery and furniture descriptors and given to vendors and contractors for them to submit bids to supply and install the items. They are also kept on file for use in future maintenance and/or revisions.

Features not expected to be moved in the future or that will become permanent parts of the building should be located first, e.g., stairways, doors, toilets, transformers, steam boilers, fuel tanks, pumps, compressors, piping, and permanent walls. Accurately dimensioned definitive drawings must be made to guide installers of equipment and services.

In addition to the layouts of the production areas, the support functions must also be planned. Support groups assist the production departments; they include research and development, testing laboratories, engineering, production planning and control, quality control, machine shop, sales and advertising, technical literature, purchasing, data processing, accounting and finance, files storage, personnel, medical, administration and management, general office, supply storage, reception lobby, conference rooms, training rooms, library, mail room, copying and reproduction, cafeteria, vending machines, water fountains, washrooms, toilets, lockers, custodial and maintenance, security, and so on. Adequate space must be provided for the people working in these areas and their workstations must be designed with ergonomics, lighting, comfort, and safety in mind.

Many industrial plants have the supervisors' offices situated on the factory floor for better contact with and control of their people. Likewise, offices for quality control inspectors, industrial engineers, and manufacturing or process engineers often are located in the production areas. Such offices may be built with the building or may be purchased and installed as preengineered, prefabricated units. General and administrative offices usually are distant from the plant's machinery and equipment, whose noise and vibrations would otherwise affect the performance of the occupants therein and their ancillary equipment (computers, for example).

Office furniture may be arranged in military style (orderly straight rows), the open plan method (fewer and movable partitions), landscaped (free form with plants and curved dividers), individual offices (glass, wallboard, steel, or masonry walls), or any combination of these. In those arrangements wherein the partitions and dividers are classified as furniture instead of parts of the building, they may be depreciated over a much shorter period of time than the permanent structure. Space is allocated on the basis of position in the organization chart, with the senior executives getting windows (if any) and the most senior getting a large corner office. Floor coverings, ranging from tile to carpeting, again depends on position, as do the amount and type of furniture.

The plant's reception lobby should measure approximately 160 ft^2 (14.9 m^2) if seating for four persons is required, and at least 200 ft^2 (18.6 m^2) for 10 visitors. Add 60 to 100 ft^2 (5.6 to 9.3 m^2) if a recep-

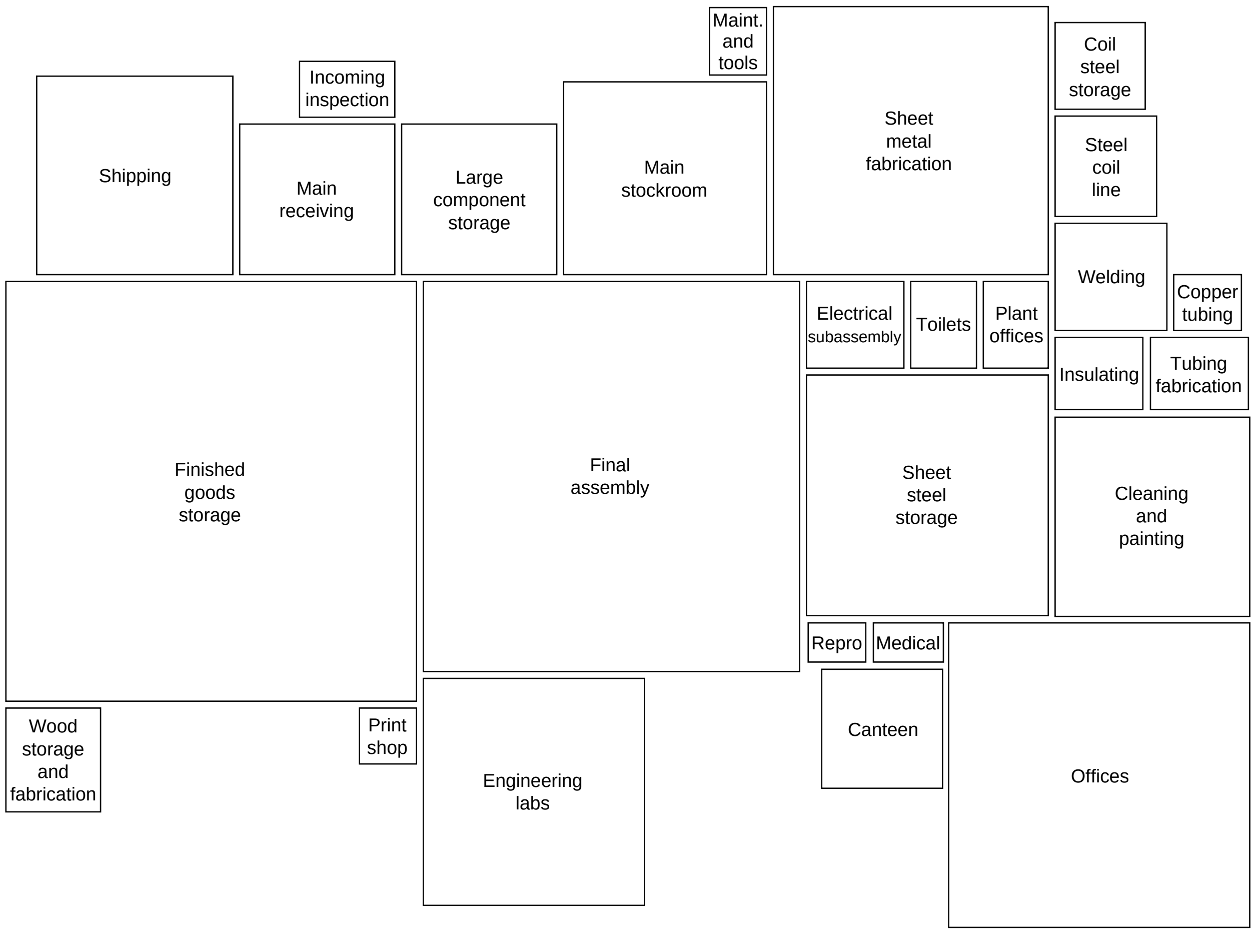


Fig. 12.1.6 A sized block arrangement that converts the prior relative position block arrangement into one that shows the required size of each department, function, and area, while maintaining the preferred relative position of each. *(Source: VMA, Inc.)*

tionist is to be seated there. Cloak rooms require 6 ft^2 (0.6 m^2) per 10 garments.

If a cafeteria is included, 20 ft^2 (1.9 m^2) per person of expected occupancy should be provided if it is equipped with tables and chairs, plus space required by any vending machines. Conference and meeting rooms should provide about 20 ft^2 (1.9 m^2) per person of expected attendance, and training rooms with theater-type seating should be 400 ft^2 (37.2 m^2) for groups of 20, 600, (55.8) for 40, and 1000 (92.9) for 80. A plant library will range from 400 to 1000 ft^2 (37.2 to 92.9 m^2), depending on its contents. Record storage requires 6 ft^2 (0.6 m^2) per file cabinet. Storage space must be provided for stationery and supplies. Slop sink and mop closets should be 12 to 15 ft^2 (1.1 to 1.4 m^2). Facilities should be placed as close as possible to those who will use them; those for universal use must be located conveniently. In very large plants, spaces and facilities for universal use must be supplied in multiples, and include toilets, clothes closets, lockers, time clocks, emergency exit doors, copy machines, vending machines, and drinking fountains. Aisle locations and widths are critical elements in the management of internal traffic, and are based on: use only for pedestrians or by material handling vehicles as well, in which case load widths must also be included as a design parameter; whether traffic is one-way or two-way, with loaded vehicles passing each other; traversing vehicular traffic only or with dropoff and/or pickup points along the route; and provision of turnaround space for vehicles (forklifts and the like) or restrictions on maneuvering within aisles. For efficient traffic flow, the configuration that will work best most often is one with one main aisle and a number of smaller feeder aisles, with straight, well-marked aisles intersecting at right angles. Aisles located at exterior walls will result in loss of storage space, and generally will be remote from the central area meant to be served. While necessary and functional, aisle space can occupy from 15 to 30 percent of the plant's total floor space. Planning for aisle space must defer to any applicable labor laws or local ordinances.

Services

An industrial plant's services are those utilities that power and supply the production and support functions. They include electric power and backup emergency power; heating, ventilating, and air conditioning (HVAC); water for processes, drinking, toilets, and cleaning; smoke, fume, and fire detection and fire fighting; natural gas and/or fuel oil, process liquids and gases, compressed air, steam; battery chargers for electric forklift trucks, AGVs, and mobile robots; communication networks and links for telephone, facsimile, computers, and other database nodes; surveillance and security systems; and waste, scrap, and effluent disposal drains and piping. The design of these requires not only the specification of the equipment, but also the layout of the distribution networks, with drops to where needed and points of interface to the apparatus served.

Flexibility is increased and unsightly and dangerous wires are elimi-

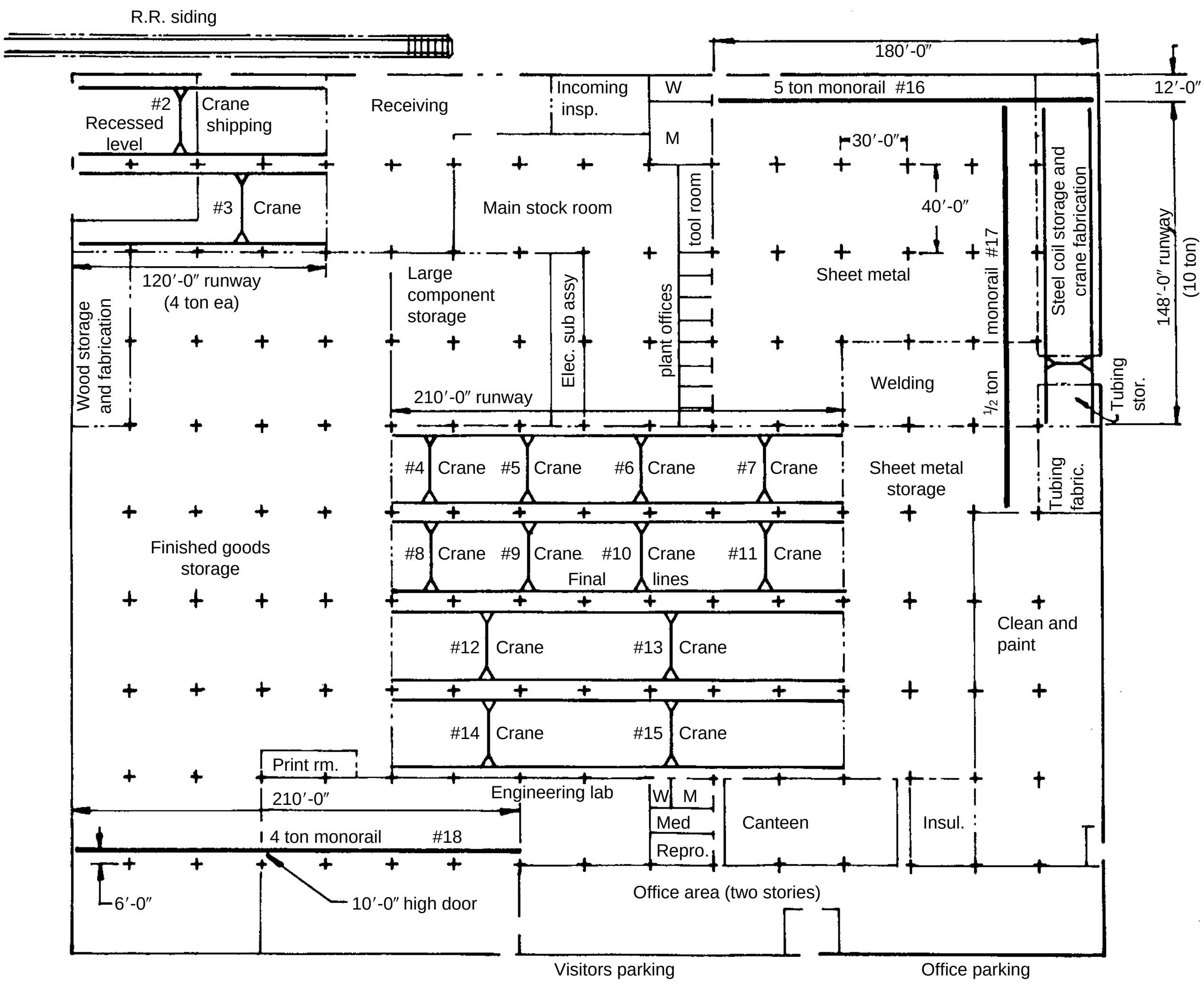


Fig. 12.1.7 A refined block diagram that converts the prior sized block arrangement onto one that makes the shape of each department, function, and area be such that, together, they fit into a building of a more conventional shape, while maintaining the size and relative position of each. *(Source: VMA, Inc.)*

nated by installing buried electric raceways in the floor before concrete is poured. Wires channeled thus are connected to floor-mounted equipment through access caps; changes in machine layout or additions to the complement of machinery are facilitated via connections into the raceways. Definitive, current records of buried raceways document exact locations of raceways and any modifications made thereto over periods of time, and while they are archival in nature, they serve to prevent confusion and guesswork. Other raceways and wire conduits are dispersed through the plant to accommodate electric convenience outlets, communication equipment, and similar services.

Electric power is usually transmitted over the utility's lines at between 22,000 and 115,000 V. The plant usually includes transformers to reduce voltage to 2,300–13,000 V. Most building codes require that these transformers be installed outside the building. The next level of voltage reduction, down to 120–480 V, is provided by transformers usually located inside the building and dispersed to strategic locations to provide balanced service with minimum-length runs of service connections. Alternatively, the plant may arrange for the local utility to supply electric power already stepped down to the levels needed; 240/120-V single phase, three-wire; 208/120-V three-phase, four-wire; 480/277-V three-phase, four wire. The last is more economical for motors and industrial lighting.

Natural light entering the plant through windows and skylights is erratic and difficult to control. All areas of the plant must be illuminated adequately for the activities conducted therein. Section 12.5 lists typical illumination levels. Density of light, illuminance, is designated in footcandles, fc (lumens per square foot) or lux, lx (lumens per square meter). One fc = 10.76 lux. In most cases, tasks requiring illuminance more than 100 to 150 fc (1080 to 1600 lux) also require directed supplemental illumination. No area should be illuminated at a level less than 20 percent of nor more than 5 times that of adjacent areas because eyes have trouble adjusting rapidly to drastic differences in illuminance. Proper illumination is also a function of the type and form of the lighting fixtures. Luminaires are selected to shed direct, indirect, or diffused light. Lamp types include incandescent, fluorescent, mercury vapor, metal halide (multivapor), and high-pressure sodium vapor. The number and type of lamps per luminaire, height, spacing, and percent reflectance of the floor, walls, and ceiling are contributing factors. The plant should have a portion of its lights attached to an emergency power source that switches on when the regular power fails. (See Rosaler,

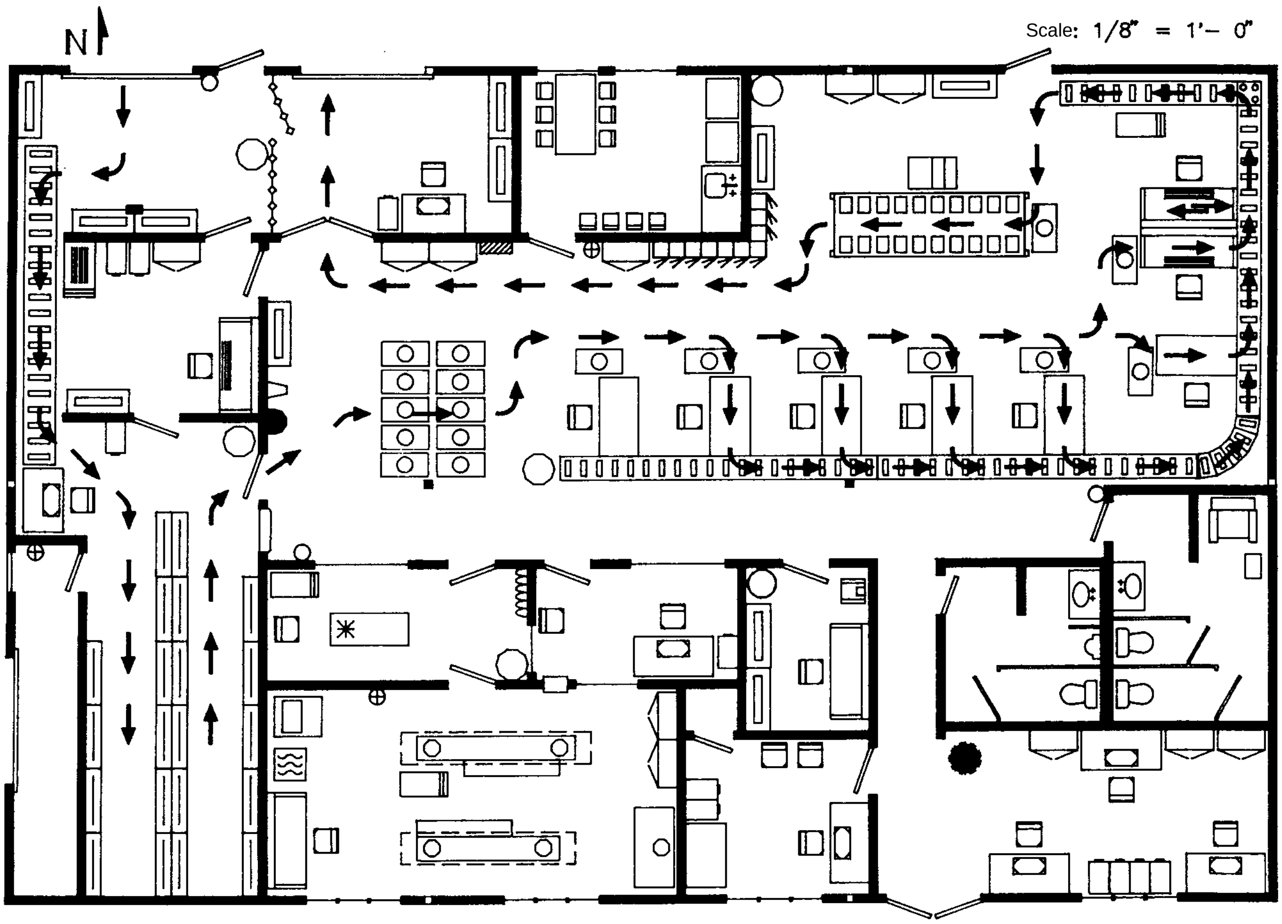


Fig. 12.1.8 A two-dimensional computer-generated detailed layout of one area of an industrial plant, showing furniture, fixtures, and flow path. *(Source: Cederleaf, ''Plant Layout and Flow Improvement,'' McGraw-Hill.)*

''Standard Handbook of Plant Engineering.'') A stationary diesel-, gas-, or gasoline-powered electric generator is usually installed to provide emergency electric power. The available fault current at all points in the electric distribution system should be determined so that protective devices can be installed to interrupt it. Selected circuits should have uninterruptible power supplies (UPSs), isolators, and regulators to protect against outages, voltage surges, sags, spikes, frequency drifts, and electrical noise. Exit signs and a clear path to the exits should be capable of being energized by emergency power, from either a standby generator or batteries.

Water, water distribution, and fixtures are essential for many plant processes, including paint booth ''waterfalls''; for cooling machines, welders, and the like; for adding water as an ingredient in some products; in toilets, showers, cafeterias, and drinking fountains; for sprinkler systems and fire fighting; and for custodial work and landscaping maintenance. If large amounts of hot and/or cold water are required by the process, boilers and/or chillers are provided, along with associated piping and pumps for fuel and water distribution. The number of toilet fixtures as required by building codes is based on the number and sex of expected building occupants. Dispensers that chill and/or heat water are useful to prepare beverages and soups. Water consumption per person per 8-hour shift in personnel facilities ranges from 30 to 80 gal (114 to 303 L).

Sprinklers are installed according to the recommendations of the National Fire Protection Association (NFPA). Automatic sprinklers can be the wet type, wherein water is always in the pipes up to each head, or the dry type, wherein the pipes are filled with air under pressure to restrain water until the fusible link in the head melts and releases the air pressure, allowing water to flow.

The dry type is used outdoors and in unheated areas where water could freeze. Sprinkler heads are either standard or deluge type. Standard heads have a fusible element in each head that is melted by the heat of a fire, thereby opening the head and releasing water. Deluge heads do not have fusible elements, but a deluge valve which is opened in response to a signal from any of several heat sensors situated in the protected area. In the standard type, only the heads whose elements are melted release water, whereas deluge heads act simultaneously. A deluge system is more likely to extinguish sparks at the periphery of a fire, but it also may ruin materials that are doused unnecessarily with water. A preaction system includes sensors and an alarm which gives plant personnel a chance to deal with the fire before sprinklers actuate and douse valuable merchandise. The alarm may also be wired to signal the local fire department. The sprinkler heads must be spaced in accordance with the prevailing code: generally one head per 200 ft^2 (18.6 m^2) for low-hazard areas, 90 ft^2 (8.4 m^2) for high-hazard areas, and about 120 ft^2 (11.2 m^2) for general manufacturing; about 8 to 12 ft (2.44 to 3.66 m) between heads and height of the highest head not over 15 ft (4.57 m) are typical. (See also Sec. 18.3). Drains should be installed to carry away sprinkler water. The supply of water for all of the above listed needs must be adequate and reliable. For fire fighting, the greatest fire hazard and the size of the water supply required to deal with it must be estimated. The expected flow from all hoses and sprinklers, the static

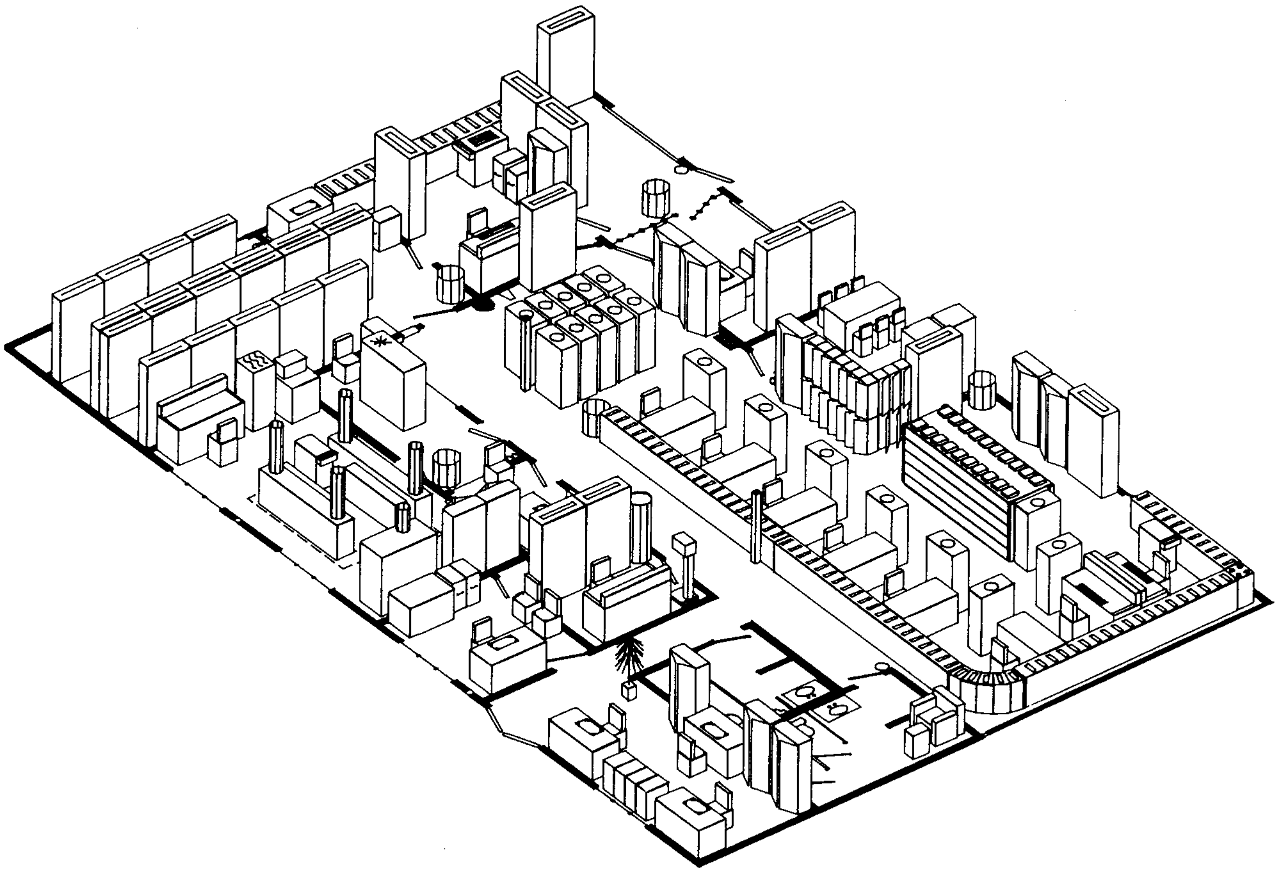


Fig. 12.1.9 A three-dimensional computer-generated detailed layout of the same area shown in Fig. 12.1.8. *(Source: Cederleaf, ''Plant Layout & Flow Improvement,'' McGraw-Hill.)*

pressure, and the minimum flow available at a given residual pressure must be considered. Again, codes and insurance company requirements control. Sources of water include city mains, gravity tanks on towers, reservoirs on roofs or in decorative ponds that are part of the landscaping, wells, nearby lakes, and rivers.

The amount of **heat** required for personnel comfort depends on the plant's location, which in turn, influences the types and capacities of heaters selected. Generally, factory areas can be kept a little cooler, about 65°F than the 72°F recommended for office areas. Heating systems include warm air, hot water, steam, electric, and radiant. Warm air requires a furnace to heat the air and ducts and blowers to distribute it. Circulating hot water and steam heat also require boilers and furnaces and a network of distribution pipes and radiators. Electric space heaters require fixed wiring and local outlets. Unit radiant heats may be fueled by gas, steam, hot water, or electricity and are placed above doors and work areas, oriented to direct heat where it is required. Piping can be embedded in the concrete slab on grade, and in other floors, walls, and ceilings to provide radiant heat from circulating hot water.

Ventilation, the introduction of fresh outside air, the exhaust of stale inside air, or merely the movement of otherwise still inside air, can be effected naturally or mechanically. Natural ventilation requires windows, skylights, louvers, or other openings. Mechanical ventilation requires fans and blowers (and sometimes ducts) to draw air in, circulate it, and exhaust it. The number of cubic feet per minute (cubic metres per minute) of air per person required by people working in an office is about 10 (0.3), and between 25 and 50 (0.7 to 1.4) for those working on the factory floor. The total amount of air needed and the number of air changes per hour determine the number and sizes of fans, motors, and ducts. One change per hour is too little, with no discernible difference in air quality; 50 to 60 changes of air per hour are too many, and the resulting high-velocity drafts cause sensations of chilling and accompanying discomfort. Minimally, 5 changes of air per hour are required.

Air conditioning adds to employee comfort, increases their productivity, and is essential for the manufacture of certain products. The calculation of the expected heat gains required to specify an **air-conditioning** installation is similar to the procedure for calculating heat loss in the design of a heating system. For air conditioning, the required cooling load is calculated in Btu per hour and converted to required tons of refrigeration by dividing by 12,000. (See Sec. 12.4.) The tonnage required would be one basis for the selection of the type of water-cooled or evaporative condensers, compressors, air handling units, motors, pumps, ducts, registers, circuitry, panels, and controls to be installed. Packaged air-conditioning units mounted on window sills, floors, ceilings, or roofs are often used. (See Merritt and Ricketts, ''Building Design and Construction Handbook.'')

The design and installation of a **compressed-air system** includes the summation of the volume and pressure of air required at all plant locations. The pipe diameters and total pressure drops between compressor and the most remote point of delivery must be determined. Pressure drop is a function of pipe and hose friction and the requirements of air-powered devices. Piping may be fixed, by and large, but the number and types of air-powered devices will change from time to time as production processes are changed or rearranged. Thus, there is some variability to be expected in the calculations to determine compressor discharge volume and pressure. Suitable allowances for unknown quantities are usually factored into the final design selection.

Internal and external communications systems must be installed. With autofacturing (see Sec. 17), the design, manufacture, production control, inventory control, storekeeping, warehousing, sales, and shipping records are all integrated and tied to the same information database. An internal local-area network (LAN), with computers, terminals, displays, and printers distributed throughout the plant and offices, will be required to plan, analyze, order, receive and accept material, record, feed back data, update files, and control and correct operating conditions. AGVs and mobile robots can be programmed to navigate off beacons installed throughout the plant.

Parking for employees and visitors must include spaces for handicapped persons. Parking lots are usually paved with 3 in (7.6 cm) of asphaltic cover over 6 in (15.2 cm) of gravel base. Lines are painted to designate spaces, which may be ''straight in'' (at a 90° angle to the curb), or at a smaller angle, typically 45° to 60°. The angle used influences the width of the aisles, depth (distance from the edge of the aisle to the curb) of each space, and the amount of curb length required for each car. For example, parking at a 45° angle requires an aisle width of about 13 to 15 ft (4.0 to 4.6 m), a space depth of about 20 to 21 ft (6.1 to 6.4 m) and uses about 13 ft (4.0 m) of curb per space (because of the overlaps); a 90° layout requires an aisle width of about 24 to 27 ft (7.3 to 8.2 m) and a space depth of about 19 to 20 ft (5.8 to 6.1 m) and uses about 9 to 10 ft (2.7 to 3.1 m) of curb per space. The width of each space (except those for the handicapped, which are wider) ranges from 9 to 10 ft (2.7 to 3.1 m) and their lengths from 19 to 20 ft (5.8 to 6.1 m). The number of parking spaces to be provided depends on the number of people expected and the extent to which public transportation is available and used. It is expected that there will be more than one employee per vehicle. Factors ranging from 1.2 to 2.5 persons per car can be used, depending on the firm's best estimate of the practices of its employees. For multiple-shift operations, it must be recognized that those working the second shift will arrive and need parking spaces before those on the first shift leave and vacate them. For those using public transportation, a shelter against the weather may be erected; often it is provided by the bus company.

In addition to parking space for automobiles, **space must be provided for trucks** that bring material to the plant and carry products away. Sizes of trucks, truck tractors, and their trailers vary widely, as do their turning radii. Many trucks will drive in frontward, maneuver to turn around, and back into the loading docks and platforms. Space must be provided for them to do this, even when there are other trucks present. The minimum size apron (measured by the distance from the outermost obstruction, whether it be a part of the building, the front of another truck already in the loading dock, or anything else that is in the way), required to maneuver a tractor-trailer into or out of a loading position, in one maneuver and with no driver error, varies with the length of the tractor-trailer expected and the width of the position to be provided. For example:

Tractor-trailer length	Position width	Minimum apron size
35 ft (10.7 m)	10 ft (3.1 m)	46 ft (14.0 m)
	12 ft (3.7 m)	43 ft (13.1 m)
	14 ft (4.3 m)	39 ft (11.9 m)
40 ft (12.2 m)	10 ft (3.1 m)	48 ft (14.7 m)
	12 ft (3.7 m)	44 ft (13.4 m)
	14 ft (4.3 m)	42 ft (12.8 m)
45 ft (13.7 m)	10 ft (3.1 m)	57 ft (17.4 m)
	12 ft (3.7 m)	49 ft (15.0 m)
	14 ft (4.3 m)	48 ft (14.6 m)

Truck heights range from about 8 ft (2.4 m) for a panel truck to around 13.5 ft (4.1 m) for double-axle semis and others. Doorways must be sized accordingly. Seals and pads may be added around the doors to fill the gap between the back of trucks and the building. Besides conventional rollup doors, plastic strips and air curtains may be used to provide a partial barrier between the plant's environment and the weather.

The **plant's security** measures should include structural protection against wind, rain, flood, lightning, earthquakes, and fire. Security against intruders, breakins and vandalism can include fencing, gates, perimeter lights, surveillance cameras, and sensors. Security guard booths may be purchased as prefabricated units, complete with lights, heat, and air conditioners.

Emergency **egress** should provide for more than one route to safety, minimal distances to doors, doors that are locked from the outside but can be opened with a push from the inside (by panic bars), all to be accessible and usable by the handicapped. When designing a plant for ease of use by handicapped employees and visitors, all physical barriers must be eliminated and aids installed, such as ramps, braille signs, wheelchair-width doors and toilet booths, wheelchair-height sinks and drinking fountains, and the like. Applicable local building codes and federal regulations will guide and control the final designs.

Most of the above services and systems are built into the structure or influence its design and, therefore, must be determined before the specifications of the building become final.

Building Structure

The specifications for an industrial plant's **structure** depend on its contents, intended use, general location, and specific site. In the usual order in which they are constructed are foundation and footings, columns (and bay sizes), beams and roof trusses, exterior walls, floor slab, roof decking and covering, exterior doors and fenestration, interior partitions, walls, doorways, services (electric power, compressed air, etc.), interior decor, and other special features.

Firm foundations and footings are required to support the columns, peripheral and some interior walls, machinery, and other equipment. Especially heavy machines, or those subject to large dynamic loads (often repetitive), may require special design that incorporates measures to isolate vibrations. Depth, size, and foundation reinforcement depends on the subsurface conditions. Installation of piles may be dictated by unsuitable load-bearing soil. Almost all foundations consist of cast-in-place concrete; in rare instances, load-bearing concrete blocks are set onto a previously poured concrete base. Site topography and location of the building may require the construction of retaining walls; these may be cast concrete or assembled with precast concrete sections which may serve also to provide a decorative treatment. The subgrade on which the concrete floor slabs will be poured must be well-compacted and made level. Often, the floor slab is not cast until heavy equipment (used to erect superstructure) is removed from the site.

Steel superstructure members are designed to provide the clear spans delineated by the selected **bay sizes**. They also support intermediate floors (if any); roof-mounted equipment; material handling equipment such as monorails; and lighting fixtures, piping, ductwork, and other utilities. The design must account for all dead and live loads, usually in accordance with applicable local building codes and other accepted structural codes. (See Secs. 5, 6, and 12.)

The sizes and locations of **columns and beams** establish the bay sizes. The longer the span, the larger the bay size, but this reflects back into construction with heavier columns, deeper beams and trusses, and concomitant higher costs. Inasmuch as larger bay sizes permit greater freedom in plant layouts and ease material handling, the added expense of large bay sizes is often worth it. Accordingly, the trend in plant design is to incorporate large bays. While any bay size is feasible, a cost/benefit tradeoff may set reasonable limits. Typical bay sizes are 30×40 ft (9×12 m), 40×60 (12×18) and 40×80 (12×24). There are warehouses whose bay size is dictated by the requirement to accommodate stacks of standard pallets with minimum waste space. Aircraft manufacturing plants and commercial hangars enclose enormous column-free cavernous spaces; lengths of 300 to 400 ft (91 to 122 m) are the norm in those applications.

When columns must support heavy traveling bridge cranes, a second row of columns is incorporated into the main columns to provide support for rails and to effect a stiffer structural configuration.

Beams are set at the top of columns and establish the clear height of the building interior; 15, 20, and 25 ft (4.5, 6.1, and 7.6 m) are typical in manufacturing areas, and 30 to 40 ft and more (9.1 to 12.2 m) are employed in warehouse space. When a two-story office is part of a single-level plant (Fig. 12.1.7) the overall height of the building is often set to the second-story height to permit a simple flat roof. Factory clear heights should be at least the height of the highest machine, with a generous margin added; for large products, the clear height is often designed to be twice the height of the largest product. Anything suspended from the beams or girders reduces the clear height. Deeper open roof trusses permit some piping, wiring, and other services to be woven through them and light fixtures placed between them, thereby not reducing clear working space. Roof decking and roofing is affixed to roof trusses or beams.

Exterior walls can be load bearing (support one end of a beam) or nonbearing. If nonbearing, all beam loads are transferred to columns spaced at intervals along the building perimeter. Walls are constructed of masonry [brick or concrete block masonry units (CMUs), sometimes incorporating glass block]; metal panels, usually integrally stiffened; wood for special applications (storage of highway deicing salts); natural stone or stone veneer/precast-concrete panels; or stone veneer on masonry backup walls. Where conditions allow, poured concrete walls are cast on the flat (at grade), then tilted up and secured into place; this technique is attractive especially for warehouses with repetitive wall construction devoid of windows and other openings. Metal panels are usually galvanized steel, with or without paint, or painted aluminum.

Factory floors may be required to sustain live loads from less than 100 pounds per square foot (psf) (0.5 kPa) to over 2,000 psf (96 kPa). A general-purpose light-assembly floor ordinarily will have no less than 100 psf (0.5 kPa) floor load capacity. A special purpose plant floor may be built with floor load capacities which vary from place to place in accordance with the requirements for different load-carrying capacity. Certainly, in the extreme, to build in a maximum floor loading capacity of, say, 2,000 psf (96 kPa) throughout a plant when there is minimal likelihood for that requirement other than in discrete areas, would not be cost-effective. Concentrated live loads (most often from wheeled material handling vehicles) are accounted for in the design of the floor slabs as required. The final design of the plant floor will meld the above factors with other requirements so that the sum of all dead and live loads can be safely sustained in the several areas of the floor.

Virtually all slab on-grade concrete floors are cast in place; in rare cases, precast concrete sections are used. Wooden plank flooring is rarely used on new construction. Upper floors are most often constructed with precast concrete planks overlaid with a cement mortar topping coat, or employ ribbed decking. When upper-floor loading capacities require it, those floors can also be cast in place; in those instances, concrete is cast into ribbed metal decking which acts as wet form work and remains in place. End grain wood blocks may be set atop a concrete floor to mitigate against unavoidable spillage of liquids. (See Sec. 12.2.)

The load-carrying capacity of concrete slabs on grade is ultimately limited not only by the strength of the concrete itself, but also by the ability of the subgrade material to resist deformation. The proper design of the floor, especially at grade, will account for all the parameters and result in a floor which will safely sustain design floor loading. Automatic guided vehicle systems and mobile robots (see Sec. 10) require level and smooth floors. The floor surface may be roughened slightly with a float to reduce slipping hazards, or have a steel trowel finish to accommodate AGV and mobile robot navigation. If it is contemplated that products or equipment will be moved by raising and floating them on films of air, the floor must be crack-free. If a slight floor slope can be tolerated from an operational point of view, that will ease cleaning by allowing water to flow to drains. The slab's surface may be coated, treated, or tiled for protection, comfort, ease of maintenance, and/or aesthetics. Expansion joints around column bases will inhibit propagation of small cracks resulting from differential settlement between column footings and floor slabs.

At this stage, the building looks like the one shown in Fig. 12.1.10.

A **flat roof** is always slightly pitched to drain water toward scuppers, gutters, and downspouts. It is constructed with ribbed metal decking or precast concrete planks, topped with a vapor barrier, insulation, a topping surface, flashing, sealants or caulking, and roof drains. The covering of a **built-up roof (BUR)** comprises three to five layers of roofing felt (fiberglass, polyester fabric, or other organic base material), each layer mopped with hot bitumen (asphalt or coal tar pitch). The wearing surface of roofing may include a cap sheet with fine mineral aggregate, reflective coating, or stone aggregate. When extensive roof traffic is anticipated, pavers or wood walkways are installed. A recent successful roof surface is composed of a synthetic rubber sheet, seamless except at lapped, adhesively bonded joints. It has proved to be a superior product, providing long, carefree life.

The seal between roofing and parapet walls or curbed openings is effected with **flashing** bent and cemented in place with bituminous cement. The flashing material may be galvanized steel aluminum, copper, stainless steel, or a membrane material.

Flat roofs lend themselves to ponding water to help cool the plant. Roof ponds (and water sprays) can reduce interior temperatures by 10 to 15°F (6 to 9°C) in the summer. Roof ponds can serve as a backup source of water for fire fighting. If water is ponded on a roof, roof construction must be handled expressly for that purpose. There are structural implications which must be considered as well.

Doors and ramps should be made 2 ft (0.6 m) larger than the largest equipment or material expected and large enough to allow ingress of fire fighting apparatus. It is often convenient to place very large pieces of equipment such as molding machines and presses inside the building envelope before the walls are completed. After exterior walls and roof are in place, the building interior is sufficiently secure for assembling materials for the remaining construction and to receiving smaller equipment.

Interior walls and **partitions** (masonry, wood, wallboard, and metal) follow, after which office flooring and framing are installed (Fig. 12.1.11). The remainder of the construction involves completion of wiring, lighting, and other services; application of paint or wall coverings, floor coverings, and decor; and so on.

Other Considerations

The **applicable standards, regulations, and procedures** of the 1971 Williams-Steiger Occupational Safety and Health Act (OSHA), as amended, must be followed in the construction and operation of the building and the design and use of the plant's equipment; likewise, the regulations of the Environmental Protection Agency (EPA), as amended, and the design standards of the Americans With Disabilities Act (ADA), as amended, must be followed.

Color can serve several purposes in an industrial plant. As an aid to safety, it can be used to identify contents of pipes, dangerous areas, aisles, moving parts of equipment, emergency switches, and fire fighting and first aid equipment. It also can be used to improve illumination, conserve energy, reduce employee fatigue and influence on morale positively.

OSHA, American National Standards Institute (ANSI) specification Z53.1, and specific safety regulations require the use of specific **identity colors** in certain applications. As a general guide, yellow or wide yellow-and-black bands are used to indicate the need for caution and to highlight physical hazards that persons might trip on, strike against, or fall into, such as edges of platforms, low beams, stairways, and trafficked aisles along which equipment moves. Orange designates dangerous parts of machines or energized equipment that may cut, crush, shock, or otherwise injure, such as the inside of gear boxes, gear covers, and exposed edges of gears, cutting devices, and power jaws. Red is the basic color for the identification of fire protection equipment and apparatus, danger and stop signs, fire alarm boxes, fire exit signs, and sprinkler piping. Green designates safety items, such as first aid kits, gas masks, and safety deluge showers, or their locations. Blue designates caution and is limited to warning against starting, use of, or movement of equipment under repair, and utilizes tags, flags, or painted barriers. Purple designates radiation hazards. Black, white, or a combination of both designated traffic control and housekeeping markings, such as aisleways, drinking fountains, and directional signs.

Fig. 12.1.10 A view of a plant during construction. Shown are its columns, roof trusses, and exterior masonry walls. The reinforced-concrete floor slab is being poured over compacted soil. *(Source: VMA, Inc.)*

There are also color conventions for the identification of fluids conducted in pipes. Instead of being painted their entire length, pipes are painted with colored bands and labels at intervals along the lines, at valves, or where pipes pass through walls. ANSI Standard A13.1-1975 specifies the following colors for pipe identification: red for fire protection; yellow for dangerous materials; blue for protective materials; green and white, black, gray, or aluminum for safe materials.

The **noises** created during the operation of a plant can be dealt with at their **sources, along their paths,** and at their **receivers**. At the sources, noise is minimized or eliminated by: changing the process; replacing (with quieter) equipment; modifying equipment by redesign or component changes; moving to another location; installing mufflers and shock mounts; using isolation pads; and shielding and enclosing equipment with material having a high sound transmission loss (STL) value. STL is a measure of the reduction in sound pressure as it passes through a material. Along the paths, attenuation of noise is enhanced by increasing the distance between sources and receivers; introducing discontinuities in the transmission path, such as barriers and baffles which interrupt direct transmission; installing acoustical barriers with an STL of at least 24 dB and with sufficient absorption to prevent reflection of the noise back to its source; and by placing sound-absorbent material on surfaces along its path, such as acoustical ceilings and floor and wall coverings. At the receivers, enclosures, workstation partitions of sound-absorbing material, earplugs, and ''white-noise'' generators can be used. (See Secs. 12.6 and 18.2.)

Provisions must be made for **waste disposal,** including: disposal of refuse and garbage, treatment of process fluids and solids, and waste and recyclables recovery, all in accordance with applicable EPA and other regulations.

Among many other things, the plant design process must address matters such as fuel storage, storm and surface drainage, snow removal facilities and procedures (if the local climate warrants), design for ease of maintenance of the building as well as the grounds and associated landscaping, the articulation of the architect's idiom, energy efficiency in the materials of construction and the equipment installed to service the plant, and diligence in compliance with environmental impact studies (if required).

After the plant is designed, but before a commitment is made to build it, its operations should be simulated to bring forth and correct any errors or omissions. In addition to testing its specifications for normal conditions, extremes (severe storms, power outages, truckers' strikes, etc.) should also be evaluated. This simulation is similar to that done before the plant's site is made final, but comes after the structure and layout have been designed. A sensitivity analysis should be made to see the effect on operations of changes in inputs and operating conditions. Depending on these analyses and best guesses as to the future, adjustments may have to be made to ensure that the plant will operate effectively and economically under all reasonable conditions, and that it has no features that will harm people or do damage to the products or the environment.

Fig. 12.1.11 A view of framing for the first- and second-story offices of a plant, with a roof beam and the steelwork supporting the second floor visible. *(Source: VMA, Inc.)*

CONTRACT PROCEDURES

Cost Estimates

Cost estimates fall into three general classes:

1. Preliminary estimates made usually from sketch drawings and brief outline specifications to determine the approximate total cost of a project.

2. Comparative estimates made usually during the progress of design to determine the relative cost of two or more alternative arrangements of equipment, type of building, type of floor framing, and the like.

3. Detail estimates made from final plans and specifications and based on a careful quantity survey of each component part of the work.

Primary quantity estimates are usually more accurate when comparison with comparable projects is lacking or not feasible. The procedure entails computations based on quantity takeoffs from preliminary plans and specifications, and can include the gross area of exterior walls, interior partitions, floors, and roof. Each is multiplied by known (or estimated) unit cost factors. Other items, such as number of electrical outlets and number of plumbing fixtures and sprinklers, are estimated, and their cost computed. Equipment costs can be based on preliminary quotations from manufacturers.

The following items should be included in preliminary estimates (or in other more detailed estimates which may follow as plans develop to the final stage): land cost; fees to real estate brokers, lawyers, architects, engineers, and contractors; interest during construction; building permits; taxes, including local sales or use taxes; demolition of existing structures including removal of old foundations; yard work including leveling, drainage, fencing, roads, walks, landscaping, yard lighting, and parking spaces; transportation facilities including railroad tracks, wharves, and docks; power supply and source; water supply and source; sewer and industrial waste disposal. A judicious **contingency factor** is included to provide for unforeseen conditions that may arise during the development of the project. It may amount to 5 to 15 percent (or more) depending on the character and accuracy of the estimate, whether the proposed design and construction will follow established procedures or incorporate new state-of-the-art features, and the exact purpose for which the estimate is made.

Especially for complex new or altered construction, estimates may be updated continually as a matter of course. This will serve to monitor the evolving cost of the project and the time constraints placed on construction.

Working Drawings, Specifications, and Contracts

The technical staff of a given industry has special knowledge of trade practices, process requirements, operating conditions, and other fundamentals affecting successful operation in that field and is best fitted to determine the basic factors of process design and plant expansion. Unless the company is extremely large, it is unlikely that they will have the specialized staff or that their own staff will have the time available to undertake the complete layout. The efficient transformation of these requirements into completed construction usually requires experience of a different nature. Therefore, it is generally advisable and economical to employ engineers or architects who specialize in this particular field.

Three general procedures are in common use. First, the employment on a percentage or fixed-fee basis of an engineering and construction organization skilled in the industrial field to prepare the necessary working drawings and specifications, purchase equipment and materials, and execute the work. This has become known as **design/build**. For the duration of the project, such an organization becomes a part of the owner's organization, working under the latter's direction and cooperating closely with the owner's technical staff in the development of the design and in the purchase and installation of equipment and materials. This procedure permits construction work to start as soon as basic arrangements and costs have been determined, but before the time required to complete all working drawings and specifications. This is often termed **fast tracking**. Such a program will result in the earliest possible completion consistent with economical construction.

A second procedure is to employ engineers or architects with wide experience in the industrial field to prepare working drawings and specifications and then to obtain **competitive lump-sum bids** and award separate contracts for each or a combination of several subdivisions of the work, such as foundations, structural steel, and brickwork. This method provides direct competition restricted to units of like character and permits intelligent consideration of the bids received. Provision must be made for proper coordination of these separate contracts by experienced and skilled field supervision. In recent years, a **construction manager** has been hired for this purpose. This procedure requires more time than that first described, since all work of a given class should be completely designed before bids for that subdivision are sought. Where construction conditions are uncertain or hazardous, the first method is likely to be more economical. A combination of the first method for uncertain conditions and the second method for the balance may prove most advantageous at times.

A third procedure is to employ engineers or architects to complete all plans and specifications and then **award a lump-sum contract** for the entire work, or one for all building work, and one or more supplementary major contracts to furnish and install equipment. This method is particularly useful where there are no serious complications or hazards affecting construction operations, but it requires considerably more time, since most of the working drawings and specifications must be complete before construction is started. It has the significant advantage, however, of fixing the total cost within narrow limits before the work starts, provided the contracts cover the complete scope of work intended and no major changes ensue.

CONSTRUCTION

The design, construction, occupancy, and operation of an industrial plant is a complex endeavor involving many people and organizations. **Project control tools and techniques** such as the critical path method (CPM), the program evaluation and review technique (PERT), bar charts, dated start/stop schedules, and daily ''do lists'' and ''hot lists'' of late items are all helpful in keeping construction on time and within budget.

Checkpoints and milestones, with appropriate feedback as the project progresses, are established to monitor progress. Bailout points are established in the event the project must be aborted sometime after the beginning of construction. On the other hand, contingency plans should be in hand and include planned reassignment of financial and personnel resources to keep the project on schedule. Figure 12.1.12 shows the scheduled and actual dates of completion of the phases noted for a small plant depicted in several of the previous figures.

Some portion of the organization (often the construction manager's office), is charged with the delicate task of coordinating contractors and the multiplicity of trades at the job site, and as part of its function, it will generate ''punch lists'' of deficient and/or incomplete work which must be completed to the owner's satisfaction before payment therefore is approved.

	Scheduled	Actual
Project planning	March	March
Basic layout	April	April
Structural design	April	April
Equipment specifications	April	April
Construction contract	May	May
Ground breaking	June	June
Detailed office layout	June	June
Detailed plant layout	July	July
Equipment purchases	August	August
Furniture purchases	September	September
Organization firmed	September	September
Steelwork completed	October	October
Masonry completed	October	October
Roof completed	November	November
Staffing and training	November	November
Systems designed	November	November
Forms designed	December	December
Offices completed	December	December
Equipment received	December	December
Building occupied	December	December

Fig. 12.1.12 The project schedule and completion dates for the single-level 202,800 ft² industrial plant used as an example in Figs. 12.1.1 to 12.1.7, 12.1.10, and 12.1.11. *(Source: VMA, Inc.)*

12.2 STRUCTURAL DESIGN OF BUILDINGS

by Aine M. Brazil

REFERENCES: ''Manual of Steel Construction—Allowable Stress Design,'' American Institute of Steel Construction. ''National Design Specification for Wood Construction,'' American Forest and Paper Association. ''Design Values for Wood Construction,'' American Forest and Paper Association. ''Uniform Building Code,'' International Conference of Building Officials. ASCE 7-93, ''Minimum Design Loads for Buildings and Other Structures,'' American Society of Civil Engineers. Blodgett, ''Design of Welded Structures,'' J. F. Lincoln Arc Welding Foundation. ''Masonry Designers Guide,'' The Masonry Society.

LOADS AND FORCES

Buildings and other structures should be designed and constructed to support safely all loads of both permanent and transient nature, without exceeding the allowable stresses for the specified materials of construction. Dead loads are defined as the weight of all permanent construction; live loads are those loads produced by the use or occupancy of the building; environmental loads include the effects of wind, snow, rain, and earthquakes.

Live loads on floors are generally regulated by the building codes in cities or states. For areas not regulated, the following values will serve as a guide for live loads in lb/ft² (kPa): rooms for habitation, 40 (1.92); offices, 50 (2.39); halls with fixed seats, 60 (2.87); corridors, halls, and other spaces where a crowd may assemble, 100 (4.76); light manufacturing or storage, 125 (5.98); heavy manufacturing or storage, 250 (11.95); foundries, warehouses 200 to 300 (9.58 to 14.37). Floor decks and beams that support only a small floor area must also be designed for any local concentrations of load that may come upon them. Girders, columns, and members that support large floor areas, except in buildings such as warehouses where the full load may extend over the whole area, may often be designed for live loads progressively reduced as the supported area becomes greater. Where live loads, such as cranes and machinery, produce **impact** or **vibration,** static loads should be increased as follows: elevator machinery, 100 percent; reciprocating machinery, 50 percent; others, 25 percent.

Roof live loads should be taken as a minimum of 20 lb per horizontal ft² (957.6 kPa) for essentially flat roofs (rise less than 4 in/ft), varying linearly with increasing slope to 12 lb/ft² for steep slopes (rise greater than 12 inches per foot). Reductions may also be made on the basis of tributary area greater than 200 ft² (18.58 m²) of the member under consideration, to a maximum of 40 percent for tributary areas greater than 600 ft². The minimum roof live load shall be 12 lb/ft² after all reduction factors have been applied. Where **snow loads** occur, appropriate design values should be based on the local building codes.

Dead loads are due to the weight of the structure, partitions, finishes, and all permanent equipment not included in the live load. The weights of common building materials used in floors and roofs are given below (see also Sec. 6).

Material	Weight, lb/ft²
Asphalt and felt, 4-ply	3
Corrugated asbestos board	5
Glass, corrugated wire	5–6
Glass, sheet, ⅛ in thick	2
Lead, ⅛ in thick	8
Plaster ceiling (suspended)	10
Acoustical tile	1–2
Sheet metal	1–2
Shingles, wood	3
Light weight-concrete over metal deck	30–45
Sheathing, 1 in wood	3
Skylight, 3⁄16 to ¼ in, glass and frame	6–8
Slate, 3⁄16 to ½ in thick	8–20
Tar and gravel, 5-ply	6
Tar and slag, 5-ply	5
Roof tiles, plain, ⅝ in thick	20

NOTE: lb/ft² × 0.04788 = kPa.

Earthquake Effects Two distinct methods of designing structures for seismic loads are currently accepted. The more familiar method, employed by the Uniform Building Code (UBC), yields equivalent loading for use with the allowable stress design approach. The National Earthquake Hazard Reduction Program (NEHRP) has developed Recommended Provisions for the Development of Seismic Regulations for New Buildings, which is based on the ultimate strength design approach. The NEHRP approach is the basis for model codes, such as BOCA (Building Officials and Code Administrators International, Inc.) National Building Code.

Following the UBC design approach, the static force procedure represents the earthquake effects as equivalent static lateral forces applied at each floor level. The total design lateral force (called **base shear**) is calculated by the formula

$$V = \frac{ZIC}{R_w} W \qquad \text{where} \qquad C = \frac{1.25\,S}{T^{2/3}} \leqq 2.75$$

V = design base shear; Z = factor representing the degree of regional seismicity, ranging from 0.4 for seismically active areas with proximity to certain earthquake faults (Zone 4) to 0.075 for areas of low seismicity (Zone 1); I = importance factor (1.25 for essential facilities, 1.0 for most others); R_w = coefficient representing the type of lateral-force-resisting system of the building, ranging from 4 for a heavy timber bearing wall system (where bracing carries gravity loads as well as lateral loads) to 12 for buildings with highly ductile systems, such as special moment-resisting frames (this coefficient is a measure of the past earthquake resistance of various structural systems); T = the fundamental period of vibration, seconds, of the building in the direction under consideration (this coefficient represents the acceleration effects of the dynamic response of the structure); S = coefficient representing possible amplification effects of soil-structure interaction and is taken as 1.5 unless a lower value is substantiated by soils data; and W = the total dead load (including partitions) plus snow loads over 30 lb/ft^2 (1.436 Pa) and 25 percent of any storage or warehouse live loads.

The **fundamental period** T, used to calculate the seismic coefficient C, may be determined by a rational analysis of the structural properties and deformation characteristics of the structure, or it may be estimated by the formula $T = C_t(h_n)^{3/4}$, where C_t = 0.035 (0.0853) for steel moment-resisting frames, 0.030 (0.0731) for reinforced-concrete moment-resisting frames and eccentrically braced frames, and 0.02 (0.0488) for all other buildings.

The **base shear** V is considered to be distributed over the height of the structure according to the formula

$$F_x = \frac{(V - F_t)w_x h_x}{\Sigma w_i h_i}$$

where $F_t = 0.07TV$ is the lateral force at the top and F_x is the lateral force at any level x; w_x is the weight assigned to level x; and h_x is the height of level x above the base.

For stiff, low-rise buildings, such as one- to three-story, steel-braced frame or concrete shear wall structures, it is common practice to compute the design base shear using the maximum values for the coefficients C. Thus, the design base shear for a two-story concrete shear wall building in Zone 4 might be taken as

$$V = ZICW/R_w = (0.4 \times 1.0 \times 2.75 \times W)/8 = 0.1375W.010$$

Where floors are **rigid diaphragms,** such as concrete fill over metal deck or concrete slabs, lateral forces are distributed to the vertical-resistive elements on the basis of their relative stiffness. Where floors or roofs are flexible diaphragms, such as some metal deck with nonstructural fill, plywood, or timber planking, lateral forces are distributed to the resistive elements on the basis of tributary area. Where a rigid diaphragm exists, a torsional moment, equal to the story shear multiplied by the greater of the real eccentricity between the center of mass and the center of rigidity of the resistive elements or 5 percent of the maximum building dimension at that level, is applied to the diaphragm around a vertical axis through the center of rigidity of the resistive elements. Direct shears in the elements are increased by those induced by the torque when additive but are unaltered when subtractive in order to arrive at design lateral seismic loads to the resistive element.

Earthquake forces on portions of structures, such as walls, partitions, parapets, stacks, appendages, or equipment, are calculated by the formula $F_p = ZI_pC_pW_p$, where F_p = the equivalent lateral static force acting at the center of mass of the element; Z and I_p = coefficients previously defined (although I_p for life safety equipment may be greater than that for the parent structure); C_p = horizontal force factor and is taken as 2.0 for cantilever chimneys, stacks, and parapets as well as ornamental appendages and as 0.75 for other elements such as walls, partitions, ceilings, penthouses, and rigidly mounted equipment; and W_p = weight of element. For flexibly mounted equipment C_p may conservatively be taken as 2.0 or may be determined by rational analysis considering the dynamic properties of both the equipment and the structure which supports it. Seismic loads are applied to walls and partitions normal to their surface and to other elements in any horizontal direction at the center of mass.

Wind Pressures on Structures Every building and component of buildings should be designed to resist wind effects, determined by taking into consideration the geographic location, exposure, and both the shape and height of the structure. For structures sensitive to dynamic effects, such as buildings with a height-to-width ratio greater than 5, structures sensitive to wind-excited oscillations, such as vortex shedding or icing, and tall buildings [height greater than 400 ft (121.9 m)] special consideration should be given to design for wind effects and procedures used should be in accordance with approved national standards. Wind loads should not be reduced for the shading effects of adjacent buildings.

Wind pressure on walls of buildings should be assumed to be a minimum of 15 lb/ft^2 (0.72 kPa) on surfaces less than 50 ft above the ground. For buildings in exposed locations and in locations with high wind velocity (over 70 mi/h or 112.5 km/h), pressures should be calculated based on the following procedure.

Design wind pressure may be determined by the following formula, which is based on the Uniform Building Code: $P = C_eC_qq_sI_w$, where P = design wind pressure; C_e = coefficient which varies with height, exposure, and gust factor (refer to Table 12.2.1); C_q = pressure coefficient (refer to Table 12.2.2), q_s = wind stagnation pressure at standard height of 33 ft (refer to Table 12.2.3); I_w = importance factor (essential or hazardous facilities, 1.15; other structures, 1.0). The **basic wind speed** is the fastest wind speed at 33 ft (10 m) above the ground of terrain Exposure C and associated with an annual probability of occurrence of 0.02 [varies from 70 to 100 mi/h (112 to 161 km/h)]. The exposure category defines the characteristics of ground surface irregularities at the specific site: Exposure B has terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger; Exposure C is flat, open terrain with scattered obstructions having a height of less than 30 ft; Exposure D is flat, unobstructed areas exposed to wind flowing over large bodies of water.

For exceptionally tall, slender or flexible buildings, it is recommended that a wind tunnel test be performed on a model of the building.

Table 12.2.1 Combined Height, Exposure, and Gust Factor Coefficient C_e*

Height above average level of adjoining ground, ft†	Exposure D	Exposure C	Exposure B
0–15	1.39	1.06	0.62
20	1.45	1.13	0.67
25	1.50	1.19	0.72
30	1.54	1.23	0.76
40	1.62	1.31	0.84
60	1.73	1.43	0.95
80	1.81	1.53	1.04
100	1.88	1.61	1.13
120	1.93	1.67	1.20
160	2.02	1.79	1.31
200	2.10	1.87	1.42
300	2.23	2.05	1.63
400	2.34	2.19	1.80

* Values for intermediate heights above 15 ft (4.6 m) may be interpolated.
† Multiply by 0.305 for meters.

Table 12.2.2 Pressure Coefficients C_q

Structure or part thereof	Description	C_q factor
1. Primary frames and systems	**Method 1** (normal force method)	
	Walls:	
	Windward wall	0.8 inward
	Leeward wall	0.5 outward
	Roofs[a]:	
	Wind perpendicular to ridge	
	Leeward roof or flat roof	0.7 outward
	Windward roof	
	Less than 2:12 (16.7%)	0.7 outward
	Slope 2:12 (16.7%) to less than 9:12 (75%)	0.9 outward or 0.3 inward
	Slope 9:12 (75%) to 12:12 (100%)	0.4 inward
	Slope > 12:12 (100%)	0.7 inward
	Wind parallel to ridge and flat roofs	0.7 outward
	Method 2 (projected area method)	
	On vertical projected area	
	Structures 40 feet (12 192 mm) or less in height	1.3 horizontal any direction
	Structures over 40 feet (12 192 mm) in height	1.4 horizontal any direction
	On horizontal projected area[a]	0.7 upward
2. Elements and components not in areas of discontinuity[b]	Wall elements	
	All structures	1.2 inward
	Enclosed and unenclosed structures	1.2 outward
	Partially enclosed structures	1.6 outward
	Parapets walls	1.3 inward or outward
	Roof elements[c]	
	Enclosed and unenclosed structures	
	Slope < 7:12 (58.3%)	1.3 outward
	Slope 7:12 (58.3%) to 12:12 (100%)	1.3 outward or inward
	Partially enclosed structures	
	Slope < 2:12 (16.7%)	1.7 outward
	Slope 2:12 (16.7%) to 7:12 (58.3%)	1.6 outward or 0.8 inward
	Slope > 7:12 (58.3%) to 12:12 (100%)	1.7 outward or inward
3. Elements and components in areas of discontinuities[b,d,e]	Wall corners[f]	1.5 outward or 1.2 inward
	Roof eaves, rakes or ridges without overhangs[f]	
	Slope < 2:12 (16.7%)	2.3 upward
	Slope 2:12 (16.7%) to 7:12 (58.3%)	2.6 outward
	Slope > 7:12 (58.3%) to 12:12 (100%)	1.6 outward
	For slopes less than 2:12 (16.7%)	
	Overhangs at roof eaves, rakes or ridges, and canopies	0.5 added to values above
4. Chimneys, tanks, and solid towers	Square or rectangular	1.4 any direction
	Hexagonal or octagonal	1.1 any direction
	Round or elliptical	0.8 any direction
5. Open frame towers[g,h]	Square and rectangular	
	Diagonal	4.0
	Normal	3.6
	Triangular	3.2
6. Tower accessories (such as ladders, conduit, lights and elevators)	Cylindrical members	
	2 inches (51 mm) or less in diameter	1.0
	Over 2 inches (51 mm) in diameter	0.8
	Flat or angular members	1.3
7. Signs, flagpoles, lightpoles, minor structures[h]		1.4 any direction

[a] For one story or the top story of multistory partially enclosed structures, an additional value of 0.5 shall be added to the outward C_q. The most critical combination shall be used for design.
[b] C_q values listed are for 10-ft^2 (0.93-m^2) tributary areas. For tributary areas of 100 ft^2 (9.29 m^2), the value of 0.3 may be subtracted from C_q, except for areas at discontinuities with slopes less than 7 units vertical in 12 units horizontal (58.3% slope) where the value of 0.8 may be subtracted from C_q. Interpolation may be used for tributary areas between 10 and 100 square feet (0.93 m^2 and 9.29 m^2). For tributary areas greater than 1,000 ft^2 (92.9 m^2), use primary frame values.
[c] For slopes greater than 12 units vertical in 12 units horizontal (100% slope), use wall element values.
[d] Local pressures shall apply over a distance from the discontinuity of 10 ft (3.05 m) or 0.1 times the least width of the structure, whichever is smaller.
[e] Discontinuities at wall corners or roof ridges are defined as discontinuous breaks in the surface where the included interior angle measures 170° or less.
[f] Load is to be applied on either side of discontinuity but not simultaneously on both sides.
[g] Wind pressures shall be applied to the total normal projected area of all elements on one face. The forces shall be assumed to act parallel to the wind direction.
[h] Factors for cylindrical elements are two-thirds those for flat or angular elements.

Table 12.2.3 Wind Stagnation Pressure q_s at Standard Height of 33 ft

Basic wind speed, mi/h*	70	80	90	100	110	120	130
Pressure q_s, lb/ft²†	12.6	16.4	20.8	25.6	31.0	36.9	43.3

* Multiply by 1.61 for kilometers per hour.
† Multiply by 0.048 for kilonewtons per square meter.

Boundary-layer wind tunnels, which simulate the variation of wind speed with height and gusting, are used to estimate the design wind loading.

The effect of the sudden application of **gust loads** has sometimes been blamed for peculiar failures due to wind. In most cases, these failures can be explained from the pressure distributions in a steady wind. If a relatively flexible structure such as a radio tower, chimney, or skyscraper with a natural period of 1 to 5 s is set into vibration, the stresses in the structure may be increased over those calculated from a static-load analysis. Provision should be made for this effect by increasing the static design wind. A rational analysis should be performed to calculate the magnitude of this increase, which will depend on the flexibility of the structure.

Even a steady wind may give rise to periodic forces which may build up into large vibrations and lead to failure of the structure when the frequency of the exciting force coincides with one of the natural frequencies of vibration of the structure. The periodic exciting force may be due to the separation of a system of **Kármán vortices** (Fig. 12.2.1) in the wake of the body. The exciting frequency n in cycles per second is related to d, the dimension of the body normal to the wind velocity V, by the equation $nd/V = C$, where $C \approx 0.207$ for circular cylinders and $C \approx 0.18$ for rectangular plates (Blenk, Fuchs, and Liebers, Measurements of Vortex Frequencies, *Luftfahrt-Forsch.,* 1935, p. 38). Dangerous vibrations related to the ''flutter'' of airplane wings may arise on bridges and similar flat bodies. These self-induced vibrations may be caused (1) by a negative slope of the curve of lift against angle of attack (Den Hartog, *op. cit.*) or (2) by a dynamic instability which arises when a body having two or more degrees of freedom (such as bending and torsion) moves in such a manner as to extract energy out of the air stream. The first of these vibrations will occur at one of the natural frequencies of the structure. The second type of vibration will occur at a frequency intermediate between the natural frequencies of the structure.

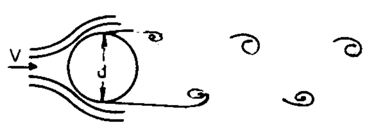


Fig. 12.2.1 Von Kármán vortices.

The wind forces and the **pressure distribution** over a structure corresponding to a design wind V can be determined by **model testing** in a wind tunnel. Extrapolation from model to full scale is based on the fact that at every other point on the body, the pressure p is proportional to the stagnation pressure q (see Sec. 11) and thus the ratio p/q = constant for a fixed point on the body, as the scale of the model or the velocity of the wind is changed. Since the principal component of the wind force is due to the pressures, the force F acting on the surface S is

$$F \approx p_{\text{avg}} S = (p/q)_{\text{avg}} qS$$

and denoting $(p/q)_{\text{avg}}$ by a normal force coefficient or **shape factor** C_N

$$F = C_N \tfrac{1}{2} \rho V^2 S = C_N qS$$

The shape factors so obtained apply to full scale for structures with sharp edges whose principal resistance is due to the pressure forces. For bodies that do not have any sharp edges perpendicular to the flow, such as spheres or streamlined bodies, the factor C_N is not constant. It depends upon the Reynolds number (see Sec. 3). For such bodies, the law for variation of the shape factor C_N must be determined experimentally before safe predictions of full-scale forces can be made from model measurements.

Radio Towers and Other Framed Structures For open frame towers, by using round structural members instead of flat and angular sections, a substantial reduction in wind force can be effected. Refer to note h in Table 12.2.2.

Load Combinations Methods of combining types of loading vary with the governing local codes. Dead loads are usually considered to act all the time in combination with either full or reduced live, wind, earthquake, and temperature loads. The reductions in live loads are based on the improbability of fully loaded tributary areas, generally when the tributary area exceeds 150 ft². Most codes consider that wind and earthquake loads need not be taken to act simultaneously. There are two basic design methods in use: allowable stress or working stress design and limit states or ultimate strength design. Whereas allowable stress design compares the actual working stresses with an allowable value, the limit states approach determines the adequacy of each element by comparing the ultimate strength of the element with the factored design loads. The following basic load combinations are applicable for allowable stress design: dead plus live (floor and roof); dead plus live plus wind; dead plus live plus earthquake. Most codes permit a one-third increase in stresses for load combinations considering either wind or earthquake effects.

DESIGN OF STRUCTURAL MEMBERS

Members are usually proportioned so that stresses do not exceed allowable **working stresses** which are based on the strength of the material and, in the case of compressive stresses, on the stiffness of the element under compression. Internal forces and moments in **simple beams,** columns, and pin-connected truss bars are obtained by means of the equations of static equilibrium. **Continuous beams,** rigid frames, and other members characterized by practically rigid joints require for analysis additional equations derived from consideration of deflections and rotations.

Design may also be on the basis of the **ultimate strength** of members, the factor of safety being embodied in stipulated increases in the design loads. In steel-frame construction, the procedures of **plastic design** determine points where the material may be allowed to yield, forming *plastic hinges,* and the resulting redistribution of internal forces permits a more efficient use of the material.

Floors and Roofs

Except in reinforced-concrete flat-slab construction, floors and roofs generally consist of flat decks supported upon beams, girders, or trusses. The decks may usually be considered a series of beamlike strips spanning between beams and themselves designed as beams. The design of a beam consists chiefly in proportioning its cross section to resist the maximum bending and shear and providing adequate connections at its supports, without exceeding the unit stresses allowed in the materials (see Sec. 5) and limiting maximum live load deflection at midspan to $1/360$ of the span.

Up to spans of 20 to 30 ft (6.1 to 9.1 m), either wood or steel beams of uniform section are generally more economical than trusses, while for spans above 50 to 70 ft (15.2 to 21.3 m), trusses are usually more economical. Between these limits, the line of economy is not well-defined. Conditions that favor the use of trusses are as follows: (1) identical trusses are repeated many times, (2) the height of the building need not be increased for the greater depth of the truss (3) fire protection of wood or metal is not required.

Roof trusses often have their top chords sloped with the roof. Common trusses for steeply pitched roofs are shown in Figs. 12.2.2 to 12.2.6, the top chord panels equal in each truss. The members shown by heavy lines are in compression under ordinary loads, those in light lines in tension. The trusses of Figs. 12.2.6 to 12.2.9 are adapted for either steel or wood. In wooden trusses, the tensile web members may be steel rods with plates, nuts, and threaded ends. The truss of Fig. 12.2.6 is usually made of steel.

The forces in any member of these trusses under a vertical load uniformly distributed may be found by multiplying the coefficients in Tables 12.2.4 to 12.2.8 by the panel load P on the truss. For other slopes, types of trusses, or loads, see ''General Procedure'' below. Trusses for flat roofs are commonly of one of the types shown in Figs. 12.2.7 to 12.2.13 except that the top chords conform to the slope of the roof.

Floor trusses normally have parallel chords. Common types are shown in Figs. 12.2.7 to 12.2.13 in which heavy lines indicate members in compression, light lines in tension, and dash lines members with only nominal stress, under equal vertical panel loads. The panel lengths l in each truss are equal. The stress in each member is written next to the member in the figure, in terms of the panel load and the lengths of members. For a truss like one of the figures turned upside down, the stresses in the chords and diagonals remain the same in magnitude but

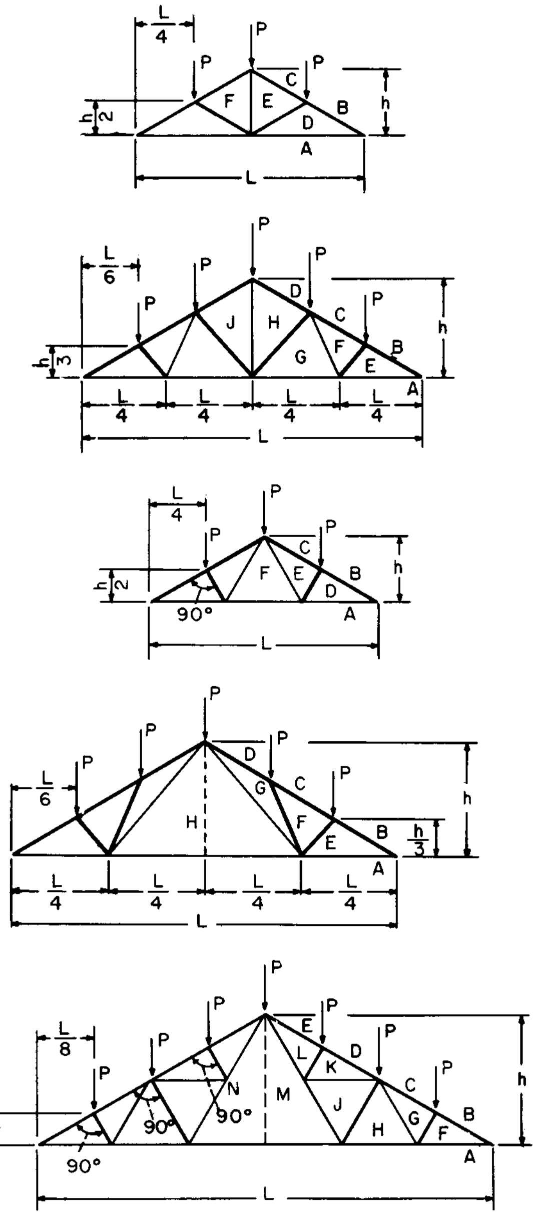


Fig. 12.2.2 to 12.2.6 Types of steep roof trusses.

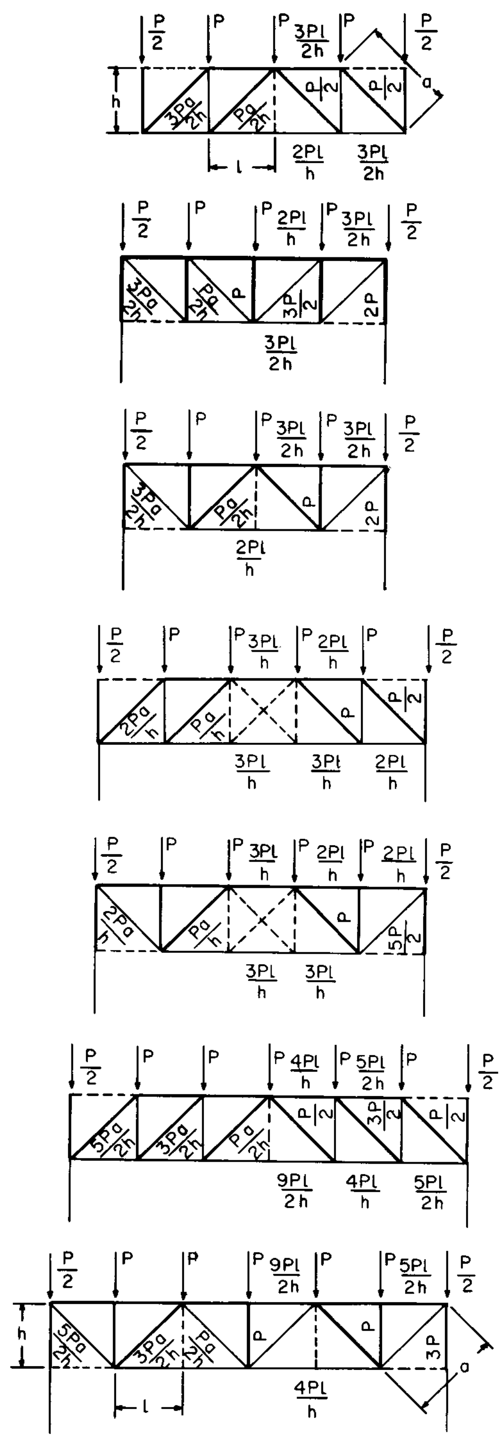


Fig. 12.2.7 to 12.2.13 Types of floor and roof trusses.

Table 12.2.4 Coefficients for Truss Shown in Fig. 12.2.2

	Coefficients of *P* for force in				
Pitch h/L	*AD*	*BD*	*CE*	*DE*	*EF*
⅓	2.25	2.71	1.80	0.90	1.00
0.288*	2.60	3.00	2.00	1.00	1.00
¼	3.00	3.35	2.24	1.12	1.00
⅕	3.75	4.03	2.69	1.35	1.00

Table 12.2.5 Coefficients for Truss Shown in Fig. 12.2.3

	Coefficients of *P* for force in								
Pitch h/L	*AE*	*AG*	*BE*	*CF*	*DH*	*EF*	*FG*	*GH*	*HJ*
⅓	3.75	3.00	4.50	2.7	3.60	0.83	0.72	1.25	2.00
0.288*	4.33	3.46	5.00	3.0	4.00	0.88	0.73	1.32	2.00
¼	5.00	4.00	5.59	3.35	4.47	0.94	0.75	1.42	2.00
⅕	6.25	5.00	6.74	4.04	5.39	1.07	0.79	1.60	2.00

Table 12.2.6 Coefficients for Truss Shown in Fig. 12.2.4

	Coefficients of *P* for force in					
Pitch h/L	*AD*	*AF*	*BD*	*CE*	*DE*	*EF*
⅓	2.25	1.50	2.70	2.15	0.83	0.75
0.288*	2.60	1.73	3.00	2.50	0.87	0.87
¼	3.00	2.00	3.35	2.91	0.89	1.00
⅕	3.75	2.50	4.04	3.67	0.93	1.25

Table 12.2.7 Coefficients for Truss Shown in Fig. 12.2.5

	Coefficients of *P* for force in							
Pitch h/L	*AE*	*AH*	*BE*	*CF*	*DG*	*EF*	*FG*	*GH*
⅓	3.75	2.25	4.51	3.91	4.51	0.83	1.42	2.50
0.288*	4.33	2.60	5.00	4.33	5.00	0.88	1.45	2.65
¼	5.00	3.00	5.59	4.84	5.59	0.94	1.49	2.83
⅕	6.25	3.75	6.73	5.83	6.73	1.07	1.57	3.20

Table 12.2.8 Coefficients for Truss Shown in Fig. 12.2.6

	Coefficients of *P* for force in											
Pitch h/L	*AF*	*AH*	*AM*	*BF*	*CG*	*DK*	*EL*	*FG* *KL*	*GH* *JK*	*HJ*	*JM*	*LM*
⅓	5.25	4.50	3.00	6.31	5.75	5.20	4.65	0.83	0.75	1.66	1.50	2.25
0.288*	6.06	5.20	3.46	7.00	6.50	6.00	5.50	0.87	0.87	1.73	1.73	2.60
¼	7.00	6.00	4.00	7.83	7.38	6.93	6.48	0.89	1.00	1.79	2.00	3.00
⅕	8.75	7.50	5.00	9.42	9.05	8.68	8.31	0.93	1.25	1.86	2.50	3.75

* 30 slope.

reversed in sign. Forces in verticals must be computed (compare Figs. 12.2.7 and 12.2.8). For other loads and other types of trusses see ''General Procedure'' below.

Weights of Trusses The approximate weight in pounds of a wooden roof truss may be taken as $W = LS(L/25 + L^2/6{,}000)$, where L is the span and S the spacing of trusses in feet. The approximate weight in pounds of a steel roof truss may be taken as $W = \frac{1}{5}LS(\sqrt{L} + \frac{1}{8}L)$.

Choice of Roof Trusses

WOODEN TRUSSES. For pitched roofs with spans up to 20 ft (6.1 m) the simple king-post truss (Fig. 12.2.2) may be used. For spans up to 40 ft (12.2 m) the trusses of Figs. 12.2.2 and Fig. 12.2.4 are good. For spans up to 60 ft (18.3 m) the trusses of Figs. 12.2.3 and 12.2.5 are good. The number of panels rarely exceeds eight or the panel length, 10 ft (3m). For flat roofs, the Howe truss (Figs. 12.2.7, 12.2.10, and 12.2.12) is built of wood with steel rods for verticals; the depth is one-eighth to one-twelfth the span. Wooden trusses are usually spaced 10 to 15 ft (3.0 to 4.6 m) on centers. Wood is rarely used in roof trusses with span over 60 ft (18.3 m) long. Steel trusses for pitched roofs may well take the form shown in Figs. 12.2.3 to 12.2.6 for spans up to 100 ft (30.5 m). For flat roofs, the Warren truss (Figs. 12.2.9, 12.2.11, and 12.2.13) is usually constructed in steel; the depth of the trusses ranges from one-eighth to one-twelfth the span, with trusses spaced from 15 to 25 ft (4.6 to 7.6 m) on centers.

Stresses in Trusses

An ideal truss is a framework consisting of straight bars or members connected at their ends by frictionless ball-and-socket joints. The external forces are applied only at these ball-and-socket joints. Internal forces and stresses in such straight bars are axial, either tension or compression, without bending. Since frictionless ball-and-socket joints are impossible, and the ends of bars are often bolted or welded, the ideal truss is never realized. For purposes of analysis, the primary stresses, which are always axial, are determined on the assumption that the truss under consideration conforms to the ideal. Secondary stresses are additional stresses, generally flexural or bending, brought about by all the factors that make the actual truss different from the ideal. In the following discussion, only primary forces and stresses will be considered.

Analytical Solution of Trusses

General Procedure After all external forces (loads and reactions) have been determined, the internal force or stress in any member is found (1) by taking a section, making an imaginary cut through the members of the truss, including the one whose stress is to be found, so as to separate the truss into two parts; (2) by isolating either of these parts; (3) by replacing each bar cut by a force, representing the force in the bar; and (4) by applying the equations of statics to the part isolated.

The various ways in which sections can be taken and the equations used to determine the forces are illustrated by a solution of the truss in Fig. 12.2.14.

A section 1–1 (Fig. 12.2.14) may be taken around a joint, L_0. Isolate the forces inside the section (Fig. 12.2.15*a*). Assume the unknown forces to be tension. Since the forces are concurrent and coplanar, two independent equations of statics will establish equilibrium. These may be either $\Sigma x = 0$ and $\Sigma y = 0$ or $\Sigma M = 0$ taken about two axes perpendicular to the plane of the forces and passing through two points selected so that neither point is the intersection of the forces, or so that the line joining the two points is not coincident with either of the unknown forces.

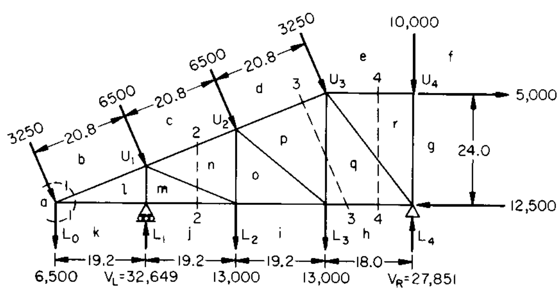


Fig. 12.2.14

Using the first set of equations and taking components of all forces along horizontal and vertical axes; e.g., the horizontal component of the 3,250 lb force is 1,250 and the vertical component is 3,000 lb.

$$\Sigma x = 0 = s_{lk} + s_{bl}(19.2/20.8) + 1{,}250$$
$$\Sigma y = 0 = s_{bl}(8/20.8) - 9{,}500$$

From these equations, $s_{lk} = -24{,}050$ and $s_{bl} = 24{,}700$.

The minus sign indicates that the force acts opposite to the assumed direction. If all the unknown forces are assumed to be in tension, then a plus sign in the result indicates that the force is tension and a minus sign indicates compression.

Hence, s_{lk} is 24,050 lb compression and s_{bl} is 24,700 lb tension.

Using the $\Sigma M = 0$ twice,

$$\Sigma M \text{ about } U_1 = 0 = -s_{lk} \times 8 - 1250 \times 8 - 9{,}500 \times 19.2$$

from which $S_{lk} = 24{,}050$ lb compression.

$$\Sigma M \text{ about } L_1 = 0 = s_{bl}(8/20.8)19.2 - 9{,}500 \times 19.2$$

from which $s_{bl} = 24{,}700$ tension.

Instead of taking a section around a joint, a cut may be made vertically or inclined, cutting a number of bars such as Fig. 12.2.15*b* or Fig. 12.2.15*c*. If only three members are cut, and they are neither concurrent nor parallel, the forces can be found by taking moments of all forces on either side of the section about axes passing through the intersections of any two members.

Considering the part to the left of section 2–2, the forces in the three members (Fig. 12.2.15*b*) may be determined by taking moments about L_0, U_1, and L_2 of all forces acting on the part on either side of the section, e.g., on the left of the section because it has the fewer forces:

$$\Sigma M \text{ about } L_0 = s_{mn}(8/20.8)38.4 + 2{,}500 \times 8 - (32{,}649 - 6{,}000)19.2$$
$$\Sigma M \text{ about } U_1 = 0 = -s_{mj} \times 8 - 1{,}250 \times 8 - 9{,}500 \times 19.2$$
$$\Sigma M \text{ about } L_2 = 0 = s_{cn}(19.2/20.8)16 + 2{,}500 \times 8 - 9{,}500 \times 38.4 + 26{,}649 \times 19.2$$

from which $s_{mn} = 33{,}290$ tension, $s_{mj} = 24{,}050$ compression, and $s_{cn} = 11{,}298$ compression.

This method is sometimes called the ‘‘method of moments.’’

Considering the part to the right of section 3–3, the forces in the three members (Fig. 12.2.15*c*) may be determined by taking moments about L_0, U_3, L_3 of all the forces acting on part or either side of the section, e.g., on the right of the section because it has the fewer forces:

$$\Sigma M \text{ about } L_0 = 0 = s_{pq} \times 57.6 + 6{,}250 \times 24 + 3{,}000 \times 57.6 - (27{,}851 - 10{,}000) \times 75.6$$
$$\Sigma M \text{ about } L_3 = 0 = -s_{dp}(19.2/20.8)24 + 6{,}250 \times 24 - 17{,}851 \times 18$$
$$\Sigma M \text{ about } U_3 = 0 = s_{qh} \times 24 + 12{,}500 \times 24 - 17{,}851 \times 18$$

from which $s_{pq} = 17{,}825$ tension, $s_{dp} = 7{,}733$ compression, and $s_{qh} = 888$ tension.

Considering the part to the right of section 4–4, the forces in the three members (Fig. 12.2.15*d*) may be found by taking moments about axes where two unknowns intersect, e.g., about U_3 and L_4. Since two unknown forces are parallel, their lines of action do not intersect. However, the equation $\Sigma y = 0$ will enable one to find the force in the member which is not parallel to the other two:

$$\Sigma M \text{ about } U_3 = 0 = s_{qh} \times 24 - (27{,}851 - 10{,}000)18 + 12{,}500 \times 24$$
$$\Sigma M \text{ about } L_4 = 0 = -s_{er} \times 24 + 5{,}000 \times 24$$
$$\Sigma y = 0 = s_{rq}(24/30) + 27{,}851 - 10{,}000$$

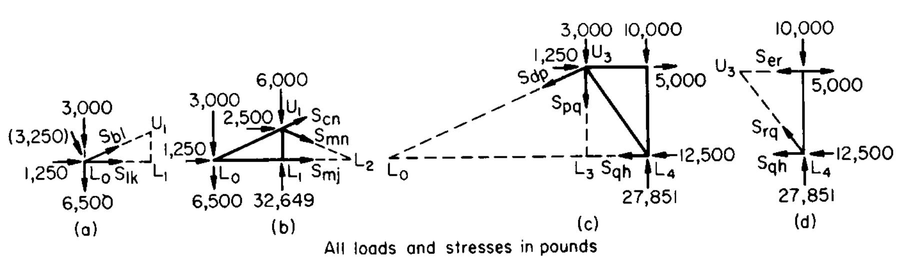


Fig. 12.2.15 Resolution of forces for truss shown in Fig. 12.2.14.

from which $s_{qh} = 888$ tension, $s_{er} = 5{,}000$ tension, and $s_{rq} = 22{,}314$ compression.

Columns and Walls

Vertical elements in building construction consist of columns, posts, or partitions that transmit concentrated loads; walls or partitions that transmit linearly distributed loads (and may, if so designed, transmit lateral loads from story to story); rigid frames that transmit lateral as well as vertical loads; and braced frames that, ideally, transmit only lateral loads from story to story.

Columns may be of timber, steel, or reinforced concrete and should be proportioned for the allowable stresses permitted for the material used and for the flexibility of the column. Care must be taken in the framing of beams and girders to avoid or to provide for the additional stresses due to connections which transfer loads to columns with large eccentricities. For instance, a beam framing to a flange of a steel column, with a seat or web connection, will produce an eccentric moment in the column equal to $Rd/2$, where R is the beam reaction and d the depth of the column section. Columns not adequately restrained against deflection of the top may be subject to considerable additional moment because of the resulting eccentricity of otherwise axial loads.

Rigid frames consist of columns and beams welded, bolted, or otherwise connected so as to produce continuity at the joints and permit the entire frame to behave as a unit, capable of resisting both vertical and lateral loads. Advantages of rigid frames are the ease and simplicity of erection, increased headroom, and more open floor plans free of braced frames. Rigid frames composed of rolled sections are commonly used for spans up to 100 ft (30.5 m) in length. Built-up members have been utilized on spans to 250 ft (76.2 m). Welded fabrication offers particular advantages for frames utilizing variable-depth members and on parabolic-shape roofs. The distribution of moments in the statically indeterminate rigid frame is effected by the relationship of the column height to span and roof rise to column height, as well as the relative stiffness of the various members. The solution for the moments in the frame is obtained from the usual equations of statics plus one or more additional equations pertaining to the elastic deformations of the frame under load.

Bearing walls, which are intended to transmit gravity loads from story to story, are designed as vertical elements of unit width such that the combined effects of axial and/or bending stresses do not exceed their allowable values according to the formula $fa/Fa + fb/Fb \leq 1.0$, where f is the actual stress in the axial or bending mode, and F is the allowable stress in the appropriate mode.

Shear walls, either concrete or masonry, which are intended to transmit earthquake, wind, or other lateral loads from story to story parallel to the plane of the wall, are designed as cantilevered vertical shear beams. Loads are distributed among the various wall elements, created by door and window openings, on the basis of their relative rigidities. Unless special conditions indicate otherwise, the assumption is made, in calculating individual stiffnesses, that the wall is fixed against rotation, in the plane of the wall, at the bottom. The individual wall elements are then designed to resist both their share of the wall shear and the moments it induces as well as any vertical loads due to bearing wall action and/or overall wall overturning. Individual wall elements, then, will have special vertical reinforcing at each side (trim reinforcement) to resist bending moments. Diagonal trim reinforcements, 96 bar diameters in total length, where possible, are placed at corners of openings in concrete walls to inhibit cracking. Trim reinforcing should consist of a minimum of two ⅝-in-diameter (1.6-cm) bars (No. 5 bars).

Uplift and downward forces at opposite ends of the shear walls, due to the tendency of the wall to overturn in its own plane when acted upon by lateral forces, must be resisted by vertical reinforcement at those locations. Special boundary elements are required for shear walls in areas of high seismicity (UBC Zones 3 and 4). Only minimum tributary dead loads may be counted upon to help resist uplift while maximum dead plus live loads should be assumed acting simultaneously with downward overturning loads. **Load reversal,** due to wind or seismic loads, must be considered.

Shear walls should be positioned throughout the plan area of the building in such a manner as to distribute the forces uniformly among the individual walls with approximately one-half of the wall area oriented in each of the two major directions of the building. At least one major wall should be positioned, if possible, near each exterior face of the building. Shear walls should be continuous, where possible, from top to bottom of the building; avoid offsetting walls from floor to floor, and particularly avoid discontinuing walls from one level to the level below. Positioning shear walls near major floor openings that would preclude proper anchorage of floor (or roof) to wall should be avoided so that diaphragm forces in the plane of the floor may have an adequate force path into the wall.

Where **rigid diaphragms** (such as concrete slabs or metal deck with concrete fill) exist, shears are distributed to the individual walls on the basis of their relative rigidity taking into account the additional forces due to the larger of either accidental or actual horizontal torsion resulting from the eccentricity of the building seismic shear (located at the center of mass) or eccentricity of applied wind load with respect to the center of rigidity of the walls. Where **flexible diaphragms** (such as metal deck with nonstructural fill or plywood) exist, shears are distributed to walls on the basis of tributary area. When diaphragms are semirigid, based on type, construction, or spacing between supporting elements, shears could be distributed by both methods (relative rigidity and tributary area) with individual walls designed to resist the larger of the two shears.

Braced frames, which are intended to transmit lateral loads from floor to floor, are designed as trusses that are loaded horizontally instead of vertically and are principally used in steel construction. Lateral loads are distributed to them on the same basis as to shear walls; therefore, the same general rules apply to their ideal placement. Bracing of individual bays may take the form of X-bracing, single diagonal bracing, or K-bracing. Where K-braces are used, the additional bracing forces associated with vertical floor loads to the braced beam must be considered. Alternative floor framing to avoid large beam loads to the braced beam should be considered where possible.

X-bracing may be designed so that either the tension diagonal takes all the lateral load or so that the tension and compression diagonals share the load. When the tension diagonal resists all the lateral load, the minimum slenderness ratio (kl/r) of the member should not exceed 300; the additional axial load in the column to which the top of the brace is connected, the connection load at each end of the brace and the horizontal footing load at the bottom of the brace, is double that obtained when braces share the load. In X-bracing systems where the tension and compression members share the lateral load, maximum slenderness ratios should be limited to 200 (the members may be considered to brace each other about axes that are normal to the plane of the bay), but connection and individual horizontal foundation loads are decreased. With either method of design, it is important to follow the path of the force from its origin through the structure until it is transferred to the ground. With any bracing system, it is wise to sketch to scale the major connection details prior to finalization of calculations; the desirable intersection of member axes is often more difficult to achieve than a single line drawing would indicate. Connection of braces to columns at intermediate points between floors should be avoided because plastic hinges in columns lead to structural instability.

Stud walls consist of wooden studs with one or more lines of horizontal bridging. The allowable vertical load on the wall is a function of the maximum permissible load on each stud as a column and the spacing of the studs.

Corrugated or flat sheet steel or aluminum, are commonly employed for walls of industrial or mill buildings. These sheets are usually supported on steel girts framing horizontally between columns and supported from heavier eave struts by one or more lines of vertical steel sag rods.

Reinforced-concrete or masonry walls should be designed so that the allowable bending and/or axial stresses are not exceeded, but the minimum thicknesses of such walls should not be less than the following:

Material	Max ratio, unsupported height or length to thickness	Nominal min thickness, in*
Reinforced concrete	25	6
Plain concrete	22	7
Reinforced brick masonry	25	6
Grouted brick masonry	20	6
Plain solid masonry	20	8
Hollow-unit masonry	18	8
Stone masonry (ashlar)	14	16
Interior nonbearing concrete or masonry (reinforced)	48	2
Interior nonbearing concrete or masonry (unreinforced)	36	2

* $\times$ 25.4 = mm.

Foundations

Bearing Pressure of Soils The bearing pressure which may be allowed on soil may vary over a large range. For important structures, the nature of the underlying soil should be ascertained by borings or test pits. If the soil consists of medium or soft clay, a settlement analysis based on consolidation tests of undisturbed soil samples from the foundation strata is necessary. Structures founded upon mud, soft clay, silt, peat, or artificial filling will almost certainly settle, and no foundation for a permanent structure should rest on or above such material without adequate provision for the resulting settlement. Table 12.2.9 gives a general classification of soils and typical safe pressures which they may support.

These values approximate the pressures allowed by the building law in most cities. Actual allowable bearing pressures should be based on the quality and engineering characteristics of the material obtained from analysis of borings, standard penetration tests, and rock cores. Other laboratory tests, when the cost thereof is warranted by the magnitude of the project, may show higher values to be safe. The foundation for a building housing heavy vibrating machinery such as steam hammers, heavy punches, and shears should receive some allowance for possible compression and rearrangement of soil due to the vibrations transmitted through it. The foundation for a tall chimney should be designed with a comparatively low pressure upon the soil, because of the disastrous results which might occur from local settlement.

Footings The purpose of footings is to spread the concentrated loads of building walls and columns over an area of soil so that the unit pressure will come within allowable limits. Footings are usually constructed of concrete, placed in open excavations with or without sheeting and bracing. In the past, stone, where available in quantity and the proper quality, has been used economically for residential building footings.

Table 12.2.9 Safe Bearing of Soils

Nature of soil	Safe bearing capacity tons/ft²	MPa
Solid ledge of hard rock, such as granite, trap, etc.	25–100	2.40–9.56
Sound shale and other medium rock, requiring blasting for removal	10–15	0.96–1.43
Hardpan, cemented sand, and gravel, difficult to remove by picking	8–10	0.76–0.96
Soft rock, disintegrated ledge; in natural ledge, difficult to remove by picking	5–10	0.48–0.96
Compact sand and gravel, requiring picking for removal	4–6	0.38–0.58
Hard clay, requiring picking for removal	4–5	0.38–0.48
Gravel, coarse sand, in natural thick beds	4–5	0.38–0.48
Loose, medium, and coarse sand; fine compact sand	1.5–4	0.15–0.38
Medium clay, stiff but capable of being spaded	2–4	0.20–0.38
Fine loose sand	1–2	0.10–0.20

Allowable bearing pressures for granular materials are typically determined as 10 percent of the standard penetration resistances (N values) obtained in the field from standard penetration tests (STPs) and are in tons/ft^2.

Concrete footings may be either plain or reinforced. Plain concrete footings are generally limited to one- or two-story residential buildings. The center of pressure in the wall or column should always pass through the center of the footing. Where columns, because of fixity, impose a bending moment on the footing, the maximum soil pressures, due to the combined axial and moment components, shall be positive throughout the area of the footing (i.e., no net uplift) and shall be less than the allowable values. Footings in ground exposed to freezing should be carried below the possible penetration of frost.

Deep foundations are required when a suitable bearing soil is deep below the surface, typically more than 10 to 15 ft. (3.0 to 4.6 m). Sometimes deep foundations are necessary even if the suitable bearing materials are shallower, but groundwater conditions make excavation for footings difficult. The most common types of deep foundations include caissons or drilled piers and piles. Where the bearing soil is clay stiff enough to stand with undercutting, and the material immediately above it is peat or silt, the **open-caisson method** may be economical. In this method, cylindrical steel casings 3 ft and more in diameter are sunk as excavation proceeds, the casings having successively smaller diameters. At the bottom of the shaft thus formed, the soil is undercut to obtain sufficient bearing area. The shaft and the enlargement at the base are then filled with concrete, the cylinders sometimes being withdrawn as the concrete is placed. The open-caisson method cannot be used where groundwater flows too freely into the excavation. Where large foundations under very heavy buildings must be carried to great depth to reach rock or hardpan, particularly where groundwater flows freely, the **pneumatic-caisson method** is used.

Drilled-in piers are formed by drilling with special power augers up to 5 ft (1.5 m) diameter or greater. The holes are drilled to the desired bearing level with or without metal casings, depending on the soil conditions. Belling of the bottom may also be performed mechanically from the surface. In poor soils, or where groundwater is present, the hole may be retained with bentonite clay slurry which is displaced as concrete is placed in the caisson by the **tremie method.**

Pile Foundations Piles for foundations may be of wood, concrete, steel, or combinations thereof. Wood piles are generally dressed and, if required, treated offsite; concrete piles may be prepared offsite or cast in place; steel piles are mill-rolled to section. They can be driven, jacked, jetted, screwed, bored, or excavated. Wood piles are best suited for loads in the range of 15 to 30 tons (133.4 to 177.9 KN) per pile and lengths of 20 to 45 feet (6.6 to 15 m). They are difficult to splice and may be driven untreated when located entirely below the permanent water table; otherwise piles treated with creosote should be used to prevent decay. Wood piles should be straight and not less than 6 in in diameter under the bark at the tip. Concrete piles are less destructible, and hence are adaptable to many conditions, including driving in dense gravels, and can be up to approximately 120 ft (40 m) long. Concrete piles are divided into two classes: those poured in place and those precast, cured, and driven. Cast-in-place piles are made by driving a mandrel into the ground and filling the resulting hole with concrete. In one well-known pile of this type (Raymond), a thin sheet-steel corrugated shell is fitted over a tapered mandrel before driving. This shell, which is left in the ground when the mandrel is removed, is filled with concrete. Prestressing of precast-concrete piles provides greater resistance to handling and driving stresses. With a concrete pile, 25 to 60 tons (222.4 to 533.8 KN) or more per pile are carried. Structural steel H columns and steel pipe with capacities of 40 to 300 tons (350 to 1800 kN) per pile have been driven. Experience has shown that corrosion is seldom a practical problem in natural soils, but if otherwise, increasing the steel section to allow for corrosion is a common solution.

Methods of Driving Piles The drop hammer and the steam hammer are usually employed in driving piles. The steam hammer, with its comparatively light blows delivered in rapid succession, is of advantage in a plastic soil, the speed with which the blows are delivered preventing the readjustment of the soil. It is also of advantage in soft soils where the driving is easy, but a light hammer may fail to drive a heavy pile satisfactorily. The water jet is sometimes used in sandy soils. Water supplied under pressure at the point of the pile through a pipe or hose run alongside it erodes the soil, allowing the pile to settle into place. To have full capacity, jetted piles should be driven after jetting is terminated particularly if the pile is to resist uplift loads.

Determination of Safe Loads for Piles Piles may obtain their supporting capacity from friction on the sides or from bearing at the point. In the latter case, the bearing capacity may be limited by the strength of the pile, considered as a column, to which, however, the surrounding soil affords some lateral support. In the former case, no precise determination of the bearing capacity can be made. Many formulas have been developed for determining the safe bearing capacity in terms of the weight of the hammer, the fall, and the penetration of the pile per blow, the most generally accepted of which is that known as the *Engineering News* formula: $R = 2wh/(s + 1.0)$ for drop hammers, $R = 2wh/(s + 0.1)$ for single-acting steam hammers, $R = 2E/(s + 0.1)$ for double-acting steam hammers, where R = safe load, lb; w = weight of hammer, lb; h = fall of hammer, ft; s = penetration of last blow, in; E = rated energy, ft·lb per blow. This formula and similar ones are based on the determination of the energy in the falling hammer, and from this the pressure which it must exert on the top of the pile. The *Engineering News* formula is currently used typically for timber piles with capacities not exceeding 30 tons. It assumes a factor of safety of 6. It is a wise practice to drive index piles and determine their bearing capacity through pile load tests typically carried to twice the service load of the pile before proceeding with the final design of important structures to be supported on piles. The design then is based on the safe service load capacity so determined, and the piles are driven to the same penetration resistance to which the successfully tested index piles where driven by the same driving hammer.

Spacing of Piles Wood piles are preferably spaced not closer than 2½ ft (0.76 m), and concrete piles 3 ft (0.91 m) on centers. If driven closer than this, one pile is liable to force another up. Piles in a group must not cause excessive pressure in soil below their tips. The efficiency, or supporting value of friction piles when driven in groups, by the Converse-Labarre method, is

$$\frac{1 - d/s[(n-1)m + (m-1)n]}{90mn}$$

where d = pile diameter, in (cm); s = spacing center to center of piles, in (cm); m = number of rows; n = number of piles in a row.

Capping of Piles Piles are usually capped with concrete; wood piles sometimes with pressure-treated timber. Concrete is the most usual material and the most satisfactory for the reason that it gets a full bearing on all piles. The piles should be embedded 4 to 6 in (10 to 15 cm) in the concrete.

Retaining Walls A wall used to sustain the pressure of earth behind it is called a retaining wall. Retaining walls which depend for their stability upon the weight of the masonry are classed as gravity walls. Such walls built on firm soil will usually be stable when they have the following proportions: top of fill level, back vertical, base, 0.4 height; top of fill level, back battered, base, 0.5 height; top of fill steeply inclined, back vertical, base, 0.5 height; top of fill steeply inclined, back battered, base, 0.6 height. An additional factor of safety is obtained by building the face on a batter. Care should be taken in the design of a wall that the allowable soil pressure is not exceeded and that drainage is provided for the back of the wall. The foundations of retaining walls should be placed below the level of frost penetration. Retaining walls of reinforced concrete are made thin, with a broad base, and the wall either cantilevered from the base or braced with buttresses or counterforts.

It is impossible to derive formulas for the earth pressure on the back of the wall which will take account of all the actual conditions. Assuming the earth to be a loose, homogeneous, granular mass, and the coefficient of friction to be independent of the pressure, Rankine deduced the following formula for a wall with vertical back:

$$P = (\tfrac{1}{2}wh^2 + vh)\cos d(\cos d - \sqrt{\cos^2 d - \cos^2 a})/(\cos d + \sqrt{\cos^2 d - \cos^2 a})$$

the center of pressure being at a height $\tfrac{1}{3}H(wh + 3v)/(wh + 2v)$ above the base, where P = earth pressure per lin ft (m) of the wall, lb (kg); h = height of the wall, ft (m); w = weight of earth per ft^3 (m^3), lb (kg); v = weight of superposed load per ft^2 (m^2) of surface, lb (kg); d = the angle with the horizontal of the earth surface behind the wall; and a = angle of internal friction of the earth, deg. (For sands, a = 30 to 38°.) The direction of the pressure is parallel to the earth's surface. The retaining wall should have sufficient thickness at the base so that the resultant of the earth pressure P combined with the weight of the wall falls well within the base. If this resultant falls at the outside edge of the middle third, the maximum vertical pressure on the foundation (at the outer edge of the base) will be equal to $2W/T$ lb/ft^2 (Pa), where W is the total vertical pressure on the base of 1 ft (m) length of wall and T the thickness of the wall at the base, ft (m).

In the design of walls of buildings which must withstand earth pressure and low independent walls, where refinement is not necessary, the earth pressure is frequently assumed to be that of a fluid weighing 40 to 45 lb/ft^3 (641 to 721 kg/m^3).

MASONRY CONSTRUCTION

The term **masonry** applies to assemblages consisting of fired-clay, concrete, or stone units, mortar, grout, and steel reinforcement (if required). The choice of materials and their proportions is based on the required strength (compressive, flexural, and shear), fire rating, acoustics, durability, and aesthetics. The strength and durability of masonry depends on the size, shape, and quality of the unit, the type of mortar, and the workmanship. Resulting bond strength is affected by the initial rate of absorption, texture and cleanliness of the masonry units.

Brick Common red bricks are made of clay burned in a kiln. Quality characteristics are hardness and density. Light-colored brick is apt to be soft and porous. Brick for masonry exposed to the weather or where strength is desired should have a crushing strength of not less than 2,500 lb/in^2 (17.3 MPa) and should absorb not over 20 percent of water by weight, after 5-h immersion in boiling water (see Sec. 6).

Mortar Mortar is the bonding agent that holds the individual units together as an assembly. All mortars contain cement, sand, lime, and water in varying proportions. Mortars are classified as portland-cement-lime mortar or masonry cement mortar. Proportions for Type M portland-cement-lime mortar are 1 part portland cement, ¼ part lime, and 3 parts sand, by volume; for masonry cement mortar, 1 part masonry cement, 1 part portland cement, and 6 parts sand. Portland-cement-lime mortar should be used for all structural brickwork (see Sec. 6).

Laying and Bonding Brick should be laid in a full bed of mortar and shoved laterally into place to secure solid bearing and a bed of even thickness and to fill the vertical joints. Clay brick should be thoroughly wet before laying, except in freezing weather. Concrete bricks/blocks should not be wetted before placement. Brick laid with long dimension parallel to the face of the work are called stretchers, perpendicular to the face, headers. Bats (half-brick) should not be used except where necessary to make corners or to form patterns on the face of the wall. Each continuous vertical section of a wall one masonry unit thick is called a **wythe.** Multiwythe walls, of brick or block faced with brick, are now commonly tied together with ties or anchors between each wythe of brick and block. Such ties are typically provided every other course. When the wythes are adequately bonded or tied; the wall may be considered as a composite wall for strength purposes. Walls may also be tied together longitudinally by overlapping stretchers in successive courses. Transverse bond is obtained by making every sixth course headers, the headers themselves overlapping in successive courses in the interior of thick walls. Variations in the arrangement of headers are often used in the face of walls for appearance. The area of cross section of full-length headers should not be less than one-twelfth the face of the

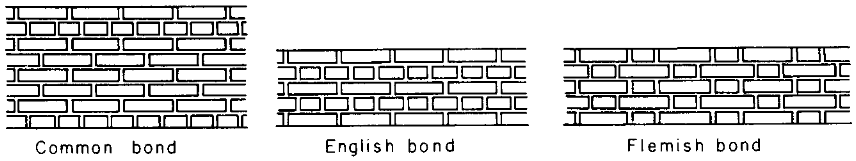


Fig. 12.2.16 Bonds used in bricklaying.

wall, in bonding each pair of transverse courses of brick. Three examples of bond are shown in Fig. 12.2.16.

Arches over windows and doorways are laid in concentric rings of headers on edge, with radial joints. The radius of the arch should be 1 to 1¼ times the width of the opening.

Lateral Support Brick walls should be supported laterally by bonding to transverse walls or buttresses, or by anchoring to floors, at intervals not exceeding 20 times the thickness. Floors and anchors must be capable of transmitting wind pressure and earthquake forces, acting outward, to transverse walls or other adequate supports, and thus to the ground. The height of piers between lateral supports should not exceed 12 times their least dimension.

Concrete Masonry Units (CMUs) Hollow or solid concrete blocks are used in building walls, often faced with brick or stone on the exterior walls. Standard block sizes are based on a brick module, nominally 4 in high.

Allowable compressive stresses in masonry are related to the masonry unit strength and the type of mortar as follows:

Kind of Masonry	Type M or S mortar lb/in²	Type M or S mortar MPa	Type N mortar lb/in²	Type N mortar MPa
Stone ashlar	360	2.48	320	2.20
Rubble	120	0.83	100	0.69
Clay brick (2500 lb/in²)	160	1.10	140	0.97
Hollow CMU (1000 lb/in²)	75	0.52	70	0.48
Solid CMU (2000 lb/in²)	160	1.10	140	0.97

Minimum thickness of load-bearing masonry walls shall be 6 in for up to one story and 8 in for more than one story.

Reinforced Masonry The design of masonry with vertical reinforcing bars placed and fully grouted in some of the cells provides increased capacity to resist flexure and axial loads. In addition, in areas where seismic design is required, due to the brittle nature of unreinforced masonry, all masonry must be reinforced to prevent a brittle failure mode. The design principles for reinforced masonry are similar to the design for reinforced concrete.

Reinforced Concrete (See Sec. 12.3.)

TIMBER CONSTRUCTION

Floors The framing of wooden floors may be divided into two general types: joist construction and solid, or mill, construction. The first consists of **joists** 2 to 6 in wide, of the necessary depth, and spaced about 12 to 16 in (30 to 40 cm) on centers. The wall ends should rest on and be anchored to walls and the interior ends carried by a line of girders on columns. These joists should be securely cross-bridged not over 8 ft (2.4 m) apart in each span to prevent twisting and to assist in distributing concentrated loads. Solid blocking should be provided at ends and at each point of support. The floor is formed of a thickness of rough boarding on which the finish flooring is laid. **Solid** or **mill-construction floors** are designed to do away with the small pockets which exist in joist construction and thus reduce the fire hazard. They are generally framed with beams spaced 8 to 12 ft (2.4 to 3.6 m) on centers and spanning 18 to 25 ft (5.5 to 7.6 m). The wall ends of beams rest on and are anchored to the wall, and the interior ends are carried on columns and tied together to form a continuous tie across the building. Ends of timbers in masonry walls should have metal bearing plates and ½ in space at sides and end for ventilation, to prevent rot. The ends should be beveled and the anchors placed low to avoid overturning the wall if the beams drop in a fire. In all cases, care should be taken to provide sufficient bearing at the points of support so that the allowable intensity of compression across the grain is not exceeded. In case it is desirable to omit columns, or the floor load requires a closer spacing of beams, girders are run lengthwise of the building over the columns to take the beams, the ends of which are hung in hangers or stirrup irons and tied together, over or through the girders. This is called **intermediate framing.** Steel beams are sometimes used in place of wooden beams in this type of construction, in which case a wooden strip is bolted to the top flange of the beam to take the nailing of the plank, or the plank is laid directly on top of the beam and secured by spikes driven from below and clinched over the flange. The floor is formed of 3 or 4 in (7.5 or 10 cm) plank grooved in each edge, put together with splines and securely spiked to beams. On

Table 12.2.10 Properties of Plank and Solid Laminated Floors
(b = breadth = 12 in, f = fiber stress)

Nominal thickness or depth in (1)	Actual thickness d, in (S4S) (2)	Area of section $A = bd$, in² (3)	Moment of inertia $I = bd^3/12$, in⁴ (4)	Section modulus $S = bd^2/6$, in³ (5)	Safe load, lb/ft² on 1-ft span*: f = 1,000 lb/in²† (6)	Safe load, lb/ft² on 1-ft span*: f = 1,600 (7)	Coef of deflection, uniform load‡: E = 1,000,000 (8)	Coef of deflection, uniform load‡: E = 1,760,000 (9)
1	¾	9.00	0.422	1.13	753	1,205	53.4	93.98
1½	1¼	15.00	1.95	3.13	2,085	3,336	11.51	20.26
2	1½	18.00	3.38	4.50	3,000	4,800	6.66	11.72
2½	2	24.00	8.00	8.00	5,334	8,534	2.82	4.96
3	2½	30.00	15.60	12.50	8,334	13,334	1.441	2.54
4	3½	42.00	42.9	24.5	16,334	26,134	0.524	0.922
5	4½	54.00	91.1	40.5	27,000	43,200	0.247	0.1404
6	5½	66.00	166.4	60.5	40,300	64,500	0.1348	0.0765
8	7½	90.00	422	112.5	75,000	120,000	0.0533	0.0303
10	9½	114.00	857	180.5	120,400	192,500	0.0263	0.0149
12	11½	138.00	1,521	264.5	176,400	282,000	0.0148	0.0084

NOTE: 1 in = 2.54 cm; 1 lb = 4.45 N; 1 lb/in² = 6.89 kPa.
* Divide tabular value by square of span in feet.
† For other fiber stress f, multiply tabular value by f/1,000.
‡ For deflection in, multiply coefficient by load, lb/ft², and by fourth power of span in ft, and divide by 1,000,000. For other modulus of elasticity E, multiply coefficient of col. 8 by 1,000,000, and divide by E.

top of the plank is laid flooring, with a layer of sheathing paper between. In case the floor loads require an excessive thickness of plank, or in localities where heavy plank is not easily obtainable, the floor is built up of 3 × 6 in (7.5 × 15 cm), or other sized pieces, placed on edge, and securely nailed together.

The roofs of buildings of joist and mill construction are framed in a manner similar to the floors of each type and should be securely anchored to the walls and columns. In case columns are not desired in the top story, steel beams or trusses of either steel or wood are used. For spans up to 35 ft (10.7 m), trussed beams can often be used to advantage.

For **unit stresses in timber,** see Sec. 6. For unit stresses in wooden columns, see Table 12.2.12. Table 12.2.10 gives the properties of mill floors made of dressed plank, and of laminated floors made of planks of edge, laid close.

Timber Beams

Properties of Timber Beams Table 12.2.11 presents those properties of wooden timbers most useful in computing their strength and deflection as beams. (The ''nominal size'' of a timber is indicated by the breadth and depth of the section in inches. The ''actual size'' indicates the size of the dressed timber, according to National Lumber

Table 12.2.11 Properties of Wooden Beams (Surfaced Size)

						Max safe uniform load, lb, based on		
Nominal size, in (1)	Actual size $b \times d$, in, dressed (S4S) size (2)	Area of section bd, in² (3)	Weight at 40 lb/ft³, lb/ft (4)	Moment of inertia $I = bd^3/12$, in⁴ (5)	Section modulus $S = bd^2/6$, in³ (6)	Bending on 1 ft span,* f = 1,000 lb/in² (7)	Shear at 100† lb/in² (8)	Coef‡ of deflection, uniform load E = 1,000,000 (9)
2 × 4	1½ × 3½	5.25	1.46	5.36	3.06	2,040	700	4.20
3 × 4	2½ × 3½	8.75	2.43	8.93	5.10	3,400	1,166	2.52
4 × 4	3½ × 3½	12.25	3.40	12.51	7.15	4,760	1,632	1.80
2 × 6	1½ × 5½	8.25	2.29	20.8	7.56	5,040	1,100	1.082
3 × 6	2⁄2 × 5½	13.75	3.82	34.7	12.60	8,390	1,835	0.648
4 × 6	3½ × 5½	19.25	5.35	48.5	17.65	11,760	2,570	0.464
6 × 6	5½ × 5½	30.3	8.40	76.3	27.7	18,490	4,040	0.295
2 × 8	1½ × 7¼	10.87	3.02	47.6	13.14	8,760	1,445	0.473
3 × 8	2½ × 7¼	18.12	5.04	79.4	21.9	14,600	2,410	0.284
4 × 8	3½ × 7¼	25.4	7.05	111.1	30.7	20,500	3,380	0.202
6 × 8	5½ × 7½	41.3	11.4	193	51.6	34,400	5,500	0.1162
8 × 8	7½ × 7½	56.3	15.6	264	70.3	46,900	7,500	0.0852
2 × 10	1½ × 9¼	13.87	3.85	98.9	21.4	14,290	1,850	0.227
3 × 10	2½ × 9¼	23.1	6.42	164.9	35.7	23,700	3,080	0.1364
4 × 10	3½ × 9¼	32.4	8.93	231	49.9	33,300	4,310	0.0974
6 × 10	5½ × 9½	52.3	14.5	393	82.7	55,200	6,970	0.0573
8 × 10	7½ × 9½	71.3	19.8	536	113	75,200	9,500	0.0421
10 × 10	9½ × 9½	90.3	25.0	679	143	95,300	12,030	0.0332
2 × 12	1½ × 11¼	16.87	4.69	178	31.6	21,100	2,250	0.1264
3 × 12	2½ × 11¼	28.1	7.81	297	52.7	35,100	3,750	0.0757
4 × 12	3½ × 11¼	39.4	10.94	415	73.9	49,300	5,250	0.0543
6 × 12	5½ × 11½	63.3	17.5	697	121	80,800	8,430	0.0323
8 × 12	7½ × 11½	86.3	23.9	951	165	110,200	11,510	0.0237
10 × 12	9½ × 11½	109.3	30.3	1,204	209	139,600	14,570	0.01864
12 × 12	11½ × 11½	132.3	36.7	1,458	253	169,000	17,620	0.01543
4 × 14	3½ × 13¼	46.4	12.88	678	102.4	68,300	6,180	0.0332
6 × 14	5½ × 13½	74.3	20.6	1,128	167	111,400	9,900	0.01987
8 × 14	7½ × 13½	101.3	28.0	1,538	228	152,000	13,500	0.01462
10 × 14	9½ × 13½	128.3	35.6	1,948	289	192,400	17,120	0.01153
12 × 14	11½ × 13½	155.3	43.1	2,360	349	233,000	20,700	0.00953
14 × 14	13½ × 13½	182.3	50.6	2,770	410	273,000	24,300	0.00812
6 × 16	5½ × 15½	85.3	23.6	1,707	220	146,800	11,380	0.01315
8 × 16	7½ × 15½	116.3	32.0	2,330	300	200,000	15,530	0.00967
10 × 16	9½ × 15½	147.3	40.9	2,950	380	254,000	19,610	0.00762
12 × 16	11½ × 15½	178.3	49.5	3,570	460	307,800	23,800	0.00630
14 × 16	13½ × 15½	209	58.1	4,190	541	360,000	27,900	0.00539
16 × 16	15½ × 15½	240	66.7	4,810	621	414,000	32,000	0.00468
8 × 18	7½ × 17½	131.3	36.4	3,350	383	255,000	17,500	0.00672
10 × 18	9½ × 17½	166.3	46.1	4,240	485	323,000	22,200	0.00531
12 × 18	11½ × 17½	201	55.9	5,140	587	391,000	26,800	0.00438
14 × 18	13½ × 17½	236	65.6	6,030	689	459,000	31,500	0.00373
16 × 18	15½ × 17½	271	75.3	6,920	791	528,000	36,200	0.00325
18 × 18	17½ × 17½	306	85.0	7,820	893	595,000	40,800	0.00288
12 × 20	11½ × 19½	224	62.3	7,110	729	485,000	29,900	0.00316
20 × 20	19½ × 19½	380	106	12,050	1,236	824,000	50,700	0.00187
24 × 24	23½ × 23½	552	153	25,400	2,160	1,440,000	73,400	0.000888
26 × 26	25½ × 25½	650	180.6	35,200	2,760	1,840,000	86,700	0.000639
28 × 28	27½ × 27½	756	210	47,700	3,470	2,320,000	100,600	0.000472
30 × 30	29½ × 29½	870	242	63,100	4,280	2,850,000	116,000	0.000356

NOTE: 1 in = 2.54 cm; 1 ft = 0.305 m; 1 lb = 4.45 N; 1 lb/in² = 6.89 kPa.

* For total safe uniform load, pounds, on beam of span L, feet, divide tabular value by L. For fiber stress f other than 1,000 lb/in² multiply by f and divide by 1,000.

† For shearing stress other than 100 lb/in², multiply by stress and divide by 100.

‡ For deflection, inches, multiply coefficient by total load, pounds, and by cube of span, feet, and divide by 1,000,000. For other modulus of elasticity E, multiply coefficient by 1,000,000 and divide by E.

Manufacturers Assoc. The moment of inertia and section modulus are with the neutral axis perpendicular to the depth at the center. The **safe bending moment** in inch-pounds for a given beam is determined from the section modulus S by multiplying the tabular value by the allowable fiber stress. To select a beam to withstand safely a given bending moment, divide the bending moment in inch-pounds by the allowable fiber stress, and choose a beam whose section modulus S is equal to or larger than the quotient thus obtained. For formulas for computing bending moments, see Sec. 5.2. Note that the allowable fiber stress must be modified by adjustment factors: C_D, load duration factor (0.9 for permanent loads); C_M, wet service factor (approximately 0.8 for moisture content greater than 16 percent); C_t, temperature factor (usually 1.0 for temperatures less than 100°F); C_F, size factor (1.0 for members up to 5 in wide by 12 in deep); and other factors which apply to laminated, curved, round, and/or flat use. (See also Sec. 6.7, ''Properties of Lumber Products.'')

Maximum loads in Table 12.2.11, cols. 7 and 8, are for uniform loading. Use half the values of col. 7 for a single load concentrated at midspan; for other loadings compute the bending moment and use the section modulus, col. 6. The values of col. 8 apply to all symmetrical loadings. For unsymmetrical loading, compute the maximum shear, which must not exceed one-half the tabular value.

The **coefficients of deflection** listed in Table 12.2.11 can be used to deduce deflection as indicated in the footnotes to the table. Coefficients of deflection under concentrated loads applied at the middle of the span may be obtained by multiplying the values in the table by 1.6. The results are only approximate, as the modulus of elasticity varies with the moisture content of the wood.

The deflection due to live load of beams intended to carry plastered ceilings should not exceed 1⁄360 of the span.

A convenient rule may be derived by assuming that the modulus of elasticity is 1,000 times the allowable fiber stress, which applies to all woods with sufficient accuracy for the purpose. Beams loaded uniformly to capacity in bending will then deflect 1⁄360 of the span when the depth in inches is 0.90 times the span in feet; and beams with central concentration, when the depth is 0.72 times the span in the same units. For such beams, the deflection in inches is, for uniform load, $0.03L^2/d$; for central concentration, $0.024L^2/d$, where L is the span, ft and d the depth, in. Variation in type of loading affects this result comparatively little.

Timber Columns

Timber columns may be either square or round and should have metal bases, usually galvanized steel, to cut off moisture and prevent lateral displacement. For supporting beams, they should have caps which, at roofs, may be of steel, or wood designed for bearing across the grain. At intermediate floors, caps should be of steel, although in some cases hardwood bolsters may be used. Except when caps or beams are of steel, columns should run down and rest directly on the baseplate. Table 12.2.12 gives **working unit stresses for wood columns** recommended where the building laws do not prescribe lower stresses. Use actual, not nominal, dimension of timbers. The column capacity $P_{\text{col}} = F'_c A_{\text{net}}$, where F'_c is interpolated from Table 12.2.12, and A_{net} is the net cross-sectional area of the column. The values for F'_c in Table 12.2.12 are generally conservative and are based on the factors cited in the table footnotes. In the event $E < 1{,}000F_c$, the value of F'_c must be computed to include the value of C_P as follows:

$$F'_c = F_c C_D C_M C_t C_F C_P$$

(Note that actual design stress $f_c \le F'_c$.)

$$C_p = \text{column stability factor} = \frac{1 + (F_{cE}/F_c^*)}{2c} - \sqrt{\left[\frac{1 + F_{cE}/F_c^*}{2c}\right]^2 - \frac{F_{cE}/F_c^*}{c}}$$

$$F_c^* = F_c C_D C_M C_t C_F$$

$$F_{cE} = \frac{K_{cE}E}{(l_e/d)^2} =$$ critical buckling design stress in compression parallel to the grain for a given wood species and geometrical configuration of column

where F_c = tabulated allowable design value for compression parallel to the grain for the species (Sec. 6.7, Tables 6.7.6 and 6.7.7); C_D = load duration factor (Sec. 6.7, ''Properties of Lumber Products''); C_M = wet use factor (Sec. 6.7, Table 6.7.8); C_t = temperature factor (Sec. 6.7, Table 6.7.9); C_F = size factor (Sec. 6.7, footnotes to Table 6.7.8); K_{cE} = 0.3 for visually and mechanically graded lumber and 0.418 for glulam members; l_e = effective length of column; d = least dimension of the column cross section; E = modulus of elasticity for the species (Sec. 6.7, Tables 6.7.6 and 6.7.7); c = constant for the type member: 0.8 for sawn lumber, 0.85 for timber piles, 0.9 for glulam members.

Glued Laminated Timber Structural glued laminated timber, commonly called glulam, refers to members which are fabricated by pressure gluing selected wood laminations of either ¾ or 1½ in (19 or 38 mm) surfaced thickness. The grain of all the laminations is approximately parallel longitudinally, with exterior laminations being of generally higher-quality wood since bending stresses are greater at the outer fibers. Curved and tapered structural members are available with the recommended minimum radii of curvature being 9 ft 4 in (2.84 m) for ¾-in laminations and 27 ft 6 in (8.4 m) for 1½-in lamination thickness. Laminations should be parallel to the tension face of members; sawn tapered cuts are permitted on the compression face.

Available net (surfaced) widths of members in inches are 2¼, 3⅛, 5⅛, 8¾, 10¾, 12¼, and 14¼; depths are determined by stress requirements. Economical spans (see ''Timber Construction Manual,'' American Institute of Timber Construction) for roof framing range from 10 to 100 ft (3 to 30 m) for simple spans. Floor framing, which is designed for much heavier live loads, economically spans from 6 to 40 ft (1.8 to 12 m) for simple beams and from 25 to 40 ft (7.5 to 12 m) for continuous beams.

Glued laminated members are generally fabricated from either Douglas fir and larch, Douglas fir (coast region), southern pine, or California redwood, depending on availability. Allowable design stresses depend on whether the condition of use is to be wet (moisture content in service of 16 percent or more) or dry (as in most covered structures), the species and grade of wood to be used, the manner of loading, and the number of laminations as well as the usual factors for duration of loading. The cumulative reduction factors described above also apply to glulam beams. Additional factors including C_v, volume factor; C_{fu}, flat use factor; and C_c, curvature factor, also must be applied to glued laminated beams. Refer to the National Design Specification for Wood Construction for further information on glued laminated timber design. (See Sec. 6.7.)

Table 12.2.12 Values of F'_c, Working Stresses for Square or Rectangular Timber Columns, lb/in²
(Compression parallel to grain.)*

F_c	l_e/d, in/in: 10	15	20	25	30	35	40	45	50	55†	60†	70†	80†
1000	680	615	508	389	293	225	176	141	116	96	81	60	46
1300	884	799	660	505	381	292	229	184	150	125	106	78	60
1600	1088	984	812	622	469	359	282	226	185	154	130	96	74
1900	1292	1168	964	739	557	427	335	268	220	183	154	114	88

* Values of F'_c in the table are based on $C_D = 0.9$ (long-duration, permanent, 50-year loading); $C_M = 0.8$ (moisture content > 16%); $C_t = 1.0$ (operating temperature < 100°F); $C_F = 1.0$ (cross section up to 5 in wide × 12 in deep); $K_{cE} = 0.3$; $E \ge 1{,}000F_c$. If $E < 1{,}000F_c$, see text for procedure to compute F'_c; $c = 0.8$.
† Columns should be limited to $l_e/d = 50$, except for individual members in stud walls, which should be limited to $l_e/d = 80$.

A summary of allowable unit stresses may be found in Sec. 6.7 for glued laminated timber.

Connections

Bolted Joints Compression may be transmitted by merely butting the timbers, with splice pieces bolted to the sides to keep alignment and resist incidental bending and shear. The same detail (Fig. 12.2.17) serves in tension, but the entire stress must then be transmitted through the bolts and splice pieces. If of wood, these should have a thickness *h* equal to ½*b*. In light, unimportant work, splice pieces may be spiked. Table 12.2.13 gives the allowable load in pounds for one bolt loaded at both ends (double shear) when *h* is at least equal to ½*b*. When steel side plates are used for side members, the tabulated loads may be increased 25 percent for parallel-to-grain loading, but no increase should be made for perpendicular-to-grain loads. When a joint consists of two members (single shear), one-half the tabulated load for a piece twice the thickness of the thinner member applies. The safe load for bolts loaded at an angle θ with the grain of the wood is given by the formula $N = PQ/(P \sin^2 \theta + Q \cos^2 \theta)$, where N = allowable load per bolt in a direction at inclination θ with the direction of the grain, lb; P = allowable load per bolt in compression parallel to the grain, lb; and Q = allowable load per bolt in compression perpendicular to the grain, lb.

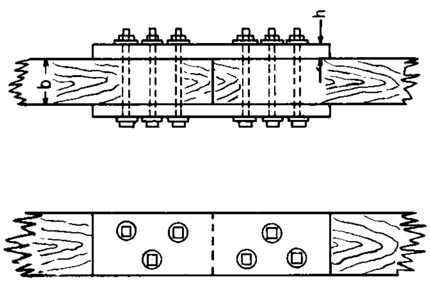


Fig. 12.2.17 Bolted splices for timber framing.

The size, arrangement, and **spacing of bolts** must be such that tension on the net section of the timber through the bolt holes and shear along the grain do not exceed allowable values. Bolts should be at least 7 diameters from the end of the timber for softwoods and 5 diameters for hardwoods and spaced at least 4 diameters on center parallel to the grain. Crossbolting, to prevent splitting the timber end, is sometimes desirable.

The efficiency of bolted timber connections may be greatly increased by the use of **ring connectors.** Split rings and shear plates are fitted into circular grooves, concentric with the bolt, in the contact surfaces, and transmit shear stresses across the joint. Grooves for split rings and shear plates are cut with a special tool, while toothed rings are usually seated by drawing together the timbers with high-strength bolts. Allowable loads for these various connectors are given in the ''Design Values for Wood Construction,'' published by the National Lumber Manufacturers Assoc. Selected values are given in Table 12.2.14.

The **holding power of wire nails** is as follows (''Design Values for Wood Construction''): The resistance to withdrawal is proportional to the length of embedment, to the diameter of the nail (where the wood does not split), and to $G^{2.5}$, where G is the ovendry specific gravity of the wood (see Sec. 6 for G values of various species). The safe resistance to withdrawal of common wire nails driven into the side grain of seasoned wood is given by Table 12.2.15. Nails withdrawn from green wood have generally slightly higher resistance, but nails driven into green wood may lose much of their resistance when the wood seasons; the allowable withdrawal load should be one-fourth of that given in Table 12.2.15. Cement and other coatings on nails may add materially to their resistance in softwoods. Drilling lead holes slightly smaller than the nail adds somewhat to the resistance and reduces danger of splitting. The structural design should be such that nails are not loaded in withdrawal from end grain.

The safe **lateral resistance** of common wire nails driven in side grain to the specified penetrations is given in Table 12.2.15 and is proportional to $D^{1.5}$ where D is the diameter, in. These values are for seasoned wood and should be reduced 25 percent for woods which will remain wet or will be loaded before seasoning. For nails driven into end grain, values should be reduced one-third.

Common wire **spikes** are larger for their lengths than nails. Their resistance to withdrawal and lateral resistance are given by the same formulas as for nails, but greater precautions need to be taken to avoid splitting.

The **resistance of wood screws to withdrawal** from side grain of seasoned wood is given by the formula $P = 2{,}850G^2D$, where P = the allowable load on the screw, lb/in penetration of the threaded portion; G = specific gravity of ovendry wood; D = diameter of screw, in. Wood screws should not be designed to be loaded in withdrawal from end grain.

The **allowable safe lateral resistance** of wood screws embedded 7 diameters in the side grain of seasoned wood is given by the formula $P = KD^2$, where P is the lateral resistance per screw, lb; D is the diameter, in; and K is 4,800 for oak (red and white), 3,960 for Douglas fir (coast region) and southern pine, and 3,240 for cypress (southern) and Douglas fir (inland region).

The following rules should be observed: (1) the size of the lead hole in soft (hard) woods should be about 70 (90) percent of the core or root diameter of the screw; (2) lubricants such as soap may be used without great loss in holding power; (3) long, slender screws are preferable generally, but in hardwood too slender screws may reach the limit of their tensile strength; (4) in the screws themselves, holding power is favored by thin sharp threads, rough unpolished surface, full diameter under the head, and shallow slots.

Table 12.2.13 Allowable Load in Pounds on One Bolt Loaded at Both Ends (Double Shear)
(For additional values and for conditions other than normal, see ''Design Values for Wood Construction'')

Length of bolt in main member, in	Diam of bolt, in	Douglas fir-larch		California redwood (open grain)		Oak, red and white		Western spruce, pine, fir, cedars	
		Parallel to grain	Perpendicular to grain	Parallel to grain	Perpendicular to grain	Parallel to grain	Perpendicular to grain	Parallel to grain	Perpendicular to grain
1½	½	1,050	470	780	310	1,410	730	760	290
	¾	1,580	590	1,170	370	2,110	890	1,140	360
	1	2,100	680	1,560	440	2,810	1,020	1,520	420
2½	½	1,230	730	990	510	1,530	960	980	490
	¾	2,400	980	1,950	620	2,890	1,480	1,900	600
	1	3,500	1,130	2,590	730	4,690	1,700	2,530	700
3½	½	1,230	730	990	580	1,530	960	980	560
	¾	2,400	1,170	2,010	740	2,890	1,770	1,990	720
	1	4,090	1,350	3,110	870	4,820	2,040	3,040	840
5½	¾	2,400	1,170	2,010	740	2,890	1,770	1,990	720
	1	3,180	1,260	2,690	810	3,780	1,920	2,660	790
	1¼	4,090	1,350	3,110	870	4,820	2,040	3,040	840

NOTE: 1 in = 2.54 cm; 1 lb = 4.45 N.

Table 12.2.14 Allowable Load in Pounds for One-Connector Unit in Single Shear*

(For additional values and for conditions other than normal, see ''Design Values for Wood Construction'')

				Group A		Group B		Group C	
				Douglas fir-larch and southern pine (dense), oak, red and white		Douglas fir-larch, southern pine (med. grain)		California redwood (close) grain), western hemlock, southern cypress	
Connector unit (diam)	Number of faces of piece with connectors on the same bolt	Net thickness of lumber, in	Min. edge distances, in	∥ to grain	⊥ to grain	∥ to grain	⊥ to grain	∥ to grain	⊥ to grain
2½-in split	1	1 min,	1¾	2,630	1,900	2,270	1,620	1,900	1,350
ring, ½-in		1½ or more		3,160	2,280	2,730	1,940	2,290	1,620
bolt	2	1½ min,		2,430	1,750	2,100	1,500	1,760	1,250
		2 or more		3,160	2,280	2,730	1,940	2,290	1,620
4-in split ring,	1	1 min,	2¾	4,090	2,840	3,510	2,440	2,920	2,040
¾-in bolt		1½ or more		6,020	4,180	5,160	3,590	4,280	2,990
	2	1½ min,		4,110	2,980	3,520	2,450	2,940	2,040
		3 or more		6,140	4,270	5,260	3,660	4,380	3,050
2⅝-in shear	1	1½ min	1¾	3,110	2,170	2,670	1,860	2,220	1,550
plate, ¾-in	2	1½ min,		2,420	1,690	2,080	1,450	1,730	1,210
bolt†		2½ or more		3,330	2,320	2,860	1,990	2,380	1,650
4-in shear	1	1½ min,	2¾	4,370	3,040	3,750	2,620	3,130	2,170
plate, ¾-in		1¾ or more		5,090	3,540	4,360	3,040	3,640	2,530
or ⅞-in bolt†	2	1¾ min,		3,390	2,360	2,910	2,020	2,420	1,680
		2½		4,310	3,000	3,690	2,550	3,080	2,140
		3½ or more		5,030	3,500	4,320	3,000	3,600	2,510

NOTE: 1 m = 2.54 cm; 1 lb = 4.45 N.

* One connector unit consists of one split ring with its bolt in single shear or two shear plates back to back in the contact faces of a timber-to-timber joint with their bolt in single shear.

† Allowable loads for all loadings, except wind, should not exceed 2,900 lb for 2⅝-in shear plates; 4,400 and 6,000 lb for 4-in shear plates with ¾- and ⅞-in bolts, respectively; multiply values by 1.33 for wind loading.

Table 12.2.15 Allowable Loads in Pounds for Common Nails in Side Grain* of Seasoned Wood

		Size of nail										
		d	6	8	10	12	16	20	30	40	50	60
	Specific gravity	Length, in	2	2½	3	3¼	3½	4	4½	5	5½	6
Type of load	*G*	Diam, in	0.113	0.131	0.148	0.148	0.162	0.192	0.207	0.225	0.244	0.263
Withdrawal	0.31		9	10	12	12	13	15	16	18	20	21
load per in	0.40		16	18	20	20	22	27	28	31	33	35
penetration	0.44		20	23	26	26	29	34	37	40	43	46
	0.47		24	27	31	31	34	40	43	47	51	55
	0.51		29	34	38	38	42	49	53	58	63	68
	0.55		34	41	46	46	50	59	64	70	76	81
	0.67		57	66	75	75	82	97	105	114	124	133
Lateral	0.60–0.75		78	97	116	116	132	171	191	218	249	276
load*†	0.50–0.55		63	78	94	94	107	139	154	176	202	223
	0.42–0.50		51	64	77	77	88	113	126	144	165	182
	0.31–0.41		41	51	62	62	70	91	101	116	132	146

NOTE: 1 in = 2.54 cm; 1 lb = 4.45 N.

* The allowable lateral load for nails driven in end grain is two-thirds the values shown above.

† The minimum penetration for full lateral resistance for the four groups listed is 10, 11, 13, and 14 diam from higher to lower specific gravities, respectively. Reduce by interpolation for lesser penetration; minimum penetration is one-third the above.

Table 12.2.16 Allowable Lateral Loads in Pounds on Lag Bolts or Lag Screws

			Overndry specific gravity of species							
			0.60–0.75		0.51–0.55		0.42–0.50		0.31–0.41	
Side member	Length of bolt, in	Diam of bolt at shank, in	∥	⊥	∥	⊥	∥	⊥	∥	⊥
1½-in wood	4	¼	200	190	170	170	130	120	100	100
	4	½	390	250	290	190	210	140	170	110
	6	⅜	480	370	420	320	360	280	290	220
	6	⅝	860	510	710	430	510	310	410	250
2½-in wood	6	½	620	410	470	310	340	220	270	180
	6	1	1,040	520	790	390	560	280	450	230
	8	¾	1,430	790	1,080	600	780	430	620	340
	8	1	1,800	900	1,360	680	970	490	780	390
½-in metal	3	¼	240	185	210	160	155	120	125	100
	3	½	550	285	415	215	295	155	240	125
	6	½	1,100	570	945	490	770	400	615	320
	6	¾	1,970	865	1,480	650	1,060	460	850	370
	10	⅞	3,420	1,420	2,960	1,230	2,340	970	1,890	785
	12	1	4,520	1,810	3,900	1,560	3,290	1,320	2,630	1,050
	16	1¼	7,120	2,850	6,150	2,460	5,500	2,200	4,520	1,810

NOTE: 1 in = 2.54 cm; 1 lb = 4.45 N.

The allowable **withdrawal load of lag screws** in side grain is given by the formula $p = 1{,}800D^{3/4}G^{3/2}$, allowable load per inch of penetration of threaded portion of lag screw into member receiving the point, lb; D = shank diameter of lag screw, in; G = specific gravity of ovendry wood. Use of lag screws loaded in withdrawal from end grain should be avoided. The allowable load in such case should not exceed 75 percent of that for side grain (see also Sec. 8).

The allowable **lateral resistance of lag screws** for parallel-to-grain loading with screws in side grain is proportional to D^2 and is dependent on species and type of side member. Selected values are given in Table 12.2.16 for one lag screw in single shear in a two-member joint.

Lead holes for lag screws (approximately 75 percent of shank diameter) should be prebored for the threaded portion. Lead holes for the shank should be of the same diameter and length as that of the unthreaded shank. Soap or other lubricant should be used to facilitate insertion and to prevent damage to the screw. Where steel-plate side pieces are used, the allowable loads given by the formula for parallel-to-grain loading may be increased by 25 percent.

The ultimate **withdrawal load per linear inch of penetration of a round drift bolt or pin** from side grain when driven into a prebored hole having a diameter ⅛ in less than that of the bolt diameter may be determined from the formula $p = 6{,}000G^2D$, where p = ultimate withdrawal load of penetration, lb/lin in; G = specific gravity of ovendry wood; D = diameter of drift bolt, in. A safety factor of about 5 is suggested for general use. The allowable load in lateral resistance for a drift bolt should ordinarily be taken as less than that for a common bolt.

STEEL CONSTRUCTION

(Note. In the design of steel structures, 1,000 lb is frequently designated as a kilopound or ''kip,'' and a stress of 1 kip per square inch is designated as 1 ksi.)

Structural steel design was based only on the allowable stress design (ASD) approach until the introduction of the load and resistance factor design (LRFD) technique in the mid 1980s. The LRFD approach is an ultimate strength design approach, similar to that adopted by the American Concrete Institute for concrete design. Both ASD and LRFD are accepted in current codes. The ASD method is still the most commonly used for design.

Specifications The following are in part condensed excerpts from the Specifications of the American Institute of Steel Construction.

Material Ordinary steel for rolled shapes, plates, and bars is typically specified by ASTM A36, with a yield stress of 36,000 lb/in² (248.2 MPa). However, advances in mill production methods have resulted in most steels satisfying the higher strength requirements of ASTM A572, Grade 50, leading to increased use of higher-strength steel at little or no cost premium. Other higher-strength steels used in structures are A440, A441, A588, and A242. Steel materials for pipe and tube, specified by ASTM A53 (welded-seam pipe) and A500 (cold-formed), have yield strengths of 33,000 to 50,000 lb/in² (227.5 to 344.7 MPa).

Ordinary unfinished machine bolts are specified by A307. Bolts used for structural steel connections are typically high-strength bolts specified by A325 or A490. Riveting is no longer used, but may often be encountered in older structures. The most common rivets were A502, Grade 1.

Allowable Stresses* in A36 Steel

	lb/in²	MPa
Tension F_t:		
On gross section	22,000	151.6
On net section, except at pinholes	29,000	200
On net section, at pinholes	16,000	110.2
Compression F_c: See Table 12.2.17		
Bending tension and compression on extreme fibers F_b:		
Basic stress, reduced in certain cases	22,000	151.6
Compact, adequately braced beams	24,000	165.3
Rectangular bearing plates	27,000	186.0
Shear F_v: Web of beams, gross section	14,500	99.9

* Allowable stresses may be increased by one-third when produced by wind or seismic loading alone or when combined with design dead and live loads.

Allowable Stresses* in Riveted and Bolted Connections

	lb/in²	MPa
Bearing: A36 steel		
Pins in reamed, drilled, or bored holes	32,400	223.3
Bolts and rivets	69,000	475.7
Roller, lb/lin in (N/lin cm)	760 × diam (in)	1131 × diam (cm)
Shear: bearing-type connections†		
A502, grade 1 hot-driven rivets	17,500	120.6
A307 bolts	10,000	68.9
A325 bolts when threading is excluded from shear planes (std. holes)	30,000	206.8
A325 bolts when threading is not excluded from shear planes (std. holes)	21,000	144.7
Shear: friction-type connections† (with threads included or excluded from shear plane)		
A325 bolts in standard holes	17,500	120.6
A325 bolts in oversized or short slotted holes	15,000	103.4
A325 bolts in long slotted holes	12,000	82.6
Tension:		
A502, grade 1, hot-driven rivets	23,000	158.5
A307 bolts	20,000	137.9
A325 bolts	44,000	303.3
Bending in pins of A36 steel	27,000	186.1

* Allowable stresses are based on nominal body area of fasteners unless indicated.
† Rivets or bolts may not share loads with welds on bearing-type connections but may do so in friction-type connections.

Table 12.2.17 Allowable Stress, in ksi, for Compression Members of A36 Steel

Main and secondary members, Kl/r not more than 120						Main members, Kl/r, 121–200			
$\frac{Kl}{r}$	F_a	$\frac{Kl}{r}$	F_a	$\frac{Kl}{r}$	F_a	$\frac{Kl}{r}$	F_a	$\frac{Kl}{r}$	F_a
1	21.56	41	19.11	81	15.24	121	10.14	161	5.76
5	21.39	45	18.78	85	14.79	125	9.55	165	5.49
10	21.16	50	18.35	90	14.20	130	8.84	170	5.17
15	20.89	55	17.90	95	13.60	135	8.19	175	4.88
20	20.60	60	17.43	100	12.98	140	7.62	180	4.61
25	20.28	65	16.94	105	12.33	145	7.10	185	4.36
30	19.94	70	16.43	110	11.67	150	6.64	190	4.14
35	19.58	75	15.90	115	10.99	155	6.22	195	3.93
40	19.19	80	15.36	120	10.28	160	5.83	200	3.73

NOTE: 1 ksi = 6.89 MPa.

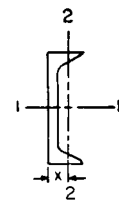


Table 12.2.18 American Standard Channels (C Shapes)

Depth of channel, in	Weight per ft, lb	Area of section, in^2	Width of flange, in	Thickness of web, in	Axis 1–1			Axis 2–2		V*	R*
					I, in^4	r, in	S, in^3	r, in	x, in	1,000 lb	
C 15	50.0	14.64	3.716	0.716	404	5.24	53.6	0.87	0.80	156	121
	40.0	11.70	3.520	0.520	349	5.44	46.2	0.89	0.78	113	88
	33.9	9.90	3.400	0.400	315	5.62	41.7	0.91	0.79	87	55
C 12	30.0	8.79	3.170	0.510	162	4.28	26.9	0.77	0.68	89	76
	25.0	7.32	3.047	0.387	144	4.43	23.9	0.79	0.68	67	55
	20.7	6.03	2.940	0.280	129	4.61	21.4	0.81	0.70	49	30
C 10	30.0	8.80	3.033	0.673	103.0	3.42	20.6	0.67	0.65	98	96
	25.0	7.33	2.886	0.526	90.7	3.52	18.1	0.68	0.62	76	75
	20.0	5.86	2.739	0.379	78.5	3.66	15.7	0.70	0.61	55	54
	15.3	4.47	2.600	0.240	66.9	3.87	13.4	0.72	0.64	35	22
C 9	20.0	5.86	2.648	0.448	60.6	3.22	13.5	0.65	0.59	58	62
	15.0	4.39	2.485	0.285	50.7	3.40	11.3	0.67	0.59	37	33
	13.4	3.89	2.430	0.230	47.3	3.49	10.5	0.67	0.61	30	22
C 8	18.75	5.49	2.527	0.487	43.7	2.82	10.9	0.60	0.57	56	
	13.75	4.02	2.343	0.303	35.8	2.99	9.0	0.62	0.56	35	
	11.5	3.36	2.260	0.220	32.3	3.10	8.1	0.63	0.58	26	
C 7	14.75	4.32	2.299	0.419	27.1	2.51	7.7	0.57	0.53	43	
	12.25	3.58	2.194	0.314	24.1	2.59	6.9	0.58	0.53	32	
	9.8	2.85	2.090	0.210	21.1	2.72	6.0	0.59	0.55	21	
C 6	13.0	3.81	2.157	0.437	17.3	2.13	5.8	0.53	0.52	38	
	10.5	3.07	2.034	0.314	15.1	2.22	5.0	0.53	0.50	27.3	
	8.2	2.39	1.920	0.200	13.0	2.34	4.3	0.54	0.52	17.4	
C 5	9.0	2.63	1.885	0.325	9.0	1.83	3.5	0.49	0.48	23.6	
	6.7	1.95	1.750	0.190	7.5	1.95	3.0	0.50	0.49	13.8	
C 4	7.25	2.12	1.720	0.320	4.5	1.47	2.3	0.46	0.46	18.6	
	5.4	1.56	1.580	0.180	3.8	1.56	1.9	0.45	0.46	10.4	
C 3	6.0	1.75	1.596	0.356	2.1	1.08	1.4	0.42	0.46	15.5	
	5.0	1.46	1.498	0.258	1.8	1.12	1.2	0.41	0.44	11.2	
	4.1	1.19	1.410	0.170	1.6	1.17	1.1	0.41	0.44	7.4	

NOTE: 1 in = 2.54 cm; 1 ft = 0.305 m; 1 lb = 4.45 N.
* V amd R values are for channels of A36 steel.

Proportion of Parts

Most simple beams, columns, and truss members are proportioned to limit the actual stresses to the allowable stresses stipulated above. Other stability or serviceability criteria may control the design. **Deflection** may govern in such members as cantilevers and lightly loaded roof beams. **Buckling,** rather than strength, may govern the design of compression members. The slenderness ratio Kl/r, where Kl is the effective length of the member and r is its radius of gyration, should be limited to 200 in compression members, and L/r limited to 300 in tension members. Kl should not be less than the actual unbraced length l in columns of a frame which depends on its bending stiffness for lateral stiffness. **Width-thickness ratios** are specified for projecting elements under compression. Repeated fluctuations in stress leading to fatigue may be a controlling factor. Rules are given for **combined stresses** of tension, compression, bending, and shear.

Tension members should be proportioned for the gross and net section, deducting for bolt or rivet holes ⅛ in (0.3 cm) larger than the nominal diameter of the fastener.

Columns and other **compression members** subject to eccentric load or to axial load and bending are governed by special rules. A long-established rule is that $f_a/F_a + f_b/F_b$ should be equal to or less than unity, where f_a is the axial stress, f_b the bending stress, and F_a and F_b are the corresponding allowable stresses if axial or bending stress alone exist. This is still considered valid when f_a/F_a is less than 0.15. Joints shall be fully spliced, except that where reversal of stress is not expected and the joint is laterally supported, the ends of the members may be milled to plane parallel surfaces normal to the stresses and abutted with sufficient splicing to hold the connected members accurately in place. Column bases should be milled on top for the column bearing, except for rolled-steel bearing plates 4 in (10 cm) or less in thickness.

Beams and girders, of rolled section or built-up, should in general be sized such that the bending moment M divided by the section modulus S is less than the allowable bending stress F_b. For built-up sections a rule of thumb is, for A36 steel, flanges in compression should have a thickness of 1⁄16 the projecting half width, and webs should have a thickness of 1⁄320 the maximum clear distance between flanges. Web stiffeners should be provided at points of high concentrated loads; additional web stiffeners are required in plate girders. Splices in the webs of plate girders should be made by plates on both sides of the web. When two or more rolled beams or channels are used side by side to form a beam, they should be connected at separators spaced no more than 5 ft (1.52 m); beams deeper than 12 in (30 cm) are to have at least two bolts to each separator.

The **lateral force on crane runways** due to the effect of moving crane trolleys may be assumed as 20 percent of the sum of the weights of the lifted loads and of the crane trolley (but exclusive of the other parts of the crane) applied at the top of the rail, one-half on each side of the runway, and shall be considered as acting in either direction normal to the runway rail. The **longitudinal force** may be assumed as 10 percent of the maximum wheel reactions of the crane applied at the top of the rail.

Bolted or riveted connections carrying calculated stress, except lacing and sag bars, should be designed to support not less than 6,000 lb (27.0 kN). Rivets or high-strength bolts are preferred in all places, and both are implied in these paragraphs wherever ''bolting'' is mentioned; unfinished bolts, A307, may be used in the shop or in field connections of small unimportant structures of secondary members, bracing, and beams.

Members in tension or compression, meeting at a joint, shall have their lines of center of gravity pass through a point, if practicable; if not, provision shall be made for the eccentricity. A group of bolts transmitting stress to a member shall have its center of gravity in the line of the stress, if practicable; if not, the group shall be designed for the resulting eccentricity. Where stress is transmitted from one member to another by bolts through a loose filler greater than ¼ in in thickness, except in slip critical connections using high-strength bolts, the filler shall be extended beyond the connected member and the extension secured by enough bolts or sufficient welding to distribute the total stress in the member uniformly over the combined sections of the member and the filler.

Most bolted connections transmit shearing forces by developing the shearing or bearing values of the bolts, but bolts in certain connections, such as shelf angles and brackets, are required to transmit tension forces.

Bolts shall be proportioned by the nominal diameter. Rivets and A307 bolts whose grip exceeds 5 diam shall be allowed 1 percent less safe stress for each 1⁄16 in (0.16 cm) excess length. The minimum distance between centers of bolt holes shall be 2⅔ diam of the bolt; but preferably not less than 3 diam.

The minimum distance from the center of any bolt hole to a sheared edge shall be 2¼ in (5.7 cm) for 1¼ in (32 mm) bolts, 2 in (5.1 cm) for 1⅛ in (28 mm) bolts, 1¾ in (4.4 cm) for 1 in (25 mm) bolts, 1½ in (3.8 cm) for ⅞ in (22 mm) bolts, 1¼ in (3.2 cm) for ¾ in (19 mm) bolts, 1⅛ in (2.8 cm) for ⅝ in (16 mm) bolts, and ⅞ (2.22 cm) for ½ in (13 mm) bolts. The distance from any edge shall not exceed 12 times the thickness of the plate and shall not exceed 6 in (15 cm).

Design of Members

Properties of Standard Structural Shapes Tables 12.2.18 to 12.2.26 give the properties of American Standard channels and I beams, wide-flange beams and columns, angles, and tees. In these tables, I = moment of inertia, r = radius of gyration, S = section modulus, x = distance from gravity axis to face, V = max web shear in kips, and R = max end reaction on 3½-in (9-mm) seat, based on crippling of web, in kips. R values are omitted where web crippling does not govern.

A great variety of tees is produced by shearing or gas-cutting stan-

Table 12.2.19 American Standard I Beams (S Shapes)

Depth of beam, in	Weight per ft, lb	Area of section, in²	Width of flange, in	Thickness of web, in	Neutral axis perpendicular to web at center: I, in⁴	r, in	S, in³	Neutral axis coincident with center line of web: I, in⁴	r, in	S, in³	V*, 1,000 lb	R*, 1,000 lb
S 24	120.0	35.13	8.048	0.798	3010.8	9.26	250.9	84.9	1.56	21.1	278	162
	105.9	30.98	7.875	0.625	2811.5	9.53	234.3	78.9	1.60	20.0	218	123
	100.0	29.25	7.247	0.747	2371.8	9.05	197.6	48.4	1.29	13.4	260	140
	90.0	26.30	7.124	0.624	2230.1	9.21	185.8	45.5	1.32	12.8	217	117
	79.9	23.33	7.000	0.500	2087.2	9.46	173.9	42.9	1.36	12.2	174	80
S 20	95.0	27.74	7.200	0.800	1599.7	7.59	160.0	50.5	1.35	14.0	232	150
	85.0	24.80	7.053	0.653	1501.7	7.78	150.2	47.0	1.38	13.3	189	124
	75.0	21.90	6.391	0.641	1263.5	7.60	126.3	30.1	1.17	9.4	186	114
	65.4	19.08	6.250	0.500	1169.5	7.83	116.9	27.9	1.21	8.9	145	83
S 18	70.0	20.46	6.251	0.711	917.5	6.70	101.9	24.5	1.09	7.8	186	123
	54.7	15.94	6.000	0.460	795.5	7.07	88.4	21.2	1.15	7.1	120	70
S 15	50.0	14.59	5.640	0.550	481.1	5.74	64.2	16.0	1.05	5.7	120	91
	42.9	12.49	5.500	0.410	441.8	5.95	58.9	14.6	1.08	5.3	89	58
S 12	50.0	14.57	5.477	0.687	301.6	4.55	50.3	16.0	1.05	5.8	120	116
	40.8	11.84	5.250	0.460	268.9	4.77	44.8	13.8	1.08	5.3	80	78
	35.0	10.20	5.078	0.428	227.0	4.72	37.8	10.0	0.99	3.9	74	66
	31.8	9.26	5.000	0.350	215.8	4.83	36.0	9.5	1.01	3.8	61	45
S 10	35.0	10.22	4.944	0.594	145.8	3.78	29.2	8.5	0.91	3.4	86	89
	25.4	7.38	4.660	0.310	122.1	4.07	24.4	6.9	0.97	3.0	45	38
S 8	23.0	6.71	4.171	0.441	64.2	3.09	16.0	4.4	0.81	2.1	51	
	18.4	5.34	4.000	0.270	56.9	3.26	14.2	3.8	0.84	1.9	31	
S 7	20.0	5.83	3.860	0.450	41.9	2.68	12.0	3.1	0.74	1.6	46	
	15.3	4.43	3.660	0.250	36.2	2.86	10.4	2.7	0.78	1.5	25	
S 6	17.25	5.02	3.565	0.465	26.0	2.28	8.7	2.3	0.68	1.3	40.5	
	12.5	3.61	3.330	0.230	21.8	2.46	7.3	1.8	0.72	1.1	20	
S 5	14.75	4.29	3.284	0.494	15.0	1.87	6.0	1.7	0.63	1.0	35.8	
	10.0	2.87	3.000	0.210	12.1	2.05	4.8	1.2	0.65	0.82	15.2	
S 4	9.5	2.76	2.796	0.326	6.7	1.56	3.3	0.91	0.58	0.65	18.9	
	7.7	2.21	2.660	0.190	6.0	1.64	3.0	0.77	0.59	0.58	11.0	
S 3	7.5	2.17	2.509	0.349	2.9	1.15	1.9	0.59	0.52	0.47	15.2	
	5.7	1.64	2.330	0.170	2.5	1.23	1.7	0.46	0.53	0.40	7.4	

NOTE: 1 in = 2.54 cm; 1 ft = 0.305 m; 1 lb = 4.45 N.
Lightweight beams of each depth are usual stock sizes.
* V and R values are for beams of A36 steel.

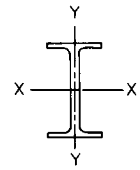


Table 12.2.20 Properties of Wide-Flange Beams and Columns (W Shapes)

Nominal size, in	Weight per ft, lb†	Area of section, in²	Depth of section, in	Flange		Web thickness, in	Neutral axis perpendicular to web at center			Neutral axis parallel to web at center			V, 1,000 lb*	R, 1,000 lb*
				Width, in	Thickness, in		I, in⁴	S, in³	r, in	I, in⁴	S, in³	r, in		
W 36	300	88.3	36.74	16.66	1.68	0.945	20,300	1,110	15.2	1,300	156	3.83	500	237
	280	82.4	36.52	16.6	1.57	0.885	18,900	1,030	15.1	1,200	144	3.81	465	215
	260	76.5	36.26	16.55	1.44	0.84	17,300	953	15	1,090	132	3.78	439	198
	245	72.1	36.08	16.51	1.35	0.8	16,100	895	15	1,010	123	3.75	416	186
	230	67.6	35.9	16.47	1.26	0.76	15,000	837	14.9	940	114	3.73	393	170
	194	57	36.49	12.12	1.26	0.765	12,100	664	14.6	375	61.9	2.56	402	163
	182	53.6	36.33	12.08	1.18	0.725	11,300	623	14.5	347	57.6	2.55	379	152
	170	50	36.17	12.03	1.1	0.68	10,500	580	14.5	320	53.2	2.53	354	137
	160	47	36.01	12	1.02	0.65	9,750	542	14.4	295	49.1	2.5	337	124
	150	44.2	35.85	11.98	0.94	0.625	9,040	504	14.3	270	45.1	2.47	323	113
W 33	241	70.9	34.18	15.86	1.4	0.83	14,200	829	14.1	932	118	3.63	409	177
	221	65	33.93	15.81	1.275	0.775	12,800	757	14.1	840	106	3.59	379	159
	201	59.1	33.68	15.75	1.15	0.715	11,500	684	14	749	95.2	3.56	347	142
	152	44.7	33.49	11.57	1.055	0.635	8,160	487	13.5	273	47.2	2.47	306	122
	141	41.6	33.3	11.54	0.96	0.605	7,450	448	13.4	246	42.7	2.43	290	109
	130	38.3	33.09	11.51	0.855	0.58	6,710	406	13.2	218	37.9	2.39	276	98
W 30	211	62	30.94	15.11	1.315	0.775	10,300	663	12.9	757	100	3.49	345	162
	191	56.1	30.68	15.04	1.185	0.71	9,170	598	12.8	673	89.5	3.46	314	141
	173	50.8	30.44	14.99	1.065	0.655	8,200	539	12.7	598	79.8	3.43	287	128
	148	43.5	30.67	10.48	1.18	0.65	6,680	436	12.4	227	43.3	2.28	287	131
	132	38.9	30.31	10.55	1	0.615	5,770	380	12.2	196	37.2	2.25	268	115
	124	36.5	30.17	10.52	0.93	0.585	5,360	355	12.1	181	34.4	2.23	254	103
	116	34.2	30.01	10.5	0.85	0.565	4,930	329	12	164	31.3	2.19	244	95
	108	31.7	29.83	10.48	0.76	0.545	4,470	299	11.9	146	27.9	2.15	234	87
W 27	178	52.3	27.81	14.09	1.19	0.725	6,990	502	11.6	555	78.8	3.26	290	141
	161	47.4	27.59	14.02	1.08	0.66	6,280	455	11.5	497	70.9	3.24	262	126
	146	42.9	27.38	13.97	0.975	0.605	5,630	411	11.4	443	63.5	3.21	239	111
	114	33.5	27.29	10.07	0.93	0.57	4,090	299	11	159	31.5	2.18	224	100
	102	30	27.09	10.02	0.83	0.515	3,620	267	11	139	27.8	2.15	201	82
	94	27.7	26.92	9.99	0.745	0.49	3,270	243	10.9	124	24.8	2.12	190	73
W 24	162	47.7	25	12.96	1.22	0.705	5,170	414	10.4	443	68.4	3.05	254	143
	146	43	24.74	12.9	1.09	0.65	4,580	371	10.3	391	60.5	3.01	232	126
	131	38.5	24.48	12.86	0.96	0.605	4,020	329	10.2	340	53	2.97	213	113
	117	34.4	24.26	12.8	0.85	0.55	3,540	291	10.1	297	46.5	2.94	192	94
	104	30.6	24.06	12.75	0.75	0.5	3,100	258	10.1	259	40.7	2.91	173	77
	103	30.3	24.53	9	0.98	0.55	3,000	245	9.96	119	26.5	1.99	194	97
	94	27.7	24.31	9.065	0.875	0.515	2,700	222	9.87	109	24	1.98	180	84
	84	24.7	24.1	9.02	0.77	0.47	2,370	196	9.79	94.4	20.9	1.95	163	70
	76	22.4	23.92	8.99	0.68	0.44	2,100	176	9.69	82.5	18.4	1.92	152	60
W 21	147	43.2	22.06	12.51	1.15	0.72	3,630	329	9.17	376	60.1	2.95	229	140
	132	38.8	21.83	12.44	1.035	0.65	3,220	295	9.12	333	53.5	2.93	204	124
	122	35.9	21.68	12.39	0.96	0.6	2,960	273	9.09	305	49.2	2.92	187	110
	93	27.3	21.62	8.42	0.93	0.58	2,070	192	8.7	92.9	22.1	1.84	181	106
	83	24.3	21.43	8.355	0.835	0.515	1,830	171	8.67	81.4	19.5	1.83	159	85
	73	21.5	21.24	8.295	0.74	0.455	1,600	151	8.64	70.6	17	1.81	139	67
	68	20	21.13	8.27	0.685	0.43	1,480	140	8.6	64.7	15.7	1.8	131	59
	62	18.3	20.99	8.24	0.615	0.4	1,330	127	8.54	57.5	13.9	1.77	121	51
W 18	119	35.1	18.97	11.27	1.06	0.655	2,190	231	7.9	253	44.9	2.69	179	123
	106	31.1	18.73	11.2	0.94	0.59	1,910	204	7.84	220	39.4	2.66	159	106
	97	28.5	18.59	11.15	0.87	0.535	1,750	188	7.82	201	36.1	2.65	143	94
	86	25.3	18.39	11.09	0.77	0.48	1,530	166	7.77	175	31.6	2.63	127	76
	76	22.3	18.21	11.04	0.68	0.425	1,330	146	7.73	152	27.6	2.61	111	60

NOTE: 1 in = 2.54 cm; 1 ft = 0.305 m; 1 lb = 4.45 N.
Flanges of wide-flange beams and columns are not tapered, have constant thickness.
Sections without values of *V* and *R* are used chiefly for columns.
Lightweight beams for each nominal size, and beams with depth in even inches, are most usually stocked.
Designation of wide-flange beams is made by giving nominal depth and weight, thus W8 × 40.
* *V* and *R* values are for beams of A36 steel.
† Some sections listed are no longer rolled but may be encountered in existing construction. Others currently rolled are not listed. Refer to producers' catalogs for sections currently available.

Table 12.2.20 Properties of Wide-Flange Beams and Columns (W Shapes) (*Continued*)

Nominal size, in	Weight per ft, lb†	Area of section, in^2	Depth of section, in	Flange		Web thickness, in	Neutral axis perpendicular to web at center			Neutral axis parallel to web at center			*V*, 1,000 lb*	*R*, 1,000 lb*
				Width, in	Thickness, in		*I*, in^4	*S*, in^3	*r*, in	*I*, in^4	*S*, in^3	*r*, in		
W 18	71	20.8	18.47	7.635	0.81	0.495	1,170	127	7.5	60.3	15.8	1.7	132	81
	65	19.1	18.35	7.59	0.75	0.45	1,070	117	7.49	54.8	14.4	1.69	119	67
	60	17.6	18.24	7.555	0.695	0.415	984	108	7.47	50.1	13.3	1.69	109	58
	55	16.2	18.11	7.53	0.63	0.39	890	98.3	7.41	44.9	11.9	1.67	102	51
	50	14.7	17.99	7.495	0.57	0.355	800	88.9	7.38	40.1	10.7	1.65	92	42
W 16	100	29.4	16.97	10.43	0.985	0.585	1,490	175	7.1	186	35.7	2.51	143	107
	89	26.2	16.75	10.37	0.875	0.525	1,300	155	7.05	163	31.4	2.49	127	92
	77	22.6	16.52	10.3	0.76	0.455	1,110	134	7	138	26.9	2.47	108	71
	67	19.7	16.33	10.24	0.665	0.395	954	117	6.96	119	23.2	2.46	93	53
	57	16.8	16.43	7.12	0.715	0.43	758	92.2	6.72	43.1	12.1	1.6	102	63
	50	14.7	16.26	7.07	0.63	0.38	659	81	6.68	37.2	10.5	1.59	89	49
	45	13.3	16.13	7.035	0.565	0.345	586	72.7	6.65	32.8	9.34	1.57	80	41
	40	11.8	16.01	6.995	0.505	0.305	518	64.7	6.63	28.9	8.25	1.57	70	32
	36	10.6	15.86	6.985	0.43	0.295	448	56.5	6.51	24.5	7	1.52	67	29
W 14	426	125	18.67	16.7	3.035	1.875	6,600	707	7.26	2,360	283	4.34	—	—
	398	117	18.29	16.59	2.845	1.77	6,000	656	7.16	2,170	262	4.31	—	—
	370	109	17.92	16.48	2.66	1.655	5,440	607	7.07	1,990	241	4.27	—	—
	342	101	17.54	16.36	2.47	1.54	4,900	559	6.98	1,810	221	4.24	—	—
	311	91.4	17.12	16.23	2.26	1.41	4,330	506	6.88	1,610	199	4.2	—	—
	283	83.3	16.74	16.11	2.07	1.29	3,840	459	6.79	1,440	179	4.17	—	—
	257	75.6	16.38	16	1.89	1.175	3,400	415	6.71	1,290	161	4.13	—	—
	233	68.5	16.04	15.89	1.72	1.07	3,010	375	6.63	1,150	145	4.1	—	—
	211	62	15.72	15.8	1.56	0.98	2,660	338	6.55	1,030	130	4.07	—	—
	193	56.8	15.48	15.71	1.44	0.89	2,400	310	6.5	931	119	4.05	—	—
	176	51.8	15.22	15.65	1.31	0.83	2,140	281	6.43	838	107	4.02	—	—
	159	46.7	14.98	15.57	1.19	0.745	1,900	254	6.38	748	96.2	4	161	145
	145	42.7	14.78	15.5	1.09	0.68	1,710	232	6.33	677	87.3	3.98	145	127
	132	38.8	14.66	14.73	1.03	0.645	1,530	209	6.28	548	74.5	3.76	136	118
	120	35.3	14.48	14.67	0.94	0.59	1,380	190	6.24	495	67.5	3.74	123	106
	109	32	14.32	14.61	0.86	0.525	1,240	173	6.22	447	61.2	3.73	108	92
	99	29.1	14.16	14.57	0.78	0.485	1,110	157	6.17	402	55.2	3.71	99	82
	90	26.5	14.02	14.52	0.71	0.44	999	143	6.14	362	49.9	3.7	89	69
	82	24.1	14.31	10.13	0.855	0.51	882	123	6.05	148	29.3	2.48	105	92
	74	21.8	14.17	10.07	0.785	0.45	796	112	6.04	134	26.6	2.48	92	72
	68	20	14.04	10.04	0.72	0.415	723	103	6.01	121	24.2	2.46	84	61
	61	17.9	13.89	9.995	0.645	0.375	640	92.2	5.98	107	21.5	2.45	75	50
	53	15.6	13.92	8.06	0.66	0.37	541	77.8	5.89	57.7	14.3	1.92	74	49
	48	14.1	13.79	8.03	0.595	0.34	485	70.3	5.85	51.4	12.8	1.91	68	41
	43	12.6	13.66	7.995	0.53	0.305	428	62.7	5.82	45.2	11.3	1.89	60	33
	38	11.2	14.1	6.77	0.515	0.31	385	54.6	5.87	26.7	7.88	1.55	63	34
	34	10	13.98	6.745	0.455	0.285	340	48.6	5.83	23.3	6.91	1.53	57	29
	30	8.85	13.84	6.73	0.385	0.27	291	42	5.73	19.6	5.82	1.49	54	26
W 12	190	55.8	14.38	12.67	1.735	1.06	1,890	263	5.82	589	93	3.25	—	—
	152	44.7	13.71	12.48	1.4	0.87	1,430	209	5.66	454	72.8	3.19	—	—
	136	39.9	13.41	12.4	1.25	0.79	1,240	186	5.58	398	64.2	3.16	—	—
	120	35.3	13.12	12.32	1.105	0.71	1,070	163	5.51	345	56	3.13	134	136
	106	31.2	12.89	12.22	0.99	0.61	933	145	5.47	301	49.3	3.11	113	112
	96	28.2	12.71	12.16	0.9	0.55	833	131	5.44	270	44.4	3.09	101	99
	87	25.6	12.53	12.13	0.81	0.515	740	118	5.38	241	39.7	3.07	93	89
	79	23.2	12.38	12.08	0.735	0.47	662	107	5.34	216	35.8	3.05	84	79
	72	21.1	12.25	12.04	0.67	0.43	597	97.4	5.31	195	32.4	3.04	76	68
	65	19.1	12.12	12	0.605	0.39	533	87.9	5.28	174	29.1	3.02	68	56
	58	17	12.19	10.01	0.64	0.36	475	78	5.28	107	21.4	2.51	63	48
	53	15.6	12.06	9.995	0.575	0.345	425	70.6	5.23	95.8	19.2	2.48	60	44
	50	14.7	12.19	8.08	0.64	0.37	394	64.7	5.18	56.3	13.9	1.96	65	51
	45	13.2	12.06	8.045	0.575	0.335	350	58.1	5.15	50	12.4	1.94	58	42
	40	11.8	11.94	8.005	0.515	0.295	310	51.9	5.13	44.1	11	1.93	51	32

NOTE: 1 in = 2.54 cm; 1 ft = 0.305 m; 1 lb = 4.45 N.
Flanges of wide-flange beams and columns are not tapered, have constant thickness.
Sections without values of *V* and *R* are used chiefly for columns.
Lightweight beams for each nominal size, and beams with depth in even inches, are most usually stocked.
Designation of wide-flange beams is made by giving nominal depth and weight, thus W8 × 40.
* *V* and *R* values are for beams of A36 steel.
† Some sections listed are no longer rolled but may be encountered in existing construction. Others currently rolled are not listed. Refer to producers' catalogs for sections currently available.

Table 12.2.20 Properties of Wide-Flange Beams and Columns (W Shapes) (*Continued*)

Nominal size, in	Weight per ft, lb†	Area of section, in^2	Depth of section, in	Flange		Web thickness, in	Neutral axis perpendicular to web at center			Neutral axis parallel to web at center			*V*, 1,000 lb*	*R*, 1,000 lb*
				Width, in	Thickness, in		*I*, in^4	*S*, in^3	*r*, in	*I*, in^4	*S*, in^3	*r*, in		
W 12	35	10.3	12.5	6.56	0.52	0.3	285	45.6	5.25	24.5	7.47	1.54	54	33
	30	8.79	12.34	6.52	0.44	0.26	238	38.6	5.21	20.3	6.24	1.52	46	25
	26	7.65	12.22	6.49	0.38	0.23	204	33.4	5.17	17.3	5.34	1.51	40	20
W 10	112	32.9	11.36	10.42	1.25	0.755	716	126	4.66	236	45.3	2.68	—	—
	100	29.4	11.1	10.34	1.12	0.68	623	112	4.6	207	40	2.65	—	—
	88	25.9	10.84	10.27	0.99	0.605	534	98.5	4.54	179	34.8	2.63	—	—
	77	22.6	10.6	10.19	0.87	0.53	455	85.9	4.49	154	30.1	2.6	—	—
	68	20	10.4	10.13	0.77	0.47	394	75.7	4.44	134	26.4	2.59	70	78
	60	17.6	10.22	10.08	0.68	0.42	341	66.7	4.39	116	23	2.57	62	68
	54	15.8	10.09	10.03	0.615	0.37	303	60	4.37	103	20.6	2.56	54	54
	49	14.4	9.98	10	0.56	0.34	272	54.6	4.35	93.4	18.7	2.54	49	45
	45	13.3	10.1	8.02	0.62	0.35	248	49.1	4.32	53.4	13.3	2.01	51	48
	39	11.5	9.92	7.985	0.53	0.315	209	42.1	4.27	45	11.3	1.98	45	39
	33	9.71	9.73	7.96	0.435	0.29	170	35	4.19	36.6	9.2	1.94	41	33
	30	8.84	10.47	5.81	0.51	0.3	170	32.4	4.38	16.7	5.75	1.37	45	35
	26	7.61	10.33	5.77	0.44	0.26	144	27.9	4.35	14.1	4.89	1.36	39	26
	22	6.49	10.17	5.75	0.36	0.24	118	23.2	4.27	11.4	3.97	1.33	35	22
W 8	67	19.7	9	8.28	0.935	0.57	272	60.4	3.72	88.6	21.4	2.12	—	—
	58	17.1	8.75	8.22	0.81	0.51	228	52	3.65	75.1	18.3	2.1	—	—
	48	14.1	8.5	8.11	0.685	0.4	184	43.3	3.61	60.9	15	2.08	49	61
	40	11.7	8.25	8.07	0.56	0.36	146	35.5	3.53	49.1	12.2	2.04	43	53
	35	10.3	8.12	8.02	0.495	0.31	127	31.2	3.51	42.6	10.6	2.03	36	41
	31	9.13	8	7.995	0.435	0.285	110	27.5	3.47	37.1	9.27	2.02	33	35
	28	8.25	8.06	6.535	0.465	0.285	98	24.3	3.45	21.7	6.63	1.62	33	34
	24	7.08	7.93	6.495	0.4	0.245	82.8	20.9	3.42	18.3	5.63	1.61	28	26
	21	6.16	8.28	5.27	0.4	0.25	75.3	18.2	3.49	9.77	3.71	1.26	30	26

NOTE: 1 in = 2.54 cm; 1 ft = 0.305 m; 1 lb = 4.45 N.
Flanges of wide-flange beams and columns are not tapered, have constant thickness.
Sections without values of *V* and *R* are used chiefly for columns.
Lightweight beams for each nominal size, and beams with depth in even inches, are most usually stocked.
Designation of wide-flange beams is made by giving nominal depth and weight, thus W8 × 40.
* *V* and *R* values are for beams of A36 steel.
† Some sections listed are no longer rolled but may be encountered in existing construction. Others currently rolled are not listed. Refer to producers' catalogs for sections currently available.

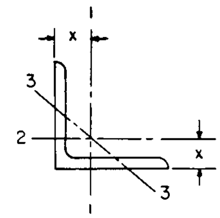


Table 12.2.21 Selected Standard Angles (L Shapes), Equal Legs
(One to three intermediate thicknesses in each size group are available, varying by 1⁄16 in)
A single angle should never be used as a beam. Two angles, bolted at frequent intervals, may be used.

Size, in	Weight per ft, lb	Areas of section, in^2	Axis 1-1 and axis 2-2				Axis 3-3, *r* min, in	Net areas after deducting holes for ⅞-in rivets	
			I, in^4	*r*, in	*S*, in^3	*x*, in		1 hole	2 holes
8 × 8 × 1⅛	56.9	16.73	98.0	2.42	17.5	2.41	1.56	15.60	14.48
1	51.0	15.00	89.0	2.44	15.8	2.37	1.56	14.00	13.00
⅞	45.0	13.23	79.6	2.45	14.0	2.32	1.57	12.36	11.48
¾	38.9	11.44	69.7	2.47	12.2	2.28	1.57	10.69	9.94
⅝	32.7	9.61	59.4	2.49	10.3	2.23	1.58	8.98	8.36
½	26.4	7.75	48.6	2.50	8.4	2.19	1.59	7.25	6.75
6 × 6 × 1	37.4	11.00	35.5	1.80	8.6	1.86	1.17	10.00	9.00
⅞	33.1	9.73	31.9	1.81	7.6	1.82	1.17	8.86	7.98
¾	28.7	8.44	28.2	1.83	6.7	1.78	1.17	7.69	6.94
⅝	24.2	7.11	24.2	1.84	5.7	1.73	1.18	6.48	5.86
½	19.6	5.75	19.9	1.86	4.6	1.68	1.18	5.25	4.75
⅜	14.9	4.36	15.4	1.88	3.5	1.64	1.19	3.98	3.61
5 × 5 × ⅞	27.2	7.98	17.8	1.49	5.2	1.57	0.97	7.10	6.23
¾	23.6	6.94	15.7	1.51	4.5	1.52	0.97	6.19	5.44
⅝	20.0	5.86	13.6	1.52	3.9	1.48	0.98	5.24	4.61
½	16.2	4.75	11.3	1.54	3.2	1.43	0.98	4.25	3.75
⅜	12.3	3.61	8.7	1.56	2.4	1.39	0.99	3.24	2.86
4 × 4 × ¾	18.5	5.44	7.7	1.19	2.8	1.27	0.78	4.69	3.94
⅝	15.7	4.61	6.7	1.20	2.4	1.23	0.78	3.98	3.36
½	12.8	3.75	5.6	1.22	2.0	1.18	0.78	3.25	2.75
⅜	9.8	2.86	4.4	1.23	1.5	1.14	0.79	2.48	2.11
¼	6.6	1.94	3.0	1.25	1.1	1.09	0.80	1.70	1.45
3½ × 3½ × ½	11.1	3.25	3.6	1.06	1.5	1.06	0.68	2.75	2.25
⅜	8.5	2.48	2.9	1.07	1.2	1.01	0.69	2.10	1.73
¼	5.8	1.69	2.0	1.09	0.79	0.97	0.69	1.44	1.19
3 × 3 × ½	9.4	2.75	2.2	0.90	1.1	0.93	0.58		
⅜	7.2	2.11	1.8	0.91	0.83	0.89	0.58		
¼	4.9	1.44	1.2	0.93	0.58	0.84	0.59		
2½ × 2½ × ½	7.7	2.25	1.2	0.74	0.72	0.81	0.49		
⅜	5.9	1.73	0.98	0.75	0.57	0.76	0.49		
¼	4.1	1.19	0.70	0.77	0.39	0.72	0.49		
2 × 2 × ⅜	4.7	1.36	0.48	0.59	0.35	0.64	0.39		
¼	3.19	0.94	0.35	0.61	0.25	0.59	0.39		
⅛	1.65	0.48	0.19	0.63	0.13	0.55	0.40		
1¾ × 1¾ × ¼	2.77	0.81	0.23	0.53	0.19	0.53	0.34		
⅛	1.44	0.42	0.13	0.55	0.10	0.48	0.35		
1½ × 1½ × ¼	2.34	0.69	0.14	0.45	0.13	0.47	0.29		
⅛	1.23	0.36	0.08	0.47	0.07	0.42	0.30		
1¼ × 1¼ × ¼	1.92	0.56	0.08	0.37	0.09	0.40	0.24		
⅛	1.01	0.30	0.04	0.38	0.05	0.36	0.25		
1 × 1 × ¼	1.49	0.44	0.04	0.29	0.06	0.34	0.20		
⅛	0.80	0.23	0.02	0.30	0.03	0.30	0.20		

NOTE: 1 in = 2.5 cm; 1 ft = 0.305 m; 1 lb = 4.45 N.

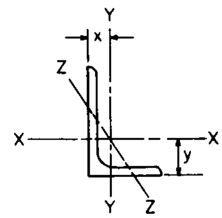


Table 12.2.22 Selected Standard Angles (L Shapes) Unequal Legs
(Intermediate thicknesses are available in each size group, varying by 1/16 in among the thinner angles)
A single angle should never be used as a beam. Two angles, bolted at frequent intervals, may be used.

Size, in	Thickness, in	Weight per ft, lb	Area of section, in²	Axis *X-X*				Axis *Y-Y*				Axis *Z-Z*	Net areas after deducting holes for ⅞-in rivets	
				I, in⁴	*S*, in³	*r*, in	*y*, in	*I*, in⁴	*S*, in³	*r*, in	*y*, in	*r*, in	1 hole	2 holes
8 × 6	1	44.2	13.00	80.8	15.1	2.49	2.65	38.8	8.9	1.73	1.65	1.28	12.00	11.00
	¾	33.8	9.94	63.4	11.7	2.53	2.56	30.7	6.9	1.76	1.56	1.29	9.19	8.44
	½	23.0	6.75	44.3	8.0	2.56	2.47	21.7	4.8	1.79	1.47	1.30	6.25	5.75
	7/16	20.2	5.93	39.2	7.1	2.57	2.45	19.3	4.2	1.80	1.45	1.31	5.49	5.06
8 × 4	1	37.4	11.00	69.6	14.1	2.52	3.05	11.6	3.9	1.03	1.05	0.85	10.00	9.00
	¾	28.7	8.44	54.9	10.9	2.55	2.95	9.4	3.1	1.05	0.95	0.85	7.69	6.94
	½	19.6	5.75	38.5	7.5	2.59	2.86	6.7	2.2	1.08	0.86	0.86	5.25	4.75
	7/16	17.2	5.06	34.1	6.6	2.60	2.83	6.0	1.9	1.09	0.83	0.87	4.62	4.18
7 × 4	⅞	30.2	8.86	42.9	9.7	2.20	2.55	10.2	3.5	1.07	1.05	0.86	7.98	7.11
	¾	26.2	7.69	37.8	8.4	2.22	2.51	9.1	3.0	1.09	1.01	0.86	6.94	6.19
	½	17.9	5.25	26.7	5.8	2.25	2.42	6.5	2.1	1.11	0.92	0.87	4.75	4.25
	⅜	13.6	3.98	20.6	4.4	2.27	2.37	5.1	1.6	1.13	0.87	0.88	3.62	3.24
6 × 4	⅞	27.2	7.98	27.7	7.2	1.86	2.12	9.8	3.4	1.11	1.12	0.86	7.10	6.23
	¾	23.6	6.94	24.5	6.3	1.88	2.08	8.7	3.0	1.12	1.08	0.86	6.19	5.44
	½	16.2	4.75	17.4	4.3	1.91	1.99	6.3	2.1	1.15	0.99	0.87	4.25	3.75
	⅜	12.3	3.61	13.5	3.3	1.93	1.94	4.9	1.6	1.17	0.94	0.88	3.24	2.86
	5/16	10.3	3.03	11.4	2.8	1.94	1.92	4.2	1.4	1.17	0.92	0.88	2.72	2.40
6 × 3½	½	15.3	4.50	16.6	4.2	1.92	2.08	4.3	1.6	0.97	0.83	0.76	4.00	3.50
	⅜	11.7	3.42	12.9	3.2	1.94	2.04	3.3	1.2	0.99	0.79	0.77	3.04	2.67
	¼	7.9	2.31	8.9	2.2	1.96	1.99	2.3	0.85	1.01	0.74	0.78	2.06	1.81
5 × 3½	¾	19.8	5.81	13.9	4.3	1.55	1.75	5.6	2.2	0.98	1.00	0.75	5.06	4.31
	½	13.6	4.00	10.0	3.0	1.58	1.66	4.1	1.6	1.01	0.91	0.75	3.50	3.00
	¼	7.0	2.06	5.4	1.6	1.61	1.56	2.2	0.83	1.04	0.81	0.76	1.81	1.56
5 × 3	½	12.8	3.75	9.5	2.9	1.59	1.75	2.6	1.1	0.83	0.75	0.65	3.25	2.75
	⅜	9.8	2.86	7.4	2.2	1.61	1.70	2.0	0.89	0.84	0.70	0.65	2.48	2.11
	¼	6.6	1.94	5.1	1.5	1.62	1.66	1.4	0.61	0.86	0.66	0.66	1.69	1.44
4 × 3½	⅝	14.7	4.30	6.4	2.4	1.22	1.29	4.5	1.8	1.03	1.04	0.72	3.68	3.05
	½	11.9	3.50	5.3	1.9	1.23	1.25	3.8	1.5	1.04	1.00	0.72	3.00	2.50
	⅜	9.1	2.67	4.2	1.5	1.25	1.21	3.0	1.2	1.06	0.96	0.73	2.30	1.92
	¼	6.2	1.81	2.9	1.0	1.27	1.16	2.1	0.81	1.07	0.91	0.73	1.56	1.31
4 × 3	⅝	13.6	3.98	6.0	2.3	1.23	1.37	2.9	1.4	0.85	0.87	0.64	3.36	2.73
	½	11.1	3.25	5.1	1.9	1.25	1.33	2.4	1.1	0.86	0.83	0.64	2.75	2.25
	¼	5.8	1.69	2.8	1.0	1.28	1.24	1.4	0.60	0.90	0.74	0.65	1.44	1.19
3½ × 3	½	10.2	3.00	3.5	1.5	1.07	1.13	2.3	1.1	0.88	0.88	0.62	2.50	
	¼	5.4	1.56	1.9	0.78	1.11	1.04	1.3	0.59	0.91	0.79	0.63	1.31	
3½ × 2½	½	9.4	2.75	3.2	1.4	1.09	1.20	1.4	0.76	0.70	0.70	0.53	2.25	
	¼	4.9	1.44	1.8	0.75	1.12	1.11	0.78	0.41	0.74	0.61	0.54	1.19	
3 × 2½	½	8.5	2.50	2.1	1.0	0.91	1.00	1.3	0.74	0.72	0.75	0.52		
	⅜	6.6	1.92	1.7	0.81	0.93	0.96	1.0	0.58	0.74	0.71	0.52		
	¼	4.5	1.31	1.2	0.56	0.95	0.91	0.74	0.40	0.75	0.66	0.53		
3 × 2	½	7.7	2.25	1.9	1.0	0.92	1.08	0.67	0.47	0.55	0.58	0.43		
	3/16	3.07	0.90	0.84	0.41	0.97	0.97	0.31	0.20	0.58	0.47	0.44		
2½ × 2	⅜	5.3	1.55	0.91	0.55	0.77	0.83	0.51	0.36	0.58	0.58	0.42		
	3/16	2.75	0.81	0.51	0.29	0.79	0.76	0.29	0.20	0.60	0.51	0.43		
2 × 1½	¼	2.77	0.81	0.32	0.24	0.62	0.66	0.15	0.14	0.43	0.41	0.32		
	⅛	1.44	0.42	0.17	0.13	0.64	0.62	0.09	0.08	0.45	0.37	0.33		
1¾ × 1¼	¼	2.34	0.69	0.20	0.18	0.54	0.60	0.09	0.10	0.35	0.35	0.27		
	⅛	1.23	0.36	0.11	0.09	0.56	0.56	0.05	0.05	0.37	0.31	0.27		

NOTE: 1 in = 2.54 cm; 1 ft = 0.305 m; 1 lb = 4.45 N.

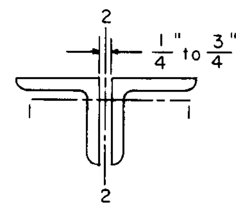


Table 12.2.23 Radii of Gyration for Two Angles, Unequal Legs

Single angle		Two angles	Radii of gyration, in							
			Long legs vertical				Short legs vertical			
				Axis 2-2				Axis 2-2		
Size, in	Weight per ft, lb	Area, in²	Axis 1-1	In contact	⅜ in apart	¾ in apart	Axis 1-1	In contact	⅜ in apart	¾ in apart
8 × 6 × 1	44.2	26.00	2.49	2.39	2.52	2.66	1.73	3.64	3.78	3.92
¾	33.8	19.9	2.53	2.35	2.48	2.62	1.76	3.60	3.74	3.88
8 × 4 × 1	37.4	22.00	2.52	1.47	1.61	1.76	1.03	3.95	4.10	4.25
½	19.6	11.50	2.59	1.38	1.51	1.64	1.08	3.86	4.00	4.14
7 × 4 × ¾	26.2	15.4	2.22	1.48	1.62	1.76	1.09	3.35	3.48	3.64
⅜	13.6	7.96	2.27	1.43	1.55	1.68	1.13	3.28	3.42	3.56
6 × 4 × ¾	23.6	13.9	1.88	1.55	1.69	1.83	1.12	2.80	2.94	3.09
⅜	12.3	7.22	1.93	1.50	1.62	1.76	1.17	2.74	2.87	3.02
5 × 3½ × ¾	19.8	11.62	1.55	1.40	1.54	1.69	0.98	2.34	2.48	2.63
5/16	8.7	5.12	1.61	1.33	1.45	1.59	1.03	2.26	2.38	2.53
4 × 3½ × ½	11.9	7.00	1.23	1.44	1.58	1.72	1.04	1.76	1.89	2.04
5/16	7.7	4.50	1.26	1.42	1.55	1.69	1.07	1.73	1.86	2.00
4 × 3 × ½	11.1	6.50	1.25	1.20	1.33	1.48	0.86	1.82	1.96	2.11
¼	5.8	3.38	1.28	1.16	1.29	1.43	0.90	1.78	1.92	2.06
3½ × 3 × ⅜	7.9	4.59	1.09	1.22	1.36	1.50	0.90	1.53	1.67	1.82
¼	5.4	3.12	1.11	1.21	1.34	1.48	0.91	1.52	1.65	1.80
3 × 2½ × ⅜	6.6	3.84	0.93	1.02	1.16	1.31	0.74	1.34	1.48	1.63
¼	4.5	2.62	0.95	1.00	1.13	1.28	0.75	1.31	1.45	1.60
2½ × 2 × ⅜	5.3	3.10	0.77	0.82	0.96	1.11	0.58	1.13	1.27	1.43
¼	3.6	2.12	0.78	0.80	0.94	1.09	0.59	1.11	1.25	1.40

NOTE: 1 in = 2.54 cm; 1 ft = 0.305 m; 1 lb = 4.45 N.

dard beams (S shapes) or wide-flange sections (W shapes) length-wise at midheight of the web, making two similar shapes of T section. Table 12.2.25 lists a selection of such tees.

For additional data regarding structural shapes, their strengths as beams and columns, and means of making connections, see ''AISC Manual of Steel Construction.''

Welding The main advantage of assembling and connecting steel frames by welding is the reduction in the amount of metal used. The saving in metal is achieved by (1) elimination of bolt holes which reduce the net section of tension members, (2) simplification of details, and (3) elimination of splice plate and gusset plate material. (See also Sec. 13.3.)

Allowable stresses in welds depend on the type of weld, the manner of loading, and the relative strengths of the weld metal and the base metal. For **complete-penetration groove welds** in which the full edge thickness of the thinner part to be joined is beveled in preparation for welding, allowable stresses due to tension or compression normal to the effective area or parallel to the axis of the weld are the same as the base metal, and the allowable shear stress on the effective area is 0.3 times the nominal tensile strength of the weld metal (limited by 0.4 times yield stress in the base metal). The effective area for a complete-penetration groove weld is the width of the part joined times the thickness of the thinner part.

For **partial-penetration groove welds,** allowable stresses due to compression normal to the effective area and tension or compression parallel to the axis of the weld are the same as the base metal. For tension normal to the effective area, the allowable stress is 0.3 times the nominal tensile strength of the weld metal (limited by 0.6 times the yield stress of the base metal); for shear parallel to the axis of the weld, the allowable stress on the effective area is 0.3 times the nominal tensile strength of weld metal (limited by 0.4 times yield stress of the base metal). The effective thickness of partial-penetration groove welds depends on the welding process, welding position, and the included angle of the groove but may be safely taken as the depth of the chamfer less ⅛ in.

For **fillet welds,** allowable shear stresses on the effective area are taken as 0.3 times nominal tensile strength of the weld (limited by 0.4 times yield stress of the base metal), and for tension or compression parallel to the axis of the weld, allowable stresses are the same as the base metal. Fillet welds are not to be loaded in tension or compression normal to the effective area; they transfer loads between members in shear only. The effective area of a fillet weld is the overall length of the full-size weld times the shortest distance from the root to the face (normally leg size × sin 45°). Allowable shear in a fillet weld is taken as 930 lb/in of length (163 N/mm) for each 1/16 in (1.59 mm) of leg size. Fillet welds should be limited to ½ in (12.5 mm) leg size in normal construction and to the thickness of the material up to ¼ in and thickness less 1/16 in for thicker material. The minimum-size fillet weld for ¼-in-thick material should

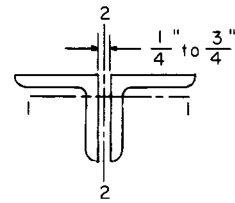


Table 12.2.24 Radii of Gyration for Two Angles, Equal Legs

Single angle		Two angles	Radii of gyration, in			
				Axis 2-2		
Size, in	Weight per ft, lb	Area, in²	Axis 1-1	In contact	⅜ in apart	¾ in apart
8 × 8 × 1⅛	56.9	33.46	2.42	3.42	3.55	3.69
½	26.4	15.50	2.50	3.33	3.45	3.59
6 × 6 × 1	37.4	22.00	1.80	2.59	2.72	2.87
⅜	14.9	8.72	1.88	2.49	2.62	2.76
5 × 5 × ⅞	27.2	15.96	1.49	2.17	2.31	2.45
⅜	12.3	7.22	1.56	2.09	2.22	2.35
4 × 4 × ¾	18.5	10.88	1.19	1.74	1.88	2.03
¼	6.6	3.88	1.25	1.66	1.79	1.93
3½ × 3½ × ⅜	8.5	4.97	1.07	1.48	1.61	1.75
¼	5.8	3.38	1.09	1.46	1.59	1.73
3 × 3 × ½	9.4	5.50	0.90	1.29	1.43	1.58
¼	4.9	2.88	0.93	1.25	1.38	1.53
2½ × 2½ × ⅜	5.9	3.47	0.75	1.07	1.21	1.36
¼	4.1	2.38	0.77	1.05	1.19	1.34
2 × 2 × ⅜	4.7	2.72	0.59	0.87	1.02	1.18
¼	3.19	1.88	0.61	0.85	0.99	1.14

NOTE: 1 in = 2.54 cm; 1 ft = 0.305 m; 1 lb = 4.45 N.

be ⅛ in; for over ¼- to ½-in material, 3⁄16 in; for over ½-in to ¾-in material, ¼ in; and for over ¾-in-thick material, 5⁄16 in. Typical details of welded connections are indicated in Fig. 12.2.18.

Safe Loads for Steel Beams To determine the safe load uniformly distributed, as limited by bending, for a structural steel beam on a given span, apply the formula $W = 8F_bs/l$, where W is the total load, lb.; F_b is the allowable fiber stress (24,000 lb/in² or any other); S is the section

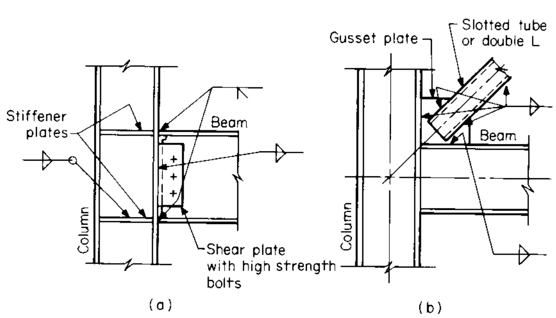


Fig. 12.2.18 Welded connections. (*a*) Moment connection; (*b*) bracing connection.

modulus for the beam in question, given in Tables 12.2.18 to 12.2.26; and l is the span, in. (This formula may also be used with equivalent metric units.) The safe load concentrated at midspan is one-half this amount. For other safe loads, note that F_bS is the safe resistance to bending in inch-pounds (or newton-meters) afforded by the beam. Compute the load, of whatever type or distribution, which will produce a maximum bending moment equal to safe moment of resistance (see Sec. 5 for bending-moment formulas).

To select a beam to support a given load, compute the maximum bending moment in inch-pounds, divide by the allowable fiber stress F_b, and refer to the table for a beam having a section modulus which is not smaller than the quotient.

Formulas for the safe loads and deflections of beams with various methods of support and of loading are given in Sec. 5.

Short beams should be investigated for crippling of the web. In the tables are given the safe end reactions for beams of A36 steel resting on a seat 3½ in (9 cm) long along the axis of the beam. Short beams should also be investigated for shear, by dividing the maximum shear, in pounds, by the area of the web, excluding the flanges.

Single angles used as beams and loaded in the plane of axis X-X or Y-Y tend to deflect laterally as well as in the plane of the loads. Unless this is prevented, as by pairing the angles back to back and securing them together, the unit fiber stress due to bending may be as much as 40 percent above that computed by dividing the bending moment by S for the axis perpendicular to the plane of the loads. The relation $f = M/S$ does not hold for single angles, and Z bars, which are unsymmetrical about both axes.

Deflection of I Beams and Other Structural Shapes Table 12.2.27 gives **coefficients of deflection** for steel shapes under uniformly distributed loads, and is based on the formula; deflection in inches = $30fL^2/Ed$, the table giving the values of $30fL^2/E$. (f = fiber stress, lb/in², L = span, ft; d = depth of section, in; E = modulus of elasticity = 29,000,000 lb/in².)

To find the deflection in inches of a section symmetrical about the neutral axis, such as a beam, channel, etc., divide the coefficient in the table corresponding to given span and fiber stress by the depth of the section in inches.

To find the deflection in inches of a section which is not symmetrical about the neutral axis but which is symmetrical about an axis at right angles thereto, such as a tee or pair of angles, divide the coefficient corresponding to given span and fiber stress by twice the distance of extreme fiber from neutral axis obtained from table of elements of sections.

To find the deflection in inches of a section for any other fiber stress than those given, multiply this fiber stress by either of the coefficients in the table for the given span and divide by the fiber stress corresponding to the coefficients used.

I beams and channels loaded to a fiber stress of 24,000 lb/in^2 (165.5 MPa) will not deflect in excess of 1⁄360 of the span (allowed for plastered ceilings) if the depth in inches (cm) is not less than 0.74 (6.21) times the span in feet (m) for uniform loads and 0.60 (5.00) times the span for central concentration.

Beam Supports Steel beams are supported at the ends generally (1) by means of web connections to girders and columns, (2) by resting on structural-steel seats, or (3) by resting on masonry. Limiting values of end reactions of the second type, for seats 3½ in (9 cm) long, are given in Tables 12.2.18 to 12.2.20. Standard AISC web connections of the first type are called *framed beam* connections and are designated by the number of rows of bolts. Examples of connections are given in Fig. 12.2.19. These connections may be specified as ''Standard 3 row, 4 row, etc., connections.'' Connections must always be designated and detailed for the calculated design reaction.

The capacity of web connections is governed by the shearing of the fastener, or the bearing of the fastener on the web or on the material to which the beam is connected, or by the strength of the connecting angles. The supporting values of standard framed beam connections, using ⅞ in fasteners in members of A36 material, are given in Table 12.2.28. For fasteners in webs thicker than 0.34 in use the values in the column headed Double Shear; for thinner webs, bearing limits the value, and the coefficients for web bearing are to be used. For ¾-in fasteners, multiply tabular bearing values by 6⁄7 and shear values by 36⁄49. Fasteners connecting the outstanding legs to the supporting metal are in double shear if two beams are framed opposite or in single shear if a beam is connected on one side only. If the supporting material of A36 steel is thinner than 0.34 in in double-shear connections or thinner than 0.17 in in single-shear connections, the capacity is limited by bearing. The value of any ⅞-in fastener in bearing on A36 material is 60,900t, where t is the thickness of the plate. The value of ⅞ in A502, grade 1 rivets or A325 HS bolts (slip-critical connections) is 9,020 lb in single shear and 20,400 lb in double shear. The corresponding values for A307 unfinished bolts are 6,000 lb and 12,000 lb, respectively.

Cast-iron columns were often used in the past instead of wood, to save space, in the lower stories of heavy buildings. Their use is now obsolete, but they are occasionally encountered in repair and alteration work to older buildings. The ratio of length to least radius of gyration l/r should not exceed 70, and the average unit stress under axial compression should not exceed $9{,}000 - 40l/r$ lb/in^2.

Steel joists consisting of lightweight rolled sections, thin for their height, or open-web trussed members fabricated by welding or otherwise, are used with economy in buildings where spans are long and loads are light, and where a plaster ceiling affords sufficient fire protection. They are rarely used in industrial buildings, except to support roof loads.

Steel pipe is often used for columns under light loads. Table 12.2.29 gives the safe loads on standard size pipes (ASTM A501 or A53, grade B) used as columns. For extra-strong and double extra-strong pipe used as columns, the safe loads will increase approximately in the same proportion as the weight per foot. (See Sec. 8.7)

Structural steel tubing (ASTM A500, grade B), in square or rectangular cross section with $F_y = 46$ Ksi (317.1 MPa), is also used for columns, bracing members, and unbraced members subjected to large torsional loads. The closed box shape makes tube sections especially suited for resisting torsional loads.

Corrugated metal deck and siding is used for roofs and walls, respectively, to span between purlins for roof loads or between girts for wind loads. The decking is sized to resist the bending caused by these loads. Roof decking is often also used as a diaphragm to transfer wind or seismic loads to the lateral bracing system below. Load tables specifying safe loads for different spans are available from metal deck manufacturers.

The spacing of purlins on roofs and girts on wall is usually 4 to 6 ft. Numbers 20 and 22, U.S. Standard gage, are generally used for roofing; No. 24 for siding.

Fire Resistance The resistance to fire of building materials has been tested extensively by various agencies. Table 12.2.30 gives the fire-resistance rating of a few of the common building materials and methods of construction as established by the Uniform Building Code from standard fire tests.

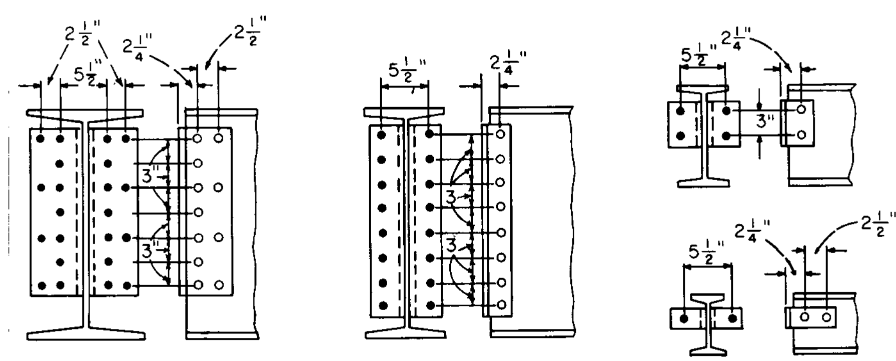


Fig. 12.2.19 Framed beam connections.

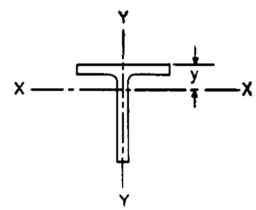
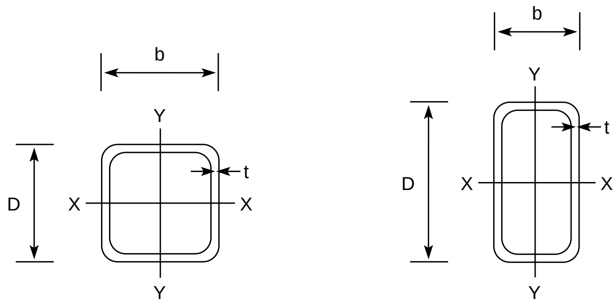


Table 12.2.25 Tees Cut from Standard Sections (WT and ST Shapes)*

				Flange			Axis X-X				Axis Y-Y		
Nominal depth, in	Weight per ft, lb	Area, in²	Depth, of tee, in	Width in	Avg thick-ness, in	Stem thick-ness, in	I, in⁴	S, in³	r, in	y, in	I, in⁴	S, in³	r, in
WT18	150	44.1	18.37	16.66	1.68	0.95	1,230	86.1	5.27	4.13	648	77.8	3.83
	115	33.8	17.95	16.47	1.26	0.76	934	67.0	5.25	4.01	470	57.1	3.73
	97	28.5	18.25	12.12	1.26	0.77	901	67.0	5.62	4.80	187	30.9	2.56
	75	22.1	17.93	11.98	0.94	0.63	698	53.1	5.62	4.78	135	22.5	2.47
WT16.5	120.5	35.4	17.09	15.86	1.40	0.83	875	65.0	4.96	3.85	466	58.8	3.63
	110.5	32.5	16.97	15.81	1.28	0.78	799	60.8	4.96	3.81	420	53.2	3.59
	100.5	29.5	16.84	15.75	1.15	0.72	725	55.5	4.95	3.70	375	47.6	3.56
	65	19.2	16.55	11.51	0.86	0.58	513	42.1	5.18	4.36	109	18.9	2.39
WT15	106.5	31.0	15.47	15.11	1.32	0.78	610	50.5	4.43	3.40	378	50.1	3.49
	86.5	25.4	15.22	14.99	1.07	0.66	497	41.7	4.42	3.31	299	39.9	3.43
	62	18.2	15.09	10.52	0.93	0.59	396	35.3	4.66	3.90	90.4	17.2	2.23
	49.5	14.5	14.83	10.45	0.67	0.52	322	30.0	4.71	4.09	63.9	12.2	2.10
WT113.5	97	28.5	14.06	14.04	1.34	0.75	444	40.3	3.95	3.03	309	44.1	3.29
	80.5	23.7	13.80	14.02	1.08	0.66	372	34.4	3.96	2.99	248	35.4	3.24
	57	16.8	13.65	10.07	0.93	0.57	289	28.3	4.15	3.42	79.4	15.8	2.18
	42	12.4	13.36	9.96	0.64	0.46	216	21.9	4.18	3.48	52.8	10.6	2.07
WT12	81	23.9	12.50	12.96	1.27	0.71	293	29.9	3.50	2.70	221	34.2	3.05
	52	15.3	12.03	12.75	0.75	0.50	189	20.0	3.51	2.59	130	20.3	2.91
	42	12.4	12.05	9.02	0.77	0.47	166	18.3	3.67	2.97	47.2	10.5	1.95
	27.5	8.1	11.79	7.01	0.51	0.40	117	14.1	3.80	3.50	14.5	4.15	1.34

WT10.5	41.5	12.2	10.72	8.36	0.84	0.52	127	15.7	3.22	2.66	40.7	9.75	1.83
	34	10.0	10.57	8.27	0.69	0.43	103	12.9	3.20	2.59	32.4	7.83	1.80
	28.5	8.37	10.53	6.56	0.65	0.41	90.4	11.8	3.29	2.85	15.3	4.67	1.35
	22	6.49	10.33	6.50	0.45	0.35	71.1	9.7	3.31	2.98	10.3	3.18	1.26
WT9	65	19.1	9.63	11.16	1.20	0.67	127	16.7	2.50	2.02	139	24.9	2.70
	53	15.6	9.37	11.20	0.94	0.59	104	14.1	2.59	1.97	110	19.7	2.66
	30	8.82	9.12	7.56	0.70	0.42	64.7	9.3	2.71	2.16	25	6.63	1.69
	20	5.88	8.95	6.02	0.53	0.32	44.8	6.73	2.76	2.29	9.6	3.17	1.27
WT8	38.5	11.3	8.26	10.30	0.76	0.46	56.9	8.59	2.24	1.63	69.2	13.4	2.47
	25	7.37	8.13	7.07	0.63	0.38	42.3	6.78	2.40	1.89	18.6	5.26	1.59
	20	5.89	8.01	7.00	0.51	0.31	33.1	5.35	2.37	1.81	14.4	4.12	1.57
	15.5	4.56	7.94	5.23	0.44	0.28	27.4	4.64	2.45	2.02	6.20	2.24	1.17
WT7	155.5	45.7	8.56	16.23	2.26	1.41	176	26.7	1.96	1.97	807	99.4	4.20
	60	17.7	7.24	14.67	0.94	0.59	51.7	8.61	1.71	1.24	247	33.7	3.74
	41	12.0	7.16	10.13	0.89	0.51	41.2	7.14	1.85	1.39	74.2	14.6	2.48
	17	5.0	6.99	6.75	0.46	0.29	20.9	3.83	2.04	1.53	11.7	3.45	1.53
WT6	95	27.9	7.19	12.67	1.74	1.06	79.0	14.2	1.68	1.62	295	46.5	3.25
	48	14.1	6.36	12.16	0.90	0.55	32.0	6.12	1.51	1.13	135	22.2	3.09
	32.5	9.54	6.06	12.00	0.61	0.39	20.6	4.06	1.47	0.99	87.2	14.5	3.02
	20	5.89	5.97	8.01	0.52	0.30	14.4	2.95	1.57	1.08	22.0	5.51	1.93
WT5	44	12.9	5.42	10.27	0.99	0.61	20.8	4.77	1.27	1.06	89.3	17.4	2.63
	30	8.82	5.11	10.08	0.68	0.42	12.9	3.04	1.21	0.88	58.1	11.5	2.57
	22.5	5.73	4.96	7.99	0.53	0.32	8.84	2.16	1.24	0.88	22.5	5.64	1.98
	15	4.42	5.24	5.81	0.51	0.30	9.28	2.24	1.45	1.1	8.35	2.87	1.37
WT4	33.5	9.84	4.50	8.28	0.94	0.57	10.9	3.05	1.05	0.94	44.3	10.7	2.12
	20	5.87	4.13	8.07	0.56	0.36	5.73	1.69	0.99	0.74	24.5	6.08	2.04
	14	4.12	4.03	6.34	0.47	0.29	4.22	1.28	1.01	0.73	10.8	3.31	1.62
	7.5	2.22	4.06	4.02	0.32	0.25	3.28	1.07	1.22	1.0	1.7	0.85	0.87
ST 9	35	10.3	9.00	6.25	0.69	0.71	84.7	14.0	2.87	2.94	12.1	3.86	1.08
6	25	7.35	6.00	5.48	0.66	0.69	25.2	6.05	1.85	1.84	7.85	2.87	1.03
4	11.5	3.38	4.00	4.17	0.43	0.44	5.03	1.77	1.22	1.15	2.15	1.03	0.80
3	6.25	1.83	3.00	3.33	0.36	0.23	1.27	0.56	0.83	0.69	0.91	0.55	0.71

NOTE: 1 in = 2.54 cm; 1 ft = 0.305 m; 1 lb = 4.45 N.
* The availability of WT sections listed is governed by the basic W sections from which they are cut. See footnote under Table 12.2.20.



Square Rectangular

Table 12.2.26 Properties of Square and Rectangular Tubing (TS Sections)*

Nominal Size D, in × b, in	t, in	Weight, lb/ft	Area of metal, in²	I_{xx}, in⁴	S_{xx}, in³	r_{xx}, in	I_{yy}, in⁴	S_{yy}, in³	r_{yy}, in
TS 12 × 12	0.5	76.07	22.4	485	80.9	4.66	485	80.9	4.66
12	0.375	58.1	17.1	380	63.4	4.72	380	63.4	4.72
TS 10 × 10	0.5	62.46	18.4	271	54.2	3.84	271	54.2	3.84
10	0.375	47.9	14.1	214	42.9	3.9	214	42.9	3.9
10	0.25	32.63	9.59	151	30.1	3.96	151	30.1	3.96
TS 8 × 8	0.5	48.85	14.4	131	32.9	3.03	131	32.9	3.03
8	0.375	37.69	11.1	106	26.4	3.09	106	26.4	3.09
8	0.25	25.82	7.59	75.1	18.8	3.15	75.1	18.8	3.15
TS 6 × 6	0.5	35.24	10.4	50.5	16.8	2.21	50.5	16.8	2.21
6	0.375	27.48	8.08	41.6	13.9	2.27	41.6	13.9	2.27
6	0.25	19.02	5.59	30.3	10.1	2.33	30.3	10.1	2.33
6	0.1875	14.53	4.27	23.8	7.93	2.36	23.8	7.93	2.36
TS 5 × 5	0.5	28.43	8.36	27.0	10.8	1.80	27.0	10.8	1.80
	0.375	22.37	6.58	22.8	9.11	1.86	22.8	9.11	1.86
	0.25	15.62	4.59	16.9	6.78	1.92	16.9	6.78	1.92
	0.1875	11.97	3.52	13.4	5.36	1.95	13.4	5.36	1.95
TS 4 × 4	0.5	21.63	6.36	12.3	6.13	1.39	12.3	6.13	1.39
4	0.375	17.27	5.08	10.7	5.35	1.45	10.7	5.35	1.45
4	0.25	12.21	3.59	8.22	4.11	1.51	8.22	4.11	1.51
4	0.1875	9.42	2.77	6.59	3.3	1.54	6.59	3.3	1.54
TS 3 × 3	0.375	10.58	3.11	3.58	2.39	1.07	3.58	2.39	1.07
	0.25	8.81	2.59	3.16	2.10	1.10	3.16	2.10	1.10
	0.1875	6.87	2.02	2.60	1.73	1.13	2.60	1.73	1.13
TS 2 × 2	0.3125	6.32	1.86	0.815	0.815	0.662	0.815	0.815	0.662
2	0.25	5.41	1.59	0.766	0.766	0.694	0.766	0.766	0.694
2	0.1875	4.32	1.27	0.668	0.668	0.726	0.668	0.668	0.726
TS 20 × 12	0.5	103.3	30.4	1,650	165	7.37	750	125	4.97
12	0.375	78.52	23.1	1,280	128	7.45	583	97.2	5.03
8	0.5	89.68	26.4	1,270	127	6.94	300	75.1	3.38
8	0.375	68.31	20.1	988	98.8	7.02	236	59.1	3.43
8	0.3125	57.36	16.9	838	83.8	7.05	202	50.4	3.46
TS16 × 12	0.5	89.68	26.4	962	120	6.04	618	103	4.84
12	0.375	68.31	20.1	748	93.5	6.11	482	80.3	4.9
8	0.5	76.07	22.4	722	90.2	5.68	244	61	3.3
8	0.375	58.1	17.1	565	70.6	5.75	193	48.2	3.36
8	0.3125	48.86	14.4	481	60.1	5.79	165	41.2	3.39
TS 12 × 6	0.625	67.82	19.9	337	56.2	4.11	112	37.2	2.37
6	0.5	55.66	16.4	287	47.8	4.19	96	32	2.42
6	0.375	42.79	12.6	228	38.1	4.26	77.2	25.7	2.48
6	0.25	29.23	8.59	161	26.9	4.33	55.2	18.4	2.53
6	0.1875	22.18	6.52	124	20.7	4.37	42.8	14.3	2.56
TS 12 × 4	0.625	59.32	17.4	257	42.8	3.84	41.8	20.9	1.55
4	0.5	48.85	14.4	221	36.8	3.92	36.9	18.5	1.6
4	0.375	37.69	11.1	178	29.6	4.01	30.5	15.2	1.66
4	0.25	25.82	7.59	127	21.1	4.09	22.3	11.1	1.71
4	0.1875	19.63	5.77	98.2	16.4	4.13	17.5	8.75	1.74

* On special order, TS sections currently are available in sizes up to 30 × 30 and 30 × 24.

Table 12.2.26 Properties of Square and Rectangular Tubing (TS Sections)* (*Continued*)

Nominal Size D, in × b, in	t, in	Weight, lb/ft	Area of metal, in²	I_{xx}, in⁴	S_{xx}, in³	r_{xx}, in	I_{yy}, in⁴	S_{yy}, in³	r_{yy}, in
TS 10 × 4	0.5	42.05	12.4	136	27.1	3.31	30.8	15.4	1.58
4	0.375	32.58	9.58	110	22	3.39	25.5	12.8	1.63
4	0.25	22.42	6.59	79.3	15.9	3.47	18.8	9.39	1.69
TS 8 × 6	0.5	42.05	12.4	103	25.8	2.89	65.7	21.9	2.31
6	0.375	32.58	9.58	83.7	20.9	2.96	53.5	17.8	2.36
6	0.25	22.42	6.59	60.1	15	3.02	38.6	12.9	2.42
4	0.625	42.3	12.4	85.1	21.3	2.62	27.4	13.7	1.49
4	0.5	35.24	10.4	75.1	18.8	2.69	24.6	12.3	1.54
4	0.375	27.48	8.08	61.9	15.5	2.77	20.6	10.3	1.6
4	0.25	19.02	5.59	45.1	11.3	2.84	15.3	7.63	1.65
2	0.375	22.37	6.58	40.1	10	2.47	3.85	3.85	0.765
2	0.25	15.62	4.59	30.1	7.52	2.56	3.08	3.08	0.819
TS 6 × 4	0.5	28.43	8.36	35.3	11.8	2.06	18.4	9.21	1.48
4	0.375	22.37	6.58	29.7	9.9	2.13	15.6	7.82	1.54
4	0.25	15.62	4.59	22.1	7.36	2.19	11.7	5.87	1.6
4	0.1875	11.97	3.52	17.4	5.81	2.23	9.32	4.66	1.63
2	0.375	17.27	5.08	17.8	5.94	1.87	2.84	2.84	0.748
2	0.25	12.21	3.59	13.8	4.6	1.96	2.31	2.31	0.802
TS 4 × 3	0.25	10.51	3.09	6.45	3.23	1.45	4.1	2.74	1.15
3	0.1875	8.15	2.39	5.23	2.62	1.48	3.34	2.23	1.18
2	0.375	12.17	3.58	5.75	2.87	1.27	1.83	1.83	0.715
2	0.25	8.81	2.59	4.69	2.35	1.35	1.54	1.54	0.77
2	0.1875	6.87	2.02	3.87	1.93	1.38	1.29	1.29	0.798
TS 3 × 2	0.25	7.11	2.09	2.21	1.47	1.03	1.15	1.15	0.742
2	0.1875	5.59	1.64	1.86	1.24	1.06	0.977	0.977	0.771
2	0.125	3.9	1.15	1.38	0.92	1.1	0.733	0.733	0.8

* On special order, TS sections currently are available in sizes up to 30 × 30 and 30 × 24.

Table 12.2.27 Coefficients of Deflection for Steel Beams under Uniformly Distributed Loads

Span, ft	Fiber stress, lb/in²		Span, ft	Fiber stress, lb/in²		Span, ft	Fiber stress, lb/in²		Span, ft	Fiber stress, lb/in²	
	24,000	10,000		24,000	10,000		24,000	10,000		24,000	10,000
1	0.026	0.011	14	4.87	2.029	27	18.1	7.54	39	37.7	15.7
2	0.098	0.041	15	5.59	2.328	28	19.5	8.12	40	39.8	16.6
3	0.223	0.093	16	6.36	2.648	29	20.9	8.71	41	41.8	17.4
4	0.398	0.166	17	7.18	2.990	30	22.4	9.32	42	43.9	18.3
5	0.621	0.259	18	8.04	3.35	31	23.9	9.94	43	45.8	19.1
6	0.892	0.372	19	8.97	3.74	32	25.4	10.60	44	48.0	20.0
7	1.23	0.507	20	9.93	4.14	33	27.0	11.27	45	50.4	21.0
8	1.59	0.662	21	10.9	4.56	34	28.7	11.96	46	52.6	21.9
9	2.01	0.838	22	12.1	5.01	35	30.5	12.7	47	54.7	22.8
10	2.48	1.034	23	13.1	5.47	36	32.2	13.4	48	57.1	23.8
11	3.00	1.251	24	14.3	5.96	37	34.1	14.2	49	59.5	24.8
12	3.58	1.489	25	15.6	6.47	38	35.8	14.9	50	62.2	25.9
13	4.20	1.748	26	16.8	7.00						

NOTE: For a load concentrated at midspan, use ⅘ of the coefficient given. 1 ft = 0.305 m; 1 lb/in² = 6.89 kPa.

Table 12.2.28 Values of Standard Framed-Beam Connections
(⅞-in A325 HS bolts in standard holes,* A36 members)

AISC designation	Two angles thickness × length	Shear 1,000 lb	Bearing on beam web (t), 1,000 lb
10 rows	5⁄16 × 2′5½″	204	609t
9 rows	5⁄16 × 2′2½″	184	548t
8 rows	5⁄16 × 1′11½″	164	487t
7 rows	5⁄16 × 1′8½″	143	426t
6 rows	5⁄16 × 1′5½″	123	365t
5 rows	5⁄16 × 1′2½″	102	304t
4 rows	5⁄16 × 0′11½″	81.8	243t
3 rows	5⁄16 × 0′8½″	61.3	182t
2 rows	5⁄16 × 0′5½″	40.9	121t

NOTE: 1 in = 2.54 cm; 1 lb = 4.45 N.

* Values indicated are for slip-critical connections or bearing type where threads are not excluded from the shear plane. For bearing-type connections where threads are excluded from the shear plane, shear values may be increased by 1.47.

† If the web of the supporting beam is thinner than 0.17 in (0.42 in if beams frame on both sides), bearing must also be investigated.

Table 12.2.29 Safe Axial Loads for Standard Pipe Columns, kips
(Stress according to AISC specification for A501 pipe*)

Nominal pipe size, in	Outside diam, in	Wall thickness, in	Effective length of column K1, ft										
			6	7	8	9	10	11	12	14	16	18	20
3	3.500	0.216	38	36	34	31	28	25	22	16	12	10	
3½	4.000	0.226	48	46	44	41	38	35	32	25	19	15	12
4	4.500	0.237	59	57	54	52	49	46	43	36	29	23	19
5	5.563	0.258	83	81	78	76	73	71	68	61	55	47	39
6	6.625	0.280	110	108	106	103	101	98	95	89	82	75	67
8	8.625	0.322	171	168	166	163	161	158	155	149	142	135	127
10	10.750	0.365	246	243	241	238	235	232	229	223	216	209	201
12	12.750	0.375	303	301	299	296	293	291	288	282	275	268	261

NOTE: 1 in = 2.54 cm; 1 ft = 0.305 m. For dimensions of standard pipe see Sec. 8. Safe loads above underscore lines are for values of K1/*r* more than 120 but not over 200.
* Yield stress is 36 ksi (248.2 MPa). Pipe ordered to ASTM A53, type E or S grade B, or to API standard 5L grade B will have a yield point of 35 ksi (241.3 MPa) and may be designed at stresses allowed for A501 pipe.

Table 12.2.30 Selected Fire-Resistance Ratings

Type	Details of construction	Rating
Reinforced-concrete beams and girders	Grade A concrete, 1½ in clear to reinforcement	4 h
	Grade B concrete, 1½ in clear to reinforcement	3 h
Steel beams, girders, and trusses	2½ in cover to steel	4 h
	1 in gypsum-perlite plaster on metal lath, 1¼ in clear of steel	3 h
	Ceiling of 1⅛ in gypsum-perlite plaster on metal lath with 2½ in min air space between lath and structural members	4 h
Reinforced concrete columns	Grade A concrete 1½ in clear to reinforcement; 12-in columns or larger	4 h
	Grade B concrete 2 in clear to reinforcement; 12-in columns or larger	4 h
Steel columns, 8 × 8 in or larger	Concrete (siliceous gravel):	
	2½ in clear to steel	4 h
	2 in clear to steel	3 h
	1 in clear to steel	2 h
	1⅛ in gypsum-perlite plaster on metal lath spaced from flanges with 1¼-in steel furring channels	4 h
	⅞ in portland-cement plaster on metal lath over ¾-in channels	1 h
Reinforced concrete slabs	5 in concrete (expanded clay, shale, slate, or slag) 1 in clear to reinforcement	4 h
	6½ in concrete (all other aggregate) 1 in clear to reinforcement	4 h
Heavy-timber floors	3 in tongue-and-groove plank floor with 1 in finish flooring	1 h
Wood joists	Wood floor; 1 in tongue-and-groove subfloor and 1 in finish floor with asbestos paper between. Ceiling of ⅝ in Underwriters' Laboratories listed wallboard	1 h
Brick walls	Solid walls, unplastered, with no combustible members framed in wall:	
	8 in nominal	4 h
	4 in nominal	1 h
Concrete masonry units	8 in Underwriters' Laboratories listed concrete blocks, laid as specified in Underwriters' Laboratories listing	4 h
	4 in Underwriters' Laboratories listed concrete blocks; laid as specified in Underwriters' Laboratories listing	3 h
Steel-stud partitions	¾ in gypsum-perlite plaster both sides on metal lath	2 h
	⅝ in gypsum wallboard on 3⅝-in steel studs; attached with 6 d nails; joints taped and cemented	2 h
Wooden-stud partitions	Exterior walls: one side covered with ½ in gypsum sheathing and wood siding; other side faced with ½ in gypsum-perlite plaster on ⅜-in perforated gypsum lath	1 h
	Interior Walls: 2 × 4 in studs with ⅝ in gypsum wallboard on each side	1 h
Plain or reinforced concrete walls	Solid, unplastered:	
	7 in thick	4 h
	6½ in thick	3 h
	5 in thick Grade B Grade A	2 h
	3½ in thick	1 h

NOTE: 1 in = 2.54 cm.
Grade A concrete is made with aggregates such as limestone, calcareous gravel, trap rock, slag, expanded clay, shale, or slate or any other aggregates possessing equivalent fire-resistance properties.
Grade B concrete is all concrete other than Grade A concrete and includes concrete made with aggregates conaining more than 40 percent quartz, cherts, or flint.

12.3 REINFORCED CONCRETE DESIGN AND CONSTRUCTION

by William L. Gamble

REFERENCES: Breen, Jirsa and Ferguson, ''Reinforced Concrete Fundamentals,'' Wiley. Winter and Nilson, ''Design of Concrete Structures,'' McGraw-Hill. Lin and Burns, ''Design of Prestressed Concrete Structures,'' Wiley. Park and Gamble, ''Reinforced Concrete Slabs,'' Wiley. ''Building Code Requirements for Reinforced Concrete (318–95),'' ''Commentary on Building Code Requirements for Reinforced Concrete,'' ''Formwork for Concrete, SP-4,'' and ''Manual of Standard Practice for Detailing Reinforced Concrete Structures,'' American Concrete Institute. ''Standard Specifications for Highway Bridges,'' American Association of State Highway and Transportation Officials (AASHTO). ''Minimum Design Loads for Buildings and Other Structures (ASCE 7),'' American Society of Civil Engineers. ''Uniform Building Code (UBC),'' International Conference of Building Officials.

The design, theory, and notation of this chapter are in general accord with the 1995 Building Code Requirements for Reinforced Concrete of the American Concrete Institute, though many detailed provisions have been omitted.

Standard Notation

Load Factors

D = dead load of structure or force caused by dead load
E = earthquake load or force
L = live load of structure or force caused by live load
W = wind load or force
U = required strength of structure to resist design ultimate loads
ϕ = understrength or capacity reduction factor

Beams and General Notation

a = depth of compression zone, using approximate method
A_b = area of individual reinforcing bar, in²
A_{ps} = area of prestressing steel
A_s = area of tension reinforcement
A'_s = area of compression reinforcement
A_v = area of steel in one stirrup
b = width of compression face of beam
b_w = width of stem of T beam
$c = k_u d$ = depth to neutral axis at ultimate, from compression face
d = effective depth of beam, compression face to centroid of tension steel
d' = depth of compression steel, from compression face
d_b = diam of individual reinforcing bar, in
E_c = Young's modulus of concrete
E_s = Young's modulus of steel
f'_c = compressive strength of concrete from tests of 6 × 12 in cylinders, lb/in²
$\sqrt{f'_c}$ = measure of shear and tensile strength of concrete, lb/in², i.e., if $f'_c = 4{,}900$ lb/in², then $\sqrt{f'_c} = 70$ lb/in²
f_{pu} = ultimate stress of prestressing steel, lb/in²
f_y = yield stress of reinforcing steel, lb/in²
h = overall height or thickness of member
k_u = ratio of ultimate neutral axis depth to effective depth
l_d = development length of reinforcing bar, in
s = spacing of shear reinforcement
M_u = ultimate moment of section or required ultimate moment
v_c = shear stress in concrete
V_c = shear force resisted by concrete
V_s = shear force resisted by web reinforcement
V_u = shear strength of section or required ultimate shear
β_1 = factor relating neutral axis position to depth of equivalent approximate stress block (see Fig. 12.3.2)
ε_{su} = reinforcement strain at time of failure of member
ε_y = yield strain of reinforcement
ρ = tension reinforcement ratio = A_s/bd
ρ' = compression reinforcement ratio = A'_s/bd
ρ_{bal} = balanced reinforcement ratio

Columns

$A_c = A_g - A_s$ = net area of concrete in cross section
A_{core} = area within spiral
A_g = gross area of column
A_s = area of steel in column
e = eccentricity of axial load on column
$M = Pe$ = applied bending moment
P = axial thrust
P_0 = failure load of short column under concentric load
ρ_g = gross steel ratio = A_s/A_g
ρ_s = spiral steel ratio = volume of spiral steel/volume of core

Floor Systems

b_0 = effective shear perimeter around column in flat plate, flat slab, or footing
c_1 = width of supporting column or capital, in direction of span being considered
c_2 = width of supporting column, in transverse direction
I_b = moment of inertia of beam
K_b = flexural stiffness of beam, moment per unit rotation
K_c = flexural stiffness of columns at joint, moment per unit rotation
K_s = flexural stiffness of slab of width l_2, moment per unit rotation
l_1 = span, center to center of supports, in direction considered
l_2 = span, center to center of supports, in transverse direction
$l_n = l_1 - c_1$ = clear span in direction considered
M_0 = static moment
w = distributed design load, including load factors
$\alpha_1 = EI$ of beam in direction $1/EI$ of slab of width l_2

Footings

A_1 = loaded area
A_2 = area of same shape and concentric with A_1
f_b = ultimate bearing stress on concrete
β = ratio of long side/short side of footing

Walls

l_c = unbraced height of wall

Prestressed Concrete

A_{ps} = area of prestressed reinforcement
A_t = area of anchorage-zone reinforcement
f'_{ci} = compressive strength of concrete at time of prestressing
f_{ps} = stress in reinforcement at time of failure of member
f_{pu} = ultimate stress of prestressing reinforcement
$f_{se} = f_{si} - \Delta f_s$ = stress in reinforcement at service load
f_{si} = reinforcement stress at time of tensioning steel
Δf_s = loss of prestress from initial tensioning value
$\rho_p = A_{ps}/bd$

MATERIALS

Reinforced concrete is a combination of concrete and steel acting as a unit because of bond between the two materials. Concrete has a high compressive strength but a relatively low tensile strength. Beams of plain concrete fail by tension at very low stresses, but if properly reinforced by embedment of steel in their tensile regions, they may be loaded to utilize the much higher compressive strength of the concrete. Reinforced concrete structures are practically monolithic, are more rigid than steel structures of the same strength, and are inherently fire-resistant. Reinforcement in the concrete also controls cracking caused by temperature changes and shrinkage.

Prestressed concrete is a form of reinforced concrete in which initial stresses opposite those caused by the applied loads are induced by tensioning high-strength steel embedded in the concrete. Members may be *pretensioned,* in which the steel is tensioned and the concrete then cast around it, or *posttensioned,* in which the concrete is cast and cured, after which steel placed in ducts through the concrete is tensioned.

Concrete For reinforced concrete work, only high-quality portland cement concrete may be used, and the aggregates must be carefully selected. The proportions are governed by the required strength, durability, economy, and the quality of the aggregates. Concretes for building construction normally have compressive strengths of 3,000 to 5,000 lb/in² (20 to 35 MPa), except that concrete for columns may be considerably stronger, with 12,000 to 14,000 lb/in² common in some geographic areas. Most concrete for prestressed members will have 5,000 lb/in² or higher compressive strength. The higher-strength concretes require thorough quality control if the strengths are to be consistently obtained. Generally, lean, harsh mixes should be avoided because the bond with the steel will be poor, permeability will be high, and durability of the concrete may be poor. A consistency of concrete that will flow sluggishly but not so wet as to produce segregation of the materials when transported must be used for all reinforced concrete work in order to embed the steel and completely fill the molds or forms. The use of vibration is almost mandatory, and enables the use of stiffer, more economical, concretes than would otherwise be possible (see also Sec. 6.9).

Steel Reinforcing steel may be deformed or plain bars, welded-wire fabric, or high-strength wire and strand for prestressed concrete. Bars with deformations on their surfaces are designed to produce mechanical bond and greater adhesion between the concrete and steel, and are used almost universally in the United States. Welded-wire fabric is suitable in many cases for slabs and walls, and may result in cost savings through labor savings. Fabric is made with both smooth and deformed wires, and the deformed fabric may have some advantage in terms of better crack control. Deformed reinforcing bars having minimum yield stresses from 40,000 to 75,000 lb/in² (275 to 517 MPa) are currently manufactured. The higher-strength steels have the advantage of allowing higher working stresses, but their ductility may be less and it may be difficult to cold-bend them successfully, especially in the larger sizes. The chemical makeup of most reinforcing steels is such that it is not readily weldable without special techniques, including careful preheating and controlled cooling. Furthermore, the variation of the material from batch to batch is so great that separate procedures must be devised for each batch. Tack welding in assembling bar cages can be particularly troublesome because of the stress raisers introduced. A weldable steel is produced with the specification ASTM A-706, but it is not widely available. Prestressing steel is heat-treated high-carbon steel, and 7-wire strand will have a breaking stress of 250,000 or 270,000 lb/in² (1,720 or 1,860 MPa). The usual steel is Grade 270, low-relaxation strand. The strength of solid wire for prestressing is slightly less. ASTM specifications cover the various steels, and all steel used as reinforcement should comply with the appropriate specification.

Reinforcing Steel Sizes The sizes of reinforcing bars have been standardized, and the designation numbers are approximately the bar diameter, in ⅛-in units. Table 12.3.1 gives the nominal diameter, cross-sectional area, and perimeter for each bar size. The areas of the four most common 7-wire prestressing strands are given below:

Diam, in	Area, in²	
	Grade 250	Grade 270
7⁄16	0.109	0.115
½	0.144	0.153

Table 12.3.1 Dimensions of Deformed Bars

No.	Diam, in	Area, in²	Perimeter, in
2*	0.250	0.05	0.786
3	0.375	0.11	1.178
4	0.500	0.20	1.571
5	0.625	0.31	1.963
6	0.750	0.44	2.356
7	0.875	0.60	2.749
8	1.000	0.79	3.142
9	1.128	1.00	3.544
10	1.270	1.27	3.990
11	1.410	1.56	4.430
14	1.693	2.25	5.32
18	2.257	4.00	7.09

* No. 2 bars are obtainable in plain rounds only.

Plain and deformed wires are used as reinforcement, usually in the form of welded mats. Plain wires are made in sizes W0.5 through W31, where the number designates the cross-sectional area of the wire in hundredths of square inches. Deformed wires are made in sizes D1 through D31, and the number has the same meaning. Not all sizes are made by all manufacturers, and local suppliers should be consulted about availabilities of sizes. The formerly used wire gage numbers are no longer used for size specifications.

Moduli of Elasticity For concrete the modulus of elasticity E_c may be taken as $w^{1.5} 33 \sqrt{f'_c}$ in lb/in², where w is the weight of the concrete between 90 and 155 lb/ft³. Normal weight concrete may be assumed to weigh 145 lb/ft³. For steel the modulus of elasticity may be taken as 29,000,000 lb/in² (200 GPa), except for prestressing steel for which the modulus shall be determined by tests or supplied by the manufacturer, but is usually about 28,000,000 lb/in².

The **modular ratio** $n = E_s/E_c$ is of importance in designing reinforced concrete. It may be taken as the nearest whole number but not less than six. The value of n for lightweight concrete may be taken as the same for normal weight concrete of the same strength, except in calculations for deflections.

Protection of Reinforcement Reinforcement, for both regular and prestressed concrete, must be protected by the concrete so as to prevent corrosion. The amount of cover needed for various degrees of exposure is as follows:

Member and Exposure	Cover, in
Concrete surface deposited against the ground	3
Concrete surface to come in contact with the ground after casting:	
Reinforcement larger than No. 5	2
Reinforcement smaller than No. 5	1½
Beams and girders not exposed to weather:	
Main steel	1½
Stirrups and ties	1
Joists, slabs, and walls not exposed to weather	¾
Column spirals and ties	1½

The clear cover and clear bar spacings should ordinarily exceed 4⁄3 times the maximum sized aggregate used in the concrete.

The amount of protection recommended is a minimum, and when corrosive environments or other severe exposure occurs, the cover should be increased. The concrete in the cover should be made as impermeable as possible. Fire-resistance requirements may also control the cover requirements.

LOADS

The dead and live loads are combined in determining the cross sections of the members. The dead load includes the weight of the structure, all finishing materials, and usually the installed equipment. The live load includes the contents and ordinarily refers to the movable items.

The **live load** (pounds per square foot) to be used for design depends upon the loadings that will occur in the particular structure as well as on the requirements of the local building code. The Boston Building Code illustrates good practice and is as follows for floor loads:

Heavy manufacturing, sidewalks, heavy storage, truck garages, 250; public garages, intermediate manufacturing, and hangars, 150; stores, heavy merchandise, light storage, 125; armories, assembly halls, gymnasiums, grandstands, public portions of hotels, theaters, and public buildings, corridors and fire escapes from public assembly buildings, light merchandising stores, stairs, first and basement floors of office buildings, theater stages, 100; upper floors of public buildings, office portions of public buildings, stairs, corridors and fire escapes except from public assembly buildings, theater and assembly halls with fixed seats, light manufacturing, locker rooms, stables, 75; church auditoriums, 60; office buildings above first floor including corridors, classrooms with fixed seats, 50; residence buildings and residence portions of hotels, apartment houses, clubs, hospitals, educational and religious institutions, 40. [Note: 100 lb/ft^2 = 4.79 kPa.]

Live loads affecting structural members supporting considerable tributary floor areas are sometimes reduced in recognition of the low probability that the entire area will be loaded to the full design load at the same time. Roofs are commonly designed to support live loads of 20 to 30 lb/ft^2. Wind loads are commonly from 15 to 30 lb/ft^2 (higher in areas subject to hurricanes) of vertical projection. In the case of heavy moving loads, allowance should be made for impact by increasing the live load by 25 to 100 percent.

Dead loads include the weight of both structure and finishing materials, and the weights of some typical wall, floor, and ceiling materials are as follows:

Description	Weight, lb/ft^2
Granolithic finish, per in of thickness	12
⅞-in hardwood, 1⅛-in plank intermediate floor, and tar base	16
3-in wood block in coal-tar pitch	10
Lightweight concrete fill, 2 in thick	14
Plaster on concrete, tile, or concrete block, two coats	5
Plaster on lath	10
6-in concrete block wall	25
Suspended ceiling	12

SEISMIC LOADINGS

Earthquakes induce forces in structures because of inertial forces which resist the ground motions. These forces have damaged or destroyed large numbers of structures throughout the world. The art and science of designing to resist seismic effects are still evolving, and may be thought of in several steps.

1. Determine the ground motion to be expected at the site of interest. This usually requires consulting a map in ASCE-7 or the prevailing local building code, such as the Uniform Building Code (UBC). Several steps may be required, including finding the expected acceleration of the bedrock, followed by an accounting for the soil types between the bedrock and the structure. There is an implicit or explicit assumption of a probability that this ground motion will not be exceeded in some particular time interval, such as 50 or 100 years.

2. Determine the effects of the ground accelerations on the structure which is being analyzed. This will require consideration of the natural period of vibration of the structure and of structural characteristics such as damping and ductility, and more elaborate analyses will be required for large and important structures than for smaller, less crucial cases. Member forces, moment, shear, thrust, torsion, and deformations such as story drift and member end rotations will result from this analysis. The major building codes all have specific requirements and provisions for this analysis, and the UBC is the most widely used in seismically active regions. In most cases, an equivalent static horizontal load will be applied to the structure, with the force in the range of 10 percent or less to as much as 30 percent of the mass of the structure.

3. Design and detail members and connections for the imposed forces. Chapter 21 of the ACI Code has many requirements for the detailing of the reinforcement in the members and joints. When compared with designs for static loadings which include only dead, live, and wind loads, seismic designs will have much more lateral reinforcement in columns, and often much heavier shear reinforcement (especially near the joints), and will usually have extra reinforcement within the joint regions. Much of this added reinforcement is referred to as **confinement reinforcement,** and the intent is to utilize the fact that triaxially confined concrete may be able to sustain much greater strains before failure than unconfined concrete. Obviously, steps 2 and 3 are parts of an iterative process which converges to an acceptable structural design solution.

The current seismic design philosophy includes the assumption that it is not economically possible to design structures to resist extremely large earthquakes without damage. It is expected that structures will resist smaller earthquakes, such as might be expected several times during the life of a structure, with minimal damage, while a very large earthquake which might be expected to occur once during a structure's design life would cause significant damage but would leave the structure still standing. The assignment of an importance factor for buildings is one consequence of this design philosophy. Hospitals, school buildings, and fire stations, for example, would be designed to a higher seismic standard than would a three-story apartment building.

LOAD FACTORS FOR REINFORCED CONCRETE

The current ACI Building Code for Reinforced Concrete is based on a **strength design** concept, in which the strength of a member or cross section is the basis of design. This approach has been adopted because of the difficulty in assigning reasonable and consistent allowable stresses to the concrete and steel. Factors of safety are expressed in terms of *overload* and *understrength* factors. The overload factors, reflecting the uncertainty of the applied loads, are expressed as
No wind or earthquake loads:

$$U = 1.4\,D + 1.7\,L \qquad (12.3.1)$$

With wind acting, use the larger of (12.3.2) or (12.3.3):

$$U = 0.75\,(1.4\,D + 1.7\,L + 1.7\,W) \qquad (12.3.2)$$

$$U = 0.9\,D + 1.3\,W \qquad (12.3.3)$$

No section may be weaker than required by Eq. (12.3.1). In case earthquake loadings are considered. 1.1 E is substituted for W in the above equations. Liquids are treated as dead loads, and other provisions are made for earth-pressure loadings. The understrength factors reflect the ductility of failure in the mode considered, and the consequences of a failure on the rest of the structure. These are expressed as ϕ factors with the following values:

Bending and tension	$\phi = 0.90$
Shear and torsion	$\phi = 0.85$
Spiral columns	$\phi = 0.75$
Tied columns and bearing	$\phi = 0.70$

These factors are used to reduce the computed ideal strengths of members, reflecting possible weaknesses related to materials, dimensions, and workmanship.

In addition to strength requirements, serviceability checks must be made to ensure freedom from excessive cracking, deflections, vibrations, etc., at working loads. Prestressed-concrete members must also satisfy a set of allowable stresses at this load level.

Deflections are usually controlled by specifying minimum member depths. The values of $l/16$ and $l/21$, for beams which are simply supported and continuous at both ends, respectively, are typical, unless an investigation is conducted to show that shallower members will result in acceptable deflections. Crack control is obtained by careful distribution of the steel through the tensile zone. In this regard, several small bars are superior to one large bar.

The approach to design is not a ''limit design'' or ''plastic design'' concept, as the ultimate forces are derived from elastic analyses of structures, using maximums for each critical section. The plastic col-

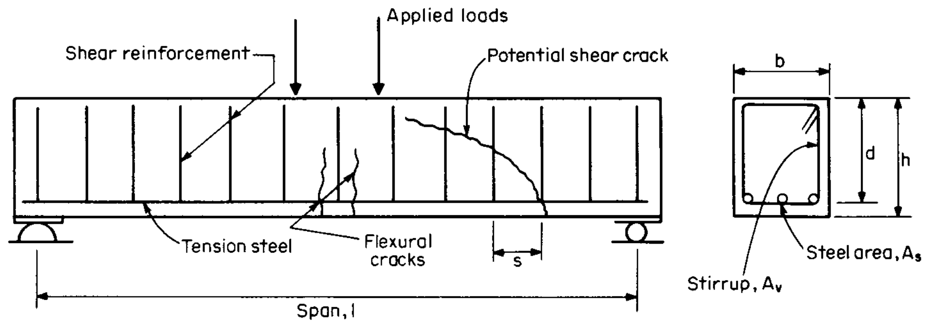


Fig. 12.3.1 Typical arrangement of reinforcement in beams.

lapse loads and mechanisms currently used in the ''plastic design'' of some steel structures in the United States are not considered.

Bridges may be designed using the same general concepts, but different overload and understrength factors are used, and the serviceability requirements include checks on the fatigue strength.

REINFORCED CONCRETE BEAMS

Concrete beams are reinforced to resist both flexural and shear forces. A typical reinforcement scheme for a simply supported beam is shown in Fig. 12.3.1.

As the load on a reinforced concrete beam is increased, vertical tension cracks appear in the maximum moment regions, and gradually grow in length, width, and number. By the time the working load is reached, some of the cracks extend to the neutral axis and the contribution of the tensile strength of the concrete to the flexural capacity of the beam has become very small. As the load is increased further, the reinforcement eventually yields. This load is nearly the maximum the member can sustain. Further attempts at loading produce large increases in deflection and crack widths with very small increases in load and a gradual reduction in the remaining concrete compression area. When a limiting concrete strain of about 0.003 is reached at the compression face of the beam, the concrete starts crushing and the capacity of the beam starts dropping. For static design purposes, the achievement of the 0.003 strain is usually regarded as the end of the useful life of the beam.

Within limits to be checked later, at the time of flexural failure of a beam the stress in the steel is equal to the yield stress, which greatly simplifies the analysis of the member. The strain and stress distributions in a beam are shown in Fig. 12.3.2, at failure.

It is assumed that plane sections remain plane, that adequate bond exists, that the stress-strain relationships for concrete and steel are known, and that tension in the concrete has a negligible influence.

The **flexural strength** of a cross section may be written as, including the understrength factor and rounding the terms in the parentheses to one significant figure:

$$\begin{aligned} M_u &= \phi A_s f_y d(1 - 0.4\, k_u) \\ &= \phi A_s f_y d(1 - 0.6\rho f_y / f'_c) \end{aligned} \qquad (12.3.4)$$

where $\rho = A_s/bd$ = reinforcement ratio. The reinforcement ratio will ordinarily be between 0.005 and 0.02.

A satisfactory approximate stress distribution is shown in Fig. 12.3.2*d*. Since $T = C = 0.85 f'_c ba$, then $a = A_s f_y / 0.85\, f'_c b$ and the flexural capacity is

$$M_u = \phi A_s f_y (d - a/2) \qquad (12.3.5)$$

It must be demonstrated for each case that the stress in the reinforcement has reached f_y, and the simplest approach is to show that $\varepsilon_{su} \geq \varepsilon_y$. From Fig. 12.3.2*b*, $\varepsilon_{su} = 0.003\,(1 - k_u)/k_u$. From equilibrium (see Fig. 12.3.2*c*), $k_u = A_s f_y / 0.85\, \beta_1 f'_c bd = \rho f_y / 0.7 f'_c$. The limiting case for the validity of Eqs. (12.3.4) and (12.3.5) is a balanced condition in which the yield strain in the steel and the 0.003 compressive strain in the concrete are reached simultaneously, and this can be found using Fig. 12.3.2 and assuming $\varepsilon_{su} = \varepsilon_y$. It can then be shown that

$$\rho_{bal} = \frac{0.85 \beta_1 f'_c}{f_y} \frac{0.003}{0.003 + \varepsilon_y} \qquad (12.3.6)$$

Values of ρ_{bal} are plotted vs. f'_c in Fig. 12.3.3 for three values of f_y. The

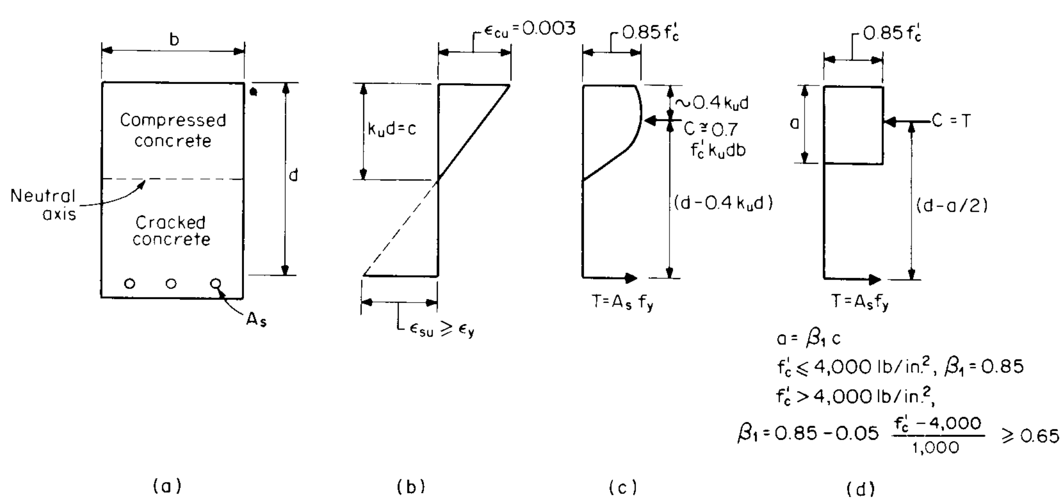


Fig. 12.3.2 Stress and strain distribution in reinforced concrete beam at failure. (*a*) Section; (*b*) strains; (*c*) stresses; (*d*) approximate stresses.

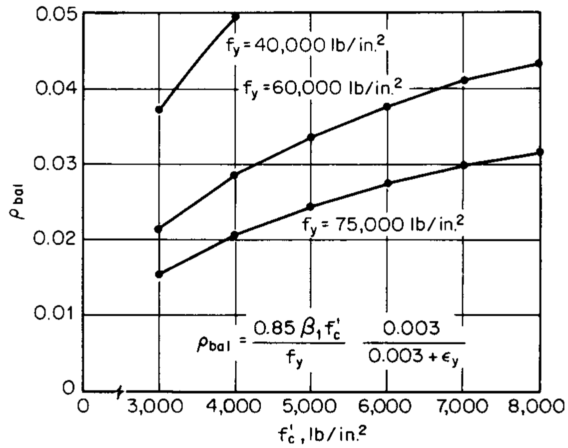


Fig. 12.3.3 Balanced steel ratio as a function of f_y and f'_c.

steel ratio should not exceed 0.75 ρ_{bal}, in order to ensure that at least some yielding, with resultant large deflections, occurs before a member fails.

Beams may contain both compression and tension reinforcement, especially when the beam must be kept as small as possible or when the long-term deflections must be minimized. The forces at ultimate are shown in Fig. 12.3.4, and the moment may be calculated as

$$M_u = \phi[A'_s f_y(d - d') + (A_s - A'_s) f_y(d - a/2)] \quad (12.3.7)$$

where $a = (A_s - A'_s) f_y / 0.85 f'_c b$. The net steel ratio $\rho - \rho' = (A_s - A'_s)/bd$ should not exceed 0.75 of the balanced value given by Eq. (12.3.6).

Many reinforced concrete beams are flanged sections, or T beams, by virtue of having a slab cast monolithically with the beam, and such a cross section is shown in Fig. 12.3.5. It will be found that the neutral axis lies within the flange in most instances, and if $k_u d \leq t$, then the beam is treated as a rectangular beam of width b. This is checked using $k_u d = A_s f_y / 0.85\, \beta_1 f'_c b$, developed from equilibrium (Fig. 12.3.2). If $k_u d > t$, the flexural capacity is computed by

$$M_u = \phi[(A_s - A_{sw}) f_y(d - a/2) + A_{sw} f_y(d - t/2)] \quad (12.3.8)$$

where $A_{sw} = (b - b_w)t0.85 f'_c/f_y$; and $a = (A_s - A_{sw}) f_y / 0.85 f'_c b_w$.

Continuous T beams are treated as rectangular beams of width b_w in the negative moment regions where the lower surface of the beam is in compression. Most continuous beams will have compression steel in the negative moment regions, as some bottom steel is always continued into the support regions.

Both T beams and beams with compression steel may be thought of in terms of dividing the beam into two components—one a rectangular beam containing part of the tension steel and the other a couple with the rest of the tension steel at the bottom and either the compression steel or the T-beam flanges at the top. Both components of the beam must satisfy horizontal equilibrium.

The reinforcement ratio should not be less than $\rho_{min} = 3\sqrt{f'_c}/f_y \geq 200/f_y$. This is to ensure that the ultimate moment is somewhat

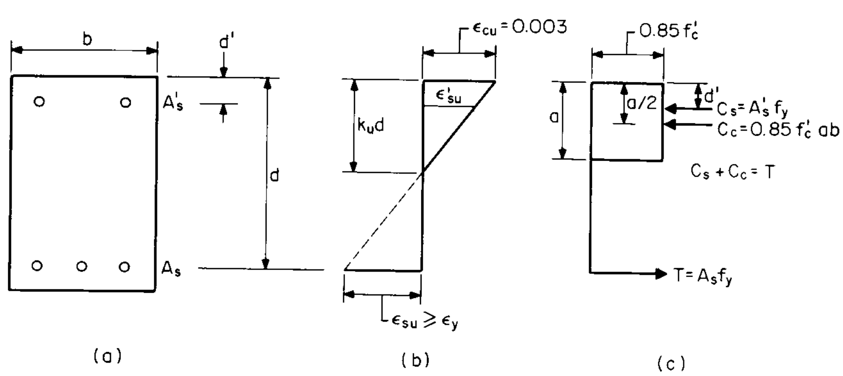


Fig. 12.3.4 Stress and strain distributions in a doubly reinforced concrete beam. (*a*) Section; (*b*) strains; (*c*) approximate stresses.

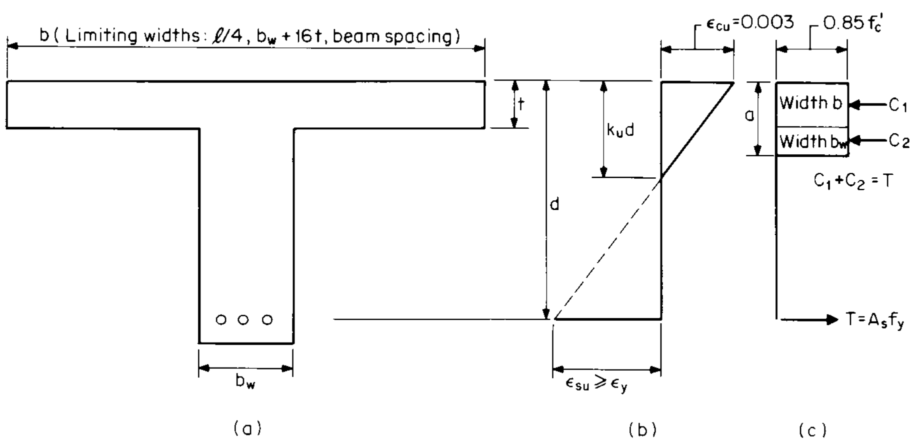


Fig. 12.3.5 Strain and stress distribution in a T beam. (*a*) Section; (*b*) strains; (*c*) approximate stresses.

greater than the initial cracking moment. For T beams, $\rho = A_s/b_w d$ for purposes of the minimum steel requirement.

In the selection of a cross section, it is convenient to transform Eq. (12.3.4) by substituting ρbd for A_s and rearranging to obtain

$$M_u/\phi bd^2 = \rho f_y(1 - 0.6\rho f_y/f'_c) \qquad (12.3.9)$$

With given materials f_y and f'_c selection of a ρ value enables calculation of the required bd^2, from which a cross section may be selected. For convenience, values of $M_u/\phi bd^2$, are plotted against ρf_y in Fig. 12.3.6, for several values of f'_c.

The strengths of prestressed-concrete beams are treated much the same as reinforced concrete beams, and the differences will be noted later.

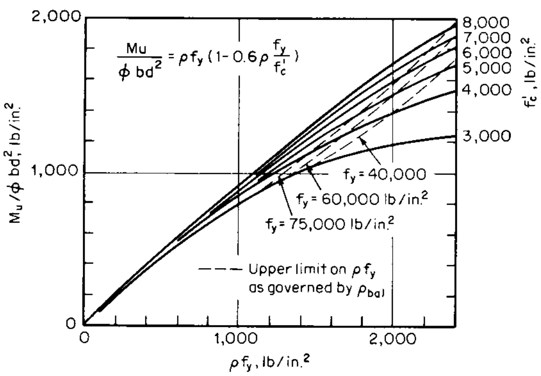


Fig. 12.3.6 Design factors for single reinforced concrete beams.

In addition to the tension stresses caused by bending forces, **shear forces** cause inclined tension stresses which may lead to inclined cracking such as is sketched in Fig. 12.3.1. Unless web reinforcement is present, the formation of such a crack usually leads directly to the complete collapse of the member at the load which caused the crack, or only slightly higher.

As a result of this undesirable behavior, shear reinforcement is required in all major beams, and the normal design procedure is to proportion the beam for the flexural requirements and then add shear steel, usually in the form of stirrups, to make the shear strength adequate.

The concrete can be assumed to resist a shear stress of $v_c = \phi 2\sqrt{f'_c}$, or a shear force of

$$V_c = \phi 2\sqrt{f'_c}\, bd \qquad (12.3.10)$$

(or $V_c = \phi 2\sqrt{f'_c}\, b_w d$ for T beams). The shear reinforcement must resist the force in excess of V_c, so that

$$V_u - V_c = V_s \qquad (12.3.11)$$

The area of shear reinforcement is then selected to satisfy

$$V_s = \phi A_v f_y d/s \qquad (12.3.12)$$

Shear reinforcement to satisfy this requirement is provided at every section of the beam, except that the region between the support and the section at the distance d from the support is supplied with the steel required at d from the support.

The stirrup spacing should not exceed $d/2$, and is reduced to a maximum of $d/4$ if $V_u > \phi 6\sqrt{f'_c}\, bd$. V_u must not exceed $\phi 10\sqrt{f'_c}\, bd$. The minimum area of shear reinforcement allowed is $A_v = 50 b_w s/f_y$. Closed stirrups of the form shown in Fig. 12.3.1 are recommended, and are essential in areas subjected to earthquake loadings.

Shear in prestressed-concrete members is handled in a similar manner, and the designer is referred to the ACI Code for details. However, it will be found that most prestressed members designed for buildings and which do not support major concentrated loads will have adequate shear strength if the minimum steel given by the following expression is supplied:

$$A_v = \frac{A_{ps}}{80}\frac{f_{pu}}{f_y}\frac{s}{d}\sqrt{\frac{d}{b_w}} \quad \text{in}^2 \qquad (12.3.13)$$

The maximum stirrup spacing is 0.75 of the member depth, or 24 in, and for constant-depth members, d is measured at the section of maximum moment.

At least the minimum area of shear reinforcement must be supplied over the full length of most reinforced and prestressed members unless it can be shown, by a test acceptable to the building official, that the members can sustain the required ultimate loads without the steel.

Recent ACI Codes have undergone major revisions to reflect the effects of bar spacing and bar cover on development length, l_d, and on splice lengths. In some common cases the current development lengths will be much greater than in ACI Codes from 1983 and earlier. The 1995 Code development lengths for straight bars are given in Code Sec. 12.2.2, and a more complex, less conservative, set of requirements are in Sec. 12.2.3. When the available anchorage lengths are less than l_d, hooks are often used. The conservative Sec. 12.2.2 requirements may be summarized as follows:

$$\frac{l_d}{d_b} = K\frac{f_y \alpha\beta\lambda}{\sqrt{f'_c}}$$

in which K is as follows:

	No. 6 and smaller bars and deformed wire	No. 7 and larger bars
1. Clear spacing of bars being developed or spliced $\geq d_b$ and clear cover $\geq d_b$ with minimum ties or stirrups or	1⁄25	1⁄20
2. Clear spacing $\geq 2d_b$ and clear cover $\geq d_b$	1⁄25	1⁄20
3. Other cases	3⁄50	3⁄40

The other terms are defined as:

d_b = diameter of bar or wire, in
α = bar location factor
= 1.3 for top bars (horizontal with more than 12 in of concrete cast below)
= 1.0 for other bars
β = coating factor
= 1.5 for epoxy-coated bars or wires with cover $\leq 3d_b$, or clear spacing $\leq 6d_b$
= 1.2 for all other epoxy-coated bars or wires
= 1.0 for uncoated reinforcement
λ = lightweight concrete factor
= 1.3 when light-weight aggregate concrete is used
= 1.0 when normal weight aggregate is used

The product $\alpha\beta$ need not be taken greater than 1.7.

Bars No. 11 and smaller are commonly spliced by simply lapping them for a distance. These splices should be avoided in regions of high computed stress, and should be spread out so that not many bars are spliced near the same section. If the computed tensile stress is less than 0.5 f_y at the design ultimate load and not more than half the bars are spliced at one section, the lap length is 1.0 l_d. For other cases the minimum lap length is 1.3 l_d. For lower stress levels, a lap of l_d is sufficient.

Development lengths in compression, important in columns and compression reinforcement, are somewhat shorter.

Requirements for reinforcement of beams subjected to torsional moments are contained in the ACI Code. The requirements are too complex for discussion here, but the basic reinforcement scheme consists of closed stirrups with longitudinal bars in each corner of the stirrup. The most efficient method of dealing with torsion in many instances will be to rearrange the structure so as to reduce or eliminate the torsional moments.

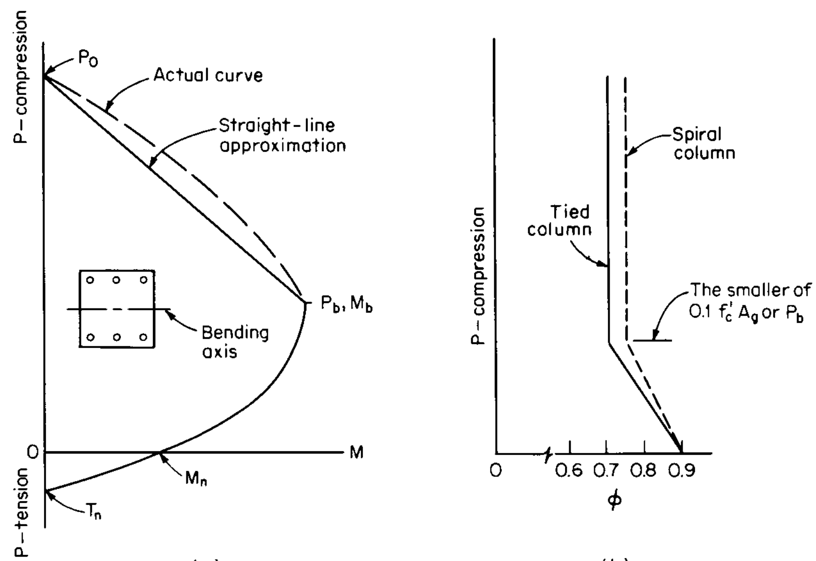


Fig. 12.3.7 Column capacity diagrams. (*a*) Typical moment-thrust interaction diagram; (*b*) variation of ϕ with *P*.

REINFORCED CONCRETE COLUMNS

Reinforced concrete compression members are proportioned taking into account the applied thrust, the bending moments, and the relationship between length and thickness for the member. The strength of a cross section or a short column can conveniently be shown with the aid of a *moment-thrust interaction diagram* such as is shown in Fig. 12.3.7*a*, which is drawn without considering the ϕ factor. The variation in ϕ with thrust is shown in Fig. 12.3.7*b* for the same column.

The load P_0 is the strength of a short column under a concentric load, and is expressed as

$$P_0 = 0.85\, A_c f_c' + A_s f_y \tag{12.3.14}$$

The contribution of the concrete is slightly less than the cylinder strength because of differences in workmanship, curing, and position of casting. M_u is simply the strength in flexure, as was discussed for beams. The $M_b - P_b$ point is the ''balance point,'' at which simultaneous crushing of the concrete and yielding of the reinforcement occur. Failure is initiated by crushing of the concrete at loads higher than P_b, and by yielding of the reinforcement in tension at lower loads. Only the reinforcement contributes to the tensile capacity of $T_u = A_s f_y$

The balance-point moment and thrust are found using the strain and stress distributions shown in Fig. 12.3.8, for a symmetrical section with steel in two faces. From equilibrium,

$$P_b = C_s + C_c - T \tag{12.3.15}$$

Summing moments about the centroidal axis gives

$$M_b = A_s f_y(d - d')/2 + 0.85\beta_1 f_c' k_u db(h/2 - \beta_1 k_u d/2) \tag{12.3.16}$$

This assumes that the compression steel has yielded, and this will be true except for very small members or members with exceptionally large cover over the steel.

The portion of the interaction diagram below P_b may be constructed in a point-by-point manner. For any value of $\varepsilon_s > \varepsilon_y$, or for any value of $k_u d < k_u d_{bal}$, the strain and stress distributions are defined. Once the forces are defined, the moments and thrusts are computed using the same formulas as for the balance point. A modification will have to be made when the compression-steel stress is less than f_y.

Care must be used in the selection of the axis about which moments are to be summed, especially if the section is not symmetrical or symmetrically reinforced, since the force system is not a pure couple. The most important thing is to remain consistent, and to be certain that the internal and external moments are summed about the same axis.

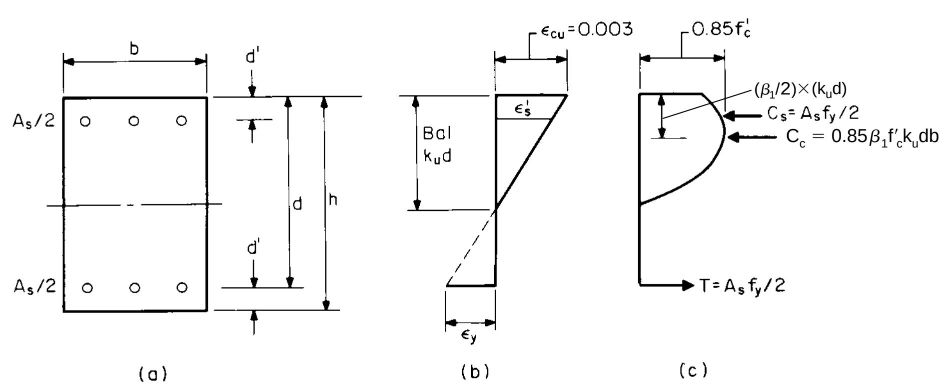


Fig. 12.3.8 Stress and strain distribution in a column at balanced moment and thrust. (*a*) Section; (*b*) strains; (*c*) stresses.

In practice, either the moment-thrust curve can be reduced by the appropriate ϕ factor, or the computed ultimate M and P increased by dividing by ϕ. If the required $M - P$ point lies on or slightly inside the interaction curve, the design is acceptable. The maximum permitted factored thrust is 0.80 ϕP_0, which limits the applied thrust capacity in cases where the computed moments are relatively small. This limitation is intended to provide resistance to accidental eccentricities. Column reinforcement consists of longitudinal bars and lateral ties or spiral bars. The ratio of longitudinal steel ρ_g should be between 0.01 and 0.08. Ties are usually No. 3 or No. 4 bars which are bent to enclose the longitudinal bars, and are spaced at not more than 16 longitudinal bar diam, 48 tie diam, or the least thickness of the column. Ties are arranged to bind each corner bar and alternate intermediate bars. Several typical arrangements are shown in Fig. 12.3.9. Ties hold the longitudinal bars in place during construction, and may provide some shear resistance and improve the behavior of the column at loads near failure.

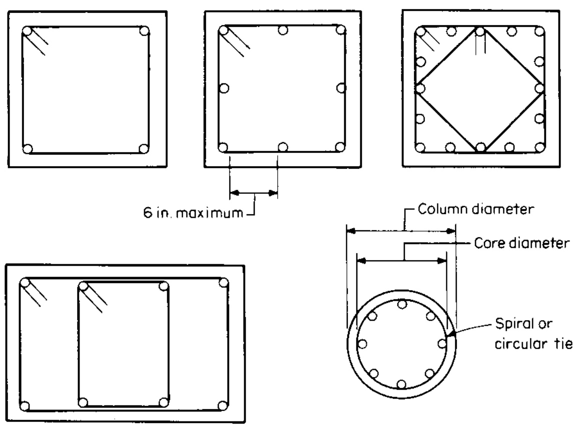


Fig. 12.3.9 Typical arrangement of steel in columns.

Spiral bars serve to confine the concrete core of the section as well as holding the longitudinal bars. The minimum amount of spiral steel, if advantage is to be taken of the higher ϕ factor for spiral columns, is

$$\rho_s = 0.45(A_g/A_{core} - 1)f'_c f_y \qquad (12.3.17)$$

where f_y is the yield stress of the spiral, but not more than 60,000 lb/in^2. The clear spacing of the turns of the spiral must be between 1 and 3 in.

The strengths of compression members may be reduced below the cross-sectional strengths by length effects. Most columns in unbraced frames (frames in which the columns resist all horizontal forces) will have some strength reduction because of length effects, and most columns in braced frames will not, but this depends on the precise details of the length, width, restraint by other frame members, reinforcement, and amount of creep expected. A comprehensive method of taking column length into account is contained in the ACI Code.

Columns are also made by encasing structural steel sections in concrete, in which case the covering concrete must contain at least some steel in order to control cracks and maintain the integrity of the concrete in case of fire. Heavy steel pipes filled with concrete may also be used as columns. These are also used as piling, in which case the pipe is filled with concrete, usually after being driven to the final location.

REINFORCED CONCRETE FLOOR SYSTEMS

Several types of reinforced concrete floors are used, with the choice depending on a number of factors such as span, live load, deflection limits, cost, story-height limitations, local custom, the nature of the rest of the structural frame or system, and the probability of future alterations.

The floor systems may be divided, somewhat arbitrarily, into one-way and two-way systems. One-way systems include solid and hollow slabs and joists spanning between parallel supporting beams or walls. Floors in which panels are subdivided into a grid by subbeams spanning between main girders have usually been designed as one-way slabs when the grid length is several times the width.

Two-way systems include slabs supported on all four sides on beams or walls, traditionally called *two-way slabs.* Slabs supported only on columns located at the corners of the panels also carry loads by developing stresses in the two major directions, and are usually termed *flat plates* if the slab is supported directly on the columns and *flat slabs* if there are capitals on the columns to increase the effective support size. A waffle slab is usually designed as a flat plate or flat slab, with pockets of concrete omitted from the lower surface, and the slab appears as a series of crossing joists.

One-way slabs and joists are designed as beams. A 12-in or other convenient width of slab is selected, analyzed as an isolated beam, and a depth and steel are picked. The main steel is perpendicular to the supports. Additional steel, parallel to the supports, is placed to control cracking and help distribute minor concentrated loads. This steel is usually one-fourth to one-third of the main steel, but not less than a gross steel ratio of 0.0018 for Grade 60 and 0.002 for lower-grade steels. These minimums govern in both directions, and in two-way systems as well.

One-way joists, such as that shown in Fig. 12.3.10, are usually cast with reusable sheet metal or fiberglass forms owned or rented by the contractor. Standard form sizes range from about 20 to 36 in wide and 8 to 20 in deep. The web thicknesses are made to suit the shear and fireproofing requirements, and special tapered end sections may be available to increase the web widths in the regions of high shear near the supports. Joists are exempted from the requirement that web steel be supplied regardless of the concrete shear stress. The allowable shear stress for the concrete is 1.1 times that for beams. The top slabs usually range from 2.5 to 4.5 in thick, and are reinforced to span from rib to rib. The joists are essentially designed as isolated T beams, and may be supported on girders or walls. Joist systems are suitable for reasonably long spans and heavy loads, and have low dead weights for the effective depths attainable.

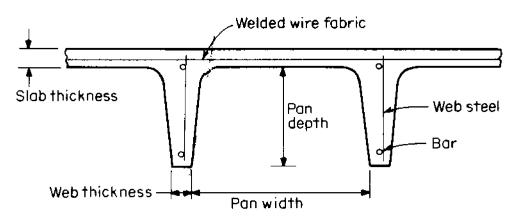


Fig. 12.3.10 Cross section of concrete floor joist.

Slabs spanning in two directions are all designed taking into account the shape of the panel and the relative stiffnesses of the supporting beams, if any. The choice of types is a matter of loadings and economics. For residential and light office loadings, the flat plate is frequently the choice, as the very simple formwork may lead to substantial economy and the story height is minimized. For heavier loads or longer spans, punching shear around the columns becomes a limiting factor, and the flat slab, with its column capitals, may be the most suitable.

In case of extremely heavy floor loads or very stringent limits on deflections, slabs with beams on all four sides of each panel will be most satisfactory. The formwork is more complex than for the other slabs, but there will be some compensating savings in the amounts of steel because of the greater depths of the beams. In addition, the two-way slab may be much more efficient if the building is to resist major lateral loads by frame action alone, because of the difficulties in transferring large moments between columns and flat plates or slabs. The design procedure is the same for slabs with and without beams. The basic steps, for each direction of span in each panel, are:

1. Compute static moment M_0.
2. Distribute M_0 to positive and negative moment sections.
3. Distribute section moments to column and middle strips and beams.

Most buildings slabs are designed for uniformly distributed loads, and the *static moment,* defined as the absolute sum of the midspan positive plus average negative moments, is

$$M_0 = wl_2(l_n)^2/8 \tag{12.3.18}$$

The dimensions are illustrated in Fig. 12.3.11.

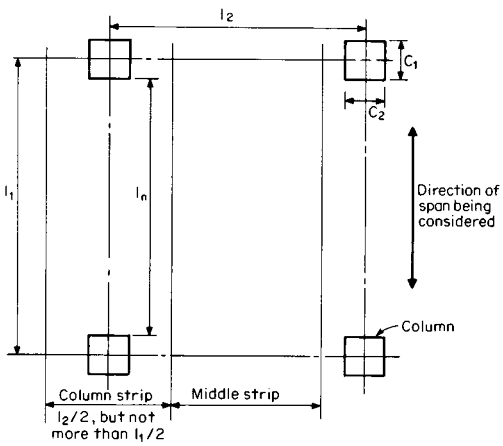


Fig. 12.3.11 Arrangement of typical slab panel.

Relatively simple rules for the distribution of the static moment to various parts of the panel exist as long as the structure meets several simple limits:

1. Minimum of three spans in each direction.
2. Panel length no more than twice panel width.
3. Successive spans differ by not more than one-third the longer span.
4. Columns on a rectangular grid, or offset no more than 10 percent of the span.
5. Live load not more than two times the dead load.
6. If beams are used, they are used on all four sides of each panel and are approximately the same size, except that spandrel beams only are acceptable.

The following is for slabs meeting these restrictions. Information on other cases is contained in the ACI Code.

The positive-negative moment distribution for interior spans is

$$+M = 0.35\,M_0 \tag{12.3.19}$$
$$-M = 0.65\,M_0 \tag{12.3.20}$$

For end spans, the stiffness of the exterior support must be taken into account. Table 12.3.2 gives the fractions of M_0 to be assigned to the three critical sections for five common cases.

Once the section moments have been determined, they are distributed to the column and middle strips and beams, taking into account the panel shape and the beam stiffness. The beam relative stiffness coefficient α_1 is calculated using an effective beam cross section as shown in Fig. 12.3.12, and the full width of the slab panel l_2. The locations of the column and middle strips are shown in Fig. 12.3.11.

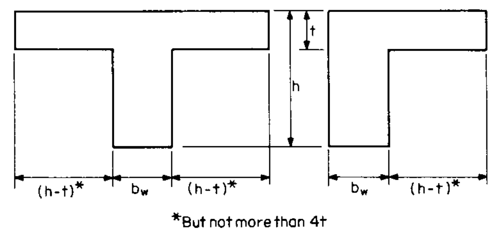


Fig. 12.3.12 Beam sections for calculation of I_b and α_1.

The interior negative and positive moments are distributed to the column strips in the proportions shown in Fig. 12.3.13, with the remainder of the moment going to the middle strip. Linear interpolations are made for intermediate beam stiffnesses, but in most instances where there are beams, they will be found to have

$$\alpha_1 l_2/l_1 \geq 1.0$$

At the exterior supports, the distribution of the negative moments is a complex function of the flexural and torsional stiffnesses of the beams

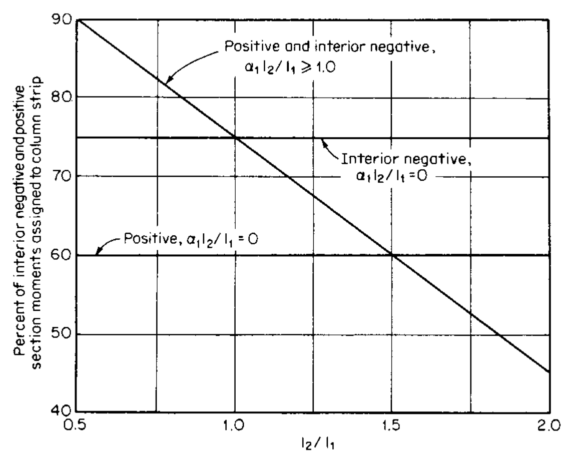


Fig. 12.3.13 Percentage of interior negative and positive moments assigned to a column strip.

and of the panel shape, but satisfactory designs can usually be achieved by assigning all the negative moment to the column strip and detailing the edge beam or edge strip of the slab for torsion, by using closed stirrups at relatively small spacings, and by placing bars parallel to the edge of the structure in each corner of the stirrups. At fully restrained edges, use the distribution for an interior negative moment section.

Table 12.3.2 Moments in End Spans

	Exterior edge unrestrained (1)	Slab with beams between all supports (2)	Slab without beams between interior supports: Without edge beam (3)	Slab without beams between interior supports: With edge beam (4)	Exterior edge fully restrained (5)
Interior negative factored moment	0.75	0.70	0.70	0.70	0.65
Positive factored moment	0.63	0.57	0.52	0.50	0.35
Exterior negative factored moment	0	0.16	0.26	0.30	0.65

Beam moments are found by dividing the column strip moment between beam and slab. If $\alpha_2 l_2/l_1 \geq 1.0$, the beam moment is 85 percent of the column strip moment. This moment is reduced linearly to zero as $\alpha_1 l_2/l_1$ approaches zero.

This design method assumes that all panels are loaded with the same uniformly distributed load at all times. This is obviously a gross simplification, and the requirement that the live load be no greater than twice the dead load limits the potential overstress caused by partial loadings.

In addition, there is a requirement for column design moments, and unless a more complete analysis is made, the following moment, divided between the columns above and below the slab in proportion to their stiffnesses, must be provided for:

$$M = 0.07[(w_d + 0.5w_l)l_2 l_n^2 - w_d' l_2'(l_n')^2] \qquad (12.3.21)$$

The loads w_d and w_l are the distributed dead and live loads including the overload factors. The terms w_d', l_2', and l_n' are for the shorter of the two spans meeting at the column considered.

The shear strength of slab structures must always be checked, and shear stresses often govern the thickness of beamless slabs, especially flat plates.

If there are beams with $\alpha_1 l_2/l_1 \geq 1.0$, all shear is assigned to the beams, and stirrups are provided to make the shear capacity adequate, as was described in earlier coverage on beams. The beam shear is linearly reduced to zero as $\alpha_1 l_2/l_1$ is reduced to zero.

For the case of no beams, punching shear around the columns becomes a controlling factor. In this case the average shear stress, calculated as

$$v_u = V_u/b_0 d \qquad (12.3.22)$$

must not exceed the smaller of $\phi 4\sqrt{f_c'}$, $\phi(2 + 4/\beta_c)\sqrt{f_c'}$, or $\phi(\alpha_s\, d/b_0 + 2)\sqrt{f_c'}$, where β_c = ratio of long side of critical shear perimeter to short side and $\alpha_s = 40$ for interior columns, 30 for edge columns, and 20 for corner columns.

The critical shear perimeter b_0 is defined by a section located $d/2$ away from and extending all around the column, as shown in Fig. 12.3.14. It is very important that holes in the slab in the vicinity of the column be taken into account in reducing the value of b_0, and that no unauthorized holes, such as for piping, be made either during or after construction.

It is possible to increase the shear resistance by the use of properly designed shear reinforcement, but this is not often done and is not recommended as a standard practice.

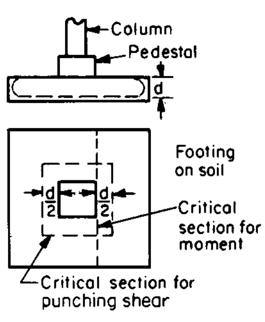


Fig. 12.3.14 Two-way reinforced concrete footing.

Transfer of moments between columns and slabs sets up shear and torsional stresses which must also be considered in the analysis of the shear strength.

FOOTINGS

Footings (Fig. 12.3.14) may be classified as wall footings, isolated column footings, and combined column footings. The bending moments, shears, and bond stresses in such footings should be determined by the principles of statics on the basis of assumed or known soil-pressure distribution over the area of the footing. The bending moment on any projecting portion of a footing may be computed as the moment of the forces acting on the area to one side of a vertical plane through the critical section.

The critical section for bending in a concrete footing supporting a concrete column, pedestal, or wall should be taken at the face of the column, pedestal, or wall. For footings under metallic column bases or under masonry walls where bond with the footings is reduced to the friction value, the critical section is assumed midway between the middle and edge of the base or wall.

Shear stresses must be considered on two sections. The footing may act as a wide beam, for which the critical section is a vertical plane located d away from the critical section for moment, and the stresses must satisfy those for a beam. Punching shear will often govern, and the critical section lies at a distance $d/2$ from the face of the column or other critical section for moment, as shown in Fig. 12.3.14, and as was the case for flat plates and slabs. Footings supported on a small number of high-capacity piles present special shear problems since the conventional critical sections for shear may not be meaningful.

The critical section for bond should be taken at the same plane as for bending. Other vertical planes where abrupt changes of section occur should also be investigated for bond and shear stresses.

In sloped or stepped footings, sections other than the critical ones may require consideration. A square footing, reinforced in two directions, should have the reinforcement uniformly distributed across the entire width. Rectangular footings, reinforced in two directions, should have the reinforcement in the long direction uniformly distributed; in the short direction a portion, Eq. (12.3.23), should be uniformly distributed across a strip equal in width to the short side and centered on the structural element supported and the remainder distributed uniformly in the outer portions. The amount included in the center strip may be computed as follows:

Reinforcement in center strip

$$= \frac{2\ (\text{total reinforcement in short direction})}{\beta + 1} \qquad (12.3.23)$$

where β is the ratio of the long side to the short side.

Combined Footings Footings supporting two or more columns may be designed with sufficient accuracy by assuming uniform soil pressure and applying the laws of statics. The footing shape must be such that the center of gravity coincides with the center of gravity of the superimposed loads; otherwise unequal settlement may occur. The longitudinal and diagonal tension reinforcement should be designed by the ordinary rules of beam design. Lateral reinforcement should be designed as for isolated footings and should preferably be concentrated in bands under and near the columns proportionate in area to the column loads. The lateral reinforcement at each column should be uniformly distributed within a width centered on the column and should not be greater than the width of the column plus twice the effective depth of the footing.

Spread or raft foundation, consisting of a slab extending over the entire area under the columns or of a slab supported by beams, may be considered as loaded by a uniform upward reaction of the ground. The principle of design is exactly the same as that applied to a floor system, except that the load acts upward instead of downward.

Concrete piles of various types are widely used for foundations as they have larger carrying capacity and greater durability under many conditions of exposure than wooden piles. Precast piles are designed as columns with allowance for driving and handling stresses. Cast-in-place piles are constructed either by driving a steel shell and filling it with concrete or by filling the hole formed by a shell as it is withdrawn. Another method forms a bulb at the bottom by means of a ram which forces the concrete into the ground. The design load or capacity of cast-in-place concrete piles is largely empirical, being based on load-test data. The concrete for precast piles is usually over 5,000 lb/in^2 strength and for cast-in-place piles, over 3,000 lb/in^2 strength.

Dowels and Bearing Plates The stress in the longitudinal reinforcement of concrete columns should be transferred to the footing by means of dowels, equal in number and area to the column rods and of sufficient length to transfer the stress as in a lap splice in the column.

Bearing stresses in concrete, under design ultimate loads, should not exceed the following values:

$$\text{Entire surface loaded: } f_b = 0.85\ \phi f'_c \tag{12.3.24}$$

$$\text{Part of surface loaded: } f_b = 0.85\ \phi f'_c \sqrt{A_2/A_1} \tag{12.3.25}$$

where A_1 = loaded area; and A_2 = surface area of same shape and concentric with A_1. $\sqrt{A_2/A_1}$ should not exceed 2.0.

WALLS AND PARTITIONS

Reinforced concrete is well suited to the construction of walls, especially where they have to withstand heavy pressures, such as the retaining walls of a cellar or basement, walls for coal pockets, silos, reservoirs, or grain elevators. Such walls must be designed for flexural shear and bond stresses as well as stability against overturning, sliding, and soil pressure. Drainage should be provided for by weep holes or drains. Partitions may be built of solid concrete 4 to 6 in thick, reinforced to control temperature and shrinkage cracks. Reinforced concrete walls need to be anchored by reinforcement to adjacent structural members. All walls must be reinforced for temperature with steel placed horizontally and vertically.

The horizontal reinforcement shall not be less than 0.25 percent and the vertical reinforcement not less than 0.15 percent of the area of the reinforced section of the wall when bars are used and three-fourths of these amounts when welded fabric is used. Adequate reinforcement must be provided around all openings for windows and doors.

Retaining walls of reinforced concrete are used to resist the pressures of earth, water, and other retained materials and are usually of T or L shape. The base must be so proportioned that there is sufficient resistance to sliding and overturning and that the safe bearing strength of the soil is not exceeded. The dimensions of the concrete section and the position and amount of steel reinforcement are determined by the moments and shears at critical vertical and horizontal sections at the junction of the wall and the base. Particular attention should be given to drainage to prevent excessive water pressure behind walls retaining earth or other materials. Walls retaining water, such as tanks, should have steel tensile stresses limited to 12,000 lb/in² unless special consideration is given to controlling cracks and should have ample reinforcement to provide for effects caused by shrinkage of the concrete and temperature change.

Bearing Walls The allowable compressive force for reinforced concrete bearing walls subject to concentric loads can be computed as follows:

$$P_u = 0.55\ \phi f'_c A_g[1 - (l_c/40h)^2] \tag{12.3.26}$$

For the case of concentrated loads, the effective width for computational purposes can be considered as the width of the bearing plus four times the wall thickness but not greater than the distance between loads. The wall thickness should be at least 1⁄25 of the unsupported height or width, whichever is smaller. For the upper 15 feet, bearing walls must be at least 6 in thick and increase at least 1 in in thickness for each successive 25 feet downward, except that walls of a two-story dwelling need to be only 6 in thick over the entire height, provided that the strength is adequate.

PRESTRESSED CONCRETE

Prestressed concrete members have initial internal stresses, set up by highly stressed steel tendons embedded in the concrete, which are generally opposite those caused by applied loads. Prestressed members are constructed in one of two ways: (1) *Pretensioned* members are factory precast products, made by tensioning steel tendons between abutments and then casting concrete directly around the steel. After the concrete has reached sufficient strength, the steel is cut and the force transferred to the concrete by bond. (2) *Posttensioned* members, either factory or site cast, contain steel in ducts cast in the concrete. After the concrete has cured, the steel is tensioned and mechanically anchored against the concrete. The ducts are preferably pumped full of grout after tensioning to provide bond and corrosion protection, or the tendons may be coated with corrosion inhibitors.

Very high strength steel is used for prestressing in order to overcome the losses of steel stress due to creep and shrinkage of concrete, and as a result of the strength, relatively small amounts of steel are required. The concrete for pretensioned members will usually be at least 5,000 lb/in² compressive strength, and at least 4,000 lb/in² for posttensioned members.

Because of the initial stress conditions, prestressed concrete members are generally crack-free at working loads and consequently are quite suitable for water-containing structures. Circular tanks and pipes are posttensioned by wrapping them with highly stressed wires, using specialized equipment.

Losses of prestress occur with time owing to creep and shrinkage of concrete and relaxation of steel stress. Pretensioned members also have an initial elastic shortening loss accompanying transfer of force to the concrete, and posttensioned members have losses due to friction between ducts and tendons and anchor set. These losses must be taken into account in the design of members.

Prestressed concrete members are checked for both strength and stresses at working loads. Because of the built-in stresses, the condition of dead load only may also govern. The flexural strength is computed using the same equations as for reinforced concrete which were developed earlier. The steel does not have a well-defined yield stress, and the steel stress at failure can be predicted from the following expressions:

Bonded tendons, low relaxation steel and no compression steel:

$$f_{ps} = f_{pu}\left(1 - \frac{0.28}{\beta_1}\rho_p \frac{f_{pu}}{f'_c}\right) \tag{12.3.27}$$

Unbonded, $l/h \leq 35$:

$$f_{ps} = f_{se} + 10{,}000 + f'_c/100\ \rho_p \tag{12.3.28}$$

but not more than f_{se} or f_{py} + 60,000.

The stresses are used directly in Eqs. (12.3.4), (12.3.7), or (12.3.8), as appropriate, substituting f_{ps} for f_y and A_{ps} for A_s.

Allowable Stresses at Working Load

Steel:	
Maximum jacking stress, but not to exceed recommendation by steel or anchorage manufacturer	$0.8\ f_{pu}$
Immediately after transfer or posttensioning	$0.7\ f_{pu}$
Concrete:	
Temporary stresses immediately after prestressing	
Compression	$0.6\ f'_{ci}$
Tension in areas without reinforcement	$3\sqrt{f'_{ci}}$
Design load stresses (after losses)	
Compression	$0.45 f'_c$
Tension in precompressed tensile zones	$6\sqrt{f'_c}$

The allowable tension may be increased to $12\sqrt{f'_c}$ if it is demonstrated, by a comprehensive analysis taking cracking into account, that the short- and long-term deflections will be satisfactory.

The final steel stress, at working loads, will usually be 30,000 to 45,000 lb/in² less than the initial stress for pretensioned members. Posttensioned members will have slightly lower losses. Losses, from initial tensioning values, for pretensioned members may be predicted satisfactorily using the following expressions from the AASHTO, Bridge Specifications, Sec. 9.16.2;

$$\Delta f_s = SH + ES + CR_c + CR_s = \text{prestress loss} \quad \text{lb/in}^2 \tag{12.3.29}$$

where SH = shrinkage loss = 17,000 − 150 RH; ES = elastic shortening loss = $(E_s/E_c)f_{cir}$; CR_c = creep loss = $12f_{cir} - 7f_{cds}$; CR_s = relaxation loss = $5{,}000 - 0.1ES - 0.05(SH + CR_c)$, for low relaxation strands; f_{cir} = concrete stress at level of center of gravity of steel (cgs) at section considered, due to initial prestressing force and dead load; f_{cds} = change in concrete stress at cgs due to superimposed composite or noncomposite dead load; and RH = relative humidity, percent. The loss calculations are carried out for each critical moment section. The average annual relative humidity of the service environment should be used in the *SH* calculation.

The shear reinforcement requirements for simple cases are covered in an earlier section. In addition to the shear steel, a few stirrups or ties should be placed transverse to the member axis as close to the ends as possible, to control potential splitting cracking. The area of steel, from the AASHTO Bridge Specification, should be $A_t = 0.04\, f_{si}A_{ps}/20{,}000$. In posttensioned beams, end blocks will often have to be used to provide space for anchorage bearing plates.

The minimum clear spacing between strands in pretensioned members is three times the strand diameter near the ends of the beam, but many plants are set up to handle only 2-in spacings. Strands may be closer together in central positions of members, which will help in maximizing member effective depths and steel eccentricity.

Few precast, pretensioned members are solid rectangular sections, and single and double T beams and hollow floor slab units are used extensively in buildings. Hollow box beams and I-section beams are used extensively in bridges and in buildings with heavy design loads. Square piling with the prestressing strands arranged in a circular pattern is widely used. Because of the large number of possible sections, it is necessary to check availability of any particular section with local producers before designing any precast structure.

PRECAST CONCRETE

Precast slabs, beams, walls, and partitions as well as piles, retaining wall units, light standards, railroad crossings, and bridge slabs are being increasingly used because of the saving in time and labor cost. Such units vary in size from small slabs for use in floors or residences to large frames for industrial buildings. The small units, such as roof slabs, are cast in steel forms at central plants. Some of the larger units, such as bridge or highway slabs and wall units, are cast in wood forms at or near the place of use. A method by which wall or partition slabs are cast so that they are simply tilted into position has found wide use in housing and industrial construction. Another special adaptation is the method of casting complete floors on top of each other, then lifting into position vertically at the columns.

Particular attention must be given in the design of precast units to reduction in weight and to details to minimize the cost of erection and installation. Reduction in weight is obtained by the use of lightweight aggregates, high-strength concrete, and hollow units. Precast reinforced concrete units are seldom designed for concrete strengths of less than 4,000 lb/in^2. They are often combined with cast-in-place concrete so as to obtain the advantages of continuity. The combination of precast beams with cast-in-place slabs gives the advantage of T-beam action. Wall units are tied together by interlocking joints or by bolts. Care must be taken in shipping and handling to avoid damage to the precast units, and the design must take care of the stresses that come from such causes. All lifting devices built into the units should be designed for 100 percent impact. All units must be identified as to proper location and orientation in the structure.

Because precast units are made under conditions which allow good control of dimensions, certain restrictions can be relaxed that must be observed for cast-in-place concrete. Cover over the reinforcement for members not exposed to freezing need not be more than the nominal diameter of the steel but not less than ⅝ in. The maximum size of the coarse aggregate can be as large as one-third of the smaller dimension of the member. Precast wall panels are not limited to the minimum thickness requirements for cast-in-place walls.

To reduce the number of connections, precast units should generally be cast as large as can be properly handled. However, some joints will be needed to transfer moments, torsion, shear, and axial loads from one member to another. The integrity of the structure depends on the adequacy of the design of the various joints and connections. They may be made by use of bolts and pins or clips and keys, by welding the reinforcement or steel insert, or by a number of other methods limited only by the ingenuity of the designer. The connections should not be the weak links in the structure. Thought as to their location will avoid many problems.

JOINTS

Contraction and expansion joints may be needed at intervals in a structure to help care for movement due to temperature changes and shrinkage. Joints at 20- to 30-ft intervals provide good crack control. A weakened plane, formed in the tension side of the member by a slot ¼ in wide and ½ in deep, will induce the formation of contraction cracks at selected points. Structures over 200 ft in length should have special consideration given to contraction provisions.

Construction joints are necessary in most structures because all sections cannot be cast continuously. They should be made at points of minimum shearing stress and reinforced across the joint with a steel area of not less than 0.5 percent of the area of the section cut. Provision must be made for the transfer of shear and other forces through the construction joint. Joints in columns should be made at the underside of the floor members, haunches, T beams, and column capitals.

The hardened concrete at a joint should be properly prepared for bonding with the new concrete by being cleaned, roughened, and wetted. On this surface, a coat of neat cement grout or other bonding agent should be applied just before depositing the new concrete.

FORMS

Forms are usually built of wood or metal but in special cases may be made of plastic or fiberglass reinforced plastic. Wooden forms may be the most economical unless the construction allows for the repeated use of the same forms. Plywood and compressed wood fiber sheets, specially treated to make them waterproof, are frequently used for form faces where good surfaces are required. Forms must be designed so that they can be easily erected, removed, and reerected. The usual order of removing forms is (1) column sides, (2) joists, (3) girder and beam sides, (4) slab bottoms, and (5) girder and beam bottoms. Column forms are held together by clamps made of wood or steel, the spacing of which is smallest at the bottom and increases with the decrease in pressure. Beam forms consist of the bottom and two sides held together by clamps or cleats and supported by posts. Slab forms consist of boards or other form material supported by joists spaced 2 or 3 ft apart or other means. The joists either rest on a horizontal joist bearer fastened to the clamps of the beam or girder or are supported by stringers, or posts, or both.

Special consideration must be given to forms for prestressed concrete members. For pretensioned members the form must be constructed such that it will permit movement of the member during release of the prestressing force. For posttensioned members, the form should provide a minimum of resistance to shortening of the member. It is also necessary to consider the deflection of the members due to the stressing force.

Design in Formwork The formwork is an appreciable portion of the cost of most concrete structures. Any efforts, however, to reduce the cost of the forms must not go beyond the point of safe design to prevent failures which would in themselves raise the cost of construction.

All forms must conform to the dimensions and shape of the members and must be sufficiently tight to prevent leakage of the mortar. They must be properly braced and tied together to maintain their position and shape during the construction procedure.

The formwork must support all the vertical and lateral loads that may be applied until these loads can be carried by the concrete structure. Loads on the form include the weight of the forms, reinforcing steel, fresh concrete, and various construction live loads. The construction live load varies with conditions but is often assumed to be 75 lb/ft^2 of floor area. The formwork should also be designed to resist lateral loads produced by wind and movement of construction equipment. Most frequently the steel and concrete will not be placed in a symmetrical pattern and frequently large impact loads will occur. Because of the many varied conditions, it is frequently impossible to determine with any great precision the loads which the form must carry. The designer must therefore make safe assumptions by which the forms can be designed such that failure will not result.

Lateral pressures in forms for walls and columns are influenced by a number of factors: weight of concrete, height of placing, vibration, temperature, size and shape of form, amount and distribution of reinforcing steel, and several other variables. Formulas have been suggested for computing safe lateral pressures to be used in form design. However, because of limited test data, they are not generally accepted by all engineers.

Form Liners Absorbent form liners are occasionally applied to the surface of forms to extract the water from the surface of the concrete, eliminate air and water voids, and produce a concrete of uniform appearance with surfaces which are superior in durability and resistance to abrasion.

The vacuum process, whereby water is absorbed from the concrete through a special form liner made of two layers of screen or wire mesh covered by a layer of cloth, has a similar effect and if properly used reduces the water content of the concrete to a depth of several inches.

Neoprene and other types of rubber have been successfully used as liners in precasting work in which a number of units are made from one form. Rubber is particularly suited for patterned work.

Plastic form liners make it easy to obtain a textured surface or a glossy smooth surface. Generally speaking, plastic liners are easily cleaned and if not too thin are suitable for a number of reuses.

Removal of Forms The time that forms should remain in place depends on the character of the members and weather conditions. The strength of concrete must be ascertained before removing the forms. Unless special precautions are taken, concrete should not be placed below 40°F. Fresh concrete should never be subjected to temperatures below freezing. As an approximate guide for the minimum time for form removal, the following rules, which assume moist curing at not less than 70°F for the first 24 h, may be observed.

WALLS IN MASS WORK. In summer, 1 day; in cold weather, 3 days.

THIN WALLS. In summer, 1 day; in cold weather, 5 days.

COLUMNS. In summer, 1 day; in cold weather, 4 days, provided girders are shored to prevent appreciable weight reaching the columns.

SLABS UP TO 7-FT SPAN. In summer, 4 days; in cold weather, 2 weeks.

BEAMS AND GIRDER SIDES. In summer, 1 day; in cold weather, 5 days.

BEAMS AND GIRDERS AND LONG-SPAN SLABS. In summer, 7 days; in cold weather, 2 weeks.

CONDUITS. 2 or 3 days, provided there is not a heavy fill upon them.

ARCHES. If a small size, 1 week; large arches with a heavy dead load, 3 weeks.

Forms for prestressed members may be removed when sufficient prestressing has been applied to enable them to carry their dead loads and the expected construction loads.

EVALUATION OF EXISTING CONCRETE STRUCTURES

This section is intended to give some guidance to the persons responsible for inspections of structures, whether these are done routinely, or before changing a loading or use, or during remodeling, or when something suspicious is found. Serious problems clearly need to be evaluated by a structural engineer experienced in such evaluations, testing, and renovation; such problems should not be evaluated by one who is primarily a structural designer.

The following are some signs of distress. Any cracks wider than about 0.02 in (0.5 mm) are potentially serious, particularly if there are more than a few. If the cracks are inclined like the shear crack shown in Fig. 12.3.1, they are an additional warning sign and should be investigated promptly. At interior supports and other locations where the beams are continuous with the columns, these cracks may also start at the top surface. Any cracking parallel to the member axis is potentially serious.

Rust stains and streaks from cracks indicate corrosion problems. Corrosion, especially from salt, disrupts the concrete surrounding the steel long before the bar areas are significantly reduced, because rust occupies much more volume than the steel it replaces. This rusting causes internal cracking, which can often be detected by tapping on the concrete surface with a hammer (1-lb size), which produces a distinctive ''hollow'' sound. ''Stalactites'' growing from the bottoms of members may be either salt or lime, but both indicate water-penetration problems and the need for waterproofing work.

Concrete exposed to freezing and thawing or to attack by some chemicals may crumble and disintegrate, leading to loss of section area and protective cover on the reinforcement. Large deflections and/or slopes in members may be indicative of impending distress or disaster, but sometimes members were not built very straight, and in such cases the warning sign is actually a *change* in the conditions.

Any reinforced concrete building designed before about 1956 has a potential weakness in the shear strength of the beams and girders because of a deficiency in the codes of that era, and major changes in loading and seemingly minor signs of distress should be investigated carefully. This problem may also exist in highway bridges designed before 1974. Prestressed members should not have this problem.

Repairs are made by injecting epoxy into cracks, by surface patching, by chipping away significant volumes of concrete and replacing it, and by other means. The repair materials range from normal concretes to highly modified concrete and polymer materials.

12.4 AIR CONDITIONING, HEATING, AND VENTILATING

By Norman Goldberg

REFERENCES: ASHRAE Handbooks ''Fundamentals,'' ''Systems and Equipment,'' and ''Applications.'' Stamper and Koral, ''Handbook of Air Conditioning, Heating and Ventilating,'' Industrial Press. Carrier, ''Handbook of Air Conditioning Design,'' McGraw-Hill.

Air conditioning is the process of treating air to meet the requirements of a conditioned space by controlling its temperature, humidity, cleanliness, and distribution. This section presents standards, basic data, and physical laws for use in the design of air conditioning and related heating and ventilating systems.

COMFORT INDEXES

The human body generates heat and disipates that heat to the surrounding air by sensible flow and the evaporationg of moisture.

Effective Temperature Effective temperature (ET) combines the effect of ambient temperature and humidity into a single index.

ASHRAE Comfort Chart The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) comfort envelope shown in Fig. 12.4.1 is based on clothing and activity. Comfort varies with skin temperature and skin wettedness.

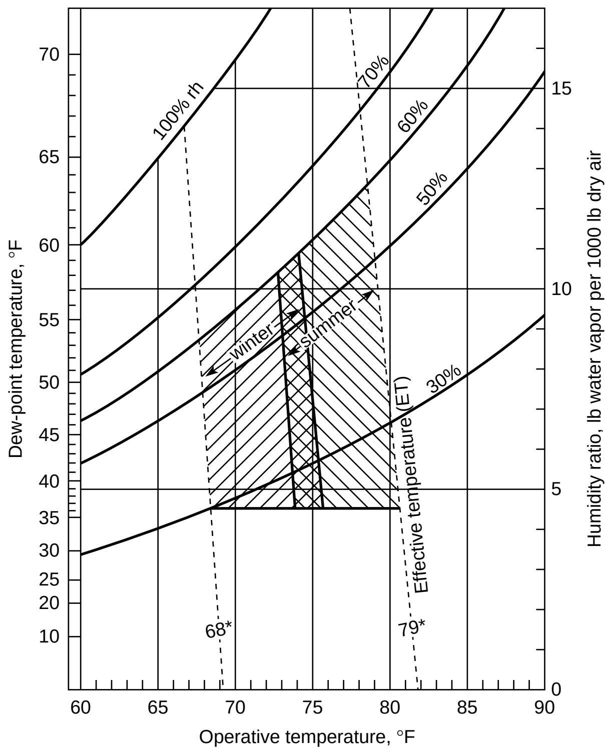


Fig. 12.4.1 Standard effective temperatures and ASHRAE comfort zones. *(ASHRAE ''Handbook of Fundamentals,'' 1993.)*

Temperature-Humidity Index

The term temperature-humidity index (THI) is used to describe the combined effects of temperature and humidity on comfort experienced by people. Since individual reactions can vary considerably from person to person, this quantity should be considered as a guide rather than as an absolute. However, relatively few people will feel discomfort when the THI is 70 or below. By the time it reaches 75, about half the people will be uncomfortable. An index of 80 in a work area may cause a decrease in workers' efficiency. To compute THI, any one of the following formulas may be used:

$$\begin{aligned} \text{THI} &= 0.4(t_d + t_w) + 15 \\ &= 0.55t_d + 0.2t_{dp} + 17.5 \\ &= t_d - (0.55 - 0.55\ \text{RH})(t_d - 58) \end{aligned} \qquad (12.4.1)$$

where t_d = dry-bulb temperature, °F; t_w = wet-bulb temperature, °F; t_{dp} = dew-point temperature, °F; and RH = relative humidity, expressed as a decimal. To convert to degrees Celsius, $t_c = \frac{5}{9}(t_f - 32)$.

Wind-Chill Index

The wind-chill index attempts to describe how much heat the body will lose under certain conditions of wind and temperature. It is determined empirically by an equation which is used to describe the rate of heat loss from a litre cylinder of water at 33°C (91.4°F) as a function of ambient temperature and wind velocity. The formulas for the wind-chill index (WCI) are:

$$\text{WCI} = (10.45 - V + 10\sqrt{V})(33 - t_a) \qquad \text{kcal/m}^2\text{/h} \qquad (12.4.2)$$

where V = metres per second, t_a = °C.

$$\text{WCI} = (10.45 - 0.447V + 6.6854\sqrt{V})(91.4 - t_a) \qquad (12.4.3)$$

where V = miles per hour, t_a = °F.

Instead of using the WCI to express the severity of a cold environment, meteorologists use an index derived from the WCI called the *equivalent wind chill temperature.* This is the ambient temperature that would produce, in a calm wind (defined for this application as 4 mi/h), the same WCI as the actual combination of air temperature and wind velocity. Equivalent wind chill temperature $t_{eq,wc}$ can be calculated by:

$$t_{eq,wc} = -0.0818\ (\text{WCI}) + 91.4 \qquad (12.4.4)$$

where $t_{eq,wc}$ is expressed as a temperature, °F. (See Table 12.4.1.)

INDOOR DESIGN CONDITIONS

Indoor design conditions are determined by the application, usually either the comfort of the people occupying the space or the control of conditions within that space to facilitate a process.

Comfort Conditions Typical indoor design conditions for summer and winter comfort are shown in Table 12.4.2.

Conditions for Process Design These vary widely, depending on the process. See the manufacturer's requirements and/or the ASHRAE Handbook ''Applications.''

Table 12.4.1 Equivalent Wind Chill Temperature of Cold Environments*

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

Little danger: In less than 5 h, with dry skin. Maximum danger from false sense of security. (WCI less than 1400)	**Increasing danger:** Danger of freezing exposed flesh within one minute. (WCI between 1400 and 2000)	**Great danger:** Flesh may freeze within 30 seconds. (WCI greater than 2000)

* Cooling power of environment expressed as an equivalent temperature under calm conditions.
† Winds greater than 43 mi/h have little added chilling effect.
SOURCE: U.S. Army Research Institute of Environmental Medicine.

Table 12.4.2 Recommended Inside Design Conditions

	Summer			Winter				
				With humidification			Without humidification	
Type of application	Dry bulb, °F (°C)	Rel. hum., %	Temp. swing, °F (°C)*	Dry bulb, °F (°C)	Rel. hum., %	Temp. swing, °F (°C)‡	Dry bulb, °F	Temp. swing, °F (°C)‡
General comfort (apartment, house, hotel, office, hospital, school, etc.)	74–76 (23–24)	50–45	2 (1.1)	68–72 (20–22)	35–30	3 to 4 (1.6–2.2)	70–74	4 (2.2)
Retail shops (short-term occupancy) (bank, barber or beauty shop, department store, supermarket, etc.)	74–76 (23–24)	50–45	2 (1.1)	68–72 (20–22)	35–30†	3 to 4 (1.6–2.2)	70–74	4 (2.2)
Low-sensible-heat-factor applications (high latent load) (auditorium, church, bar, restaurant, kitchen, etc.)	74–76 (23–24)	55–50	2 (1.1)	68–72 (20–22)	40–35	2 to 3 (1.1–1.7)	70–74	4 (2.2)
Factor comfort (assembly areas, machining rooms, etc.)	76–78 (24–26)	55–45	2 (1.1)	68–70 (18–21)	35–30	4 to 6 (2.2–3.3)	65–70	6 (3.3)

* Temperature swing is above the thermostat setting at peak summer load conditions.
† Winter humidification in retail clothing stores is recommended to maintain the quality texture of goods.
‡ Temperature swing is below the thermostat setting at peak winter load conditions (no lights, people, or sun).
°C = 5⁄9(°F − 32)
SOURCE: Adapted from Carrier Corp. ''System Design Manual,'' with permission.

OUTDOOR DESIGN CONDITIONS

Outdoor design conditions are based primarily on the geographical location but they are affected to some extent by the criticality of the application and by the economics of maintaining indoor conditions at specified design levels during unusual outdoor weather conditions.

Outdoor design conditions for comfort applications are usually not the most severe conditions that have been experienced in a locality, and recommended levels may be exceeded for an average of 5 percent of the hours during the cooling season.

Frequently used winter outside dry-bulb design temperature are shown in Fig. 12.4.2. Summer outdoor design dry-bulb, wet-bulb, and dew-point temperatures for comfort applications are shown in Figs. 12.4.3 to 12.4.5, respectively.

Design of critical air-conditioning systems and selection of atmospheric evaporative cooling equipment are normally based on more severe outdoor conditions than for comfort applications. Figure 12.4.6 shows wet-bulb temperatures in the United States that are exceeded 1 percent of the time during the cooling season.

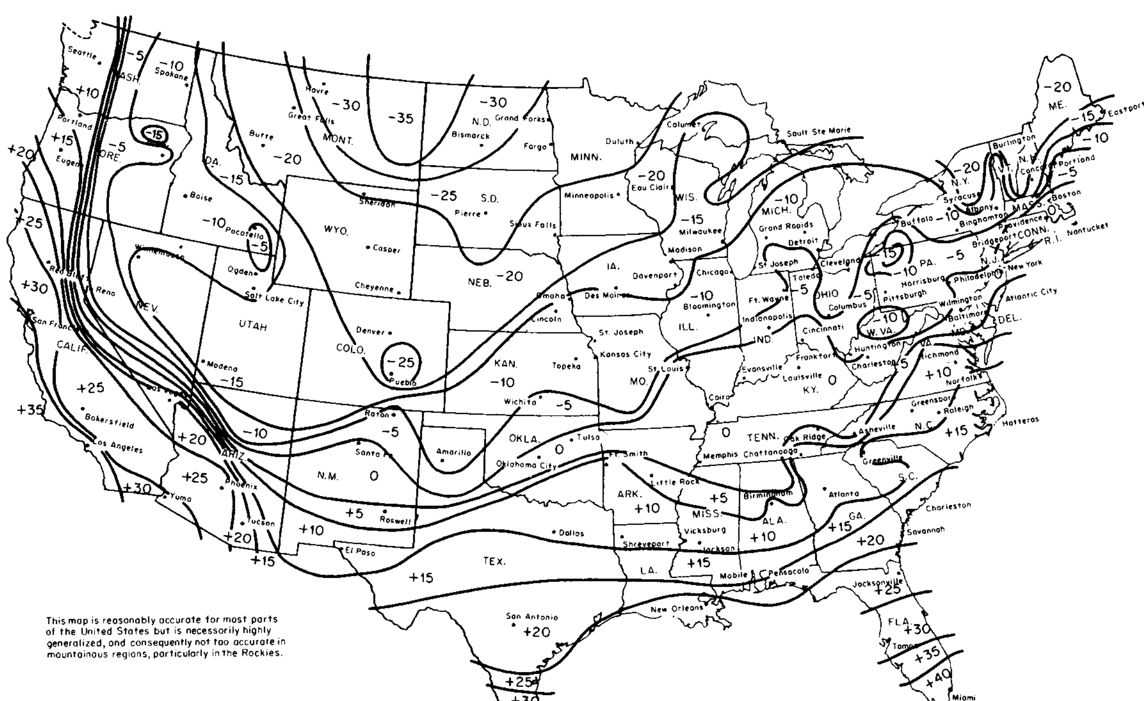


Fig. 12.4.2 Isotherms of winter outdoor temperatures, °F. *[E. Stamper and L. Koral (eds.), ''Handbook of Air Conditioning, Heating and Ventilating,'' 3d ed., 1979, Industrial Press.]*

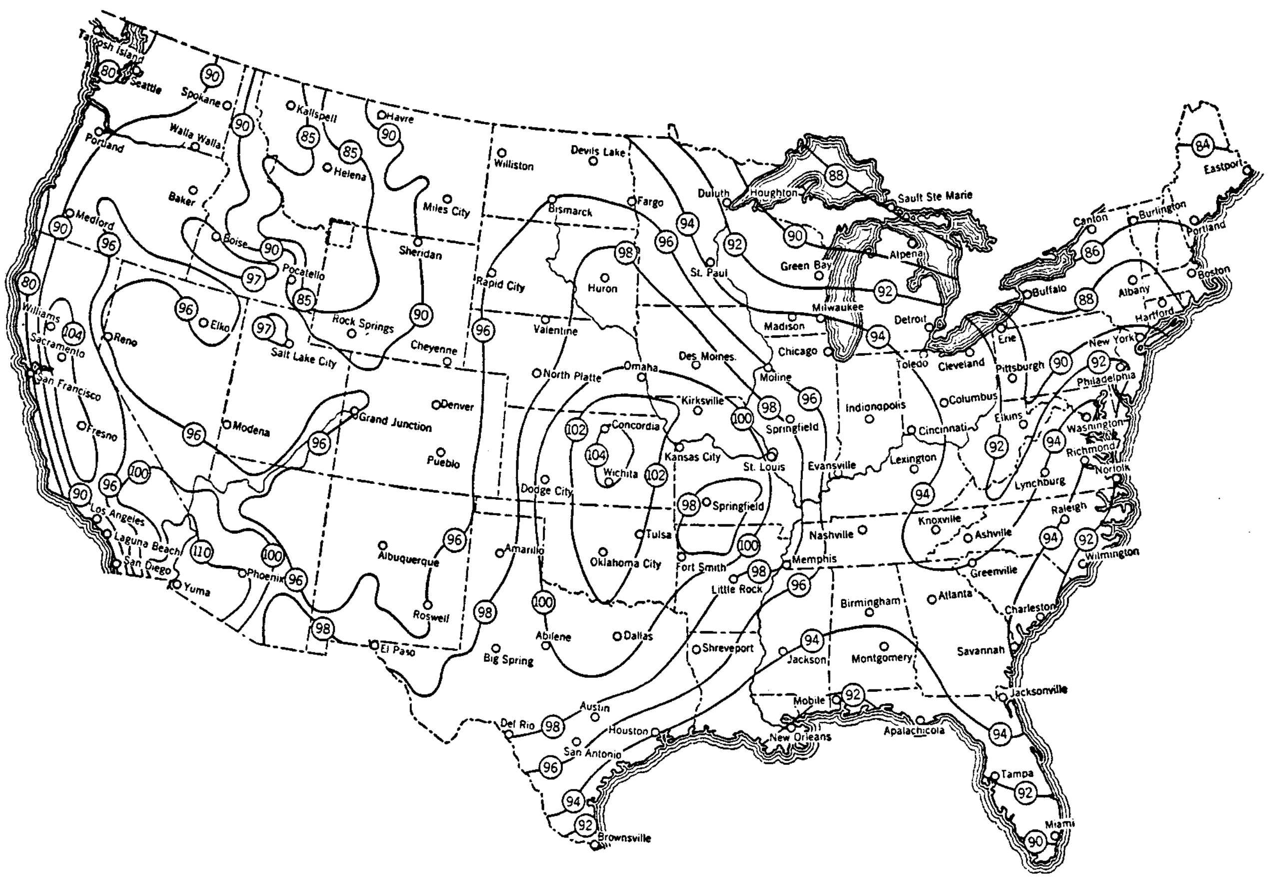


Fig. 12.4.3 Summer dry-bulb temperature data. *(Marley Co.)*

Ventilation and Infiltration

Ventilation Ventilation rates must be adequate to control levels of indoor contaminants and provide makeup air for exhaust systems. It must be recognized that the introduction of outdoor air into a conditioned space represents a significant load on the system since it affects both temperature and moisture levels.

Mechanical ventilation is controllable and is the desirable way to introduce outdoor air into a space. Infiltration is uncontrolled airflow through cracks and other openings and, where feasible, it should be limited. ASHRAE Standard 62-1989, ''Ventilation for Indoor Air Quality,'' presents recommendations for outdoor air rates to maintain acceptable indoor air quality for a wide variety of applications. Requirements of local building codes may differ and may require more, or accept less, ventilation air. An extract from the ASHRAE Standard 62-1989, ''Table of Air Requirements,'' is shown in Table 12.4.3.

Infiltration Infiltration during the summer is due primarily to wind velocity creating a positive pressure on the windward side of a building. During the winter, when the density of indoor and outdoor air differ significantly, stack effect adds substantially to the wind effect. Completely offsetting infiltration by the introduction of sufficient outdoor air through the air-conditioning system is costly. Consequently, outdoor air infiltration should be curtailed by the use of vestibules and, if feasible, revolving doors at frequently used entrances, and tightly fitting windows and/or storm sash throughout. See Tables 12.4.4 and 12.4.5.

Flow of Water Vapor through Building Construction Components Water vapor flow through building construction adds to the latent load, and although it is usually a minor load factor in comfort applications, it can affect the integrity of insulation and other building components.

Vapor transmission is determined by the differences in vapor pressure and the permeability of the construction, but can be reduced by the use of vapor barriers on the high-vapor-pressure side of the construction. In applications where interior design dew points are either high or low, the vapor transmission should be calculated.

The permeance of some materials that will affect the transmission of water vapor is shown in Table 12.4.6.

Infiltration of Moisture

Infiltration of air, and particularly moisture, into a conditioned space is frequently a source of sizable heat gain or loss.

The moisture entering a building as water vapor may be expressed as

$$W_t = W_{trans} + W_{inf} + W_{vent} \qquad (12.4.5)$$

where W_t = total weight of vapor, grains (grams). Assuming that W_{trans} is negligible as a load factor,

$$W_1 = W_{inf} + W_{vent} \qquad (12.4.6)$$

$$W_{inf} = \text{air-infiltrated vapor} = W(M_o - M_i)\text{grains(grams)}$$
$$= W(M_o - M_i)\,\Delta p \text{ grains (grams)} \qquad (12.4.7)$$

$$W_{vent} = \text{ventilation air vapor}$$
$$= W(M_o - M_i) \text{ grains (grams)} \qquad (12.4.8)$$

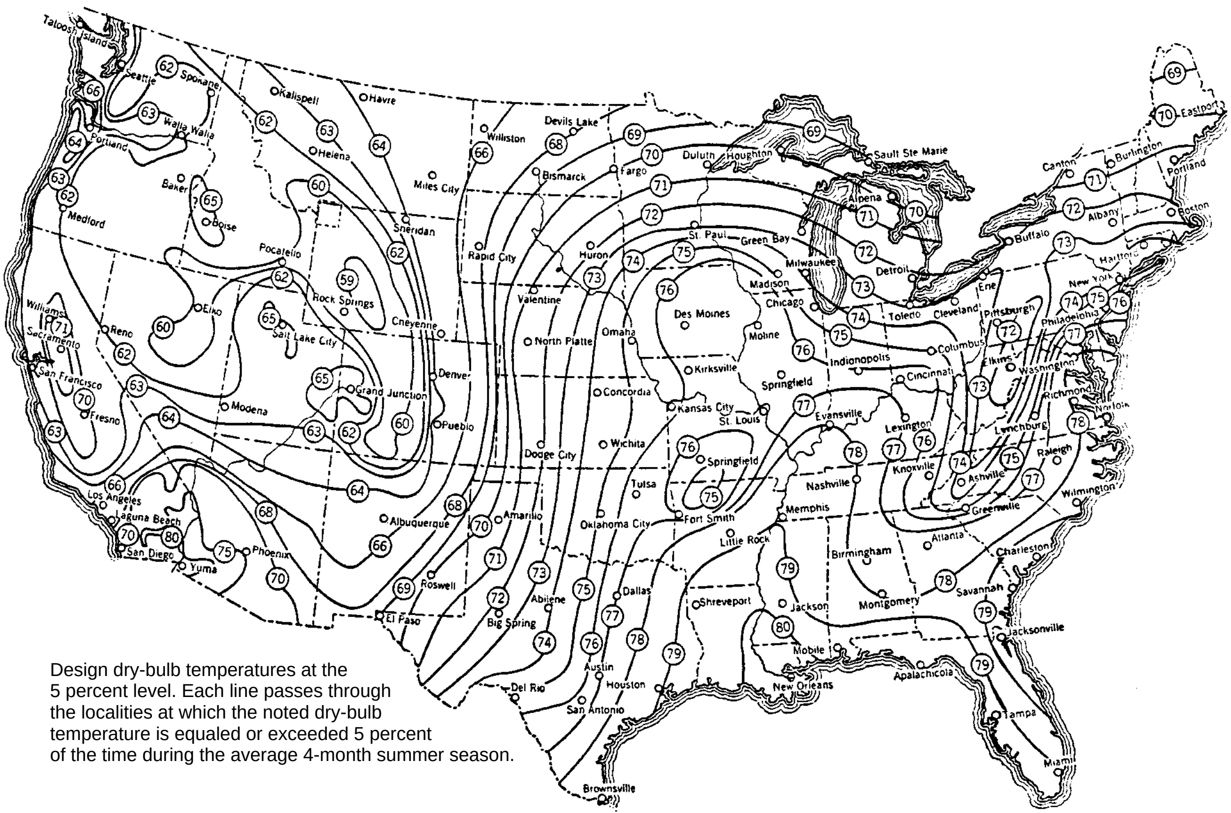


Fig. 12.4.4 Summer wet-bulb temperature data. *(Marley Co.)*

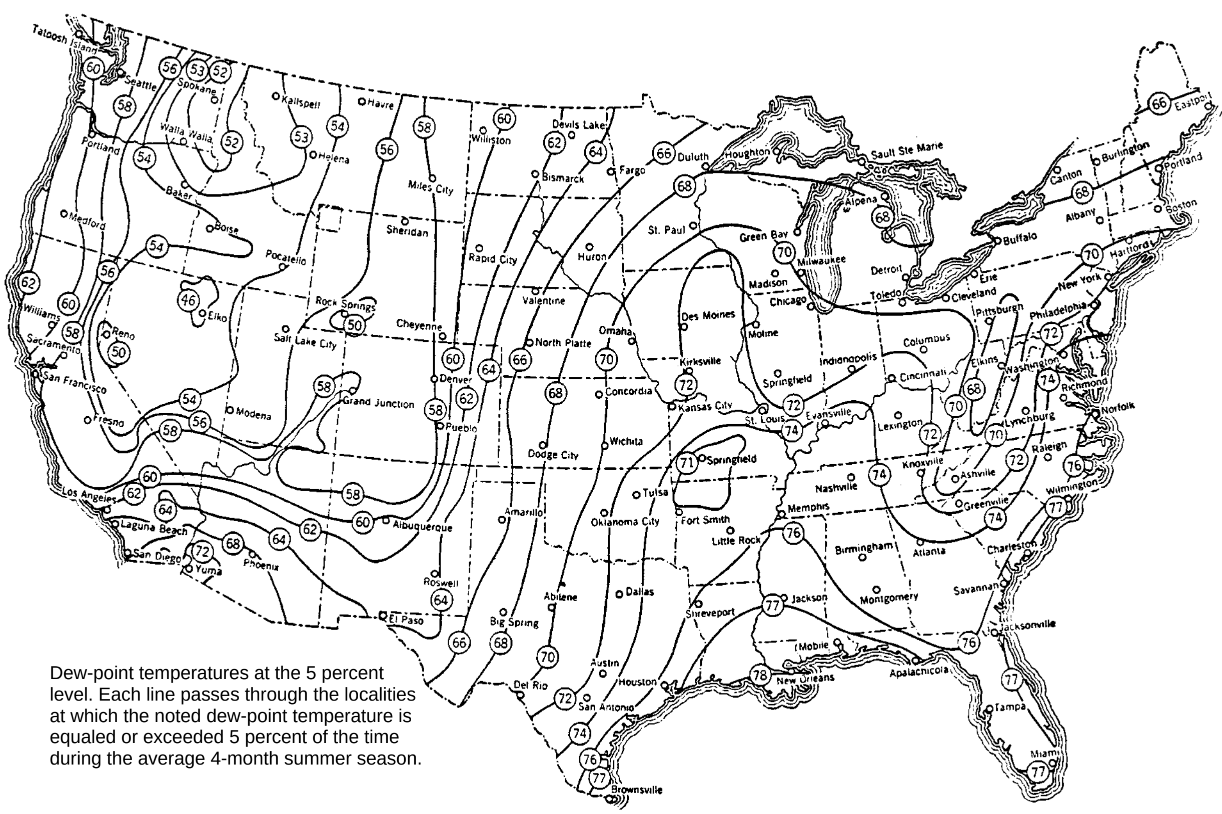


Fig. 12.4.5 Summer dew-point temperature data. *(Marley Co.)*

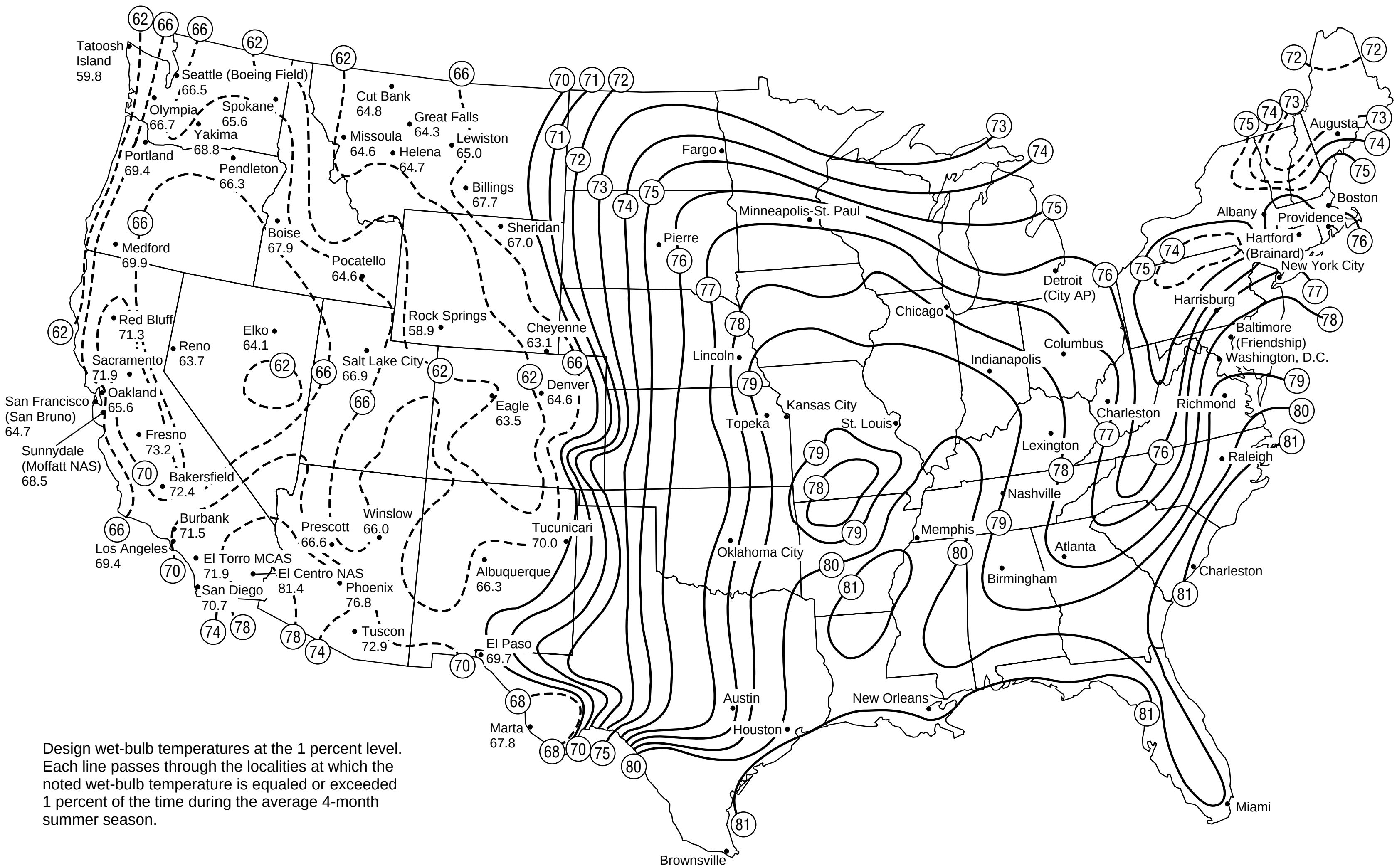


Fig. 12.4.6 High wet-bulb temperature data. *(Fluor Products Co.)*

Table 12.4.3 Outdoor Air Requirements for Ventilation*

Application	Estimated maximum† occupancy, persons/1000 ft² or 100 m²	Outdoor air requirements				Comments
		cfm/person	L/s·person	cfm/ft²	L/s·m²	
		Commercial facilities				
Hotels, motels, resorts, dormitories						
Bedrooms				30	15	Per room.
Living rooms				30	15	Per room.
Baths				35	18	Per room. Installed capacity for intermittent use.
Lobbies	30	15	8			
Conference rooms	50	20	10			
Assembly rooms	120	15	8			
Dormitory sleeping areas	20	15	8			See also food and beverage services, merchandising, barber and beauty shops, garages.
Gambling casinos	120	30	15			Supplementary smoke-removal equipment may be required.
Offices						
Office space	7	20	10			Some office equipment may require local exhaust.
Reception areas	60	15	8			
Telecommunication centers and data entry areas	60	20	10			
Conference rooms	50	20	10			Supplementary smoke-removal equipment may be required.
Public spaces						
Corridors and utilites				0.05	0.25	
Public restrooms, cfm/wc or cfm/urinal		50	25			Normally supplied by transfer air. Local mechanical exhaust with no recirculation recommended.
Locker and dressing rooms				0.5	2.5	
Smoking lounge	70	60	30			
Food and beverage service						
Dining rooms	70	20	10			Supplementary smoke-removal equipment may be required. (Dining rooms; Cafeteria, fast food; Bars, cocktail lounges)
Cafeteria, fast food	100	20	10			
Bars, cocktail lounges	100	30	15			
Kitchens (cooking)	20	15	8			Exhaust min. 1.5 cfm/ft²
Retail stores, sales floors, and show room floors						
Basement and street	30			0.30	1.50	
Upper floors	20			0.20	1.00	
Storage rooms	15			0.15	0.75	
Dressing rooms				0.20	1.00	
Malls and arcades	20			0.20	1.00	
Shipping and receiving	10			0.15	0.75	
Warehouses	5			0.05	0.25	
Smoking lounge	70	60	30			Normally supplied by transfer air, local mechanical exhaust; exhaust with no recirculation recommended.
Sports and Amusement						
Spectator areas	150	15	8			When internal combustion engines are operated for maintenance of playing surfaces, increased ventilation rates may be required.
Game rooms	70	25	13			
Ice arenas (playing areas)				0.50	2.50	
Swimming pools (pool and deck area)				0.50	2.50	Higher values may be required for humidity control.
Playing floors (gymnasium)	30	20	10			
Ballrooms and discos	100	25	13			
Bowling alleys (seating areas)	70	25	13			
Theaters						Specifal ventilation will be needed to eliminate special stage effects (e.g., dry ice vapors, mists, etc.)
Ticket booths	60	20	10			
Lobbies	150	20	10			
Auditorium	150	15	8			
Stages, studios	70	15	8			
Miscellaneous						
Photo studios	10	15	8			
Darkrooms	10			0.50	2.50	
Pharmacy	20	15	8			
Bank vaults	5	15	8			
Duplicating, printing				0.50	2.50	Installed equipment must incorporate positive exhaust and control (as required) of undesirable contaminants (toxic or otherwise).

Table 12.4.3 Outdoor Air Requirements for Ventilation* (*Continued*)

Application	Estimated maximum† occupancy, persons/1000 ft^2 or 100 m^2	Outdoor air requirements cfm/person	L/s·person	cfm/ft^2	L/s·m^2	Comments
		Institutional Facilities				
Education						
Classroom	50	15	8			
Laboratories	30	20	10			Specifal contaminant control systems may be required for processes or functions including laboratory animal occupancy.
Training shop	30	20	10			
Music rooms	50	15	8			
Libraries	20	15	8			
Locker rooms				0.50	2.50	
Corridors				0.10	0.50	
Auditoriums	150	15	8			
Smoking lounges	70	60	30			Normally supplied by transfer air. Local mechanical exhaust with no recirculation recommended.
Hospitals, nursing and convalescent homes						
Patient rooms	10	25	13			Special requirements or codes and pressure relationships may determine minimum ventilation rates and filter efficiency. Procedures generating contaminants may require higher rates.
Medical procedure	20	15	8			
Operating rooms	20	30	15			
Recovery and ICU	20	15	8			
Autopsy rooms				0.50	2.50	Air shall not be recirculated into other spaces.
Physical Therapy	20	15	8			
Correctional facilities						
Cells	20	20	10			
Dining halls	100	15	8			
Guard stations	40	15	8			

* This table prescribes supply rates of acceptable outdoor air required for acceptable indoor air quality. These values have been chosen to control CO_2 and other contaminants with an adequate margin of safety and to account for health variations among people, varied activity levels, and a moderate amount of smoking. Rationale for CO_2 control is presented in Appendix D of Standard 62-1989.
† Net occupable space.
SOURCE: Abstracted from ASHRAE Standard 62-1989, with permission.

Table 12.4.4 Infiltration through Doors—Winter*
15 mi/h (24 km/h) wind velocity†; doors on one or adjacent windward sides‡

	ft^3/min per ft^2 area (m^3/min per m^2)§									
	Infrequent use		Average use: 1 and 2 story buildings		Tall buildings, ft (m)					
	ft^3/min per ft^2	m^3/min per m^2	ft^3/min per ft^2	m^3/min per m^2	50	(15.25 m)	100	(30.5 m)	200	(61 m)
Revolving door	1.6	0.48	10.5	3.15	12.6	3.78	14.2	4.26	17.3	5.19
Glass door [3⁄16 in (5 mm) crack]	9.0	2.70	30.0	9.00	36.0	10.80	40.5	12.15	49.5	14.85
Wood door 3 × 7 ft (0.9 × 2 m)	2.0	0.60	13.0	3.90	15.5	4.65	17.5	5.25	21.5	6.45
Garage and shipping-room door	4.0	1.2	9.0	2.70						

SOURCE: Carrier Corporation ''System Design Manual,'' Part 1, Load Estimating, 1970.
* All values are based on the wind blowing directly at the window or door. When the prevailing wind direction is oblique to the window or doors, multiply the values by 0.60 and use the total window and door areas on the windward side(s).
† Based on a wind velocity of 15 mi/h (24 km.p.a). For design wind velocities different from the base, multiply the table values by the ratio of velocities.
‡ Stack effect in tall buildings may also cause infiltration on the leeward side. To evaluate this, determine the equivalent velocity V_i and subtract the design velocity V. The equivalent velocity is

$$V_i = \sqrt{V^2 - 1.75a} \text{ (upper section)}$$
$$= \sqrt{V^2 - 1.75b} \text{ (lower section)}$$

where a and b are the distances above and below the midheight of the building, respectively, in feet.
Multiple the table values by the ratio $(V_i - V)/15$ for one-half of the windows and doors on the leeward side of the building. (Use values under one- and two-story building for doors on leeward side of tall buildings.)
§ Doors on opposite sides increase values 25%.

Table 12.4.5 Infiltration Through Windows and Doors—Crack Method—Summer–Winter*

Double-hung windows, unlocked on windward side.

	cfm per linear foot of crack											
	Wind velocity, mi/h											
	5		10		15		20		25		30	
Type of double-hung window	No W strip	W strip	No W strip	W strip	No W strip	W strip	No W strip	W strip	No W strip	W strip	No W strip	W strip
Wood sash												
Average Window	0.12	0.07	0.35	0.22	0.65	0.40	0.98	0.60	1.33	0.82	1.73	1.05
Poorly Fitted Window	0.45	0.10	1.15	0.32	1.85	0.57	2.60	0.85	3.30	1.18	4.20	1.53
Poorly Fitted—with Storm Sash	0.23	0.05	0.57	0.16	0.93	0.29	1.30	0.43	1.60	0.59	2.10	0.76
Metal Sash	0.33	0.10	0.78	0.32	1.23	0.53	1.73	0.77	2.3	1.00	2.8	1.27

SOURCE: Carrier ''Handbook of Air Conditioning Design,'' McGraw-Hill, 1965.
* Infiltration caused by stack effect must be calculated separately during the winter.
† No allowance has been made for usage.

Table 12.4.6 Water Vapor Transmission Through Various Materials

Description of material or construction	Permeance, Btu/(h · 100 ft²) (gr/lb diff) latent heat
Packaging materials	
Cellophane, moisture-proof	0.01–0.25
Glassine (1 ply waxed or 3 ply plain)	0.0015–0.006
Kraft paper soaked with paraffin wax, 4.5 lb per 100 ft²	1.4–3.1
Pliofilm	0.01–0.025
Paint films	
2 coats aluminum paint, estimated	0.05–0.2
2 coats asphalt paint, estimated	0.05–0.1
2 coats lead and oil paint, estimated	0.1–0.6
2 coats water emulsion, estimated	5.0–8.0
Papers	
Duplex or asphalt laminae (untreated)	
30-30-30, 3.1 lb per 100 ft²	0.15–0.27
30-60-30, 4.2 lb per 100 ft²	0.051–0.091
Kraft paper	
1 sheet	8.1
2 sheets	5.1
Aluminum foil on one side of sheet	0.016
Aluminum foil on both sides of sheet	0.012
Sheathing paper	
Asphalt impregnated and coated, 7 lb per 100 ft²	0.02–0.10
Slaters felt, 6 lb per 100 ft², 50% saturated with tar	1.4
Roofing Felt, saturated and coated with asphalt	
25 lb/ft²	0.015
50 lb/ft²	0.011
Tin sheet with 4 holes 1/16-in diameter	0.17
Crack 12 in long by 1/32 in wide (approximate from above)	5.2

Painted surfaces: Two coats of a good vapor seal paint on a smooth surface give a fair vapor barrier. More surface treatment is required on a rough surface than on a smooth surface. Data indicates that either asphalt or aluminum paint is good for vapor seals.

Aluminum foil on paper: This material should also be applied over a smooth surface and joints lapped and sealed with asphalt. The vapor barrier should always be placed on the side of the wall having the higher vapor pressure if condemnation of moisture in wall is possible.

Application: The heat gain due to water vapor transmission through walls may be neglected for the normal air-conditioning or refrigeration job. This latent gain should be considered for air-conditioning jobs where there is a great vapor pressure difference between the room and the outside, particularly when the dew point inside must be low. Note that moisture gain due to infiltration usually is of much greater magnitude than moisture transmission through building structures.

Conversion factors: To convert above table values to:
grain/(hr) (sq ft) (inch mercury vapor pressure difference), multiply by 9.8. grain/(hr) (sq ft) (pounds per sq inch vapor pressure difference), multiply by 20.0.
To convert Btu latent heat to grains, multiply by 7000/1060 = 6.6.

SOURCE: Carrier ''Air Conditioning Design Manual,'' 1965.

Table 12.4.7 Overall Heat-Transfer Coefficient *U*

Outside air 15 mi/h wind, inside still air.

Example	Construction	Btu/(h · ft² · °F)	W/(m² · K)
Frame walls	Wood siding, insulation board, air space, gypsum board	0.19	1.079
Frame partition	Gypsum board, air space, gypsum board	0.34	1.931
Frame construction ceilings and floors	Linoleum or tile, felt, plywood, wood subfloor, air space, metal lath, plaster	0.23	1.306
Pitched roofs	Asphalt shingles, building paper, wood sheathing, air space, gypsum, lath, plaster	0.28	1.590
Masonry wall	Face brick 4 in, common brick 4 in	0.48	2.725
	Face brick 4 in, common brick 4 in, air space, gypsum lath, plaster	0.29	1.647
Masonry partition	Cement block (cinder aggregate), plaster on both sides	0.31	1.760
Flat masonry roof	Built-up roofing, roof insulation 1 in, concrete slab 4 in, air space, metal lath, plaster	0.18	1.022

SOURCE: ASHRAE ''Handbook of Fundamentals,'' 1981.

Table 12.4.8 Coefficient Heat Transmission *U* for Windows and Skylights

Air-to-air heat transfer, Btu/(h · ft² · °F) and W/(m² · K); outside air 0°F, 15 mi/h (24 km/h) wind, no solar radiation; inside still air.

	Vertical glass sheets				Horizontal glass sheets			
	Outdoor exposure		Indoor exposure		Outdoor exposure		Indoor exposure	
	Btu/ (h · ft² · °F)	W/(m² · K)	Btu/ (h · ft² · °F)	W/(m² · K)	Btu/ (h · ft² · °F)	W/(m² · K)	Btu/ (h · ft² · °F)	W/(m² · K)
Common window glass, single sheet	1.13	6.416	0.75	4.259	1.22	6.927	0.96	5.450
Common window glass, two sheets, 1-in air space (2.54 cm)	0.53	3.009	0.45	2.555	0.63	3.577	0.56	3.180

SOURCE: ASHRAE ''Handbook of Fundamentals,'' 1981.

Table 12.4.9 Coefficient of Heat Transmission *U* for Wood Doors

	Single		With glass storm door	
Construction	Btu/(h · ft² · °F)	(m² · K)	Btu/(h · ft² · °F)	W/(m² · K)
1 in-thick solid door (25⁄32 in) (2 cm)	0.64	3.634	0.37	2.101
2 in-thick solid door (1⅝ in) (4 cm)	0.43	2.442	0.28	1.590
Door containing wood or glass panels	0.85	4.826	0.39	2.214

SOURCE: ASHRAE ''Handbook of Fundamentals,'' 1981.

Table 12.4.10 Surface Conductances and Resistances for Air

Position of surface	Direction of heat flow	Nonreflective $\varepsilon = 0.90$				Surface emissivity, reflective $\varepsilon = 0.20$				Reflective $\varepsilon = 0.05$			
		C	C'	R	R'	C	C'	R	R'	C	C'	R	R'
Still air:													
Horizontal	Upward	1.63	9.26	0.61	0.108	0.91	5.17	1.10	0.193	0.76	4.32	1.32	0.232
Vertical	Horizontal	1.46	8.29	0.68	0.121	0.74	4.20	1.35	0.238	0.59	3.35	1.70	0.299
Horizontal	Downward	1.08	6.76	0.92	0.148	0.37	2.10	2.70	0.476	0.22	1.25	4.55	0.800
Moving air (any position):													
15 mi/s (24 km/h) wind (for winter)	Any	6.00	34.07	0.17	0.029								
7½ mi/h (12 km/h) wind (for summer)	Any	4.00	22.71	0.25	0.044								

SOURCE: Adapted from ASHRAE ''Handbook of Fundamentals,'' 1993.
NOTES: C = conductance, Btu/(h · ft² · °F temp. diff.)
C' = conductance W/(m² · K).
R = resistance = $1/C$.
R' = resistance = $1/C'$.

Table 12.4.11 Determination of *U* value Resulting from Addition of Insulation to Any Given Building Section

Given building section property*, †				Added R‡, § (R')													
				$R = 4$	$R' = 0.70$	$R = 6$	$R' = 1.05$	$R = 8$	$R' = 1.41$	$R = 12$	$R' = 2.13$	$R = 16$	$R' = 2.86$	$R = 20$	$R' = 3.57$	$R = 24$	$R' = 4.17$
U	U'	R	R'	U	U'	U	U'	U	U'	U	U'	U	U'	U	U'	U	U'
1.00	5.68	1.00	0.18	0.20	1.13	0.14	0.79	0.11	0.62	0.08	0.45	0.06	0.34	0.05	0.28	0.04	0.23
0.90	5.11	1.11	0.20	0.20	1.13	0.14	0.79	0.11	0.62	0.08	0.45	0.06	0.34	0.05	0.28	0.04	0.23
0.80	4.54	1.25	0.22	0.19	1.08	0.14	0.79	0.11	0.62	0.08	0.45	0.06	0.34	0.05	0.28	0.04	0.23
0.70	3.97	1.43	0.25	0.19	1.08	0.13	0.74	0.11	0.62	0.07	0.40	0.06	0.34	0.05	0.28	0.04	0.23
0.60	3.41	1.67	0.29	0.19	1.08	0.13	0.74	0.10	0.57	0.07	0.40	0.06	0.34	0.05	0.28	0.04	0.23
0.50	2.84	2.00	0.35	0.18	1.02	0.13	0.74	0.10	0.57	0.07	0.40	0.06	0.34	0.05	0.28	0.04	0.23
0.40	2.27	2.50	0.44	0.16	0.91	0.12	0.68	0.10	0.57	0.07	0.40	0.05	0.28	0.05	0.28	0.04	0.23
0.30	1.70	3.33	0.59	0.14	0.79	0.11	0.62	0.09	0.51	0.07	0.40	0.05	0.28	0.04	0.23	0.04	0.23
0.20	1.14	5.00	0.88	0.11	0.62	0.09	0.51	0.08	0.45	0.06	0.34	0.05	0.28	0.04	0.23	0.03	0.17
0.10	0.57	10.00	1.75	0.06	0.34	0.06	0.34	0.06	0.34	0.05	0.28	0.04	0.23	0.04	0.23	0.03	0.17
0.08	0.45	12.50	2.22	0.06	0.34	0.05	0.28	0.05	0.28	0.04	0.23	0.04	0.23	0.03	0.17	0.03	0.17

SOURCE: Abstracted from ASHRAE ''Handbook of Fundamentals,'' 1981, with permission.
NOTE: U and R expressed in U.S. customary units. U' and R' in SI units.
* For U and R values not shown in table, interpolate as necessary.
† Enter column 1 with U or R of the design building section.
‡ Under appropriate column heading for Added R, find U value of resulting design section.
§ If the insulation occupies a previously considered air space, an adjustment must be made in the given building section R value.

where Δp = vapor-pressure difference through flow path, in Hg (N/m^2); W = weight of air, lb (kg); M_o = moisture content of outside air, g/lb (g/kg); M_i = moisture content of inside air, g/lb (g/kg).

For a given locality, the moisture content of the outdoor air may be determined from Fig. 12.4.5 (summer dew-point temperature data) and the appropriate psychrometric chart.

Conductance Coefficients Tables 12.4.7 to 12.4.9 list conductance heat-transfer coefficients U for various building components. Table 12.4.10 shows conductance heat transfer coefficients for reflective and nonreflective surfaces. Table 12.4.11 facilitates the computation of the enhancement of the U value by the addition of insulation. Table 12.4.12 presents an example of calculation of U for an assembly of various building components.

AIR CONDITIONING

Cooling Load

Cooling load Q_1, the total simultaneous cooling load, expressed in Btu/hour or (watts):

$$Q_t = Q_{ext} + Q_{int} + Q_{outside\ air} \tag{12.4.9}$$

$$\begin{aligned} Q_{ext} &= \text{external heat gains} \\ &= Q_{transmission} + Q\text{-}_{solar} \end{aligned} \tag{12.4.10}$$

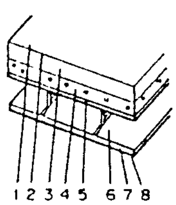
For walls and roofs

$$Q_{tr-sol} = AU\,(\text{Sa}\ \Delta t) \qquad \text{Btu/h (watts)} \tag{12.4.11}$$

Table 12.4.12 Example of Calculation of Coefficient of Transmission *U* for Composite Building Components

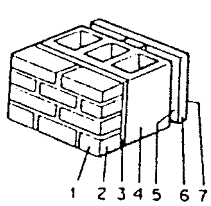
U and R expressed in U.S. customary units, U' and R' in SI units

Example 1. Coefficients of transmission U of flat masonry roofs with built-up roofing



Construction (heat flow up)	Resistance R	Resistance R'
1. Outside surface (15 mi/h wind 24 km/h)	0.17	0.03
2. Built-up roofing ⅜ in (9 mm)	0.33	0.06
3. Roof insulation (none)		
4. Concrete slab (lt. wt. agg.) (2 in) (50 mm)	2.22	0.39
5. Corrugated metal	0	0
6. Air space	0.85	0.15
7. Metal lath and ¾ in (19 mm) plaster (lt. wt. agg.)	0.47	0.08
8. Inside surface (still air)	0.61	0.11
Total resistance	4.65	0.82
U = 1/R = 1/4.65 =	0.22	
U' = 1/R' = 1/0.82 =		1.22

Example 2. Coefficients of transmission U of masonry walls



Construction (beat flow up)	Resistance R	Resistance R'
1. Outside surface (15 mi/h wind) (24 km/h)	0.17	0.03
2. Face brick (4 in) (100 mm)	0.44	0.08
3. Cement mortar (½ in) (12.5 mm)	0.10	0.02
4. Concrete block (cinder agg.) (8 in) (200 mm)	1.72	0.30
5. Air space (reflective)	2.80	0.49
6. Gypsum wallboard, foil back (½ in) (12.5 mm)	0.45	0.08
7. Inside surface (still air)	0.68	0.12
Total resistance	6.36	1.12
U = 1/R = 1/6.36 =	0.36	
U' = 1/R' = 1/1.12 =		0.89

SOURCE: Abstracted from ASHRAE ''Handbook of Fundamentals,'' 1981, with permission.

Table 12.4.13 Total Equivalent Temperature Differentials for Calculating Heat Gain through Sunlit Walls

North latitude wall facing	Sun time: A.M. 8		10		12		P.M. 2		4		6		8		10		12		South latitude 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	
Group A																			
NE	27	16	31	18	26	17	24	17	24	18	23	17	20	15	17	13	15	11	SE
E	32	18	41	24	37	22	29	20	28	20	26	19	23	16	20	14	18	13	E
SE	25	15	36	21	38	23	33	21	28	20	26	18	22	16	19	14	18	12	NE
S	14	9	20	13	28	18	33	22	31	21	25	18	20	15	17	13	15	11	N
SW	17	11	20	13	24	16	34	22	42	27	41	26	28	19	20	14	18	12	NW
W	17	11	20	13	24	16	30	20	42	27	48	30	33	22	22	15	19	13	W
NW	14	9	17	11	21	14	23	17	31	21	38	25	28	19	18	13	16	11	SW
N	14	9	15	10	18	12	20	15	21	16	21	16	18	14	14	11	12	9	S
Group B																			
NE	12	7	27	14	31	17	30	19	31	21	30	22	27	20	21	17	16	13	SE
E	14	8	34	18	45	24	43	25	39	25	35	24	30	22	23	18	17	14	E
SE	9	5	25	13	39	21	44	26	41	26	37	25	31	23	24	18	17	14	NE
S	4	3	7	4	18	11	32	19	41	26	39	27	33	24	25	19	18	15	N
SW	5	3	7	4	11	7	23	15	41	26	54	34	51	33	38	25	26	19	NW
W	6	4	7	4	11	4	18	12	35	23	55	34	59	37	43	28	30	20	W
NW	5	3	6	4	11	7	17	12	26	18	41	27	47	31	36	24	25	18	SW
N	6	4	9	5	12	8	18	12	22	17	25	20	27	21	22	17	16	14	S
Group C																			
NE	9	6	19	10	26	15	28	17	29	18	29	20	28	20	24	19	20	16	SE
E	10	7	22	12	36	19	40	23	39	23	36	24	33	23	28	20	22	17	E
SE	8	6	16	9	29	16	38	21	39	24	37	24	34	23	28	21	23	17	NE
S	7	5	7	4	12	7	22	14	32	20	36	24	34	24	29	21	23	17	N
SW	9	6	8	5	10	6	16	10	28	18	42	26	48	30	42	28	35	22	NW
W	10	7	9	5	10	6	14	9	24	16	40	25	52	32	47	30	37	24	W
NW	8	6	8	5	9	6	13	9	19	14	30	20	40	27	38	26	30	21	SW
N	7	5	8	5	10	7	14	9	18	13	22	16	25	19	23	18	19	16	S
Group D																			
NE	8	5	19	10	28	15	29	17	30	19	30	21	28	21	24	19	19	16	SE
E	9	6	23	12	38	20	42	24	40	24	37	24	33	23	27	20	21	17	E
SE	7	5	16	9	30	16	40	22	41	25	38	25	34	24	28	21	22	17	NE
S	5	4	6	4	12	7	23	14	34	21	38	25	35	24	29	21	23	17	N
SW	8	5	7	4	9	6	16	10	30	19	44	28	51	32	43	28	33	22	NW
W	8	6	7	5	9	6	14	9	25	16	42	27	55	34	49	31	37	25	W
NW	7	5	7	4	9	6	13	9	20	14	31	21	42	28	40	27	31	21	SW
N	6	4	8	5	10	6	14	10	19	14	23	17	25	19	24	19	19	16	S
Group E																			
NE	10	6	23	12	30	16	30	18	30	20	30	21	28	21	23	18	18	14	SE
E	11	6	28	15	42	22	43	24	39	24	36	24	32	23	25	19	19	15	E
SE	8	5	20	11	35	19	42	24	41	25	38	25	33	23	26	20	20	16	NE
S	4	3	6	4	15	9	28	17	38	24	39	26	34	24	27	20	20	16	N
SW	6	4	7	4	10	6	19	12	35	22	49	31	52	33	41	27	30	21	NW
W	7	5	7	4	10	6	16	11	30	20	48	31	57	36	47	30	34	23	W
NW	6	4	6	4	10	6	15	10	23	16	36	24	45	30	38	26	28	20	SW
N	6	4	8	5	11	7	16	11	21	15	24	18	26	20	23	18	18	15	S
Group F																			
NE	9	7	14	9	21	12	25	15	27	17	29	19	28	20	26	19	23	17	SE
E	10	8	17	10	28	15	35	19	37	22	37	23	35	23	31	22	26	19	E
SE	10	7	13	8	22	12	31	17	36	21	37	23	35	23	32	22	27	19	NE
S	9	7	7	5	10	6	17	10	26	16	32	20	33	22	31	22	27	19	N
SW	12	9	10	6	9	6	13	8	22	14	33	21	42	27	42	27	37	25	NW
W	14	9	11	7	10	6	12	8	19	12	31	20	43	27	46	29	41	27	W
NW	12	8	9	6	9	6	11	8	16	11	24	16	33	22	36	24	33	23	SW
N	8	7	8	6	9	6	12	8	15	11	19	14	22	17	23	18	21	17	S

SOURCE: Adapted from Carrier ''System Design Manual,'' 1970.
NOTE: To convert temperature differentials in °F to °C, multiply by 5/9.

where Sa Δt = sol-air equivalent temperature differential, °F (°C). Tables 12.4.13 and 12.4.14.

Heat Transmission

Heat gain through exterior walls and roofs is highly variable and is caused by a combination of solar heat and the temperature difference between indoor and outdoor air. Total heat flow is affected by the type and weight of the construction, exposure, sun time, latitude, and design conditions. The equivalent temperature difference from Tables 12.4.13 and 12.4.14 combined with the appropriate heat-transfer coefficients U for the construction, Tables 12.4.15 and 12.4.16, permits estimating the total heat flow through walls and roofs.

Heat flow through interior construction is essentially constant and may be determined by using the actual temperatures on either side of the construction and the appropriate U values.

Solar Heat Gain

Heat gain through glass is a combination of the heat gains by conduction and solar radiation. Both factors are highly variable and one or both are affected by the type of glass, shading, day of the year, time of day, location and orientation angle to the sun, and outside and inside temperatures.

For glass:

$$Q_{\text{glass}} = Q_u + Q_{\text{solar}} \tag{12.4.12}$$

$$= A_1 U(t_o - t_i) + A_2(\text{MSHGF})(\text{CLF})(\text{SC}) \tag{12.4.13}$$

where A_1 = area of total glass, ft^2 (m^2); A_2 = area of sunlit glass, ft^2 (m^2); U = heat-transfer coefficient (Table 12.4.16); t_0 = outside design temperature, °F (°C) (Fig. 12.4.4); t_i = inside design temperature, °F (°C) (Table 12.4.2); MSHGF = maximum solar heat gain factor (Table 12.4.17); CLF = cooling load factor (Tables 12.4.18, 12.4.19, and 12.4.20); SC = shading coefficient (Tables 12.4.21, 12.4.22, 12.4.23, and 12.4.24).

Note that the data in Table 12.4.17 is for vertical and horizontal glass; the data in Tables 12.4.18 to 12.4.24 addresses the effect of heat storage within the space.

Internal Heat Gains

Internal heat gains are primarily from lighting, equipment, and occupants. They are independent of outdoor temperature and solar effect and include both sensible and latent heat.

$$Q_{\text{int}} = \text{internal heat gains}$$

$$= Q_{\text{people}} + Q_{\text{lighting}} + Q_{\text{equipment}} \tag{12.4.14}$$

In some applications such as general office space, internal heat gains are relatively constant; in others where equipment cycles and/or occupancy is not constant, these loads will vary widely.

Heat gains from people vary with the activity and the proportion of men and women. The proportion of sensible latent heat varies with the temperature of the space. Table 12.4.25 lists adjusted heat gains from people for different activities and typical applications.

Lighting heat gains are based on the total electrical wattage of the operating lights, including ballasts, converted to BTU/hr. Note that under some circumstances the entire electrical input to the lights may not immediately become part of the cooling load. This depends on the type and arrangement of the lights, type of air supply and return, space furnishings, the thermal characteristics of the space, and length of time the lights will be on. Unless all of these can be forseen with a high degree of certainty, and lighting represents a significant portion of the cooling load, most designers will use the full electrical input of the operating lights as the lighting load.

Representative heat gains at various lighting levels for the most common lighting fixtures are shown in Fig. 12.4.7. Curves A, B, and C are drawn for fixtures with newer electronic ballasts and high-efficiency lamps. For a given footcandle level of illumination, they use about 40

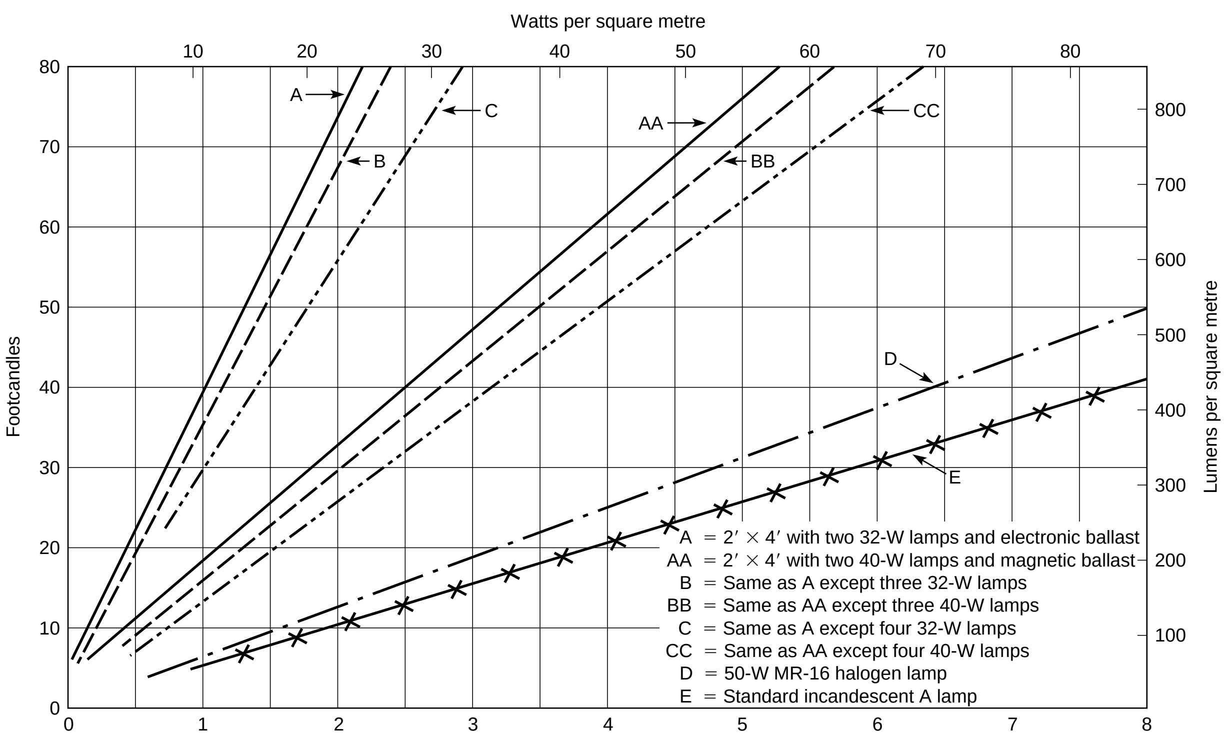


Fig. 12.4.7 Heat gain from typical lighting fixtures. *(Courtesy: S. Ricketts.)*

Table 12.4.14 Total Equivalent Temperature Differentials for Calculating Heat Gain through Flat Roofs

Description of roof construction*, †	Wt., lb/ft²	kg/m²	*U* value Btu/(h · ft² · °F)	*U* value W/(m² · K)
2 in (50 mm) insulation + steel siding	7.8	38.06	0.125	0.710
2 in (50 mm) insulation + 1 in (25 mm) wood‡	8.5	41.48	0.122	0.693
2 in (50 mm) insulation + 2.5 in (62.5 mm) wood‡	13.1	63.93	0.117	0.664
2 in (50 mm) insulation + 4 in (100 mm) wood‡	17.8	88.86	0.113	0.642
2 in (50 mm) insulation + 2 in (50 mm) h.w. concrete	28.8	140.54	0.122	0.693
4 in (100 mm) l.w. concrete	17.8	86.86	0.213	1.209
2 in (50 mm) insulation + 4 in (100 mm) h.w. concrete	52.1	254.25	0.120	0.681
2 in (50 mm) insulation + 6 in (150 mm) h.w. concrete	75.4	367.95	0.117	0.664

* Includes outside surface resistance, ½ in (12.5 mm) membrane and ⅜ in (9 mm) felt on the top and inside surface resistance on the bottom.
† Dark roof (D) = 0.30; light roof (L) = 0.15.
‡ Nominal thickness of wood.

Explanation: Total heat transmission from solar radiation and temperature difference between outdoor and room air, Btu/(h)(ft²)(W/m²) of roof area = equivalent temperature differential from above table × heat-transmission coefficient for summer, Btu/(h · ft² · °F) [W/(m² · K)].

Application. These values may be used for all normal air conditioning estimated; usually without correction (except as noted below in latitude 0 to 50° north or south when the load is calculated for the hottest weather.

Corrections. The values in the table were calculated for an inside temperature of 75°F (24°C) and an outdoor maximum temperature of 95°F (35°C) with an outdoor daily range of 21°F (12°C). The table remains approximately correct for other outdoor maximum (93 to 102°F) (34 to 39°C) and other outdoor daily ranges (16 to 34°F) (9 to 19°C) provided the outdoor daily average temperature remains approximately 85°F (30°C). If the room air temperature is different from 75°F (24°C) and/or the outdoor daily average temperature is different from 85°F (30°C), the following rules can be applied:

1. For room air temperature less than 75°F (24°C) add the difference between 75°F (24°C) and room air temperature; if greater than 75°F (24°C), subtract the difference.
2. For outdoor daily average temperature less than 85°F (30°C) subtract the difference between 85°F (30°C) and the daily average temperature, if greater than 85°F (30°C), add the difference.

Attics or other spaces between the roof and ceiling. If the ceiling is insulated and a fan is used for positive ventilation in the space between the ceiling and roof, the total temperature differential for calculating the room load may be decreased by 25 percent. If the attic space contains a return duct or other air plenum, care should be taken in determining the portion of the heat gain that reaches the ceiling.

Light color. Credit should not be taken for light-colored roofs except where the permanence of light color is established by experience as in rural areas or where there is little smoke.

For solar transmission in other months. The table values of temperature differentials that were calculated for July 21 will be approximately correct for a roof in the following months.

North latitude: Latitude, deg	North latitude: Months	South latitude: Latitude, deg	South latitude: Months
0	All months	0	All months
10	All months	10	All months
20	All months except Nov., Dec., Jan.	20	All months except May, June, July
30	Mar., Apr., May, June, July, Aug., Sept.	30	Sept., Oct., Nov., Dec., Jan., Feb., March
40	April, May, June, July, Aug.	40	Oct., Nov., Dec., Jan., Feb.
50	May, June, July	50	Nov., Dec., Jan.

percent of the energy of earlier fixtures with magnetic ballasts and standard 40-W lamps; see curves AA, BB, and CC. Curves D and E show heat gains from recessed incandescent fixtures.

Heat gain from equipment located within the conditioned space is often a significant portion of the air-conditioning load. Lists of equipment that will be installed, manufacturers' heat release (or wattage) data, and anticipated use and load factors should be obtained from the user early in the design process. Tables 12.4.26, 12.4.27, and 12.4.28 show anticipated gains from a variety of office equipment, restaurant appliances and electric motors. For restaurant cooking equipment, a properly designed, mechanically exhausted hood will reduce the total load of the hooded equipment by about 50 percent.

Miscellaneous Heat Gains Additional heat gains that add to the system load are the heat added at the supply and return fans and heat transferred from unconditioned areas to the distribution ductwork. An additional load on a chilled-water system is the heat equivalent of the chilled-water pump motor work.

Fan heat is the heat added by the fan motor, and manifests itself as the total power input to the fan motor when the motor is located within the airstream or conditioned space, or the net output of the fan motor when it is located out of the airstream or conditioned space. Since air can be considered to be a perfect gas, all the fan heat is added at the fan and the conditioned air temperature will increase as it flows through the fan. If the motor is in the airstream, its inefficiency will add to fan heat.

The contribution of fan heat to temperature rise Δt (°F) is computed as follows:

$$\Delta t = Q_{\text{motor}}/1.08 \quad \text{ft}^3/\text{min} \tag{12.4.15}$$

where Q_{motor} is obtained from data in Table 12.4.28.

Sun time																			
A.M.						P.M.													
8		10		12		2		4		6		8		10		12			
D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	λ	δ
Light construction roofs exposed to sun																			
24	8	61	29	88	46	96	53	81	46	48	30	10	8	2	2	−3	−3	0.99	1
8	0	41	18	72	36	90	48	88	49	65	38	30	19	9	7	1	0	0.93	2
1	−2	19	6	43	20	65	33	76	41	72	40	53	31	33	20	18	11	0.68	4
Medium construction roofs exposed to sun																			
6	1	13	4	28	12	45	22	58	30	63	34	56	31	43	25	32	18	0.48	5
2	−2	23	9	49	23	70	36	79	43	71	40	49	29	28	17	15	9	0.73	3
1	−3	28	11	59	28	82	43	88	48	74	42	44	27	19	12	6	4	0.87	3
Heavy construction roofs exposed to sun																			
7	2	15	6	30	13	46	23	58	30	61	33	54	30	41	23	31	17	0.45	5
15	7	17	7	25	11	36	17	46	23	51	27	50	27	43	24	36	20	0.30	6

Table 12.4.15 Descriptions of Wall Construction

Group	Components	Weight		*U* value	
		lb/ft²	kg/m²	Btu/(h · ft² · °F)	W/(m² · K)
A	1 in (2.5 cm) stucco + 4 in (10 cm) l.w. concrete block + air space	28.6	139.63	0.267	1.516
	1 in (2.5 cm) stucco + air space + 2 in (5 cm) insulation	16.3	79.58	0.106	0.601
B	1 in (2.5 cm) stucco + 4 in (10 cm) common brick	55.9	272.90	0.393	2.232
	1 in (2.5 cm) stucco + 4 in (10 cm) l.w. concrete	62.5	305.13	0.481	2.731
C	4 in (10 cm) face brick + 4 in (10 cm) l.w. concrete block + 1 in (2.5 cm) insulation	62.5	305.13	0.158	0.897
	1 in (2.5 cm) stucco + 4 in (10 cm) h.w. concrete + 2 in (5 cm) insulation	62.9	307.08	0.114	0.647
D	1 in (2.5 cm) stucco + 8 in (20 cm) l.w. concrete block + 1 in (2.5 cm) insulation	41.4	202.11	0.141	0.801
	1 in (2.5 cm) stucco + 2 in (5 cm) insulation + 4 in (10 cm) h.w. concrete block	36.6	178.68	0.111	0.630
E	4 in (10 cm) face brick + 3 in (10 cm) l.w. concrete block	62.2	303.66	0.333	1.891
	1 in (2.5 cm) stucco + 8 in (20 cm) h.w. concrete block	56.6	276.32	0.349	1.982
F	4 in (10 cm) face brick + 4 in (10 cm) common brick	89.5	436.94	0.360	2.044
	4 in (10 cm) face brick + 2 in (5 cm) insulation + 4 in (10 cm) l.w. concrete block	62.5	305.13	0.103	0.585

Table 12.4.16 Coefficients of Transmission *U* of Windows, Skylights, and Light Transmitting Partitions

These values are for heat transfer from air to air, Btu/(h · ft^2 · °F).

Part A—Vertical panels (exterior windows, sliding patio doors, and partitions)—flat glass, glass block, and plastic sheet

Description	Exterior[a]		
	Winter	Summer	Interior
Flat glass[b]			
Single glass	1.10	1.04	0.73
Insulating glass—double[c]			
0.1875-in airspace[d]	0.62	0.65	0.51
0.25-in airspace[d]	0.58	0.61	0.49
0.5-in airspace[e]	0.49	0.56	0.46
0.5-in airspace, low-emittance coating[f]			
$e = 0.20$	0.32	0.38	0.32
$e = 0.40$	0.38	0.45	0.38
$e = 0.60$	0.43	0.51	0.42
Insulating glass—triple[c]			
0.25-in airspaces[d]	0.39	0.44	0.38
0.5-in airspaces[g]	0.31	0.39	0.30
Storm windows			
1-in to 4-in airspace[d]	0.50	0.50	0.44
Plastic sheet			
Single glazed			
0.125-in thick	1.06	0.98	—
0.25-in thick	0.96	0.89	—
0.5-in thick	0.81	0.76	—
Insulating unit—double[c]			
0.25-in airspace[d]	0.55	0.56	—
0.5-in airspace[c]	0.43	0.45	—
Glass block[h]			
6 × 6 × 4 in thick	0.60	0.57	0.46
8 × 8 × 4 in thick	0.56	0.54	0.44
—with cavity divider	0.48	0.46	0.38
12 × 12 × 4 in thick	0.52	0.50	0.41
—with cavity divider	0.44	0.42	0.36
12 × 12 × 2 in thick	0.60	0.57	0.46

Part B—Horizontal panels (skylights)—flat glass, glass block, and plastic domes

Description	Exterior[a]		
	Winter[i]	Summer[j]	Interior[l]
Flat glass[e]			
Single glass	1.23	0.83	0.96
Insulating glass—doubles[c]			
0.1875-in airspace[d]	0.70	0.57	0.62
0.25-in airspace[d]	0.65	0.54	0.59
0.5-in airspace[c]	0.59	0.49	0.56
0.5-in airspace, low-emittance coating[f]			
$e = 0.20$	0.48	0.36	0.39
$e = 0.40$	0.52	0.42	0.45
$e = 0.60$	0.56	0.46	0.50
Glass block[h]			
11 × 11 × 3 in thick with cavity divider	0.53	0.35	0.44
12 × 12 × 4 in thick with cavity divider	0.51	0.34	0.42
Plastic domes[k]			
Single-walled	1.15	0.80	—
Double-walled	0.70	0.46	—

Part C—adjustment factors for various window and sliding patio door types (multiply *U* values in parts A and B by these factors)

Description	Single glass	Double or triple glass	Storm windows
Windows			
All Glass[l]	1.00	1.00	1.00
Wood sash—80% glass	0.90	0.95	0.90
Wood sash—60% glass	0.80	0.85	0.80
Metal sash—80% glass	1.00	1.20[m]	1.20[m]
Sliding patio doors			
Wood frame	0.95	1.00	—
Metal frame	1.00	1.10[m]	—

SOURCE: Abstracted from ASHRAE ''Handbook of Fundamentals,'' 1977, with permission.
[a] See Part C for adjustment for various window and sliding patio door types.
[b] Emittance of uncooled glass surface = 0.84.
[c] Double and triple refer to the number of lights of glass.
[d] 0.125-in glass.
[e] 0.25-in glass.
[f] Coating on either glass surface facing airspace; all other glass surfaces uncoated.
[g] Window design: 0.25-in glass–0.125-in glass–0.25-in glass.
[h] Dimensions are nominal.
[i] For heat flow up.
[j] For heat flow down.
[k] Based on area of opening, not total surface area.
[l] Refers to windows with negligible opaque area.
[m] Values will be less than these when metal sash and frame incorporate thermal breaks. In some thermal break designs, *U* values will be equal to or less than those for the glass. Window manufacturers should be consulted for specific data.

Table 12.4.17 Maximum Solar Heat Gain Factor (MSHGF), Btu/h · ft², for Sunlit Glass

0°N Lat

	N	NNE/ NNW	NE/ NW	ENE/ WNW	E/ W	ESE/ WSW	SE/ SW	SSE/ SSW	S	Hor.
Jan.	34	34	88	177	234	254	235	182	118	296
Feb.	36	39	132	205	245	247	210	141	67	306
Mar.	38	87	170	223	242	223	170	87	38	303
Apr.	71	134	193	224	221	184	118	38	37	284
May	113	164	203	218	201	154	80	37	37	265
June	129	173	206	212	191	140	66	37	37	255
July	115	164	201	213	195	149	77	38	38	260
Aug.	75	134	187	216	212	175	112	39	38	276
Sep.	40	84	163	213	231	213	163	84	40	293
Oct.	37	40	129	199	236	238	202	135	66	299
Nov.	35	35	88	175	230	250	230	179	117	293
Dec.	34	34	71	164	226	253	240	196	138	288

8°N Lat

	N	NNE/ NNW	NE/ NW	ENE/ WNW	E/ W	ESE/ WSW	SE/ SW	SSE/ SSW	S	Hor.
Jan.	32	32	71	163	224	250	242	203	162	275
Feb.	34	34	114	193	239	248	219	165	110	294
Mar.	37	67	156	215	241	230	184	110	55	300
Apr.	44	117	184	221	225	195	134	53	39	289
May	74	146	198	220	209	167	97	39	38	277
June	90	155	200	217	200	141	82	39	39	269
July	77	145	195	215	204	162	93	40	39	272
Aug.	47	117	179	214	216	186	128	51	41	282
Sep.	38	66	149	205	230	219	176	107	56	290
Oct.	35	35	112	187	231	239	211	160	108	288
Nov.	33	33	71	161	220	245	233	200	160	273
Dec.	31	31	55	149	215	246	247	215	179	265

16°N Lat

	N	NNE/ NNW	NE/ NW	ENE/ WNW	E/ W	ESE/ WSW	SE/ SW	SSE/ SSW	S	Hor.
Jan.	30	30	55	147	210	244	251	223	199	248
Feb.	33	33	96	180	231	247	233	188	154	275
Mar.	35	53	140	205	239	235	197	138	93	291
Apr.	39	99	172	215	227	204	150	77	45	289
May	52	132	189	218	215	179	115	45	41	282
June	66	142	194	217	207	167	99	41	41	277
July	55	132	187	214	210	174	111	44	42	277
Aug.	41	100	168	209	219	196	143	74	46	282
Sep.	36	50	134	196	227	224	191	134	93	282
Oct.	33	33	95	174	223	237	225	183	150	270
Nov.	30	30	55	145	206	241	247	220	196	246
Dec.	29	29	41	132	198	241	254	233	212	234

24°N Lat

	N	NNE/ NNW	NE/ NW	ENE/ WNW	E/ W	ESE/ WSW	SE/ SW	SSE/ SSW	S	Hor.
Jan.	27	27	41	128	190	240	253	241	227	214
Feb.	30	30	80	165	220	244	243	213	192	249
Mar.	34	45	124	195	234	237	214	168	137	275
Apr.	37	88	159	209	228	212	169	107	75	283
May	43	117	178	214	218	190	132	67	46	282
June	55	127	184	214	212	179	117	55	43	279
July	45	116	176	210	213	185	129	65	46	278
Aug.	38	87	156	203	220	204	162	103	72	277
Sep.	35	42	119	185	222	225	206	163	134	266
Oct.	31	31	79	159	211	237	235	207	187	244
Nov.	27	27	42	126	187	236	249	237	224	213
Dec.	26	26	29	112	180	234	247	247	237	199

32°N Lat

	N	NNE/ NNW	NE/ NW	ENE/ WNW	E/ W	ESE/ WSW	SE/ SW	SSE/ SSW	S	Hor.
Jan.	24	24	29	105	175	229	249	250	246	176
Feb.	27	27	65	149	205	242	248	232	221	217
Mar.	32	37	107	183	227	237	227	195	176	252
Apr.	36	80	146	200	227	219	187	141	115	271
May	38	111	170	208	220	199	155	99	74	277
June	44	122	176	208	214	189	139	83	60	276
July	40	111	167	204	215	194	150	96	72	273
Aug.	37	79	141	195	219	210	181	136	111	265
Sep.	33	35	103	173	215	227	218	189	171	244
Oct.	28	28	63	143	195	234	239	225	215	213
Nov.	24	24	29	103	173	225	245	246	243	175
Dec.	22	22	22	84	162	218	246	252	252	158

40°N Lat

	N (Shade)	NNE/ NNW	NE/ NW	ENE/ WNW	E/ W	ESE/ WSW	SE/ SW	SSE/ SSW	S	Hor.
Jan.	20	20	20	74	154	205	241	252	254	133
Feb.	24	24	50	129	186	234	246	244	241	180
Mar.	29	29	93	169	218	238	236	216	206	223
Apr.	34	71	140	190	224	223	203	170	154	252
May	37	102	165	202	220	208	175	133	113	265
June	48	113	172	205	216	199	161	116	95	267
July	38	102	163	198	216	203	170	129	109	262
Aug.	35	71	135	185	216	214	196	165	149	247
Sep.	30	30	87	160	203	227	226	209	200	215
Oct.	25	25	49	123	180	225	238	236	234	177
Nov.	20	20	20	71	151	201	237	248	250	132
Dec.	18	18	18	60	135	188	232	249	253	113

48°N Lat

	N (Shade)	NNE/ NNW	NE/ NW	ENE/ WNW	E/ W	ESE/ WSW	SE/ SW	SSE/ SSW	S	Hor.
Jan.	15	15	15	53	118	175	216	239	245	85
Feb.	20	20	36	103	168	216	242	249	250	138
Mar.	26	26	80	154	204	234	239	232	228	188
Apr.	31	61	132	180	219	225	215	194	186	226
May	35	97	158	200	218	214	192	163	150	247
June	46	110	165	204	215	206	180	148	134	252
July	37	96	156	196	214	209	187	158	146	244
Aug.	33	61	128	174	211	216	208	188	180	223
Sep.	27	27	72	144	191	223	228	223	230	182
Oct.	21	21	35	96	161	207	213	241	242	136
Nov.	15	15	15	52	115	172	212	234	240	85
Dec.	13	13	13	36	91	156	195	225	233	65

56°N Lat

	N (Shade)	NNE/ NNW	NE/ NW	ENE/ WNW	E/ W	ESE/ WSW	SE/ SW	SSE/ SSW	S	Hor.
Jan.	10	10	10	21	74	126	169	194	205	40
Feb.	16	16	21	71	139	184	223	239	244	91
Mar.	22	22	65	136	185	224	238	241	241	149
Apr.	28	58	123	173	211	223	223	213	210	195
May	36	99	149	195	215	218	206	187	181	222
June	53	111	160	199	213	213	196	174	168	231
July	37	98	147	192	211	214	201	183	177	221
Aug.	30	56	119	165	203	216	215	206	203	193
Sep.	23	23	58	126	171	211	227	230	231	144
Oct.	16	16	20	68	132	176	213	229	234	91
Nov.	10	10	10	21	72	122	165	190	200	40
Dec.	7	7	7	7	47	92	135	159	171	23

60°N Lat

	N (Shade)	NNE/ NNW	NE/ NW	ENE/ WNW	E/ W	ESE/ WSW	SE/ SW	SSE/ SSW	S	Hor.
Jan.	7	7	7	7	46	88	130	152	164	21
Feb.	13	13	13	58	118	168	204	225	231	68
Mar.	20	20	56	125	173	215	234	241	242	128
Apr.	27	59	118	168	206	222	225	220	218	178
May	43	98	149	192	212	220	211	198	194	208
June	58	110	162	197	213	215	202	186	181	217
July	44	97	147	189	208	215	206	193	190	207
Aug.	28	57	114	161	199	214	217	213	211	176
Sep.	21	21	50	145	160	202	222	229	231	123
Oct.	14	14	14	56	111	159	193	215	221	67
Nov.	7	7	7	7	45	86	127	148	160	22
Dec.	4	4	4	4	16	51	76	100	107	9

64°N Lat

	N (Shade)	NNE/ NNW	NE/ NW	ENE/ WNW	E/ W	ESE/ WSW	SE/ SW	SSE/ SSW	S	Hor.
Jan.	3	3	3	3	15	45	67	89	96	8
Feb.	11	11	11	43	89	144	177	202	210	45
Mar.	18	18	47	113	159	203	226	236	239	105
Apr.	25	59	113	163	201	219	225	225	224	160
May	48	97	150	189	211	220	215	207	204	192
June	62	114	162	193	213	216	208	196	193	203
July	49	96	148	186	207	215	211	202	200	192
Aug.	27	58	109	157	193	211	217	217	217	159
Sep.	19	19	43	103	148	189	213	224	227	101
Oct.	11	11	11	40	83	135	167	191	199	46
Nov.	4	4	4	4	15	44	66	87	93	8
Dec.	0	0	0	0	1	5	11	14	15	1

SOURCE: Abstracted from ASHRAE ''Handbook of Fundamentals,'' 1989, with permission.

Table 12.4.18 Cooling Load Factors (CLF) for Glass without Interior Shading, in North Latitude Spaces Having Carpeted Floors

Dir.	Room mass	Solar time 0100	0200	0300	0400	0500	0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
	L	0.00	0.00	0.00	0.00	0.01	0.64	0.73	0.74	0.81	0.88	0.95	0.98	0.98	0.94	0.88	0.79	0.79	0.55	0.31	0.12	0.04	0.02	0.01	0.00
N	M	0.03	0.02	0.02	0.02	0.02	0.64	0.69	0.69	0.77	0.84	0.91	0.94	0.95	0.91	0.86	0.79	0.79	0.56	0.32	0.16	0.10	0.07	0.05	0.04
	H	0.10	0.09	0.08	0.07	0.07	0.62	0.64	0.64	0.71	0.77	0.83	0.87	0.88	0.85	0.81	0.75	0.76	0.55	0.34	0.22	0.17	0.15	0.13	0.11
	L	0.00	0.00	0.00	0.00	0.01	0.51	0.83	0.88	0.72	0.47	0.33	0.27	0.24	0.23	0.20	0.18	0.14	0.09	0.03	0.01	0.00	0.00	0.00	0.00
NE	M	0.01	0.01	0.00	0.00	0.01	0.50	0.78	0.82	0.67	0.44	0.32	0.28	0.26	0.24	0.22	0.19	0.15	0.11	0.05	0.03	0.02	0.02	0.01	0.01
	H	0.03	0.03	0.03	0.02	0.03	0.47	0.71	0.72	0.59	0.40	0.30	0.27	0.26	0.25	0.23	0.20	0.17	0.13	0.08	0.06	0.05	0.05	0.04	0.04
	L	0.00	0.00	0.00	0.00	0.00	0.42	0.76	0.91	0.90	0.75	0.51	0.30	0.22	0.18	0.16	0.13	0.11	0.07	0.02	0.01	0.00	0.00	0.00	0.00
E	M	0.01	0.01	0.00	0.00	0.01	0.41	0.72	0.86	0.84	0.71	0.48	0.30	0.24	0.21	0.18	0.16	0.13	0.09	0.04	0.03	0.02	0.01	0.01	0.01
	H	0.03	0.03	0.03	0.02	0.02	0.39	0.66	0.76	0.74	0.63	0.43	0.29	0.24	0.22	0.20	0.18	0.15	0.12	0.08	0.06	0.05	0.05	0.04	0.04
	L	0.00	0.00	0.00	0.00	0.00	0.27	0.58	0.81	0.93	0.93	0.81	0.59	0.37	0.27	0.21	0.18	0.14	0.09	0.03	0.01	0.00	0.00	0.00	0.00
SE	M	0.01	0.01	0.01	0.00	0.01	0.26	0.55	0.77	0.88	0.87	0.76	0.56	0.37	0.29	0.24	0.20	0.16	0.11	0.05	0.04	0.03	0.02	0.02	0.01
	H	0.04	0.04	0.03	0.03	0.03	0.26	0.51	0.69	0.78	0.78	0.68	0.51	0.35	0.29	0.25	0.22	0.19	0.15	0.09	0.08	0.07	0.06	0.05	0.05
	L	0.00	0.00	0.00	0.00	0.00	0.07	0.15	0.23	0.39	0.62	0.82	0.94	0.93	0.80	0.59	0.38	0.26	0.16	0.06	0.02	0.01	0.00	0.00	0.00
S	M	0.01	0.01	0.01	0.01	0.01	0.07	0.14	0.22	0.38	0.59	0.78	0.88	0.88	0.76	0.57	0.38	0.28	0.18	0.09	0.06	0.04	0.03	0.02	0.02
	H	0.05	0.05	0.04	0.04	0.03	0.09	0.15	0.21	0.35	0.54	0.70	0.79	0.79	0.69	0.52	0.37	0.29	0.21	0.13	0.10	0.09	0.08	0.07	0.06
	L	0.00	0.00	0.00	0.00	0.00	0.04	0.09	0.13	0.16	0.19	0.23	0.39	0.62	0.82	0.94	0.94	0.81	0.54	0.19	0.07	0.03	0.01	0.00	0.00
SW	M	0.02	0.02	0.01	0.01	0.01	0.05	0.09	0.13	0.16	0.19	0.22	0.38	0.60	0.78	0.89	0.89	0.77	0.52	0.20	0.10	0.07	0.05	0.04	0.03
	H	0.07	0.06	0.05	0.05	0.04	0.07	0.11	0.14	0.16	0.18	0.21	0.35	0.55	0.71	0.80	0.79	0.69	0.48	0.20	0.14	0.11	0.10	0.08	0.07
	L	0.00	0.00	0.00	0.00	0.00	0.03	0.07	0.10	0.13	0.15	0.16	0.18	0.31	0.55	0.78	0.92	0.93	0.73	0.25	0.10	0.04	0.01	0.01	0.00
W	M	0.02	0.02	0.01	0.01	0.01	0.04	0.07	0.10	0.13	0.14	0.16	0.17	0.30	0.53	0.74	0.87	0.88	0.69	0.24	0.12	0.07	0.05	0.04	0.03
	H	0.06	0.06	0.05	0.04	0.04	0.06	0.09	0.11	0.13	0.15	0.16	0.17	0.28	0.49	0.67	0.78	0.79	0.62	0.23	0.14	0.11	0.09	0.08	0.07
	L	0.00	0.00	0.00	0.00	0.00	0.04	0.09	0.14	0.17	0.20	0.22	0.23	0.24	0.31	0.53	0.78	0.92	0.81	0.28	0.10	0.04	0.02	0.01	0.00
NW	M	0.02	0.02	0.01	0.01	0.01	0.05	0.10	0.13	0.17	0.19	0.21	0.22	0.23	0.30	0.52	0.75	0.88	0.77	0.26	0.12	0.07	0.05	0.04	0.03
	H	0.06	0.05	0.05	0.04	0.04	0.07	0.11	0.14	0.17	0.19	0.20	0.21	0.22	0.28	0.48	0.68	0.79	0.69	0.23	0.14	0.10	0.09	0.08	0.07
	L	0.00	0.00	0.00	0.00	0.00	0.08	0.25	0.45	0.64	0.80	0.91	0.97	0.97	0.91	0.80	0.64	0.44	0.23	0.08	0.03	0.01	0.00	0.00	0.00
Hor.	M	0.02	0.02	0.01	0.01	0.01	0.08	0.24	0.43	0.60	0.75	0.86	0.92	0.92	0.87	0.77	0.63	0.45	0.26	0.12	0.07	0.05	0.04	0.03	0.02
	H	0.07	0.06	0.05	0.05	0.04	0.11	0.25	0.41	0.56	0.68	0.77	0.83	0.83	0.80	0.71	0.59	0.44	0.28	0.17	0.13	0.11	0.10	0.09	0.08

SOURCE: Abstracted from ASHRAE ''Handbook of Fundamentals,'' 1989, with permission.
Values for nominal 15 ft × 15 ft × 10 ft high space, with ceiling, and 50% or less glass in exposed surface at listed orientation.
L = lightweight construction.
M = mediumweight construction.
H = heavyweight construction.

Table 12.4.19 Cooling Load Factors (CLF) for Glass without Interior Shading, in North Latitude Spaces Having Uncarpeted Floors

Dir.	Room mass	Solar time																							
		0100	0200	0300	0400	0500	0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
	L	0.00	0.00	0.00	0.00	0.01	0.64	0.73	0.74	0.81	0.88	0.95	0.98	0.98	0.94	0.88	0.79	0.79	0.55	0.31	0.12	0.04	0.02	0.01	0.00
N	M	0.12	0.09	0.07	0.06	0.05	0.33	0.45	0.53	0.61	0.69	0.76	0.82	0.85	0.86	0.85	0.81	0.80	0.70	0.60	0.43	0.32	0.24	0.19	0.15
	H	0.24	0.21	0.19	0.18	0.16	0.43	0.48	0.51	0.56	0.61	0.66	0.71	0.73	0.74	0.73	0.71	0.71	0.62	0.52	0.42	0.36	0.32	0.29	0.26
	L	0.00	0.00	0.00	0.00	0.01	0.51	0.83	0.88	0.72	0.47	0.33	0.27	0.24	0.23	0.20	0.18	0.14	0.09	0.03	0.01	0.00	0.00	0.00	0.00
NE	M	0.03	0.02	0.02	0.02	0.02	0.24	0.45	0.57	0.58	0.49	0.41	0.36	0.32	0.29	0.27	0.24	0.21	0.17	0.13	0.10	0.07	0.06	0.05	0.04
	H	0.08	0.07	0.07	0.06	0.06	0.27	0.43	0.49	0.45	0.37	0.32	0.29	0.28	0.27	0.26	0.24	0.22	0.19	0.16	0.14	0.12	0.11	0.10	0.09
	L	0.00	0.00	0.00	0.00	0.00	0.42	0.76	0.91	0.90	0.75	0.51	0.30	0.22	0.18	0.16	0.13	0.11	0.07	0.02	0.01	0.00	0.00	0.00	0.00
E	M	0.03	0.02	0.02	0.02	0.01	0.20	0.41	0.57	0.65	0.64	0.55	0.44	0.36	0.31	0.26	0.23	0.19	0.16	0.12	0.09	0.07	0.06	0.04	0.04
	H	0.08	0.08	0.07	0.06	0.06	0.24	0.40	0.50	0.53	0.50	0.41	0.33	0.30	0.28	0.26	0.24	0.22	0.19	0.16	0.14	0.13	0.11	0.10	0.09
	L	0.00	0.00	0.00	0.00	0.00	0.27	0.58	0.81	0.93	0.93	0.81	0.59	0.37	0.27	0.21	0.18	0.14	0.09	0.03	0.01	0.00	0.00	0.00	0.00
SE	M	0.04	0.03	0.02	0.02	0.02	0.13	0.31	0.48	0.62	0.69	0.69	0.61	0.50	0.41	0.35	0.30	0.25	0.20	0.15	0.12	0.09	0.07	0.06	0.05
	H	0.10	0.09	0.08	0.08	0.07	0.18	0.32	0.45	0.53	0.56	0.54	0.47	0.39	0.35	0.32	0.29	0.26	0.23	0.19	0.17	0.15	0.14	0.12	0.11
	L	0.00	0.00	0.00	0.00	0.00	0.07	0.15	0.23	0.39	0.62	0.82	0.94	0.93	0.80	0.59	0.38	0.26	0.16	0.06	0.02	0.01	0.00	0.00	0.00
S	M	0.05	0.04	0.04	0.03	0.02	0.05	0.09	0.14	0.24	0.38	0.53	0.65	0.72	0.71	0.63	0.52	0.42	0.33	0.24	0.18	0.14	0.11	0.09	0.07
	H	0.13	0.12	0.10	0.09	0.09	0.11	0.14	0.17	0.25	0.36	0.47	0.55	0.58	0.56	0.49	0.41	0.36	0.30	0.25	0.21	0.19	0.17	0.16	0.14
	L	0.00	0.00	0.00	0.00	0.00	0.04	0.09	0.13	0.16	0.19	0.23	0.39	0.62	0.82	0.94	0.94	0.81	0.54	0.19	0.07	0.03	0.01	0.00	0.00
SW	M	0.08	0.07	0.05	0.04	0.03	0.05	0.07	0.09	0.12	0.15	0.17	0.26	0.40	0.54	0.66	0.73	0.72	0.61	0.43	0.31	0.23	0.17	0.13	0.10
	H	0.15	0.14	0.12	0.11	0.10	0.11	0.12	0.14	0.15	0.17	0.18	0.26	0.37	0.48	0.56	0.59	0.57	0.47	0.33	0.27	0.23	0.21	0.19	0.17
	L	0.00	0.00	0.00	0.00	0.00	0.03	0.07	0.10	0.13	0.15	0.16	0.18	0.31	0.55	0.78	0.92	0.93	0.73	0.25	0.10	0.04	0.01	0.01	0.00
W	M	0.08	0.07	0.05	0.04	0.04	0.04	0.06	0.08	0.10	0.12	0.13	0.15	0.21	0.35	0.50	0.63	0.71	0.67	0.46	0.33	0.24	0.18	0.14	0.11
	H	0.14	0.13	0.12	0.11	0.10	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.21	0.33	0.45	0.54	0.58	0.52	0.33	0.26	0.22	0.19	0.18	0.16
	L	0.00	0.00	0.00	0.00	0.00	0.04	0.09	0.14	0.17	0.20	0.22	0.23	0.24	0.31	0.53	0.78	0.92	0.81	0.28	0.10	0.04	0.02	0.01	0.00
NW	M	0.08	0.06	0.05	0.04	0.03	0.05	0.07	0.10	0.13	0.15	0.17	0.19	0.20	0.24	0.36	0.51	0.64	0.66	0.46	0.32	0.23	0.17	0.13	0.10
	H	0.13	0.12	0.11	0.10	0.09	0.10	0.12	0.13	0.15	0.16	0.17	0.18	0.19	0.23	0.33	0.46	0.55	0.53	0.33	0.25	0.21	0.18	0.16	0.15
	L	0.00	0.00	0.00	0.00	0.00	0.08	0.25	0.45	0.64	0.80	0.91	0.97	0.97	0.91	0.80	0.64	0.44	0.23	0.08	0.03	0.01	0.00	0.00	0.00
Hor.	M	0.07	0.06	0.05	0.04	0.03	0.06	0.14	0.26	0.40	0.53	0.64	0.73	0.78	0.80	0.77	0.70	0.59	0.45	0.33	0.24	0.19	0.14	0.11	0.09
	H	0.16	0.15	0.13	0.12	0.11	0.13	0.20	0.29	0.39	0.48	0.56	0.61	0.65	0.65	0.63	0.57	0.49	0.40	0.32	0.28	0.25	0.22	0.20	0.18

SOURCE: Abstracted from ASHRAE ‘‘Handbook of Fundamentals,’’ 1989, with permission.
Values for nominal 15 ft × 15 ft × 10 ft high space, with ceiling, and 50% or less glass in exposed surface at listed orientation.
L = lightweight construction.
M = mediumweight construction.
H = heavyweight construction.

Table 12.4.20 Cooling Load Factors (CLF) for Glass with Interior Shading, North Latitudes (All Room Constructions)

Fenes-tration facing	Solar time																							
	0100	0200	0300	0400	0500	0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
N	0.08	0.07	0.06	0.06	0.07	0.73	0.66	0.65	0.73	0.80	0.86	0.89	0.89	0.86	0.82	0.75	0.78	0.91	0.24	0.18	0.15	0.13	0.11	0.10
NNE	0.03	0.03	0.02	0.02	0.03	0.64	0.77	0.62	0.42	0.37	0.37	0.37	0.36	0.35	0.32	0.28	0.23	0.17	0.08	0.07	0.06	0.05	0.04	0.04
NE	0.03	0.02	0.02	0.02	0.02	0.56	0.76	0.74	0.58	0.37	0.29	0.27	0.26	0.24	0.22	0.20	0.16	0.12	0.06	0.05	0.04	0.04	0.03	0.03
ENE	0.03	0.02	0.02	0.02	0.02	0.52	0.76	0.80	0.71	0.52	0.31	0.26	0.24	0.22	0.20	0.18	0.15	0.11	0.06	0.05	0.04	0.04	0.03	0.03
E	0.03	0.02	0.02	0.02	0.02	0.47	0.72	0.80	0.76	0.62	0.41	0.27	0.24	0.22	0.20	0.17	0.14	0.11	0.06	0.05	0.05	0.04	0.03	0.03
ESE	0.03	0.03	0.02	0.02	0.02	0.41	0.67	0.79	0.80	0.72	0.54	0.34	0.27	0.24	0.21	0.19	0.15	0.12	0.07	0.06	0.05	0.04	0.04	0.03
SE	0.03	0.03	0.02	0.02	0.02	0.30	0.57	0.74	0.81	0.79	0.68	0.49	0.33	0.28	0.25	0.22	0.18	0.13	0.08	0.07	0.06	0.05	0.04	0.04
SSE	0.04	0.03	0.03	0.03	0.02	0.12	0.31	0.54	0.72	0.81	0.81	0.71	0.54	0.38	0.32	0.27	0.22	0.16	0.09	0.08	0.07	0.06	0.05	0.04
S	0.04	0.04	0.03	0.03	0.03	0.09	0.16	0.23	0.38	0.58	0.75	0.83	0.80	0.68	0.50	0.35	0.27	0.19	0.11	0.09	0.08	0.07	0.06	0.05
SSW	0.05	0.04	0.04	0.03	0.03	0.09	0.14	0.18	0.22	0.27	0.43	0.63	0.78	0.84	0.80	0.66	0.46	0.25	0.13	0.11	0.09	0.08	0.07	0.06
SW	0.05	0.05	0.04	0.04	0.03	0.07	0.11	0.14	0.16	0.19	0.22	0.38	0.59	0.75	0.83	0.81	0.69	0.45	0.16	0.12	0.10	0.09	0.07	0.06
WSW	0.05	0.05	0.04	0.04	0.03	0.07	0.10	0.12	0.14	0.16	0.17	0.23	0.44	0.64	0.78	0.84	0.78	0.55	0.16	0.12	0.10	0.09	0.07	0.06
W	0.05	0.05	0.04	0.04	0.03	0.06	0.09	0.11	0.13	0.15	0.16	0.17	0.31	0.53	0.72	0.82	0.81	0.61	0.16	0.12	0.10	0.08	0.07	0.06
WNW	0.05	0.05	0.04	0.03	0.03	0.07	0.10	0.12	0.14	0.16	0.17	0.18	0.22	0.43	0.65	0.80	0.84	0.66	0.16	0.12	0.10	0.08	0.07	0.06
NW	0.05	0.04	0.04	0.03	0.03	0.07	0.11	0.14	0.17	0.19	0.20	0.21	0.22	0.30	0.52	0.73	0.82	0.69	0.16	0.12	0.10	0.08	0.07	0.06
NNW	0.05	0.05	0.04	0.03	0.03	0.11	0.17	0.22	0.26	0.30	0.32	0.33	0.34	0.34	0.39	0.61	0.82	0.76	0.17	0.12	0.10	0.08	0.07	0.06
Hor.	0.06	0.05	0.04	0.04	0.03	0.12	0.27	0.44	0.59	0.72	0.81	0.85	0.85	0.81	0.71	0.58	0.42	0.25	0.14	0.12	0.10	0.08	0.07	0.06

SOURCE: Abstracted from ASHRAE ''Handbook of Fundamentals,'' 1989, with permission.

Table 12.4.21 Shading Coefficients for Single Glass and Insulating Glass*

Single glass				
			Shading coefficient	
Type of glass	Nominal thickness,† in (mm)	Solar trans.†	$b_0 = 4.0$	$b_0 = 3.0$
Regular sheet	3⁄32, ⅛ (2, 3)	0.87	1.00	1.00
Regular plate/float	¼ (6)	0.80	0.95	0.97
	⅜ (9)	0.75	0.91	0.93
	½ (12)	0.71	0.88	0.91
Gray sheet	⅛ (3)	0.59	0.78	0.80
	3⁄16 (5)	0.74	0.90	0.92
	7⁄32 (6)	0.45	0.66	0.70
	7⁄32 (6)	0.71	0.88	0.90
	¼	0.67	0.86	0.88
Heat-absorbing plate/float§	3⁄16 (5)	0.52	0.72	0.75
	¼ (6)	0.47	0.70	0.74
	⅜ (9)	0.33	0.56	0.61
	½ (12)	0.24	0.50	0.57

Insulating glass*					
		Solar trans.†		Shading coefficient	
Type of glass	Nominal thickness, ‡ in (mm)	Outer pane	Inner pane	$b_0 = 4.0$	$b_0 = 3.0$
Regular sheet out, regular sheet in	3⁄32, ⅛ (2, 3)	0.87	0.87	0.90	0.90
Regular plate/float out, regular plate/float in	¼ (6)	0.80	0.80	0.83	0.83
Heat-absorbing plate/float out, regular plate/float in	¼ (6)	0.46	0.80	0.56	0.58

SOURCE: Abstracted from ASHRAE ''Handbook of Fundamentals,'' 1993, with permission.
* Refers to factory-fabricated units with 3⁄16 (5), ¼ (6), or ½ (12) in (mm) airspace or to prime windows plus storm windows.
† Refer to manufacturer's literature for values.
‡ Thickness of each pane of glass, not thickness of assembled unit.
§ Refers to gray-, bronze-, and green-tinted heat-absorbing plate/float glass.

Table 12.4.22 Shading Coefficients for Single Glass with Indoor Shading by Venetian Blinds and Roller Shades

			Type of shading				
			Venetian blinds		Roller shade		
					Opaque		Translucent
Type of glass	Nominal thickness,* in (mm)	Solar trans.†	Medium	Light	Dark	White	Light
Regular sheet	3⁄32–¼ (2–6)	0.87–0.80					
Regular plate/float	¼–½ (6–12)	0.80–0.71					
Regular pattern	⅛–9⁄32 (3–7)	0.87–0.79	0.64	0.55	0.59	0.25	0.39
Heat-absorbing pattern	⅛ (3)						
Gray sheet	3⁄16, 7⁄32 (5, 6)	0.74,0.71					
Heat-absorbing plate/float‡	3⁄16, ¼ (5, 6)	0.46					
Heat-absorbing pattern	3⁄16, ¼ (5, 6)		0.57	0.53	0.45	0.30	0.36
Gray sheet	⅛, 7⁄32 (3, 5)	0.59,0.45					
Heat-absorbing plate/float or pattern		0.44–0.30	0.54	0.52	0.40	0.28	0.32
Heat-absorbing plate/float‡	⅜ (10)	0.34					
Heat-absorbing plate or pattern		0.29–0.15 0.24	0.42	0.40	0.36	0.28	0.31
Reflective coated glass							
SC§ = 0.30			0.25	0.23			
0.40			0.33	0.29			
0.50			0.42	0.38			
0.60			0.50	0.44			

SOURCE: Abstracted from ASHRAE ''Handbook of Fundamentals,'' 1993, with permission.
* Refer to manufacturer's literature for values.
† For vertical blinds with opaque white and beige louvers in the tightly closed position. SC is 0.25 and 0.29 when used with glass of 0.71 to 0.80 transmittance.
‡ Refers to gray-, bronze-, and green-tinted heat-absorbing plate/float glass.
§ Shading coefficient for glass with no shading device.

Table 12.4.23 Shading Coefficients for Insulating Glass* with Indoor Shading by Venetian Blinds and Roller Shades

Type of glass	Nominal thickness, each light in (mm)	Solar trans† Outer pane	Solar trans† Inner pane	Type of shading: Venetial blinds‡ Medium	Venetial blinds‡ Light	Roller shade Opaque Dark	Roller shade Opaque White	Roller shade Translucent Light
Regular sheet out, regular sheet in	3⁄32, 1⁄8 (2, 3)	0.87	0.87	0.57	0.51	0.60	0.25	0.37
Regular plate/float out,	1⁄4 (6)	0.80						
Regular plate/float in			0.80					
Heat absorbing plate/float§ out, regular plate/float in	1⁄4 (6)	0.46	0.80	0.39	0.36	0.40	0.22	0.30
Reflective coated glass								
SC¶ = 0.20				0.19	0.18			
0.30				0.27	0.26			
0.40				0.34	0.33			

SOURCE: Abstracted from ASHRAE ''Handbook of Fundamentals,'' 1993, with permission.
* Refers to factors-fabricated units with 3⁄16 (2), 1⁄4 (3), or 1⁄2 (12), in (mm) airspace, or to prime windows plus storm windows.
† Refer to manufacturer's literature for exact values.
‡ For vertical blinds with opaque white or beige louvers, tightly closed, SC is approximately the same as for opaque white roller shades.
§ Refers to bronze- or green-tinted heat-absorbing plate/flat glass.
¶ Shading coefficient for glass with no shading device.

Table 12.4.24 Shading Coefficients for Double Glazing with Between-Glass Shading

Type of glass	Nominal thickness, each pane	Solar trans.* Outer pane	Solar trans.* Inner pane	Description of airspace	Type of shading: Venetian blinds Light	Venetian blinds Medium	Louvered sun screen
Regular sheet out, regular sheet in	3⁄32, 1⁄8 (2, 3)	0.87	0.87	Shade in contact with glass or shade separated from glass by air space	0.33	0.36	0.43
Regular plate out, regular plate in	1⁄4 (6)	0.80	0.80	Shade in contact with glass void-filled with plastic			0.49
Heat-absorbing, plate/float† out,	1⁄4 (6)	0.46	0.80	Shade in contact with glass or shade separated from glass by air space	0.28	0.30	0.37
Regular plate in				Shade in contact with glass voids filled with plastic			0.41

SOURCE: Abstracted from ASHRAE ''Handbook of Fundamentals,'' 1993, with permission.
* Refer to manufacturer's literature for exact values.
† Refers to gray-, bronze-, and green-tinted heat-absorbing plate/float glass.

Table 12.4.25 Rates of Heat Gain from Occupants of Conditioned Spaces*†

Degree of activity	Typical application	Total heat adult male, Btu/h	Total heat adjusted,‡ Btu/h	Sensible heat, Btu/h	Latent heat, Btu/h
Seated at theater	Theater—Matinee	390	330	225	105
Seated at theater	Theater—Evening	390	350	245	105
Seated, very light work	Offices, hotels, apartments	450	400	245	155
Moderately active office work	Offices, hotels, apartments	475	450	250	200
Standing, light work; walking	Department store, retail store	550	450	250	200
Walking; standing	Drug store, bank	550	500	250	250
Sedentary work	Restaurant§	490	550	275	275
Light bench work	Factory	800	750	275	475
Moderate dancing	Dance hall	900	850	305	545
Walking 3 mi/h; light machine work	Factory	1,000	1,000	375	625
Bowling¶	Bowling alley	1,500	1,450	580	870
Heavy work	Factory	1,500	1,450	580	870
Heavy machine work; lifting	Factory	1,600	1,600	635	965
Athletics	Gymnasium	2,000	1,800	710	1,090

SOURCE: Abstracted from ASHRAE ''Handbook of Fundamentals,'' 1989, with permission.
* Tabulated values are based on 75°F room dry-bulb temperature. For 80°F room dry-bulb, the total heat remains the same, but the sensible heat values should be decreased by approximately 20%, and the latent heat values increased accordingly.
† All values are rounded to nearest 5 Btu/h.
‡ *Adjusted heat gain* is based on normal percentage of men, women, and children for the application listed, with the postulate that the gain from an adult female is 85% of that for an adult male, and that the gain from a child is 75% of that for an adult male.
§ Adjusted total heat gain for *Sedentary work, Restaurant,* includes 60 Btu/h for food per individual (30 Btu/h sensible and 30 Btu/h latent).
¶ For *Bowling,* figure one person per alley actually bowling, and all others as sitting (400 Btu/h) or standing and walking slowly (550 Btu/h).

Table 12.4.26 Rate of Heat Gain from Selected Office Equipment

Appliance	Size	Maximum input rating, Btu/h	Standby input rating, Btu/h	Recommended rate of heat gain, Btu/h
Cheek processing workstation	12 pockets	16,400	8,410	8,410
Computer devices				
Card puncher		2,730 to 6,140	2,200 to 4,800	2,200 to 4,800
Card reader		7,510	5,200	5,200
Communication/transmission		6,140 to 15,700	5,600 to 9,600	5,600 to 9,600
Disk drives/mass storage		3,410 to 34,100	3,412 to 22,420	3,412 to 22,420
Magnetic ink reader		3,280 to 16,000	2,600 to 14,400	2,600 to 14,400
Microcomputer	16 to 640 Kbyte*	340 to 2,050	300 to 1,800	300 to 1,800
Minicomputer		7,500 to 15,000	7,500 to 15,000	7,500 to 15,000
Optical reader		10,240 to 20,470	8,000 to 17,000	8,000 to 17,000
Plotters		256	128	214
Printers				
Letter quality	30 to 45 char/min	1,200	600	1,000
Line, high speed	5,000 or more lines/min	4,300 to 18,100	2,160 to 9,040	2,500 to 13,000
Line, low speed	300 to 600 lines/min	1,540	770	1,280
Tape drives		4,090 to 22,200	3,500 to 15,000	3,500 to 15,000
Terminal		310 to 680	270 to 600	270 to 600
Copiers/Duplicators				
Blue print		3,930 to 42,700	1,710 to 17,100	3,930 to 42,700
Copiers (large)	30 to 67* copies/min	5,800 to 22,500	3,070	5,800 to 22,500
Copiers (small)	6 to 30* copies/min	1,570 to 5,800	1,020 to 3,070	1,570 to 5,800
Feeder		100	—	100
Microfilm printer		1,540	—	1,540
Sorter/collator		200 to 2,050	—	200 to 2,050
Electronic equipment				
Cassette recorders/players		200	—	200
Receiver/tuner		340	—	340
Signal analyzer		90 to 2,220	—	90 to 2,220
Mail processing				
Folding machine		430	—	270
Inserting machine	3,600 to 6,800 pieces/h	2,050 to 11,300	—	1,330 to 7,340
Labeling machine	1,500 to 30,000 pieces/h	2,050 to 22,500	—	1,330 to 14,700
Postage meter		780	—	510
Word processors/typewriters				
Letter-quality printer	30 to 45 char/min	1,200	600	1,000
Phototypesetter		5,890	—	5,180
Typewriter		270	—	230
Word processor		340 to 2,050	—	300 to 1,800
Vending machines				
Cigarette		250	51 to 85	250
Cold food/beverage		3,920 to 6,550	—	1,960 to 3,280
Hot beverage		5,890	—	2,940
Snack		820 to 940	—	820 to 940
Miscellaneous				
Bar-code printer		1,500	—	1,260
Cash register		200	—	160
Coffee maker	10 cups	5,120	—	3,580 sensible 1,540 latent
Microfiche reader		290	—	290
Microfilm reader		1,770	—	1,770
Microfilm reader/printer		3,920	—	3,920
Microwave oven	1 ft^3	2,050	—	1,360
Paper shredder		850 to 10,240	—	680 to 8,250
Water cooler	32 qt/h	2,390	—	5,970

SOURCE: Abstracted from ASHRAE ''Handbook of Fundamentals,'' 1993, with permission.
* Input is not proportional to capacity.

Heat transfer to the distribution duct depends on the duct area exposed, the amount of insulation on the duct, and the temperature differential between the air in the duct and the surroundings.

Outside Air

Outside air loads depend on the amount of outside air intake and its condition. Table 12.4.3 shows recommended outdoor air ventilation rates for different occupancies. Tables 12.4.4 and 12.4.5 can be used to determine the quantity of outside air that will infiltrate because of wind effects. In all cases, sufficient outside air should be provided to balance mechanical exhaust systems.

$$\begin{aligned} Q_{outside\ air} &= q_{sensible} + q_{latent} \qquad \text{Btu/h (watts)} \\ &= AU(t_o - t_i)\ \text{ft}^3/\text{min} \\ &\quad + 0.68\ (M_o - M_i)\ \text{ft}^3/\text{min} \qquad \text{Btu/h} \end{aligned} \tag{12.4.16a}$$

where M_o = outside moisture content at design wet bulb, °F, gr/lb; and M_i = inside moisture content at design relative humidity, gr/lb. A comparable equation in SI units is

$$\begin{aligned} Q_{outside\ air} &= 1.2(t'_o - t'_i)\ \text{m}^3/\text{s} \\ &\quad + 42.6\ (M'_o - M'_i)\ \text{m}^3/\text{s} \qquad \text{kW} \end{aligned} \tag{12.4.16b}$$

Table 12.4.27 Heat Gain from Restaurant Appliances
Not hooded,* gas burning and steam heated.

Appliance	Type of control	Miscellaneous data	Manufacturer's max. rating, Btu/h	Maintaining rate, Btu/h	Recommended heat gain from average use		
					Sensible heat, Btu/h	Latent heat, Btu/h	Total heat, Btu/h
			Gas burning				
Coffee brewer ½ gal Warmer, ½ gal	Man. Man.	Combination brewer and warmer	3,400 500	 500	1,350 400	350 100	1,700 500
Coffee brewer unit with tank		4 brewers and 4½-gal tank			7,200	1,800	9,000
Coffee urn, 3 gal	Auto.	Black finish	3,200	3,900	2,900	2,900	5,800
Coffee urn, 3 gal	Auto.	Nickel plated		3,400	2,500	2,500	5,000
Coffee urn, 5 gal	Auto.	Nickel plated		4,700	3,900	3,900	7,800
Food warmer, values per sq. ft top surface	Man.	Water bath type	2,000	900	850	450	1,300
Fry kettle, 15 lb fat	Auto.	Frying area 10 × 10	14,250	3,000	4,200	2,800	7,000
Fry kettle, 28 lb fat	Auto.	Frying area 11 × 16	24,000	4,500	7,200	4,800	12,000
Grill, Broil-O-Grill Top burner Bottom burner	Man.	Insulated 22,000 Btu/h 15,500 Btu/h	37,000		14,400	3,600	18,000
Stoves, short order—closed top; values per sq. ft top surface	Man.	Ring-type burners 12,000 to 22,000 Btu each	14,000		4,200	4,200	8,400
Stoves, short order—closed top; values per sq. ft top surface	Man.	Ring-type burners 10,000 to 12,000 Btu each	11,000		3,300	3,300	6,600
Toaster, continuous	Auto.	2 slices wide, 360 slices/h	12,000	10,000	7,700	3,300	11,000
			Steam heated				
Coffee urn, 3 gal 3 gal 5 gal	Auto. Auto. Auto.	Black finish Nickel plated Nickel plated			2,900 2,400 3,400	1,900 1,600 2,300	4,800 4,000 5,700
Coffee urn, 3 gal 3 gal 5 gal	Man. Man. Man.	Black finish Nickel plated Nickel plated			3,100 2,600 3,700	3,100 2,600 3,700	6,200 5,200 7,400
Food warmer, per sq. ft top surface	Auto.				400	500	900
Food warmer, per sq. ft top surface	Man.				450	1,150	1,500
Coffee brewer, ½ gal Warmer, ½ gal	Man. Man.		2,240 306	306 306	900 230	220 90	1,120 320
4 coffee brewing units with 4½-gal tank	Auto.	Water heater, 2,000 W Brewers, 2,960 W	16,900		4,800	1,200	6,000
Coffee urn, 3 gal 3 gal 5 gal	Man. Auto. Auto.	Black finish Nickel plated Nickel plated	11,900 15,300 17,000	3,000 2,600 3,600	2,600 2,200 3,400	1,700 1,500 2,300	4,300 3,700 5,700
Doughnut machine	Auto.	Exhaust system to outdoors, ½-hp motor	16,000		5,000		5,000
Egg boiler	Man.	Med. ht., 550 W Low ht., 275 W	3,740		1,200	800	2,000
Food warmer with plate warmer, per sq. ft top surface	Auto.	Insulated, separate heating unit for each pot, plate warmer in base	1,350	500	350	350	700
Food warmer without plate warmer, per sq. ft top surface	Auto.	Insulated, separate heating unit for each pot	1,020	400	200	350	550
Fry kettle, 11½ lb fat	Auto.		8,840	1,100	1,600	2,400	4,000
Fry kettle, 25 lb fat	Auto.	Frying area 12 × 14 in	23,800	2,000	3,800	5,700	9,500
Griddle, frying	Auto.	Frying top 18 × 14 in	8,000	2,800	3,100	1,700	4,800
Grille, meat	Auto.	Cooking area 10 × 12 in	10,200	1,900	3,900	2,100	6,000
Grille, sandwich	Auto.	Grill area 12 × 12 in	5,600	1,900	2,700	700	3,400
Roll warmer	Auto.	One drawer	1,500	400	1,100	100	1,200
Toaster, continuous	Auto.	2 slices wide, 360 slices/h	7,500	5,000	5,100	1,300	6,400
Toaster, continuous	Auto.	4 slices wide, 720 slices/h	10,200	6,000	6,100	2,600	8,700
Toaster, pop-up	Auto.	2 slices	4,150	1,000	2,450	450	2,900
Waffle iron	Auto.	One waffle 7-in diam.	2,480	600	1,100	750	1,850
Waffle iron for ice cream sandwich	Auto.	12 cakes, each 2½ × 3¾ in	7,500	1,500	3,100	2,100	5,200

SOURCE: Carrier manual.
* If properly designed positive exhaust hood is used, multiple recommended value by 0.50.

Table 12.4.28 Heat Gain from Typical Electric Motors

				Location of motor and driven equipment with respect to conditioned space or airstream		
				A	B	C
Motor nameplate or rated horsepower	Motor type	Nominal r/min	Full load motor efficiency, %	Motor in, driven equipment in, Btu/h	Motor out, driven equipment in, Btu/h	Motor in, driven equipment out, Btu/h
0.05	Shaded pole	1,500	35	360	130	240
0.08	Shaded pole	1,500	35	580	200	380
0.125	Shaded pole	1,500	35	900	320	590
0.16	Shaded pole	1,500	35	1,160	400	760
0.25	Split phase	1,750	54	1,180	640	540
0.33	Split phase	1,750	56	1,500	840	660
0.50	Split phase	1,750	60	2,120	1,270	850
0.75	3-phase	1,750	72	2,650	1,900	740
1	3-phase	1,750	75	3,390	2,550	850
1.5	3-phase	1,750	77	4,960	3,820	1,140
2	3-phase	1,750	79	6,440	5,090	1,350
3	3-phase	1,750	81	9,430	7,640	1,790
5	3-phase	1,750	82	15,500	12,700	2,790
7.5	3-phase	1,750	84	22,700	19,100	3,640
10	3-phase	1,750	85	29,900	24,500	4,490
15	3-phase	1,750	86	44,400	38,200	6,210
20	3-phase	1,750	87	58,500	50,900	7,610
25	3-phase	1,750	88	72,300	63,600	8,680
30	3-phase	1,750	89	85,700	76,300	9,440
40	3-phase	1,750	89	114,000	102,000	12,600
50	3-phase	1,750	89	143,000	127,000	15,700
60	3-phase	1,750	89	172,000	153,000	18,900
75	3-phase	1,750	90	212,000	191,000	21,200
100	3-phase	1,750	90	283,000	255,000	28,300
125	3-phase	1,750	90	353,000	318,000	35,300
150	3-phase	1,750	91	420,000	382,000	37,800
200	3-phase	1,750	91	569,000	509,000	50,300
250	3-phase	1,750	91	699,000	636,000	62,900

SOURCE: Adapted from ASHRAE ''Handbook of Fundamentals,'' 1993, with permission.

where M'_o = outside moisture content at design wet bulb, °C, g/kg; and M'_i = inside moisture content at design relative humidity, g/kg. t'_o, t'_i are expressed in °C.

Moisture Load

Moisture as a cooling load is a latent heat gain expressed in BTU per hour and is computed with the following equations:

$$Q_t = Q_{inf} + Q_{vent} \qquad (12.4.17)$$
$$Q_{inf} = 0.68 \times \text{ft}^3/\text{min} \times (M_o - M_i) \quad \text{Btu/h} \qquad (12.4.18a)$$
$$Q_{vent} = 0.68 \times \text{ft}^3/\text{min} \times (M_o - M_i) \quad \text{Btu/h} \qquad (12.4.19a)$$

where 0.68 = 60/13.5 × 1,076/7,000; 60 = min/h; 13.5 = specific volume of moist air at 70°F dB and 50% RH; 1,076 = average heat removal required to condense 1 lb of water vapor from the room air; and 7,000 = grains per pound.

Comparable equations in SI units are:

$$Q_{inf} = 42.6\ \text{m}^3/\text{s}\ (M'_o - M'_i) \quad \text{kW} \qquad (12.4.18b)$$
$$Q_{vent} = 42.6\ \text{m}^3/\text{s}\ (M'_o - M'_i) \quad \text{kW} \qquad (12.4.19b)$$

M'_o = moisture content of outside air, g/kg; and M'_i = moisture content of inside air, g/kg.

HEATING

Heating Load

$$Q_t = Q_{tr} + Q_{inf} + Q_{vent} \qquad (12.4.20a)$$

where Q_1 = total heating load, Btu/h; Q_{tr} = transmission load = $AU(t_i - t_o)$, Btu/h; Q_{inf} = infiltration load = 1.08 (ft³/min)$(t_i - t_o)$, Btu/h; Q_{vent} = ventilation load = 1.08 (ft³/min)$(t_i - t_o)$, Btu/h; A = area through which heat flow occurs, ft²; U = overall heat-transfer coefficient = $1/R_t$ Btu/(h)(ft²)(°F); t_o = outside-air design dry-bulb temperature, °F (Fig. 12.4.1); t_i = inside design dry-bulb temperature, °F (Table 12.4.1); R_t = thermal resistance, °F/(Btu · h · ft²) = $R_1 + R_2 + R_3 + \cdots + R_n$; and $R_1, R_2, \ldots$ = resistances to heat flow to the individual components of a composite construction. See Fig. 12.4.2 and Table 12.4.2.

A comparable equation in SI units is

$$Q_1 = Q_{tr} + Q_{inf} + Q_{vent} \qquad (12.4.20b)$$

where Q_t = total heating load, kW; $Q_{tr} = AU(t_i - t_o)$, kW; Q_{inf} = 1.2 (m³/s)$(t_i - t_o)$, kW; Q_{vent} = 1.2 (m³/s)$(t_i - t_o)$, kW; A = area through which heat flow occurs, m²; U = overall heat-transfer coefficient = $1/R_t$, W/(m² · K); t_o = outside-air design dry-bulb temperature, °C; t_i = inside design dry-bulb temperature, °C; m³/s = cubic meters per second, air; and R_t = thermal resistance, K/(W · m²).

PSYCHROMETRICS

The psychrometric chart can be used to simplify the analysis of air-conditioning processes. The processes can be shown simply and visualized clearly, and the chart lends itself to quick graphical computations. In addition, the state of any air–water vapor mixture can be fixed on the psychrometric chart with reasonable accuracy by means of any two psychrometric characteristics. Usually dry-bulb temperature and wet-bulb temperature are used because they are the simplest to measure.

Figures 12.4.8 and 12.4.9 are psychrometric charts for normal temperatures in inch-pound and SI units, respectively.

Psychrometric charts at different temperatures and barometric pressures are useful for problems falling outside the ranges shown in Figs. 12.4.8 and 12.4.9. A collection of different psychrometric charts, in both USCS and SI units, for low, normal, and high temperatures, at sea

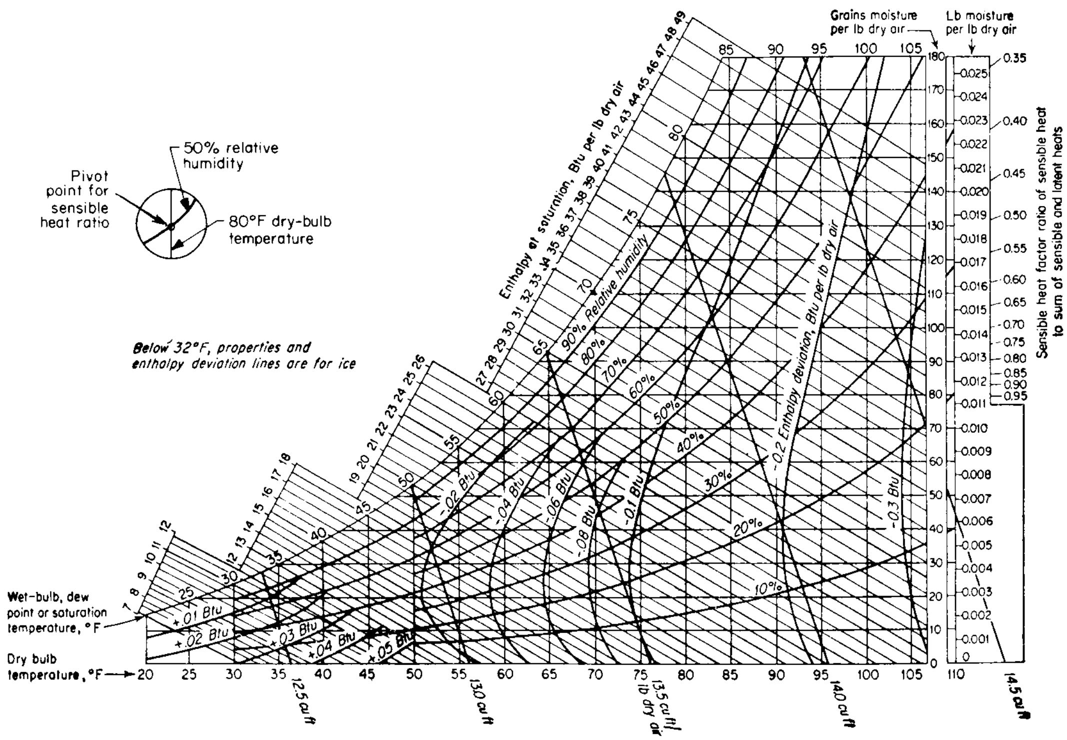


Fig. 12.4.8 Psychrometric chart for normal temperatures in USCS units. *(Carrier Corp.)*

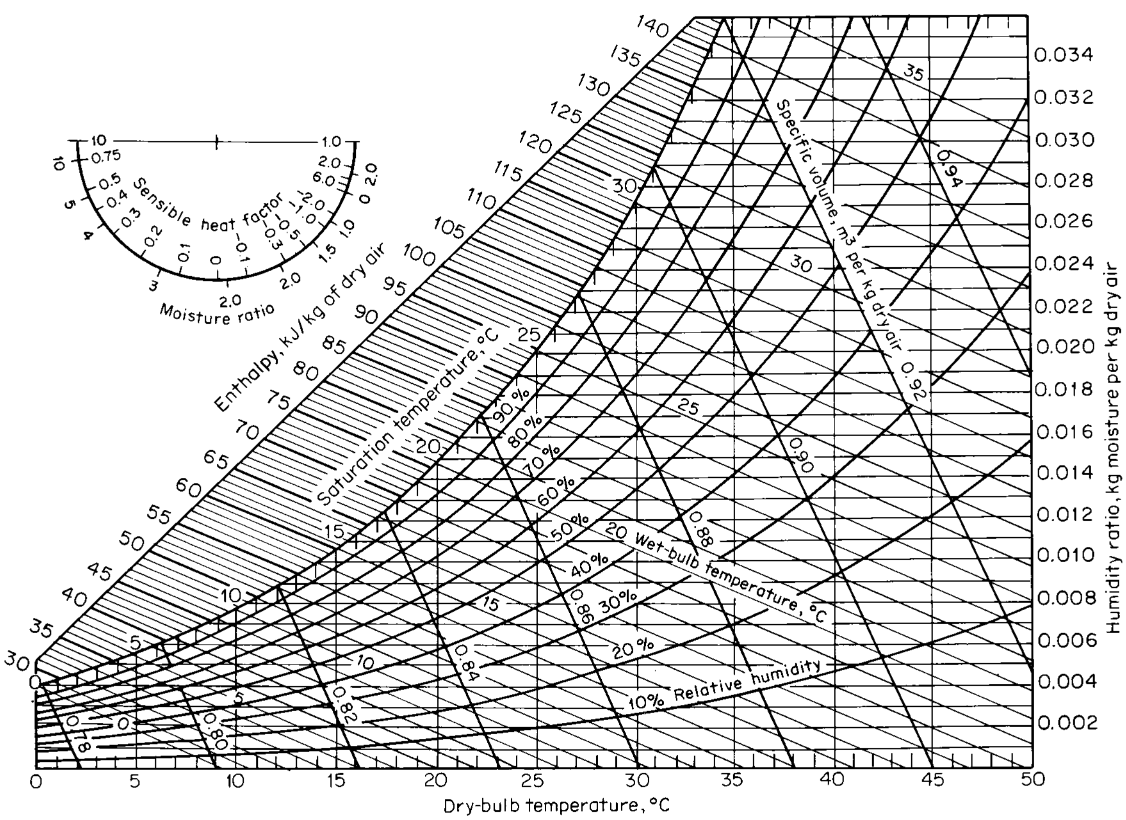


Fig. 12.4.9 Psychrometric chart for normal temperatures in SI units. *(Adapted from material published by Business News Publishing Co., 1975.)*

level and at four elevations above sea level, are available from ASHRAE, the Carrier Corp. of Syracuse, NY, and from other equipment manufacturers.

Figure 12.4.10 shows a psychrometric chart simplified in skeleton form.

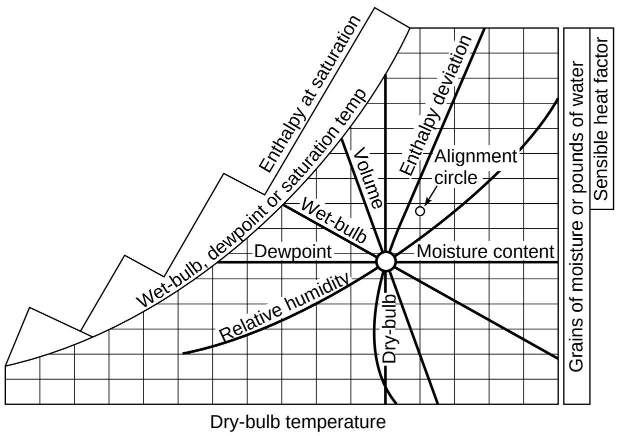


Fig. 12.4.10 Skeleton psychrometric chart.

Terminology

Dry-bulb temperature: The temperature of air as registered by an ordinary thermometer.

Wet-bulb temperature: The temperature registered by a thermometer whose bulb is covered by a wetted wick and exposed to a current of rapidly moving air.

Dew-point temperature: The temperature at which condensation of moisture begins when the air is cooled.

Relative humidity: Ratio of the actual water vapor pressure of the air to the saturated water vapor pressure of the air at the same temperature.

Specific humidity or moisture content: The weight of water vapor in grains (or pounds) of moisture per pound of dry air.

Enthalpy: A thermal property indicating the quantity of heat in the air above an arbitrary datum, in Btu per pound of dry air. The datum for dry air is 0°F and, for the moisture content, 32°F water.

Enthalpy deviation: Enthalpy should be corrected by the enthalpy deviation due to the air not being in the saturated state. On normal air conditioning estimates it is omitted.

Specific volume: The cubic feet of the mixture per pound of dry air.

Sensible heat factor: The ratio of sensible to total heat.

Alignment circle: Used in conjunction with the sensible heat factor to plot the various air-conditioning process lines.

Pounds of dry air: The basis for all psychrometric calculations. Remains constant during all psychrometric processes.

The dry-bulb, wet-bulb, and dew-point temperatures and the relative humidity are so related that, if two properties are known, all other properties shown may then be determined. When **air is saturated,** dry-bulb, wet-bulb, and dew-point temperatures are all equal.

Room sensible heat factor is the ratio of room sensible heat to the total of room sensible and room latent heat.

A line drawn between the room design condition at the slope of the sensible heat factor is the **condition line** and it will intersect the saturation line at the apparatus dew point. See Fig. 12.4.11. In order to maintain design conditions, supply air must be provided to the space at a temperature and moisture level that, when plotted, must fall on the condition line. If air is provided at conditions of apparatus dew point, the minimum quantity of conditioned air would be required to obtain design conditions.

Supply Air Temperature The room cooling load is the sum of external and internal sensible and latent heat gains plus the difference in

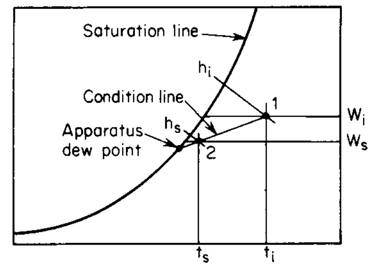


Fig. 12.4.11 Apparatus dew point and condition line.

enthalpy between outside and room air for that portion of outside air which does not contact the cooling-coil surfaces. The percentage of air that passes through a cooling coil untreated is the numerical value of the *coil bypass factor;* e.g., a bypass factor of 20 percent represents a cooling-coil saturation efficiency of 80 percent.

The ratio of room sensible heat gains to total room sensible and latent heat gains is the **room sensible heat ratio** (RSHR).

$$\text{RSHR} = \frac{Q_{rs}}{Q_{rs} + Q_{rl}} \qquad (12.4.21)$$

It represents the ratio of sensible cooling capacity to the total cooling capacity required of the supply air to satisfy room conditions. It is used to plot the slope of the *room-condition line* on a psychrometric chart for the determination of the *apparatus dew point* (ADP). See Fig. 12.4.11.

The actual supply air temperature and off coil wet-bulb temperature will depend on the bypass characteristic of the selected cooling coil (Fig. 12.4.11).

Supply Air Rate The rate of supply air required is expressed by

$$Q_{sa} = Q_{rs}/1.08(t_r - t_s) \qquad \text{ft}^3/\text{min} \qquad (12.4.22a)$$

In SI units:

$$Q'_{sa} = Q'_{rs}/1.2(t_r - t_s) \qquad \text{m}^3/\text{s} \qquad (12.4.22b)$$

where Q_{sa} = supply air, ft³/min (m³/s); Q'_{rs} = room sensible heat, kW; t_r = room design temperature, °F (K); t_s = supply air temperature, °F (K).

The bypass factor is used to express the effectiveness of a cooling coil. It is based on the artificial premise that a portion of the air that enters a cooling coil is cooled completely to saturation, that is, to the apparatus dew point, and the remaining air is not cooled at all. The actual condition of the air that leaves the coil is then represented to be a mixture of the fully conditioned and completely unconditioned air. The ratio of unconditioned air to total air is the **bypass factor**.

The bypass factor is a function of the type and amount of coil surface and the time available for contact as the air passes over the coil. Table 12.4.29 gives approximate bypass factors for various finned coil surfaces and air velocities. A larger bypass factor requires the circulation of more conditioned air; where outside air is introduced, the bypassed air increases the room air load.

Table 12.4.29 Typical Bypass Factors for Unsprayed Coils

Depth of coils (rows)	5-in spacing	
	8 fins/in	14 fins/in
	Face velocity, ft/min	
	300–700	300–700
2	0.42–0.55	0.22–0.38
3	0.27–0.40	0.10–0.23
4	0.19–0.30	0.05–0.14
5	0.12–0.25	0.02–0.09
6	0.08–0.18	0.01–0.06
8	0.03–0.08	

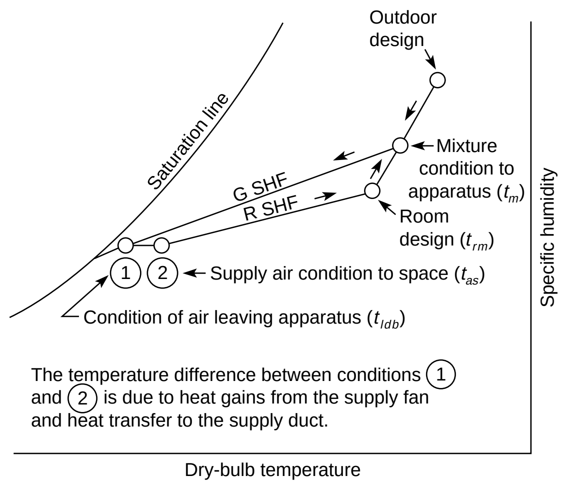


Fig. 12.4.12 Typical cooling process.

Typical Air-Conditioning Cooling Process Figure 12.4.12 depicts a typical cooling process adjusted for fan heating and duct losses.

DUCT DESIGN

Air Velocity Supply and return air ducts and apparatus are sized on the basis of air quantity and are kept within the limitations of allowable friction losses, velocity, and noise. Conveying air at low velocity will be quieter and require less pressure, less fan power and less carefully constructed ductwork than conveying air at medium or high velocity. Lower velocities are preferred where space is available.

Pressure Loss in Duct Systems Pressure losses in duct systems are due to friction of the air in contact with the sides of the duct and dynamic losses caused by changes of duct shape or direction and by obstructions to flow.

$$\text{Friction } H_f = f\frac{L}{D}\left(\frac{V}{4{,}005}\right)^2 \qquad (12.4.23a)$$

where H_f = head loss due to friction, in H_2O: L = length of duct, ft; D = diameter of duct, ft; V = velocity of air, ft/min; and f = nondimensional friction coefficient. A comparable equation in SI units is

$$H_f = f\frac{L}{d}\frac{(V)^2}{2}\rho \qquad (12.4.23b)$$

where H_f = head loss due to friction, N/m²; L = length of duct, m; D = diameter of duct, m; V = velocity of air, m/s; f = nondimensional friction coefficient; and ρ = density of air, kg/m³.

$$\text{Dynamic losses } H_v = C\left(\frac{V}{4{,}005}\right)^2 \qquad (12.4.24a)$$

where H_v = velocity-head loss, in H_2O; C = experimentally determined constant; $V = Q/A$ = air velocity, ft/min; Q = airflow rate, ft³/min; and A = cross-sectional area of duct, ft². A comparable equation in SI units is

$$H'_v = C'\frac{(V')^2}{2} \qquad (12.4.24b)$$

where H'_v = velocity-head loss, N/m²; V' = air velocity, m/s; and = density of air, kg/m³. When the equation for H'_v is written in the form above, $C' = C$.

Duct Design Methods Two methods are frequently used: **equal friction** and **static regain.**

Equal Friction The equal friction method is applicable primarily to systems using low or moderate velocities, where the velocity head is not an important factor. A friction drop per 100 ft of length is chosen, and the duct mains and branches are all sized on the basis of this friction drop. This will invariably result in higher velocities in the mains, where they can be tolerated, and low velocities in the branches, where they are desirable. Limitations are established for friction loss per 100 feet and for velocities in the mains and branches.

Static Regain The static regain method is used for both conventional and high velocity systems. It is especially applicable in the latter, where the velocity head may be appreciable. In the static regain method, the static pressure required to give proper airflow through the system outlets is determined, and this pressure is maintained by reducing the velocity at each branch or takeoff, so that the recovery in pressure due to reduction of velocity balances the friction loss in the preceding section of duct. This is possible because of the convertibility of static and velocity pressures. For practical applications it is usually assumed that 50 percent of the velocity pressure available will be converted to static pressure.

$$H_R = 0.5\left(\frac{V_1}{4{,}005}\right)^2 - \left(\frac{V_2}{4{,}005}\right)^2 \qquad (12.4.25a)$$

where H_R = head recovered, in H_2O; V_1 = system inlet velocity, ft/min; and V_2 = system outlet velocity, ft/min. A comparable equation in SI units is

$$H'_R = \frac{0.5(V'_1)^2}{2} - \frac{(V'_2)^2}{2} \qquad (12.4.25b)$$

where $H_{R'}$ = head recovered, N/m²; V'_1 = system inlet velocity, m/s; and V'_2 = system outlet velocity, m/s.

Figure 12.4.13 may be used to determine directly the friction loss per

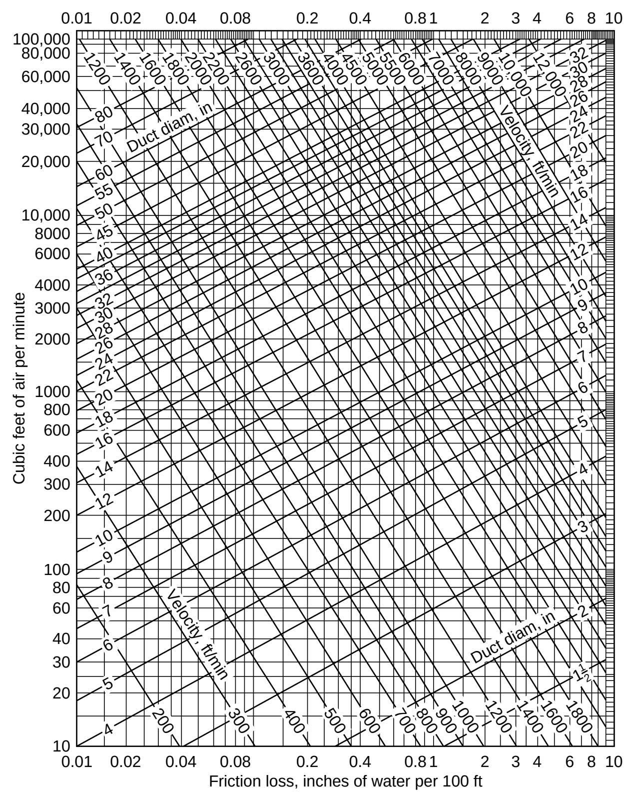


Fig. 12.4.13 Friction loss for usual conditions in round ducts. (This chart applies to smooth, round, galvanized steel ducts, and is based on air at 70°F and 29.96 in Hg absolute pressure. For air of different density, the friction may be assumed to vary directly with the density.)

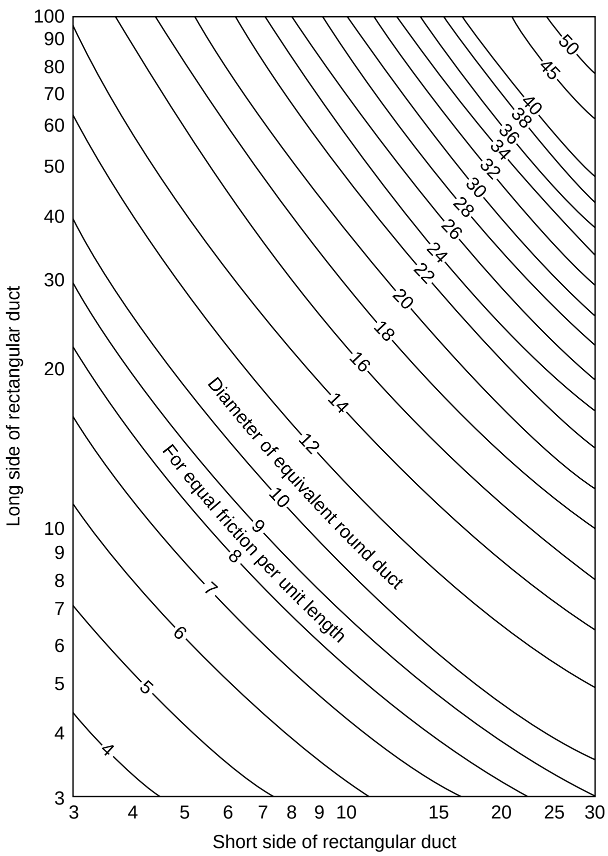


Fig. 12.4.14 Equivalent diameters of round ducts. Use with rectangular ducts, with capacity constant. *(Buffalo Forge.)*

100 ft for round ducts. Figure 12.4.14 provides a conversion from round to rectangular ductwork with the same air capacity. Table 12.4.30 presents a range of friction loss per 100 ft and velocity limits for low- and high-velocity air systems. Typical velocities through some air system components are shown in Table 12.4.31.

Table 12.4.30 Duct System Pressure Losses and Design Velocities

	Pressure loss, in H_2O, gage, per 100 ft	Maximum velocity, ft/min
Low-velocity systems		
Noise critical	0.05–0.07	1,400
Usual design	0.08–0.1	1,800
Straight runs without takeoffs	0.08–0.12	2,400
High-velocity systems		
Usual design	0.4–0.6	2,600
Straight runs without takeoffs	0.6	3,400

Air Distribution

Air outlets are designed to control air motion, noise level, and temperature gradients caused by the introduction of air into a conditioned space and the removal of air from that space.

Supply Outlets Supply outlets (and diffusers) are usually located at near ceiling height with grilles or registers high on the sidewall. Supply outlets may be located below windows or in the floor as long as they satisfy the criteria for the space and are unobstructed. Factors which usually affect the selection of supply outlets are noise, location of outlet, temperature of supply air, and area of diffusion. Manufacturers' performance data for supply outlets should be used as the basis for selection.

Return Outlets Selection of return outlets (and registers or grilles) is usually governed by face velocity to limit discomfort to occupants from drafts and/or noise. See Table 12.4.32.

Table 12.4.31 Typical Velocities through Air System Components

	Residences		Nonresidential buildings	
Designation	ft/min	m/min	ft/min	m/min
Outdoor-air intakes*	300	80	500	150
Filters*	250	75	300	90
Heating coils*	450	140	500	150
Cooling coils*	450	140	500	150
Air washers	500	150	500	150

SOURCE: Adapted from ASHRAE ''Handbook of Fundamentals,'' 1993, with permission.

* These velocities are for total face area, not the net free area; other velocities in the table are for net free area.

Table 12.4.32 Recommended Return Face Velocities

	Velocity over gross area	
Intake location	ft/min	m/min
Above occupied zone	800 up	245 up
Within occupied zone, not near seats	600–800	185–245
Within occupied zone, near seats	400–600	120–185
Door or wall louvers	200–300	60–90
Undercutting of doors (through undercut area)	200–300	60–90

SOURCE: Adapted from ASHRAE, ''Handbook of Fundamentals,'' 1993, with permission.

FANS

Supply and **return fans** must convey the conditioned air through the system efficiently and with a minimum of disturbing noise and vibrations.

Fans produce pressure by increasing airflow velocity. Velocity change is the result of tangential and radial velocity components in the case of centrifugal fans, and of axial and tangential velocity components in the case of axial-flow fans.

Centrifugal fans are most frequently used, but **axial-flow fans** have been applied successfully. Figures 12.4.15 to 12.4.17 show typical performance curves for forward-curved and backward-curved centrifugal fans

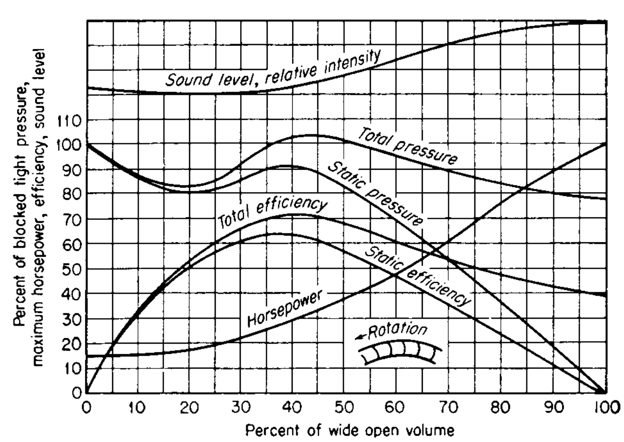


Fig. 12.4.15 Percentage performance curves for a forward-curved blade centrifugal fan.

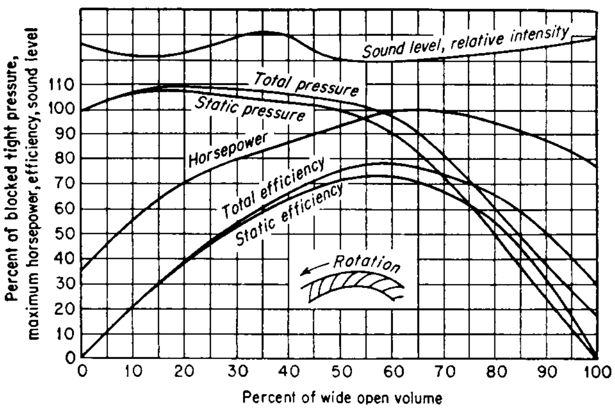


Fig. 12.4.16 Percentage performance curves for a backward-curved blade centrifugal fan.

and axial-flow fans. Table 12.4.33 summarizes the relative characteristics of centrifugal fans. Figure 12.4.18 shows the zone of optimum performance for a backward-curved-blade centrifugal fan.

FAN LAWS

Fan laws in Table 12.4.34 relate the performance variables for any dynamically similar series of fans. (See also Sec. 14.5.) They can be

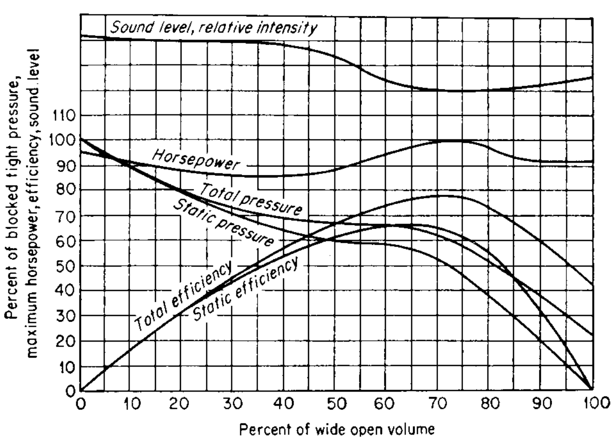


Fig. 12.4.17 Percentage performance curves for an axial fan.

used to predict the performance of any fan in a series when test data are available for a given fan in the series. Fan laws may also be used with a particular fan to determine the effect of speed change. Unless otherwise identified, fan performance data are based on dry air at standard conditions: 14.696 lb/in^2 abs and 70°F (0.075 lb/ft^3). In applications where the fan may be required to handle air or gas at some other density, because of temperature or altitude, fan performance will be affected. Table 12.4.35 shows correction factors to air volume for altitude and temperature.

Testing and Balancing Each fan and air duct system component should be tested, adjusted, and balanced to assure that it conforms to the design requirements.

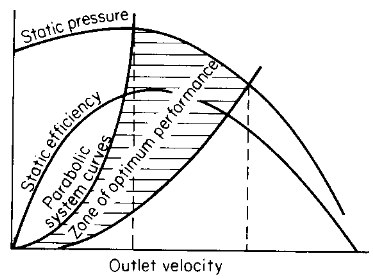


Fig. 12.4.18 Zone of optimum performance for backward-curved blade centrifugal fans.

System and Duct Noise The major sources of noise from air-conditioning systems are fans, diffusers, grilles, ducts, fittings, and vibration. **Sound control** for components consists of selecting devices that meet the design goal under all operating conditions and installing them properly so that no additional sound is generated. The sound power

Table 12.4.33 Relative Characteristics of Centrifugal Fans

Characteristic	Backward curved	Forward curved
First cost	High	Low
Efficiency	High	Low
Stability of operation	Good	Poor
Space required	Medium	Small
Tip speed	High	Low

Table 12.4.34 Fan Laws*†

For all fan laws: $N_{t1} = N_{t2}$ and (Pt. of Rtg.)$_1$ = (Pt. of Rtg.)$_2$

No.	Dependent variables	Independent variables	
1a	$Q_1 = Q_2$	$\times \left(\frac{D_1}{D_2}\right)^3 \times \frac{N_1}{N_2}$	$\times 1$
1b	$\text{Press.}_1 = \text{Press.}_2$‡	$\times \left(\frac{D_1}{D_2}\right)^2 \times \left(\frac{N_1}{N_2}\right)^2$	$\times \frac{\rho_1}{\rho_2}$
1c	$H_1 = H_2$	$\times \left(\frac{D_1}{D_2}\right)^3 \times \left(\frac{N_1}{N_2}\right)^3$	$\times \frac{\rho_1}{\rho_2}$
2a	$Q_1 = Q_2$	$\times \left(\frac{D_1}{D_2}\right)^2 \times \left(\frac{\text{Press.}_1}{\text{Press.}_2}\right)^{1/2}$	$\times \left(\frac{\rho_2}{\rho_1}\right)^{1/2}$
2b	$N_1 = N_2$	$\times \left(\frac{D_2}{D_1}\right) \times \left(\frac{\text{Press.}_1}{\text{Press.}_2}\right)^{1/2}$	$\times \left(\frac{\rho_2}{\rho_1}\right)^{1/2}$
2c	$H_1 = H_2$	$\times \left(\frac{D_1}{D_2}\right)^2 \times \left(\frac{\text{Press.}_1}{\text{Press.}_2}\right)^{3/2}$	$\times \left(\frac{\rho_2}{\rho_1}\right)^{1/2}$
3a	$N_1 = N_2$	$\times \left(\frac{D_2}{D_1}\right)^3 \times \frac{Q_1}{Q_2}$	$\times 1$
3b	$\text{Press.}_1 = \text{Press.}_2$	$\times \left(\frac{D_2}{D_1}\right)^4 \times \left(\frac{Q_1}{Q_2}\right)^2$	$\times \frac{\rho_1}{\rho_2}$
3c	$H_1 = H_2$	$\times \left(\frac{D_2}{D_1}\right)^4 \times \left(\frac{Q_1}{Q_2}\right)^3$	$\times \frac{\rho_1}{\rho_2}$

NOTE: D = fan size, N = revolutions per minute, ρ = gas density, Q = volume flow rate, P = pressure, and H = horsepower.

* The subscript 1 denotes that the variable is for the fan under consideration.

† The subscript 2 denotes that the variable is for the tested fan.

‡ P_{total} or P_{static}.

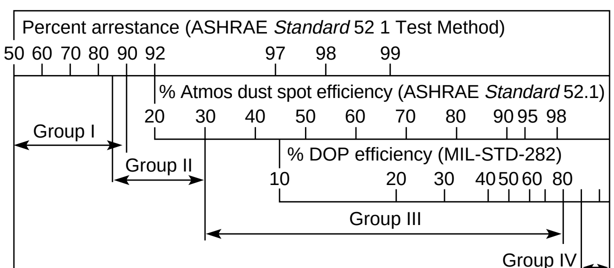
Table 12.4.35 Air Volume Correction Factors for Altitude and Temperature

Altitude, ft (m) above sea level	0	1,000 (305)	2,000 (610)	3,000 (915)	4,000 (1,220)	5,000 (1,525)	6,000 (1,880)	7,000 (2,135)	8,000 (2,440)
Barometric pressure, in Hg (kN/m^2)	29.92 (101.3)	28.86 (97.7)	27.82 (94.2)	26.81 (90.8)	25.84 (87.5)	24.89 (84.3)	23.98 (81.2)	23.09 (78.2)	22.2 (75.2)
Air temp, °F (°C)					Correction factors				
70 (21.1)	1.040	1.003	0.967	0.932	0.898	0.865	0.833	0.803	0.772
100 (38)	0.984	0.948	0.915	0.882	0.850	0.818	0.788	0.759	0.731
150 (66)	0.904	0.872	0.840	0.801	0.781	0.752	0.724	0.698	0.672
200 (93)	0.835	0.805	0.777	0.749	0.722	0.694	0.668	0.645	0.620
250 (121)	0.777	0.749	0.722	0.696	0.671	0.647	0.622	0.599	0.577
300 (149)	0.725	0.699	0.674	0.649	0.628	0.603	0.580	0.560	0.538
350 (177)	0.680	0.656	0.632	0.609	0.588	0.566	0.545	0.525	0.505
400 (204)	0.641	0.618	0.596	0.574	0.553	0.533	0.512	0.495	0.476
450 (232)	0.605	0.583	0.564	0.543	0.523	0.503	0.485	0.467	0.450
500 (260)	0.574	0.553	0.534	0.515	0.496	0.477	0.460	0.443	0.426
550 (288)	0.546	0.526	0.508	0.490	0.472	0.454	0.438	0.421	0.406
660 (316)	0.520	0.501	0.484	0.466	0.449	0.433	0.416	0.401	0.387
650 (343)	0.496	0.478	0.462	0.444	0.428	0.413	0.397	0.383	0.368
700 (371)	0.475	0.458	0.442	0.426	0.411	0.395	0.381	0.367	0.354

SOURCE: ''Bulletin 3576-B, Correction Factors for Temperature and Altitude,'' Buffalo Forge Co., Buffalo, NY.

NOTE: Equivalent $= \dfrac{\text{ft}^3 \text{ min at actual conditions}}{\text{correction factor}}$.

output of a fan is determined by the type of fan, airflow, and pressure. Sound control in the duct system requires proper duct layout, sizing, and provision for installing duct noise attenuators, if required. The noise generated in a system increases with both duct velocity and system pressure. The ASHRAE Handbook ''Applications'' and other related sources present methods for sound control in air-conditioning systems.



Group I
Panel-type filters of spun glass, open cell foams, expanded metal and screens, synthetics, textile denier woven and nonwoven, or animal hair.

Group II
Pleated panel-type filters of fine denier nonwoven synthetic and synthetic-natural fiber blends, or all natural fiber.

Group III
Extended surface supported and nonsupported filters of fine glass fibers, fine electret synthetic fibers, or wet-laid paper of cellulose-glass or all-glass fibers.

Group IV
Extended-area pleated HEPA-type filters of wet-laid ultra-fine glass fiber paper. Biological grade air filters are generally 95% DOP efficiency; HEPA filters are 99.97 and 99.99%; and ULPA filters are 99.999%.

Notes:
1. Group numbers have no significance other than their use in this figure.
2. Correlation between the test methods shown are approximations for general guidance only.

Fig. 12.4.19 Comparative performance of viscous impingement and dry media filters. *(ASHRAE ''Handbook of Fundamentals,'' 1993.)*

FILTRATION

Filters are provided in air-conditioning systems to assure that the conditioned air will satisfy space cleanliness criteria and to protect air treatment equipment from fouling due to dirt accumulation. Figure 12.4.19 describes types of dry media filters and shows their range of performance. In addition, it shows an approximate comparison of the filtration efficiencies obtained by the use of three different testing methods.

The filters designated as Group I are usually used in least critical applications and as a prefilter to extend the operating life of more costly, higher-efficiency filters. Filters designated as Groups II and III are used in good-quality comfort and process air-conditioning applications. The very high efficiency HEPA and ULPA filters are costly and result in high pressure losses. They are applied in clean rooms and for nuclear and toxic particulate filtration.

HEAT REJECTION APPARATUS

All the heat removed from a conditioned space and the heat equivalent of the work performed by the refrigeration equipment must be removed through the cooling system and dissipated via the refrigeration condenser. Table 12.4.36 lists approximate refrigeration equipment energy consumption values.

In most systems the heat is rejected to the atmosphere, but in some cases, water-cooled refrigeration condensers are used to transfer the rejected heat to surface water or to well water. Some examples of the most common systems used to transfer rejected heat to the atmosphere are shown in Fig. 12.4.20. The **air-cooled condenser and evaporative condenser** are arranged with the refrigeration condenser in the outdoor airstream. Refrigerant is piped directly with no intervening heat transfer. The **air-cooled condenser** is the simplest arrangement, but the condenser must operate at temperatures sufficiently high so that condensing takes place well above the outdoor ambient dry-bulb temperature. The **evaporative condenser** adds a spray system to permit condensing above the outdoor ambient wet-bulb temperature.

Closed-Circuit Coolers For larger systems and where extensive piping of refrigerant is either not desired or otherwise precluded, a water-cooled condenser is utilized. The rejected heat is transferred to water piped to an outdoor radiator—a closed-circuit dry cooler or evaporatively cooled device. The **closed-circuit dry cooler,** or **radiator,** is a simple indirect cooling arrangement, but can operate at temperatures higher than the air-cooled condenser because of the additional heat-transfer process involved.

Table 12.4.36 Refrigeration Energy Consumption per 12,000 Btu/h Cooling Capacity

Electric consumption, kW/ton cooling capacity		
	Type of heat rejection, kW/ton	
Item	Mechanical-draft cooling tower	Air-cooled condensers
Room-air conditioners		1.2–2.45*
Refrigeration compressors (motor-driven):		
Reciprocating (20 to 100 tons)	1.03–0.86	1.27–1.09
Centrifugal-hermetic	0.94–0.74	
Centrifugal-external drive (350 to 1,250 tons)	1.02–0.81	
Auxiliary equipment:		
Pump, cooling water	0.15	
Blower for air conditioner	0.10	0.10
Blower for rejection air	0.15	0.15
Steam-consumption rate lb/h/ton (kg/h/ton) cooling capacity		
	Steam rate	
Item	lb/h/ton	kg/h/ton
Centrifugal compressors (steam-driven):		
Condensing (27 in vacuum)	14.5	6.6
Noncondensing (14.7 psig)	30–35	13.6–15.9
Absorption chillers (100 to 1,200 ton) (low-pressure steam)	18–18.5	8.2–8.4
Absorption chillers (high-pressure steam)	11–11.5	5–5.2
Gas-consumption rate, Btu/ton (J/ton) cooling capacity		
	Gate rate	
Item	Btu/ton	kJ/ton
Refrigeration compressors (natural-gas-engine-driven)	8,500	8,970

* Depending on the EER (energy efficiency ratio) rating for the different manufacturers.

The dry cooler water circuit operating with antifreeze permits year-round operation.

The **closed-circuit evaporative cooler** has an indirect condenser water circuit, but uses a spray system and evaporative cooling to reduce the head pressure. In both the dry cooler and closed-circuit cooler there is no contact of either condenser water or antifreeze with the outdoor atmosphere; often this proves highly desirable.

Cooling Towers In large systems and systems where maximum overall efficiency is important, a portion of the condenser water is evaporated into the atmosphere to cool the remaining condenser water. The water lost by evaporation must be made up, usually from a domestic water source. Figure 12.4.20 shows two cooling tower configurations. The **counterflow** arrangement requires a spray system and is usually taller than the crossflow type. **Crossflow** towers have simpler gravity distribution systems.

All cooling towers and all evaporative spray systems that operate during subfreezing weather must be protected against freezing. A number of methods are available to add heat to the piping circuits and the basins or sumps.

Condenser Water System For electrically driven refrigeration compressors a temperature differential of 10°F (5.5°C) may be assumed, and for steam-driven equipment a temperature differential of 20°F (11°C) is usual. In the latter case the refrigeration and steam condensers are piping in series with a temperature rise of approximately 10°F (5.5°C) each.

Condenser water, gal/min

$$= \frac{\text{Total heat rejected, Btu/h}}{500 \times \text{temperature differential, °F}} \qquad (12.4.26a)$$

In SI units,

Condenser flow, m^3/s

$$= \frac{\text{Total heat rejected, kW}}{4190 \times \text{temperature differential, °C}} \qquad (12.4.26b)$$

Atmospheric Evaporative Cooling Equipment The lowest temperature to which water can be cooled in atmospheric cooling equipment is the wet-bulb temperature of the ambient air.

Water-Cooling Effectiveness in Percent

$$E = \frac{(\text{hot-water temp.} - \text{cold-water temp.}) \times 100}{\text{hot-water temp.} - \text{wet-bulb temp. entering}} \qquad (12.4.27)$$

The cold-water temperature must be chosen to place the requirement within the effectiveness range of the equipment used.

Makeup Water for Atmospheric Cooling Equipment Makeup water is introduced to replace losses due to evaporation, drift, and blowdown. If all water were cooled by evaporation, the loss by evaporation for the usual 10°F (5.5°C) cooling range would be:

$$\text{Evaporation, \%} = \frac{Q \times 100}{8.3 \times \text{gal/min} \times \text{hfg}} \qquad (12.4.28a)$$

where Q = total heat rejected. Btu/h; gal/min = total condenser water circulated; and hfg = evaporation heat of water, Btu/lb, at ambient design temperature. In SI units:

$$\text{Evaporation, \%} = \frac{Q' \times 100}{1{,}000 \times m^3/s \times \text{hfg}} \qquad (12.4.28b)$$

where Q' = total heat rejected, kJ/min; m^3/s = total condenser water circulated; and hfg = evaporation heat of water, kJ/kg, at ambient design temperature.

Drift losses depend on the tower design, but generally, from the cooling tower, they are limited to 0.2 percent of the circulated rate.

The makeup water replacing losses due to evaporation, drift, and blowdown introduces dissolved solids into the system.

To prevent excessive concentration, a portion of the circulating water is wasted. The quantity of blowdown depends on the original quantity of dissolved solids in the makeup water and the permissible concentration.

For most open systems, chemical water treatment is used to inhibit corrosion and minimize blowdown.

Water Distribution, Chilled Water Systems' Temperature Differential Design temperature differentials for chilled-water systems are determined by the need to supply chilled water at an average temperature sufficiently low to provide adequate cooling and dehumidification and the desire to minimize the costs of piping, pumping energy, and refrigeration. These differentials normally range from 10°F (5.6°C) for average systems to as much as 15°F (8.3°C) or more for very large systems with widely separated loads.

Volume flow rate, gal/min

$$= \frac{(\text{total load} + \text{piping heat gains} + \text{pump heat}),\ \text{Btu/h}}{500 \times \text{temperature differential, °F}} \qquad (12.4.29a)$$

A comparable equation in SI units is

Volume flow rate, m^3/s

$$= \frac{(\text{total load} + \text{piping heat gains} + \text{pump heat}),\ \text{kW}}{4{,}190 \times \text{temperature differential, °C}} \qquad (12.4.29b)$$

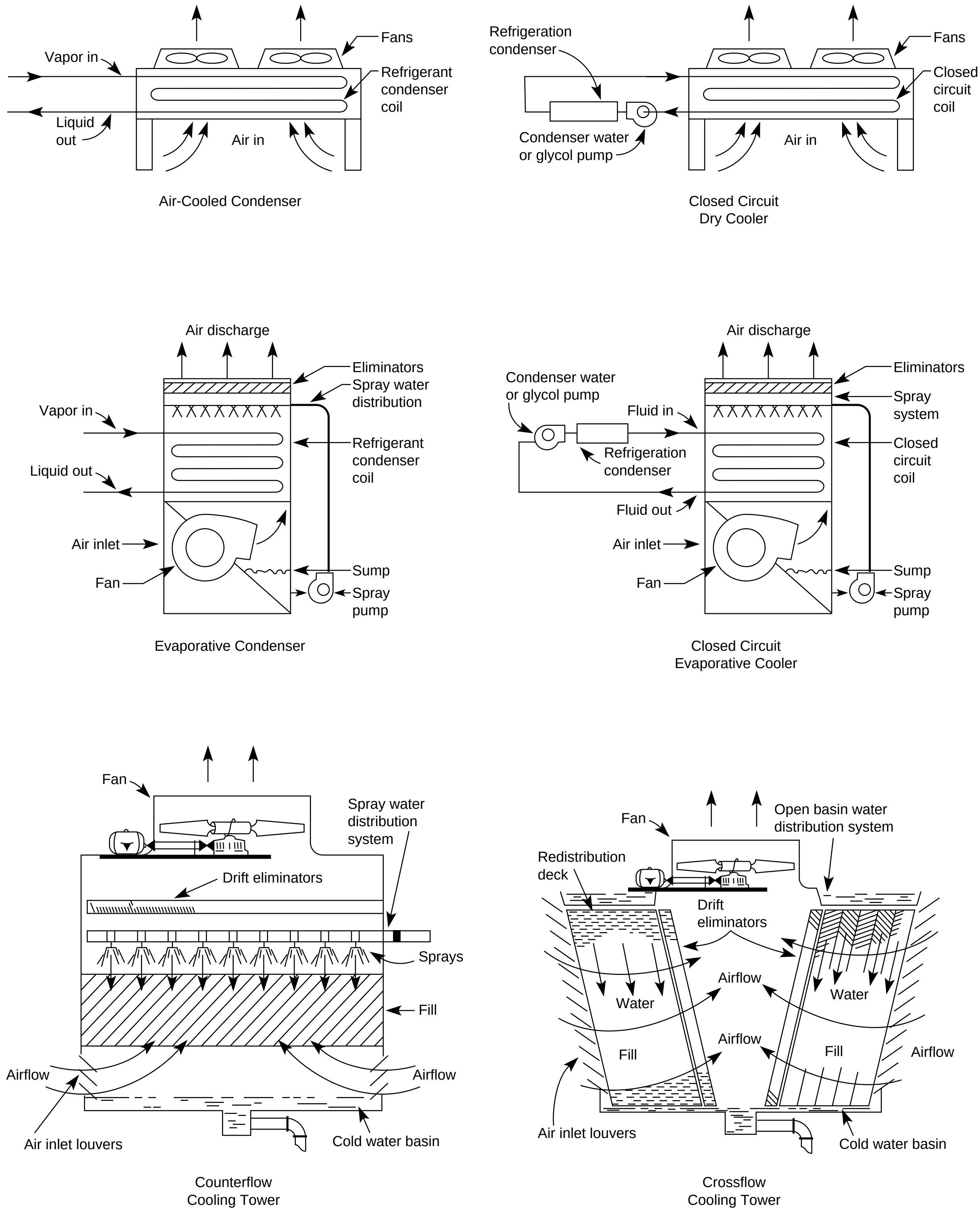


Fig. 12.4.20 Heat rejection equipment. *(Courtesy of E. Revzina.)*

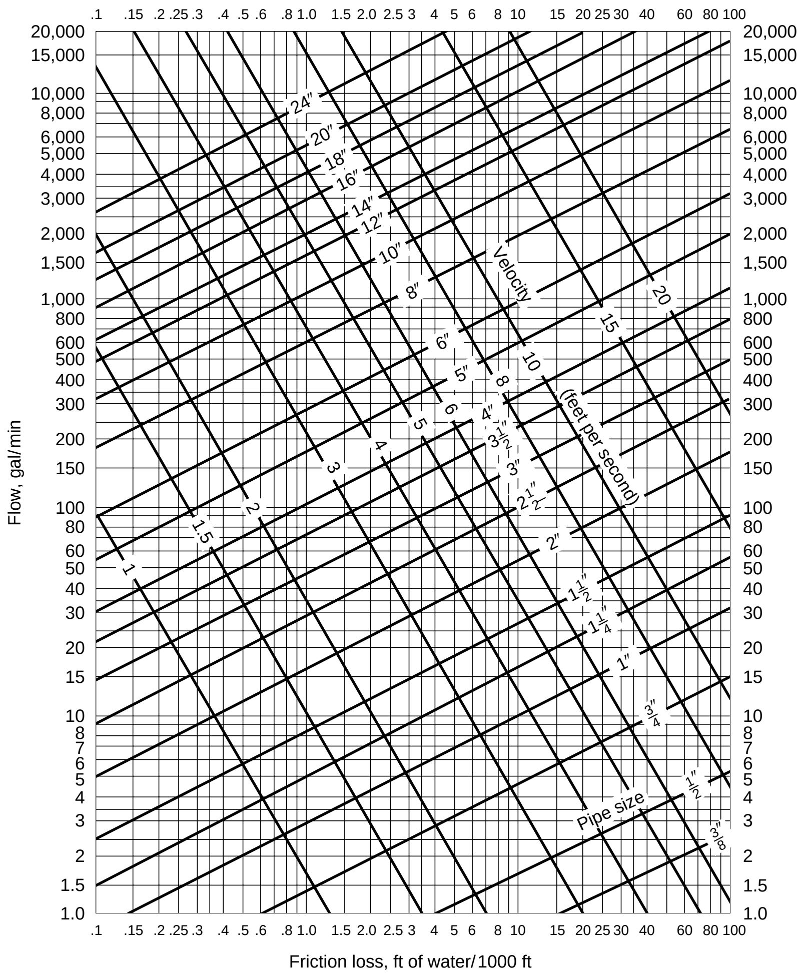


Fig. 12.4.21 Friction loss for open piping systems using schedule 40 pipe.

Table 12.4.37 Low-Pressure Steam System Pipe Capacities (lb/h), with Condensate Flowing with the Steam Flow

Nom. pipe size, in	Pressure drop per 100 ft											
	1⁄16 psi (1 oz)		⅛ psi (2 oz)		¼ psi (4 oz)		½ psi (8 oz)		¾ psi (12 oz)		1 psi	
	Saturated pressure (psig)											
	3.5	12	3.5	12	3.5	12	3.5	12	3.5	12	3.5	12
¾	9	11	14	16	20	24	29	35	36	43	42	50
1	17	21	26	31	37	46	54	66	68	82	81	95
1¼	36	45	53	66	78	96	111	138	140	170	162	200
1½	56	70	84	100	120	147	174	210	218	260	246	304
2	108	134	162	194	234	285	336	410	420	510	480	590
2½	174	215	258	310	378	460	540	660	680	820	780	950
3	318	380	465	550	660	810	960	1,160	1,190	1,430	1,380	1,670
3½	462	550	670	800	990	1,218	1,410	1,700	1,740	2,100	2,000	2,420
4	726	800	950	1,160	1,410	1,690	1,980	2,400	2,450	3,000	2,880	3,460
5	1,700	1,430	1,680	2,100	2,440	3,000	3,570	4,250	4,380	5,250	5,100	6,100
6	1,920	2,300	2,820	3,350	3,960	4,850	5,700	7,000	7,200	8,600	8,400	10,000
8	3,900	4,800	5,570	7,000	8,100	10,000	11,400	14,300	14,500	17,700	16,500	20,500
10	7,200	8,800	10,200	12,600	15,000	18,200	21,000	26,000	26,200	32,000	30,000	37,000
12	11,400	13,700	16,500	19,500	23,400	28,400	33,000	40,000	41,000	49,500	48,000	57,500

NOTE: The weight flow rates at 3.5 psig can be used to cover saturated pressures from 1–6 psig and the weight flow rates at 12 psig can be used to cover saturated pressures from 8–16 psig with an error not exceeding 8%.

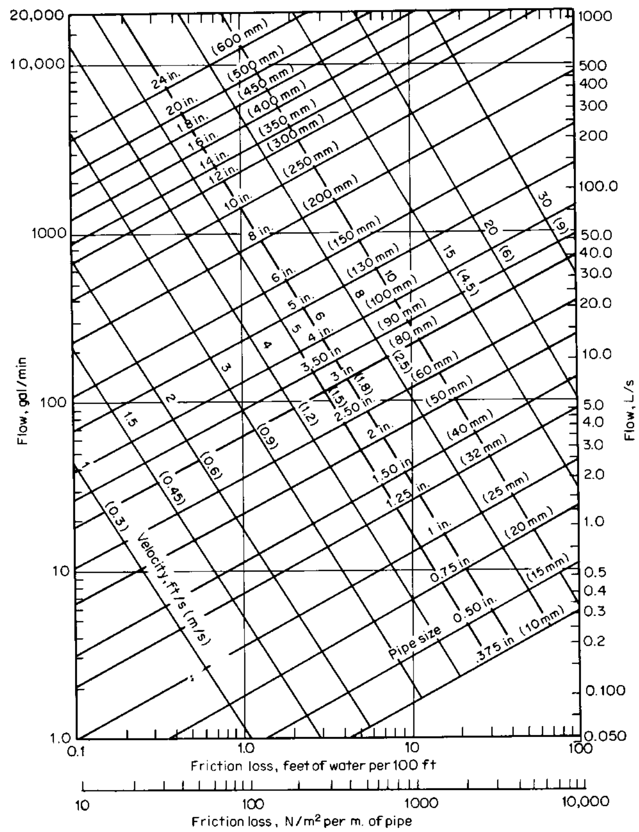


Fig. 12.4.22 Friction loss for closed piping systems using schedule 40 pipe.

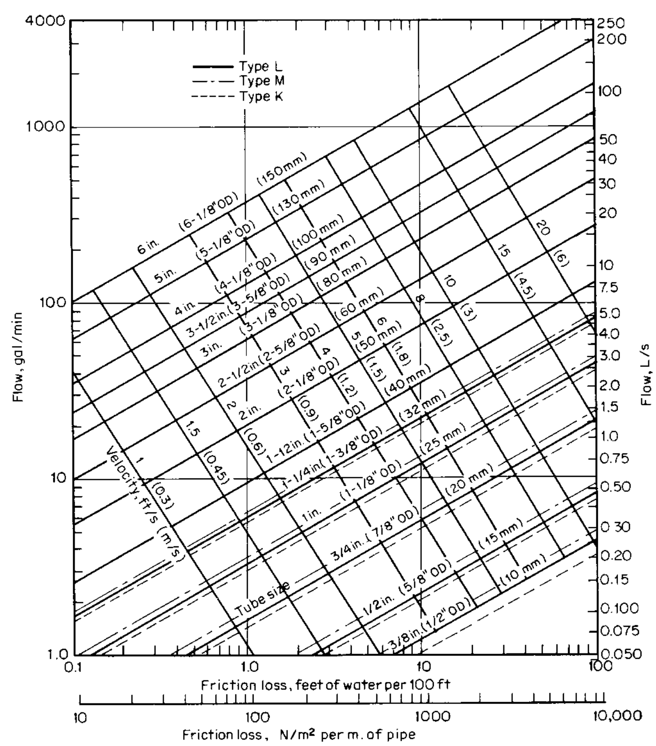


Fig. 12.4.23 Friction loss for closed and open piping systems using copper tubing.

Table 12.4.38 Return Main and Riser Capacities for Low-Pressure Steam Systems

Pipe size, in	Pressure drop per 100 ft														
	1/32 psi (½ oz)			1/24 psi (⅔ oz)			1/16 psi (1 oz)			⅛ psi (2 oz)			¼ psi (4 oz)		
	Wet*	Dry	Vac	Wet*	Dry	Vac	Wet*	Dry	Vac	Wet*	Dry	Vac	Wet*	Dry	Vac
Return mains															
¾						42			100			142			200
1	125	62		145	71	143	175	80	175	250	103	249	350	115	350
1¼	213	130		248	149	244	300	168	300	425	217	426	600	241	600
1½	338	206		393	236	388	475	265	475	675	340	674	950	378	950
2	700	470		810	535	815	1,000	575	1,000	1,400	740	1,420	2,000	825	2,000
2½	1,180	760		1,580	868	1,360	1,680	950	1,680	2,350	1,230	2,380	3,350	1,360	3,350
3	1,880	1,460		2,130	1,560	2,180	2,680	1,750	2,680	3,750	2,250	3,800	5,350	2,500	5,350
3½	2,750	1,970		3,300	2,200	3,250	4,000	2,500	4,000	5,500	3,230	5,680	8,000	3,580	8,000
4	3,880	2,930		4,580	3,350	4,500	5,500	3,750	5,500	7,750	4,830	7,810	11,000	5,380	11,000
5						7,880			9,680			13,700			19,400
6						12,600			15,500			22,000			31,000
Return risers															
¾		48			48	143		48	175		48	249		48	350
1		113			113	244		113	300		113	426		113	600
1¼		248			248	388		248	475		248	674		248	950
1½		375			375	815		375	1,000		375	1,420		375	2,000
2		750			750	1,360		750	1,680		750	2,380		750	3,350
2½						2,180			2,680			3,800			5,350
3						3,250			4,000			5,680			8,000
3½						4,480			5,500			7,810			11,000
4						7,880			9,680			13,700			19,400
5						12,600			15,500			22,000			31,000

* Vacuum values may be used for wet return risers and mains.

Water Distribution, Chilled-Water Systems Temperature Differential

Application	Temp rise °C	Temp rise °F
Close-coupled system on one floor	5–8	3–4.5
Two- or three-story building	8–11	4.5–6
Multistory building	12–20	6.5–11

Water Piping Design

There is a **friction loss** in any pipe through which water is flowing. This loss depends on the following factors:

1. Water velocity
2. Pipe diameter
3. Interior surface roughness
4. Pipe length

System pressure has no effect on the head loss of the equipment in the system. However, higher than normal system pressures may dictate the use of heavier pipe, fittings, and valves along with specially designed equipment.

To properly design a water piping system, the engineer must evaluate not only the pipe friction loss but the loss through valves, fittings, and other equipment. In addition to these friction losses, the use of diversity in reducing the water quantity and pipe size should be considered in designing the water piping system.

Most air conditioning applications use either steel pipe or copper tubing in the piping system. For friction loss values in steel pipe or copper tubing, refer to Figs. 12.4.21 to 12.4.23.

Pipe size determination, especially for very long systems and/or unusual construction or operating cost considerations, is based on an economic analysis, but smaller systems with less critical economic factors are often based on average conditions. In a typical system pipe sizes are selected for a pressure loss of from 3 to 6 ft per 100 ft of pipe.

Pipe Length The total friction loss in a water piping system is the sum of losses in:

1. The total straight lengths of pipe
2. The equivalent lengths of pipe due to fittings, valves, and other elements in the piping system.

Figure 12.4.24 shows the resistance of some valves and fittings in terms of equivalent length of straight pipe.

Steam System Piping

Steam systems which operate below 15 psig are classified as low-pressure systems. Tables 12.4.37 and 38 may be used to determine the size of piping for low-pressure steam and condensate systems pitched in the direction of flow and for risers in which steam and condensate flow in opposite directions.

Table 12.4.39 lists total pressure drop limitations for long-length piping systems. In such systems, pipe sizes may have to be increased to keep total pressure loss in supply and return piping within the system limits. For systems in which pressure may vary, i.e., when steam is supplied by a boiler, the distribution pressure must be based on the minimum pressure that will be available.

Table 12.4.39 Total Pressure Drop for Two-Pipe Low-Pressure Steam Piping Systems

Initial steam pressure, psig	Total pressure drop in supply piping, psi	Total pressure drop in return piping, psi
2	½	½
5	1¼	1¼
10	2½	2½
15	3¾	3¾
20	5	5

Tables 12.4.40 and 41 are used to size piping for use in medium- and high-pressure systems, respectively, and assume piping is installed with proper pitch and adequate provisions to remove condensate.

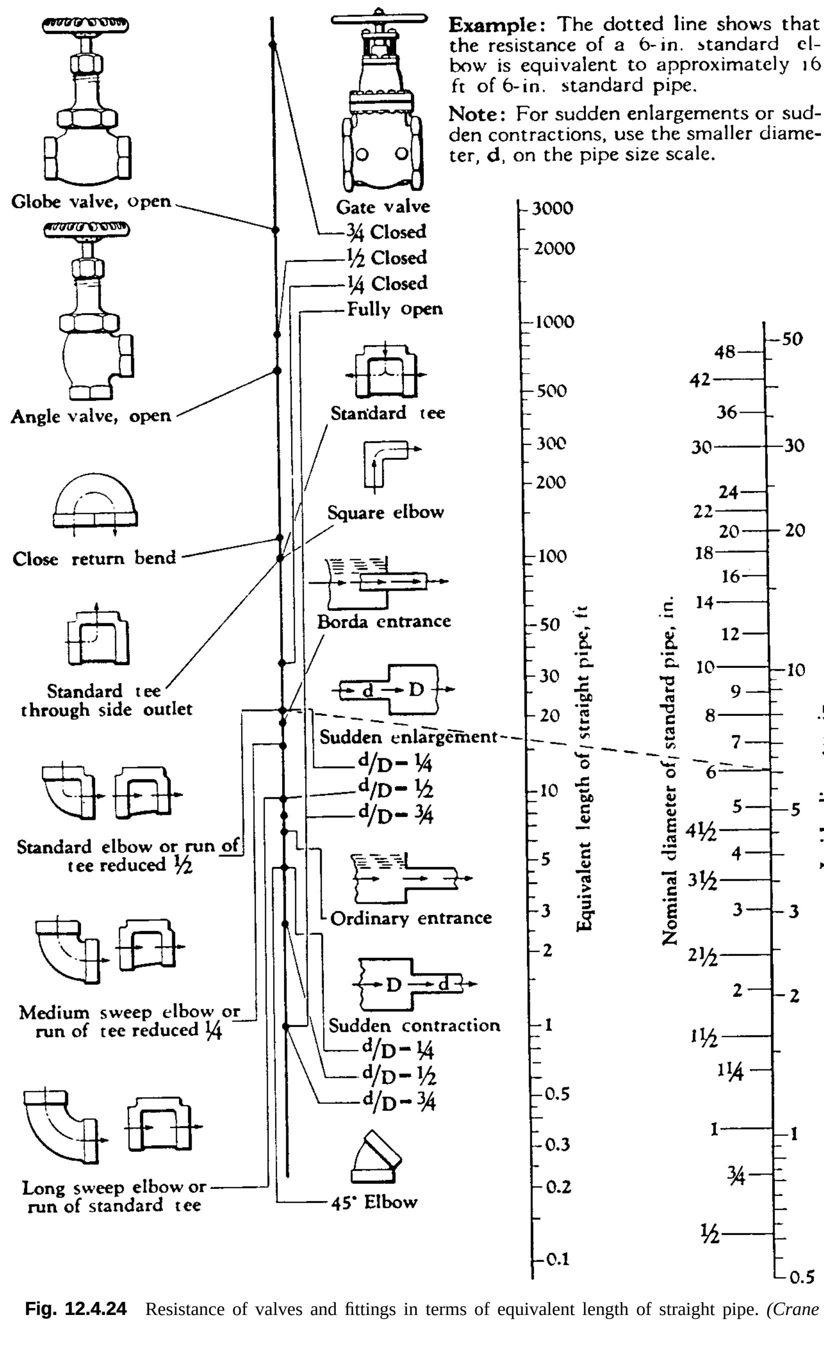


Fig. 12.4.24 Resistance of valves and fittings in terms of equivalent length of straight pipe. *(Crane Co.)*

Table 12.4.40 Medium-Pressure Steam System (30 psig) Pipe Capacities (lb/h)

Pipe size, in	Pressure drop per 100 ft: ⅛ psi (2 oz)	¼ psi (4 oz)	½ psi (8 oz)	¾ psi (12 oz)	1 psi (16 oz)
Supply mains and risers 25–35 psig—max. error 8%					
¾	15	22	31	38	45
1	31	46	63	77	89
1¼	69	100	141	172	199
1½	107	154	219	267	309
2	217	313	444	543	627
2½	358	516	730	924	1,033
3	651	940	1,330	1,628	1,880
3½	979	1,414	2,000	2,447	2,825
4	1,386	2,000	2,830	3,464	4,000
5	2,560	3,642	5,225	6,402	7,390
6	4,210	6,030	8,590	10,240	12,140
8	8,750	12,640	17,860	21,865	25,250
10	16,250	23,450	33,200	40,625	46,900
12	25,640	36,930	52,320	64,050	74,000
Return mains and risers 0–4 psig—max. return pressure					
¾	115	170	245	308	365
1	230	340	490	615	730
1¼	485	710	1,025	1,285	1,530
1½	790	1,155	1,670	2,100	2,500
2	1,575	2,355	3,400	4,300	5,050
2½	2,650	3,900	5,600	7,100	8,400
3	4,850	7,100	10,250	12,850	15,300
3½	7,200	10,550	15,250	19,150	22,750
4	10,200	15,000	21,600	27,000	32,250
5	19,000	27,750	40,250	55,500	60,000
4	31,000	45,500	65,500	83,000	98,000

Table 12.4.41 High-Pressure Steam System (150 psig) Pipe Capacities (lb/h)

Pipe size, in	Pressure drop per 100 ft: ⅛ psi (2 oz)	¼ psi (4 oz)	½ psi (8 oz)	¾ psi (12 oz)	1 psi (16 oz)	2 psi (32 oz)	5 psi
Supply mains and risers 130–180 psig—max, error 8%							
¾	29	41	58	82	116	184	300
1	58	82	117	165	233	369	550
1¼	130	185	262	370	523	827	1,230
1½	203	287	407	575	813	1,230	1,730
2	412	583	825	1,167	1,650	2,000	3,410
2½	683	959	1,359	1,920	2,430	3,300	5,200
3	1,237	1,750	2,476	3,500	4,210	6,000	9,400
3½	1,855	2,626	3,715	5,250	6,020	8,500	13,100
4	2,625	3,718	5,260	7,430	8,400	12,300	19,200
5	4,858	6,875	9,725	13,750	15,000	21,200	33,100
6	7,960	11,275	15,950	22,550	25,200	36,500	56,500
8	16,590	23,475	33,200	46,950	50,000	70,200	120,000
10	30,820	43,430	61,700	77,250	90,000	130,000	210,000
12	48,600	68,750	97,250	123,000	155,000	200,000	320,000
Return mains and risers 1–20 psig—max, return pressure							
¾	156	232	360	465	560	890	
1	313	462	690	910	1,120	1,780	
1¼	650	960	1,500	1,950	2,330	3,700	
1½	1,070	1,580	2,460	3,160	3,800	6,100	
2	2,160	3,300	4,950	6,400	7,700	12,300	
2½	3,600	5,350	8,200	10,700	12,800	20,400	
3	6,500	9,600	15,000	19,500	23,300	37,200	
3½	9,600	14,400	22,300	28,700	34,500	55,000	
4	13,700	20,500	31,600	40,500	49,200	78,500	
5	25,600	38,100	58,500	76,000	91,500	146,000	
6	42,000	62,500	96,000	125,000	150,000	238,000	

12.5 ILLUMINATION

by Abraham Abramowitz

REFERENCES: Amick, ''Fluorescent Lighting Manual,'' McGraw-Hill. ''IES Lighting Handbook'' (1981). Design publications of General Electric Co., North American Philips Co. (successor to Westinghouse Electric Co. Lamp Division), and GTE-Sylvania.

BASIC UNITS

Candela, cd (formerly candle) is the unit of luminous intensity of a light source. One candela is defined as the luminous intensity in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hz (approximately 555 nm) and of which the radiant intensity in that direction 1⁄683 W per steradian (W/sr).

Lumen, lm, is the unit of luminous flux ϕ. It is equal to the flux on a unit surface all points of which are one unit distant from a uniform point source of one candela. Such a point source emits 4π lumens. (For an additional definition of lumen, see the following material on vision.)

Illuminance E is the density of luminous flux on a surface. If the foot is taken as the unit of length and the flux is uniformly distributed over the surface, the density in **lumens per square foot** is called **footcandles, fc;** in SI units **lumens per square metre, lux (lx),** is used. (One footcandle equals 10.76 lux.) In order to make the units comparable, dekalux (10 lux) is frequently used.

The term *illumination* is frequently used for the word *illuminance.* Modern practice reserves *illumination* for the process of lighting and *illuminance* for the result.

Luminance is the luminance intensity of any surface in a given direction per unit of projected area of the surface as viewed from that direction. The unit of luminance is candela/in^2; in SI units cd/m^2 is used. (1 cd/in^2 = 1,550 cd/m^2.) In general, a luminous surface will have a different luminance when viewed from different angles. An important exception is a **perfectly diffuse reflecting (lambertian) surface** which has a constant luminance regardless of the viewing angle. If such a surface has a luminance of 1 cd/in^2, it emits 452 lm/ft^2. **Footlamberts,** fL, in lumens per square foot, is the unit of luminance applied to this case. While this conversion applies only to the perfectly diffuse case, it is frequently used in all cases. Thus, a perfectly diffuse surface with a luminance of 1 cd/in^2 is said to have a luminance of 452 fL. In practice the average lumens emitted per square foot of surface is taken to be the footlamberts. This conversion practice is deprecated.

Subjective brightness is the subjective attribute of any light sensation giving rise to the whole scale of qualities of becoming bright, light, brilliant, dim, or dark. Unfortunately, the term ''brightness'' often is used when referring to luminance.

NOTE. The above definitions are adapted from the ''IES Lighting Handbook.''

Absorption, reflection, and transmission are the general processes by which incident light flux interacts with a medium. **Absorption** is the process whereby incident flux is dissipated. **Reflection** is the process by which the incident flux leaves a surface or medium from the incident side.

NOTE. Reflection may occur as from a mirror (specular reflection), it may be reflected at angles different from that of the incident flux to incident plane (diffuse reflection), or it may be a combination of the two types of reflection.

Transmission is the process by which incident flux leaves a surface or medium on a side other than the incident side. If the light ray is reduced only in intensity, the transmission is called *regular.* If the ray emerges in all directions, transmission is called *diffuse.* Both modes may exist in combination.

The incident flux ϕ_i equals the flux absorbed ϕ_a, reflected ϕ_r, and transmitted ϕ_t. That is,

$$\phi_i = \phi_a + \phi_r + \phi_t$$

Dividing this equation by ϕ_i, we obtain

$$1 = \phi_a/\phi_i + \phi_r/\phi_i + \phi_t/\phi_i$$

or

$$1 = \alpha + \rho + \tau$$

α is the *absorptance,* ρ is the *reflectance,* and τ is the *transmittance.* In each case, the incident flux may be restricted to a single wavelength, a particular direction, and a given solid angle. These must be specified.

The **wavelength** of electromagnetic radiation is measured in metres. For the frequencies involved in illumination, the wavelength is given in nanometres, nm, equal to 10^{-9} m, and micrometres, μm, equal to 10^{-6} m.

VISION

Most engineering designs, (bridges, structures, roads etc.) are based on strength and are not concerned with the way the human organism reacts. The **response of the eye** is central to illuminating engineering. The **lens** of the **eye** focuses an image on the **retina.** Here a photochemical process takes place which sends nerve impulses to the brain via the optic nerve. The amount of light entering the eye is controlled by the **pupil.** The normal eye automatically accommodates itself to focus on an object, while the pupil adjusts itself to allow for a high or low level of object luminance. The sensors in the eye are known as **rods** and **cones.** The cones are clustered in a small central part of the retina called the **fovea.** They transmit a sharp image to the brain and give color response. Outside the fovea the rods predominate. They give neither a sharp image nor a color response. When the luminance of the visual field is 0.01 fL or lower, as at night, seeing is due to the rods only and is called **scotopic vision.** At higher levels, with the cones primarily involved, seeing is called **photopic vision.** There is an intermediate region called **mesopic vision.**

The response of the eye to colors of different wavelengths is given in Fig. 12.5.1. Note the shift in maximum response at lower luminance levels called the ''Purkinje shift.'' Note that these curves are relative ones, and that the two peaks do not correspond to the same levels of illumination. The **luminous efficacy** (lumen output per radiated watt) is 683 lm/W at the wavelength of maximum photopic response 555 nm. For white light, radiation which has the characteristic of an equal energy spectrum with all the energy in the visual region, it is approximately 220 lm/W.

Spectral Lumen If the response curve of the eye for photopic vision, versus λ in nanometers, is expressed as $k(\lambda)$, and the spectral power function of the source in watts per nanometer is taken to be $Q_e(\lambda)$, then the luminous flux is given by the equation

$$\phi_{\text{lumens}} = 683 \int_{380}^{780} k(\lambda)\, Q_e(\lambda)\, d(\lambda) \qquad (12.5.1)$$

LIGHT METERS

Early light meters compared the luminance of a diffuse highly reflecting surface with that obtained from a calibrated standard. The most common light meter in use today is similar to a photographic exposure meter. A photovoltaic cell is directly connected to a sensitive microammeter calibrated in footcandles (or dekalux). The best meters (called color-corrected) have a response similar to that of the eye in photopic vision. Special shapes are used on the cover to avoid total reflection of

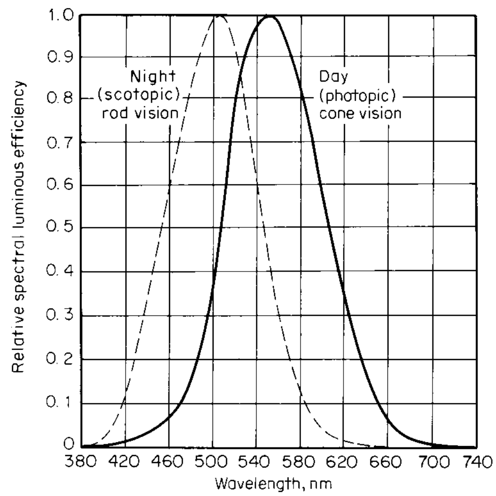


Fig. 12.5.1 Relative spectral luminous efficiency curves for photopic and scotopic vision, showing the Purkinje shift on the wavelength of maximum efficiency. Note the wavelength of the visual region of the electromagnetic spectrum. *(IESNA Lighting Handbook, 5th ed. This material has been modified from its original version and is not reflective of its original form as recognized by the IESNA.*)

light from the glass surface of the cell. Such meters are said to be cosine law corrected. The microammeter is frequently replaced with an electronic amplifier using an analog or digital readout.

LIGHT SOURCES

The original and still major source of light is the sun. Next came fire, derived from candles, oil, and gas lamps. With the discovery of electricity came arc lamps, gas-discharge lamps, and hot-filament lamps. ''Flame'' or hot sources give a continuous spectrum. Gas-discharge devices such as neon lamps and mercury-arc lamps give discrete, or line, spectra. The lines may be modified in various ways: by pressure broadening, use of phosphor coatings (to convert ultraviolet radiation into visible light), and using a mixture of gases. The continuous spectra of phosphors have colors which depend upon the mixture used. Light-emitting diodes, LED, consisting of a layer of two different semiconductors, are in use for display purposes.

Color Temperature and Luminance

In general, three quantities are required to specify the color of a light and its luminous level. However, an approximate designation is used by specifying the temperature of a hot (black-body) emitter whose color almost matches that of the light. The **color temperature** of daylight is about 6000 K and that of tungsten lamps about 2300 to 3300 K.

Table 12.5.1 Approximate Luminances of Various Light Sources (IES)

Light source	Approximate average luminance	
	cd/in²	kcd/m²
Clear sky	5.16	8
Candle flame (sperm)	6.45	10
60-W inside frosted bulb	77.4	120
60-W ''white bulb''	19.35	30
Fluorescent lamp, cool white, T-12 bulb, medium loading	5.3	8.2
High-intensity mercury-arc type H33, 2.5 atm	968	1,500
Clear glass neon tube 15 mm, 60 mA	1.03	1.6

Different light sources have markedly different luminances as shown in Table 12.5.1. ''Large'' sources have low luminances, while ''small'' sources have high luminances.

Lamps

Electric lamps are the principal source of artificial light in common use. They convert electrical energy into light or radiant energy.

An **incandescent-filament lamp** contains a filament which is heated by the current passing through it. The filament is enclosed in a glass bulb which has a base suitable to connect the lamp to an electrical socket. To prevent oxidation of the filament at elevated temperature, the bulb is evacuated of air or filled with an inert gas. The bulb also serves to control the light from the incandescent filament, which is essentially a point source. High luminance of the source is typically reduced by acid etching to frost the inside surface of the bulb. Silica coating will also provide additional diffusion and can alter the color of the light emitted. Portions of the bulb's interior can be covered with reflecting material to give a predetermined direction to the emitted light. Chemical tinting of clear glass bulbs provides a variety of colors. Whenever the color that is normally produced by an incandescent filament is changed, the filtering process removes from the radiated light the energy of all wavelengths except those necessary to produce the desired color. This subtractive method of color alteration is less efficacious than the generation of light of varying colors by gaseous discharge.

Sizes and **shapes** of lamp bulbs are designated by a letter code followed by a numeral; the letter indicates the shape (Fig. 12.5.2), and the number indicates the diameter of the bulb in eighths of an inch. Thus a T-12 lamp has a tubular shape and is $1\frac{4}{8}$ or $1\frac{1}{2}$ in in diameter.

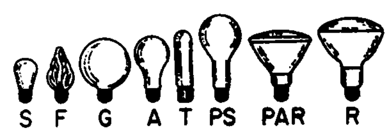


Fig. 12.5.2 Typical filament lamp shapes: S, straight; F, flame; G, globe; A, general service; T, tubular; PS, pear shape; PAR, parabolic; R, reflector.

Incandescent lamps are available with several **types of bases** (Fig. 12.5.3). Most general-service lamps have medium screw bases; larger or smaller screw bases are used depending on lamp wattage. Bipost and prefocus bases accurately position the filament, as in optical projection systems. Bipost lamps also serve where ruggedness and greater heat dissipation are required.

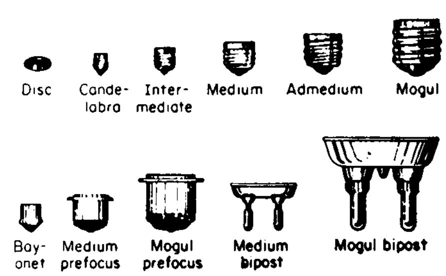


Fig. 12.5.3 Typical incandescent lamp bases.

Incandescent-lamp filaments are generally constructed of tungsten. Tungsten has a high melting point and a low vapor pressure, which permits high operating temperatures without evaporation: the higher the operating temperature, the higher the efficacy (lumens per watt) and the shorter the life. Filament evaporation throughout the life of the lamp causes blackening of the bulb and thinning of the filament with consequent lower light output. Argon-nitrogen gas filling reduces the rate of evaporation. Figure 12.5.4 shows steps in lamp manufacture.

Tungsten filaments are also placed in compact quartz tubes filled with a halogen atmosphere where the tungsten halide lighting source continuously returns evaporated tungsten particles to the filament. The inside walls do not blacken, and light output remains fairly constant throughout the life of the lamp.

For exposed outdoor lamp signs, **gas-filled incandescent lamps** are often used, especially when high-speed animation is to be depicted by

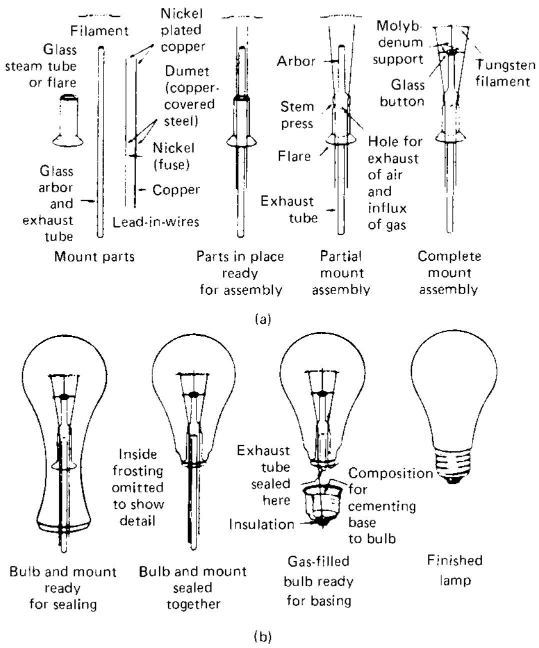


Fig. 12.5.4 Steps in the manufacture of a typical filament incandescent lamp. (*a*) Assembly of inner structure; (*b*) final assembly. *(IESNA. This material has been modified from its original version and is not reflective of its original form as recognized by the IESNA.)*

the on-off sequencing of the lamps. The lamp envelope is filled with a gas which enhances the speed with which the filament is heated and cooled. The very fast quenching of the filament without the usual decay trail of light permits a sharply defined illusion of motion.

A **fluorescent lamp** consists of a glass tube coated on the inside with phosphor powders which fluoresce when excited by ultraviolet light; filament electrodes are mounted in end seals connected to base pins (Fig. 12.5.5). The tube is filled with rare gases (such as argon, neon, and

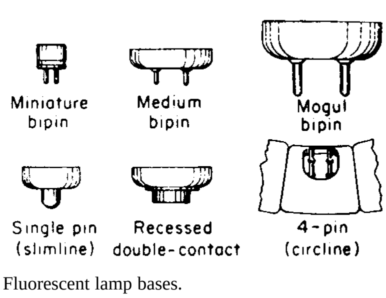


Fig. 12.5.5 Fluorescent lamp bases.

krypton) and a drop of mercury (Fig. 12.5.6), and operates at a relatively low pressure. In operation, electrons are emitted from the hot electrodes. These electrons are accelerated by the voltage across the tube until they collide with mercury atoms, causing them to be ionized and excited. When the mercury atom returns to its normal state, mercury spectral lines in both the visible and the ultraviolet region are generated. The low pressure enhances ultraviolet radiation. The ultraviolet radiation excites the phosphor coating to luminance. The resulting light output is not only much higher than that obtained from the mercury lines alone but also results in a continuous spectrum with colors dependent upon the phosphors used.

As with all gas-discharge devices, these lamps have negative voltampere characteristics. Unless the voltage difference between the applied voltage and the lamp operating voltage is absorbed in some way, damaging currents will result. A reactor is used in series with the lamp. It may be capacitive or inductive (many turns of wire on an iron core). The supply voltage should be at least twice the lamp operating voltage. Where this is not the case, the supply voltage (up to 277 V is used) is stepped up by an autotransformer. The necessary reactance is frequently part of the transformer leakage inductance.

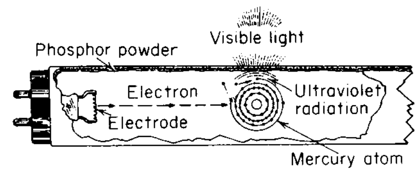


Fig. 12.5.6 Fluorescent lamp operation. *(Westinghouse.)*

For starting purposes, voltages higher than twice lamp operating voltages may be used. For minimum line current a power-factor-correcting capacitor is used and assembled with the autotransformer. A capacitor is put across the lamp to reduce radio-frequency interference with nearby radio receivers. All these elements are placed inside a case filled with a potting compound. The assembly is called a **ballast.** The object of the compound is to reduce noise from the core lamination vibrations and to improve heat dissipation. Built-in thermal protectors, which deenergize the ballast when dangerous temperatures are reached, are now required in the United States. Ballast manufacturers rate their units by noise levels. Some ballasts use solid-state, high-frequency generators.

To start a fluorescent lamp, electron emission from the electrodes must be induced. Two methods are generally employed: (1) the filament electrodes are heated by passing current through them; (2) a high voltage, sufficient to start an electric discharge in the lamp, is applied across it. Once a discharge starts, mercury-ion bombardment keeps the filaments at a hot electron-emitting temperature. Lamps are designed for either type of operation. The first group is further divided into preheat lamps and rapid-start lamps. Some lamps can be used for both types of circuits. The lamp current is carried primarily by electrons emitted from the filaments. The end or weakening of electron emission is an important cause of the end of lamp life.

Preheat circuits contain starters (Fig. 12.5.7) which are switches, closed when power is first applied, permitting current to flow and preheat the electrodes. After a predetermined period of time, the starter switch opens, throwing a potential across the lamp which starts the discharge. Lamps used for preheat circuits have bipin bases (Fig. 12.5.5).

Instant-start circuits have ballasts which apply sufficient voltage across the lamp to induce current flow without preheating the electrodes. **Slimline lamps** are the principal instant-start type. They have single-pin bases because no preheating is required, are available in sizes up to 8 ft in length, and can have varying lumen outputs dependent upon the ballast current rating and wattage. Because of their high starting voltage, they generally employ spring-loaded push-pull lampholders which disconnect the ballast circuit unless the lamps are properly seated in position.

Instant-start lamps are sometimes available with bipin bases similar to those used in preheat lamps. In these instances the lead wires from the pins are connected together inside the lamp. These lamps, marked ''instant start,'' are not interchangeable with rapid-start equipment. Cold-cathode lamps employ the instant-start principle, have cylindrical iron electrodes, and tend to be less efficacious at shorter lengths because of high wattage losses at the electrodes. They are limited to low current densities because the electrodes operate at temperatures below that necessary for thermionic emission. Cold-cathode lamps, whose operation is not affected by dimming or flashing, have long life and are generally used for custom-built shapes and patterns that require bending, such as for electric signs.

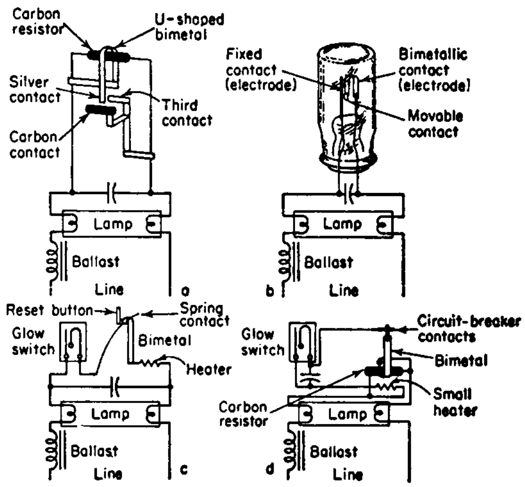


Fig. 12.5.7 Starter switches for preheat cathode circuits. *(IESNA)*

Rapid-start circuit ballasts have separate windings for the electrodes which are immediately and continuously heated when the circuit is energized. This rapid heating causes sufficient ionization in the lamp for a discharge to start from the voltage of the main ballast windings. Two-lamp rapid-start ballasts are of the series sequence type, in which the lamps start in sequence and, when fully lighted, operate in series.

A new type **screw-in fluorescent lamp** with built-in ballast can be used in a standard medium-screw socket. These lamps consume less power than incandescent lamps for the same luminance; accordingly, albeit their first cost is significantly higher, they are expected to prove to be more economical by virtue of their reduced power consumption and much longer life. The verdict of the consuming public is yet to come as significant numbers of them make their way into household and commercial applications.

Fluorescent lamps used in low-ambient-temperature applications, as in outdoor signs, are of the **high-output (HO)** type, and require special high-output ballasts to permit the lamps to maintain their luminance at lower operating temperatures.

Typical fluorescent lamp circuits are shown in Fig. 12.5.8.

High-intensity-discharge lamps consist of tubes in which electric arcs in a variety of materials are produced. Outer glass jackets provide thermal insulation in order to maintain the arc tube temperature. The temperature and amount of material is controlled so that the discharge operates in a vapor pressure of several atmospheres. This results in enhancing the radiation in the visible region.

Mercury-vapor lamps consist of mercury-argon-filled quartz tubes surrounded by a nitrogen-filled glass jacket. Clear lamps radiate the visible mercury lines (bluish green). Ultraviolet radiation is absorbed to some extent by the outer jackets. The color of the light and the lumen output is improved by coating the inside of the outer jackets with a phosphor. When excited by the ultraviolet radiation of the arc, the phosphors add light in the red part of the spectrum to the output. The resulting lamps are called white, color improved, or deluxe white. The lamps start by a discharge in argon between an electrode and a starting electrode (see Fig. 12.5.9). As the mercury vaporizes, the pressure builds up and the discharge transfers to a mercury discharge. This takes several minutes. After shutdown, the lamps cannot be restarted until the inner tube pressure drops so that an argon discharge can start.

Metal halide (multivapor) lamps use small quantities of sodium, thallium, scandium, dysprosium, and indium iodides in addition to the usual mercury-argon mix. Color is improved and output substantially increased over high-intensity-discharge lamps using mercury alone. While the construction is similar to mercury lamps, a bimetal switch is built into the lamp to short out the starting resistor after the lamps start. A vacuum jacket is used around the quartz discharge tube (see Fig. 12.5.9).

High-pressure sodium-vapor lamps use metallic sodium sealed in translucent aluminum oxide tubes. This material is used to withstand the corrosive effect of hot sodium vapor. For starting purposes a xenon fill gas and a sodium-mercury amalgam is used. Arc temperatures are maintained by an outer vacuum jacket. The lamp is started by generating a high-voltage pulse for about a microsecond (see Fig. 12.5.9).

High-pressure discharge lamps, like fluorescent lamps, require ballasts. These provide the necessary voltage, reactances, and power-factor-correcting capacitors. Typical circuits are shown in Fig. 12.5.8.

Table 12.5.2 Comparable Luminous Efficacies (lumens/watt)* (IES)

Lamp	Lumens/watt
Tungsten incandescent	8–33
High-intensity mercury†	24–63‡
Fluorescent†	19–100‡
Metal halide (multivapor)†	69–125
High-pressure sodium†	73–140

* Constantly being improved.
† Ballast losses not included.
‡ Depends upon lamp size, type, and color.

Comparative lamp efficacies (lumens/watt) are given in Table 12.5.2. Lamp data for commonly used incandescent, fluorescent, and high-intensity-discharge lamps are listed in Tables 12.5.3, 12.5.4, and 12.5.5.

Luminaires

Luminaires are generally categorized as **industrial, commercial,** or **residential.** Use within these categories usually determines the quality and ruggedness of materials of construction. Generally speaking, style, ornament, and in most cases low cost are prime considerations for residential fixtures. Industrial fixtures require low maintenance, low operating cost, efficiency, and durability. Commercial fixtures combine the elements of all of these and place heavy emphasis on visual comfort.

Luminaires are classified by the International Commission on Illumination (ICI) in accordance with the percentages of total luminaire output emitted above and below the horizontal (Fig. 12.5.10). Industrial fixtures usually are direct or semidirect.

Table 12.5.3 Incandescent-Lamp Data

Watts	Bulb size	Initial lumens	Rated life, h
25	A-19	230	2,500
40	A-19	474	1,500
60	A-19	1,060	1,000
75	A-19	1,190	750
100	A-19	1,740	750
150	A-21	2,873	750
200	A-23	4,000	750
300	PS-30	6,130	750
500	PS-35	10,675	1,000
750	PS-52	16,935	1,000
1,000	PS-52	23,510	1,000

For general-service lamps 115-, 120-, and 125-V service, inside frosted.
NOTE: Lamps are constantly being improved. The latest manufacturer's data should be used for accuracy.
SOURCE: ''IESNA Handbook,'' 8th ed., 1993, reprinted with permission. (This material has been modified from its original version and is not reflective of its original form as recognized by the IESNA.)

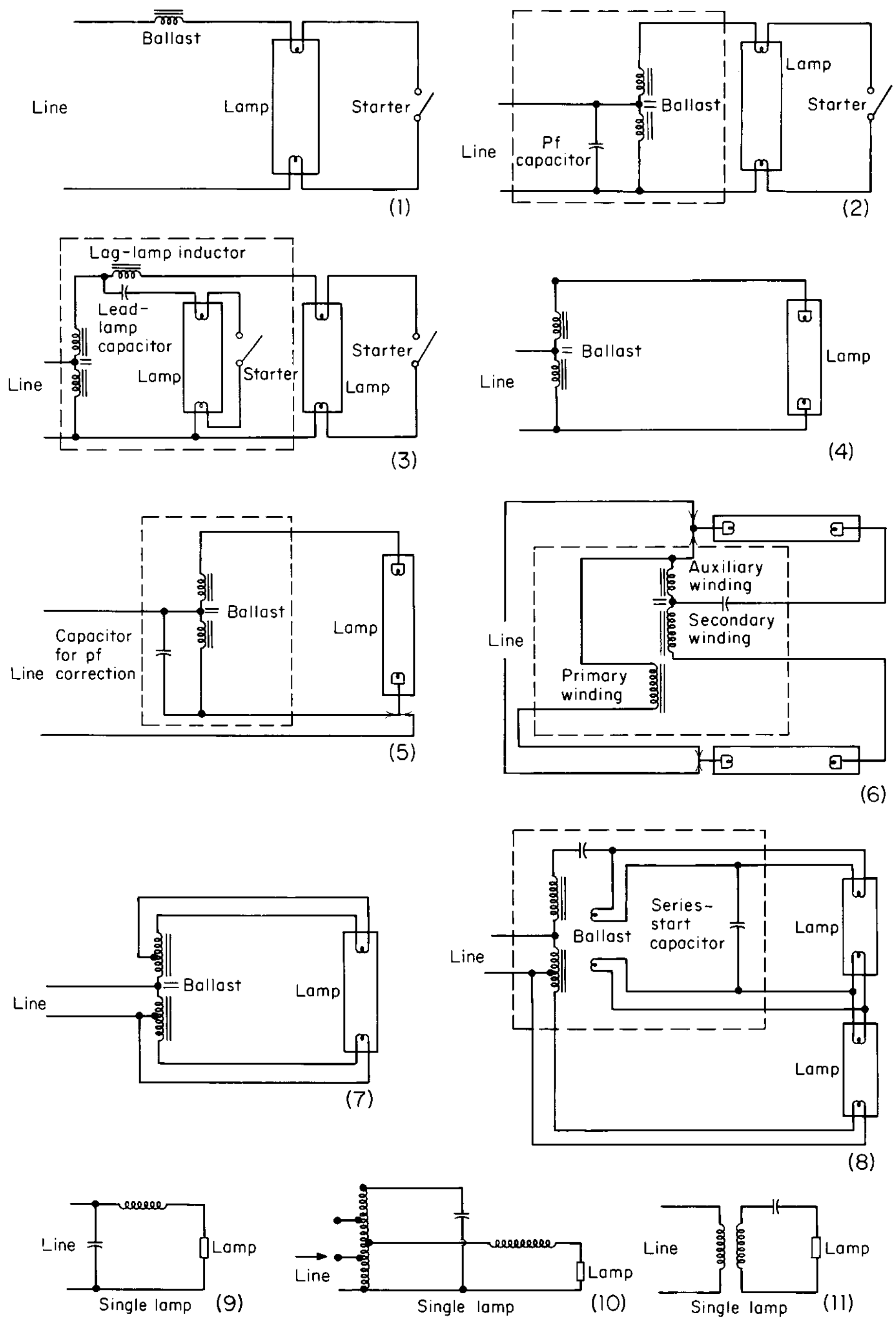


Fig. 12.5.8 Typical circuits for fluorescent and high-intensity discharge lamps. (1) Basic preheat circuit; (2) preheat circuit with autotransformer to step up voltage and capacitor to correct power factor; (3) leadlag preheat; (4) basic instant-start circuit; (5) instant-start circuit showing disconnect lampholder; (6) typical series instant-start circuit; (7) basic rapid-start circuit; (8) two-lamp series lead circuit; (9) mercury reactor ballast circuit; (10) mercury autotransformer circuit; (11) mercury stabilizing ballast circuit. *(GE.)*

Table 12.5.4 Fluorescent Lamp Data*

Lamp designation	Nominal length		Approx lamp			Single-lamp circuit watts		Two-lamp circuit watts		Cool white lumens at	Rated average life, h
	mm	in	Current (ma)	Volts	Watts	Ballast	Total	Ballast	Total	100 h	3 h burning/start
Preheat starting†											
F15T12	450	18	325	47	15	4.5	19.5	9	39	830	9,000
F20T12	600	24	380	57	20.5	5	25.5	10	51	1,283	9,000
F30T8	900	36	355	99	30.5	10.5	41	17	78	2,330	7,500
F40T12	1,200	48	430	101	40	12	52	16	96	2,150	15,000
F90T12	1,500	60	1,500	65	90	20	110	24	204	6,025	9,000
Rapid start† (lightly loaded lamps)											
F30T12	900	36	430	81	33.5	10.5	44			2,210	18,000
F40T12	1,200	48	430	101	41	13	54	13	95	3,150	21,000
Rapid start† (medium loaded lamps)											
F48T12	1,200	48	800	78	63		85		146	4,300	12,000
F72T12	1,800	72	800	117	87		106		200	6,650	12,000
F96T12	2,400	96	800	153	113		140		252	9,150	12,000
Rapid start† (highly loaded lamps and power grove§)											
F48T12/48PG17	1,200	48	1,500	84	116		146		252	6,900/7,450	9,000
F72T12/72PG17	1,800	72	1,500	125	168		213		326	10,640/11,500	9,000
F96T12/96PG17	2,400	96	1,500	163	215		260		450	15,250/16,000	9,000
Instant start† (slimline)											
F48T12 lead/lag	1,200	48	425	100	39			26	104	3,000	7,500–12,000
F48T12 series	1,200	48	425	100	39			17	95	3,000	7,500–12,000
F72T12 lead/lag	1,800	72	425	149	57			47	161	4,585	7,500–12,000
F72T12 series	1,800	72	425	149	57			25	139	4,585	7,500–12,000
F96T12 lead/lag	2,400	96	425	197	75			40	190	6,300	12,000
F96T12 series	2,400	96	425	197	75			22	172	6,300	12,000
Circline lamps¶											
C8T9	200 OD	8¼ OD	370	61	22.5	7.5	30			1,065	12,000
C12T9	300 OD	12 OD	425	81	33	9	42			1,870	12,000
C16T9	400 OD	16 OD	415	108	41.5	16.5	58			2,580	12,000

SOURCE: Adapted from ''IESNA Handbook,'' 8th ed., 1993, reprinted with permission. (This material has been modified from its original version and is not reflective of its original form as recognized by the IESNA.)
* Lamps are continuously being improved. For design purposes consult the latest manufacturers' data. Data shown is for standard lamps. Energy-saving ballasts and fluorescent lamps are available.
† The first number is the ''nominal'' lamp wattage, while the second number is the tube diameter in eighths of an inch.
§ General Electric Co. trademark.
¶ The first number is the nominal outside diameter of the lamp, while the second number is the tube diameter in eighths of an inch.

Table 12.5.5 High-Intensity-Discharge Lamp Data*

Watt	Nominal lamp Voltage	Nominal lamp Amperes	Approx ballast loss, watts	Approx initial lumens† (100 h)	Life, h
Mercury lamps					
100	130	0.85	10–35	2,500–4,400	24,000+
175	130	1.5	15–35	6,000–8,600	24,000+
250	130	2.1	25–35	8,000–13,000	24,000+
400	135	3.2	20–55	15,000–23,000	24,000+
700	265	2.8	35–65	36,000–43,000	24,000+
1,000	265	4.0	40–90	43,000–63,000	24,000+
Metal-halide lamps					
175	130	1.4	35	12,000–14,000	7,500
400	135	3.2	60	31,000–40,000	15,000–20,000
1,000	250	4.3	50–100	105,000–125,000	10,000–12,000
High-pressure sodium-vapor lamps					
250	100	3.0	55–60	25,000–30,000	24,000
400	100	4.7	65–75	47,500–50,000	24,000

SOURCE: Abstracted from ''IES Lighting Handbook'' and General Electric Co. data.
* Lamps are continuously being improved. For design purposes, consult the latest manufacturers' data.
† Depending upon ballast used, lamps may have outputs which change with burning position.

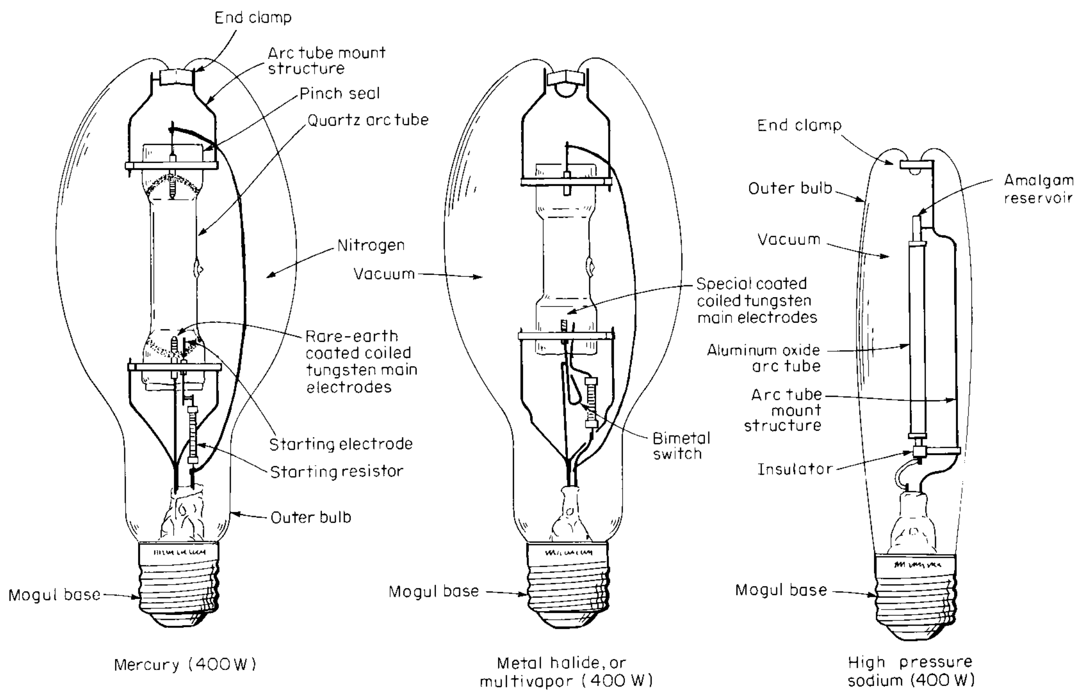


Fig. 12.5.9 High-output lamps. *(GE.)*

Luminaires control the source of light so that it can be better used for a given seeing task. Materials used in luminaires are designed to reflect, refract, diffuse, or obscure light.

Reflectors are commonly made of specular alzak aluminum, glass, baked-enamel steel, and porcelain-enamel steel.

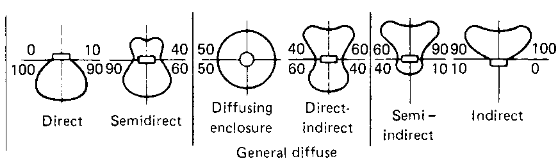


Fig. 12.5.10 Light distribution curves by ICI classifications of luminaires. Upward and downward components are in percentage ranges. *(IES.)*

Lenses with prismatic patterns refract light sources to disperse the rays or to direct them most effectively. Lenses are of glass, acrylic plastic (Plexiglas), or polystyrene. **Glass** is generally superior for incandescent fixtures because of its heat resistance. Fluorescent lamps with **acrylic** lenses have a life at least twice that of **polystyrene** because of their color stability. **Translucent** glass and plastic are used in bottom lenses, louvers, and side panels to diffuse light and to obscure light sources. Baked-enamel steel **louvers,** in egg-crate, concentric ring, or cellular configurations are widely used to shield light sources from normal viewing angles.

Fixture bodies, trims, and lens frames are commonly constructed of steel, electrogalvanized, and/or treated with a rust-inhibiting coating, and painted with several coats of baked enamel. Stamped, spun, cast, and die cast aluminum are also used.

PRESCRIBING ILLUMINATION

The object of a **lighting design** is to provide sufficient illuminance for a given seeing task without introducing discomfort. Sufficient light is not difficult to obtain with modern light sources, but unless properly placed and controlled, uncomfortable, glaring light will result.

A given task has a size, luminance contrast, luminance, and color. The luminance of a perfectly diffusing reflecting surface is given by

$$L = E\rho \qquad (12.5.2)$$

where E is illuminance in footcandles, ρ its reflectance (ratio of reflected light flux to incident flux), and luminance L is in footlamberts. The contrast C between two adjacent areas is given by

$$C = (L_b - L_o)/L_b \qquad (12.5.3)$$

where L_b is the luminance of the larger or background area and L_o is the object or task luminance for a given illuminance E. Substituting Eq. (12.5.2) into Eq. (12.5.3),

$$C = \frac{E\rho_b - E\rho_o}{E\rho_b} = (\rho_b - \rho_o)/\rho_b \qquad (12.5.4)$$

Thus, contrast is basically a function of the task-to-background reflectance. Most surfaces are not perfectly diffuse and require the use of the luminance factor β (ratio of actual luminance for a given viewing angle to the illumination under actual conditions) instead of ρ. The contrast which can just be seen or detected (minimum perceptible contrast) is a function of background luminance for a given task.

Unfortunately most visual tasks have mirrorlike (specular) or semimirrorlike surfaces. This results in reducing the work contrast. Where a highly luminous object such as an incandescent-lamp filament is reflected from a polished surface, ''reflected glare'' results. Reflections of a large luminous area by matte or semimatte material results in ''veiling glare.'' For work on a horizontal surface, the line of sight from the eye for most people is from 0 to 40° from the vertical, with a peak angle of about 25°. If light from the source is directly reflected into the eyes, contrast and resulting visibility are greatly reduced. When a highly luminous source is directly reflected into the eye, it is possible to completely obliterate a task. Veiling reflections are controlled by proper luminaire design and placement of fixtures. Some designs keep flux out of the 0 to 40° zone. As far as possible the work area should have a matte surface without shining details, and light should come from the side or behind the worker.

In addition to veiling reflectance, there is a reduction in contrast due to light directly entering the eye from the source. This is called the disability glare effect. It produces a light veil over the image of the task on the retina. It is not a serious problem in interior lighting, but it is important in roadway lighting and similar situations.

Visual-Comfort Criteria High luminances directly or reflected in the field of view can cause discomfort without necessarily interfering with seeing even though visual performance may be impaired. This discomfort glare can be caused by direct glare from sources which have too high a luminance, are inadequately shielded, or have too great an area. Lighting systems are rated by a **visual-comfort probability, VCP,** expressed as a percentage of people who, if seated in the most undesirable location, will be expected to find it acceptable. (For a complete description of VCP, see the IESNA Handbook.) If the following conditions are met, direct glare will not be a problem in lighting installations:

1. The VCP is 70 or more.
2. The ratio of maximum-to-average luminaire luminance does not exceed 5 : 1 (preferably 3 : 1) at 45, 55, 65, 75, and 85° from the nadir crosswise and lengthwise.
3. Maximum luminaire luminances crosswise and lengthwise do not exceed the following values:

Angle above nadir, deg	*Maximum luminance*	
	cd/m²	*fL*
45	7,710	2,250
55	5,500	1,605
65	3,860	1,125
75	2,570	750
85	1,695	495

Design of Interior Lighting Systems

Lighting is as much an art as a science. While many studies have been made on what constitutes adequate lighting along with proper quality, the effect to be achieved depends upon the designer. In this section emphasis will be primarily on achieving adequate illumination.

The design approach is to consider the space to be lighted and the task to be performed. An illuminance is then selected. A suitable luminaire is picked, and calculations are made in order to determine the number and layout of the fixtures. The overall quality is then checked. If unsatisfactory, a new layout is made. An economic study is made to check costs. If these are too high, new layouts are studied until all design restraints are met.

Selection of illuminance Levels

From 1958, the Illuminating Engineering Society (IES) published single-value illuminance levels. Their latest publication, the 1993 ''IESNA Lighting Handbook,'' gives a range of values which permits lighting designers to tailor lighting systems to specific needs. This flexibility permits levels to be adjusted for (1) the visual task; (2) the age of the observers; (3) the need for speed and/or accuracy for visual performance; (4) the reflectance of the task. An illumination-level guide for selected tasks is given in Table 12.5.6. The data are based on an assumption of average conditions for people, tasks, and visual performance requirements. For other conditions see the 1993 ''IESNA Lighting Handbook.''

Room, Furniture, and Equipment Finishes

The color and finish of rooms, furniture, and equipment are important in the overall lighting design. Best results are obtained when the lighting designer coordinates his or her work with the architect, interior decorator, or plant designer.

Table 12.5.6 Illuminance Guide for Selected Tasks

	Footcandles (lm/ft)	Lux (lm/m²)
Commercial drafting		
Conventional	150*	1,600*
Libraries		
Reading good print, typed originals	30	320
Reading small print, handwriting, photocopies	75	800
Active stacks (vertical, illumination)	30	320
Offices		
Conference rooms—conferring	30	320
Conference rooms—typical visual tasks	75–100	800–1,080
Corridors, stairs, elevators	20	220
General tasks, varying difficulty	100	1,080
Lobbies, reception areas	30	320
Private	75	880
Rest rooms	30	320
Video display areas	75	800
School		
Classrooms, laboratories	75	800
Shops	100	1,080
Sight-saving rooms, hearing-impaired classes	150	1,600
Store		
Mass merchandizing, high activity	100	1,080
Self-service	200	2,200
Circulation, low activity	30	320
Feature displays, low, medium, high activity	150,* 300,* 500*	1,600,* 3,200*, 5,400*
Industrial		
Garages		
Repair	75	800
Active traffic areas	15	160
Loading platform	20	220
Machine shops and assembly areas		
Rough bench-machine work, simple assembly	50	540
Medium bench-machine work, moderately difficult assembly	100*	1,080*
Difficult machine work, assembly	150*	1,600*
Fine bench-machine work, assembly	300*	3,200*
Receiving and shipping	30	320
Warehouse storage rooms		
Active large items	15	160
Active small items, labels	30	320
Inactive	5	54
Outdoor areas		
Storage yards		
Active	20	220
Inactive	1	11
Parking areas		
Open, high activity	2	22
Open, medium activity	1	11
Covered parking, pedestrian areas	5	54
Covered night entrance	5	54
Covered day entrance	50	54

SOURCE: Adapted from General Electric Co. design data.
* Requires supplementary lighting. Care should be taken that the supplementary lighting does not introduce direct and reflected glare.

A color scheme should be selected to give light reflectance values as follows:

Area or unit	*Percent reflectance*
Ceilings	70–90
Floors	20–40*
Walls, draperies	40–60†
Bench top, desks, machine, and equipment	25–45

* In storage areas, keep reflectance of aisle floors as high as possible in order to reflect light onto the lower shelves. This should also be done where the underside of objects has to be seen.

† These values should be 30 to 40 where video display terminals (VDTs) are used to avoid veiling reflections in the VDT faces.

The color and finish of a space and equipment therein sets the psychological feel of the space. For example, the trend is away from drab finishes on machinery and dark gray filing cabinets. Colors such as yellow, orange, red, and light gray seem to advance toward the eye. They tend to make large spaces feel smaller. Receding colors such as violet, blue, blue green, and dark grays make small spaces feel larger. Some colors are used for safety purposes. Various areas are painted to designate safe or hazardous locations in a fashion similar to piping identification discussed in Sec. 8. These colors have been carefully standardized in ANSI Z53.1-1979.

Designating Color

In order to be able to obtain designed values of a lighting system, it is necessary to be able to specify the exact color wanted. Many methods have been devised for so doing. One method uses carefully controlled sets of colored chips, each one of which has a particular designation. The desired color is matched against these chips. The **Munsell system** uses *scales of hue* (the actual basic color such as red), *value* (a 10-step scale ranging from black through grays to white), and *chroma* (the amount of gray mixed in with the color). This system is used by many manufacturers to designate their colors. The **Ostwald system** describes color in terms of *color content, white content,* and *black content.* The **Inter-Society Color Council–National Bureau of Standards** (ISCC-NBS) **method** designates one-inch square samples with names. For color designation by the **ICI method,** a spectroradiometric curve of the source is determined together with a spectrophotometric curve of the reflecting or transmitting surface. By mathematical manipulation using spectral tristimulus values, chromaticity coordinates are obtained. See the IESNA Handbook for details. Chromaticity coordinates are extensively used for fluorescent lamp colors. These coordinates can be measured directly by photoelectric colorimeters. They are designed with filter photocell responses to be close to each of the ICI tristimulus values. Built-in logic circuitry results in direct reading of the chromaticity. Incandescent and vapor-type lamp colors are specified by color temperature.

LIGHTING DESIGN

Interior lighting is designed by the **lumen** method. This takes into account the interreflections of light inside a room. The average illuminance on the work plane equals the incident luminous flux ϕ divided by the area, or $E = \phi/A$. Lumens reaching the work plane is equal to lamp lumens multiplied by the **coefficient of utilization** CU. This factor is a function of room size, shape, and finish, mounting height of fixture, and type of luminaire used. The lumens ϕ_L initially available from the lamps may be reduced by ambient temperature, lower voltage, and the ballast used. As time goes by the room surfaces and luminaires become dirty, which further reduces the illuminance. In addition, lamp output falls, and some of them burn out. The total effect of all these factors is expressed by the *light-loss factor* LLF. The maintained illuminance E_m is the initial illumination times the LLF, or

$$E_m = (\phi_L \times \text{CU} \times \text{LLF})/A \qquad (12.5.5)$$

The required maintained illuminance is selected from Table 12.5.6 or from the more extensive data in the IESNA Handbook. A fixture and lamp is selected, and Eq. (12.5.5) is solved for the necessary lamp flux ϕ_L. The number of luminaires N is found by dividing the total lamp lumens ϕ_L by the lumens per fixture ϕ_F. A trial layout is then made. A simple layout keeps spacing between units equal to twice the distance between fixtures and wall. Spacing is checked against the maximum allowable luminaire spacing from manufacturers' data to ensure uniform illumination. However, this criterion results in inadequate lighting near the walls. In order to light desks and benches along the walls, a spacing of 2½ ft from the luminaire center to the wall is used. The ends of fluorescent luminaire rows should be 6 to 12 in from the walls with a maximum distance of 2 ft.

Wall and ceiling cavity luminances can be obtained by using luminance coefficients (LC) for the fixtures (see the IESNA Handbook). For interior areas, maximum luminance ratios should be 3 : 1 or 1 : 3 between tasks and immediate surround, and 10 : 1 or 1 : 10 between tasks and remote surfaces. To ensure eye comfort, the visual-comfort probability (VCP) is investigated.

The **coefficient of utilization** is found by using the **zonal-cavity** method. In this method effects of the room proportion, luminaire suspension lengths, and work-plane height on the CU are found by dividing the room into three cavities as shown in Fig. 12.5.11. For each cavity a cavity ratio is calculated:

$$\text{Cavity ratio} = \frac{5h\ (\text{room length} + \text{room width})}{(\text{room length}) \times (\text{room width})} \qquad (12.5.6)$$

where $h = h_{RC}$ for the room cavity ratio RCR; $= h_{CC}$ for the ceiling cavity ratio CCR; and $= h_{FC}$ for the floor cavity ratio FCR.

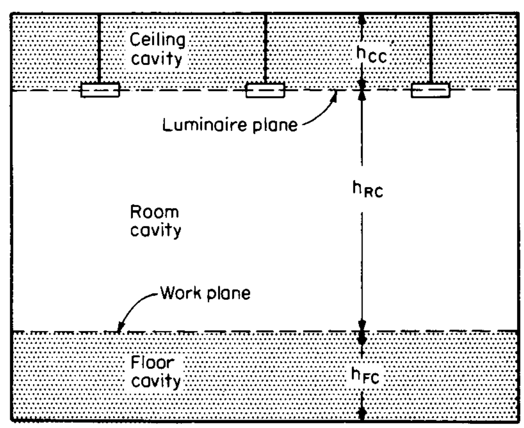


Fig. 12.5.11 The three cavities used in the zonal cavity method.

Table 12.5.7 is used to obtain a single effective ceiling cavity reflectance ρ_{CC} and a single effective floor cavity reflectance ρ_{FC}. For surface-mounted and recessed luminaires, CCR $= 0$ and the ceiling reflectance is used as ρ_{CC}. Figure 12.5.12 gives CU for selected fixtures. In using Fig. 12.5.12, interpolation may be necessary. Additional fixture data are given in the IES Handbook. Fixture manufacturers furnish such data for their units. Those data should be used for the best accuracy. If the effective floor cavity reflectance ρ_{FC} differs from 20 percent, an adjustment is made by using Table 12.5.8.

For simplicity in calculating the light-loss factor, the effects of ambient temperature, luminaire voltage variation, ballasts, and burnouts will be neglected. Room-surface dirt depreciation factors are shown in Fig. 12.5.13; luminaire dirt depreciation factors are in Fig. 12.5.14. The importance of frequent cleaning is evident. Categories are given for each fixture in Fig. 12.5.12. Lamp lumen depreciation (LLD) depends upon when lamps are replaced before complete burnout. If replacement

Table 12.5.7 Percent Effective Ceiling or Floor Cavity Reflectances for Various Reflectance Combinations (IES)

% base* reflectance: 90

Cavity ratio \ % wall reflectance:	90	80	70	60	50	40	30	20	10	0
0.2	89	88	88	87	86	85	85	84	84	82
0.4	88	87	86	85	84	83	81	80	79	76
0.6	87	86	84	82	80	79	77	76	74	73
0.8	87	85	82	80	77	75	73	71	69	67
1.0	86	83	80	77	75	72	69	66	64	62
1.2	85	82	78	75	72	69	66	63	60	57
1.4	85	80	77	73	69	65	62	59	57	52
1.6	84	79	75	71	67	63	59	56	53	50
1.8	83	78	73	69	64	60	56	53	50	48
2.0	83	77	72	67	62	56	53	50	47	43
2.2	82	76	70	65	59	54	50	47	44	40
2.4	82	75	69	64	58	53	48	45	41	37
2.6	81	74	67	62	56	51	46	42	38	35
2.8	81	73	66	60	56	49	44	40	36	34
3.0	80	72	64	58	52	47	42	38	34	30
3.2	79	71	63	56	50	45	40	36	32	28
3.4	79	70	62	54	48	43	38	34	30	27
3.6	78	69	61	53	47	42	36	32	28	25
3.8	78	69	60	51	45	40	35	31	27	23
4.0	77	69	58	51	44	39	33	29	25	22
4.2	77	62	57	50	43	37	32	28	24	21
4.4	76	61	56	49	42	36	31	27	23	20
4.6	76	60	55	47	40	35	30	26	22	19
4.8	75	59	54	46	39	34	28	25	21	18
5.0	75	59	53	45	38	33	28	24	20	16
6.0	73	61	49	41	34	29	24	20	16	11
7.0	70	58	45	38	30	27	21	18	14	08
8.0	68	55	42	35	27	23	18	15	12	06
9.0	66	52	38	31	25	21	16	14	11	05
10.0	65	51	36	29	22	19	15	11	09	04

% base* reflectance: 80

Cavity ratio \ % wall reflectance:	90	80	70	60	50	40	30	20	10	0
0.2	79	78	78	77	77	76	76	75	74	72
0.4	79	77	76	75	74	73	72	71	70	68
0.6	78	76	75	73	71	70	68	66	65	63
0.8	78	75	73	71	69	67	65	63	61	57
1.0	77	74	72	69	67	65	62	60	57	55
1.2	76	73	70	67	64	61	58	55	53	51
1.4	76	72	68	65	62	59	55	53	50	48
1.6	75	71	67	63	60	57	53	50	47	44
1.8	75	70	66	62	58	54	50	47	44	41
2.0	74	69	64	60	56	52	48	45	41	38
2.2	74	68	63	58	54	49	45	42	38	35
2.4	73	67	61	56	52	47	43	40	36	33
2.6	73	66	60	55	50	45	41	38	34	31
2.8	73	65	59	53	48	43	39	36	32	29
3.0	72	65	58	52	47	42	37	34	30	27
3.2	72	65	57	51	45	40	35	33	28	25
3.4	71	64	56	49	44	39	34	32	27	24
3.6	71	63	54	48	43	38	32	30	25	23
3.8	70	62	53	47	41	36	31	28	24	22
4.0	70	61	53	46	40	35	30	26	22	20
4.2	69	60	52	45	39	34	29	25	21	18
4.4	69	60	51	44	38	33	28	24	20	17
4.6	69	59	50	43	37	32	27	23	19	15
4.8	68	58	49	42	36	31	26	22	18	14
5.0	68	58	48	41	35	30	25	21	18	14
6.0	66	55	44	38	31	27	22	19	15	10
7.0	64	53	41	35	28	24	19	16	12	07
8.0	62	50	38	32	25	21	17	14	11	05
9.0	61	49	36	30	23	19	15	13	10	04
10.0	59	46	33	27	21	18	14	11	08	03

% base* reflectance: 70

Cavity ratio \ % wall reflectance:	90	80	70	60	50	40	30	20	10	0
0.2	70	69	68	68	67	67	66	66	65	64
0.4	69	68	67	66	65	64	63	62	61	58
0.6	69	67	65	64	63	61	59	58	57	54
0.8	68	66	64	62	60	58	56	55	53	50
1.0	68	65	62	60	58	55	53	52	50	47
1.2	67	64	61	59	57	54	50	48	46	44
1.4	67	63	60	58	55	51	47	45	44	41
1.6	67	62	59	56	53	47	45	43	41	38
1.8	66	61	58	54	51	46	42	40	38	35
2.0	66	60	56	52	49	45	40	38	36	33
2.2	66	60	55	51	48	43	38	36	34	32
2.4	65	60	54	50	46	41	37	35	32	30
2.6	65	59	54	49	45	40	35	33	30	28
2.8	65	59	53	48	43	38	33	30	28	26
3.0	64	58	52	47	42	37	32	29	27	24
3.2	64	58	51	46	40	36	31	28	25	23
3.4	64	57	50	45	39	35	29	27	24	22
3.6	63	56	49	44	38	33	28	25	22	20
3.8	63	56	49	43	37	32	27	24	21	19
4.0	63	55	48	42	36	31	26	23	20	17
4.2	62	55	47	41	35	30	25	22	19	16
4.4	62	54	46	40	34	29	24	21	18	15
4.6	62	53	45	39	33	28	24	21	17	14
4.8	62	53	45	38	32	27	23	20	16	13
5.0	61	52	44	36	31	26	22	19	16	12
6.0	60	51	41	35	28	24	19	16	13	09
7.0	58	48	38	32	26	22	17	14	11	06
8.0	57	46	35	29	23	19	15	13	10	05
9.0	56	45	33	27	21	18	14	12	09	04
10.0	55	43	31	25	19	16	12	10	08	03

% base* reflectance: 60

Cavity ratio \ % wall reflectance:	90	80	70	60	50	40	30	20	10	0
0.2	60	59	59	59	58	57	56	56	55	53
0.4	60	59	59	58	57	55	54	53	52	50
0.6	60	58	57	56	55	53	51	51	50	46
0.8	59	57	56	55	54	51	48	47	46	43
1.0	59	57	55	53	51	48	45	44	43	41
1.2	59	56	54	51	49	46	44	42	40	38
1.4	59	56	53	49	47	44	41	39	38	36
1.6	59	55	52	48	45	42	39	37	35	33
1.8	58	55	51	47	44	40	37	35	33	31
2.0	58	54	50	46	43	39	35	33	31	29
2.2	58	53	49	45	42	37	34	31	29	28
2.4	58	53	48	44	41	36	32	30	27	26
2.6	58	53	48	43	39	35	31	28	26	24
2.8	58	53	47	43	38	34	29	27	24	22
3.0	57	52	46	42	37	32	28	25	23	20
3.2	57	51	45	41	36	31	27	23	22	18
3.4	57	51	45	40	35	30	26	23	20	17
3.6	57	50	44	39	34	29	25	22	19	16
3.8	57	50	43	38	33	29	24	21	19	15
4.0	57	49	42	37	32	28	23	20	18	14
4.2	56	49	42	37	32	27	22	19	17	14
4.4	56	49	42	36	31	27	22	19	16	13
4.6	56	49	41	35	30	26	21	18	16	13
4.8	56	48	41	34	29	25	21	18	15	12
5.0	56	48	40	34	28	24	20	17	14	11
6.0	55	45	37	31	25	21	17	14	11	07
7.0	54	43	35	30	24	20	15	12	09	05
8.0	53	42	33	28	22	18	14	11	08	04
9.0	52	40	31	26	20	16	12	10	07	03
10.0	51	39	29	24	18	15	11	09	07	02

% base* reflectance: 50

Cavity ratio \ % wall reflectance:	90	80	70	60	50	40	30	20	10	0
0.2	50	50	49	49	48	48	47	46	46	44
0.4	50	49	48	48	47	46	45	45	44	42
0.6	50	48	47	46	45	44	43	42	41	38
0.8	50	48	47	45	44	42	40	39	38	36
1.0	50	48	46	44	43	41	38	37	36	34
1.2	50	47	45	43	41	39	36	35	34	29
1.4	50	47	45	42	40	38	35	34	32	27
1.6	50	47	44	41	39	36	33	32	30	26
1.8	50	46	43	40	38	35	31	30	28	25
2.0	50	46	43	40	37	34	30	28	26	24
2.2	50	46	42	38	36	33	29	27	24	22
2.4	50	46	42	37	35	31	27	25	23	21
2.6	50	46	41	37	34	30	26	23	21	20
2.8	50	46	41	36	33	29	25	22	20	19
3.0	50	45	40	36	32	28	24	21	19	17
3.2	50	44	39	35	31	27	23	20	18	16
3.4	50	44	39	35	30	26	22	19	17	55
3.6	50	44	39	34	29	25	21	18	16	14
3.8	50	44	38	34	29	25	21	17	15	13
4.0	50	44	38	33	28	24	20	17	15	12
4.2	50	43	37	32	28	24	20	17	14	12
4.4	50	43	37	32	27	23	19	16	13	11
4.6	50	43	36	31	26	22	18	15	13	10
4.8	50	43	36	31	26	22	18	15	12	09
5.0	50	42	35	30	25	21	17	14	12	09
6.0	50	42	34	29	23	19	15	13	10	06
7.0	49	41	32	27	21	18	14	11	08	05
8.0	49	40	30	25	19	16	12	10	07	03
9.0	48	39	29	24	18	15	11	09	07	03
10.0	47	37	27	22	17	14	10	08	06	02

* Ceiling, floor, or floor of cavity.

Table 12.5.7 Percent Effective Ceiling or Floor Cavity Reflectance for Various Reflectance Combinations (*Continued*)

% base* reflectance: 40

Cavity ratio \ % wall reflectance:	90	80	70	60	50	40	30	20	10	0
0.2	40	40	39	39	39	38	38	37	36	36
0.4	41	40	39	39	38	37	36	35	34	34
0.6	41	40	39	38	37	36	34	33	32	31
0.8	41	40	38	37	36	35	33	32	31	29
1.0	42	40	38	37	35	33	32	31	29	27
1.2	42	40	38	36	34	32	30	29	27	25
1.4	42	39	37	35	33	31	29	27	25	23
1.6	42	39	37	35	32	30	27	25	23	22
1.8	42	39	36	34	31	29	26	24	22	21
2.0	42	39	36	34	31	28	25	23	21	19
2.2	42	39	36	33	30	27	24	22	19	18
2.4	43	39	35	33	29	27	24	21	18	17
2.6	43	39	35	32	29	26	23	20	17	15
2.8	43	39	35	32	28	25	22	19	16	14
3.0	43	39	35	31	27	24	21	18	16	13
3.2	43	39	35	31	27	23	20	17	15	13
3.4	43	39	34	30	26	23	20	17	14	12
3.6	44	39	34	30	26	22	19	16	14	11
3.8	44	38	33	29	25	22	18	16	13	10
4.0	44	38	33	29	25	21	18	15	12	10
4.2	44	38	33	29	24	21	17	15	12	10
4.4	44	38	33	28	24	21	17	14	11	09
4.6	44	38	32	28	23	19	16	14	11	08
4.8	44	38	32	27	22	19	16	13	10	08
5.0	45	38	31	27	22	19	15	13	10	07
6.0	44	37	30	25	20	17	13	11	08	05
7.0	44	36	29	24	19	16	12	10	07	04
8.0	44	35	28	23	18	15	11	09	06	03
9.0	44	35	26	21	16	12	10	08	05	02
10.0	43	34	25	20	15	12	08	07	05	02

% base* reflectance: 30

Cavity ratio \ % wall reflectance:	90	80	70	60	50	40	30	20	10	0
0.2	31	31	30	30	29	29	29	28	28	27
0.4	31	31	30	30	29	28	28	27	26	25
0.6	32	31	30	29	28	27	26	26	25	23
0.8	32	31	30	29	28	26	25	25	23	22
1.0	33	32	30	29	27	25	24	23	22	20
1.2	33	32	30	28	27	25	23	22	21	19
1.4	34	32	30	28	26	24	22	21	19	18
1.6	34	33	29	27	25	23	22	20	18	17
1.8	35	33	29	27	25	23	21	19	17	16
2.0	35	33	29	26	24	22	20	18	16	14
2.2	36	32	29	26	24	22	19	17	15	13
2.4	36	32	29	26	24	22	19	16	14	12
2.6	36	32	29	25	23	21	18	16	14	12
2.8	37	33	29	25	23	21	17	15	13	11
3.0	37	33	29	25	22	20	17	15	12	10
3.2	37	33	29	25	22	19	16	14	12	10
3.4	37	33	29	25	22	19	16	14	11	09
3.6	38	33	29	24	21	18	15	13	10	09
3.8	38	33	28	24	21	18	15	13	10	08
4.0	38	33	28	24	21	18	14	12	09	07
4.2	38	33	28	24	20	17	14	12	09	07
4.4	39	33	28	24	20	17	14	11	09	06
4.6	39	33	28	24	20	17	13	10	08	06
4.8	39	33	28	24	20	17	13	10	08	05
5.0	39	33	28	24	19	16	13	10	08	05
6.0	39	33	27	23	18	15	11	09	06	04
7.0	40	33	26	22	17	14	10	08	05	03
8.0	40	33	26	21	16	13	09	07	04	02
9.0	40	33	25	20	15	12	09	07	04	02
10.0	40	32	24	19	14	11	08	06	03	01

% base* reflectance: 20

Cavity ratio \ % wall reflectance:	90	80	70	60	50	40	30	20	10	0
0.2	21	20	20	20	20	20	19	19	19	17
0.4	22	21	20	20	20	19	19	18	18	16
0.6	23	21	21	20	19	19	18	18	17	15
0.8	24	22	21	20	19	19	18	17	16	14
1.0	25	23	22	20	19	18	17	16	15	13
1.2	25	23	22	20	19	17	17	16	14	12
1.4	26	24	22	20	18	17	16	15	13	12
1.6	26	24	22	20	18	17	16	15	13	11
1.8	27	25	23	20	18	17	15	14	12	10
2.0	28	25	23	20	18	16	15	13	11	09
2.2	28	25	23	20	18	16	14	12	10	09
2.4	29	26	23	20	18	16	14	12	10	08
2.6	29	26	23	20	18	16	14	11	09	08
2.8	30	27	23	20	18	15	13	11	09	07
3.0	30	27	23	20	17	15	13	11	09	07
3.2	31	27	23	20	17	15	12	11	09	06
3.4	31	27	23	20	17	15	12	10	08	06
3.6	32	27	23	20	17	15	12	10	08	05
3.8	32	28	23	20	17	15	12	10	07	05
4.0	33	28	23	20	17	14	11	09	07	05
4.2	33	28	23	20	17	14	11	09	07	04
4.4	34	28	24	20	17	14	11	09	07	04
4.6	34	29	24	20	17	14	11	09	07	04
4.8	35	29	24	20	17	13	10	08	06	04
5.0	35	29	24	20	16	13	10	08	06	04
6.0	36	30	24	20	16	13	10	08	05	02
7.0	36	30	24	20	15	12	09	07	04	02
8.0	37	30	23	19	15	12	08	06	03	01
9.0	37	29	23	19	14	11	08	06	03	01
10.0	37	29	22	18	13	10	07	05	03	01

% base* reflectance: 10

Cavity ratio \ % wall reflectance:	90	80	70	60	50	40	30	20	10	0
0.2	11	11	11	10	10	10	10	09	09	09
0.4	12	11	11	11	11	10	10	09	09	08
0.6	13	13	12	11	11	10	10	09	08	08
0.8	15	14	13	12	11	10	10	09	08	07
1.0	16	14	13	12	12	11	10	09	08	07
1.2	17	15	14	13	12	11	10	09	07	06
1.4	18	16	14	13	12	11	10	09	07	06
1.6	19	17	15	14	12	11	09	08	07	06
1.8	19	17	15	14	13	11	09	08	06	05
2.0	20	18	16	14	13	11	09	98	06	05
2.2	21	19	16	14	13	11	09	07	06	05
2.4	22	19	17	15	13	11	09	07	06	05
2.6	23	20	17	15	13	11	09	07	06	04
2.8	23	20	18	16	13	11	09	07	05	03
3.0	24	21	18	16	13	11	09	07	05	03
3.2	25	21	18	16	13	11	09	07	05	03
3.4	26	22	18	16	13	11	09	07	05	03
3.6	26	22	19	16	13	11	09	06	04	03
3.8	27	23	19	17	14	11	09	06	04	02
4.0	27	23	20	17	14	11	09	06	04	02
4.2	28	24	20	17	14	11	09	06	04	02
4.4	28	24	20	17	14	11	08	06	04	02
4.6	29	25	20	17	14	11	08	06	04	02
4.8	29	25	20	17	14	11	08	06	04	02
5.0	30	25	20	17	14	11	08	06	04	02
6.0	31	26	21	17	14	11	08	06	03	01
7.0	32	27	21	17	13	11	08	06	03	01
8.0	33	27	21	17	13	10	07	05	03	01
9.0	34	28	21	17	13	10	07	05	02	01
10.0	34	28	21	17	12	10	07	05	02	01

% base* reflectance: 0

Cavity ratio \ % wall reflectance:	90	80	70	60	50	40	30	20	10	0
0.2	02	02	02	01	01	01	01	00	00	0
0.4	04	03	03	02	02	02	01	01	00	0
0.6	05	05	04	03	03	02	02	01	01	0
0.8	07	06	05	04	04	03	02	02	01	0
1.0	08	07	06	05	04	03	02	02	01	0
1.2	10	08	07	06	05	04	03	02	01	0
1.4	11	09	08	07	06	04	03	02	01	0
1.6	12	10	09	07	06	05	03	02	01	0
1.8	13	11	09	08	07	05	04	03	01	0
2.0	14	12	10	09	07	05	04	03	01	0
2.2	15	13	11	09	07	06	04	03	02	0
2.4	16	13	11	09	08	06	04	03	01	0
2.6	17	14	12	10	08	06	05	03	02	0
2.8	17	15	13	10	08	07	05	03	02	0
3.0	18	16	13	11	09	07	05	03	02	0
3.2	19	16	14	11	09	07	05	03	02	0
3.4	20	17	14	12	09	07	05	03	02	0
3.6	20	17	15	12	10	08	05	04	02	0
3.8	21	18	15	12	10	08	05	04	02	0
4.0	22	18	15	13	10	08	05	04	02	0
4.2	22	19	16	13	10	08	06	04	02	0
4.4	23	19	16	13	10	8	06	04	02	0
4.6	23	20	17	13	11	08	06	04	02	0
4.8	24	20	17	14	11	08	06	04	02	0
5.0	25	21	17	14	11	08	06	04	02	0
6.0	27	23	18	15	12	09	06	04	02	0
7.0	28	24	19	15	12	09	06	04	02	0
8.0	30	25	20	15	12	09	06	04	02	0
9.0	31	25	20	15	12	09	06	04	02	0
10.0	31	25	20	15	12	09	06	04	02	0

* Ceiling, floor, or floor of cavity.

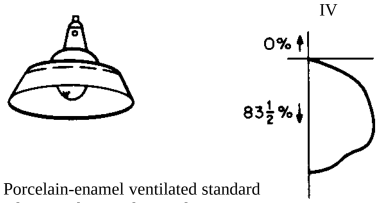
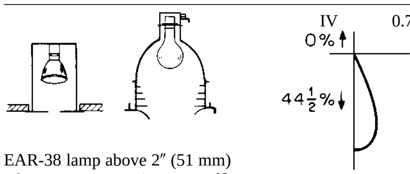
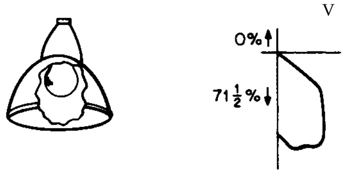
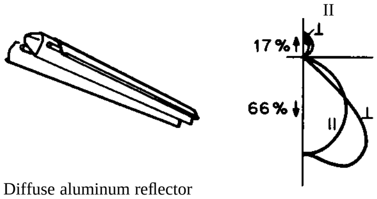
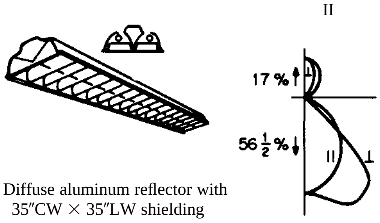
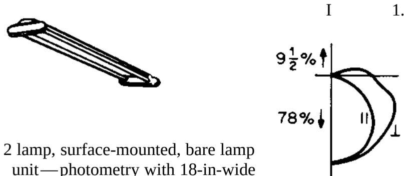
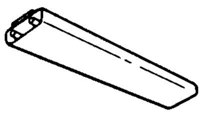
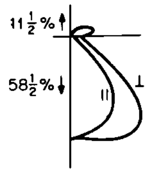
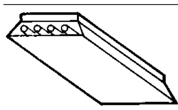
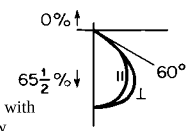
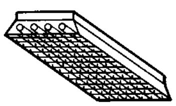
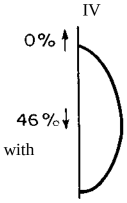
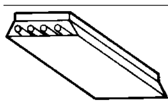
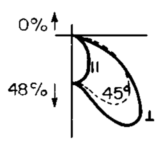
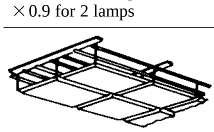
Typical luminaire	Typical distribution and % lamp lumens: Maint. cat.	Max *S/MH* guide§	ρ_{CC}*→	80			70			50			30			10			0
			ρ_W†→	50	30	10	50	30	10	50	30	10	50	30	10	50	30	10	0
			RCR‡ ↓	Coefficients of utilization for 20% effective floor cavity reflectance (ρFC = 20)															
 Porcelain-enamel ventilated standard dome with incandescent lamp	IV	1.3	0	.99	.99	.99	.97	.97	.97	.93	.93	.93	.89	.89	.89	.85	.85	.85	.83
			1	.87	.84	.81	.85	.82	.79	.82	.79	.77	.79	.76	.74	.76	.74	.72	.71
			2	.76	.70	.65	.74	.69	.65	.71	.67	.63	.69	.65	.62	.66	.63	.60	.59
			3	.66	.59	.54	.65	.59	.53	.62	.57	.53	.60	.56	.52	.58	.54	.51	.49
			4	.58	.51	.45	.57	.50	.45	.55	.49	.44	.53	.48	.44	.51	.47	.43	.41
			5	.52	.44	.39	.51	.44	.38	.49	.43	.38	.47	.42	.37	.46	.41	.37	.35
			6	.46	.39	.33	.46	.38	.33	.44	.38	.33	.43	.37	.33	.41	.36	.32	.31
			7	.42	.34	.29	.41	.34	.29	.40	.33	.29	.39	.33	.29	.38	.32	.28	.27
			8	.38	.31	.26	.37	.31	.26	.36	.30	.26	.35	.30	.25	.34	.29	.25	.24
			9	.35	.28	.23	.34	.28	.23	.33	.27	.23	.32	.27	.23	.32	.26	.23	.21
			10	.32	.25	.21	.32	.25	.21	.31	.25	.21	.30	.24	.21	.29	.24	.20	.19
 EAR-38 lamp above 2″ (51 mm) diameter aperture (increase efficiency to 54½% for 3″ (76 mm) diameter aperture	IV	0.7	0	.52	.52	.52	.51	.51	.51	.48	.48	.48	.46	.46	.46	.45	.45	.45	.44
			1	.49	.48	.47	.48	.47	.46	.46	.45	.45	.44	.44	.43	.43	.43	.42	.41
			2	.46	.44	.43	.45	.44	.43	.44	.43	.42	.43	.42	.41	.41	.41	.40	.39
			3	.43	.41	.40	.43	.41	.40	.42	.40	.39	.41	.39	.38	.40	.39	.38	.37
			4	.41	.39	.37	.41	.39	.37	.40	.38	.37	.39	.37	.36	.38	.37	.36	.35
			5	.39	.37	.35	.39	.37	.35	.38	.36	.35	.37	.36	.34	.36	.35	.34	.34
			6	.37	.35	.33	.37	.35	.33	.36	.34	.33	.35	.34	.33	.35	.34	.32	.32
			7	.35	.33	.31	.35	.33	.31	.34	.33	.31	.34	.32	.31	.33	.32	.31	.30
			8	.34	.31	.30	.33	.31	.30	.33	.31	.30	.32	.31	.29	.32	.31	.29	.29
			9	.32	.30	.28	.32	.30	.28	.31	.30	.28	.31	.29	.28	.31	.29	.28	.28
			10	.31	.28	.27	.31	.28	.27	.30	.28	.27	.30	.28	.27	.30	.28	.27	.26
 Enclosed reflector with an incandescent lamp	V	1.4	0	.85	.85	.85	.83	.83	.83	.80	.80	.80	.76	.76	.76	.73	.73	.73	.72
			1	.77	.75	.73	.76	.74	.72	.73	.71	.69	.70	.69	.67	.67	.66	.65	.64
			2	.70	.66	.63	.68	.65	.62	.66	.63	.60	.64	.61	.59	.61	.60	.58	.56
			3	.63	.58	.54	.62	.57	.54	.60	.56	.53	.58	.54	.52	.56	.53	.51	.50
			4	.56	.51	.47	.56	.51	.47	.54	.50	.46	.52	.49	.46	.51	.48	.45	.44
			5	.51	.46	.42	.50	.45	.41	.49	.44	.41	.48	.44	.40	.46	.43	.40	.39
			6	.46	.41	.37	.46	.41	.37	.45	.40	.36	.43	.39	.36	.42	.39	.36	.34
			7	.42	.37	.33	.42	.37	.33	.41	.36	.33	.40	.36	.32	.39	.35	.32	.31
			8	.39	.33	.30	.38	.33	.29	.37	.33	.29	.37	.32	.29	.36	.32	.29	.28
			9	.36	.30	.27	.35	.30	.27	.35	.30	.27	.34	.30	.26	.33	.29	.26	.25
			10	.33	.28	.24	.33	.28	.24	.32	.27	.24	.31	.27	.24	.31	.27	.24	.23
 Diffuse aluminum reflector with 35″ CW shielding	II	1.5/1.3	0	.95	.95	.95	.91	.91	.91	.83	.83	.83	.76	.76	.76	.69	.69	.69	.66
			1	.85	.82	.79	.81	.79	.76	.75	.73	.71	.69	.67	.66	.63	.62	.61	.58
			2	.75	.71	.67	.72	.68	.65	.67	.63	.61	.62	.59	.57	.57	.55	.53	.51
			3	.67	.61	.57	.65	.59	.55	.60	.56	.52	.55	.52	.49	.51	.49	.46	.44
			4	.60	.54	.49	.58	.52	.48	.54	.49	.45	.50	.46	.43	.46	.43	.41	.39
			5	.54	.47	.43	.52	.46	.42	.49	.43	.40	.45	.41	.38	.42	.39	.36	.34
			6	.49	.42	.37	.47	.41	.37	.44	.39	.35	.41	.37	.33	.38	.35	.32	.30
			7	.44	.38	.33	.43	.37	.32	.40	.35	.31	.38	.33	.30	.35	.31	.28	.27
			8	.40	.34	.29	.39	.33	.29	.37	.31	.28	.34	.30	.27	.32	.28	.26	.24
			9	.37	.31	.26	.36	.30	.26	.34	.29	.25	.32	.27	.24	.30	.26	.23	.21
			10	.34	.28	.24	.33	.27	.23	.31	.26	.23	.29	.25	.22	.28	.24	.21	.19
 Diffuse aluminum reflector with 35″CW × 35″LW shielding	II	1.5/1.1	0	.91	.91	.91	.86	.86	.86	.77	.77	.77	.68	.68	.68	.61	.61	.61	.57
			1	.80	.77	.75	.76	.74	.71	.69	.67	.65	.62	.60	.59	.55	.54	.53	.50
			2	.71	.67	.63	.68	.64	.60	.61	.58	.55	.55	.53	.51	.50	.48	.46	.43
			3	.63	.58	.53	.60	.55	.51	.55	.51	.47	.50	.46	.44	.45	.42	.40	.38
			4	.57	.51	.46	.54	.49	.44	.49	.45	.41	.45	.41	.38	.41	.38	.35	.33
			5	.51	.45	.40	.49	.43	.39	.45	.40	.36	.41	.37	.34	.37	.34	.31	.29
			6	.46	.40	.35	.44	.38	.34	.41	.36	.32	.37	.33	.30	.34	.30	.28	.26
			7	.42	.36	.31	.40	.35	.30	.37	.32	.29	.34	.30	.27	.31	.28	.25	.23
			8	.38	.32	.28	.37	.31	.27	.34	.29	.26	.31	.27	.24	.29	.25	.23	.21
			9	.35	.29	.25	.34	.28	.25	.31	.27	.23	.29	.25	.22	.27	.23	.21	.19
			10	.33	.27	.23	.31	.26	.22	.29	.24	.21	.27	.23	.20	.25	.21	.19	.17
 2 lamp, surface-mounted, bare lamp unit—photometry with 18-in-wide panel above luminaire (lamps on 6-in centers)	I	1.3	0	1.02	1.02	1.02	.99	.99	.99	.92	.92	.92	.86	.86	.86	.81	.81	.81	.78
			1	.85	.80	.76	.82	.78	.74	.76	.73	.70	.71	.68	.66	.67	.64	.62	.60
			2	.72	.65	.59	.70	.63	.58	.65	.60	.55	.61	.56	.52	.57	.53	.50	.47
			3	.63	.55	.48	.60	.53	.47	.56	.50	.45	.53	.47	.43	.49	.45	.41	.38
			4	.55	.46	.40	.53	.45	.39	.50	.43	.37	.46	.41	.36	.43	.38	.34	.32
			5	.49	.40	.34	.47	.39	.33	.44	.37	.32	.41	.35	.31	.39	.34	.29	.27
			6	.43	.35	.29	.42	.34	.29	.40	.33	.28	.37	.31	.27	.35	.30	.26	.23
			7	.39	.31	.25	.38	.30	.25	.36	.29	.24	.34	.28	.23	.32	.26	.22	.20
			8	.36	.28	.22	.35	.27	.22	.33	.26	.21	.31	.25	.21	.29	.24	.20	.18
			9	.33	.25	.20	.32	.25	.20	.30	.24	.19	.28	.23	.18	.27	.22	.18	.16
			10	.30	.23	.18	.29	.22	.18	.28	.21	.17	.26	.21	.17	.25	.20	.16	.14

Fig. 12.5.12 Coefficients of utilization for typical luminaires. (*Abstracted from IESNA Handbook, 8th ed., 1993. Reprinted with permission. This material has been modified from its original version and is not reflective of its original form as recognized by the IESNA.*)

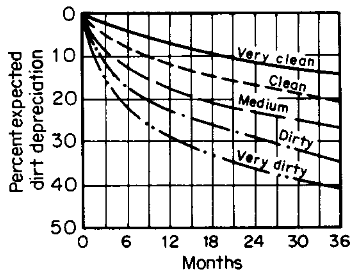
Typical luminaire	Typical distribution and % lamp lumens	Maint. cat.	Max S/MH guide§	RCR‡ ↓	ρ_{CC}*→ 80			70			50			30			10			0
				ρ_W†→	50	30	10	50	30	10	50	30	10	50	30	10	50	30	10	0
					Coefficients of utilization for 20% effective floor cavity reflectance (ρFC = 20)															
 2 lamp prismatic wraparound—multiply by 0.95 for 4 amps		V	1.5/1.2	0	.81	.81	.81	.78	.78	.78	.72	.72	.72	.66	.66	.66	.61	.61	.61	.59
				1	.71	.68	.66	.68	.66	.63	.63	.61	.59	.58	.57	.56	.54	.53	.52	.50
				2	.63	.58	.55	.60	.56	.53	.56	.53	.50	.52	.50	.47	.48	.46	.45	.43
				3	.56	.50	.46	.54	.49	.45	.50	.46	.43	.47	.43	.41	.43	.41	.39	.37
				4	.50	.44	.40	.48	.43	.39	.45	.40	.37	.42	.38	.35	.39	.36	.34	.32
				5	.45	.39	.34	.43	.38	.34	.40	.36	.32	.38	.34	.31	.35	.32	.30	.28
				6	.40	.34	.30	.39	.34	.30	.37	.32	.28	.34	.30	.27	.32	.29	.26	.25
				7	.37	.31	.27	.35	.30	.26	.33	.29	.25	.31	.27	.24	.30	.26	.23	.22
				8	.33	.28	.24	.32	.27	.23	.30	.26	.23	.29	.25	.22	.27	.24	.21	.20
				9	.31	.25	.21	.30	.25	.21	.28	.24	.20	.26	.23	.20	.25	.22	.19	.18
				10	.28	.23	.19	.27	.22	.19	.26	.21	.18	.24	.21	.18	.22	.20	.17	.16
 4 lamp, 2′ (610 mm) wide unit with sharp cutoff (high angle—low luminance) flat prismatic lens—×1.05 for 3 lamps ×0.9 for 2 lamps		V	1.4/1.3	0	.71	.71	.71	.70	.70	.70	.66	.66	.66	.64	.64	.64	.61	.61	.61	.60
				1	.64	.62	.60	.63	.61	.60	.60	.59	.58	.58	.57	.56	.56	.55	.54	.53
				2	.57	.54	.51	.56	.53	.51	.54	.52	.50	.52	.50	.48	.51	.49	.47	.46
				3	.51	.47	.44	.50	.46	.43	.49	.45	.43	.47	.44	.42	.46	.43	.41	.40
				4	.46	.41	.38	.45	.41	.37	.44	.40	.37	.42	.39	.36	.41	.38	.36	.35
				5	.41	.36	.33	.40	.36	.32	.39	.35	.32	.38	.35	.32	.37	.34	.31	.30
				6	.37	.32	.28	.36	.32	.28	.35	.31	.28	.34	.31	.28	.34	.30	.28	.27
				7	.33	.29	.25	.33	.28	.25	.32	.28	.25	.31	.27	.25	.30	.27	.24	.23
				8	.30	.26	.22	.30	.25	.22	.29	.25	.22	.28	.25	.22	.28	.24	.22	.21
				9	.28	.23	.20	.27	.23	.20	.27	.23	.20	.26	.22	.20	.25	.22	.19	.18
				10	.25	.21	.18	.25	.21	.18	.25	.20	.18	.24	.20	.18	.23	.20	.18	.17
 4 lamp, 2′ (610 mm) wide troffer with 45° white metal louver—×1.05 for 3 lamps ×0.9 for 2 lamps		IV	0.9	0	.55	.55	.55	.54	.54	.54	.51	.51	.51	.49	.49	.49	.47	.47	.47	.46
				1	.49	.48	.46	.48	.47	.46	.46	.45	.44	.45	.44	.43	.43	.42	.42	.41
				2	.44	.42	.40	.43	.41	.39	.42	.40	.38	.40	.39	.37	.39	.38	.37	.36
				3	.40	.37	.34	.39	.36	.34	.38	.36	.33	.37	.35	.33	.36	.34	.32	.32
				4	.36	.33	.30	.36	.33	.30	.35	.32	.30	.34	.31	.29	.33	.31	.29	.28
				5	.33	.30	.27	.33	.29	.27	.32	.29	.27	.31	.28	.26	.30	.28	.26	.25
				6	.30	.27	.24	.30	.27	.24	.29	.26	.24	.29	.26	.24	.28	.25	.24	.23
				7	.28	.25	.22	.28	.24	.22	.27	.24	.22	.26	.24	.22	.26	.23	.22	.21
				8	.26	.23	.20	.26	.22	.20	.25	.22	.20	.25	.22	.20	.24	.22	.20	.19
				9	.24	.21	.19	.24	.21	.19	.23	.20	.18	.23	.20	.18	.23	.20	.18	.18
				10	.23	.19	.17	.22	.19	.17	.22	.19	.17	.22	.19	.17	.21	.19	.17	.16
 Bilateral batwing distribution −4 lamp, 2′ (610 mm) wide fluorescent unit with flat prismatic lens and overlay—×1.05 for 3 lamps ×0.9 for 2 lamps		V	N.A.	0	.57	.57	.57	.56	.56	.56	.53	.53	.53	.51	.51	.51	.49	.49	.49	.48
				1	.50	.48	.46	.49	.47	.45	.47	.45	.44	.45	.43	.42	.43	.42	.41	.40
				2	.43	.40	.37	.42	.39	.36	.40	.38	.35	.39	.37	.35	.37	.36	.34	.33
				3	.37	.33	.30	.37	.33	.30	.35	.32	.29	.34	.31	.29	.33	.30	.28	.27
				4	.33	.28	.25	.32	.28	.25	.31	.27	.24	.30	.27	.24	.29	.26	.24	.23
				5	.29	.24	.21	.28	.24	.21	.27	.24	.21	.26	.23	.20	.25	.23	.20	.19
				6	.26	.21	.18	.25	.21	.18	.24	.21	.18	.24	.20	.18	.23	.20	.17	.16
				7	.23	.19	.16	.23	.18	.15	.22	.18	.15	.21	.18	.15	.21	.17	.15	.14
				8	.21	.17	.14	.21	.16	.14	.20	.16	.13	.19	.16	.13	.19	.16	.13	.12
				9	.19	.15	.12	.19	.15	.12	.18	.14	.12	.18	.14	.12	.17	.14	.12	.11
				10	.17	.13	.11	.17	.13	.11	.17	.13	.11	.16	.13	.11	.16	.13	.10	.10
 Diffusing plastic or glass 1. Ceiling efficiency ~60%; diffuser transmittance ≈50%; diffuser reflectance ~40%. Cavity with minimum obstructions and painted with 80% reflectance paints—use pc = 70 2. For lower reflectance paint or obstructions—use ρc = 50	ρ_{cc} from below ~65%			1			.60	.58	.56	.58	.56	.54								
				2			.53	.49	.45	.51	.47	.43								
				3			.47	.42	.37	.45	.41	.36								
				4			.41	.36	.32	.39	.35	.31								
				5			.37	.31	.27	.35	.30	.26								
				6			.33	.27	.23	.31	.26	.23								
				7			.29	.24	.20	.28	.23	.20								
				8			.26	.21	.18	.25	.20	.17								
				9			.23	.19	.15	.23	.18	.15								
				10			.21	.17	.13	.21	.16	.13								

* ρ_{cc} = percent effective ceiling cavity reflectance.
† ρ_w = percent wall reflectance.
‡ RCR = room cavity ratio.
§ Maximum S/MH guide—ratio of maximum luminaire spacing to mounting or ceiling height above work plane.

Fig. 12.5.12 (*Continued*)

Table 12.5.8 Multiplying Factors for Other than 20 Percent Effective Floor Cavity Reflectance (IES)

% effective ceiling cavity reflectance ρ_{CC}:	80				70				50			30			10		
% wall reflectance ρ_W:	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10
Room cavity ratio	For 30% effective floor cavity reflectance (20% = 1.00)																
1	1.092	1.082	1.075	1.068	1.077	1.070	1.064	1.059	1.049	1.044	1.040	1.028	1.026	1.023	1.012	1.010	1.008
2	1.079	1.066	1.055	1.047	1.068	1.057	1.048	1.039	1.041	1.033	1.027	1.026	1.021	1.017	1.013	1.010	1.006
3	1.070	1.054	1.042	1.033	1.061	1.048	1.037	1.028	1.034	1.027	1.020	1.024	1.017	1.012	1.014	1.009	1.005
4	1.062	1.045	1.033	1.024	1.055	1.040	1.029	1.021	1.030	1.022	1.015	1.022	1.015	1.010	1.014	1.009	1.004
5	1.056	1.038	1.026	1.018	1.050	1.034	1.024	1.015	1.027	1.018	1.012	1.020	1.013	1.008	1.014	1.009	1.004
6	1.052	1.033	1.021	1.014	1.047	1.030	1.020	1.012	1.024	1.015	1.009	1.019	1.012	1.006	1.014	1.008	1.003
7	1.047	1.029	1.018	1.011	1.043	1.026	1.017	1.009	1.022	1.013	1.007	1.018	1.010	1.005	1.014	1.008	1.003
8	1.044	1.026	1.015	1.009	1.040	1.024	1.015	1.007	1.020	1.012	1.006	1.017	1.009	1.004	1.013	1.007	1.003
9	1.040	1.024	1.014	1.007	1.037	1.022	1.014	1.006	1.019	1.011	1.005	1.016	1.009	1.004	1.013	1.007	1.002
10	1.037	1.022	1.012	1.006	1.034	1.020	1.012	1.005	1.017	1.010	1.004	1.015	1.009	1.003	1.013	1.007	1.002
	For 10% effective floor cavity reflectance (20% = 1.00)																
1	0.923	0.929	0.935	0.940	0.933	0.939	0.943	0.948	0.956	0.960	0.963	0.973	0.976	0.979	0.989	0.991	0.993
2	0.931	0.942	0.950	0.958	0.940	0.949	0.957	0.963	0.962	0.968	0.974	0.976	0.980	0.985	0.988	0.991	0.995
3	0.939	0.951	0.961	0.969	0.945	0.057	0.966	0.973	0.967	0.975	0.981	0.978	0.983	0.988	0.988	0.992	0.996
4	0.944	0.958	0.969	0.978	0.950	0.963	0.973	0.980	0.972	0.980	0.986	0.980	0.986	0.991	0.987	0.992	0.996
5	0.949	0.964	0.976	0.983	0.954	0.968	0.978	0.985	0.975	0.983	0.989	0.981	0.988	0.993	0.987	0.992	0.997
6	0.953	0.969	0.980	0.986	0.958	0.972	0.982	0.989	0.977	0.985	0.992	0.982	0.989	0.995	0.987	0.993	0.997
7	0.957	0.973	0.983	0.991	0.961	0.975	0.985	0.991	0.979	0.987	0.994	0.983	0.990	0.996	0.987	0.993	0.998
8	0.960	0.976	0.986	0.993	0.963	0.977	0.987	0.993	0.981	0.988	0.995	0.984	0.991	0.997	0.987	0.994	0.998
9	0.963	0.978	0.987	0.994	0.965	0.979	0.989	0.994	0.983	0.990	0.996	0.985	0.992	0.998	0.988	0.994	0.999
10	0.965	0.980	0.989	0.995	0.967	0.981	0.990	0.995	0.984	0.991	0.997	0.986	0.993	0.998	0.988	0.994	0.999
	For 0% effective floor cavity reflectance (20% = 1.00)																
1	0.859	0.870	0.879	0.886	0.873	0.884	0.893	0.901	0.916	0.923	0.929	0.948	0.954	0.960	0.979	0.983	0.987
2	0.871	0.887	0.903	0.919	0.886	0.902	0.916	0.928	0.926	0.938	0.949	0.954	0.963	0.971	0.978	0.983	0.991
3	0.882	0.904	0.915	0.942	0.898	0.918	0.934	0.947	0.936	0.950	0.964	0.958	0.969	0.979	0.976	0.984	0.993
4	0.893	0.919	0.941	0.958	0.908	0.930	0.948	0.961	0.945	0.961	0.974	0.961	0.974	0.984	0.975	0.985	0.994
5	0.903	0.931	0.953	0.969	0.914	0.939	0.958	0.970	0.951	0.967	0.980	0.964	0.977	0.988	0.975	0.985	0.995
6	0.911	0.940	0.961	0.976	0.920	0.945	0.965	0.977	0.955	0.972	0.985	0.966	0.979	0.991	0.975	0.986	0.996
7	0.917	0.947	0.967	0.981	0.924	0.950	0.970	0.982	0.959	0.975	0.988	0.968	0.981	0.993	0.975	0.987	0.997
8	0.922	0.953	0.971	0.985	0.929	0.955	0.975	0.986	0.963	0.978	0.991	0.970	0.983	0.995	0.976	0.988	0.998
9	0.928	0.958	0.975	0.988	0.933	0.959	0.980	0.989	0.966	0.980	0.993	0.971	0.985	0.996	0.976	0.988	0.998
10	0.933	0.962	0.979	0.991	0.937	0.963	0.983	0.992	0.969	0.982	0.995	0.973	0.987	0.997	0.977	0.989	0.999



% expected dirt depreciation:	Luminaire distribution type: Direct				Semidirect				Direct-indirect				Semi-indirect				Indirect			
Room cavity ratio	10	20	30	40	10	20	30	40	10	20	30	40	10	20	30	40	10	20	30	40
1	.98	.96	.94	.92	.97	.92	.89	.84	.94	.87	.80	.76	.94	.87	.80	.73	.90	.80	.70	.60
2	.98	.96	.94	.92	.96	.92	.88	.83	.94	.87	.80	.75	.94	.87	.79	.72	.90	.80	.69	.59
3	.98	.95	.93	.90	.96	.91	.87	.82	.94	.86	.79	.74	.94	.86	.78	.71	.90	.79	.68	.58
4	.97	.95	.92	.90	.95	.90	.85	.80	.94	.86	.79	.73	.94	.86	.78	.70	.89	.78	.67	.56
5	.97	.94	.91	.89	.94	.90	.84	.79	.93	.86	.78	.72	.93	.86	.77	.69	.89	.78	.66	.55
6	.97	.94	.91	.88	.94	.89	.83	.78	.93	.85	.78	.71	.93	.85	.76	.68	.89	.77	.66	.54
7	.97	.94	.90	.87	.93	.88	.82	.77	.93	.84	.77	.70	.93	.84	.76	.68	.89	.76	.65	.53
8	.96	.93	.89	.86	.93	.87	.81	.75	.93	.84	.76	.69	.93	.84	.76	.68	.88	.76	.64	.52
9	.96	.92	.88	.85	.93	.87	.80	.74	.93	.84	.76	.68	.93	.84	.75	.67	.88	.75	.63	.51
10	.96	.92	.87	.83	.93	.86	.79	.72	.93	.84	.75	.67	.92	.83	.75	.67	.88	.75	.62	.50

Fig. 12.5.13 Room surface dirt depreciation factors. *(IES)*

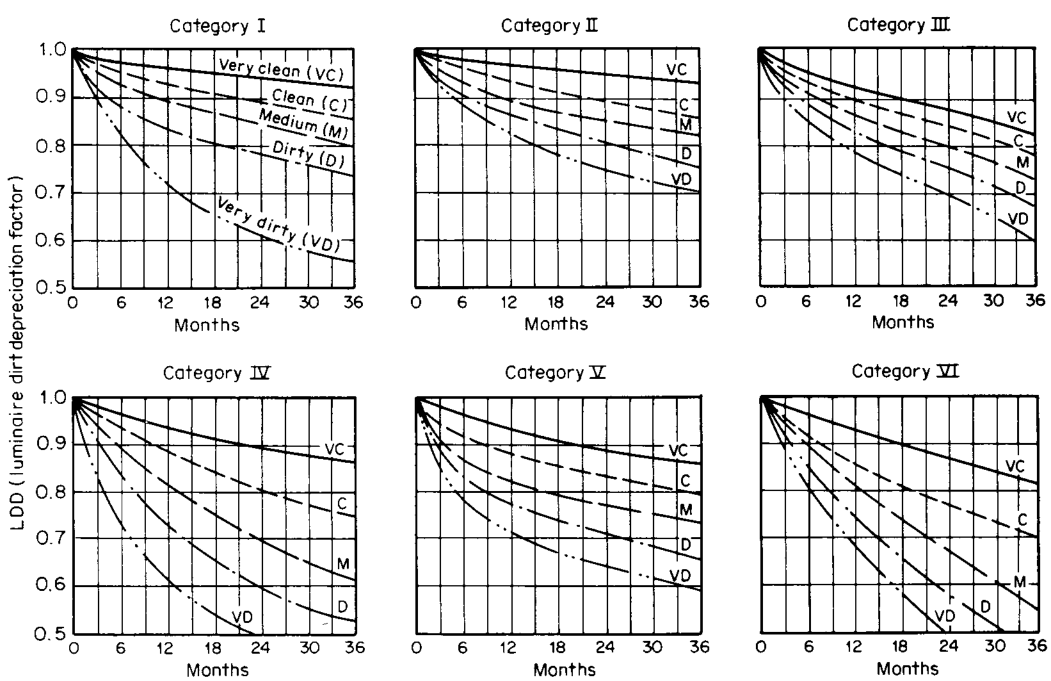


Fig. 12.5.14 Luminaire dirt depreciation (LLD) factors for six luminaire categories (I to VI) and for five degrees of dirtiness. *(IES.)*

GENERAL INFORMATION

Project identification: ______________________________

(Give name of area and/or building and room number)

Average maintained illumination for design: ___ footcandles or

Luminaire data: ___ lux

Manufacturer: ______________________

Catalog number: ______________________

Lamp data:

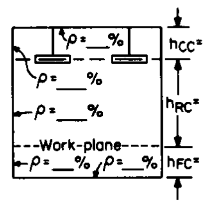
Type and color: ______________________

Number per luminaire: ______________________

Total lumens per luminaire: ______________________

SELECTION OF COEFFICIENT OF UTILIZATION

Step 1: Fill in sketch at right.



Step 2: Determine cavity ratios [Eq. (12.5.6)]

Room cavity ratio RCR = ______________

Ceiling cavity ratio CCR: = ______________

Floor cavity ratio FCR = ______________

room length: ______________

room width: ______________

Step 3: Obtain effective ceiling cavity reflectance ρ_{CC} from Table 12.5.7 ρ_{CC} = ______________

Step 4: Obtain effective floor cavity reflectance ρ_{FC} from Table 12.5.7 ρ_{FC} = ______________

Step 5: Obtain coefficient of utilization CU from manufacturer's data (or Fig. 12.5.12 and Table 12.5.8) CU = ______________

SELECTION OF LIGHT-LOSS FACTORS

Nonrecoverable		Recoverable	
Luminaire ambient temperature	______	Room surface dirt depreciation RSDD	______
Voltage to luminaire	______	Lamp lumen depreciation LLD	______
Ballast factor	______	Lamp burnouts factor LBO	______
Luminaire surface depreciation	______	Luminaire dirt depreciation LDD	______

Total light loss factor, LLF (product of individual factors above) = ______

CALCULATIONS
(Average maintained illumination level)

$$\text{Number of luminaires} = \frac{(\text{footcandles}) \times (\text{area*, ft}^2)}{(\text{lumens per luminaire}) \times (\text{CU}) \times (\text{LLF})}$$

$$= \underline{\hspace{8cm}} =$$

$$\text{Footcandles} = \frac{(\text{number of luminaires}) \times (\text{lumens per luminaire}) \times (\text{CU}) \times (\text{LLF})}{(\text{area*, ft}^2)}$$

$$= \underline{\hspace{12cm}} =$$

Calculated by: ______________________________ Date: ______________

*If lux is used, area is in m².

Fig. 12.5.15 Average illumination calculation sheet. *[Abstracted from ''IESNA Handbook,'' 8th ed., 1993; reprinted with permission. (This material has been modified from its original version and is not reflective of its original form as recognized by the IESNA.)]*

at 30 percent rated life is used, the LLD for incandescent lamps varies from 78 to 90 percent, with an average about 87 percent. For fluorescent lamps the LLD varies from 67 to 91, with an average about 82 percent. For better values consult the IES Handbook or manufacturers' data.

A design summary sheet is given in Fig. 12.5.15.

While the lumen method is the accepted procedure for calculating interior lighting levels, it is often necessary to have a quick approximation of the quantity of lighting equipment needed to satisfy an illumination-level specification. There are several rules of thumb which serve that purpose.

Spacing Method Table 12.5.9 indicates approximate *base*-maintained footcandle levels according to fixture spacing. For levels other than the base quantity, the level is changed inversely and proportionally to a change in spacing—i.e., doubling the spacing (in one direction) halves the level; halving the spacing doubles the level. Doubling the spacing in both directions reduces the level to one-fourth.

Lumens-per-Square-Foot Method (see footnote for Table 12.5.10);

Less accurate than the previous method, this one permits a fairly reasonable calculation by using the lamp lumens as given in the GE Lamp Catalog and substituting in the formula:

$$\text{Footcandle} = \frac{\text{total lamp lumens per fixture}}{2 \times \text{area per fixture}}$$

Or, for a given footcandle level, transposing the formula to determine area per fixture:

$$\text{Area per fixture} = \frac{\text{total lamp lumens per fixture}}{2 \times \text{footcandles}}$$

The ''2'' in the denominator assumes loss of half the lumens in fixture utilization, lamp depreciation and dirt accumulation. *(Source: General Electric.)*

Watts-per-Square-Foot Method Table 12.5.10 shows another way to arrive at a quick approximation.

Point Method of Design

If uniformity of lighting is to be investigated, or if outdoor lighting is to be designed, the point method is used. Manufacturers furnish candlepower distribution curves for their fixtures. An average curve is given for symmetrical fixtures while curves in various planes are given for asymmetrical ones. The basic equation for calculating the illumination from such curves is

$$\begin{aligned} E_h &= (I_\theta \cos \theta)/D^2 \\ &= I_\theta H/D^3 \end{aligned} \tag{12.5.7}$$

Table 12.5.10 Watts-per-Square-Foot Method*

A convenient, popular, quick approximation

Lamp	Per 100 fc
Lucalox	1.6 W/ft²
Multi-vapor	2.5 W/ft²
Fluorescent	3.0 W/ft²
Mercury-vapor	3.5 W/ft²
Incandescent (reflector lamp)	8.5 W/ft²

SOURCE: General Electric Co.

* Both Table 12.5.9 and lumen-per-square-foot method are based upon *large* industrial areas, where room width (W) is six times the fixture mounting height (MH). For medium-sized areas (where W = 3MH), reduce footcandles and increase wattage 15 percent. For small areas (where W = MH), reduce footcandles and increase wattage 50 percent. Lucalox fixtures and incandescent reflector lamps tend to be more efficient and have higher lumen-maintenance characteristics; thus, for these sources increase the footcandle value about 25 percent.

where E_h is the illumination on the horizontal plane, I_θ the candlepower in the given direction, and D the distance of the luminaire to the point P. See Fig. 12.5.16.

$$\begin{aligned} E_v &= (I_\theta \sin \theta)D^2 \\ &= I_\theta R/D^3 \end{aligned}$$

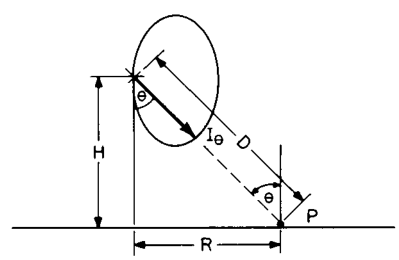


Fig. 12.5.16 Footcandle calculation diagram.

Table 12.5.9 Approximate Footcandle Levels According to Fixture Spacing*

Lighting system		Spacings†				
Lamp	Watts	10 × 10 ft	15 × 15 ft	20 × 20 ft	25 × 25 ft	30 × 30 ft
Lucalox	70	35	15	10	—	—
	100	55	25	15	10	—
	150	95	45	25	15	10
	250	180	80	45	30	20
	400	300	135	75	50	35
	1,000	—	—	210	135	95
Multivapor	175	85	35	20	15	10
	400	200	90	50	35	25
	1,000	—	300	165	105	75
Continuous rows of 2-lamp fixtures on spacing† of:						
Fluorescent (cool white)		6 ft	8 ft	10 ft	12 ft	15 ft
40W Rapid Start		120	90	70	60	50
75W Slimline		120	90	70	60	50
110W High Output		185	140	110	90	75
215W Power Groove		300	225	180	150	120

SOURCE: General Electric Co.

* See footnote for Table 12.5.10.

† Spacings assumed within maximums established by fixture manufacturer.

For vertical surfaces

$$E_v = (I_\theta \sin \theta)D^2 = I_\theta R/D^3 \qquad (12.5.8)$$

Nomograms and graphical solutions are available for Eqs. (12.5.7) and (12.5.8).

THE ECONOMICS OF LIGHTING INSTALLATIONS

The cost of lighting is computed by summing the annual cost of energy; relamping; cost of labor for cleaning, relamping, and servicing; interest; and depreciation.

Different lighting systems can be evaluated by comparing the costs per million lumen hours per luminaire. This is given by Eq. (12.5.9),

$$U = \frac{10}{Q \times D}\left[\frac{(P + h)}{L} + W \times R + \frac{(F + M)}{H}\right] \qquad (12.5.9)$$

where U = unit cost of light in dollars per million lumen-hours; Q = mean lamp lumens; D = luminaire dirt depreciation (average between cleanings); P = price of lamp in cents; h = cost (in cents) to replace one lamp; L = average rated lamp life in thousands of hours; W = mean luminaire input watts (lamps plus ballast); R = energy cost in cents per kilowatthour; F = fixed or owning costs in cents per luminaire-year; M = cleaning costs in cents per luminaire-year; and H = annual hours of operation in thousands of hours.

In the above equations the area can be expressed in square metres. These equations are general and basic. With the advent of energy conservation, it has become important to use electric power effectively and efficiently. The IES, in its 1981 Handbook, established a watts per square foot (square metre) for various occupancies, called a *base unit power density* (UPD). These values are used to establish a power limit for a facility. For this purpose approximate values are used for CU, lamp plus ballast, lumens per watt, and LLF. For LLF, 0.7 is used.

Another way to compare installations is to compute the watts per square foot for each proposed installation. This is computed by either method:

$$\text{watts/ft}^2 = \frac{\text{total lamp lumens}}{\text{area, ft}^2} \times \frac{1}{\text{lumens/watt of lamp and ballast}} \qquad (12.5.10)$$

$$\text{watts/ft}^2 = \frac{\text{designed illuminance}}{\text{CU} \times \text{LLF}} \times \frac{1}{\text{lumens/watt of lamp and ballast}} \qquad (12.5.11)$$

Typical values are shown in Table 12.5.10.

DIMMING SYSTEMS

Dimming systems are used in theaters, auditoriums, ballrooms, etc. Originally, power-consuming rheostats were used. These have been replaced by continuously variable autotransformers, variable reactors, silicon controlled rectifiers (SCR) and triacs. The development of controlled solid-state devices has resulted in small, reliable dimmers which can be readily programmed. Only incandescent and cold-cathode lamps can be dimmed easily. Fluorescent lamps require special ballasts which keep the electrodes hot at all times. Dimmers have been developed for high-intensity discharge (H.I.D.) lamps.

HEAT FROM LIGHTING

Lighting installations are a substantial source of heat, have long been a factor in the design of air-conditioning (cooling) systems, and are increasingly significant in the design of heating systems. The heating effect for 1 W is 3.413 Btu/h. Approximate wattage data for lighting systems at various lighting levels can be calculated by using watts per-square foot calculated from Eq. (12.5.10) or (12.5.11). Heat generated is delivered to surrounding areas in several ways, with energy distribution for fluorescent and incandescent lamps as illustrated in Fig. 12.5.17. With the prevalent high lighting intensities of modern buildings, it is essential to control the heat generated by a lighting system. Substantial portions of the energy which is not radiated into the room may be conducted away from the luminaire by an air stream or by water flowing through a coil attached to the luminaire. In the heating season, this heat energy is delivered to the perimeter of the building for effective space warming. In the cooling season, the heat is rejected to the exterior, thus reducing the load on the cooling system. Air-handling luminaires (Fig. 12.5.18) are receiving wide acceptance.

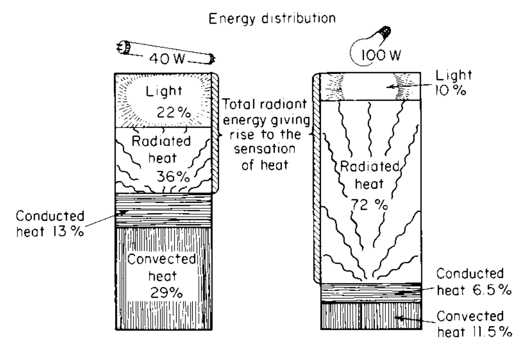


Fig. 12.5.17 Energy distribution of lamps.

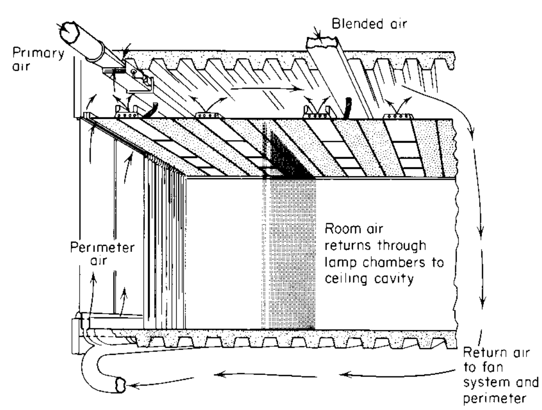


Fig. 12.5.18 Typical air handling system. *(Barber-Colman.)*

12.6 SOUND, NOISE, AND ULTRASONICS

by Benson Carlin and expanded by staff

REFERENCES: ANSI 51.1 Acoustical Terminology. *J Acoust. Soc. Am.* 1929 et seq. Beranek, ''Acoustics,'' McGraw-Hill. Carlin, ''Ultrasonics,'' McGraw-Hill. Morse and Ingard, ''Theoretical Acoustics.'' Harris, ''Handbook of Noise Control,'' McGraw-Hill. Mason, ''Physical Acoustics,'' Academic Press.

DEFINITIONS

Sound is an alteration in pressure, stress, particle displacement, and particle velocity, which is propagated in an elastic material. It is longitudinal in gases but may also be transverse (shear), surface, or other types in elastic media which can support such energy. It may be reflected, diffracted, or refracted at boundaries and under suitable conditions may be changed from one form to another. In longitudinal waves, the molecules move in the direction of wave motion, in the others at right angles to it. Waves may also be plane or circular depending on the source.

In general, the speed of sound V in a medium with mass density ρ is a function of its elastic properties. In solids, $V = \sqrt{E/\rho}$, where E is Young's modulus. In liquids, $V = \sqrt{E'/\rho}$, where E' is the bulk modulus of the liquid (see Table 3.3.2). In gases, the velocity is independent of the pressure, because the elasticity changes to compensate for the density changes; the general equation is $V = \sqrt{kp/\rho}$, where k is the ratio of specific heats and p is the pressure. The velocity in air at 68°F is 1,126 ft/s (33,160 cm/s) and increases by 0.1 percent per °F. In liquids, empirical formulas are easier to use than theoretical ones to predict actual velocities, since velocity varies in a complex way with temperature, pressure, and other factors. With sea water, a standard velocity of 5,100 ft/s (150,000 cm/s) may be used. The velocity of sound in liquids and solids is usually much higher than in gases (see Table 12.6.1 and Kinsler, ''Fundamentals of Acoustics,'' Wiley).

The **frequency** of a sound is the number of periods (cycles) occurring in unit time, customarily expressed as cycles per sec (cps) or ''hertz'' (Hz); kilocycles per sec, kc = 10^3 cps (kHz); megacycles per sec, Mc = 10^6 cps (MHz). Sound frequencies are usually defined as 20 to 20,000 cps **(audible),** higher **(ultrasonic),** and lower **(infrasonic).** Frequencies as high as the thousand-megacycle range (GHz) are now generated (see Table 12.6.2).

The relation between frequency f and wavelength λ is $V = \lambda f$. In air, at 1,126 cps, the wavelength is 1 ft. In nature, the waves may be simple sinusoidal, complex, or explosive (shock) depending on the source. The first is, of course, rare.

Attenuation of sound depends on the media of propagation and the frequency and is caused by absorption, spreading, and scattering. At audible frequencies in air attenuation is small except for the spreading of the energy over wide areas as the sound waves are propagated. By this means the intensity drops according to the inverse square law. However, in other media, the absorption, scattering, or other characteristic may be predominant.

The sound **intensity** is the average rate of sound energy transmitted through a unit area normal to the wave direction at the point considered. This is a definition of power and may be expressed in watts per sq metre. It is usual, however, to express power in **decibels,** dB, which is a term used to give the relative magnitude of two powers by comparing the one under consideration to a standard. The sound-pressure level in decibels, dB, is defined as twenty times the logarithm to the base 10 of the ratio of sound pressure to the reference sound pressure. All values are for air at 20°C and atmospheric pressure. Pressure measurements in air use a pressure reference (rms) of 0.0002 dyne/cm^2; 1 dyne/cm^2 is used underwater.

Intensity references for air are 10^{-16} w/cm^2 [equivalent to a pressure (rms) of 0.0002 dyne/cm^2, and 0.02 erg/cm^{2}s, equivalent to a pressure of 1 dyne/cm^2]. Since the references are equivalent (i.e., the reference pressure corresponds to the reference intensity in this particular case), numerical results are identical for plane waves using either expression $IL = 10 \log (I/I_0)$ or $PL = 20 \log (P_e/P_0)$, where IL and PL are the intensity and pressure levels, I_0 and P_0 are the reference intensity and pressure, P_e is the effective pressure, and I is the intensity in question.

Table 12.6.2 Sound Spectrum

Frequency	Action
20–40 cps	Thunder
128 cps	Average speech (male)
250–2,740 cps	Telephone bandwidth
90–5,000 cps	Radio broadcast
15 cps–15 kc	Limits of average human hearing
10–90 kc	Ultrasonic cleaning
15–50 kc	Ultrasonic depth sounding, sonar
20 kc	Ultrasonic bulgar alarm, control apparatus, door opening
30 kc	Highest frequency obtained by friction
40 kc	Highest frequency of Hartmann generator
48 kc	Bat cries
90 kc	Top limit of tuning fork
100 kc	Highest frequency of Galton whistle
500–15,000 kc	Ultrasonic pulse-echo testing
1,000 kc	Medical therapy
1,500–30,000 kc	Ultrasonic delay lines
15,000 kc	Radar trainer

Table 12.6.1 Velocity of Sound

Material	Sound velocity, ft/s	Density, lb/ft^3	Density × velocity, lb/(ft^2·s)
Aluminum	16,740	168	2.82×10^6
Brass	11,480	530	6.08×10^6
Copper	11,670	555	6.47×10^6
Iron and soft steel	16,410	486	7.98×10^6
Lead	4,026	1125	4.54×10^6
Brick	11,980	125	1.5×10^6
Cork	1,640	15	0.025×10^6
Wood	10,000–15,000	30–50	0.3×10^6–0.75×10^6
Water	4,794	62.4	0.299×10^6
Air, dry, CO_2 free, 32°F	1,088.5	0.0808	88.0
Hydrogen	4,165	0.00560	23.3
Water vapor, 212°F	1,564	0.0372	58.2

NOTE: Approximate values from Smithsonian Tables.

When making measurements with pressure or velocity microphones, it is the pressure level or velocity level which is measured and the relationship between the measurement and the intensity is unknown except in the special cases indicated.

Decibels do not add numerically as linear figures do; i.e., 70 dB + 70 dB = 73 dB since doubling power results in a 3-dB increase in sound pressure. Figure 12.6.1 shows how to add decibels within 14 dB of each other. If the difference is greater between two readings, ignore the weaker one.

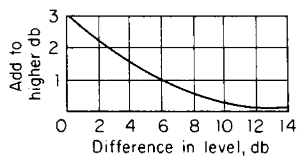


Fig. 12.6.1 Chart for addition of decibels.

Specific Acoustic Impedance The relationship between the pressure and the associated particle velocity at a point in a medium is called the specific acoustic impedance; its unit is the kilogram per meter second or mks rayl. The magnitude ρ_c is called the characteristic impedance of the medium, or the radiation resistance. This applies in the case of plane waves. The ρ_c of material is one of its most useful acoustic characteristics, since by means of it the amount of energy reflected at boundaries may be computed, horns may be analyzed according to the acoustic resistance at throat, and other calculations analogous to those made in electrical design may be carried out.

THE PRODUCTION AND RECEPTION OF SOUNDS

REFERENCES: Rinsler and Frey, ‘‘Fundamentals of Acoustics,’’ Wiley. Mason, ‘‘Electromechanical Transducers and Wave Filters,’’ Van Nostrand. Olsen, ‘‘Elements of Acoustical Engineering,’’ Van Nostrand.

Transducer A device for converting energy from one form to another, e.g., from electrical to acoustic or vice versa, is called a transducer. Among these are loudspeakers, microphones, hydrophones, and piezoelectric and magnetostrictive transducers.

Loudspeakers are usually classified as direct-radiator or horn type. The direct-radiator type consists of a cone, a magnet, a voice coil moving in the magnetic field, a vibrating diaphragm coupled to the cone, and suitable supports. The attachment of a horn improves the impedance match between the speaker and the air since it is essentially an acoustic transformer. The dimensions and flare of the horn contribute to its matching ability.

One of the more common types of horn is exponential, although straight and other types are also possible. In a similar manner, mechanical transformers may be used to concentrate the energy of ultrasonic transducers. In such forms they operate to concentrate rather than to spread the energy. The operation of the speaker may be variously influenced by its enclosure, by the baffle which separates the front from the back radiation, or by its resonances.

Microphones (for gases) and **hydrophones** (for liquids) are transducers for converting mechanical to electrical energy. They may be piezoelectric, electromagnetic, magnetostrictive, or capacitive. The variation in electrical output is proportional to the effect of the acoustic field on the characteristics. Ultrasonic transducers may be any of the above types but are usually crystal (piezoelectric) or magnetostrictive. Among the common piezoelectric materials are quartz, barium titanate, lithium sulfate, ADP (ammonium dihydrogen phosphate), and rochelle salt. In sonar and high-power industrial systems, mosaics of crystals are used; in low-power, high-frequency systems, a single crystal is usual.

Whistles and **sirens** may also be used to produce intense sound fields in gases and liquids. These are devices which produce sound by passing a fluid over an obstacle, thereby creating turbulence in the fluid. When the obstacle is an edge, these are referred to as edge or E tones; when an orifice, as jet tones. Organ pipes, whistles, and nozzles for spraying are devices of this class. Frequencies up to 100,000 cps are possible, although 30,000 cps is the approximate limit at which appreciable power can be generated. Resonators may be placed in the sound field to reinforce it and to stabilize the frequency. These take the form of small pipes tuned to the approximate frequency. Common types of whistles are the Hartmann and Galton (for gases) and the jet edge (for liquids).

Sirens are devices in which a revolving disk with holes in it interrupts a jet from a nearby tube. Compressed air, steam, and water have been used. Frequencies up to 30 kc may be produced at efficiencies of 50 percent approximately; a 1-hp motor produces between 300 and 1,000 W (see also Jones, *J Acoust. Soc. Am.*, 1946).

Transducers are generally driven by electronic generators, motor generators, or air compressors. As receivers, they activate amplifiers or indicating devices.

The Perception of Sound The average young observer perceives sound between 20 and 20,000 cps. High-frequency response deteriorates with advancing age. The ear responds to a wide range of intensities; e.g., between 500 and 5,000 cps, the ratio of tolerated intensities is about 10^{12}. The minimum intensity perceived varies with frequency. Figure 12.6.2 shows the audible frequency and intensity range for a standard listener, where the lowest curve represents the threshold of hearing and the top one the beginning of sensation in the ear. These curves show the pressure levels required for a given tone to sound as loud as the corresponding reference tone of 1,000 cps (see also Fletcher and Munson, *J. Acoust. Soc. Am.*, 1933).

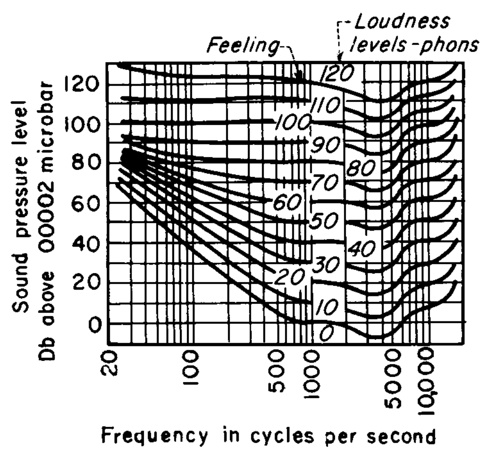


Fig. 12.6.2 Loudness contours.

Loudness is a subjective rather than a purely physical attribute. To provide a qualitative basis, the loudness level in **phons** is defined as the pressure level in decibels of a pure 1,000 cps tone which a typical observer judges to sound as loud as the sound in question. Observers can experimentally judge the loudness of pure or complex tones. However, this does not means that the apparent level is proportional to its level in phons; i.e., a level of 10 phons is not twice as loud as one of 5 phons. An additional expression, **sones,** defined as the loudness of a 1,000 cps tone at 40 dB intensity, is necessary to compare various loudness. The relationship between sones and phons is shown in Fig. 12.6.3.

Quality is a subjective attribute of sound in which equally loud sounds may be distinguished as to kind. Basically, differences in quality arise from differences in the distribution of energy in different parts of the frequency spectrum. In *music* this takes the form of the energy relationship of fundamental and harmonics; in *noise* it is random. These differences affect the sensation of loudness of noise and the psychological annoyance it produces. Shrill, high-pitched, and irregular sounds are usually judged less pleasant than low-pitched and regular sounds.

Among terms used to define quality are **pitch,** determined by frequency (mostly), together with intensity and waveshape (unit is the mel); **timbre,** determined by wave shape (mostly), together with intensity and frequency (see Seashore, ''Psychology of Music,'' Dover).

Masking describes the ability of one sound to make the ear incapable of perceiving a second one. See ANSI 53.20, Psychoacoustical Terminology. It is measured by the shift in the threshold of audibility of the masked sound in decibels. The partial deafening of the ear by the masking effect of noise affords a direct quantitative measure of the interfering effect of the noise. If the masking is measured at several frequencies throughout the audible ranges, the overall pressure level of the sound can be computed. For any given frequency, the masking is expressed in decibels relative to the unmasked threshold for a **critical bandwidth** centered on the frequency of the masked tone. This critical bandwidth is that beyond which an increase in the passband has little effect on the masking of a pure tone at its center frequency. Critical bandwidths vary from 40 cycles at 100 cps to 200 cycles at 6,000 cps.

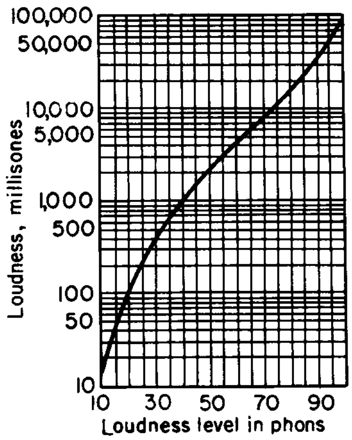


Fig. 12.6.3 Relation between loudness and loudness level.

Noise is an undesired sound. It implies an unwanted disturbance in a useful band which interferes with the useful information. Any elastic structure may produce noise when set into vibration. Generally the motion is an unwanted concomitant of some desired function, e.g., the vibration of a machine tool.

The term has a connotation of unpleasantness in quality or loudness. Typical examples are gear noises, 60-cycle hum, motor traffic, hammer blows, pneumatic-tool operations, and hissing of gases in an orifice. Noise measurements are usually made with a **sound-level meter,** comprising a microphone, attenuator, amplifier, frequency-weighing networks, and an indicator or recorder. See ANSI 51.4, Sound Level Meters. A **sound analyzer** indicates sound pressure as a function of frequency. In some cases electrical filters may be included which permit measurement in certain restricted frequency ranges. By using these instruments the components of the heterogeneous noise may be identified, and this helps to correlate it with its production. Once located, techniques for elimination flow and the results may be used to compute masking. Individual frequencies may be identified by beating against a known source **(beat-frequency oscillator)** until a null is observed.

Contact transducers (vibration pickups) may be used to locate sources of noise, such as in partitions and machine parts. They may be piezoelectric or magnetic and may be used in place of the microphone or the sound-level meter; hydrophones may also be used.

Where the frequency distribution of the noise is significant, an analyzer may be used since the level meter tells nothing about frequency distribution. Analyzers are manufactured in various forms, e.g., the octave-band analyzer, the impact-noise analyzer, and the wave analyzer, each of which uses a different method of finding out which frequency components are present.

Typical sound levels are shown in Table 12.6.3.

Table 12.6.3 Typical Sound Levels

	Decibels	
	120	Threshold of feeling
		Thunder, artillery
Deafening	100	Nearby riveter
		Elevated train
	100	Boiler factory
		Loud street noise
Very loud	90	Noisy factory
		Truck unmuffled
	80	Police whistle
		Noisy office
Loud	70	Average street noise
		Average radio
	60	Average factory
		Noisy home
Moderate	50	Average office
		Average conversation
	40	Quiet radio
		Quiet home or private office
Faint	30	Average auditorium
		Quiet conversation
	20	Rustle of leaves
		Whisper
Very faint	10	Soundproof room
		Threshold of audibility
	0	

NOISE CONTROL

REFERENCES: General Radio Co., ''Handbook of Noise Measurement.'' Harris, ''Handbook of Noise Control,'' McGraw-Hill. Bolt, ''Handbook of Acoustic Noise Control.'' Faulkner, ''Handbook of Industrial Noise Control,'' Industrial Press.

Noise control may be carried out at several stages: (1) at the source, by design changes or by quieting procedures, (2) during transmission, by attention to the path by which it is propagated to the listener, and (3) by quieting at the listening position. It may also be controlled architecturally as by the careful placement of necessarily noisy rooms in a building.

The Source By inspection and test procedures, a noise is tracked to its source. In some cases, design procedures which attempt to reduce the vibration or to prevent its radiation may be used. This may require the redesign of elements, such as cams, gears, housings, or provisions for cushioning. Viscous damping materials, e.g., putty or tar, may be applied to the vibratory surfaces in the form of nonhardening plastic mixtures. A machine may be isolated by sections or shock mounts to prevent transmission of vibration from one section to another. Absorbing materials may be placed on walls to absorb sound after it has been radiated.

Transmission Isolation If the vibrations of noisy machinery cannot be suppressed at the source, their transmission to the listener should be impeded. For the higher frequencies constituting noise, the most effective isolation method is the introduction of elastic discontinuities in the structure transmitting the noise (measured by the difference between density-velocity products as given in Table 12.6.1). The discontinuities may be obtained by the use of felt, cork, rubber, or springs in machinery mountings, or by the introduction of alternate lead and cork sheeting at masonry junctions. The isolation treatment should be applied as close to the source as possible in order to eliminate sound radiation from the structures transmitting the vibrations. Where this is not possible, the listening space itself may be isolated. Thus **quiet rooms,** constructed especially for noise measurements, are usually built as separate structures isolated from the main building.

Filtration Some problems of noise transmission through air lend themselves to solution by methods of filtration. Typical examples are the transmission of sound in ventilating ducts and the noise production at engine exhaust pipes. In each of these cases, the steady flow of gas must not be impeded, but the alternating flow, representing sound transmission, must be effectively suppressed.

For ventilating ducts, an acceptable degree of noise suppression may be obtained by lining the ducts (on at least two nonopposite walls) with an efficient sound absorbent for a distance of 10 to 15 ft from both the inlet and the outlet. Where the length of duct available is insufficient, or where additional noise suppression is required, baffles, covered with absorbing material, may be introduced in the duct. A plenum chamber, used to serve several ducts, should be lined with sound absorbents. If the air velocities are high, it may be necessary to introduce additional baffles at bends in the ducts to avoid noise production through turbulence.

Exhaust mufflers are usually modifications of the elementary low-pass acoustical filter, comprising a through tube to which closed cavities are coupled through small holes at intervals along the tube. Mufflers of this type find application other than in internal combustion engine exhaust systems, and often are termed *passive mufflers.* Typical structures of this type (Fig. 12.6.4) produce little increase in back pressure and considerable attenuation of sound waves having frequencies above a cutoff frequency determined by the size of the holes and cavities. Porous packing, such as steel wool, in the side cavities or studied irregularity in the size and spacing of the cavities will increase the uniformity of noise suppression, whereas increasing the number of side cavities

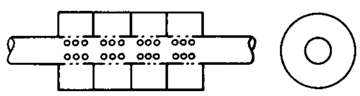


Fig. 12.6.4 Section through a passive exhaust muffler.

and the length of the muffler will increase the amount of suppression. Baffles in the tailpipe or irregular obstructions producing devious flow paths, e.g., the stone-filled pit for stationary engine exhausts, produce muffling action at the expense of appreciable increase in exhaust back pressure.

Shielding of airborne noise must be done by sound-opaque screens large in comparison with the wavelength of the sounds whose transmission they are to impede. This is seldom possible in building interiors except by utilization of building partitions as screens. Sound is transmitted through such partitions principally by minute flexure of the wall as a whole in response to the incident sound pressure on the noisy side, with consequent reradiation on the quiet side. Reduction of sound transmission is obtained by increasing the mass per unit area of the partition, by constructing the partition of material comprising a hollow air-filled or fibrous-filled sandwich with a pattern of holes in one of the surfaces, or by the use of double partitions, vibrationally isolated.

Sound-transmission loss is usually greater for high frequencies than for low and is measured by comparing the average sound level on each side of the partition under standardized conditions. Average values of transmission loss, for frequencies from 125 to 4,000 cps, for typical partitions, are shown in Table 12.6.4. In any specific case, a more exact measure of the effectiveness of an insulating partition can be obtained by direct comparison of the transmission-loss vs. frequency curve for the partition and the intensity vs. frequency curve for the noise. Additional data on transmission loss for a wide variety of building materials and structures are available in the NIST publications TRBM-44; BMS 17 and Supplements 1 and 2.

In general, double partitions (including floated floor constructions) provide greater transmission loss than equally heavy concrete, masonry, or brick walls but, except for special designs, less transmission loss than equally thick masonry walls. Double walls must be constructed carefully to avoid loss of vibration isolation through mechanical bridging between the opposite surfaces. Sound-absorbing fillers (e.g., mineral wool) are usually detrimental to sound insulation if in contact with both interior surfaces, and a single bridging nail may alter significantly the insulating efficiency. For maximum effectiveness, one of the wall surfaces should be hung structurally free at all four edges with the boundary cracks sealed, with felt or asphalt compounds, against sound leakage. Through piping should be made vibrationally discontinuous by introducing canvas or metallic sylphon sections, and clearance holes at the walls should be sealed. Sound leakage through small clearance cracks contributes to the low transmission loss of ordinary doors. Special self-sealing soundproof doors are required to maintain the effectiveness of an efficient sound-insulating partition.

Quieting The sound level established in a room by a noise source is higher than that which the same source would produce in free space on account of successive reflections of sound at the walls. It is the function of **quieting** to avoid such enhancement of noise by providing a high degree of sound absorption at all interior reflecting surfaces exposed to the noise. Commercially available sound-absorbing materials may be cemented to flat surfaces or secured to wood or metal furring strips. They derive their absorbing property either from capillary porosity of the surface or from the dissipative vibration of surface layers. Hanging ''functional absorber'' units comprising vibratile matte surfaces, enclosing a volume of about 1 ft^3, can be used where surface absorbents cannot be installed conveniently. The effectiveness of sound absorbents varies with frequency, usually being greater for high and intermediate than for low frequencies. It may be measured by determining the **absorption coefficient,** defined as the fraction of sound energy diffusely incident on the material that is not reflected, or by determining the **specific acoustic impedance** of the material. The measured absorption coefficient is not a property of the material alone, but depends partly on the size and mounting of the test sample and the size and shape of the test chamber; thus comparison of the coefficients for different materials should be based only on measurements made under identical conditions. Such measurements on a wide variety of materials have been made available by the Acoustical Materials Assoc. (Chicago, Ill.), although it is to be expected that the absorption coefficients effective in various practical applications may differ somewhat from the published values.

Table 12.6.4 Sound-Transmission Loss in Building Partitions

Wall	Thickness, in	Weight lb/ft^2	Transmission loss, dB
Wood	0.2	0.45	18.5
Plate glass	0.25	3.2	27.0
Hollow gypsum tile, unplastered	3	11.1	27.2
Brick wall, unplastered	. . . .	22.0	33
Brick wall, plastered	6	46	43
Brick wall, plastered	10.5	93	49
Double wall; metal lath, ½-in gypsum plaster, on staggered 2 × 4 in wood studs	7.5	19.8	44
Double 3-in hollow gypsum tile, unplastered, 3-in airspace	9	22.0	42.6
1-in Thermax nailed over building paper to 3-in Thermax laid up in mortar, ½-in plaster on both sides	5	15	47
Double 2-in solid-gypsum tile, unplastered, completely isolated structurally by separate foundations, 4-in airspace	8	20.4	59

SOURCE: Based on Sabine, ''Acoustics and Architecture,'' McGraw-Hill.

Table 12.6.5 Sound-Absorption Coefficients

Maker, material thickness	Absorption coef at indicated frequencies 128	256	512	1,024	2,048	4,096	Noise-reduction coef	Weight, lb/ft²	Surface	AMA test No.
Armstrong Cork Co.										
Cushiontone A, ¾ in.	0.10	0.28	0.66	0.91	0.82	0.69	0.65	1.05	484 holes per sq ft, 3⁄16 in diam, 5⁄8 in deep. Painted by mfr	47–28
Travertone, ¾ in.	0.06	0.23	0.78	0.97	0.84	0.80	0.70	1.20	Fissured, painted	48–58
The Celotex Corp.										
Acousti-Celotex										
Type C-9, ¾ in	0.11	0.23	0.80	0.93	0.58	0.50	0.65	0.96	441 holes per sq ft, 3⁄16 in diam. Any paint	46–132
Type M-1, 5⁄8 in	0.07	0.21	0.64	0.86	0.93	0.83	0.65	1.31	676 holes per sq ft, 5⁄32 in diam. Any paint	46–12
Q-T Ductliner, in	0.21	0.42	0.71	0.86	0.79	0.75	0.70	1.3	Unpainted	A48–10
Johns-Manville Corp.										
Sanacoustic, KK, pad plus metal facing and pad supports 19⁄16 in	0.25	0.58	0.96	0.97	0.85	0.72	0.85	Pad 1.28	4,608 holes per sq ft, 0.068 in diam. Enameled metal pan backed with wool pad	46–88
Fibretone, 13⁄16 in	0.14	0.37	0.69	0.80	0.76	0.73	0.65	1.17	484 holes per sq ft, 3⁄16 in diam. Any paint	46–124
Airacoustic, 1 in	0.29	0.31	0.70	0.82	0.79	0.80	0.70	1.50	Unpainted	46–71
National Gypsum Co.										
Acoustifibre, 5⁄8 in	0.10	0.16	0.62	0.97	0.81	0.73	0.65	0.56	441 holes per sq ft, 3⁄16 in diam, 5⁄16 in deep. Painted	46–137
Owens-Corning Fiberglas Corp.										
Fiberglas Acoustical Tile, plain type, ¾ in	0.04	0.20	0.63	0.91	0.82	0.82	0.65	0.69	Painted	A48–99
United States Gypsum Co.,										
Acoustone F, 11⁄16 in	0.08	0.25	0.76	0.84	0.78	0.73	0.65	1.35	Fissured, painted	46–50
Brick wall, painted	0.012		0.017		0.023		0.02			
Concrete wall or floor	0.01		0.015		0.02		0.02			
Wood floor	0.05		0.03		0.03		0.03			
Cork or rubber tile on concrete			0.03–0.08				0.05			
Glass	0.035		0.027		0.02		0.02			

NOTE: This tabulation is based on *Bull.* XI (1949), Acoustical Materials Assoc. All samples were cemented to plasterboard for test, except that the Sanacoustical unit is attached to wood furring with special clips, and the duct linings are laid on 24 gage sheet iron, nailed to 1 × 3-in wood furring, 24-in O.C.

For ordinary noise quieting, the average of absorption coefficients measured at frequencies of 250, 500, 1,000, and 2,000 cps, called the **noise-reduction coefficient,** may be used. Typical values of this coefficient for representative materials are given in Table 12.6.5. In making quantitative estimates of noise reduction, the **total sound absorption** of the room boundaries may be computed by multiplying the noise-reduction coefficient of each different material present by the total exposed area of that material and summing up the resulting products. The noise reduction is then given by

$$\text{Noise reduction in decibels} = 10 \log \frac{\text{total absorption after treatment}}{\text{total absorption before treatment}}$$

When the frequency spectrum of the offending noise is known, greater precision in calculation of total absorption is obtained by replacing the noise-reduction coefficient by the absorption coefficient measured at the frequency of maximum loudness level from the noise source. Subjective judgments of the loudness reduction obtained by quieting can be estimated by using the noise reduction in decibels in connection with the loudness chart of Fig. 1.2.6.3.

In general, the larger the area of absorbing material introduced and the higher its noise-reduction coefficient, the more effectively the noise is reduced. No amount of quieting treatment can reduce the level of the noise received directly from the source. If full coverage of walls and ceiling is not possible, distribution of the material in several small patches is more effective than the same total area of material concentrated in one location. Similarly, the same area of material is more effective when applied to nonopposite walls and ceiling than when concentrated on either of these areas, and more effective when located near the edges and corners of a given area than when located in the center. Recent advances in noise control have resulted from advances made in signal processing chips and in the significant reduction in the cost of those components. These electronic components are built into electronic equipment, the whole of which constitutes an active noise control system, and which is based on the principle that a sound signal can be canceled by an almost identical sound signal produced 180° out of phase with the first one. This concept of an electronic noise muffler has been successfully adapted to control offensive noise in a variety of industrial applications. Further developments are expected along these lines.

APPLICATIONS

REFERENCES: Carlin, ‘‘Ultrasonics,’’ McGraw-Hill. Bergmann, ‘‘Ultrasonics,’’ S. Hirzel Verlag. ANSI Z24.18, Ultrasonic Therapeutic Equipment.

Industrial Applications Acoustic waves of high powers used in industrial applications are generally called **sonic** (or **ultrasonic,** when greater than about 20,000 cps). High-intensity sonic waves, in the 10,000 cps to the megacycle range (10^6 cps), are applied to many industrial processes. The effects seem to be a function of cavitation, heating, particle acceleration, short wavelength, and other characteristics of the waves. Application categories are (1) high amplitude and (2) low amplitude.

High-amplitude waves are used in operations such as cleaning, welding, drilling, emulsification, soldering, atomization, chemical and biological applications, medical therapy, and sonar. The energy may be continuous, pulsed, or modulated, in various ways.

Low-amplitude waves are used in operations such as material testing, burglar alarms, delay lines, or medical diagnoses. Any waveshape may be used; basically, a physical characteristic of the waves, such as velocity, is measured.

Cavitation may be defined as the formation and collapse of gas- or vapor-filled bubbles. Most significant industrial applications, e.g., cleaning, take place during the vaporous phase. The amount and force of cavitation are affected by the character of the liquid and the gas in it. The bubble collapse generates powerful local forces which cause the desired action. Levels of power in the liquid of approximately 3 W/cm^2 are required for intense cavitation and are dependent upon factors such as the liquid, temperature, and external pressure; powers as low as 0.3 W/cm^2 in water will produce a threshold cavitation (see also Briggs et al., *J. Acoust. Soc. Am.,* 1947).

High-Amplitude Applications

(See Fig. 12.6.5.)

Cleaning An ultrasonically agitated bath will erosively clean dirt from immersed articles. A high-power generator, usually electronic, produces sonic energy which is impressed on a transducer to drive the bath. Barium titanate transducers prevail, but magnetostrictive designs may be used. 10,000 to 90,000 cps are commonly used, with the lower frequencies generally more effective. Generator tuning may be manual or by feedback from the transducer controls. Power levels of 5 ± W/cm^2 are commonly used; size (depth) of the tank may affect the output; 50 ± W/gal is a rough empirical relationship; cavitation must exist for effective, speedy cleaning. A proper cleaning solution must be used, i.e., one which supports intense cavitation and also cleans (e.g., water solutions of alkalines or acids, or solvents like hydrofluoroether); temperatures between 120 and 160°F prevail. Among items commonly cleaned are jewelry (lost-wax castings), eyeglass frames, lenses, metal parts, and watches and clocks.

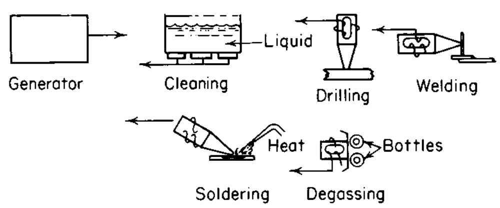


Fig. 12.6.5 High-amplitude systems.

An alternative form of ultrasonic cleaning can be performed by the introduction of an ultrasonic probe in a cleaning bath. The probe can be made to focus a large amount of energy over a small area or volume of the cleaning solution in which the workpiece is submerged. This method fosters removal of tenacious contaminents from normally inaccessible locations.

Foaming of Beverages Air content, which determines the life of a carbonated beverage, is reduced by foaming the bottles or cans before capping. Magnetostrictive transducers at 20,000 cps and 250 W, in contact with the containers, produce enough foam from the CO_2 to expel the air. The ultrasonic power requirement is basically small, but the losses in the coupling dictate the use of large generators. Similar techniques and apparatus may be used for the removal of gases from materials and for chemical effects such as the acceleration of iodine reactions and oxidation.

Soldering Some materials, such as aluminum, oxidize when exposed to air so that soldering is not possible. However, an ultrasonically driven solder bath will cause wetting of the material with solder and tinning of the surface. Magnetostrictive units are indicated because of the temperature requirements, with external heating and high tin-content solders; pots, as well as irons, may be constructed. Applications include aluminum wire, foil capacitors, and the filling of holes in castings (see also Sec. 13).

Welding Similar equipment (between 100 and 5,000 W output) may be used to weld thin metal or thin-to-thick sections. Such units apply the ultrasonics in a shear direction with respect to the parts to be welded. The process depends primarily on the sonic energy, the clamping force, and the amount of external heating. Either spot or lap welds are possible, but in all cases one of the sections must be thin (see also Sec. 13 and ''AWS Welding Handbook'').

Drilling is effected with the same sort of apparatus, but the force is longitudinal rather than shear. An abrasive is flowed over the tool head and is driven by the cavitation against the part to be drilled, causing the material to erode away. Any shape may be obtained in this manner. The head is usually mounted on an apparatus similar to a milling machine. Tolerances depend principally on the physical rigidity of the system and on grit size. Applications include hard materials such as ceramics, jewels, and glasses. The same apparatus has been applied to dental drilling, but the time required and the necessity for use of a slurry have kept it from greater acceptance. However, the method is widely applied to cleaning the surface of the teeth. The technique has been applied to forming lesions in the brain and spinal column of human beings, using a focused beam of sound at 3 ± Mc rather than a velocity transformer.

A **whistle** may be operated in a gas for agglomeration or foam settling and in a liquid for emulsification. Ultrasonic fields introduce additional forces on particles suspended in a gas, causing them to come together. Materials such as smoke, dust, and fog have been experimentally treated in this way. Generally, the whistle drives a resonant cavity, generating about 150 dB intensity (power output of 150 ± W) at 10 to 20 kc. Atomization of a liquid may be effected by introducing the liquid into a strong sonic field, either passing it directly over or through the whistle. The use of waves has been reported for drying solids, such as sugar, for atomically driven sound beacons under the sea, and for emulsification of liquid rubber and other materials.

Sonar Underwater signaling and detection are among the older applications of ultrasonics and comprise the active (pulse-echo, Doppler) and passive (listening) systems. The principles of operation are similar to those of pulse-echo testing in the active case (see Albers, ''Underwater Acoustics Handbook,'' Penn State Univ. Press).

Among the **miscellaneous applications** of high-power ultrasonics is metal treatment, atomization of oil for burners and of cleaning solutions used in the manufacture of delicate electronic devices such as circuit boards, ultrasonic diathermy for bursitis, humidification, and ultrasonic neurosonic surgery.

Testing Materials (See Sec. 5 and McMaster, ''Nondestructive Testing Handbook,'' Ronald.) The most common industrial use of low-power ultrasonic waves is for testing materials. The technique basically depends on the ability of a discontinuity in a material to reflect part of the energy hitting it. Various types of ultrasonic waves such as longitudinal, shear, or surface may be used. Transducers are usually crystal, such as barium titanate or quartz, and measure from ¼ to 1 in. diam (Fig. 12.6.6).

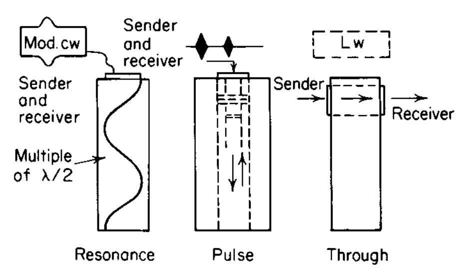


Fig. 12.6.6 Low-amplitude systems.

The basic types of ultrasonic systems are (1) pulse-echo, (2) through-transmission, and (3) resonance. The **pulse-echo system** uses a pulse ranging in length (time) from a fraction of a microsecond to several microseconds and an amplitude from 50 to 250 V radio frequency across the transducer. The pulse travels in the material and is reflected by an interface; the time of travel is measured. The pulse-echo method has also been applied to medical mapping of the body interior and for tracing brain centerline displacement and heart valve action.

The **through-transmission system** places continuous pulsed or modulated waves on a transducer coupled to one side of a part with pickup on the other side. If a flaw interrupts, the waves do not penetrate the part.

The **resonance system** uses a single transducer and varies the frequency applied to it. Within the applied frequencies is one whose wavelength is related to the thickness of the part in such a way that less power is required of the driving system. This condition is indicated, and since the wavelength within the material is known, the thickness is determined. The most common applications of the resonance system are (1) for thickness measurement when one side only is available, and (2) for finding laminations in thin sections and lack of bond (see also Sec. 5).

The **sonic burglar alarm** depends on the Doppler shift caused in a sonic field by a moving object. The unit operates at 20 kc and will find minimum objects of 0.03 ft^2 in an enclosure of 100 ft^2. Magnetostrictive transducers are used coupled to diaphragms; they are not unlike radio speaker systems in appearance.

Liquid-Level Sensors Ultrasonic devices may be used to measure the level of liquid in a tank either by the pulse-echo technique or by indicating the transducer lead, i.e., a transducer driven by an oscillator where the reaction of the liquid load causes a change in the driving current.

Sonic microscopes are devices in which a beam of sound illuminates a part; the shadows of the field are scanned on a cathode-ray tube (usually constructed of barium titanate) by a flying spot.

SAFETY

Under the Occupational Safety and Health Act (OSHA), definitions have been made which legally define levels either as safe or as hazardous. Moreover, noise is now recognized as a pollutant, both as a nuisance and as the cause of hearing impairment.

General noise levels in the environment have already been defined (Fig. 12.6.2). There is some evidence that noise may cause ailments such as anxiety and heart disorders.

Protection from noise is required when sound levels exceed those in Table 12.6.6 (Table G-16 of the Act), when measured on the A scale at slow response on a standard sound-level meter (except for certain alarms, etc., as provided in the Act). When several successive exposures occur, they are combined (see paragraph 1910.95, reference above).

Conversion from octave-band analysis levels to A-weighted levels may be made from the figure in the Act. This figure has been also adopted by some local or state laws (Fig. 12.6.7).

When the environmental noise is greater than specified in the Act, protection must be provided.

However, when the noise is intermittent, if the peaks occur within 1 s or less, it is considered continuous. When protective equipment is required, it must be provided by a trained person and periodic checks made of the effectiveness.

In addition to the levels, time of exposure is also involved, as shown in Table 12.6.6.

OSHA also requires, when 90 dBA is exceeded, ''a continuing effective hearing conservation program shall be administered,'' i.e., consisting of periodic hearing checks and noise surveys.

The type of facility required for these tests is spelled out in the reference above.

Table 12.6.6 Permissible Noise Exposures

Duration per day, h	Sound level, dBA slow response
8	90
6	92
4	95
3	97
2	100
1½	102
1	105
½	110
¼ or less	115

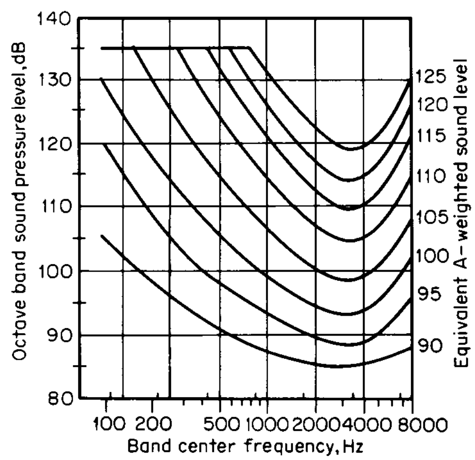


Fig. 12.6.7 Equivalent sound-level contours. Octave-band sound-pressure levels may be converted to the equivalent A-weighted sound level by plotting them on this graph and noting the A-weighted sound level corresponding to the point of highest penetration into the sound-level contours. This equivalent A-weighted sound level, which may differ from the actual A-weighted sound level of the noise, is used to determine exposure limits.