Cold Water Systems

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Note: In determining your answers to the CE questions, use only the material presented in the corresponding continuing education article. Using information from other materials may result in a wrong answer.

The primary task of a building cold water service and distribution system is to provide adequate flow, pressure, and volume suitable for use at every device that uses water, even when the system is at peak demand. The designer's task is to ensure that this is done in a reliable, cost-effective, code-compliant, and safe manner.

CODES AND STANDARDS

The requirements for cold water system design can be found in the approved local plumbing code, which must be the primary resource used for the accepted methods and sizing of a particular project. The tables and charts appearing in this chapter are used only to illustrate and augment discussions of sizing methods, sizing procedures, and design methods and should not be used for actual design purposes. Always check with the local authority having jurisdiction (AHJ) for the most current requirements.

DOMESTIC COLD WATER METERS

Many major municipalities furnish, specify, and/or install or require a particular type of water meter. In such locations, the meter characteristics (type, make, model, size, flow, pressure drop, remote readouts, costs/fees, etc.) can be obtained from the local water department. Depending on the type of project being contemplated, a utility may request or provide a particular type of meter (e.g., compound meter vs. turbine meter).

Whether a utility company's meter or a meter from another source is used, the above-mentioned characteristics must be taken into consideration. The location of the meter is of prime importance. The meter shall not be subjected to freezing or submerged conditions. To discourage tapping of the piping ahead of the meter, the meter may be located directly inside the building wall. Some jurisdictions prefer the meter to be located immediately adjacent to the tap to prevent illegal connections between the meter and the tap. A meter in an outside pit or manhole should be watertight against both surface and groundwater conditions. Electric heat trace cable or tape also may be required.

Backflow prevention at the building meter discharge is required by most codes and municipalities. This is common whether the water service and fire protection use the same water lateral or not.

Water meters for plumbing usually are classified as the positive-displacement type, which indicates direct flow and records water passage in gallons (liters), cubic feet (cubic meters), or square feet (square meters). Various types of meters can be equipped with optional accessories. Remote-readout systems, strip-chart recorders, etc. are available for specific applications.

Water meters are listed in American Water Works Association (AWWA) standards.

Meter Types

Domestic cold water meters are available in the following types.

Disc Meter

These meters are normally ½, ¾, 1, 1½, and 2 inches (15, 20, 25, 40, and 50 millimeters) in size; are manufactured to have a 150-pounds-per-square-inch (psi) (1,034-kilopascal) maximum working pressure; and measure flow in one direction. This type of meter is common for residential and small commercial installations and is adaptable for remote readout systems.

Compound Meter

These meters are normally 2, 3, 4, and 6 inches (50, 80, 100, and 150 mm) in size; are manufactured to meet the requirements of 150-psi (1,034-kPa) maximum working pressure; and measure flow in one direction. This type of meter is used when most of the flow is low, but high flows are anticipated. It is capable of recording low flows and has the capacity for high flow rates.

Turbine Meter

The sizes of this meter are 2, 3, 4, 6, and 10 inches (50, 80, 100, 150, and 250 mm). This type of meter has the characteristics of a compound meter, but it is more suitable for encountering a variety of flows. (A strainer should be installed upstream of the meter.)

Propeller Meter

The sizes of this meter are 2–72 inches (50–1,830 mm). Propeller meters are used where low flows never occur.

Fire-Line Meter or Detector-Check Meter

One of these types of meters may be required by local codes in a water service that feeds a fire-protection sprinkler system or fire-hydrant system. In such a case, the installation must meet the requirements of the local fire official and the appropriate insurance company. The design should include a minimum of 8 pipe diameters of straight pipe upstream of the meter before any change in direction or connections.

Sizing the Water Meter

The following design criteria may be used as a guide for selecting the proper meter:

- Building occupancy type
- Minimum and maximum demand, in gallons per minute (gpm) (liters per minute) or cubic feet per gallon (cubic meters per liter)
- Water pressure available at the meter
- Size of building service
- Piping, valve, and elevation pressure losses
- Meter costs and tap fees
- Maintenance costs and fees

Table 5-1 from AWWA M22: *Sizing Water Service Lines and Meters, Second Edition* is provided here as additional guidelines for water meter sizing and selection. Engineers need to also check local water purveyors for modifications or additional designs subject to local conditions or guidelines.

Table 5-1 Flow Pressure Loss Averages for Meters Meeting AWWA Specifications

Size, in. (mm)	Maximum Capacity—AWWA Flow Criteria		Recommended Design Criteria—80% of Maximum Capacity		Recommended for Continuous Flow—50% of Maximum Capacity		Brands of Meters Avgs.
	gpm (L/s)	gpm (L/s)	gpm (L/s)	gpm (L/s)	gpm (L/s)	gpm (L/s)	
Displacement-Type Meters							
⅝ x ¾ (16 × 19.1)	20 (1.26)	10.4 (71.76)	16 (1.00)	6.1 (42.19)	10 (0.63)	1.0 (6.9)	6
¾ (19.1)	30 (1.89)	10.6 (73.13)	24 (1.51)	6.9 (47.61)	15 (0.95)	1.05 (7.24)	6
1 (25.4)	50 (3.15)	9.3 (64.14)	40 (2.52)	6.3 (43.47)	25 (1.58)	1.0 (6.9)	6
1½ (38.1)	100 (6.30)	11.3 (77.10)	80 (5.05)	8.6 (59.34)	50 (3.15)	0.9 (6.21)	6
2 (50.8)	160 (10.08)	10.4 (71.76)	128 (8.08)	6.5 (44.85)	80 (5.04)	0.5 (3.45)	6
3 (76.2)	300 (18.93)	13.1 (90.39)	240 (15.14)	8.3 (57.27)	150 (9.46)	1.1 (7.59)	3
Compound-Type Meters							
2 (30)	160 (10.08)	9.2 (63.48)	128 (8.07)	6.1 (42.09)	80 (5.04)	2.6 (17.94)	3
3 (80)	320 (20.19)	13.4 (92.46)	250 (15.77)	8.9 (61.36)	160 (10.08)	4.2 (28.98)	5
4 (100)	500 (31.54)	9.6 (66.24)	400 (25.23)	6.3 (43.47)	250 (15.77)	3.5 (24.15)	5
6 (150)	1,000 (63.09)	9.4 (64.86)	800 (50.46)	5.8 (40.02)	500 (31.54)	2.5 (17.25)	4
8 (203)	1,600 (100.94)	12.0 (82.8)	1,280 (80.75)	7.8 (53.82)	800 (50.46)	4.0 (27.60)	3
Turbine-Type Meters							
2 (50)	160 (10.08)	4.5 (31.05)	128 (7.57)	2.8 (19.32)	80 (5.04)	1.0 (6.9)	5
3 (80)	350 (22.37)	4.6 (31.74)	280 (17.66)	3.0 (20.69)	175 (11.04)	1.2 (8.3)	4
4 (100)	600 (37.85)	3.5 (24.15)	480 (30.28)	2.1 (14.5)	300 (18.93)	0.8 (5.5)	4
6 (150)	1,250 (78.86)	3.5 (24.15)	1,000 (69.09)	2.0 (13.8)	625 (39.43)	0.7 (4.9)	4

Source: AWWA M22

CROSS-CONNECTION CONTROL

Preventing reverse flows at hazardous connection points of a water supply system is referred to as cross-connection control. Since the topic is covered in its own chapter in this series (*PEDH Volume 4,* Chapter 9), it is only briefly described here as it relates to cold water systems.

The fundamental principle for selecting a cross-connection control is based on the sciences of hydrostatics and hydrodynamics. When water is motionless, hydrostatics applies, and the pressure within a given volume depends only on elevation. When water is in motion, viscous forces, velocity, and momentum add other factors to consider. Controls to prevent reverse flows recognize basic static pressure conditions while accommodating for dynamic factors.

When water supply pressure is lost, low pressures may occur that can draw contaminants into the supply piping if no controls are provided. These contaminants then may emerge in other parts of the piping when the pressure is restored. Controls, however, prevent contaminants from being drawn into the piping by devices or piping design. If pressure immediately downstream of the device is less than atmospheric (a situation defined as backsiphonage), the control device may be a vacuum breaker. If pressure immediately downstream of the device is greater than atmospheric (a situation defined as backpressure), the control device may be a backflow preventer. If the outlet from a water supply is located above its receptor, as in a faucet spout, the type of control typically used is called an air gap.

Design Guidelines for Cross-Connection Control

Thoughtful consideration should be given to the anticipated emergency discharge of backflow preventers, such as the reduced-pressure zone (RPZ) and reduced-pressure detector assemblies. Conditions such as a leaking check valve, clogged sensing line, ruptured relief valve diaphragm, or dislodged relief valve O-ring will cause the RPZ to discharge from the atmospheric vent (located on the relief valve).

First, the designer should consider how to minimize these potential conditions. In most cases, with the exception of fire protection due to the overriding urgency of not compromising water flow to the sprinkler system, the use of a Y-type strainer is strongly encouraged to help prevent debris from entering the valve and fouling the checks. The strainer body material should be consistent with the valve to prevent electrolysis. The ½-through 2-inch (15-mm through 50-mm) strainers typically are bronze, and valves 2½ to 10 inches (65 to 250 mm) are stainless steel or cast iron with an FDA coating. For ½- through 2-inch (15-mm through 50-mm) strainers, the screen should be 20 mesh, and the perforated screen for 2½- to 10-inch (65- to 250-mm) strainers should be no larger than 1/8 inch (3 mm). The designer may wish to include a blowdown valve with the strainer to make maintenance easier. A strainer with only a pipe plug may not be cleaned regularly and needlessly adds to the pressure drop.

In some cases, such as industrial facilities and car washes, water hammer can cause a spitting type of discharge. This can be avoided with a properly installed and selected mechanical shock arrestor or the use of supplemental checks. It is recommended to use a spring-loaded and soft-seated check design and install it directly downstream (the outlet side) of the RPZ.

Before an RPZ is located, consideration should be given to both how much water will be discharged as well as where it will drain. Consideration must be given to the drain system to ensure that the drainage system can handle the load.

The discharge of drains flowing full at different pitches is found in Table 5-2. If a drain is not capable of accepting the flow, other choices regarding the location of the valve, such as outside in a heated enclosure, could be made. At a minimum, the proper air gap fittings should be specified to capture the majority of the discharge and then be connected to the drainage system. Many varieties of air gap designs are available, including both funnel and sink styles.

Table 5-2 Maximum Discharge of Drains Flowing Full, gpm (L/m)

Drain Size, in. (dn)	Pitch	
	1/8 in./ft (0.5 cm/m)	¼ in./ft (1.0 cm/m)
2 (50)	13 (100)	18 (135)
3 (75)	36 (275)	51 (390)
4 (100)	77 (585)	110 (835)
6 (150)	220 (1,670)	314 (2,385)
8 (200)	494 (3,755)	696 (5,290)
10 (250)	934 (7,100)	1,300 (9,900)

Thermal expansion problems should be anticipated when water utilities require a containment method backflow prevention program. Mainline valve applications such as this will result in a closed piping system. Without properly installing and sizing domestic water expansion tanks, a number of annoying or potentially dangerous problems can result. This can include a buildup of unusually high pressure, causing water heater failures and other plumbing issues.

BOOSTER PUMP SYSTEMS

If the city water pressure or the well pump pressure is not sufficient to meet the water supply demands of a building, a booster pump system should be considered. The pump system may be for the entire building, for the upper floors, in one or more zones, or for select equipment connections having high-pressure requirements.

The required capacity of the pump system is determined when the building demand is evaluated in terms of peak flow. The peak flow is determined as described for the water service. The pressure requirement is derived from the Bernoulli equation. Recall that between any two points of an ideal flow stream, $h+p/d+v^2/2g$ is a constant. In a more realistic flow, the friction head and pump head are considered. Thus,

Equation 5-1

$$h_1 + \frac{p_1}{d} + \frac{{v_1}^2}{2g} + h_p = h_2 + \frac{p_2}{d} + \frac{{v_1}^2}{2g} + h_f$$

where

h = Flow stream's elevation above a datum, feet (m)

p = Flow stream's static pressure, pounds per square foot (kPa)

d = Flow stream's density, pounds per cubic foot (kg/m^3)

v = Flow stream's velocity, feet per second (fps) (m/s)

hp = Pump head (total dynamic head)

g = Acceleration of gravity, 32.2 feet/second^2 (9.8 m/s^2)

hf = Friction head loss between Points 1 and 2, feet (m)

When Point 1 is the location of a known pressure such as the street main and Point 2 is a fixture, the equation can be rearranged to derive the required pump head to adequately supply that fixture. Various fixtures in a building can be selected to derive various pump heads. The maximum pump head is generally the top fixture of the most remote riser. Additionally, if the velocities are similar between Points 1 and 2, the two velocity terms can be omitted. Thus,

Equation 5-2

$$h_p = h_2 - h_1 + \frac{(p_2 - p_1)}{d} + h_f$$

The friction head includes various losses such as friction from straight pipe, fittings, valves, meter, tanks, treatment devices, and backflow preventers. The head loss through the booster pump system piping and its control valves also is added. These are typically 4 feet (1.22 m) and up to 18 feet (5.49 m) respectively.

The design of a booster pump system generally consists of one or more electrically driven centrifugal pumps, connecting piping, and various controls such as pressure-reducing valves, motor controls, and a possible hydropneumatic tank. The pump impellers are generally one stage, but they may be multiple stages if high head is required. Rotational speed choices are generally 1,750 revolutions per minute (rpm), 3,500 rpm, or other similar synchronous speeds.

Example 5-1

Determine the required total dynamic head of a booster pump system for a building with the following assumptions:

- The most remote fixture is a pressure-balancing shower valve (assumed 20 psi [138 kPa]) located 48 feet (14.6 m) above the pump.
- The street pressure is 25 psi (172 kPa) as read from a gauge near the pump.
- The total equivalent length of pipe is 400 feet (120 m), and the uniform pressure loss of this length is 5 psi (35 kPa) per 100 feet (30 m).
- The pressure loss through the service meter is 6 psi (41 kPa).
- The pressure loss through the water softener is 9 psi (62 kPa).

Using Equation 5-2, the calculation is as follows:

$$(p_2 - p_1) \div d = (20 - 25) \times 144 \div 62.4 = -11.5 \text{ feet}$$
$$[(138 - 172) \div 9.8 = -3.50 \text{ m}]$$

$$\text{Building friction head} = (400 \times 0.05 + 6 + 9) \times 144 \div 62.4 = 80.8 \text{ feet}$$
$$[(120 \times 35 \div 30 + 41 + 62) \div 9.8 = 24.6 \text{ m}]$$

$$\text{Pump system friction head} = 4 + 18 = 22 \text{ feet}$$
$$[1.22 + 5.49 = 6.70 \text{ m}]$$

$$\text{Total dynamic head} = 48 - 11.5 + 80.8 + 22 = 139 \text{ feet}$$
$$[14.6 - 3.50 + 24.6 + 6.70 = 42.4 \text{ m}]$$

Pump Economy

When using centrifugal pumps on a building water supply, as faucets and valves close throughout the system, pump pressure increases until the pump dead-heads. For example, the difference in pump head from maximum flow to no flow may be 30 feet (9.14 m) on a 7.5-horsepower (hp) (5.60-kilowatt) pump. This head variation will cause flow variations from each plumbing fixture, which may be objectionable to building occupants as well as faucet and valve manufacturers. Hence, pump systems with a constant pressure feature have been developed. The discharge of each pump in the pump system flows through a pressure-reducing valve.

Another method of control, variable-speed drives, involves reducing the rotational speed of the pump impeller as building flow demand decreases. With the trend toward decreasing costs of adjustable-frequency drives, such drives are chosen for this speed reduction. Obviously, variable-speed pump systems have a lower operating cost than constant-pressure pump systems, not only at maximum flow but also more significantly at the lower flow. Less obvious is the operating penalty of an oversized constant-pressure pump, whether the excess size is derived from an overestimate of the building flow demand or an erroneously low indication of the typical street pressure. Variable-speed pumps do not have a penalty from either cause.

The best economy of a variable-speed pump is obtained when its pressure sensor is located at the top of a riser. At this location, the sensor's setpoint is merely what is desired of a fixture, such as 20 psi (138 kPa) for a shower valve. At low building demand, the pump system will adjust for this setpoint, combined with the static amount for elevation. As demand grows, the pump adds the appropriate amount for friction. When the sensor is located near the pump, its sensitivity to friction requirements decreases.

Further economy of either system type is obtained by multiple pumps. In this way, many pumps operate to meet the building demand, with all but one pump operating at its most efficient flow and pressure. The last pump then takes up minor demand variations. The number of pumps in the system may be as few as two and up to any number. In addition, the size of each pump may be identical or may vary. A triplex arrangement may distribute the building flow demand at 33 percent for each pump or two pumps at 40 percent and the third at 20 percent. When redundancy is desired, the split of a triplex may be each pump at 50 percent. A common control method to stage the pumps is to measure motor current. When the current reaches the pump motor's rating, the next pump is brought online. Other methods include power measurement and flow measurement.

Booster Pump Features

Pump systems generally have a variety of features. Low-flow shutdown senses either temperature increase or flow decrease. A low-suction-pressure switch detects suction pressure below the pump's net positive suction head (NPSH) limit or perhaps a regulatory limit. Similarly, a high-pressure switch avoids excessive pressures on the building's plumbing. A high-temperature control either relieves discharge or shuts down the pump motor.

Motor control includes under-voltage control, over-current control, motor-overload control, and electric power disconnect. An alternator control switches which pump first operates on rising demand so that each pump of the system receives uniform wear.

Minimum run timers avoid pump short-cycling. Proof timers delay pump staging to avoid a pump start that may not be needed. A differential pressure switch on each pump detects pump failure, and a time clock controls operating times according to an occupancy schedule. A building management control interface allows pump system status to be remotely monitored or controlled. A microprocessor control is economically attractive when these features involve a dozen input sensors or more.

Alternate Applications

A booster pump system also may be used when code regulations only permit an air gap as the cross-connection control method for the water service. Since the air gap destroys the utility pressure, a booster pump is required. The additional components to complete the arrangement, referred to as a break tank, include a tank open to atmosphere, an inlet float valve, an overflow pipe, and perhaps a low water sensor. The float valve is connected to the water service, and water in the tank feeds the pump. The pump head can be minimized if the break tank is located on an upper floor or even a penthouse. A smaller version of a break tank may be substituted elsewhere in the building for any type of backflow preventer or vacuum breaker.

Another application of a booster pump system is when a high-rise building is zoned by floor levels, with storage tanks at multiple levels. This is used to decrease the static head at the lower levels.

Hydropneumatic Tank

As part of a booster pump system, a hydropneumatic tank can be chosen to meet a low-flow demand without operating a pump. A hydropneumatic tank also may provide a method to shave peak flows on an existing water service or a distribution main.

The fundamental principle for sizing hydropneumatic tanks is based on the ideal gas law:

Equation 5-3

$$PV = nRT$$

where

P = Pressure
V = Volume
n = Number of moles
R = Gas constant
T = Temperature

This law is applied to the air inside the tank as the volume changes to serve minor demands in the building during minimal occupancy. The design of the tank is a pressure vessel with a flexible partition, with water on one side and air on the other. Typically the flexible partition is a rubber diaphragm, which moves as pressure varies. It effectively isolates the air from the water. The amount of air can be varied during installation through a port and then is assumed to be constant thereafter. The amount of water in the tank varies continuously.

The product of pressure and volume of an ideal gas is proportional to its mass and temperature. Since the air is captured in the tank, its mass is constant, and its temperature is assumed to be constant. Hence, pV = a constant, or:

Equation 5-4 (Boyle's Law)

$$p_1V_1 = p_2V_2$$

where

p = Tank air pressure, pounds per square inch absolute (psia) (kPa)

V = Volume of air in the tank, cubic feet (m^3)

The drawdown volume (V_d) can be defined as:

$$(dV/dt)(t_p)$$

where

dV/dt = Average flow over time period t_p during low system demand

Thus, the tank volume between two pressure levels in the tank can be examined and equated to the drawdown volume. That is,

$$V_1 - V_2 = V_d$$

Designating V_1 as the tank with all water expelled from it and applying the ideal gas law provides:

$$V_1 - V_2 = V_1 - V_1\left(\frac{p_1}{p_2}\right) = V_1\left(1 - \frac{p_1}{p_2}\right) = V_t\left(1 - \frac{p_1}{p_2}\right) \text{, or}$$

$$V_1 - V_2 = V_t\left(\frac{p_2 - p_1}{p_2}\right)$$

where

V_t = Total tank volume, cubic feet (m^3)

Rearranging and combining this with the average low flow provides the tank volume formula:

Equation 5-5

$$V_t = \frac{V_d}{\left(\frac{p_2 - p_1}{p_2}\right)}$$

The pressure ratio is a convenient volume ratio of drawdown volume to tank volume. For average near-sea-level conditions, Table 5-3 shows this ratio between any two levels of air pressure in a tank. For example, two pressure levels of 50 psi (345 kPa) and 40 psi (276 kPa) for a tank to draw out 60 gallons (227 liters) require a tank volume of 60 ÷ 0.155 = 387 gallons [227 ÷ 0.155 = 1,465 L].

In practice, tanks are chosen larger than as calculated to avoid a completely empty tank. The average flow during low system demand is taken as a fraction of the building's peak flow, typically 0.5 percent for apartment buildings and 4 percent for hospitals. Other buildings generally fall in between these extremes. The time period typically is chosen to be 10 to 30 minutes, and $p_2 - p_1$ is 10 psi (69 kPa). For tanks on private wells, $p_2 - p_1$ typically is taken to be 20 psi (138 kPa). Note that since p_2 is derived from the ideal gas law, it is an absolute pressure and must include the local prevailing atmospheric pressure (14.7 psi [100 kPa] at sea level).

In Table 5-4, an example of a four-story building with a 10-gpm (37.8-L/min) requirement for 10 minutes is shown with a hydropneumatic tank selected in three different locations. When it is located at a high elevation, the tank is smaller than it is when located at a low elevation such as near the booster pump. The tank is smaller when positioned upstream of the pump's pressure-reducing valve than when downstream because of the larger range of pressures upstream of the valve.

ELEVATED WATER TANK SYSTEM

In an elevated water tank system, water is pumped from the street main to an elevated water storage tank (commonly called a gravity tank or house tank) located above the highest and most hydraulically remote point in the water supply system of the building. The height of the tank provides additional static head, which results in a higher pressure in the water distribution system. For each 2.31 feet (0.7 m) of elevation, the pressure increases 1 psi (6.9 kPa).

An elevated water tank is made up of the following components:

- A gravity tank, which stores water at atmospheric pressure
- Pumps (commonly called house pumps), which fill the tank by pumping water into it from the source
- Controls, which turn the pump on and off when the water inside the tank reaches pre-set levels
- Alarms, which alert operating personnel that a malfunction exists
- Safety devices, which operate when a malfunction occurs to avoid potential accidents

Table 5-3 Hydropneumatic Tank Volume Ratios

Maximum Pressure, psi (kPa)	Minimum Pressure, psi (kPa)									
	10 (69)	20 (138)	30 (207)	40 (276)	50 (345)	60 (414)	70 (483)	80 (552)	90 (621)	100 (690)
20 (138)	0.288									
30 (207)	0.447	0.224								
40 (276)	0.548	0.366	0.183							
50 (345)	0.618	0.464	0.309	0.155						
60 (414)	0.669	0.536	0.402	0.268	0.134					
70 (483)	0.708	0.590	0.472	0.354	0.236	0.118				
80 (552)	0.739	0.634	0.528	0.422	0.317	0.211	0.106			
90 (621)	0.764	0.669	0.573	0.478	0.382	0.287	0.191	0.096		
100 (690)	0.785	0.697	0.610	0.523	0.436	0.349	0.262	0.174	0.087	
110 (758)	0.802	0.722	0.642	0.561	0.481	0.401	0.321	0.241	0.160	0.080
120 (827)	0.817	0.742	0.668	0.594	0.520	0.445	0.371	0.297	0.223	0.148
130 (896)	0.829	0.760	0.691	0.622	0.553	0.484	0.415	0.346	0.276	0.207
140 (965)	0.840	0.776	0.711	0.646	0.582	0.517	0.453	0.388	0.323	0.259
150 (1,034)	0.850	0.789	0.729	0.668	0.607	0.546	0.486	0.425	0.364	0.304
160 (1,103)	0.859	0.801	0.744	0.687	0.630	0.572	0.515	0.458	0.401	0.343
170 (1,172)	0.866	0.812	0.758	0.704	0.650	0.596	0.541	0.487	0.433	0.379
180 (1,241)	0.873	0.822	0.770	0.719	0.668	0.616	0.565	0.514	0.462	0.411
190 (1,310)	0.879	0.830	0.782	0.733	0.684	0.635	0.586	0.537	0.489	0.440
200 (1,379)	0.885	0.838	0.792	0.745	0.699	0.652	0.606	0.559	0.512	0.466

Table 5-4 Tank Size Varying by Its Location in a Building

Minimum Pressure, psi (kPa)	Maximum Pressure, psi (kPa)	(p2-p1)/(p2)	Tank Location	Example Tank Size, gal (L)
50 (345)	60 (414)	0.134	Top floor	747 (2,830)
85 (586)	100 (690)	0.131	Before pressure-reducing valve	765 (2,895)
70 (483)	80 (551)	0.106	After pressure-reducing valve	947 (3,584)

The advantages of an elevated water tank system are as follows:

- It is less complex than other systems.
- The least number of components is required to control and operate the system.
- The efficiency is greater and operating costs are lower than for other systems.
- A smaller pump capacity is required than for other systems.
- Pressure fluctuation in the system is minimal.
- Maintenance requirements are minimized.

The disadvantages of the elevated water tank system compared with other systems are as follows:

- An exposed tank (or the enclosure around it) may be considered unsightly.
- The building structure will require reinforcement to support the additional weight of the tank and water.
- The water in the tank and the supply pipes from the tank are subject to freezing where tanks are installed in cold climates.
- The water pressure on the highest floor may be inadequate.
- The possibility exists that a catastrophic tank failure would flood the roof with water.

The capacity of a house tank depends on the type of facility it will serve. Refer to Table 5-5 to find a recommended minimum domestic storage volume of gravity tanks for various building types.

To use Table 5-5, first determine the total number of fixtures, regardless of type. Multiply the number of fixtures by the gpm per fixture. Then multiply the resulting figure by the tank size multiplier. This figure is the domestic storage only. To this add 10 percent for constant uses of water, such as HVAC makeup and any process requirements if necessary. Fire protection water storage is also additional. Select a standard tank size equal to or exceeding the storage required. Standard wood roof tank sizes are given in Table 5-6. If the building's occupants are predominantly women, add 15 percent to the water storage requirement.

The capacity of the house pump is determined by the quantity of water stored for domestic use. In general, a house pump should be capable of replacing the domestic reserve in about one-half to two hours, with one hour being a generally accepted value. A duplex pump arrangement (i.e., two pumps in parallel) with each pump full size should be provided to allow one pump to be out of service without impairing the system.

A common problem with a gravity tank system is the lack of adequate water pressure on the upper floors of the building unless the tank is elevated to an impractical height. Under these conditions, a hybrid system comprised of the elevated tank plus a small booster pump or hydropneumatic system only for the top several floors can be used.

Table 5-5 Size of Gravity Tanks

Number of fixtures	gpm per fixture	Tank size multiplier	Minimum domestic capacity, gal	Minimum pump capacity, gpm
Hotels and clubs				
1–50	0.65	30	2,000	25
51–100	0.55	30	2,000	35
101–200	0.45	30	3,000	60
201–400	0.35	25	3,000	100
401–800	0.275	25	3,000	150
801–1,200	0.25	25	3,000	225
1,201 and above	0.2	25	3,000	300
Hospitals				
1–50	1	30	2,000	25
51–100	0.8	30	2,000	55
101–200	0.6	25	3,000	85
201–400	0.5	25	3,000	125
401 and above	0.4	25	3,000	210
Schools				
1–10	1.5	30	2,000	10
11–25	1	30	2,000	15
26–50	0.8	30	2,000	30
51–100	0.6	30	2,000	45
101–200	0.5	30	3,000	65
201 and above	0.4	30	3,000	110
Industrial buildings				
1–25	1.5	30	2,000	25
26–50	1	30	2,000	40
51–100	0.75	30	3,000	60
101–150	0.7	25	3,000	80
151–250	0.65	25	3,000	110
251 and above	0.6	25	3,000	165
Office buildings and laboratories				
1–25	1.25	30	2,000	25
26–50	0.9	30	2,000	35
51–100	0.7	30	2,000	50
101–150	0.65	25	3,000	75
151–250	0.55	25	3,000	100
251–500	0.45	25	3,000	140
501–750	0.35	25	3,000	230
751–1,000	0.3	25	3,000	270
1,001 and above	0.275	25	3,000	310

Table 5-6 Standard Wood House Tanks

Capacity, gal	Dimension, ft			Number of dunnage beams	Dunnage, in.
	Diameter	×	Stave		
5,000	10	×	10	5	4 × 6
5,000	9	×	12	5	4 × 6
5,000	11	×	8	6	4 × 6
6,000	11	×	10	6	4 × 6
7,000	11.5	×	10	6	4 × 6
7,500	12	×	10	6	4 × 6
7,500	11	×	12	6	4 × 6
8,000	12.5	×	10	6	4 × 6
9,000	12	×	12	6	4 × 6
10,000	13	×	12	7	4 × 6
10,000	12	×	14	6	4 × 6
10,000	11	×	16	6	4 × 6
12,000	14	×	12	7	4 × 6
12,000	13	×	14	7	4 × 6
12,000	12	×	16	6	4 × 6
15,000	14	×	14	7	4 × 6
15,000	13.5	×	16	8	4 × 6
20,000	16	×	16	8	6 × 6
25,000	17.5	×	16	9	6 × 6
30,000	18	×	18	9	6 × 6
40,000	20	×	20	10	6 × 6
50,000	20	×	20	11	6 × 8

Note: 1 gal = 3.8 L, 1 ft = 0.3 m, 1 in = 25.4 mm
Source: Isseks Bros. Co.

EXPANSION TANK

Besides the ideal gas law, another fundamental principle of sizing an expansion tank includes the density change of water. A water heater requires a check valve on its cold water inlet, and an expansion tank connection typically is installed between the inlet connection to the heater and the check valve. Temperature changes of the water in the heater tank and hot water distribution pipes cause volume changes of this water. Without the expansion tank, a temperature rise will add pressure to the heater tank and distribution system. A sufficient increase will open the water heater pressure relief valve. An ideally sized expansion tank will allow an initial charge of cold water at minimum pressure to increase to the temperature setpoint of the water heater without the pressure relief valve opening.

The design of the expansion tank is generally the same as the hydropneumatic tank, but typically of smaller volume. Its initial charge of air should correspond to the building's minimum water pressure.

In a water heater and its related piping, the mass of water is constant during times of no demand. From the definition of density, this constant mass is equal to the product of volume and density. Hence, between any two points of time:

Equation 5-6

$$V_{S1} d_1 = V_{S2} d_2$$

Where:

V_{S1} = Volume of system at density d_1 (cubic feet [m^3]), pounds per cubic foot (kg/ m^3)

V_{S2} = Volume of system at density d_2 (cubic feet [m^3]), pounds per cubic foot (kg/m^3)

The volume change of water in the system is the same as the volume change of the air in the expansion tank. Hence, together with the density change of water in the system and the ideal gas law applied to the air in the tank, the change in volume between any two points of time can be set to equal:

$$V_{S2} - V_{S1} = V_1 - V_2$$

Where:

V_1 = Volume of air in the tank at pressure p_1 (cubic feet [m^3]), psia (kPa)

V_2 = Volume of air in the tank at pressure p_2 (cubic feet [m^3]), psia (kPa)

Therefore,

$$V_{S1}\left(\frac{d_1}{d_2}\right) - V_{S1} = V_1 - V_1\left(\frac{p_1}{p_2}\right)$$

$$V_{S1}\left(\frac{d_1}{d_2} - 1\right) = V_1\left(1 - \frac{p_1}{p_2}\right)$$

$$V_{S1}\left(\frac{d_1 - d_2}{d_2}\right) = V_1\left(\frac{p_2 - p_1}{p_2}\right)$$

When choosing d_1 and p_1 as the conditions of the system at minimum temperature and pressure and d_2 and p_2 as the conditions at maximum temperature and pressure, the minimum size of the expansion tank will be $V_t = V_1$, or:

Equation 5-7

$$V_1 = V_t = V_{S1}\left(\frac{d_1 - d_2}{d_2}\right)\left(\frac{p_2}{p_2 - p_1}\right)$$

Hence, from a given volume of water in the pipe system and water heater, a minimum size expansion tank is found from the product of a water density ratio and a pressure ratio. From Equation 5-7, Table 5-7 shows water density ratios for several maximum temperatures, and Table 5-8 shows pressure ratios for average sea-level conditions.

In practice, expansion tanks are chosen slightly larger than as calculated to avoid a completely empty tank; the volume of water in the hot water distribution is rarely significant compared to the tank volume; and p_2 is the pressure rating of the water heater. With the use of backflow preventers on the water service, it is encouraged to include the volume of both the cold and hot water distribution piping. Note that since p_2 is derived from the ideal gas law, it is an absolute pressure and must include the local prevailing atmospheric pressure (14.7 psi [101 kPa] at sea level).

Finding the density ratio is fairly simple. As an example for the temperature range from 38°F (3.3°C) to 140°F (60°C):

$$(d_1 - d_2) \div d_2 = (62.425 - 61.38) \div 61.38 = 0.0171$$
$$[(1 - 0.9832) \div 0.9832 = 0.0171]$$

Manufacturers regard $V_1 - V_2$ as an acceptable volume.

Table 5-7 Water Expansion Above 40°F

Temperature, °F (°C)	Water Density Ratio
100 (37.8)	0.0069
120 (48.9)	0.0115
130 (54.4)	0.0142
140 (60.0)	0.0171
150 (65.6)	0.0202
160 (71.1)	0.0235
170 (76.7)	0.0270
180 (82.2)	0.0307

Table 5-8 Expansion Tank Pressure Ratios

Maximum Pressure, psi (kPa)	Minimum Pressure, psi (kPa)	Pressure Ratio
100 (690)	40 (276)	1.91
100 (690)	50 (345)	2.29
100 (690)	60 (414)	2.87
100 (690)	70 (483)	3.82
100 (690)	80 (552)	5.73
125 (862)	40 (276)	1.64
125 (862)	50 (345)	1.86
125 (862)	60 (414)	2.15
125 (862)	70 (483)	2.54
125 (862)	80 (552)	3.10
150 (1,034)	40 (276)	1.50
150 (1,034)	50 (345)	1.65
150 (1,034)	60 (414)	1.83
150 (1,034)	70 (483)	2.06
150 (1,034)	80 (552)	2.35

EXCESS WATER PRESSURE

One of the main sources of trouble in a water distribution system is excessive pressure. Unless a piece of equipment, fixture, or operation requires a specified high pressure, a water system should not exceed a maximum of 80 psi (551.6 kPa) (check the local code). To ensure this, a pressure-regulating valve (PRV) should be installed if the pressure on the outlet side of the meter and backflow preventer is more than 80 psi (551.6 kPa).

Pressure-Regulating Valves

The purpose of a PRV is to reduce water pressure from higher supply-main pressures to desirable and adequate flow pressures when water is required at fixtures, appliances, or equipment.

All PRVs fall into the following general categories:

- Single-seated, direct operated or pilot operated
- Double-seated, direct operated or pilot operated

Single-seated PRVs are used for dead-end service and when the flow to be regulated is intermittent. For dead-end service, the valve must be able to shut tight and not permit the passage of any water when there is no demand.

Double-seated PRVs are used for continuous-flow conditions. They are not suited for dead-end service and never should be used for this purpose.

Direct-operated PRVs reduce the outlet pressure in direct proportion with the increase of the flow rate (falloff pressure). Pilot-operated PRVs maintain a close fluctuation of the outlet pressure independent of the flow rate, assuming that the valve was sized properly.

Initial cost, maintenance cost, and specific project requirements regarding flow rates and pressures should be used to determine which PRV is suitable for a particular application.

Selecting and Sizing PRVs

Selecting and sizing a PRV can be performed after the following criteria are estimated: inlet pressure, outlet pressure, and capacity (flow rate).

Inlet pressure is the maximum pressure expected upstream of the regulating valve. Outlet pressure is the pressure required downstream of the regulating valve. Falloff pressure is the pressure drop through the PRV at full flow (subtract from set pressure).

For example, for a self-contained valve, 100 gpm at 60 psi is desired. If you pick the value at 100 gpm of 80-psi set pressure with 20-psi falloff pressure, 60 psi will be the pressure. For remote-sensor automatic PRVs, the set pressure will be held.

For large-capacity systems, which may experience periods of low flow, or when extreme pressure reductions are expected, it is advisable to include more than one regulating valve. A PRV sized to accommodate both low and high flows generally is very noisy during operation. In addition, low flows will produce wire-drawing of the seat and possible chatter.

In addition to the economic advantages, proper application of PRVs can greatly influence the overall performance of the system. Under most circumstances, a good application can increase system performance, reduce operating costs, and ensure a longer life expectancy for regulators.

For example, where initial pressures exceed 200 psi (1,379 kPa), where there is a wide variation between the initial pressure and the reduced pressure, or where the initial pressure varies considerably, two-stage reduction is beneficial. Two-stage reduction is the use of two PRVs to reduce high service pressure proportionately and to eliminate an extremely wide variance between the initial and reduced pressures. The advantage of this installation is that neither valve is subjected to an excessive range of pressure reductions. This seems to stabilize the final reduced pressure, ensuring close and accurate performance. Also, this type of installation reduces the flow velocity (less pressure drop across two regulators than across one), providing longer valve life. Selection of PRVs and pressure settings is fairly simple. The first PRV could reduce from 250 to 150 psi (1,723.7 to 1,034.2 kPa) and the second from 150 to approximately 50 psi (1,034.2 to 344.7 kPa), or there could be some similar division. PRV size can be selected according to the manufacturer's capacity tables if it is remembered that each PRV should exceed the total capacity of the system.

Installing PRVs

Where there is a wide variation of demand requirements and where it is vital to maintain a continuous water supply as well as provide greater capacity, parallel installation is recommended. Parallel installation is the use of two or more small PRVs serving a larger supply main. It has the advantage of providing increased capacity beyond that provided by a single valve where needed. This installation improves valve performance for widely variable demands and permits the servicing of an individual valve without the complete shutdown of the line, thus preventing costly shutdowns.

For a two-valve parallel installation, the total capacity of the valves should equal or exceed the capacity required by the system. One valve should be set at a 10-psi (69-kPa) higher delivery pressure than the other.

For example, assume that the system requires 400 gpm (25.2 L/s) and the set pressure required is 50 psi (344.7 kPa). Select two valves, each rated at 200 gpm (12.6 L/s), with one valve set at 50 psi (344.7 kPa) and the other valve set 10 psi (69.0 kPa) higher at 60 psi (413.7 kPa). Thus, when low volume is required, the higher-set valve operates alone. When a larger volume is demanded, both valves open, delivering full-line capacity.

Another possible choice is to install two PRV combinations of different sizes. This is practical on large installations where supply lines are 2 inches (50 mm) and larger and where there are frequent periods of small demand. The smaller PRV would have the 10-psi (69-kPa) higher delivery pressure and thus operate alone to satisfy small demands, such as urinals and drinking fountains. When a larger volume is needed, the main PRV would open to satisfy the system demand.

For example, take an apartment building requiring 300 gpm (18.9 L/s) at a 60-psi (413.7-kPa) set pressure. The selection might be a 4-inch (100-mm) PRV rated for 240 gpm (15.1 L/s) (80 percent of total maximum flow rate) and set at 60 psi (413.7 kPa) and a 1½-inch (40-mm) PRV rated for 60 gpm (3.8 L/s) and set at 70 psi (482.6 kPa).

Manufacturers provide tables indicating the recommended capacities and valve sizes for use in parallel installations.

WATER HAMMER

A well-designed cold water distribution system minimizes velocity-related problems in a cost-effective manner. For an open system, every time a valve opens or a fixture is used, both flow and pressure change, but when excessive velocity is also present, these hydrodynamic changes can be destructive. Excessive velocity-related problems include erosion, cavitation, entrained air separation, whistling, and water hammer.

Water hammer (or more formally hydraulic shock, which reminds the designer that there are non-audible components) is the term commonly used to describe the destructive forces, pounding noises, and vibrations that develop in a piping system when a column of non-compressible liquid flowing at a given velocity is stopped abruptly. The dynamic pressure wave generated at the point of impact travels back and forth through the piping system until the wave energy is dissipated, producing the characteristic sound associated with this phenomenon, as if someone was hitting the pipe with a hammer.

Water hammer can occur in any non-compressible liquid piping system. A pumped waste system, closed hydronic system, or purified water system, as examples, all will exhibit water hammer for the same reasons as a cold water distribution system. Steam systems can produce sounds similar to that caused by hydraulic shock, and these sounds also are commonly known as water hammer. However, steam system water hammer is caused by either a too rapid condensation of steam or a slug of condensate captured by high-velocity steam and then forced through the pipe until slammed into an elbow.

Any device that abruptly stops the flow of water will generate a shock wave and, depending on installation circumstances, may cause water hammer. Common devices of concern include quick-closing electrical solenoid valves and pneumatic valves and pumps, as well as the quick hand closure of quarter-turn valves or fixture trim. Because of their high instantaneous flow and therefore accompanying high fluid velocity, water closet flushometer valves (flush valves) also frequently act as the source of water hammer.

Although sound generally is associated with the occurrence of hydraulic shock, the absence of such noise does not necessarily prove that hydraulic shock is nonexistent. The sound may be annoying, but it is not inherently dangerous; like thunder and lightning, the cause of the sound is the dangerous part. For a given piped system, the designer should verify that the circumstances that produce water hammer are either not present or, if present, are effectively controlled.

Shock Intensity

The intensity of a pressure wave is related directly to valve closure time. As valve closure time from full-open position to full-closed position approaches zero, the maximum pressure rise is reached, calculated by Equation 5-8, known as Joukowsky's formula:

Equation 5-8

$$P_r = \frac{wav}{144g}$$

where

P_r = Pressure rise above flow pressure, psi (kPa)

w = Specific weight of liquid (water = 62.4 pounds per cubic foot [1,000 kg/m^3])

a = Velocity of pressure wave, fps (m/s)

v = Change in flow velocity, fps (m/s)

g = Acceleration due to gravity, 32 ft/s^2 (9.8 m/s^2)

The value of the pressure wave velocity (a) can be determined by Equation 5-9:

Equation 5-9

$$a = \frac{A_w}{(1 + KB)^{1/2}}$$

where

A_w = Velocity of sound in water (at room temperature approximately 4,900 fps [1,490 m/s])

K = Ratio of the fluid's modulus of elasticity to the pipe's modulus of elasticity

B = Ratio of pipe diameter to pipe wall thickness

For an installed cold water system, the velocity of the pressure wave can be taken to be a constant. For a typical metal pipe water system, the pressure wave velocity averages 4,000–4,500 fps (1,200–1,400 m/s). Using Equation 5-8, the maximum pressure rise is approximately 60 times the change in velocity, and at a typical maximum design velocity of 8 fps (2.4 m/s), quick valve closure can produce a shock pressure of 480 psi (3,300 kPa). Most valves and fittings used in a water distribution system are designed and constructed for a normal maximum working pressure of 150 psi (1,000 kPa). Subjecting a system to repeated pressure surges of almost 500 psi (3,450 kPa) can cause serious damage.

The time interval required for a pressure wave to travel from the point of closure (origin) to the point of reflection and back again is denoted by:

$$2L/a$$

where

L = Length of pipe from the point of closure to the point of reflection (typically a point of relief, as defined in PDI-WH201: *Water Hammer Arrestors,* such as a pipe at least two sizes larger or a water tank)

Quick valve closure may be defined as a closure time equal to or less than 2L/a seconds, with a beginning flow of at least 15 percent of full-open flow. When a valve closes in a time equal to or less than 2L/a seconds, the initial wave returns to hit the now completely closed valve, reflecting the full force of the wave back into the system. This oscillation continues every 2L/a seconds until the wave energy is dissipated. It is interesting to note that for a common branch length of 20 feet (6 m), a 4,000-fps (1,200-m/s) pressure wave would complete this oscillation at a rate of 200 hertz, definitely within the audible range.

As can be seen by reviewing Equation 5-8, shock intensity (P_r) is independent of flow pressure; however, for an open system this can be misleading. A standard hose bibb flows more water at high pressure than at low pressure, with no difference in the time of closure. For a standard 1.6-gallon-per-flush (gpf) (6-Lpf) flushometer, with a beginning static pressure of 25 psi (170 kPa), the maximum instantaneous flow reaches 40 gpm (150 L/s) with full closure about 12 seconds after peak flow. At 80 psi (550 kPa), the same flushometer will deliver 75 gpm (280 L/s) with closure only eight seconds later. Clearly, an open system operating at high flow pressure is likely to have high flow velocity and will generate intense water hammer.

Plastic pipe cold water systems are becoming more common. From Equations 5-8 and 5-9, it is seen that the magnitude of the pressure wave is some function of pipe elasticity and wall thickness. Thermoplastic pipe materials such as PVC, CPVC, PVDF, and polypropylene have thicker walls than metal pipe, but their modulus of elasticity is about 100 times lower (10^5 versus 10^7 psi), which lowers the velocity of the pressure wave and therefore lowers the overall magnitude of the shock pressure wave. Where water hammer is a concern in a plastic pipe system, the pipe manufacturer should be contacted for appropriate design constants.

System Protection

The layout of the distribution system along with the designer-controlled parameters of Equations 5-8 and 5-9 must be manipulated to minimize velocity-related problems in a cost-effective manner. For instance, a spring-loaded check valve could be installed at the discharge of a pump. A water PRV could be installed, or the outlet pressure of an existing PRV could be lowered. A pipe branch to a troublesome fixture could be upsized, or air chambers or water hammer arresters could be installed.

It has been said that the existence of water hammer simply means that the pipe is too small. After all, the cross-sectional area of a 1½-inch (38-mm) pipe is about 2.5 times that of a 1-inch (25-mm) pipe. This larger size branch line to a water closet flushometer, for example, would decrease the water velocity and therefore the shock wave intensity by 60 percent. A set of 1½-inch (38-mm) supplies to a lavatory would surely eliminate all possibility of dangerous water hammer on that branch, but of course it also would be difficult to economically justify this unusually large pipe.

Air Chambers

For hydraulic shock system protection, air chambers essentially have been replaced by pre-manufactured water hammer arresters. The air chamber device consists of a capped piece of pipe of various lengths, some with fittings to facilitate draining and recharging. Air chamber capacity requirements are shown in Table 5-9.

Table 5-9 Required Air Chamber Capacity

Nominal Pipe Diameter, in. (mm)	Pipe Length, ft (m)	Flow Pressure, psi (kPa)	Velocity, fps (m/s)	Required Air Chamber	
				Volume, in.^{3} (cm^3)	Physical Size, in. (cm)
½ (12.71)	25 (7.62)	30 (207)	10 (3.04)	8 (1.3)	¾ × 15 (1.9 × 38.1)
½ (12.71)	100 (30.5)	60 (414)	10 (3.04)	60 (9.8)	1 × 69½ (2.5 × 176.5)
¾ (19.1)	50 (15.25)	60 (414)	5 (1.52)	13 (2.1)	1 × 5 (2.5 × 12.7)
¾ (19.1)	200 (61.0)	30 (207)	10 (3.04)	108 (17.7)	1¼ × 72½ (3.2 × 184.2)
1 (25.4)	100 (30.5)	60 (414)	5 (1.52)	19 (3.1)	1¼ × 127/10 (3.2 × 32.3)
1 (25.4)	50 (15.25)	30 (207)	10 (3.04)	40 (6.6)	1¼ × 27 (3.2 × 68.6)
1¼ (31.8)	50 (15.25)	60 (414)	10 (3.04)	110 (18.0)	1¼ × 54 (3.2 × 137.2)
1½ (38.1)	200 (61.0)	30 (207)	5 (1.52)	90 (14.8)	2 × 27 (5.1 × 68.6)
1½ (38.1)	50 (15.25)	60 (414)	10 (3.04)	170 (27.9)	2 × 50½ (5.1 × 128.3)
2 (50.8)	100 (30.5)	30 (207)	10 (3.04)	329 (53.9)	3 × 44½ (7.6 × 113.0)
2 (50.8)	25 (7.62)	60 (414)	10 (3.04)	150 (24.6)	2½ × 31 (6.4 × 78.7)
2 (50.8)	200 (61.0)	60 (414)	5 (1.52)	300 (49.2)	3 × 40½ (7.6 × 102.9)

Source: PDI-WH201

The two main components of any shock absorber are variable displacement and energy dampening. Air chambers exhibit superior variable displacement and rely on the naturally occurring dampening effects of the piping medium for their effectiveness.

However, properly sized air chambers are suitable only for the temporary control of shock. The entrapped air charge is rapidly depleted for a number of reasons, and, once gone, the waterlogged device provides no shock protection. Two primary reasons for the depletion of the entrapped air are entrainment caused by turbulence at a shock event and the increased solubility of gas under pressure. For the same reason that the opening of a can of soda releases carbon dioxide or freshly drawn hot water forms white milky clouds of tiny bubbles, holding air at pressure against unsaturated water results in oxygen, nitrogen, carbon dioxide, and other trace gases of air being absorbed into the water (Dalton's law of partial pressures combined with Henry's law of proportional solubility). This depletion of the air charge occurs continuously, even as the system sits idle.

Water Hammer Arresters

The appropriate use of engineered water hammer arresters, also known as water shock absorbers, is an integral part of an overall cost-effective design. Water hammer arresters can rapidly attenuate shock pressure and confine its effects to the section of piping in which it was generated. To ensure consistent, long-term operation, commercially available water hammer arresters have a sealed gas chamber separated from the non-compressible fluid by either a bellows or piston arrangement.

High-pressure, purified water, or other special-application water hammer arrester models are available with varying construction materials and field-adjustable gas chamber contents and pressures. For a purified water system or an application where bacterial control is required, the detrimental stagnant water and dead-end nature of a water hammer arrester must be weighed against the hydraulic shock-relieving benefits.

Manufacturers of engineered water hammer arresters may obtain industry-accepted certifications from the ASSE International and the Plumbing and Drainage Institute (PDI). Engineered water hammer arresters can be certified in any of six sizes, each having a different capacity to control shock, ranging from Type A through Type F. The certified size is based on successful completion of tests under specific experimental conditions, such as pipe size, pipe length, flow pressure, endurance, and limiting surge pressures to less than 150 psi.

Table 5-10 was devised by PDI, based on industry experience and the supply fixture unit (SFU) sizing method for single and multiple fixture branch lines, to help the designer rapidly choose appropriately sized water hammer arresters. The SFU values used to complete Table 5-10 were taken from a certain edition of the National Plumbing Code. As plumbing codes evolved, fixture unit values changed. Without diminishing the value of Table 5-10, the designer, by understanding its history and purpose, is thus better able to use the tool appropriately.

Water hammer arrester sizing and placement guidelines according to PDI-WH201 include the following:

- Size water hammer arresters for use on cold and hot water branch lines according to Table 5-10.
- When water flow pressure exceeds 65 psi (450 kPa), select the next larger size water hammer arrester.
- When the branch line exceeds 20 feet (6 m) in length, an additional water hammer arrester should be used, each sized for half the total fixture unit load.
- The preferred location for the water hammer arrester is at the end of the branch line between the last two fixtures served.
- The preferred location for the second water hammer arrester, when required, is approximately midway along the branch line.
- A water hammer arrester for a branch serving a piece of equipment with a quick-closing valve should be placed as close as possible to the equipment isolation valve.

Table 5-10 Water Hammer Arrester Sizing

PDI Units	AA	A	B	C	D	E	F
Fixture Units	1–3	1–11	12–32	33–60	61–113	114–154	155–330

Source: Plumbing and Drainage Institute

SIZING WATER PIPING

Water can be regarded as a non-compressible fluid, and, for calculations, it is customary to assume that water has a uniform density of 62.4 pounds per cubic foot (1 kg/L), which holds nearly constant through a temperature range of 32–60°F (0–15.6°C) (see Table 5-11).

For calculations involving high temperatures (above 200°F [93.3°C]), it is desirable to take into account the changes in density, vapor pressure, and viscosity with temperature.

Hazen-Williams Formula

Among the empirical formulas for piping friction losses that have been developed, the Hazen-Williams equation is widely used for fire protection and city water systems. In a convenient form, it reads as follows:

Table 5-11 Densities of Pure Water at Various Temperatures

Temperature, °F	Density, lb/cu.ft.
32	62.418
35	62.421
39.2	82.424
40	62.423
50	62.408
60	62.388
70	62.300
80	82.217
100	61.988
120	61.719
140	61.386
160	61.008
180	60.586
200	60.135
212	59.843

Equation 5-10

$$f = 0.2082 \left(\frac{100}{C} \right)^{1.852} \left(\frac{q^{1.852}}{d^{4.8655}} \right)$$

where

f = Friction head, feet of liquid per 100 feet of pipe (meters of liquid per 100 m of pipe)
C = Surface roughness constant (dimensionless, see Table 5-12)
q = Fluid flow, gpm (L/s)
d = Inside diameter of pipe, inches (mm)

This formula is most accurate for water flow in pipes larger than 2 inches (50.8 mm) and at velocities less than 10 fps (3 m/s).

Equation 5-10 yields accurate results only when the kinematic viscosity of the liquid is about 1.1 centistokes, which is the case for water at 60°F (15.6°C). However, the kinematic viscosity of water varies with temperature, from 1.8 centistokes at 32°F (0°C) to 0.29 centistokes at 212°F (100°C); therefore, the tables using Hazen-Williams are subject to this error, which may increase the friction loss by as much as 20 percent at 32°F (0°C) and decrease it by as much as 20 percent at 212°F (100°C). Table 5-12 shows the corresponding multipliers that should apply to the values of the head loss, f, for various temperatures.

Table 5-12 Surface Roughness Coefficient (C) Values for Various Types of Pipe

Type of Pipe	Values of C		
	Range (High = Best, smooth, well-laid Low = Poor or corroded)	Average Value for Good, Clean, New Pipe	Value Commonly Used for Design Purposes
Asbestos cement	160–140	150	140
Fiber	—	150	140
Bitumastic-enamel-lined iron or steel centrifugally applied	160–130	148	140
Cement-lined iron or steel centrifugally applied	—	150	140
Copper, brass, lead, tin or glass pipe and tubing	150–120	140	130
Wood stave	145–110	120	110
Welded and seamless steel	150–80	140	100
Continuous-interior, riveted steel (no projecting rivets or joints)	—	139	100
Wrought iron	150–80	130	100
Cast iron	150–80	130	100
Tar-coated cast iron	145–80	130	100
Girth-riveted steel (projecting rivets in girth seams only)	—	130	100
Concrete	152–85	120	100
Full-riveted steel (projecting rivets in girth and horizontal seams)	—	115	100
Vitrified clay	—	115	100
Spiral-riveted steel (flow with lap)	—	110	100
Spiral-riveted steel (flow against lap)	—	110	90
Corrugated steel	—	60	60

Value of C	150	140	130	120	110	100	90	80	70	60
Multiplier to Correct Tables	0.47	0.54	0.62	0.71	0.84	1.0	1.22	1.50	1.93	2.57

N 1.85 graph paper can be used to analyze water flow at various velocities. Connecting a line between two points on the graph will show the pressure at any other flow in gpm. Static head at 0 gpm typically is used as one of the points, and the other point is at a residual pressure with a certain gpm flowing.

Darcy-Weisbach Formula

The more popular equation used by the plumbing and process piping industry is the Darcy-Weisbach formula. In a convenient form, it reads as follows:

Equation 5-11

$$h_f = f\left(\frac{L}{D}\right)\left(\frac{V^2}{2g}\right)$$

To convert to psi, the equation is:

Equation 5-11a

$$p = h_f \times \left(\frac{j}{144}\right)$$

where

h_f = Friction head loss, feet (m) of fluid
p = Friction head loss, psi (kPa)
f = Coefficient of friction or friction factor, dimensionless (from Colebrook equation or Moody diagram)
L = Length of pipe, feet (m)
D = Inside diameter of pipe, feet (m)
V = Average velocity of flow, fps (m/s)
g = Gravitational acceleration, 32.2 ft/sec/sec
j = Pounds per cubic foot (kg/m^3)

The assumptions made for deriving this formula from test data are uniform flow, cold or hot water distribution systems, round pipe or duct, and turbulent flow (more than Reynolds number 4,000).

The friction factor (f) takes into account viscosity (temperature), pipe roughness, and the Reynolds number.

For laminar flow (less than Reynolds number 2,000), the roughness of the pipe has no effect on friction, and f becomes 64/R.

For turbulent flow, the friction factor can be determined by the Colebrook formula (Equation 5-12), Moody diagrams, or from manufacturer data or various handbooks.

Equation 5-12

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left[\left(\frac{\varepsilon}{3.7D}\right) + \left(\frac{2.51}{R\sqrt{f}}\right)\right]$$

To get the Reynolds number, the equation is:

$$R = \frac{VD}{v}$$

where

R = Reynolds number
f = Friction factor, dimensionless
ε = Absolute roughness, ft (see Table 5-13)
D = Inside diameter of pipe, ft
V = Average pipe velocity, ft/sec
v = Kinematic viscosity, ft^2/sec

Since the Colebrook equation is complicated, the friction factor may be obtained from a graph developed by L.F. Moody. This graph shows the relation between the friction factor, the Reynolds Number R, and the relative roughness ε/D. The f obtained is valid for any selected fluid and fluid temperatures since viscosity and density are accounted for in the Reynolds number.

See Table 5-13 for some values of ε (absolute roughness) and Table 5-14 for some values of the friction coefficient.

For domestic plumbing, pipe sizing design tables or graphs can be found in local code documents or various ASPE publications or obtained from the pipe

Table 5-13 Values of ε (Absolute Roughness)

Type of Pipe (new, clean, condition)	Absolute roughness (in feet)
Drawn tubing—glass, brass, plastic	0.000005
Commercial steel or wrought iron	0.00015
Cast iron—asphalt dipped	0.0004
Galvanized iron	0.0005
Cast iron—uncoated	0.00085
Wood stave	0.0006-0.0003
Concrete	0.001-0.01
Riveted steel	0.003-0.03

Table 5-14 Average Values for Coefficient of Friction, f

Nominal Pipe Size, in.	Brass, Copper, or Lead	Galvanized Iron or Steel
½	0.022	0.044
¾	0.021	0.040
1¼	0.020	0.038
1½	0.020	0.036
1	0.019	0.035
2	0.018	0.033
2½	0.017	0.031
3	0.017	0.031
4	0.016	0.030

manufacturers. The graphs, which are preferred to be used, show the relationships of pressure drop (in psi or feet of water head) per 100 feet of equivalent length (actual length plus allowance for valves and fittings), gpm or liters per minute, pipe size, and velocity. To size piping, you must keep in mind all four items, and a graph shows them best. You must know two items to plot on the graph.

Make sure that the piping material used is compatible with the water quality and chemistry. This includes fittings, gaskets, valves, etc.

Note: This chapter uses the most current technical information sources available. However, the manufacturer information provided in this chapter should not be used for a design. When picking a product, use the latest manufacturer literature and the latest code that applies to the location of the building.

Factors Affecting Domestic Water Pipe Sizing

The three factors affecting the sizing of a water line are the maximum demand flow rate (gpm [L/s]), maximum velocity desired (fps [m/s]), and the pressure available for piping friction loss per 100 feet (psi [kPa]).

Demand

To size piping, you must know the maximum gpm (L/s) in the pipe at each size location. To determine this, use the water supply fixture units (WSFU) for the various plumbing fixtures. The WSFU can be found in the various plumbing codes (see Table 5-15, which was taken from the International Plumbing Code and Table 5-16 taken from the Uniform Plumbing Code). If an exact fixture is not listed in the applicable table, pick a fixture that has similar water usage.

Note that the fixtures are listed as flush valve or flush tank depending on their water control device. They also are listed as public or private. Private fixtures are those used only by the space occupant (such as a hotel room) and are not open to the public for walk-in use.

For piping systems that have both domestic plumbing fixtures and process equipment that has a certain infrequent gpm, divide the domestic plumbing-related gpm by

Table 5-15 IPC Water Supply Fixture Unit Values

Fixture[a]	Occupancy	Type of Supply Control	WSFU		
			Cold	Hot	Total
Bathroom group	Private	Flush tank	2.7	1.5	3.6
Bathroom group	Private	Flush valve	6.0	3.0	8.0
Bathtub	Private	Faucet	1.0	1.0	1.4
Bathtub	Public	Faucet	3.0	3.0	4.0
Bidet	Private	Faucet	1.5	1.5	2.0
Combination fixture	Private	Faucet	2.25	2.25	3.0
Dishwashing machine	Private	Automatic	—	1.4	1.4
Drinking fountain	Offices, etc.	3/8-in. valve	0.25	—	0.25
Kitchen sink	Private	Faucet	1.0	1.0	1.4
Kitchen sink	Hotel, restaurant	Faucet	3.0	3.0	4.0
Laundry trays (1 to 3)	Private	Faucet	1.0	1.0	1.4
Lavatory	Private	Faucet	0.5	0.5	0.7
Lavatory	Public	Faucet	1.5	1.5	2.0
Service sink	Offices, etc.	Faucet	2.25	2.25	3.0
Shower head	Public	Mixing valve	3.0	3.0	4.0
Shower head	Private	Mixing valve	1.0	1.0	1.4
Urinal	Public	1-in. flush valve	10.0	—	10.0
Urinal	Public	¾-in. flush valve	5.0	—	5.0
Urinal	Public	Flush tank	3.0	—	3.0
Washing machine (8 lb)	Private	Automatic	1.0	1.0	1.4
Washing machine (8 lb)	Public	Automatic	2.25	2.25	3.0
Washing machine (15 lb)	Public	Automatic	3.0	3.0	4.0
Water closet	Private	Flush valve	6.0	—	6.0
Water closet	Private	Flush valve	2.2	—	2.2
Water closet	Public	Flush valve	10.0	—	10.0
Water closet	Public	Flush valve	5.0	—	5.0
Water closet	Public or private	Flushometer tank	2.0	—	2.0

For SI: 1 inch = 25.4 mm, 1 pound = 0.454 kg

[a] For fixtures not listed, loads should be assumed by comparing the fixture to one listed using water in similar quantities and at similar rates. The assigned loads for fixtures with both hot and cold water supplies are given for separate hot and cold water loads and for total load. The separate hot and cold water loads being three-fourths of the total load for the fixture in each case.

Table 5-16 UPC Water Supply Fixture Unit Values

Individual Fixtures	Minimum Fixture Branch Pipe Size, in.	WSFU	
		Private Installation	Public Installation
Bathtub	½	4	4
Bathtub with ¾-in. fill valve	¾	10	10
Bidet	½	1	—
Dishwasher, domestic	½	1.5	1.5
Drinking fountain	½	0.5	0.5
Hose bibb	½	2.5	2.5
Lavatory	½	1	1
Bar sink	½	1	2
Clinic faucet sink	½	3	—
Kitchen sink, domestic	½	1.5	1.5
Laundry sink	½	1.5	1.5
Service or mop basin	½	1.5	3
Washup basin	½	2	—
Shower head	½	2	2
Urinal with flush tank	½	2	2
Wash fountain	¾	4	—
Water closet with gravity tank	½	2.5	2.5
Water closet with flushometer tank	½	2.5	2.5
Water cooler	½	0.5	0.5

7.5 gpm per WSFU and add that to the total. For process equipment that has continuous or semi-continuous flow, add the gpm where it occurs when sizing the pipe.

Determine the total WSFU for flush tank and flush valve fixtures separately. Then, determine the gpm of each (flush tank and flush valve separately). The one that has the greater gpm is predominant. Thereafter, to get the total gpm for branches with both flush valves and flush tanks, use the predominant fixture type. (For gpm conversions, see Table 5-17). Add the WSFU values (hot and cold separately) from the ends of the piping to the meter or water heater (for hot water). Then convert the WSFU to gpm separately for hot and cold water (do not exceed the WSFU fixture total).

After determining the gpm of all branches and mains as well as the pressure drop per 100 feet to be allowed (to size the

Table 5-17a Estimating Demand for Supply Systems Predominantly for Flush Tanks

Load, WFSU	Demand	
	gpm	cubic feet per minute
1	3.0	0.04104
2	5.0	0.0684
3	6.5	0.86892
4	8.0	1.06944
5	9.4	1.256592
6	10.7	1.430376
7	11.8	1.577424
8	12.8	1.711104
9	13.7	1.831416
10	14.6	1.951728
11	15.4	2.058672
12	16.0	2.13888
13	16.5	2.20572
14	17.0	2.27256
15	17.5	2.3394
16	18.0	2.90624
17	18.4	2.459712
18	18.8	2.513184
19	19.2	2.566656
20	19.6	2.620128
25	21.5	2.87412
30	23.3	3.114744
35	24.9	3.328632
40	26.3	3.515784
45	27.7	3.702936
50	29.1	3.890088
60	32.0	4.27776
70	35.0	4.6788
80	38.0	5.07984
90	41.0	5.48088
100	43.5	5.81508
120	48.0	6.41664
140	52.5	7.0182
160	57.0	7.61976
180	61.0	8.15448
200	65.0	8.6892
225	70.0	9.3576
250	75.0	10.026
275	80.0	10.6944
300	85.0	11.3628
400	105.0	14.0364
500	124.0	16.57632
750	170.0	22.7256
1,000	208.0	27.80544
1,250	239.0	31.94952
1,500	269.0	35.95992
1,750	297.0	39.70296
2,000	325.0	43.446
2,500	380.0	50.7984
3,000	433.0	57.88344
4,000	535.0	70.182
5,000	593.0	79.27224

Table 5-17b Estimating Demand for Supply Systems Predominantly for Flush Valves

Load, WSFU	Demand	
	gpm	cubic feet per minute
5	15.0	2.0052
6	17.4	2.326032
7	19.8	2.646364
8	22.2	2.967696
9	24.6	3.288528
10	27.0	3.60936
11	27.8	3.716304
12	28.6	3.823248
13	29.4	3.930192
14	30.2	4.037136
15	31.0	4.14408
16	31.8	4.241024
17	32.6	4.357968
18	33.4	4.464912
19	34.2	4.571856
20	35.0	4.6788
25	38.0	5.07984
30	42.0	5.61356
35	44.0	5.88192
40	46.0	6.14928
45	48.0	6.41664
50	50.0	6.684
60	54.0	7.21872
70	58.0	7.75344
80	61.2	8.181216
90	64.3	8.595624
100	67.5	9.0234
120	73.0	9.75864
140	77.0	10.29336
160	81.0	10.82808
180	85.5	11.42964
200	90.0	12.0312
225	95.5	12.76644
250	101.0	13.50168
275	104.5	13.96956
300	108.0	14.43744
400	127.0	16.97736
500	143.0	19.11624
750	177.0	23.66136
1,000	208.0	27.80544
1,250	239.0	31.94952
1,500	269.0	35.95992
1,750	297.0	39.70296
2,000	325.0	43.446
2,500	380.0	50.7984
3,000	433.0	57.88344
4,000	525.0	70.182
5,000	593.0	79.27224

pipe), go to the pipe graphs. Most codes provide the minimum pipe size to the final fixture connection and also the maximum length (see Table 5-18). They also provide the minimum flow rate and the minimum flow pressure (see Table 5-19). Check this information against the manufacturer's requirements for the fixtures that are being used on the project.

Table 5-18 Minimum Sizes of Fixture Water Supply Pipes

Fixture	Minimum Pipe Size, in.
Bathtuba (60″ × 32″ and smaller)	½
Bathtuba (larger than 60″ × 32″)	½
Bidet	3/8
Combination sink and tray	½
Dishwasher, domestic[a]	½
Drinking fountain	3/8
Hose bibb	½
Kitchen sink[a]	½
Laundry, 1, 2 or 3 compartmentsa	½
Lavatory	3/8
Shower, single head[a]	½
Sinks, flushing rim	¾
Sinks, service	½
Urinal, flush tank	½
Urinal, flush valve	¾
Wall hydrant	½
Water closet, flush tank	3/8
Water closet, flush valve	1
Water closet, flushometer tank	3/8
Water closet, one piece[a]	½

For SI: 1 inch = 25.4 mm, 1 foot = 304.8 mm, 1 pound per square inch = 6.895 kPa

a Where the developed length of the distribution line is 60 feet or less, and the available pressure at the meter is [a] minimum of 35 psi, the minimum size of an individual distribution line supplied from a manifold and installed as part of a parallel water distribution system shall be one nominal tube size smaller than the sizes indicated.

Table 5-19 Water Distribution System Design Criteria Required Capacity at Fixture Supply Pipe Outlets

Fixture Supply Outlet Serving	Flow Rate, gpm	Flow Pressure, psi
Bathtub	4	8
Bidet	2	4
Combination fixture	4	8
Dishwasher, residential	2.75	8
Drinking fountain	0.75	8
Laundry tray	4	8
Lavatory	2	8
Shower	3	8
Shower, temperature controlled	3	20
Sillcock, hose bibb	5	8
Sink, residential	2.5	8
Sink, service	3	8
Urinal, valve	1.5	15
Urinal valve, low flow	0.125–1.0	20
Water closet, blowout, flushometer valve	3.5	25
Water closet, flushometer tank	1.6	15
Water closet, siphonic, flushometer valve	2.5	15
Water closet, flushommeter valve, low flow	1.6	20-25
Water closet, tank, close coupled	3	8
Water closet, flushometer valve, ultra low flow	1.28	30
Water closet, tank, one piece	6	20

For SI: 1 pound per square inch = 6.895 kPa, 1 gallon per minute = 3.785 L/m

As stated previously, the plumbing code that applies to the project's location must be used. The IPC values are based on the Hunter's curve fixture unit conversion to gpm, which was developed in 1924. Since that time, however, many authorities have determined that use of these curves leads to oversized piping, mainly due to the reduced water flow and different life patterns of modern fixtures. The use of modified Hunter's curves also should be considered due to different building uses. If this code is not the approved code for the local area, the use of modern fixture units to gpm conversions is recommended. Fixture groups must also be accounted for in the design.

Velocity

The second factor affecting the sizing of a water line is velocity. A maximum velocity of 10 fps (3 m/s) based on material type, which is suggested by some model plumbing codes, is much too high for domestic plumbing installations. Even 8 fps (2.4 m/s), as listed in other codes, is very high for many types of domestic water piping and subject to water hammer. A velocity above 6 or 7 fps (1.8 or 2.1 m/s) normally creates noise. Also, depending on the piping material used and the temperature, hardness, contained air bubbles, and pH of the water, velocities above 4 fps (1.2 m/s) can erode some piping material.

See the pipe manufacturer's information for the specific type of pipe, maximum desired flow rates, and chemical resistance. Suggested maximum velocities for various pipe materials are presented below:

- Steel: 4–8 fps (1.2–2.1 m/s)
- Copper (K, L) cold: 5–8 fps (1.5–2.1 m/s)
- Copper (K, L) >140°F: 2–3 fps (0.3–0.9 m/s)
- Copper (K, L) <140°F: 4–5 fps (1.2–1.5 m/s)
- PVC: 4–6 fps (1.2–1.8 m/s)
- CPVC: 5 fps (1.5 m/s)
- Polyethylene: 6–8 fps (1.8–2.1 m/s)
- FRP: 4–6 fps (1.2–1.8 m/s)

In general, velocities above 5 fps (1.5 m/s) should be avoided for PVC and CPVC.

Table 5-20 indicates some recommended maximum velocity rates for different systems. The fluid flow velocities in water systems should not exceed certain limits to avoid noise and damaging wear and tear of pipes and fittings.

Table 5-20 Recommended Maximum Velocities

Application	Maximum Velocity, fps (m/s)
Tap water (low noise)	1.6 - 2.3 (0.5 - 0.7)
Tap water	3.3 - 8.2 (1.0 - 2.5)
Cooling water	4.9 - 8.2 (1.5 - 2.5)
Suction boiler feed water	1.6 - 3.3 (0.5 - 1.0)
Discharge boiler feed water	4.9 - 8.2 (1.5 - 2.5)
Condensate	3.3 - 6.5 (1.0 - 2.0)
Heating circulation	3.3 - 9.8 (1.0 - 3.0)

Pressure

The third factor affecting the sizing of a water line is the pressure available for piping friction loss. The first step in ascertaining the pressure available for friction loss is determining (from the local water department or by a hydrant flow test) the maximum and minimum water pressures at the street connection (or the stop valve at a well system) at the flow rate to be encountered at the project site. (Make sure to know the time of day and why the test was taken by the local purveyor. Always get a written reply and ask for the following information: location, date, time, hydrant number, hydrant model, water main size, static reading at hydrant, static reading on main, residual reading on hydrant, residual reading on main, pilot reading, and name of testers.) The maximum and minimum pressures may be nearly the same or they may vary greatly depending on the time of year, hour of day, type of adjacent buildings, etc. The fire hydrant flow test, which is taken as close to the site as possible, includes static and residual pressures at the desired flow rate (above normal use with the project building added). The residual pressure is the pressure to be used as a starting point in calculating other pressure requirements. The effective pressure point is where flowing and non-flowing water meet.

Care must be taken to handle the high pressure as well as the low pressure. If the maximum pressure is more than 80 psi (552 kPa) and a pressure-regulating device is installed, the pressure regulator will introduce an additional pressure loss (falloff) in the piping system when water is flowing. If a pressure-regulating device is installed, the available pressure after the falloff pressure must be used (on the outlet side of the meter or backflow preventer).

When dealing with well water, a well drawdown test should be performed to determine the best stress test for this kind of system. If well water is used for irrigation, this is highly recommended.

The water meter creates a loss of pressure, and the pressure drop is available from the manufacturer's flow charts. The designer must decide to lose or preserve the water pressure available at the street.

The flow rate from the most hydraulically remote fixture or piece of equipment that has the highest total pressure drop from the outlet of the meter when all flow pressure losses are added, excluding that for the piping, also must be determined. Some iteration will be required to find the one place with the highest pressure drop.

The pressure required at each fixture or appliance can be determined from the applicable code and/or the manufacturer's information. Manufacturer's information governs. If there is an elevation difference between the meter and the governing fixture or appliance, the static pressure loss required to reach the governing fixture or appliance must be calculated. The static loss (or gain) is figured at 0.433 psi per foot (9.8 kPa/m) of elevation difference, above or below the meter. The difference in elevation is usually a pressure loss to the system, as fixtures are normally at a higher elevation than the source. If the fixture is lower than the source, the pressure will increase, so the static pressure is added to the initial pressure. This holds true when calculating the meter outlet pressure. The elevation difference between the city main and the meter must be accounted for in the design.

Step-by-Step Guide to Sizing Water Pipe

1. Determine the lowest effective pressure available at the city water main connection. This is known as the residual pressure of the main.
2. Select a water service pipe size and type (to the meter) and calculate its pressure drop. Also determine any pressure drop or increase due to elevation change (water main to water meter) plus the service losses through the service pipe, which includes the tapping sleeve and valve or a curb stop. An allowance should be made for future development of the area where the project is located, generally 5 psi.
3. Select (or obtain from the jurisdiction) the water meter type and size and determine its pressure drop.
4. Determine the outlet pressure at the meter from the values obtained in Steps 1 through 3.
5. Determine the most hydraulically remote point (the piping main and branch) using the greatest amount of needed end pressure and the total pressure drop of the appliances and devices in the circuit piping to the end fixture or appliance when flowing. Several circuits may need to be analyzed. Valves and fittings are omitted at this step. To do so, add the flow pressure drops of all appliances and devices in the critical circuit.
6. Determine the pressure needed at the final fixture or appliance, as well as the static pressure drop or increase due to elevation.
7. Calculate the pressure drop allowed for the piping using the values obtained in Steps 5 and 6.
8. Determine the equivalent length (sometimes called the developed length) of pipe to which the available pressure drop will be applied and the allowable pressure drop per 100 feet of equivalent length. To do so, measure the actual length of the critical circuit. To get the equivalent length, multiply the actual length by some factor. Some codes suggest 1.25, others 1.5. If the critical circuit has many fittings, use the higher number. For a more detailed com-

putation, a full takeoff of piping, fittings, valves, meters, backflow preventers, filters, softeners, and/or appliances and fixtures will need to be accounted for in addition to the water source and elevation differences. Computer software is available for this type of calculation.

9. Determine the available flow pressure drop per 100 feet for the critical circuit by dividing the Step 7 value by the Step 8 value and multiplying by 100.
10. Using the totals, starting from the farthest connection back to the meter and using the allowable pressure drop per 100 feet, refer to the pipe graphs and select the pipe sizes for the most hydraulically remote point. Don't go above the maximum desired velocity. Follow the maximum velocity line to the left (the maximum flow rate).
11. Now determine how to size all of the other piping using one of several methods:
    Uniform pressure loss method: Use the same pressure drop for all piping, including the critical circuit. This is the most commonly used method.
    Branch length method: Use the uniform pressure loss for the critical circuit piping. Then calculate a new equivalent length for each branch and size the branches (not the critical circuit) based on the new equivalent length pressure drop per 100 feet, or (Step 7 value ÷ New equivalent length) x 100.
    Constant velocity method: Base the size on velocity only, and then add the pressure drops not to exceed the total allowable (used for short lengths and/or few connections).
    Total pressure loss method: Every circuit uses all the available pressure from the meter to the end user. This is very difficult to do by hand, but some computer programs can help. However, the pipe sizes for the branches become very small, and the velocity becomes too high at the branches near the meter (available pressure is too high).

Velocity Method

Another method designers use to size water piping is the velocity method. The average pressure drop available for piping friction is calculated, and if it is greater than 7 or 8 psi per 100 feet (158.4 or 181 kPa per 100 m), the lines are sized on the basis of a 4- to 6-fps (1.2- or 1.8-m/s) velocity. In this method, the main line is conservatively sized, and the short branches may slightly exceed the average pressure drop. However, the total pressure drop of the system cannot exceed the allowable piping pressure loss for friction. This sometimes is used for small systems with few connections of similar type.

Pressure Loss in Pipe Fittings and Valves

It is not unusual for a designer to need to determine the pressure drop in an existing system. Also, a designer may wish to confirm the pressure drop in a critical system just sized, particularly if an equipment change is made.

In this case, determine the pressure drop in all piping from the piping graphs. By measurement or other manufacturer information, determine the actual pressure drop of the installed fixtures and appliances and the pressure at the meter outlet.

For fittings and valves, you can use equivalent lengths (see Table 5-21). Note that these are not affected by the flow velocity and therefore are very inaccurate.

For a more accurate pressure drop, use K values or C_v values (design coefficients), which can be calculated using Equation 5-13.

Equation 5-13

$$\Delta h = KV_2/2g$$

Table 5-21 Allowance for Friction Loss in Valves and Threaded Fittings

Diameter of Fitting, in. (mm)	Equivalent Length of Pipe for Various Fittings, ft (m)						
	90° Standard Elbow	45° Standard Elbow	Standard Tee 90°	Coupling or Straight Run of Tee	Gate Valve	Globe Valve	Angle Valve
⅜ (10)	1 (0.3)	0.6 (0.2)	1.5 (0.5)	0.3 (0.09)	0.2 (0.06)	8 (2.4)	4 (1.2)
½ (15)	2 (0.6)	1.2 (0.4)	3 (0.9)	0.6 (0.18)	0.4 (0.12)	15 (4.6)	8 (2.4)
¾ (20)	2.5 (0.8)	1.5 (0.5)	4 (1.2)	0.8 (0.24)	0.5 (0.15)	20 (6.1)	12 (3.7)
1 (25)	3 (0.9)	1.8 (0.6)	5 (1.5)	0.9 (0.27)	0.6 (0.18)	25 (7.6)	15 (4.6)
1¼ (32)	4 (1.2)	2.4 (0.7)	6 (1.8)	1.2 (0.4)	0.8 (0.24)	35 (10.7)	18 (5.5)
1½ (40)	5 (1.5)	3 (0.9)	7 (2.1)	1.5 (0.5)	1 (0.3)	45 (13.7)	22 (6.7)
2 (50)	7 (2.1)	4 (1.2)	10 (3.1)	2 (0.6)	1.3 (0.4)	55 (16.8)	28 (8.5)
2½ (65)	8 (2.4)	5 (1.5)	12 (3.7)	2.5 (0.8)	1.6 (0.5)	65 (19.8)	34 (10.4)
3 (75)	10 (3.1)	6 (1.8)	15 (4.6)	3 (0.9)	2 (0.6)	80 (24.4)	40 (12.2)
4 (100)	14 (4.3)	8 (2.4)	21 (6.4)	4 (1.2)	2.7 (0.8)	125 (38.1)	55 (16.8)
5 (125)	17 (5.2)	10 (3.1)	25 (7.6)	5 (1.5)	3.3 (1)	140 (42.7)	70 (21.3)
6 (150)	20 (6.1)	12 (13.7)	30 (9.1)	6 (1.8)	4 (1.2)	165 (50.3)	80 (24.4)

Note: Allowances are based on nonrecessed threaded fittings. Use one-half the allowance for recessed threaded fittings or streamline solder fittings.

$$\text{Also, } Q = C_v \sqrt{(\Delta P/SG)}$$
$$\Delta P = (Q/C_v)2\ SG$$
$$\Delta h = \text{Fluid head (ft)}$$

where

- V = Velocity, fps (m/s)
- g = Acceleration of gravity
- ΔP = Pressure, psi (kPa)
- Q = Flow, gpm (L/s)
- SG = Specific gravity, water = 1.0 (for water, Dh x 0.43 = psi)
- K = Coefficient
- C_v = Flow through a valve where a pressure loss of 1 psi occurs

TESTING

Prior to disinfection, connection to faucets and equipment, and installation of pipe insulation, the domestic water system should be hydrostatically tested for leakage. A typical test for interior piping is accomplished by capping all system openings, filling the system with water, and then pumping a static head into the system at a minimum 1.5 times the working pressure (100 psi [689.5 kPa] minimum) for a period of not less than two hours. These test requirements are acceptable to most inspectors, but note that 80 psi (551.6 kPa) is the maximum pressure allowed by most designs and codes for the distribution piping.

Under conditions where systems are subject to freezing and with the approval of the AHJ, an air test may be substituted for the water test. This can be accomplished by connecting an air compressor to a metal pipe system, bringing the system up to 40 psi (275.8 kPa), checking for leaks with liquid soap, repairing any leaks, and then subjecting the system to a minimum 1.5 times the working pressure (100 psi [689.5 kPa] minimum) for a minimum of two hours. Do not use an air test for most plastic piping, particularly PVC or CPVC.

Any equipment that may be damaged by these tests should be disconnected or isolated and shut off from the system.

CLEANING AND DISINFECTING

New or repaired potable water systems shall be cleaned and disinfected prior to use whenever required by the administrative authority. The methods to be used should be per AWWA or as follows (or as required by the AHJ).

- Cleaning and disinfection applies to both hot and cold domestic (potable) water systems and should be performed after all pipes, valves, fixtures, and other components of the systems are installed, tested, and ready for operation.
- All domestic hot and cold water piping should be thoroughly flushed with clean, potable water prior to disinfection to remove dirt and other contaminants. Faucet and strainer screens should be removed before flushing and reinstalled after disinfection is completed.
- Disinfection should be done using chlorine, either gas or liquid. Calcium or sodium hypochlorite or another approved disinfectant may be used. Use nonhazardous materials that can be drained to the city sewer.
- A service cock should be provided and located at the water service entrance. The disinfecting agent should be injected into and through the system from this cock only.
- The disinfecting agent should be injected by a proportioning pump or device through the service cock slowly and continuously at an even rate. During disinfection, flow of the disinfecting agent into the main connected to the public water supply is not permitted.
- All sectional valves should be opened during disinfection. All outlets should be fully opened at least twice during injection and the residual checked with orthotolidine solution.
- If chlorine is used, when the chlorine residual concentration, calculated on the volume of water the piping will contain, indicates not less than 50 parts per million (ppm) or milligrams per liter at all outlets, then all valves should be closed and secured. Make sure the pipe material is compatible with chlorine.
- The residual chlorine should be retained in the piping systems for a period of at least 24 hours.
- After the retention, the residual should be at least 5 ppm. If it is less than 5 ppm, then the process should be repeated as described above.
- If the residual level is satisfactory, then all fixtures should be flushed with clean, potable water until residual chlorine by the orthotolidine test is not greater than that of the incoming water supply (this may be zero).
- All work and certification of performance should be performed by approved applicators or qualified personnel with chemical and laboratory experience. Certification of performance should indicate the job name and location and the date when disinfection was performed, material used for disinfection, retention period of the disinfectant in

the piping system, ppm (mg/L) of chlorine during retention, ppm (mg/L) of chlorine after flushing, a statement that disinfection was performed as specified, and the signature and address of the person performing the disinfection.

- Upon completion of final flushing (after the retention period), the contractor should obtain at least one water sample from each hot and cold water line and submit the samples to an approved laboratory. Samples should be taken from faucets located at the highest floor and furthest from the meter or main water supply. The laboratory report should show the name and address of the approved laboratory testing the sample, name and location of the job, date the samples were obtained, coliform organism count, and any other tests required by local code authorities. Note that an acceptable test shall show the absence of coliform organisms, and some codes require an acceptable test for two consecutive days.
- If the analysis does not satisfy the minimum requirements, the disinfection procedure must be repeated.
- Before acceptance of the systems, the contractor should submit to the architect or engineer for review three copies of the laboratory report and three copies of the certification of performance as specified.
- Under no circumstances should the contractor permit the use of any portion of the domestic water system until it is properly disinfected, flushed, and certified.

Note: It should be understood that local code requirements, if more stringent than the above suggested procedures, shall be included in the specifications.

GLOSSARY

Accuracy The degree of falloff in the outlet pressure from the set pressure at full-flow capacity. Also the capability of producing the same results for repetitive operations with identical conditions of flow.

Backflow Any reversal of the flow of water from its intended direction.

Backsiphonage Backflow caused by a lowering of normal pressure on the upstream side.

Branch length method A pipe sizing methodology that uses the uniform pressure loss for the critical circuit piping to calculate a new equivalent length for each branch and then sizes the branches (not the critical circuit) based on the pressure drop of the new equivalent length per 100 feet.

Constant velocity method A pipe sizing methodology based on velocity only plus the pressure drop not to exceed the total allowable (used for short lengths and/or few connections).

Dead-end service A type of service in which the pressure-regulating valve is required to close bottle-tight when there is no demand on the system.

Effective pressure The lowest anticipated residual pressure at the connection to the city water main (or the stop valve at a well system) when water is flowing.

Elevation pressure The pressure change due to a change of elevation (0.433 psi per foot or 2.31 feet per psi for water).

Falloff The amount that the pressure-regulating valve pressure is decreased from set pressure to meet demand. The amount of falloff depends on the quantity of flow: the greater the flow, the greater the falloff. A falloff of 20 psi (1,37.9 kPa) is considered to be the maximum desirable.

Fixture supply The final piping connection from the water distribution system to the plumbing fixture.

Flow pressure The pressure required at the fixture or appliance.

Flow pressure drop The pressure drop through a device or fitting in a flowing system. Sometimes called dynamic pressure drop as compared to pipe friction pressure drop.

No-flow pressure The pressure maintained in the system when the pressure-regulating valve is shut tight so that high pressure at the inlet of the valve is not permitted to enter the system.

Reduced-flow pressure The pressure maintained at the pressure-regulating valve outlet when water is flowing. The no-flow (closed) setpoint pressure of a pressure-regulating valve is always higher than the reduced-flow (open) pressure. A pressure-regulating valve that is set to open at 45-psi (310.3-kPa) pressure (no flow) would deliver a reduced-flow pressure of 30 psi (206.8 kPa) at peak demand if a 15-psi (103.4-kPa) falloff had been selected.

Residual pressure The pressure measured at any point in the system when water is flowing.

Response The capability of a pressure-regulating valve to respond to changes in outlet pressure.

Sensitivity The ability of a pressure-regulating valve to sense a change in pressure. If the valve is too sensitive and quick to respond, the results are over-control and a hunting effect. Not enough sensitivity results in operation that is sluggish and has great variations in the outlet pressure.

Set pressure The pressure at the outlet of the pressure-regulating valve at which the valve will start to open.

Static pressure The pressure measured at any point in a system when no water is flowing.

Total pressure loss method A pipe sizing methodology in which every circuit uses up all of the available pressure from the meter to the end user. It is very difficult to calculate by hand. Some computer programs can do this, but the pipe sizes for the branches become very small and the velocity too high.

Uniform pressure loss method A pipe sizing methodology using the same pressure drop for all piping, including the hydraulically most remote point.

Vacuum breaker A check valve device that lets air into a piping system to prevent a vacuum.
Water service (water lateral) The water pipe from the city water main to the building.
Water distribution All piping in the building that carries water to the fixtures.

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CE Questions — "Cold Water Systems" (CEU 229)

1. A _______ water meter is used where low flows never occur.
   a. propeller
   b. disc
   c. turbine
   d. compound

2. What is the maximum discharge of a 3-inch drain flowing full at a pitch of ¼ inch per foot?
   a. 18 gpm
   b. 36 gpm
   c. 51 gpm
   d. 110 gpm

3. Which of the following is an advantage of an elevated water tank system?
   a. Maintenance requirement are minimized.
   b. Pressure fluctuation in the system is minimal.
   c. It is less complex than other systems.
   d. All of the above

4. Unless required by a specific operation or piece of equipment, the pressure in a water system should not exceed _______.
   a. 60 psi
   b. 70 psi
   c. 80 psi
   d. 90 psi

5. When two water hammer arrestors are used, the preferred location for the second is _______.
   a. at the end of the branch line
   b. midway along the branch line
   c. between the last two fixtures served
   d. none of the above

6. What is the surface roughness coefficient value of cast iron pipe commonly used for design purposes?
   a. 100
   b. 110
   c. 130
   d. 140

7. For turbulent flow, the friction factor can be found using the _______.
   a. Darcy-Weisbach formula
   b. Colebrook equation
   c. Hazen-Williams formula
   d. Joukowsky's formula

8. What is the absolute roughness of galvanized iron pipe?
   a. 0.0004 foot
   b. 0.00015 foot
   c. 0.0005 foot
   d. 0.00085 foot

9. Which of the following is a factor affecting the sizing of a water line?
   a. maximum demand flow rate
   b. maximum velocity desired
   c. pressure available for piping friction loss per 100 feet
   d. all of the above

10. What is the minimum size of a water supply pipe serving a flush tank urinal?
   a. 3/8 inch
   b. ½ inch
   c. ¾ inch
   d. 1 inch

11. What is the equivalent length of pipe of a 2-inch globe valve?
   a. 35 feet
   b. 45 feet
   c. 55 feet
   d. 65 feet

12. _______ is the pressure measured at any point in the system when water is flowing.
   a. set pressure
   b. residual pressure
   c. static pressure
   d. effective pressure