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Chapter 7
Pumping, Storage, and Distribution

7-1. Introduction

The various components of a water supply system should be designed to work together effectively and efficiently to ensure that sufficient water is available to meet variable rates of demand. This is especially true of smaller systems since maximum demand rates are often many times greater than average rates. In order to accomplish the dual goals of effectiveness and economy, the design process must be a carefully integrated activity. Hence, the implications of the design and operation of each component on the design and operation of every other component should be considered. The relationships among the pumping, storage, and distribution functions are especially important and are, therefore, considered together in a single chapter. In reality all three must be considered essentially simultaneously; but for the sake of clarity, pumping will be discussed first, storage second, and distribution third.

7-2. Pumping

It is almost never possible to remove raw water from its source, process it, and deliver potable water to the ultimate users by gravity flow alone. Thus, pumping is almost always required. However, for many small water systems (e.g., single well with relatively high yield), only one pump may be required. On the other hand (e.g., surface water requiring substantial treatment), several different pumps may be needed. Regardless of the application, the procedure to be followed in selecting pumps and designing pumping facilities is essentially the same.

a. Selecting pumps. Pump selection is discussed in many water supply textbooks, speciality handbooks, and manuals. Examples include Campbell and Lehr (1973), Clark, Viessman, and Hammer (1977), Daffer and Price (1980), Hicks and Edwards (1971), Linsley and Franzini (1979), Merritt (1976), Salvato (1982), Sanks (1978), Steel and McGhee (1979), USEPA (1974), Walker (1976), and Wright (1977). Guidelines, specifications, and standards for pumps are issued by a number of agencies and organizations including the Department of the Army (EP 310-1-5) and AWWA. References that may be especially helpful to designers of small systems include the Manual of Individual Water Supply Systems (USEPA 1974), Manual for Safety Rest Area Water Supply Systems (Folks 1977), Environmental Engineering and Sanitation (Salvato 1982), and Pump Selection: A Consulting Engineer's Manual (Walker 1976). A brief discussion of pumping requirements applicable to military (Army and Air Force) installations is presented in TM 5-813-1.

(1) Data requirements. It is not possible to select the best pump for a given application until the expected operating conditions are fairly well defined. Thus, design (at least preliminary design) of distribution and intake piping must proceed pump selection. Consideration of storage requirements may proceed more or less simultaneously with pump selection. The following specific information must be available:

(a) Maximum safe rate at which water can be supplied to the pump (e.g., well or reservoir yield).

(b) Average and maximum rates at which water must be delivered by the pump to the distribution/storage system (this requires knowledge of the type and volume of storage that will be available) .

(c) Minimum available net positive suction head (this requires knowledge of the maximum lift required and all head losses on the intake side of the pump).

(d) The range of discharge heads the pump must work against (this requires knowledge of the system head/flow characteristics, which include the effects of all head losses on the discharge side of the pump and the maximum and minimum allowable pressures in the system).

(e) Characteristics of the water to be pumped (e.g., temperature, sand content, corrosiveness).

(f) Availability of suitable electric power at the site.

(g) Expected level of operation and maintenance capability (i.e., operator time per day, skill level of operator, availability of maintenance and repair support).

(h) Desired placement of pump (e.g., indoors, outdoors, submerged, in a dry well).

(i) Design period.

Once these and perhaps other site-specific factors are known, it is possible to consult manufacturers' literature and consider the available pumps. A major portion of this process involves consideration of trade-offs among the reliability, first cost, and operation and maintenance cost of various pumps having suitable flow/head/efficiency characteristics.

(2) Types of pumps. Several kinds of pumps are available, but centrifugal pumps are almost always chosen for deep well or surface-supplied water systems. In the latter case, either horizontal or vertical pumps may be used. The choice depends largely on the type of intake and storage systems used

and the desired placement of the pump. For deep well applications, vertical turbines or submersible pumps are usually used. Both types are actually multiple-stage (stages stacked vertically) centrifugal pumps. They differ in that for the vertical turbine type, only the pumping head is submerged, while for the submersible type, the pumping head and driver are closely coupled and the entire unit is submerged. Vertical turbine pumps offer some extra convenience since the driver is easily accessible for maintenance or replacement, but require a drive shaft to connect the driver to the pumping head. Therefore, the well must be aligned well enough to accommodate the shaft. Submersible pumps can be installed in poorly aligned wells so long as there is sufficient clearance to lower the pump to the desired depth. Detailed discussions of the advantages and disadvantages of various types of pumps and the factors to consider when choosing among them are readily available in the literature (e.g., Folks 1977; Hicks and Edwards 1971; USEPA 1974; and Walker 1976) and are not reproduced herein. The pump chosen should conform to EP 310-1-5 and/or AWWA.

(3) Operating reliability. Regardless of project size, economic considerations are important in pump selection. However, the very nature of small water systems puts a premium on minimizing operational difficulty and expense. As a result, it is usually best to use a pump and control system that is simple, rugged, and reliable even though less expensive (first cost) options may be available. For this reason, constant speed units are usually preferred. Whenever feasible, pumps and drivers should be selected that will operate near their peak efficiencies under the actual operating conditions that are expected. Maximizing the efficiency of pumps and drivers (subject to the constraints of operational ease and reliability) will tend to reduce operating costs without reducing dependability significantly, when compared to overdesigned facilities.

(4) Overdesign. Inefficiencies arising from overdesigning (i.e., choosing a pump that will, for a given head, deliver more water than is needed) are common since both engineers and manufacturers' representatives tend to be "conservative." The result of "conservative" design is often a system that operates inefficiently because it is capable of delivering more water than is ever required. Such systems are wasteful in terms of both initial investment and continuing operating cost. To avoid this pitfall, designers must consider pump characteristics and system head curves carefully and work closely with manufacturers' representatives (Daffer and Price 1980). In this regard the efficiency of both the pump and the driver should be considered. Fortunately, electric motors are usually fairly efficient over a broad load range (e.g., 50 to 125 percent of the rated capacity). However, in the smaller sizes, high-efficiency motors may be as much as 10 percent more efficient than their standard counterparts. At typical electrical power rates, such motors are likely to be a good investment. Pumps with fairly steep characteristic curves are usually preferred since their capacity to deliver water is relatively unaffected by changes in head. As pumps, water lines, valves, etc., age, head losses will tend to increase. This can significantly affect flow rates if both the pump characteristic and system head curves are fairly flat.

b. Pumping stations. Pumping stations should protect pumps and other equipment from weather and vandalism. They should be located on high ground (e.g., 0.3 m (1 ft) above the 100-year flood level), or protected by adequate earthwork. Floors should be raised at least 150 mm (6 in.) above finished grade and adequate interior drainage should be supplied. In the case of well houses, the floor should be sloped to direct drainage away from the well. Freeze protection, including adequate insulation and heaters, should be provided as should ventilation to prevent the overheating of equipment during warm weather. Care should be taken to ensure that neither raw nor treated water can be contaminated by lubricants, maintenance materials, insects, birds, small animals, etc. Where architecturally acceptable, windows should be kept to a minimum and a security-type fence should be provided to discourage unauthorized entry. Pumping stations should be large enough to allow free access to all equipment and to facilitate maintenance work. Repairs that are technically quite simple can be made very complex by poor placement of pipes and equipment and insufficient room to maneuver. It is good practice to go over pipe layouts and equipment and valve placement with experienced operators before deciding on a final design. Another good approach is to assume that sooner or later every piece of equipment, pipe, or fitting will fail, and then consider what will have to be done to make the necessary repair or exchange. Special attention should be given to ensuring that craneways, hoist beams, eye bolts, or double doors are provided to allow for removal and replacement of heavy items such as pumps, motors, or tanks. When the pumping station doubles as a treatment facility, room must be allowed for chemical storage and laboratory activities as well as the treatment units. In some cases, e.g., gas chlorination, a separate room must be provided. Generally, the local or state regulatory agency will have a number of specific requirements relative to pumping stations.

c. Piping and appurtenances. Each pump should be equipped with a pressure gauge and flowmeter on the discharge line so that performance can be monitored. The piping should be arranged to result in minimal head losses, and valves should be located so that each pump can be completely isolated when necessary. Where multiple pumps are used, each one should have its own intake, or the multiple intake should be carefully designed to ensure that all pumps have essentially the same inlet conditions. Care must be exercised to make sure that the pumps always draw water, not an air/water mixture, or air alone. The specific locations of check valves and other appurtenances will depend on the inlet conditions, type of storage, piping layout, and regulatory requirements. Provisions for sampling and possible future chemical addition locations should be considered in the final design.

d. Capacity. Where feasible, at least two pumps, each having capacity equalling the required demand, should be provided. Common practice is to have the pumps alternate in service. For multiple-pump systems, at least one pump should be capable of meeting the average demand and the remaining pumps should have a combined capacity at least equal to the average demand. Where fire protection is afforded, other requirements may be imposed (paragraph 4-7*b*(1)(c)). For well systems, if practical, it is good to have at least two wells (and pumps) with each one capable of meeting the average demand in a fraction of a day (e.g., 16 hours of operation). However, for small systems, this may be impractical. In such cases, a spare pump and motor should be available. Multiple pump and complex control arrangements relying on various sizes of pumps to meet varying demand for water are usually not practical for small systems. Generally, it is better to use identical pumps in alternating service and meet higher rates of demand from storage or by longer and/or more frequent pumping cycles.

e. Emergency operation. As a general rule, some type of emergency operating capability should be maintained. The relative importance of such a capability is, of course, a function of the local situation (i.e., type of water service provided, storage capacity, the ramifications of interrupted service). For small well systems and small surface water systems, it is usually more practical to provide emergency electrical power by a gasoline or diesel fuel powered portable generator. Deep well systems, depending on importance of the operation, may have permanent fuel powered or dual drive pumps installed. In some cases, local regulations may require the capability for temporary/emergency power connections.

f. Lightning protection. Electric motors should be provided with some type of protection from “near miss” lightning strikes. This is especially true for submersible pumps. It is virtually impossible, however, to provide protection from a direct hit. The best source of information concerning lightning protection is usually the utility company providing the electricity.

g. Pump installation. Pumps should be installed according to instructions provided by the manufacturer. Strict attention should be given to correct anchoring and alignment and to protecting every part of the pump, frame, and driver from loads or stresses (including those of thermal origin) induced by the piping. Failure to observe these precautions can lead to operational problems ranging from excessive vibration and noise to complete failure of the bearings, drive shaft, pump base, or casing.

7-3. Storage

The primary purpose of water storage is to ensure that an adequate supply of water is available at all times. Careful sizing and siting of storage facilities permit the use of economical pipe sizes in the distribution system, reduce the magnitude of pressure variation within the system, can make it possible to operate production facilities at reasonably uniform average rates rather than substantially higher peak demand rates, or can allow production facilities to operate according to some convenient schedule. As emphasized in paragraph 7-1, it is not possible to isolate the design of storage facilities from that of other water supply system components. Thus, design of storage facilities is highly site-specific, and there is no simple procedure that can always be used to size and locate the various tanks that may be required. Rather, the designer must consider the given water supply system as a whole, and choose storage facilities that are compatible with other system components, in order to achieve a total system design that will be both economical and able to serve the intended purpose well. General discussions of water storage requirements are presented in many textbooks and handbooks (Clark, Viessman, and Hammer 1977; Folks 1977; Linsley and Franzini 1979; Merritt 1976; Salvato 1992; Steel and McGhee 1979; USEPA 1974; and TM 5-813-1) and in paragraph 4-3 of this manual. In addition, many state and local regulatory agencies publish guidance for meeting their specific design requirements. In the discussion presented below, primary emphasis is given to treated (finished) water storage.

a. Types of storage. Finished water may be stored in underground, ground level, elevated, or hydropneumatic (pressurized) tanks. In essence, the choice of the type of storage to be used depends upon the purpose for which the water is to be stored, the volume of water that must be stored, topography, climate, the areal distribution of the customers, and economic factors.

(1) Underground and ground-level tanks. Underground and ground-level tanks are usually used for intermediate storage (i.e., following treatment, but prior to entrance into the distribution system), but may also be used for distribution when the topography is such that a beneficial location is available. They are commonly constructed of either concrete or steel. The choice is usually dictated by economic factors.

(2) Elevated tanks. Elevated storage tanks are usually constructed from steel and used primarily for distribution purposes, although at larger treatment plants they may be used to supply water for use in backwashing filters. Elevated storage tanks (and underground or ground-level tanks located at sufficiently high elevations) can supply water for distribution by gravity flow. In addition, they offer certain operational

advantages in that they can be designed to "float on the system." In this type of arrangement both the pump(s) and storage tank(s) are connected directly (but independently) to the distribution system. During periods of high demand, water is supplied from both the pump and the tank. When demand is less than the pumping rate, the tank is gradually filled to some preselected high-water level at which time pump operation ceases. Water is then supplied by the tank alone until the preselected low-water level is reached and pumping begins again. The operation of the pump may be controlled automatically or manually. If the pump and tanks are located properly (usually on opposite sides of the service area), pipeline friction losses can be held to a minimum, even during high demand periods. This saves pumping energy (and possibly capital) costs and reduces the magnitude of the pressure variations in the distribution system. If the volume of the storage tank is large enough in comparison to the daily demand for water, it may be possible to provide an uninterrupted supply, even when it is necessary to make major repairs to pumps or other equipment. When it is not feasible to connect the pump directly to the distribution system, peak demands must be satisfied from the tank alone. This type of operation is less flexible than that described above, but may prove to be completely satisfactory for many small water systems.

(3) Hydropneumatic tanks. Hydropneumatic (pressure) tanks are very commonly used to distribute water in smaller water systems, especially those drawing on a groundwater source. The actual useful storage provided in a hydropneumatic tank is usually quite small in comparison with the nominal volume of the tank. Typical values range from 10 to 40 percent. The former is indicative of situations where all the pressure is supplied by the pump and the latter of designs that include an air compressor to boost pressure. In operation, the pump supplies water to the tank in response to signals from a control system designed to maintain the pressure in the tank between preselected high and low limits. (Note: these control pressures correspond to high-water and low-water levels in the tank.) As the water enters and the level in the tank increases, the air in the tank is compressed and thus the water is stored under pressure. When the pressure rises to the preselected value, the control system automatically shuts off the pump. Additional air may or may not be added, depending upon the particular system design. Water flows out of the tank into the distribution system upon demand. As this occurs, the pressure in the tank drops. When it reaches the preselected minimum value, the pump is automatically activated by the control system and the cycle described above is repeated. Over the course of time, there is a tendency for the water to gradually absorb the air in the tank and, thus, the tank may become "waterlogged." This can be avoided by using a control system that does not allow the water in the tank to rise above the design high-water level in combination with an air compressor to add air as needed. It is also possible for tanks to become "air bound" if too much air is added, or if the water pumped into the tank contains excessive concentrations of dissolved gases. This problem can be avoided if the tank is equipped with a valve that acts automatically to release excess air and a control system that is responsive to both pressures and water levels. Some manufacturers supply hydropneumatic tanks with flexible dividers between the air and water compartments referred to as "diaphragm" or "bladder tanks." This physical separation of the air and water minimizes problems associated with waterlogging and air binding. These tanks eliminate the need for multiple control devices as described earlier to prevent "waterlogging" or "air bound" conditions, thus providing more reliable and maintenance-free service. Thus, this type of tank should be used when available in an appropriate size. Often, up to three tanks in parallel are placed in service to provide adequate storage and system pressure. Hydropneumatic tanks are ideally suited to many small water systems; however, as a practical matter, the pump must be sized to meet peak demand requirements alone, since it is not feasible to provide sufficient storage in the tank to respond adequately to sustained high rates of demand. Occasionally, hydropneumatic tanks are used in concert with intermediate underground or ground-level storage, for example when the source yield is low in comparison to peak demand rates, or to enable economical or convenient operation of treatment facilities. Hydropneumatic tanks are almost never used together with elevated storage.

b. Storage volume. The mass diagram (paragraph 4-3*b*(1)), or some similar approach, may be used to size any storage facility so long as inflow (supply) and outflow (demand) rates are known. In practice, distribution storage volumes are usually determined from consideration of a combination of factors including the ramifications of supply interruptions, the reliability and expected repair frequency of key system components (e.g., pumps), expected time required to make repairs, availability of emergency backup equipment or water supply, regulatory agency requirements, economics, and some type of inflow/outflow analysis. For small systems, economic and regulatory considerations often combine to establish the design storage volume.

(1) Nonpressurized storage. Where it is feasible to use elevated tanks (or underground or ground-level tanks located at sufficiently high elevations) for distribution storage, it is good practice to provide reserve storage for emergencies. Considering the delays that may occur in repairing pumps or other equipment (especially for small rural systems having little in-house repair capability), or in restoring electrical power to rural areas following a major storm, a 2- or 3-day supply is desirable. Ideally, the decision of how much reserve capacity to build into a design should be determined by consideration of the trade-off between losses that would result from an interruption in water service and the cost of reserve

storage capacity. For small water systems, limited investment capital often controls this aspect of design.

(2) Hydropneumatic storage. As a general rule, the nominal volume of a hydropneumatic storage tank should be about 10 times the feeder pump capacity per minute. The following expression may be used to size such a tank more precisely:

$$V = \frac{(Q)(T)}{1 - \frac{P_{\min}}{P_{\max}}} \tag{7-1}$$

where

V = required tank volume, liters

Q = design flow rate, liters per minute

T = desired storage time at flow rate Q, minutes

P_{min} = minimum desired absolute operating pressure (atmospheric), kilopascals (kPa)

P_{max} = maximum desired absolute operating pressure (gauge pressure plus atmospheric pressure), kPa

In common practice, the maximum hourly flow rate is used for Q, T ranges from 15 to 20 minutes, and the pump is designed to meet the maximum instantaneous demand. Many regulatory agencies have very specific rules governing the design of hydropneumatic tanks. An excellent design example is presented by Salvato (1992).

c. Storage tank design. Water storage tanks may be constructed of reinforced concrete, prestressed concrete, steel, or other suitable material, depending upon the function of the tank, economic factors, and regulatory agency requirements. Some specific points to consider are outlined below. Information sources that should be consulted prior to final selection include manufacturer's literature and representatives, applicable AWWA Standards, American Society of Mechanical Engineers Code requirements (primarily for hydropneumatic tanks). U.S. Army Corps of Engineers Guide Specifications, and state and local regulatory agency rules and regulations.

(1) General requirements. All finished water storage tanks should be located and protected such that the contents will not be subjected to contamination resulting from precipitation, surface runoff, flooding, groundwater intrusion, or discharges from storm drains or sewers. Use of single common-wall separation between treated and untreated water should be avoided. Tanks should be covered and all vents and access points should be covered or screened to exclude the entry of birds, animals, insects, airborne dust, etc. Overflow pipes should be provided for nonpressurized tanks and should be terminated near the ground in a way that will prevent the discharge from the overflow from eroding the ground surface. However, overflow pipes should be terminated far enough above the ground surface to prevent the entry of surface water. Some type of access, generally through the top of the tank, should be provided to facilitate cleaning and maintenance. Provisions should be made for securing the covers of all access points to preclude contamination of the contents. Non-pressurized tanks should be vented and the vents should be protected to prevent contamination of the contents. All metal surfaces should be protected by suitable paints or other protective coatings conforming to AWWA Standards or U.S. Army Corps of Engineers Guide Specifications and meeting local regulatory requirements for portable water service. Finished water storage tanks should always be disinfected prior to being placed in service. Allowing a treated water solution containing an initial chlorine concentration of at least 50 milligrams per liter to remain in the tank in contact with all surfaces normally in contact with the water (i.e., up to the high-water level) for at least 24 hours will usually be sufficient. However, the effectiveness of this or other disinfection method should be confirmed by draining the tank completely, refilling with treated water, and carefully analyzing several representative bacteriological samples. The public health agency with jurisdiction will generally have detailed procedures that must be followed for taking and processing the samples. In most cases, these agencies will perform the actual analyses themselves.

(2) Ground-level and elevated tanks. Ground-level and elevated storage tanks should be provided with interior and exterior ladders (with removable bottom sections), water level indicators, sampling taps, and appropriate freeze protection, and should be, to the maximum extent possible, vandal proofed. They should be enclosed by a sturdy fence (for example, 1.8-m- (6-ft-) high chain link with three strands of barbed wire on top) provided with a securable gate. As a general rule, the tank overflow should be located so that the maximum hydrostatic pressure in any part of the distribution system will not exceed 24 m (80 ft) of water. Also, it is good practice to choose a design such that the working elevation of the water surface in the tank will not vary more than 6 or 8 m (20 or 25 ft) during normal operation. For tanks that float on the system, valving should be arranged so that the tank can be isolated and completely drained without causing loss of pressure in the distribution system.

(3) Hydropneumatic tanks. Hydropneumatic tanks are usually cylindrical and may be oriented with the long axis either horizontal or vertical. The former is more common for larger tanks, while the latter is usually used for very small (e.g., individual home or farm) systems. In either case, the tanks should be provided with bypass piping, pressure gauge, sight glass (for viewing the water level), automatic blow-off valve, a mechanical means for adding air, drain, and pump/ pressure/water level control system. It is highly desirable that the entire tank and all appurtenances be located indoors; however, it may (depending upon climate and regulatory agency requirements) be permissible to house only that end of the tank where the pressure gauge, sight glass, controls, etc., are located. The enclosure should be heated and ventilated. This is very important to ensure dependable control system operation. Considerable care should be given to selection of a simple, rugged, dependable pump/pressure/water level control system. It is unreasonable to expect operators of small water systems to be able to make delicate adjustments and repairs to operating control systems.

7-4. Distribution

The purpose of a water distribution system is to deliver water of suitable quality to individual users in an adequate amount, and at a satisfactory pressure. In this section, some basic distribution system design concepts are introduced and discussed.

a. Introduction. Most standard water supply textbooks and many specialized design manuals and handbooks have chapters or sections dealing with the design of distribution systems. Examples are TM 5-813-5, AWWA (1962), Clark, Viessman, and Hammer (1977), Folks (1977), Linsley and Franzini (1979), Merritt (1976), Salvato (1992), Stephenson (1976), Steel and McGhee (1979), and USEPA (1974). The AWWA, Cast Iron Pipe Research Association, National Sanitation Foundation, American Society for Testing Materials, U.S. Army Corps of Engineers, and other professional and technical organizations have developed design techniques, testing and certification procedures, standards, guide specifications, and installation recommendations applicable to pipelines and most distribution system appurtenances. Where applicable, following the recommendations of these organizations will generally result in an adequate design. State and local regulatory agencies usually have rather detailed requirements relative to distribution system design and construction that must be adhered to rigorously. In some cases, distribution system design and construction will be heavily influenced by transportation agencies such as highway departments and railroad companies, and by utilities such as those providing gas, telephone, or electric service. The reason is that water pipelines are usually laid within the rights of way of public highways and roads, and must of necessity cross other rights of way. Traditionally, agencies and utilities such as those mentioned above have insisted on rather conservative pipeline design and construction practices in order to avoid potential interferences with their own activities. Distribution system planners and designers should be aware of this situation and make every effort to cooperate fully with the agencies and companies affected from the very outset of project development. To do otherwise is to invite lengthy delays at every stage of the planning/design/ construction sequence.

b. Purpose. In view of the wealth of information and design guidance already available, the primary purpose of this section is to call attention to some specific points, or factors, that should be considered in the design of small water distribution systems rather than to present detailed design procedures. Since the distribution system often represents the bulk of the capital investment for a water supply system, economic considerations are of a paramount importance.

c. Design flows and pressures. A water distribution system should be capable of delivering the maximum instantaneous design flow at a satisfactory pressure. While exactly what constitutes a satisfactory pressure depends upon system-specific considerations, a typical minimum value is 140 kPa (20 psi). In emergency situations, for example a major fire, system pressures as low as 70 kPa (10 psi) may be acceptable. Absolute maximum allowable pressures are dictated by the pressure ratings of the pipes and appurtenances used and regulatory requirements. However, system pressures should be kept as low as is commensurate with the needs of water users. Unnecessarily high pressures are wasteful in terms of the extra costs of the equipment and energy required to produce them, and the increased volume of water lost to leakage. For most small water systems there is no compelling need for the maximum pressure to exceed 410 or 480 kPa (60 or 70 psi). Thus, a typical approach is to initially design distribution piping for pressures ranging from about 280 to 410 kPa (40 to 60 psi) at the peak hourly flow rate, and then check to see if the design is still adequate at the peak instantaneous flow. A trial and error approach may be used until both conditions are satisfied. Where fire protection is provided, the fire flow will usually govern the design. When absolutely necessary, pressure reducing valves can be used to limit maximum pressures in low-lying areas. However, breaking a small distribution system into multiple pressure zones should be avoided if possible. The estimation of design flow rates is covered in detail in Chapter 4.

d. Pipe sizes. Pipe sizes are ordinarily selected so that flow velocities will range from 0.6 to 1.5 m (2 to 5 ft) per second at design flow rates. However, many regulatory agencies insist on certain minimum pipe diameters and practice oriented rules of thumb for sizing pipes. Where fire protection is provided, it is a good idea to avoid using pipes smaller than 150 mm (6 in.) in diameter. Where no fire protection is provided, pipes as small as 50 mm (2 in.) in diameter may be used. In either case, final pipe size selection should be based upon a complete hydraulic analysis of the system and not solely upon rules of thumb or required minimum diameter.

e. System layout. Textbooks generally call for distribution piping to be laid out in a grid pattern with pipes interconnected at intervals varying from 90 to 360 m (300 to 1200 ft). It is usually also recommended that feeder mains be looped whenever possible. This type of layout is highly desirable because, for any given area on the grid, water can be supplied from more than one direction. This results in substantially lower head losses than would otherwise occur and, with valves located properly, allows for minimum inconvenience when repairs or maintenance activities are required. Unfortunately, grid systems are practical only when water users are distributed more or less uniformly in a grid pattern (e.g., in city blocks). Thus, for small water systems, branching type distribution systems are more common. Nevertheless, it is good practice to loop or interconnect pipes whenever feasible. Normally, underground piping should be located along streets, roads, or utility strips. Minimize locating waterlines under paved areas as much as practical. A typical design approach is to sketch the tentative location of all pipes, connections, hydrants, valves, etc., on a map of the area to be served. Then, using the design flow rates and velocities discussed in AWWA (1962), tentative pipe sizes can be selected. A complete hydraulic analysis can then be performed and pipe sizes and location can be revised until a suitable design is obtained.

f. Hydraulic analysis. The hydraulic analysis of a water distribution system usually involves the use of the Hazen-Williams or Darcy-Weisbach equations to determine frictional head losses in the various pipes and appurtenances for various design flow rates. This information can be combined with topographical data to estimate operating pressures at various locations within the system.

(1) Friction losses. Movement of any fluid through a conduit results in a resistance to flow. This resistance or energy loss is referred to as friction and is usually measured in units of length (meters or feet) or pressure (kPa or psi). As mentioned above, the two most common equations applied to friction loss determination are the Hazen-Williams and Darcy-Weisbach forms. The use of the Darcy-Weisbach equation can provide the best, most reliable solutions for pipe flow problems. However, the roughness of the pipe is still an unknown making the empirical Hazen-Williams equation of equal uncertainty. For direct hand calculations, the determination of friction factor, f is more time-consuming than the direct substitution used in the Hazen-Williams equation. The designer must ensure that proper coefficients and exponents are used depending on whether computations are in the metric or English systems. Virtually all recent engineering textbooks and handbooks provide detail coverage of hydraulics analysis using these two equations.

(2) The Hazen-Williams Equation. A commonly used form of the Hazen-Williams equation is

$$V = 0.85\,(C)\,(R)^{0.63}\ (S)^{0.54} \tag{7-2}$$

where

V = the flow velocity in meters per second

C = a coefficient depending upon the smoothness of the interior of the pipe

R = the hydraulic radius of the pipe in meters

S = the dimensionless slope of the energy grade line

For circular pipes flowing full (as is almost always the case in water distribution systems) the hydraulic radius, in feet, is given by

$$R = D/48 \tag{7-3}$$

where D is the pipe diameter in inches. The dimensionless slope of the energy grade line, S, can be represented as

$$S = h/L \tag{7-4}$$

where

h = the frictional head loss in the pipe

L = the length of the pipe

Obviously, for S to be dimensionless, h and L must be expressed in the same units of length. The Hazen-Williams equation is easily manipulated with the aid of a small calculator; however, virtually all standard water supply engineering textbooks and handbooks provide nomographs that may be used with sufficient accuracy.

(3) Selection of friction factors. The C factor, or coefficient, used in the Hazen-Williams equation reflects the relative smoothness of the inside surface of the pipe under consideration. Typical values range from about 100 for 20-year-old cast iron, to about 130 for asbestos-cement, to 140 or more for plastic pipe. Most water supply textbooks and handbooks provide guidance in selecting C factors (Clark, Viessman, and Hammer 1977; Folks 1977; Lamont 1981; Linsley and Franzini 1979; Merritt 1976; Stephenson 1976; and Steel and McGhee 1979).

(4) Complex systems. Application of the Hazen-Williams equation to single pipelines or small branching- type distribution systems is straightforward and may be readily accomplished by direct hand calculations. However, for more complicated looped and interconnected grid-type systems, some form of network analysis is needed to predict operating pressures. By far the most commonly used technique is that developed by Hardy Cross. The Hardy Cross method is amendable to both small and large systems and is readily computerized. Many textbooks and handbooks (e.g., Clark, Viessman, and Hammer 1977; Linsley and Franzini 1979; Merritt 1976; and Steel and McGhee 1979) present detailed instructions for the use of the method and include worked example problems.

(5) Minor losses. Minor losses are frictional head losses associated with pipe bends, elbows, tees, valves, hydrants, and other distribution system fittings and appurtenances. For long pipelines, these losses are generally negligible. However, in pumping stations, treatment plants, and other locations where equipment is concentrated or piping layouts are complex, they can be substantial. Guidance needed to estimate minor losses is abundant in the water supply literature (e.g., AWWA; Clark, Viessman, and Hammer 1977; Folks 1977; Linsley and Franzini 1979; Merritt 1976; Rao 1982; Stephenson 1976; Steel and McGhee 1979; and Warring 1982).

(6) Water hammer. When the velocity of flow in a pipe changes suddenly, surge pressures are generated as some, or all, of the kinetic energy of the fluid is converted to potential energy and stored temporarily via elastic deformation of the system. As the system “rebounds,” and the fluid returns to its original pressure, the stored potential energy is converted to kinetic energy and a surge pressure wave moves through the system. Ultimately, the excess energy associated with the wave is dissipated through frictional losses. This phenomenon, generally known as “water hammer,” occurs most commonly when valves are opened or closed suddenly, or when pumps are started or stopped. The excess pressures associated with water hammer can be significant under some circumstances. For example, the maximum pressure surge caused by abruptly stopping the flow in a single pipe is given by

$$a = \frac{4660}{\left(1 + \frac{kd}{Et}\right)^{0.5}} \tag{7-5}$$

where

k = bulk modulus of the fluid, pounds per square inch

d = internal diameter of the pipe, inches

E = modulus of elasticity of the pipe materials, pounds per square inch

t = thickness of the pipe wall, inches

As illustrated by Equation 7-5, the magnitude of the maximum potential water hammer pressure surge is a function of fluid velocity and the pipe material. In water distribution systems, water hammer is usually not a problem because flow velocities are typically low (___ to ___ m (3 to 5 ft) per second), and an allowance for surge pressure is built into the pressure ratings of commonly used pipe materials. In the case of hydro-pneumatic systems, there is an extra margin of safety since the pressure tank acts as a buffer against pressure surges. When higher than normal flow velocities are expected, consideration should be given to the use of slow-operating control valves, safety valves, surge tanks, air chambers, and special pump control systems. Since estimation of surge pressures for complex systems involving interconnected pipes and hydraulic equipment can be very involved, it is usually best to obtain the services of an expert in the area of analysis of hydraulic transients when it is anticipated that water hammer may be a problem. Chaudhry (1979) has presented a rather complete discussion of various transient hydraulic phenomena, including water hammer.

g. Pipe materials. The most commonly used water distribution pipe materials are wrought or ductile iron, asbestos-cement, and various plastics. Galvanized steel, copper, and polyethylene are often used for individual water services. The choice of pipe, or service line, material is usually based upon a combination of factors including cost, local availability, bedding conditions, maintenance requirements, ease of installation, and regulatory requirements. With regard to this last point, many agencies and utilities are reluctant to approve the use of plastic pipe and service lines because other agencies and utilities have reported serious problems with them. While it is probable that most of these difficulties have resulted from poor quality control at manufacture; improper storage, handling, and installation; or operational conditions that were not properly considered and accounted for in design, care should be exercised to rigorously follow the recommendations of the AWWA (1980a) when designing polyvinyl chloride (PVC) pipe systems. In critical applications, where replacement would be especially difficult or expensive, it would seem prudent to avoid the use of plastic pipe. Regardless of the choice, the pipe, or service line, should confirm to the applicable AWWA and National Sanitation Foundation Standards, as well as local regulatory requirements.

(1) Distribution pipes. Historically, cast iron has been the most popular type of pipe for water distribution system applications. However, in recent years the plastics, especially PVC, have become increasingly popular for small distribution

systems. Advantages of PVC include the typically lower cost, light weight, ease of installation, and virtual immunity from corrosion. Some regulatory agencies and water utilities have not, however, approved the use of plastic pipe within their jurisdictions. Discussions of the advantages and disadvantages of various pipe materials are presented in many textbooks, handbooks, and design manuals (Folks 1977; Merritt 1976; Stephenson 1976; Steel and McGhee 1979; and Warring 1982). AWWA (1980a) and the Cast Iron Pipe Research Association (1978) have presented excellent discussions of the design and installation of PVC and cast and ductile iron pipe, respectively.

(2) Service lines. Traditionally, copper and galvanized steel have been used for water services. However, recently plastic tubing, especially polyethylene (PE), has become popular for small water systems. The major advantages of PE tubing are its relatively low cost, corrosion immunity, and ease of installation. This last point is especially important because PE tubing can be installed without the use of the special gooseneck connectors needed for more rigid materials.

h. Valves. Several types of valves may be used in water distribution systems. Four common types are discussed below. The locations of all valves should be clearly marked on as-built plans, and described in relation to readily identifiable landmarks or prominent physical features, so that they can be easily found in the field. All valves should be protected by suitable valve boxes (usually cast iron, concrete, or high-density plastic) and located so that they will not be affected by normal street or highway maintenance operations. Warring (1982) has presented an excellent discussion of various types of valves.

(1) Isolating valves. Valves are needed to allow portions of the distribution system, fire hydrants, storage tanks, and major hydraulic equipment to be isolated for repairs and maintenance with minimal disruption of system operation. Double disk gate valves are usually used for this purpose since they are widely available, relatively low in cost, create very little head loss in the fully open position, seat dependably, and effectively stop flow in the fully closed position. They are, however, of only limited value for throttling or controlling flow and are, therefore, not usually used for such purposes. Butterfly valves are commonly used when throttling or flow control is desired. Gate valves should be placed at all pipe intersections and on all pipe branches. On long pipe runs, gate valves should be spaced no more than ___ km (1 mile) apart.

(2) Air relief and vacuum valves. Air tends to accumulate at high points along waterlines and can significantly interfere with flow, especially on longer lines. Therefore, air relief valves should be placed at all high points on long waterlines. Manually controlled valves are available, but it is much more common to use the automatic type. The exact locations of air relief valves should be determined in the field as the pipe is being installed. Valves are also needed to protect pipelines from collapse as they are emptied, by allowing air to enter the pipes. Vacuum valves are used for this purpose. Combination air relief-vacuum valves are available. Air relief and vacuum valves are normally not needed within interconnected grid portions of distribution systems.

(3) Flushing valves. Flushing valves, or hydrants, are needed at the ends of all dead-end lines. They serve a dual purpose: to release air as lines are filled, and to allow occasional flushing to remove sediment that invariably accumulates at dead ends. The simplest type consists of an ordinary gate valve to which a short piece of pipe can be attached when needed. The function of this length of pipe is merely to direct the flow as desired to avoid excessive erosion and other related problems. Since flushing and/or filling lines are needed only occasionally, manually operated valves are sufficient.

(4) Pressure reducing valves. Occasionally, topography will be such that excessive pressures result in low-lying regions of the distribution system. In such cases, pressure reducing valves can be quite useful. They operate automatically to throttle flow to maintain the desired downstream pressure as long as the upstream pressure is sufficient. For small systems, it is generally best to avoid using pressure-reducing valves on distribution lines if at all possible. Pressure reducing valves are frequently used on individual water service lines to protect house plumbing and appliances such as water heaters.

i. Fire hydrants. When fire protection is provided, hydrants meeting the requirements of the AWWA should be installed. Generally, fire hydrants should not be located on mains smaller than ___ mm (6 in.) in diameter, and should be connected to the main by a short run of ___-mm- (6-in.-) diameter pipe controlled by a gate valve. In operation, this valve should always remain open unless it is necessary to prevent flow to the hydrant. Hydrants should never be installed on lines that are unable to supply an adequate flow. When the hydrant will be exposed to possible damage from vehicular impact, the type that is designed to fail near the ground level and minimize the chance of damage to the distribution system (and the resulting water loss) is preferred.

j. Water meters. Several types of water meters are available. The rotor type has become increasingly popular since models that are accurate at very low flow rates were introduced. Complete details for meter selection and installation are presented by the AWWA (1962).

k. Thrust blocking. Thrust blocks are used to prevent the movement of pipes and appurtenances that would otherwise result from changes in flow rate or direction, or unbalanced pressure forces. They are needed at changes in alignment (e.g., tees, bends, elbows, and crosses), wherever reducers are used, at stops or dead ends, and at valves or hydrants where thrust develops when flow is started or stopped. Poured-in-place concrete is usually used. Many design methods and nomographs are available to help designers size blocks for specific situations. Standard techniques are presented in Appendix A. Thrust blocks are usually designed using methods similar to those used to design foundations and footings. Factors that affect design include pipe or appurtenance size, maximum operating pressure, type of fitting or appurtenance, pipeline profile, and soil bearing capacity.

l. Loads on pipes. Loads that may be superimposed on buried pipes generally fall into two categories: earth loads and live loads. When calculating the total load on a pipe, separate earth and live load analyses are usually performed and the results summed. The commonly used methods of estimating earth loads are based upon theories originally proposed by Anson Marston in the early 1900s. Suitable techniques are presented in references in Appendix A. Live loads generally result from vehicular traffic and are often insignificant when compared to earth loads. Exceptions arise when pipes are placed at shallow depths underneath roadways. The exact meaning of the term "shallow" is controlled by site-specific conditions. However, as a rule, live loads diminish rapidly for laying depths greater that about ___ m (4 ft) for highways and ___ m (10 ft) for railroads. Information needed to estimate live loads resulting from various standard loading criteria are presented in references in Appendix A. In many cases, local regulatory or transportation agencies and utilities will have rather restrictive rules concerning waterlines crossing roads and railroads.

m. Boring and casing. It is common for regulatory and transportation agencies and utilities to require that steel pipe casings be used when waterlines cross highways and railroads or other rights-of-way. Casings protect roadbeds from excessive damage during construction, or when failures occur and repairs must be made; limit the inconvenience associated with construction, failures, and repairs; and may be cheaper than excavating and backfilling, especially when expensive roadway surfaces must be replaced. Casings are usually installed by boring and jacking. The agency or utility that requires boring and casing will generally have specific requirements governing the type and size casing to use. However, casings generally must be ___ to ___ mm (4 to 8 in.) larger in diameter than the waterline to accommodate the pipe joints. Pipes placed in casings should be supported so that the weight of the pipe (and water) is not borne solely by the joints.

n. Pipe laying. Specific instructions for laying various types of pipe are presented in references in Appendix A. It is important for the designer to make sure that the contract documents are written to clearly specify installation procedures. Important points that should be addressed are pipeline alignment (vertical and horizontal) and trench construction. Generally, trenches should be kept as narrow as is commensurate with installation of the given pipe size, adequate clearance should be given to sewer lines, and some minimum pipe cover should be maintained. Minimum cover of ___ to ___ m (3 to 4 ft) is commonly specified, except in very cold areas. All pipes should be bedded so that uniform longitudinal support is provided. Care should be taken to see that the pipe and connections are not damaged during laying, all appurtenances are properly installed, adequate thrust blocking is provided, and the trench is properly backfilled. Regulatory agencies may have their own requirements, but generally rely on manufacturers' recommendations and the appropriate AWWA Standards.

o. Disinfection. Distribution systems should be disinfected prior to being placed in service. The commonly used methods are presented in the AWWA Standards. Contract documents should require that care be taken, during both the storage and construction periods, to prevent excessive contamination from occurring, and should specify the disinfection procedures to be used. In general, disinfection involves flushing with clean water, heavy chlorination for an extended period (usually 24 hours), flushing again with clean water, and bacteriological testing to confirm the efficacy of the process.

p. Testing. New waterlines must be tested to ensure that they will hold the specified pressure and not leak more than some specified amount. Usually the tests are conducted simultaneously. Step-by-step procedures are given in the AWWA Standards for the particular type of pipe being tested. Testing should be performed after thrust blocks have developed adequate strength (usually 7 days), but before the trench is backfilled, except that some backfilling may be needed to hold the pipe in place and prevent incidental damage. In general, the procedure calls for the pipe to be gradually filled with clean water; for all air to be expelled; for the test section to be isolated by capping, plugging, or closing valves; and for the section to be connected to a pump capable of maintaining the desired pressure (plus or minus ___ MPa (5 psi). The typical test duration is 2 hours. During this period, the pipe and all appurtenances should be carefully inspected. Any visible leaks should be repaired and the section retested. The pressure should not drop by more than ___ MPa (5 psi) and the leakage should be less than or equal to the volume calculated as follows:

$$L = \frac{(N)(D)(P)^{0.5}}{7400} \qquad (7\text{-}6)$$

L = the maximum allowable leakage in gallons per hour

N = the number of joints in the length of the pipe being tested

D = the nominal diameter for the pipe in inches

P = the average test pressure (gauge pressure) in pounds per square inch.

The test pressure is usually the greater of 150 percent of the working pressure at the test location or 125 percent of the working pressure at the highest elevation along the section of line being tested.