American Society of Plumbing Engineers

Plumbing Engineering Design Handbook

A Plumbing Engineer's Guide to System Design and Specifications

Volume 2

Plumbing Systems

American Society of Plumbing Engineers
2980 S. River Road
Des Plaines, IL 60018

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ISBN 978-1-891255-17-5
Printed in China

10 9 8 7 6 5 4 3 2 1

Plumbing Engineering Design Handbook

Volume 2

Plumbing Systems

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About ASPE

The American Society of Plumbing Engineers (ASPE) is the international organization for professionals skilled in the design and specification of plumbing systems. ASPE is dedicated to the advancement of the science of plumbing engineering, to the professional growth and advancement of its members, and to the health, welfare, and safety of the public.

The Society disseminates technical data and information, sponsors activities that facilitate interaction with fellow professionals, and, through research and education programs, expands the base of knowledge of the plumbing engineering industry. ASPE members are leaders in innovative plumbing design, effective materials and energy use, and the application of advanced techniques from around the world.

Worldwide Membership — ASPE was founded in 1964 and currently has 6,500 members. Spanning the globe, members are located in the United States, Canada, Asia, Mexico, South America, the South Pacific, Australia, and Europe. They represent an extensive network of experienced engineers, designers, contractors, educators, code officials, and manufacturers interested in furthering their careers, their profession, and the industry. ASPE is at the forefront of technology. In addition, ASPE represents members and promotes the profession among all segments of the construction industry.

ASPE Membership Communication — All members belong to ASPE worldwide and have the opportunity to belong and participate in one of the 61 state, provincial or local chapters throughout the U.S. and Canada. ASPE chapters provide the major communication links and the first line of services and programs for the individual member. Communications with the membership is enhanced through the Society's magazine, *Plumbing Systems and Design,* the newsletter *ASPE Report,* which is incorporated as part of the magazine, and the e-newsletter "ASPE Pipeline."

Technical Publications — The Society maintains a comprehensive publishing program, spearheaded by the profession's basic reference text, the ASPE *Plumbing Engineering Design Handbook*. The *Plumbing Engineering Design Handbook,* encompassing approximately 50 chapters in four volumes, provides comprehensive details of the accepted practices and design criteria used in the field of plumbing engineering. Recent additions to ASPE's published library of professional technical manuals and handbooks include the *Plumbineering Dictionary, Engineered Plumbing Design II,* and *The Hunter Papers*.

Convention and Technical Symposium — The Society hosts biennial Conventions in even-numbered years and Technical Symposia in odd-numbered years to allow professional plumbing engineers and designers to improve their skills, learn original concepts, and make important networking contacts to help them stay abreast of current trends and technologies. In conjunction with each Convention there is an Engineered Plumbing Exposition, the greatest, largest gathering of plumbing engineering and design products, equipment, and services. Everything from pipes to pumps to fixtures, from compressors to computers to consulting services is on display, giving engineers and specifiers the opportunity to view the newest and most innovative materials and equipment available to them.

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ASPE Research Foundation — The ASPE Research Foundation, established in 1976, is the only independent, impartial organization involved in plumbing engineering and design research. The science of plumbing engineering affects everything… from the quality of our drinking water to the conservation of our water resources to the building codes for plumbing systems. Our lives are impacted daily by the advances made in plumbing engineering technology through the Foundation's research and development.

American Society of Plumbing Engineers

Plumbing Engineering Design Handbook

(4 Volumes — 47 Chapters)

Volume 1 Fundamentals of Plumbing Engineering (Revised 2009)

Chapter 1 Formulas, Symbols, and Terminology
2 Standards for Plumbing Materials and Equipment
3 Specifications
4 Plumbing Cost Estimates
5 Job Preparation, Drawings, and Field Checklists
6 Plumbing for People with Disabilities
7 Energy and Resource Conservation in Plumbing Systems
8 Corrosion
9 Seismic Protection of Plumbing Systems
10 Acoustics in Plumbing
11 Basics of Value Engineering
12 Ensuring High-quality Plumbing Installations
13 Existing Building Job Preparation and Condition Survey

Volume 3 Special Plumbing Systems (Revision date: 2011)

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2 Plumbing Design for Healthcare Facilities
3 Treatment of Industrial Waste
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5 Reflecting Pools and Fountains
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Volume 4 Plumbing Components and Equipment (Revision date: 2012)

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12 Potable Water Coolers and Central Water Systems
13 Bioremediation Pretreatment Systems
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1 Sanitary Drainage Systems

The purpose of the sanitary drainage system is to remove effluent discharged from plumbing fixtures and other equipment to an approved point of disposal. A sanitary drainage system generally consists of horizontal branches, vertical stacks, a building drain inside the building, and a building sewer from the building wall to the point of disposal.

To economically design a sanitary drainage system, the designer should use the smallest pipes possible according to the applicable code that can rapidly carry away the soiled water from individual fixtures without clogging the pipes, leaving solids in the piping, generating excessive pneumatic pressures at points where the fixture drains connect to the stack (which might cause the reduction of trap water seals and force sewer gases back through inhabitable areas), and creating undue noise.

Since vents and venting systems are described in Chapter 3 of this volume, the following discussion centers only on the design of drain and waste systems.

CODES AND STANDARDS

Plumbing codes establish a minimum acceptable standard for the design and installation of systems, including sanitary drainage. There are various model codes, but some states and large cities have adopted their own plumbing codes, rather than the ones usually associated with the region. Because of this non-standardization, the actual plumbing code used for each specific project must be obtained from a responsible code official.

A variety of different codes are used to lay out and size interior sanitary drainage systems, and the information pertaining to sanitary design for a specific project appears in the approved local plumbing code, which must be the primary method used for the accepted methods and sizing. 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.

FLOW IN STACKS

A stack is the main vertical pipe that carries away discharge from water closets and urinals (soil stack) or other clear water waste from equipment and non-sanitary fixtures (waste stack). Flow in the drain empties into the vertical stack fitting, which may be a long-turn tee-wye or a short-turn or sanitary tee. Each of these fittings permits flow from the drain to enter the stack with a component directed vertically downward. Depending on the rate of flow out of the drain into the stack, the diameter of the stack, the type of stack fitting, and the flow down the stack from higher levels (if any), the discharge from the fixture drain may or may not fill the cross-section of the stack at the level of entry. In any event, as soon as the water enters the stack, the force of gravity rapidly accelerates it downward, and before it falls very far, it assumes the form of a sheet around the wall of the stack, leaving the center of the pipe open for the flow of air.

This sheet of water continues to accelerate until the frictional force exerted by the wall of the stack on the falling sheet of water equals the force of gravity. From that point on, if the distance the water falls is sufficient enough and provided that no flow enters the stack at lower levels to interfere with the sheet, the sheet remains unchanged in thickness and velocity until it reaches the bottom of the stack. The ultimate vertical velocity the sheet attains is called the "terminal velocity." The distance the sheet must fall to attain this terminal velocity is called the "terminal length."

Following are the formulae developed for calculating the terminal velocity and terminal length:

Equation 1-1a (terminal velocity)

$$V_T = 3.0(Q/d)^{2/5}$$

Equation 1-1b (terminal length)

$$L_T = 0.052V_T^2$$

where

V_T = Terminal velocity in the stack, feet per second (fps) (meters per second)
L_T = Terminal length below the point of flow entry, feet (meters)
Q = Quantity rate of flow, gallons per minute (gpm) (liters per second)
d = Diameter of stack, inches (millimeters)

Terminal velocity is approximately 10 to 15 fps (3.05 to 4.57 meters per second), and this velocity is attained within 10 to 15 feet (3.05 to 4.57 meters) of fall from the point of entry.

At the center of the stack is a core of air that is dragged along with the water by friction. A supply source of air must be provided to avoid excessive pressures in the stack. The usual means of supplying this air are through the stack vent or vent stack. The entrained air in the stack causes a pressure reduction inside the stack, which is caused by the frictional effect of the falling sheet of water dragging the core of air with it.

If the sheet of water falling down the stack passes a stack fitting through which the discharge from a fixture is entering the stack, the water from the branch mixes with or deflects the rapidly moving sheet of water. An excess pressure in the drain from which the water is entering the stack is required to deflect the sheet of water flowing downward or to mix the branch water with it. The result is a back-pressure created in the branch, which increases with the flow rate and flow velocity down the stack and with the flow rate out of the drain.

The importance of this knowledge is that it conclusively abolishes the myth that water falling from a great height will destroy the fittings at the base of a stack. The velocity at the base of a 100-story stack is only slightly and insignificantly greater than the velocity at the base of a three-story stack. The concern is the weight of the stack, which must be supported by clamps at each floor level.

Flow in Building Drains

When the sheet of water reaches the bend at the base of the stack, it turns at approximately right angles into the building drain. Flow enters the horizontal drain at a relatively high velocity compared to the flow velocity in a horizontal drain under uniform flow conditions. The slope of the building drain is not adequate to maintain the velocity that existed in the vertical sheet when it reached the base of the stack and must flow horizontally. The velocity of the water flowing along the building drain and sewer decreases slowly and then increases suddenly as the depth of flow increases and completely fills the cross-section of the drain. This phenomenon is called a "hydraulic jump."

The critical distance at which the hydraulic jump may occur varies from immediately at the stack fitting to 10 times the diameter of the stack downstream. Less hydraulic jump occurs if the horizontal drain is larger than the stack. After the hydraulic jump occurs and water fills the drain, the pipe tends to flow full until the friction resistance of the pipe retards the flow to that of uniform flow conditions.

Flow in Fixture Drains

Determination of the required drain size is a relatively simple matter, since the fixture drain must be adequate only to carry the discharge from the fixture to which it is attached. Because of the problem of self-siphonage, however, it is advisable to select a diameter large enough that the drain flows little more than half-full under the maximum discharge conditions likely to be imposed by the fixture.

For example, a lavatory drain capable of carrying the flow discharged from a lavatory may still flow full over part or all of its length. This occurs for several reasons. The vertical component of the flow out of the trap into the drain tends to make the water attach to the upper elements of the drain, and a slug of water is formed, filling the drain at that point. If insufficient air is aspirated through the overflow, the pipe will flow full for part of its length, with the average flow velocity being less than the normal velocity for the flow rate in the drain at a given slope.

In the past, with a fixture such as a toilet, the surge of water from the toilet continued almost without change even along a very long drain until it reached the stack. This still is generally true, but the use of low-flow and dual-flush toilets requires the design of the horizontal piping to be reconsidered. It cannot be assumed, for all practical purposes, that the surge caused by the discharge of a toilet through a fixture drain reaches the stack or horizontal branch with practically the same velocity it had when it left the fixture.

PNEUMATIC PRESSURES IN A SANITARY DRAINAGE SYSTEM

Due to the pressure conditions in a stack and a building drain, wastewater does not fill the cross-section anywhere, so the air can flow freely with the water. The water flowing down the wall of the stack drags air with it by friction and carries the air through the building drain to the street sewer. The air is then vented through the main street sewer system so dangerous pressures do not build up. The generally accepted pressure is ±1 inch of water column.

When air enters the top of the stack to replace the air being carried with the water, the pressure inside the stack decreases. However, because of the head loss necessary to accelerate the air and to provide for the energy loss at the entrance, this pressure reduction is negligible, amounting to only a small fraction of an inch of water. Appreciable pressure reductions are caused by the partial or complete blocking of the

stack by water flowing into the stack from a horizontal branch.

A small increase in pneumatic pressure will occur in the building drain even if the airflow is not completely blocked by a hydraulic jump or by submergence of the outlet and the building sewer. This is due to the decrease in cross-sectional area available for airflow when the water flowing in the drain has adapted to the slope and diameter of the drain.

FIXTURE DISCHARGE CHARACTERISTICS

The discharge characteristic curves—flow rates as a function of time—for most toilet bowls have the same general shape, but some show a much lower peak and a longer period of discharge. The discharge characteristics for various types of bowls, particularly for low-flow toilets, have a significant impact on estimating the capacity of a sanitary drainage system. Other plumbing fixtures, such as sinks, lavatories, and bathtubs, may produce similar surging flows in drainage systems, but they do not have the same effect as water closets.

Drainage Loads

Single-family dwellings contain certain plumbing fixtures, such as one or more bathroom groups, each consisting of a toilet, lavatory, and bathtub or shower stall, a kitchen sink, dishwasher, and washing machine. Large buildings also have other fixtures, such as slop sinks and drinking water coolers. The important characteristic of these fixtures is that they are not used continuously. Rather, they are used with irregular frequencies that vary greatly during the day. In addition, the various fixtures have quite different discharge characteristics regarding both the average flow rate per use and the duration of a single discharge. Consequently, the probability of all the fixtures in the building operating simultaneously is small.

Assigning drainage fixture unit (dfu) values to fixtures to represent their load-producing effect on the plumbing system originally was proposed in 1923 by Dr. Roy B. Hunter. The fixture unit values were designed for application in conjunction with the probability of simultaneous use of fixtures to establish the maximum permissible drainage loads expressed in fixture units rather than in gpm of drainage flow. Table 1-1 gives the recommended fixture unit values. The plumbing engineer must conform to local code requirements.

Dr. Hunter conceived the idea of assigning a fixture unit value to represent the degree to which a fixture loads a system when used at its maximum assumed flow and frequency. The purpose of the fixture unit concept is to make it possible to calculate the design load of the system directly when the system is a combination of different kinds of fixtures, with each having a unique loading characteristic. Current or recently conducted studies of drainage loads on drainage systems may change these values. These include studies of reduced flow from water-saving fixtures, models of stack, branch, and house drain flows, and actual fixture use.

Table 1-1 Residential Drainage Fixture Unit (dfu) Loads

Fixture	IPC	UPC
Bathtub	2	3
Clothes washer	3	3
Dishwasher	2	2
Floor drain	3	–
1¼-inch trap loading	–	1
1½-inch trap loading	–	3
2-inch trap loading	–	4
3-inch trap loading	–	6
4-inch trap loading	–	8
Laundry tray	2	2
Lavatory, single	1	1
Lavatory, in sets of two or three	2	2
Shower (each head)	2	2
Kitchen sink (including dishwasher and garbage disposal)	3	3
Toilet (1.6-gpf gravity tank)	4	4
Toilet (1.6-gpf flushometer tank)	5	5
Toilet (1.6-gpf flushometer valve)	4	4

Stack Capacities

The criterion of flow capacities in drainage stacks is based on the limitation of the water-occupied cross-section to a specified fraction (r_s) of the cross-section of the stack where terminal velocity exists, as suggested by earlier investigations.

Flow capacity can be expressed in terms of the stack diameter and the water cross-section.

Equation 1-2

$$Q = 27.8 \times r_s^{5/3} \times D^{8/3}$$

where

Q = Capacity, gpm (liters per second)

r_s = Ratio of the cross-sectional area of the sheet of water to the cross-sectional area of the stack

D = Diameter of the stack, inches (millimeters)

Values of flow rates based on r = ¼, 7/24, and are tabulated in Table 1-2.

Whether or not Equation 1-2 can be used safely to predict stack capacities remains to be confirmed and accepted. However, it provides a definite law of variation of stack capacity with diameter. If this law can be shown to hold for the lower part of the range of stack diameters, it should be valid for the larger diameters. It should be remembered that both F.M. Dawson and Dr. Hunter, in entirely independent investigations, came to the conclusion that slugs of water, with their accompanying violent pressure fluctuations, did not occur until the stack flowed one-quarter to one-third

Table 1-2 Capacities of Stacks

Pipe Size, in. (mm)	Flow, gpm (L/s)					
	r = ¼		r = 7/24		r = ⅓	
2 (50)	17.5	(1.1)	23.0	(1.45)	28	(1.77)
3 (80)	52	(3.28)	70	(4.41)	85	(5.36)
4 (100)	112	(7.07)	145	(9.14)	180	(11.35)
5 (125)	205	(12.93)	261	(16.5)	324	(20.44)
6 (150)	330	(20.82)	424	(26.8)	530	(33.43)
8 (200)	710	(44.8)	913	(57.6)	1,140	(72)
10 (250)	1,300	(82.0)	1,655	(104.4)	2,068	(130.5)
12 (300)	2,082	(131.4)	2,692	(170)	3,365	(212.3)

Table 1-3 Maximum Permissible Fixture Unit Loads for Sanitary Stacks

Diameter of Pipe, in. (mm)	Maximum dfu that May Be Connected			
	Any horizontal fixture branch[a]	One stack of three or fewer branch intervals	Stacks with more than three branch intervals	
			Total for stack	Total at one branch interval
1½ (40)	3	4	8	2
2 (50)	6	10	24	6
2½ (65)	12	20	42	9
3 (80)	20[b]	48[b]	72[b]	20[b]
4 (100)	160	240	500	90
5 (125)	360	540	1,100	200
6 (150)	620	960	1,900	350
8 (200)	1,400	2,200	3,600	600
10 (250)	2,500	3,800	5,600	1,000
12 (300)	3,900	6,000	8,400	1,500
15 (380)	7,000	–	–	–

a Does not include branches of the building drain.

b No more than two water closets or bathroom groups within eachbranch interval or more than six water closets or bathroom groups on the stack.

full. Most model codes have based their stack loading tables on a value of r = ¼ or 7/24.

The recommended maximum permissible flow in a stack is 7/24 of the total cross-sectional area of the stack. By substituting r = 7/24 into Equation 1-2, the corresponding maximum permissible flow for the various sizes of pipe in gpm can be determined. Table 1-3 lists the maximum permissible fixture units (fu) to be conveyed by stacks of various sizes. The table was created by taking into account the probability of simultaneous use of fixtures. For example, if 500 fixture units is the maximum loading for a 4-inch (100-millimeter) stack, then 147 gpm (9.3 liters per second) is equivalent to 500 fixture units. This is the total load from all branches.

It should be noted that there is a restriction on the amount of flow permitted to enter a stack from any branch when the stack is more than three branch intervals. If an attempt is made to introduce an overly large flow into the stack at any one level, the inflow will fill the stack at that level and will back up the water above the elevation of inflow, which will cause violent pressure fluctuations in the stack—resulting in the siphoning of trap seals—and also may cause sluggish flow in the horizontal branch. This problem was solved in a study of stack capacities made by Wyly and Eaton at the National Bureau of Standards for the Housing and Home Finance Agency in 1950.

The water flowing out of the branch can enter the stack only by mixing with the stream flowing down the stack or by deflecting it. Such a deflection of the high-velocity stream coming down the stack can be accomplished only if there is a significant hydrostatic pressure in the branch, since a force of some kind is required to deflect the downward flowing stream and change its momentum. This hydrostatic pressure is created by the water backing up in the branch until the head changes the momentum of the stream already in the stack to allow the flow from the branch to enter the stack.

The maximum hydrostatic pressure that should be permitted in the branch as a result of the backing up of the spent water is based on this consideration: The backup should not be of a magnitude that would cause the water to back up into a shower stall or cause sluggish flow. It is half of the diameter of the horizontal branch at its connection to the stack. That is, it is the head measured at the axis of the pipe that will cause the branch to flow full near the exit.

When a long-turn tee-wye is used to connect the branch to the stack, the water has a greater vertical velocity when it enters the stack than it does when a sanitary tee is used. The back-pressures should be smaller in this case for the same flows down the stack and in the branch.

Table 1-3 shows the maximum permissible fixture unit loads for sanitary stacks. The procedure for sizing a multistory stack (greater than three floors) is to first size the horizontal branches connected to the stack. This is done by totaling the fixture units connected to each branch and using the corresponding figure in column 2 of Table 1-3. Next, total all the fixture units connected to the stack and determine the size from the same table, under column 4. Immediately check the next column, "Total at One Branch Interval," and determine if this maximum is exceeded by any of the branches. If it is exceeded, the stack as originally determined must be increased at least one size, or the loading of the branches must be redesigned so the maximum conditions are satisfied.

For example, consider a 4-inch (100-millimeter) stack more than three stories high. The maximum loading for a 4-inch (100-millimeter) branch is 160 fixture units, as shown in column 2 of Table 1-3. This load is limited by column 5 of the same table, which permits only 90 fixture units to be introduced into a 4-inch (100-millimeter) stack in any one-branch interval. The stack would have to be increased in size to accommodate any branch load exceeding 90 fixture units.

To illustrate the requirements of a stack with an offset of more than 45 degrees from the vertical, Figure 1-1 shows the sizing of a stack in a 12-story building, with one offset between the fifth and sixth floors and another offset below the street floor.

Sizing is computed as follows:

1. Compute the fixture units connected to the stack. In this case, assume 1,200 fixture units are connected to the stack from the street floor through the top floor.
2. Size the portion of the stack above the fifth-floor offset. There are 400 fixture units from the top floor down through the sixth floor. According to Table 1-3, column 4, 400 fixture units require a 4-inch (100-millimeter) stack.
3. Size the offset on the fifth floor. An offset is sized and sloped like a building drain.
4. Size the lower portion of the stack from the fifth floor down through the street floor. The lower portion of the stack must be large enough to serve all of the fixture units connected to it, from the top floor down (in this case, 1,200 fixture units). According to Table 1-3, 1,200 fixture units require a 6-inch (150-millimeter) stack.
5. Size and slope the offset below the street floor the same as a building drain.

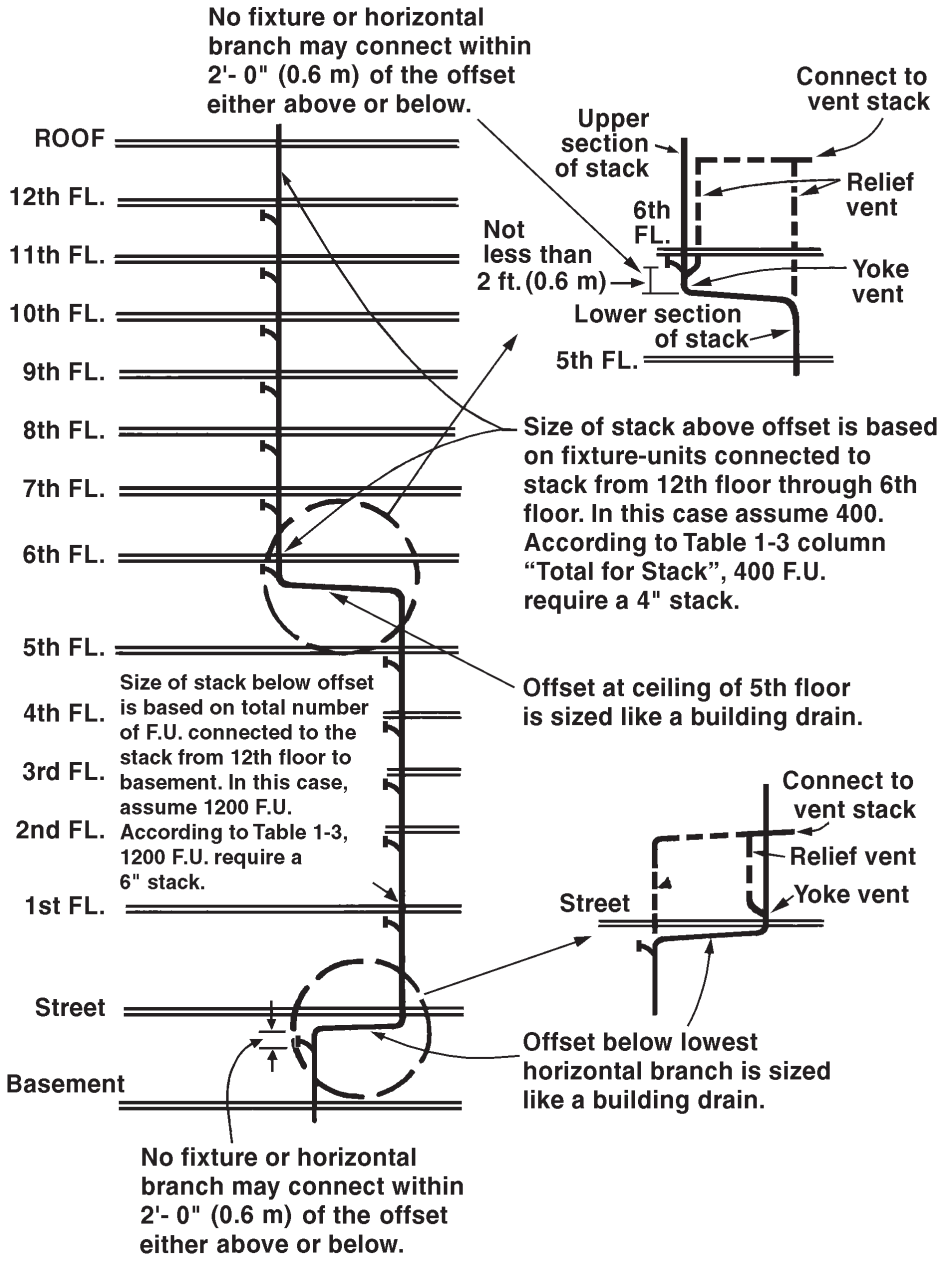


Figure 1-1 Procedure for Sizing an Offset Stack

The fixture on the sixth floor should be connected to the stack at least 2 feet (0.6 meter) above the offset. If this is not possible, then connect them separately to the stack at least 2 feet (0.6 meter) below the offset. If this is not possible either, run the fixture drain down to the fifth or fourth floor and connect to the stack at that point.

CAPACITIES OF SLOPING DRAINS

The characteristics of sewage are the same as plain water. The capacities of horizontal or sloping drains are complicated by surging flow.

Determining drain size is based on highly fluctuating or surging flow conditions in the horizontal branches carrying the discharge of fixtures to the soil or waste stack. After falling down the vertical stack, the water is assumed to enter the building drain with surge peaks leveled off somewhat, but still in a surging condition.

A large building covering considerable ground area probably has several primary branches and certainly at least one secondary branch. After the water enters the building drain, the surge continues to level off, becoming more and more nearly uniform, particularly after the hydraulic jump has occurred. If the secondary branch is long enough and if the drain serves a large number of fixtures, the flow may become substantially uniform before it reaches the street sewer.

Steady, Uniform Flow Conditions in Sloping Drains

Although the equations of steady, uniform flow in sloping drains should not be used to determine the capacities of sloping drains in which surging flow exists, flow computations based on these formulas afford a rough check on values obtained by the more complicated methods that are applicable to surging flow. Hence, three of the commonly used formulas for flow in pipes will be considered: Hazen and Williams, Darcy-Weisbach, and Manning.

Hazen-Williams Formula

This formula usually is written as follows:

Equation 1-3

$$V = 1.318 \times C \times R^{0.63} \times S^{0.54}$$

where
V = Mean velocity of flow, fps (meters per second)
C = Hazen and Williams coefficient
R = Hydraulic radius of pipe, feet (meters)
S = Slope of pressure gradient

The exponents of R and S in Equation 1-3 have been selected to make the coefficient C as nearly constant as possible for different pipe diameters and for different velocities of flow. Thus, C is approximately constant for a given pipe roughness.

Darcy-Weisbach Formula

In this formula, the dimensionless friction coefficient f varies with the diameter of the pipe, the velocity of flow, the kinematic viscosity of the fluid flowing, and the roughness of the walls. It usually is written as follows:

Equation 1-4

$$h_f = \frac{FLV^2}{D2g}$$

where
h_f = Pressure drop or friction loss, feet (meters)
f = Friction coefficient
L = Length of pipe, feet (meters)
D = Diameter of pipe, feet (meters)
V = Mean velocity of flow, fps (meters per second)
g = Acceleration of gravity, 32.2 fps^2 (9.8 m/s^2)

Manning Formula

The Manning formula, which is similar to the Hazen and Williams formula, is meant for open-channel flow and usually is written as follows:

Equation 1-5

$$V = \frac{1.486}{n} \times R^{2/3} \times S^{1/2} = \frac{1.486}{n} \times R^{0.67} \times S^{0.50}$$

In this formula, n is the Manning coefficient, which varies with the roughness of the pipe and the pipe diameter.

The flow quantity is equal to the cross-sectional area of the flow times the flow velocity obtained from the above three equations. This can be expressed as:

Equation 1-5a

$$Q = AV$$

where
Q = Quantity rate of flow, cubic feet per second (cfs) (cubic meters per second)
A = Cross-sectional area of flow, square feet (square meters)
V = Velocity of flow, fps (meters per second)

By substituting the value of V from Manning's formula, the quantity of flow in variously sized drains of the same material can be calculated as:

Equation 1-5b

$$Q = A \times \frac{1.486}{n} \times R \times S^{1/2}$$

This is the formula used by many plumbing engineers to deal with sloping drain problems. The

Table 1-4 Values of R, $R^{2/3}$, A_F, and A_H

Pipe Size, in. (mm)	R = ¼, ft (mm)	$R^{2/3}$, ft (mm)	A_F (Cross-sectional Area for Full Flow), ft^2 (m^2)	A_H (Cross-sectional Area for Half-full Flow), ft^2 (m^2)
1½ (40)	0.0335 (1.02)	0.1040 (3.17)	0.01412 (0.0013)	0.00706 (0.00065)
2 (50)	0.0417 (1.27)	0.1200 (3.66)	0.02180 (0.0020)	0.01090 (0.0009)
2½ (65)	0.0521 (1.59)	0.1396 (4.24)	0.03408 (0.0031)	0.01704 (0.0015)
3 (80)	0.0625 (1.90)	0.1570 (4.78)	0.04910 (0.0046)	0.02455 (0.0023)
4 (100)	0.0833 (2.54)	0.1910 (5.82)	0.08730 (0.0081)	0.04365 (0.0040)
5 (125)	0.1040 (3.17)	0.2210 (6.74)	0.13640 (0.0127)	0.06820 (0.0063)
6 (150)	0.1250 (3.81)	0.2500 (7.62)	0.19640 (0.0182)	0.09820 (0.0091)
8 (200)	0.1670 (5.09)	0.3030 (9.23)	0.34920 (0.0324)	0.17460 (0.0162)
10 (250)	0.2080 (6.33)	0.3510 (10.70)	0.54540 (0.0506)	0.27270 (0.0253)
12 (300)	0.2500 (7.62)	0.3970 (12.10)	0.78540 (0.0730)	0.39270 (0.0364)
15 (380)	0.3125 (9.53)	0.4610 (14.05)	1.22700 (0.0379)	0.61350 (0.0570)

Table 1-5 Approximate Discharge Rates and Velocities in Sloping Drains, n = 0.015[a]

Actual Inside Diameter of Pipe, in. (mm)	Actual Inside Half-full Flow Discharge Rate and Velocity							
	1/16 in./ft (1.6 mm/m) Slope		1/8 in./ft (3.2 mm/m) Slope		1/4 in./ft (6.4 mm/m) Slope		1/2 in./ft (12.7 mm/m) Slope	
	Discharge, gpm (L/s)	Velocity, fps (mm/s)	Discharge, gpm (L/s)	Velocity, fps (mm/s)	Discharge, gpm (L/s)	Velocity, fps (mm/s)	Discharge, gpm (L/s)	Velocity, fps (mm/s)
1¼ (31.8)							3.40 (0.21)	1.78 (45.5)
1⅜ (34.9)					3.13 (0.20)	1.34 (0.41)	4.44 (0.28)	1.90 (48.3)
1½ (38.9)					3.91 (0.247)	1.42 (0.43)	5.53 (0.35)	2.01 (51.1)
1⅝ (41.28)					4.81 (0.30)	1.50 (0.46)	6.80 (0.38)	2.12 (53.9)
2 (50.8)					8.42 (0.53)	1.72 (0.52)	11.9 (0.75)	2.43 (61.8)
2½ (63.5)			10.8 (0.68)	1.41 (0.43)	15.3 (0.97)	1.99 (0.61)	21.6 (1.36)	2.82 (71.7)
3 (76.3)			17.6 (1.11)	1.59 (0.49)	24.8 (1.56)	2.25 (0.69)	35.1 (2.21)	3.19 (81.1)
4 (101.6)	26.70 (1.68)	1.36 (34.6)	37.8 (2.38)	1.93 (0.59)	53.4 (3.37)	2.73 (0.83)	75.5 (4.76)	3.86 (98.2)
5 (127)	48.3 (3.05)	1.58 (40.2)	68.3 (4.30)	2.23 (0.68)	96.6 (6.10)	3.16 (0.96)	137 (8.64)	4.47 (113.7)
6 (152.4)	78.5 (4.83)	1.78 (45.3)	111 (7.00)	2.52 (0.77)	157 (10)	3.57 (1.09)	222 (14.0)	5.04 (128.2)
8 (203.2)	170 (10.73)	2.17 (55.2)	240 (15.14)	3.07 (0.94)	340 (21.5)	4.34 (1.32)	480 (30.3)	6.13 (155.9)
10 (256)	308 (19.43)	2.52 (64.1)	436 (27.50)	3.56 (1.09)	616 (38.9)	5.04 (1.54)	872 (55.0)	7.12 (181.0)
12 (304.8)	500 (31.55)	2.83 (72.0)	707 (44.60)	4.01 (1.22)	999 (63.0)	5.67 (1.73)	1,413 (89.15)	8.02 (204.0)

[a] n = Manning coefficient, which varies with the roughness of the pipe.

For full flow: Multiply discharge by 2.

For full flow: Multiply velocity by 1.

For smoother pipe: Multiply discharge and velocity by 0.015 and divide by n of another pipe.

Table 1-6 Slopes of Cast Iron Soil Pipe Sanitary Sewer Required to Obtain Self-cleansing Velocities of 2.0 and 2.5 ft/sec. (based on Manning formula with n = 0.012)

Pipe Size (in.)	Velocity (ft/sec.)	1/4 Full		1/2 Full		3/4 Full		Full	
		Slope (ft/ft)	Flow (gpm)	Slope (ft/ft)	Flow (gpm)	Slope (ft/ft)	Flow (gpm)	Slope (ft/ft)	Flow (gpm)
2.0	2.0	0.0313	4.67	0.0186	9.34	0.0148	14.09	0.0186	18.76
	2.5	0.0489	5.04	0.0291	11.67	0.0231	17.62	0.0291	23.45
3.0	2.0	0.0178	10.71	0.0107	21.46	0.0085	32.23	0,0107	42.91
	2.5	0.0278	13.47	0.0167	26.62	0.0133	40.29	0.0167	53.64
4.0	2.0	0.0122	19.03	0.0073	38.06	0.0058	57.01	0.0073	76.04
	2.5	0.0191	23.79	0.0114	47.58	0.0091	71.26	0.0114	95.05
5.0	2.0	0.0090	29.89	0.0054	59.79	0.0043	89.59	0.0054	119.49
	2.5	0.0141	37.37	0.0085	74.74	0.0067	111.99	0.0085	149.36
6.0	2.0	0.0071	43.18	0.0042	86.36	0.0034	129.54	0.0042	172.72
	2.5	0.0111	53.98	0.0066	101.95	0.0053	161.93	0.0066	215.90
8.0	2.0	0.0048	77.20	0.0029	154.32	0.0023	231.52	0.0029	308.64
	2.5	0.0075	96.50	0.0045	192.90	0.0036	289.40	0.0045	385.79
10.0	2.0	0.0036	120.92	0.0021	241.85	0.0017	362.77	0.0021	483.69
	2.5	0.0056	151.15	0.0033	302.31	0.0026	453.46	0.0033	604.61
12.0	2.0	0.0028	174.52	0.0017	349.03	0.0013	523.55	0.0017	678.07
	2.5	0.0044	218.15	0.0026	436.29	0.0021	654.44	0.0026	612.58
15.0	2.0	0.0021	275.42	0.0012	550.84	0.0010	826.26	0.0012	1101.68
	2.5	0.0032	344.28	0.0019	688.55	0.0015	1032.83	0.0019	1377.10

significant hydraulic parameters used in the above equation are listed in Table 1-4.

Slope of Horizontal Drainage Piping

Horizontal drains are designated to flow at half-full capacity under uniform flow conditions to minimize the generation of pneumatic pressure fluctuations. The minimum slopes are as follows:

- Pipe 3 inches (80 millimeters) and smaller: ¼ inch per foot (6.4 millimeters per meter)
- 4- to 6-inch (100- to 150-millimeter) pipe: ⅔ inch per foot (3.2 millimeters per meter)
- Pipe 8 inches (200 millimeters) and larger: 1/16 inch per foot (1.6 millimeters per meter)

These slopes are not a hard and fast rule and might be less under unusual conditions. The designer must confirm the required slopes with the local code

Table 1-7 Building Drains and Sewers[a]

Diameter of Pipe, in. (mm)	Maximum Permissible Fixture Units for Sanitary Building Drains and Runouts from Stacks			
	Slope, in./ft (mm/m)			
	1/16 (1.6)	1/8 (3.2)	1/4 (6.4)	1/2 (12.7)
2 (50)			21	26
2½ (65)			24	31
3 (80)		20	42[b]	50[b]
4 (100)		180	216	250
5 (125)		390	480	575
6 (150)		700	840	1,000
8 (200)	1400	1600	1,920	2,300
10 (250)	2500	2900	3,500	4,200
12 (300)	2900	4600	5,600	6,700
15 (380)	7000	8300	10,000	12,000

[a] On-site sewers that serve more than one building may be sized according to the current standards and specifications of the administrative authority for public sewers.

[b] No more than two water closets or two bathroom groups, except in single-family dwellings, where no more than three water closets or three bathroom groups may be installed. Check the local codes in the area served for exact requirements or restrictions.

authority. These minimum slopes are required to maintain a velocity of flow greater than 2 fps for scouring action. Table 1-5 gives the approximate velocities for given flow, slopes, and diameters of horizontal drains based on the Manning formula for half-full pipe and n = 0.015.

A flow velocity of 2 fps will prevent the solids within a pipe from settling out and forming a system stoppage. Table 1-6 has been prepared to give the size of a pipe in conjunction with the flow rate to maintain a self-cleansing velocity of 2 fps.

Loads for Drainage Piping

The recommended loads for building drains and sewers are tabulated in Table 1-7. This table shows the maximum number of fixture units that may be connected to any portion of the building drain or building sewer for given slopes and diameters of pipes. For example, an offset below the lowest branch with 1,300 fu at a slope of ¼ inch per foot (6.4 millimeters per meter) requires an 8-inch (200-millimeter) pipe.

For devices that provide continuous or semi-continuous flow into the drainage system, such as sump pumps, ejectors, and air-conditioning equipment, a value of 2 fixture units can be assigned for each gpm (liter per second) of flow. For example, a sump pump with a discharge rate of 200 gpm (12.6 liters per second) is equivalent to 200 x 2 = 400 fixture units.

COMPONENTS OF SANITARY DRAINAGE SYSTEMS

Sumps and Ejectors

The distinction between sump and ejector pumps is more terminology than actual fact. A sump pump is designed to transport clear, non-sanitary wastewater with some turbidity and suspended solids no larger than sand grains. An ejector pump is designed to transport sanitary waste and larger solids suspended in the effluent. All effluent is a liquid with solids suspended in it, but it has the same hydraulic characteristics as water.

Building drains that cannot flow directly into a sewer by gravity must be discharged into a covered basin. From there, the fluid is lifted into the building's gravity drainage system by automatic pump equipment or by any equally efficient method approved by the administrative authority.

An ejector basin must be of airtight construction and must be vented. It is airtight to prevent the escape of foul odors generated by sanitary waste from the sub-drainage system. Since it is airtight, a vent is required to relieve the air in the basin as wastes discharge into it and also to supply air to the basin while the contents are being discharged to the sanitary gravity drainage system. A duplex pump system shall be used. If one pump breaks down, the control system will alert the second pump to start. Thus, the system will remain in operation, and no damage will be caused by the cessation of system operation. When a duplex unit is used, each pump should be sized for 100 percent flow, and it is good practice to automatically alternate the operation of the pumps.

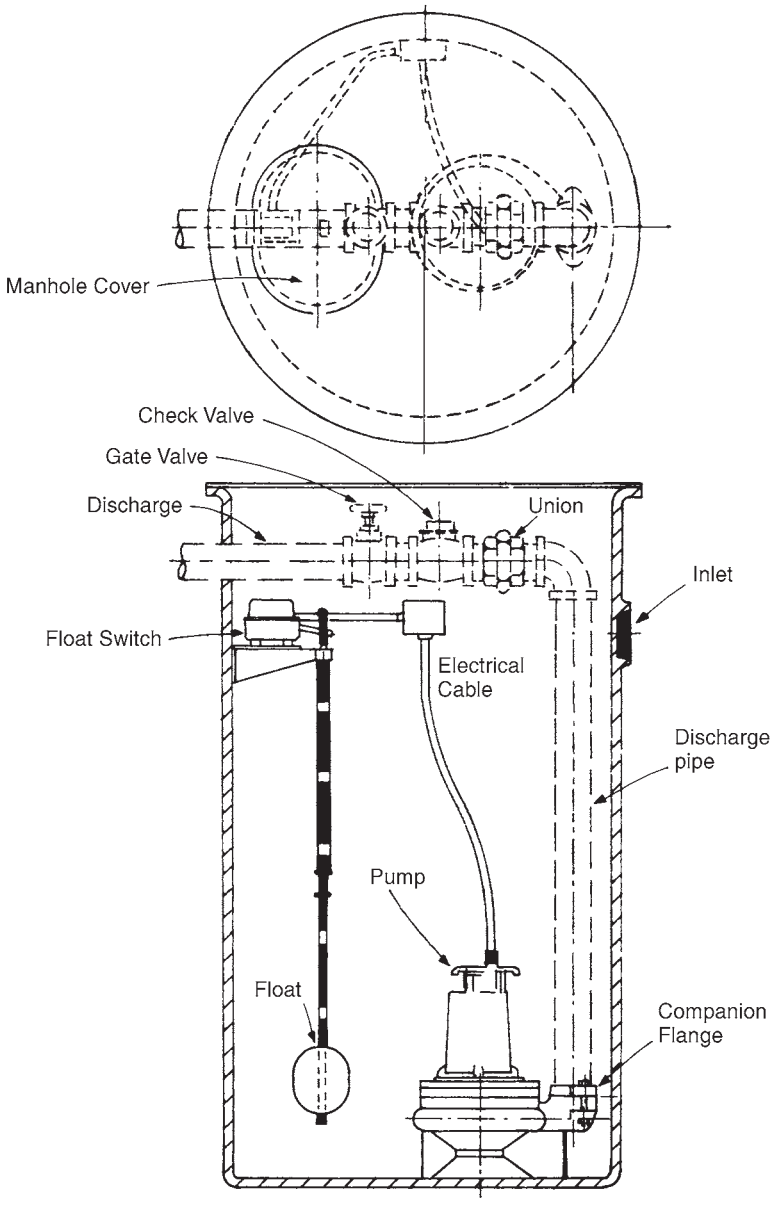


Figure 1-2 Typical Ejector Pump Installation

A sump basin need not be airtight or vented because of the lack of objectionable odors. Incoming water is collected in the sump before it is pumped to the gravity drain pipe. Heavy-flow drains require large sumps to retain greater-than-usual amounts of water, thereby creating more head pressure on the pipe inlet. It is good practice to install the sump basin's rim a minimum of 1 inch above the finished floor in case the sanitary building drain backs up. This will prevent sewerage infiltration into the clear water system. Most manufacturers make their basins with bottom, side, or angle inlets and with inside caulk, no-hub, push-on, spigot, or screwed connections. Outlet connections are made to accept pressure-type pipe joints. No-hub pipe and fittings are not acceptable on pumped discharge piping due to the pressure limitations of the pipe joints.

Sump and ejector systems normally use a wet pit, with the pumps either above the slab or submerged. They are controlled with a float switch or electronically with control switches mounted inside the basin. A typical ejector pump installation is illustrated in Figure 1-2. A typical submerged sump pump installation is illustrated in Figure 1-3.

Cleanouts

A cleanout provides access to horizontal and vertical lines to facilitate inspection and provide a means of removing obstructions such as solid objects, greasy wastes, and hair. Cleanouts, in general, must be gas- and water-tight, provide quick and easy plug removal, allow ample space for the operation of cleaning tools, have a means of adjustment to finished surfaces, be attractive in appearance, and be designed to support whatever traffic is directed over them.

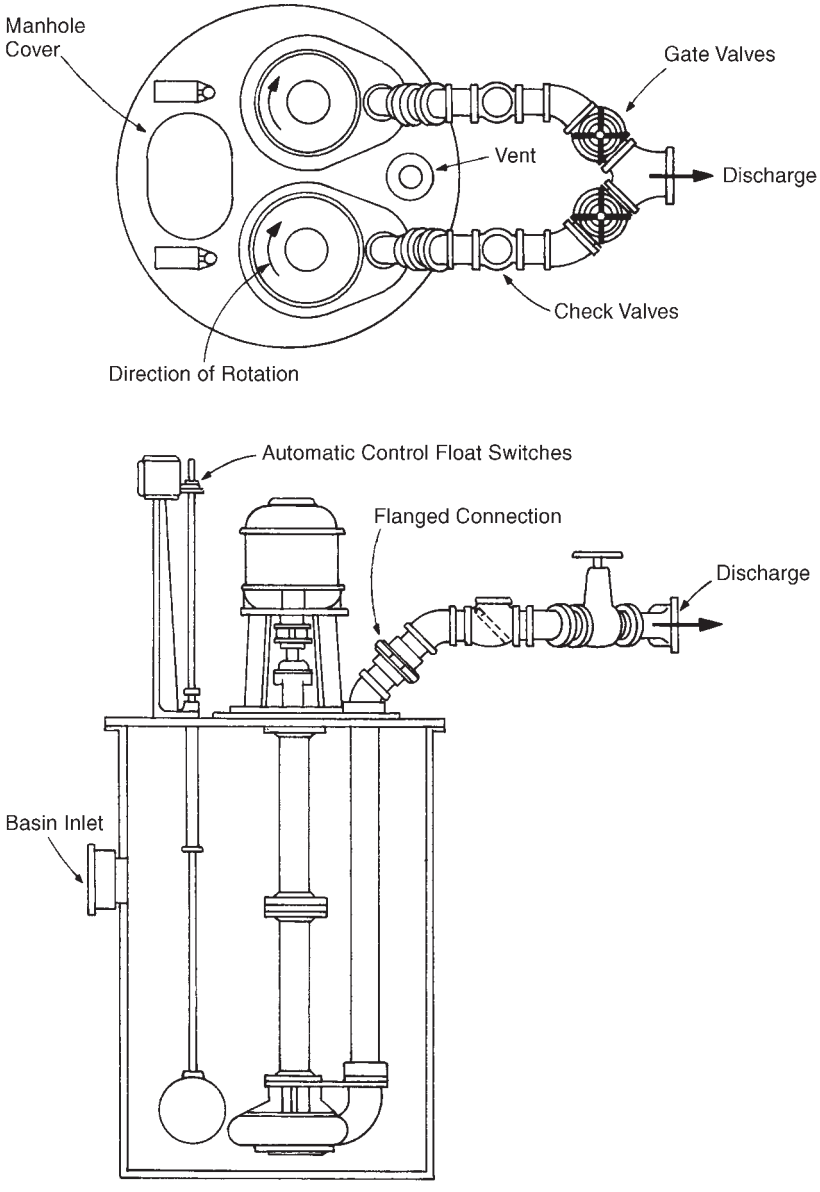


Figure 1-3 Typical Submerged Sump Pump Installation

Some cleanouts are designed with a neoprene seal plug, which prevents it from "freezing," or binding, to the ferrule. All plugs are machined with a straight or running thread and a flared shoulder for the neoprene gasket, permitting quick and certain removal when necessary. A maximum opening is provided for tool access. Recessed covers are available to accommodate carpet, tile, terrazzo, and other surface finishes and are adjustable to the exact floor level established by the adjustable housing or by the set screws.

Waste lines typically are laid beneath the floor slabs at a distance sufficient to provide adequate backfill over the joints. Cleanouts then are brought up to floor level by pipe extension pieces. Where the sewer line is at some distance below grade and not easily accessible through extensions, small pits or manholes with access covers must be installed. When cleanouts are installed in traffic areas, the traffic load must be considered when the construction materials are selected.

The size of the cleanout within a building should be the same size as the piping, up to 4 inches (100 millimeters). For larger size interior piping, 4-inch (100-millimeter) cleanouts are adequate for their intended purpose; however, 6-inch (150-millimeter) cleanouts are recommended to allow for a

larger variety of access needs such as for sewer video equipment.

Cleanouts should be provided at the following locations:

- Five feet (1.5 meters) outside or inside the building at the point of exit
- At every change of direction greater than 45 degrees
- At every change of direction and every 150 feet (45.7 meters)for underground sanitary sewer piping larger than 10 inches (250 millimeters) in diameter
- At the base of all stacks—it is good practice to install cleanouts a minimum of 6 inches above the flood rim of the highest fixture served on the lowest level
- To comply with applicable codes
- Optional locations include:
- At the roof stack terminal
- At the end of horizontal fixture branches or waste lines
- At fixture traps, which can be pre-manufactured with cleanout plugs, although some codes prohibit the installation of this kind of trap
- A maximum distance between cleanouts of 50 feet (15.1 meters) should be maintained for piping 4 inches (100 millimeters) and smaller and of 75 feet (22.9 meters) for larger piping. Greasy waste piping shall have a maximum distance of 40 feet (12.2 meters) between cleanouts.

Floor Drains and Floor Sinks

A large-diameter drain with a deep sump connected to a large-diameter pipe passes more water faster than a smaller drain. However, economics do not allow the designer to arbitrarily select the largest available drain when a smaller, less-expensive unit will do a satisfactory job. High-capacity drains are intended for use primarily in locations where the flow reaches high rates, such as malls, wash-down areas, and certain industrial applications. Table 1-8, which shows the minimum ratio of open grate area based on pipe diameter, is offered as a guide for the selection of drains where the drain pipe diameter is known.

The only drawback to using the open-area, pipe-diameter ratio method is that all drain manufacturers do not list the total open areas of grates in their catalogs. However, this information usually can be obtained upon request.

When sizing floor drains for most indoor applications, the capacity of a drain is not extremely critical because the drain's primary function is to handle

Table 1-8 Recommended Grate Open Areas for Various Floor Drains with Outlet Pipe Sizes

Nominal Pipe Size, in. (mm)	Recommended Minimum Grate Open Area for Floor Drains	
	Transverse Area of Pipe, in.[2a] (× 10 mm²)	Minimum Inside Area, in.² (× 10 mm²)
1½ (40)	2.04 (1.3)	2.04 (1.3)
2 (50)	3.14 (2.0)	3.14 (2.0)
3 (80)	7.06 (4.6)	7.06 (4.6)
4 (100)	12.60 (8.1)	12.06 (8.1)
5 (125)	19.60 (12.7)	19.60 (12.7)
6 (150)	28.30 (18.3)	28.30 (18.3)
8 (200)	50.25 (32.4)	50.24 (32.4)

[a] Based on extra-heavy soil pipe, nominal internal diameter.

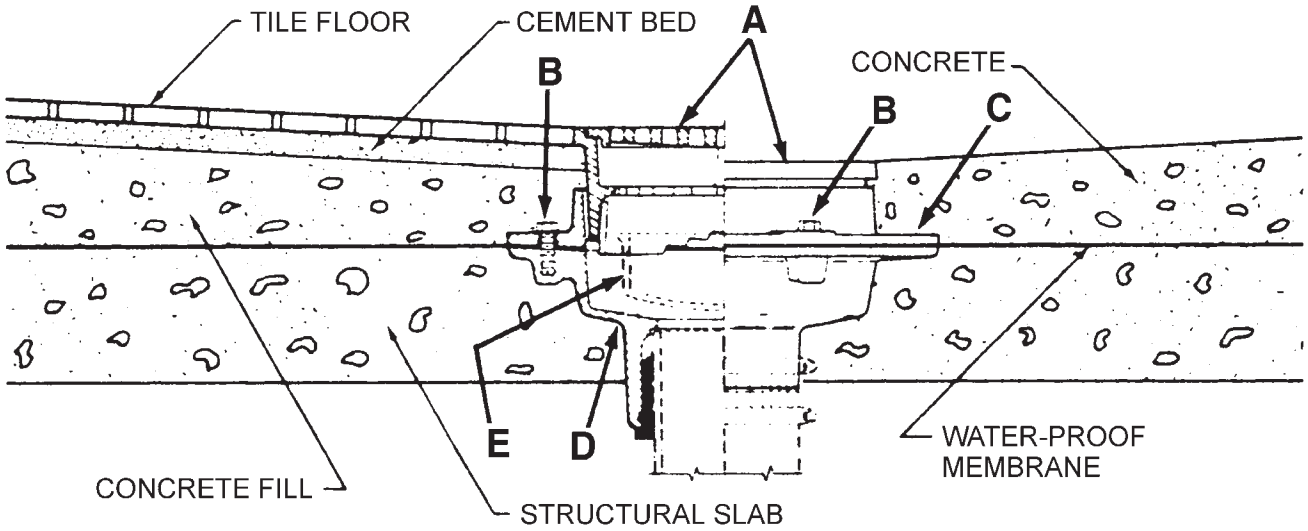


Figure 1-4 Basic Floor-Drain Components: (A) Removable Grate; (B) Rust-resistant Bolts; (C) Integral, One-piece Flashing Ring; (D) Cast Drain Body with Sump; (E) Sediment Bucket (optional)

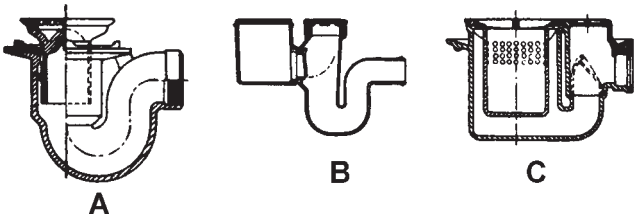


Figure 1-5 Types of Floor Drain: (A) Typical Drain with Integral Trap that May Be Cleaned Through Removable Strainer at Floor Level; (B) Floor Drain with Combination Cleanout and Backwater Valve, for Use Where Possibility of Backflow Exists; (C) Drain with Combined Cleanout, Backwater Valve, and Sediment Bucket

minor spillage or fixture overflow. The exceptions are, of course, cases where equipment discharges to the drain, where automatic fire sprinklers may deluge an area with large amounts of water, and where flushing of the floor is required for sanitation.

Floor drains or drains installed to anticipate a failure may not receive sufficient water flow to prevent the protective water seal or plumbing trap from evaporating. If the seal does evaporate, sewer gases will enter the space. Thus, automatic or manual trap primers should be installed to maintain a proper trap seal. (A small amount of vegetable oil will dramatically reduce the evaporation rate of infrequently used floor drains and floor sinks.)

Figure 1-4 shows the basic components of a floor drain.

Floor drains shall connect to a trap that can be readily cleaned and sized to efficiently serve the purpose for which it is intended. A deep-seal trap or an approved automatic priming device should be provided. The trap shall be accessible either from the floor-drain inlet or by a separate cleanout within the drain. Figure 1-5 illustrates several types of drains that meet these conditions.

Grates/Strainers

The selection of grates is based on use and the amount of flow. Light-traffic areas may have a nickel-bronze grate, while mechanical areas may have a large, heavy-duty, ductile iron grate.

The wearing of spike-heeled shoes prompted the replacement of grates with a heel-proof, ¼-inch (6.4-millimeter) square grate design in public toilet rooms, corridors, passageways, promenade decks, patios, stores, theaters, and markets. Though this type of grating has less drainage capacity than typical grates, its safety feature makes it well worth the change.

Grates or strainers should be secured with stainless-steel screws in nickel-bronze tops. If the public may access the roof, consideration must be given to protecting vent openings from vandals, and vandal-proof fasteners are available from most manufacturers.

In school gymnasium shower rooms, where the blocking of flat-top shower drains with paper towels can cause flooding, dome grates in the corners of the room or angle grates against the walls can be specified in addition to the regular shower drains. Shower-room gutters and curbs have become undesirable because of code requirements and the obvious dangers involved. Therefore, the passageways from shower areas into locker areas need extended-length drains to prevent runoff water from entering the locker areas.

Where grates are not secured and are subject to vehicular traffic, it is recommended to install non-tilting and/or tractor-type grates. With these grates, when it moves out of position the skirt catches the side of the drain body, and the grate slides back into its original position. Ramp-drain gratings should be slightly convex because rapidly flowing ramp water has a tendency to flow across flat grates. A better solution to this problem is to place flat-top grates on a level surface at the bottom of the ramp, rather than on the ramp slope.

Flashing Ring

This component makes an effective seal, which prevents water from passing around the drain to the area below.

Sediment Bucket

A sediment bucket is an additional internal strainer designed to collect debris that gets by the regular strainer. It is required wherever the drain can receive solids, trash, or grit that could plug piping, such as the following situations:

- Toilet rooms in industrial/manufacturing buildings should be equipped with floor drains with sediment buckets to facilitate cleaning.
- Floor drains with sediment buckets must be provided in mechanical equipment rooms, where pumps, boilers, water chillers, heat exchangers, and HVAC equipment regularly discharge and/or must be periodically drained for maintenance and repairs. HVAC equipment requires the drainage of condensate from cooling coils using indirect drains.
- Boilers require drains with sediment buckets. Strategically located floor drains also are required in buildings with wet sprinkler systems to drain water in case the sprinkler heads are activated. The maximum temperature of liquids discharged should be 140°F (60°C).
- Where a residential garage requires a floor drain, a sediment bucket shall be used.

Accessories

A variety of accessories are available to make the basic drain adaptable to various types of structures. The designer must know the construction of the building, particularly the floor and deck structures, to specify the appropriate drain accessories.

Backwater Valves

A backwater valve can be installed on a building sewer/house drain when the drain is lower than the sewer line, when unusual sewer discharges may occur due to combined storm water and sanitary sewer systems, or when old municipal sewers incur high rates of infiltration.

A backwater valve reacts similarly to a check valve. The device consists of a mechanical flapper or disc, which requires a certain amount of maintenance; therefore, these devices must be placed to provide a free area and access for maintenance. Sediment can accumulate on the flapper valve seat, preventing the flapper from closing tightly. Also, many valves employ a spring or mechanical device to exert a positive pressure on the flapper device, which requires occasional lubrication. Most manufacturers of backwater valves provide an access cover plate for maintenance, which also may be used as a building sewer cleanout.

Figure 1-6 illustrates two types of backwater valves that may be installed where there is a possibility of backflow.

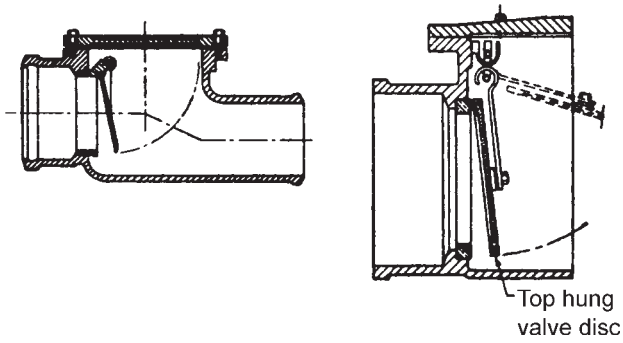


Figure 1-6 Types of Backwater Valve

Oil Interceptors

In commercial establishments such as service stations, garages, auto repair shops, dry cleaners, laundries, industrial plants, and process industries having machine shops, metal-treating process rooms, chemical process or mixing rooms, etc., flammable or volatile liquids may enter the drainage system, which can contaminate the sewer line and cause a serious fire or explosion.

Oil interceptors are designed to separate and collect oils and other light-density, volatile liquids, which would otherwise be discharged into the drainage system. An oil interceptor is required wherever lubricating oil, cutting oil, kerosene, gasoline, diesel fuel, aircraft fuel, naphtha, paraffin, tri-sodium phosphate, or other light-density and volatile liquids are present in or around the drainage system.

The interceptor is furnished with a sediment bucket, which collects debris, small parts, chips, particles, and other sediment frequently present in industrial waste and could clog the drainage system. A gasketed, removable cover permits access for cleaning. To eliminate pressure buildup inside the interceptor, a connection on each side of the body allows venting of the interceptor.

Oil interceptors are sized in accordance with the maximum anticipated gpm (liter per second) flow rate of wastewater that could be discharged through a tailpiece and typically are protected from back-siphonage by a vacuum breaker mounted at the tailpiece entrance.

Fixture Wastewater Type

These devices are mounted on the trap of frequently used fixtures. A tapping at the overflow line will allow small amounts of wastewater to enter an adjacent, infrequently used drain as the trap surges during use.

Automatic trap primers can be obtained as preengineered devices, which have widely accepted approval. All direct connections between the sewer system and the potable water system must be protected from potential contamination. Primers can be manufactured or fitted with devices that are approved to prevent cross-contamination.

Supports

The location of pipe supports usually is specified by code. They are located to maintain a slope that is as uniform as possible and will not change with time. In this regard, the rigidity of pipe and joints and the possibility of creep and bedding settlement are primary considerations. When building settlement may be significant, special hanging arrangements may be necessary. Underground piping should be continuously and firmly supported, but blocking below metal pipe is usually acceptable. Consult the manufacturer for recommendations for piping materials not covered in the code and for special problems.

Hangers should be designed adequately. To protect them from damage by building occupants, allow at least a 250-pound (113.4-kilogram) safety factor when designing hangers. See *Plumbing Engineering Design Handbook*, *Volume 4,* Chapter 6 for further information on hangers and supports.

Seismic restraint also must be considered.

PIPING MATERIALS

The materials recommended for soil and waste piping, installed aboveground within buildings, are copper alloy, copper, cast iron (hub-and-spigot or hubless), galvanized steel, and PVC. Underground building drains should be cast iron soil pipe, hard-temper cop-

per tube, ABS, PVC, PVDF, or DWV pattern Schedule 40 with compression joints or couplings, installed with a minimum cover of 12 inches (300 millimeters). Corrosive wastes require suitably acid-resistant materials such as high-silicon cast iron, borosilicate glass, or polypropylene. (Note: Some blood analyzers discharge sodium azide, which forms a very dangerous, explosive compound with copper pipes. Other piping must be used, or the sodium azide must be kept out of the system.)

The materials used for the pipe fittings must be compatible with the piping materials. Fittings should slope in the direction of flow and have smooth interior surfaces without ledges, shoulders, or reductions that may obstruct the flow in the piping.

Drains specified with cast iron or PVC bodies should be suitable for most installations. Where extra corrosion resistance is required, high-silica cast iron, polypropylene, borosilicate glass, stainless steel, galvanized iron, or other acid-resisting material should be selected. Where a sediment bucket is used, it should be bronze, galvanized, or stainless steel. Enameled sediment buckets are impractical because they chip when cleaned.

In the selection of materials for top surfaces, such as grates, where floor drains are visible in finished areas, appearance is a prime consideration. As cast iron will rust and galvanizing and chrome plating eventually will be worn off by traffic, the preferred material is solid, cast nickel-bronze, which maintains its attractive appearance. In a swimming pool, however, chlorine necessitates the use of chlorine-resistant materials. For large grates that will be subject to hand-truck or forklift traffic, a ductile iron grate with or without a nickel-bronze veneer is recommended.

Polished brass or bronze for floor service will discolor unless there is constant traffic over it. Cast aluminum has also been found inadequate for certain floor-service applications due to excessive oxidation and its inability to withstand abrasion.

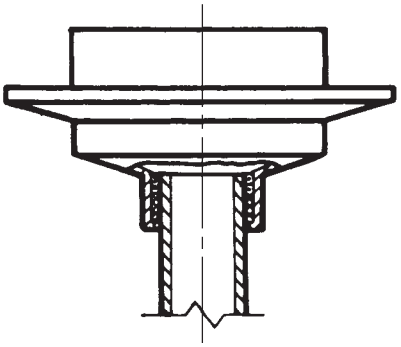


Figure 1-7 Inside Caulk Drain Body

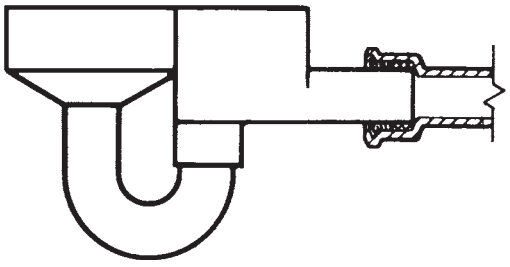


Figure 1-8 Spigot Outlet Drain Body

JOINING METHODS

Drain and cleanout outlets are manufactured in five basic types.

Inside Caulk

In the inside caulk arrangement, the pipe extends up into the drain body, and oakum is packed around the pipe tightly against the inside of the outlet. Molten lead then is poured into this ring and later stamped or caulked to correct for lead shrinkage. Current installation methods use a flexible gasket for the caulking material. See Figure 1-7.

Spigot Outlet

The spigot outlet utilizes the caulking method as outlined above for the inside caulk, except that the spigot outlet is caulked into the hub or bell of the downstream pipe or fitting. See Figure 1-8.

Push-seal Gasketed Outlet

The push-seal gasketed outlet utilizes a neoprene gasket similar to standard ASTM C564 neoprene gaskets approved for hub-and-spigot cast iron soil pipe. A ribbed neoprene gasket is applied to the accepting pipe, thus allowing the drain outlet to be pushed onto the pipe.

No-hub Outlet

The no-hub type utilizes a spigot (with no bead on the end) that is stubbed into a neoprene coupling with a stainless-steel bolting band (or other type of clamping device), which, in turn, accepts a downstream piece of pipe or headless fitting. See Figure 1-9.

IPS or Threaded Outlet

The threaded type is a tapered female thread in the drain outlet designed to accept the tapered male thread of a downstream piece of pipe or fitting. See Figure 1-10.

Noise Transmission

Avoiding direct metal-to-metal connections may reduce noise transmission along pipes. Using heavier materials generally reduces noise transmission through pipe walls. Isolating piping with resilient materials, such as rugs, belts, plastic, or insulation may reduce noise transmission to the building. See Table 1-9 for relative noise-insulation absorption values.

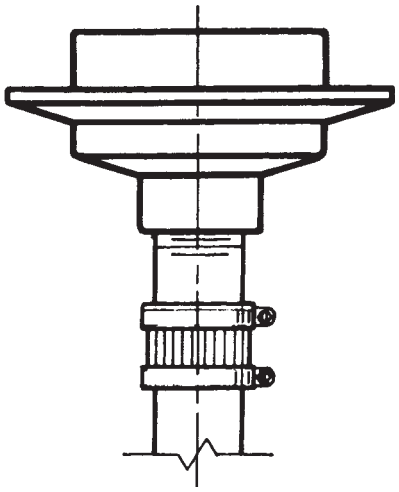


Figure 1-9 No-hub Outlet Drain Body

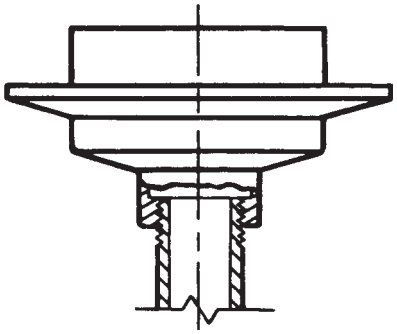


Figure 1-10 IPS or Threaded Outlet Drain Body

BUILDING SEWER INSTALLATION

The installation of building sewers is very critical to the operation of the sewer. Inadequate bedding in poor soils may allow the sewer to settle, causing dips and low points in the sewer. The settlement of sewers interrupts flow, diminishes minimum cleansing velocity, reduces capacity, and creates a point where solids can drop out of suspension and collect.

Following are some guidelines for installing building sewers.

- Where natural soil or compacted fill exists, the trench must be excavated in alignment with the proposed pitch and grade of the sewer. Depressions need to be cut out along the trench line to accept the additional diameter at the piping joint or bell hub. A layer of sand or pea gravel is placed as a bed in the excavated trench because it is easily compacted under the pipe, allowing more accurate alignment of the pipe pitch. The pipe settles into the bed and is firmly supported over its entire length.
- Where shallow amounts of fill exist, the trench can be over-excavated to accept a bed of sand, crushed stone, or similar material that is easily compacted. Bedding should be installed in lifts (layers), with each lift compacted to ensure optimum compaction of the bedding. The bed must be compacted in alignment with the proposed pitch and grade of the sewer. It is recommended that pipe joints or bell hub depressions be hand-prepared due to the coarse crushed stone. The soil-bearing weight determines trench widths and bedding thickness.
- Where deep amounts of fill exist, the engineer should consult a geotechnical engineer, who will perform soil borings to determine the depths at which soils with proper bearing capacities exist. Solutions include compacting existing fill by physical means or removing existing fill and replacing it with crushed stone structural fill.
- Backfilling of the trench is just as critical as the compaction of the trench bed and the strength of existing soils. Improper backfill placement can dislodge pipe and cause uneven sewer settlement, with physical depressions in the surface. The type of backfill material and compaction requirements must be reviewed to coordinate with the type of permanent surface. Landscaped areas are more forgiving of improper backfill placement than hard surface areas such as concrete or bituminous paving.
- Care must be taken when using mechanical means to compact soils above piping. Mechanical compaction of the first layer above the pipe by vibrating or tamping devices should be done with caution. Compacting the soil in 6-inch (150-millimeter) layers is recommended for a good backfill.

Table 1-9 Relative Properties of Selected Plumbing Materials for Drainage Systems

Materials	Noise Absorption	Corrosion Resistance[a]
ABS	Fair	Good
Cast iron	Excellent	Good
Clay	[b]	Excellent
Concrete	[c]	Fair[d]
Copper	Fair	Good
Glass borosilicate	[b]	Excellent
Polypropylene	Fair	Excellent
PVC	Fair	Excellent
Silicon iron	[c]	Excellent
Steel, galvanized	Good	Fair

[a] This refers to domestic sewage. Consult manufacturer for resistance to particular chemicals.
[b] Since these materials are used only aboveground for chemical waste systems, this is not applicable.
[c] This material is usually allowed only belowground.
[d] Susceptible to corrosion from hydrogen sulfide gas.

Proper sewer bedding and trench backfill will result in an installation that can be counted on for long, trouble-free service.

SANITATION

All drains should be cleaned periodically, particularly those in markets, hospitals, food-processing areas, animal shelters, morgues, and other locations where sanitation is important.

For sanitation purposes, an acid-resisting enameled interior in floor drains is widely accepted. The rough surfaces of brass and iron castings collect and hold germs, fungus-laden scum, and fine debris that usually accompany drain waste, and there is no easy or satisfactory way to clean these rough surfaces. The most practical approach is to enamel them, and the improved sanitation compensates for the added expense. However, pipe threads cannot be cut into enameled metals because the enameling will chip off in the area of the machining. Also, pipe threads themselves cannot be enameled; therefore, caulked joints should be specified on enameled drains. Most adjustable floor drains utilize threaded adjustments, so these drains cannot be enameled. However, adjustable drains that use sliding lugs on a cast thread may be enameled.

A grate or the top ledge of a drain can be enameled, but the enamel will not tolerate traffic abrasion without showing scratches and, eventually, chipping. The solution to this problem is a stainless-steel or nickel-bronze rim and grate over the enameled drain body, a common practice on indirect waste receptors, sometimes referred to as "floor sinks." Specifiers seem to favor the square, indirect waste receptor, but the round receptor is easier to clean and has better antisplash characteristics. For cases where the choice of square or round is influenced by the floor pattern, round sinks with square tops are available.

In applications such as hospital morgues, cystoscopic rooms, autopsy laboratories, slaughterhouses, and animal dens, where blood or other objectionable materials might cling to the sidewalls of the drain, it is recommended to fit the enameled drain with a flushing rim.

Where the waste being drained can clog the trap, a heel inlet on the trap with a flushing connection is recommended in addition to the flushing rim, which merely keeps the drain sides clean. (This option may not be allowed by certain codes.) A 2-inch (50-millimeter) trap flushes more effectively than a 3-inch (80-millimeter) trap because it allows the flushing stream to drill through the debris rather than completely flush it out. A valve in the water line to the drain is the best way to operate the flushing-rim drain. Flush valves have been used and can save water; however, they are not as convenient or effective as a shutoff valve. In any flushing water-supply line to a drain, a vacuum breaker installed according to code must be provided.

KITCHEN AREAS

When selecting kitchen drains, the designer must know the quantity of liquid and solid waste the drains will be required to accept, as well as which equipment emits waste on a regular basis and which produces waste only by accidental spillage. Dishwashing machines, steamers, booster heaters, and other kitchen equipment may discharge waste of 180°F or higher into the sanitary drain, so cast iron piping or coolers may be required in these cases.

Floor-cleaning procedures should be ascertained to determine the amount of water used. If any amount of solid waste is to be drained, receptors must be specified with removable sediment buckets made of galvanized or stainless steel. Also, sufficient vertical clearance over these drains must be provided to conveniently remove the sediment buckets for cleaning.

Many kitchen planners mount kitchen equipment on a 5-inch (125-millimeter) curb. Placing the drain on top of the curb and under the equipment makes connection of indirect drain lines difficult and the receptor inaccessible for inspection and cleaning. Mounting the receptor in front of the curb takes up floor space, and the myriad of indirect drains that discharge into it create a potential hazard for employees who may trip over them. The solution requires close coordination between the engineer and the kitchen designer. Figure 1-11 shows an arrangement whereby any spillage in front of the curb can be drained by half of the receptor, while indirect drains are neatly tucked away.

Where equipment is on the floor level and an indirect waste receptor must be provided under the equipment, a shallow bucket that can be removed easily is recommended.

WATERPROOFING

Whenever a cast-iron drain is cemented into a slab, separation due to expansion and contraction occurs and creates several problems. One is the constant wet area in the crevice around the drain that promotes mildew odor and the breeding of bacteria. Seepage to the floor below is also a possibility. A seepage or flashing flange can correct this problem. Weep holes in the flashing flange direct moisture into the drain. Also, this flange accepts membrane material, and when used, the flashing ring should lock the membrane to the flange.

One prevalent misconception about the flashing flange is that it can have weep holes when used with cleanouts; however, there can be no weep holes into

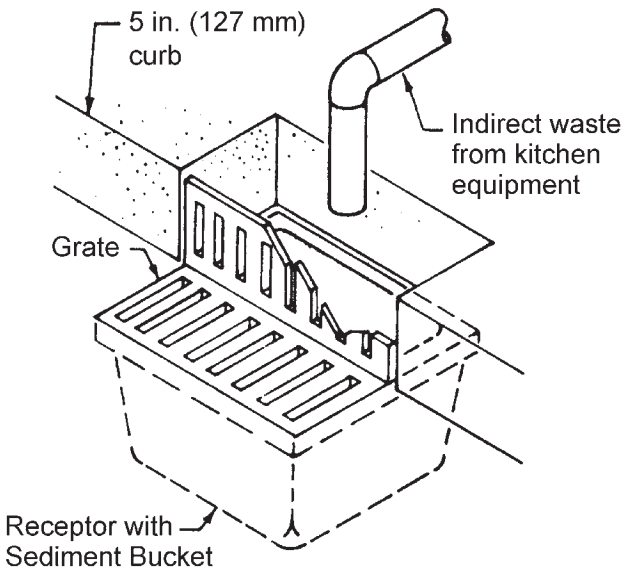


Figure 1-11 Combination Floor Drain and Indirect Waste Receptor

a cleanout to which moisture can run. Weep holes also should be eliminated from the flashing flanges of drains, such as reflection-pool drains, where an overflow standpipe to maintain a certain water level shuts off the drain entrance.

The term "non-puncturing," used in reference to membrane-flashing, ring-securing methods, is now obsolete, as securing bolts have been moved inboard on flashing L flanges, and the membrane need not be punctured to get a seal. Of the various arrangements, this bolting method allows the greatest squeeze pressure on the membrane.

FLOOR LEVELING

A major problem in setting floor drains and cleanouts occurs when the concrete is poured level with the top of the unit, ignoring the fact that the addition of tile on the floor will cause the drain or cleanout to be lower than the surrounding surface. To solve the problem, cleanouts can be specified with tappings in the cover rim to jack the top part of the cleanout up to the finished floor level. Floor drains can be furnished with adjustable tops to attain an installation that is flush with the finished floor.

THERMAL EXPANSION

When excessive thermal expansion is anticipated, pipe movement should be controlled to avoid damaging changes in slope. Anchoring, using expansion joints, or using expansion loops or bends may accomplish this. When anchoring, avoid excessive stress on the structure and the pipe. Piping or mechanical engineering handbooks should be consulted if stress analysis is to be performed due to excessive stresses or to the differing expansion characteristics of materials.

PROTECTION FROM DAMAGE

Following are some common hazards that may damage drains and drain piping and some methods of protection.

- Abrasion: Use plastic or rubber sleeves or insulate where copper pipe leaves the slab.
- Condensation: Insulate the piping.
- Corrosion: Use methods recommended in *Plumbing Engineering Design Handbook Volume 1,* Chapter 8: "Corrosion."
- Heavy earth loads: Use stronger pipe or pipe sleeves.
- Expansion and contraction: Use flexible joints, loops, swing joints, or offsets.
- Fire: Use an appropriate building construction around the pipe. Some jurisdictions require metal piping within 2 feet (0.6 meter) of an entry into a firewall. All materials must conform to the appropriate fire ratings.
- Heat: Keep thermoplastic pipe away from sources of heat or use insulation.
- Nails: Use ferrous pipe, steel sleeves, or steel plates or do not locate pipe near possible nail penetration areas.
- Seismic activity: Brace pipe and provide flexible joints at connections between piping braced to walls or the structure and piping braced to the ceiling and between stories (where differential movements will occur).
- Settlement: Use sleeves or flexible joints. When embedded in concrete, cover piping with three layers of 15-pound (6.8-kilogram) felt.
- Sunlight: Protect thermoplastic pipe by insulation and a jacket or shade it to avoid warping.
- Vandals: Install pipe above reach or in areas protected by building construction. Piping must be supported to withstand 250 pounds (113.4 kilograms) hanging from the moving pipe.
- Wood shrinkage: Provide slip joints and clearance for pipe when wood shrinks. Approximately ⅝ inch (16 millimeter) per floor is adequate for typical frame constructions, based on 4 percent shrinkage perpendicular to wood grain. Shrinkage along the grain usually does not exceed 0.2 percent.

ALTERNATE SANITARY SYSTEMS

The design and installation of alternative engineered plumbing systems are permitted in all codes, so long as they are designed by a licensed professional engineer who is responsible for the proper operation of

the systems. If an alternative system is contemplated, submission to and approval by the authority having jurisdiction must be obtained. To expedite approval, the following steps are suggested.

1. Indicate on the design documents that the plumbing system (or parts thereof) is an alternative design.
2. Submit enough technical data to support the proposed alternative design and prove that the system conforms to the intent of the code. This shall include suitability for the intended purpose, strength, equivalent level of performance compared to traditional installations, safety, and quality of materials.
3. Include floor plans, riser diagrams, and an indication of the proposed flow.
4. Provide assurance that the manufacturer's installation instructions will be followed.
5. If approval is given, indicate on the permit and all construction applications that an alternative engineered design is part of the approved installation.
6. Alternative systems are characterized by, but not limited to, using a single stack for both sanitary and vent or no vent at all. One exception is a conventional drainage, reduced-vent system. All of the following systems have been used successfully in the United States and around the world for many years and have proven effective in actual use. All of the alternative systems discussed have combined sanitary and vent systems.

SOVENT AND PROVENT

The Sovent system was developed in 1959 in Switzerland. It is a patented, combination drainage and vent system that uses a single stack instead of a conventional two-pipe drainage and vent stack. The Sovent system uses cast iron and/or copper pipe and is suitable only for multistory buildings because it allows substantial economy in piping installation.

The Provent system is similar to the Sovent system, but it uses PVC. Although installed in many countries throughout the world, it remains an alternative, unconventional system with only limited usage in the United States.

It is not the intent of this chapter to provide specific design criteria for a Sovent or Provent system, but rather to discuss the individual component characteristics that will enable a plumbing engineer to obtain a working knowledge of how these systems work. A typical Sovent single-stack system is illustrated in Figure 1-12.

A Sovent or Provent system consists of three principal parts: piping for all branch wastes and stacks, an aerator fitting at each floor level where the branch waste lines connect to the stack, and a deaerator fitting at the base of the stack where it enters the house drain.

The starting point is the horizontal soil and waste branches. The fixture units and branch sizes are similar to those figures found in conventional systems. The maximum fixture units that may be connected to a branch or stack are also similar to that of conventional systems.

Branch sizes must be adjusted according to the following.

- A second vertical drop or a vertical drop of more than 3 feet (0.9 meter) requires an increase in the downstream side of the connection.
- When three 90-degree changes in direction occur in a horizontal branch, the horizontal branch shall be increased in size at the upstream side of the third change.
- When a branch serves two water closets and one or more additional fixtures, the soil line shall be increased to 4 inches (100 millimeters) at the point where one water closet and one additional fixture are connected.
- The branch must be increased one size when a soil branch exceeds 12 feet (3.7 meters) in horizontal length.
- The branch must be increased one size when a waste line exceeds 15 feet (4.6 meters) in horizontal length.

Stacks must be carried full size through the roof. Two stacks can be connected at the top above the highest fixture or at the bottom prior to entering the building drain. The size is based on the total fixture units. Fixtures may be connected into a horizontal offset in a stack below the deaerator fitting.

An aerator fitting is required at each level where a soil branch, a waste line the same size as the stack, or a waste branch one size smaller than the stack is connected. The aerator consists of an upper stack inlet, a mixing chamber, and a baffle in the center of the fitting. This provides a chamber where the flow from the branches may gradually mix smoothly with the air and liquid already flowing in the stack. It also limits the turbulence and velocity of the incoming water. A 2-inch (50-millimeter) horizontal branch may enter the stack with no fitting. Two basic styles of aerator fitting meet the needs of most design conditions: the double-side entry fitting and the single-entry fitting. Face entry and top entry are used in special cases.

A deaerator fitting is required at the bottom of the stack and is designed to overcome the tendency of the falling waste to build up excessive back pressure at the bottom of the stack when the flow is decelerated by the bend into the horizontal drain. The deaerator consists of an air separation chamber, a nose piece, a pressure relief outlet at the top connected to the

building drain, and a stack outlet at the bottom. The purpose of the deaerator is to separate the airflow from the stack to ensure the smooth flow of liquid into the building drain and to relieve the positive pressure generated at the stack's base. The configuration of the fitting causes part of the air falling with the liquid to flow through the pressure relief line, and the remainder of the air goes directly into the building drain.

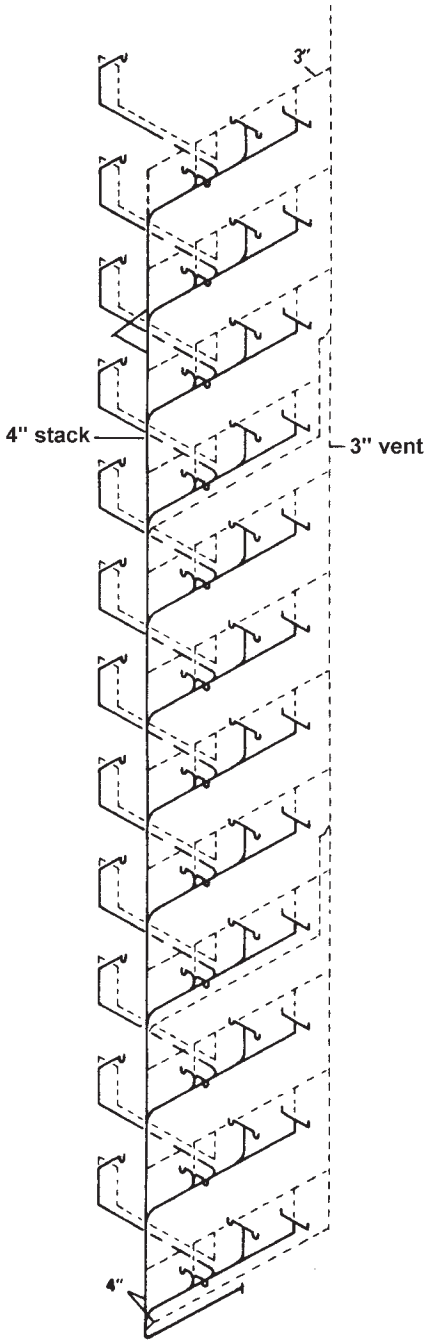


Figure 1-12 Typical Sovent Single-stack System

The plumbing engineer must explain the special requirements of the Sovent or Provent system to the installing contractor. The engineer also should make regular inspections of the project to ensure that the design conditions are met. A complete set of contract documents shall be provided to the owner to allow proper alteration or expansion of the project in the future.

SINGLE-STACK SYSTEM

The single-stack system is a combination drainage and vent system consisting of a single stack instead of conventional separate drainage and vent stacks. In this drainage system, the drainage stack serves as both a single-stack drainage and vent system when properly sized. To relieve internal air pressures, the one-pipe system must be larger than that required for drainage purposes alone. The drainage stack and branch piping shall be considered vents for the drainage system as a whole. Although the pipe sizing is larger in a single-stack system than in a conventional one, installation savings are achieved by reducing the amount of vent piping required.

The major components of the one-pipe system are oversize, unvented S traps instead of the conventionally sized and vented P traps and fixtures that allow water to run off after the tap is closed to fill the traps with water to maintain the trap seal. The trap arm length is limited to reduce any suction buildup, and the stack is oversized to limit internal air pressure and vacuum buildup.

Often referred to as the Philadelphia stack, this unconventional system has operated successfully for more than 100 years with no problems. Consideration has been made by code bodies to include this system as an engineered design, which allows it to be used providing the engineer has designed it in accordance with code.

REDUCED-SIZE VENTING

In 1974, the National Bureau of Standards (NBS) conducted a laboratory study of one-story and split-level experimental drainage systems where the vents varied from one to six pipe sizes smaller than those for conventional systems. They showed satisfactory hydraulic and pneumatic performance under various loading conditions. At the same time, the 10-story wet vent system at the Stevens Institute Building Technology Laboratory had been modified by reducing the vents one to three pipe sizes in accordance with the plans and specifications of the NBS. The results also indicated that the vents in a two-story housing unit can safely be made smaller than previously allowed without jeopardizing the trap seals.

This system may allow economies of pipe size in the venting design of low-rise residential buildings,

although this particular system has not been accepted by authorities. It is limited to special conditions and requires the vent pipes to be of a material such as copper or plastic that will resist the buildup of corrosion products.

VACUUM DRAINAGE SYSTEM

Vacuum drainage operates on the principle that the majority of the system is under a continuous vacuum. The system is proprietary and is made by various manufacturers, all of which have different names for devices performing similar operations, so generic identification is used here. Various designs are capable of sanitary and waste disposal, either separate or in combination, and are used for various projects such as prisons, supermarkets, and ships. There is no direct connection from the sanitary waste to the vacuum system. The one big advantage is that piping is installed overhead and no pipe is required to be placed underground.

The system consists of three basic components: a vacuum network of piping and other devices that collects and transports waste from its origin, vacuum generation pumps, and a vacuum interface device at the point of origin that isolates the vacuum piping from atmospheric pressure. When the system serves water closets, the water closets must be purpose made, designed to rinse and refill with 0.5 gallon (2.2 liters) of water.

The piping network for a vacuum waste system is held under a constant vacuum between 12 and 18 inches of mercury (in Hg) (40–65 kilopascals) and generally is fabricated from PVC, copper, or other nonporous, smooth-bore material. Horizontal piping shall slope at a rate of ⅛ inch per foot (1.18 millimeter per meter) toward the vacuum center. This piping slope is the same as in conventional systems. If this slope cannot be maintained, the traps created in the piping runs when routed around obstacles would be cleared because of the differential pressure that exists between the vacuum center and the point of origin. The discharge of the piping system is into the waste storage tanks.

The vacuum generation system includes vacuum pumps, which create a vacuum in the piping and storage tanks that collect and discharge the waste into the sewer system. The vacuum pumps run only on demand, and redundancy is provided. They also have sewage pumps that pump the drainage from the storage tanks into the sewer.

The vacuum interface is different for sanitary drainage than for clear waste. Vacuum toilets operate instantly upon flushing, and when a vacuum toilet is cycled, a discharge control panel assembly is activated, sending the discharge to the tank. A valve acts as an interface between the vacuum and the atmosphere. The tank will discharge into the sewer when a predetermined level of discharge is reached.

When clear water is discharged, the water goes into an accumulator. When a controller senses that sufficient waste is present, it opens the normally closed extraction valve, which separates the atmospheric pressure from the vacuum and removes the waste from the accumulator.

Because vacuum toilets use 0.5 gallon per flush, the holding tanks can be smaller than those for conventional toilets. A flush control panel is designed to provide all of the control functions associated with the vacuum toilet. The control panel consists of a flush valve, flush controller, water valve, and vacuum breaker. All controls are pneumatically operated. The flush controller controls the opening of the flush valve and the rinse valve as well as the duration of the time the flush valve is open.

REFERENCES

1. Daugherty, Robert L., Joseph B. Franzini, and E. John Finnemore, *Fluid Mechanics with Engineering Applications*, McGraw-Hill, 1985.
2. Dawson, F.M. and A.A. Kalinske. *Report on Hydraulics and Pneumatics of Plumbing Drainage Systems*, State University of Iowa Studies in Engineering, Bulletin No. 10, 1937.

2 On-site Wastewater Reuse and Storm Water Harvesting

In many regions, water is a limited natural resource, so extreme measures to optimize the use of water are necessary. Water reuse and storm water use offer considerable savings of water resources, which is appealing in localities where underground aquifers are in danger of depletion or where adequate supplies of water are not available. Storm water use (and wastewater reuse) is sometimes attractive when compared to the treatment required for groundwater sources to achieve potable or drinking water standards. For example, numerous Wisconsin wells contain some of the highest arsenic concentrations in the world (15,000 parts per billion [ppb], when the drinking water standard is 5 ppb). In such an instance it may be more reasonable to treat storm water for potable use. Wastewater management is also a significant reason for water reuse and storm water use systems.

On-site recycling of relatively clean, nonpotable water and storm water use are considered for the following reasons.

- The availability of potable water is in short supply or restricted, and codes require reuse or storm water use.
- The public liquid sewage disposal capacity is either limited or inadequate.
- Obtaining potable water or disposing of liquid waste is very costly.
- Payback typically occurs in less than five years, and the system can reduce sewer and water usage fees, electrical costs, or water heating costs, resulting in operating cost savings.
- The 2009 LEED certification has options for plumbing. Reuse could earn a facility up to four points in the LEED system by reducing water usage by 40 percent. A 35 percent reduction earns three points, and a 30 percent reduction earns two points.

The most common reuse of water is for the flushing of urinals and water closets, especially in high-rises, hotels, schools, office buildings, and large dwellings. Appropriately treated water also may be used for the following proposes:

- Flushing water for water closets and urinals
- Landscape irrigation
- Cooling tower makeup
- Decorative pool and fountain fill water
- Floor and general hard-surface washdown
- Laundry water supply

Less frequently, storm water is collected and used for potable purposes, but the public does not widely accept this process.

Note: This chapter is written primarily to familiarize the reader with the general subject area. It is not intended for system design without reference and adherence to other technical data and local code requirements.

TERMINOLOGY

In plumbing, wastewater is the general term for water that has been discharged or collected from a fixture, receptor, or appliance (see Figure 2-1).

The terms for a variety of recycled waters often are used interchangeably. In general, graywater is intended to include appropriately treated water that has been recovered from fixtures such as lavatories, bathtubs, showers, and clothes washers. In some jurisdictions, waste potentially containing grease, such as that from dishwashers, and waste from food disposals in kitchens are excluded due to the possibility of solid particles in the water. Black water, on the other hand, is water recovered from plumbing fixtures discharging human excrement, such as water closets and urinals. Storm water includes the wastewater from precipitation events (and sometimes groundwater).

THE WATER BALANCE EQUATION

On-site water efficiency, whether mandated or an ecologically minded choice, requires plumbing system designers to evaluate the constructed environment water balance prior to completing a plumbing design (see Figure 2-2).

The constructed environment water balance equation is:

Equation 2-1

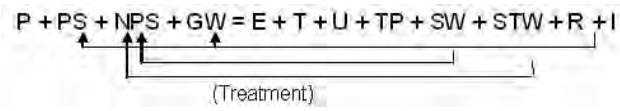
$$P + PS + NPS + GW = E + T + U + TP + SW + STW + R + I$$

where
P = Precipitation
PS = Potable source
NPS = Nonpotable source
GW = Groundwater
E = Evaporation
T = Transpiration
U = Usage in product (personal use carried off site)
TP = Treated product water (as marketable water)
SW = Sanitary sewer
STW = Storm water sewer
R = Storm water runoff
I = Infiltration

The water balance is impacted by storage; however, the long-term balance is always maintained.

When reuse or storm water harvesting is included in the plumbing design, the water balance equation can be modified to:

Equation 2-2



CODES AND STANDARDS

The number of jurisdictions requiring water reuse or storm water harvesting is increasing. Even the Great Lakes areas are considering supplementing withdrawals from the lakes with these and other conservation practices. However, no national model codes mandate storm water use or wastewater reuse. The Uniform Plumbing Code discusses graywater, but limits the discussion to single-family dwellings. The International Plumbing Code includes graywater recycling systems in an appendix.

Many specific local areas have established standards and guidelines for the use of graywater in facilities and homes. Where graywater use is permitted, the authority having jurisdiction may have established minimum treatment standards. In these localities, you must check for regulations applicable to reuse and storm water use as is done for plumbing and building codes.

Table 2-1 is from the Canadian Mortgage and Housing Corporation's Research Report, which includes a summary of international treatment standards for water reuse. The limitations represented in Table 2-1 illustrate concerns that you should address when developing a water reuse plan. Since such requirements are constantly undergoing revision, you must contact the local authorities for current standards.

Some jurisdictions allow irrigation with untreated graywater, and this typically is accomplished subsurface. This chapter assumes that the irrigation system is provided with treated graywater to the standards listed in Table 2-1.

GRAYWATER REUSE

Graywater reuse systems collect water discharged from fixtures, devices, and appliances that do not contain human excrement. This water can be treated to a level of quality consistent with its intended use.

A graywater system requires modifications to the standard plumbing systems throughout a facility—in particular, duplicate drainage systems and duplicate water supplies. Rather than all plumbing fixture discharge going to the sanitary sewer, the effluent from selected fixtures is routed for recovery by the graywater treatment system. The remainder goes to the sanitary sewer. Potable water goes to lavatories, sinks, and showers, and the graywater supplies water closets, urinals, irrigation systems, and other fixtures, depending on the quality of the graywater treatment.

Special care must be taken during the installation of a graywater system. Clear identification and labeling of the graywater system and piping are mandatory to minimize the risk of cross-connection during installation or repair of the system.

Many newly formed, planned communities have adopted graywater systems for their irrigation systems. Warning "nonpotable water" signs or colored piping is now visible across city landscapes. Blue dye has become a clear identification of the use of graywater.

System Components

The following components generally are used for most systems. Their arrangement and type depend on the specific treatment system selected.

- A separate graywater collection piping system
- A primary waste treatment system consisting of turbidity removal, storage, biological treatment, and filtering
- Disinfecting systems consisting of ozone, ultraviolet irradiation, chlorine, or iodine
- Treated water storage and system distribution pressure pumps and piping

Design Criteria for Graywater Supply and Consumption

It is estimated that two-thirds of the wastewater discharged from a typical household in one day is graywater. The remaining wastewater is black water from water closets. The discharge from the separate piping systems supplying the graywater system should be sized based on the applicable plumbing code.

The following issues should be considered in the design of any graywater system:

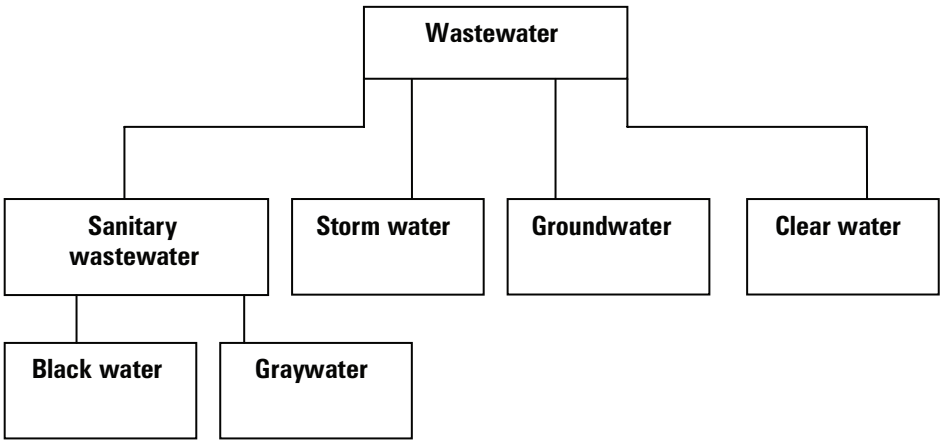


Figure 2-1 Wastewater Designations

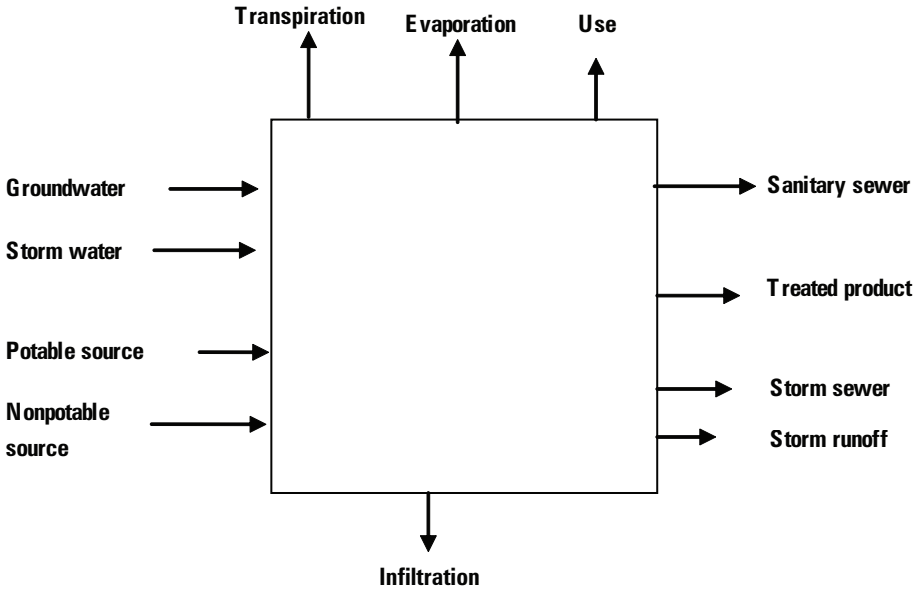


Figure 2-2 The Constructed Environment Water Balance

- The design flow is based on the number of people in the home or facility.
- Lavatory use is estimated at 0.25 gallon (0.95 liter) per use.
- Men use urinals 75 percent of the time and water closets 25 percent of the time.
- The average person uses a toilet three times a day.

The LEED 2009 baselines for plumbing fixtures that affect the design of reuse and water conservation systems when you apply for LEED credit are shown in Table 2-2.

Design Estimates for Commercial Buildings

Graywater Supply

Estimates of graywater supply sources vary in commercial buildings. In an office building, fixtures such as lavatories, water coolers, mop sinks, and coffee sinks are estimated to generate 1 gallon (3.79 liters) per person per day. Thus, for an office building with 500 employees, you could expect to recover 500 gallons (1,893 liters) per day for graywater reuse. Based on five working days per week and approximately 50 working

weeks per year, 125,000 gallons (473,177 liters) per year could be available for graywater reuse.

Graywater Demand

The demand for fixtures served by treated graywater in an office building is estimated based on three toilet or urinal uses per person per day. For calculation purposes, assume that the population is 50 percent male and 50 percent female and that men use urinals 75 percent of the time and water closets 25 percent of the time. (This assumption is general and may be adjusted for any particular installation.)

In shopping centers, flow rates are based on square feet (square meters) of space, not the number of persons. The flow demand is 0.06 gallon (0.23 liter) per day per square foot (meter).

Table 2-1 Water Reuse Issues of Concerns

Parameter	Units	Low Risk[a]	High Risk[b]
BOD[5c]	mg/L	$\leq$ 30	$\leq$ 10
TSS[c]	mg/L	$\leq$ 30	$\leq$ 10
Turbidity	NTU	$\leq$ 5	$\leq$ 2
Fecal coliforms[c]	CFU/100 mL	< 200[d]	< 1 CFU/100 mL
Total coliforms[c]	CFU/100 mL	< 1,000[d]	< 1 CFU/100 mL
E coli[c]	CFU/100 mL	< 200	< 1 CFU/100 mL
Viruses			
Worms			
Total nitrogen	mg/L		
Total phosphorus	mg/L		
Cl residual	mg/L		0.1 to 1.0

Units: mg/L = milligrams per liter; NTU = nephelometric turbidity units; CFU = colony-forming units
aLow-risk applications include toilet flushing and subsurface irrigation.
bHigh-risk applications include landscape surface irrigation and laundry.
cMedian values
dRecreational water quality standards
Source: Canadian Mortgage and Housing Corp.

The calculations for food service resemble those for grease interceptor sizing. The number of seats, hours of operation, single-serving utensils, and other, similar factors change the equations for graywater calculations.

Graywater Design Estimates for Residential Buildings

The number of occupants of each dwelling unit shall be calculated as follows:

- Occupants, first bedroom: Two
- Occupants, each additional bedroom: One

The estimated graywater flows for each occupant shall be calculated as follows:

- Showers, bathtubs, and wash basins: 25 gallons (95 liters) per occupant per day
- Laundry: 15 gallons (57 liters) per occupant per day

The total number of occupants shall be multiplied by the applicable estimated graywater discharge as provided above and the type of fixtures connected to the graywater system.

Example 2-1

Calculate the flow of graywater per day for a single-family dwelling with three bedrooms, showers, bathtubs, wash basins, and laundry facilities all connected to the graywater system.

1. Total number of occupants = 2 + 1 + 1 = 4
2. Estimated graywater flow = 4 x (25 + 15) = 160 gallons per day [4 x (95 + 57) = 608 liters per day]

Example 2-2

Calculate the flow of graywater for a single-family dwelling with four bedrooms and only the clothes washer connected to the graywater system.

1. Total number of occupants=2 + 1 + 1 + 1=5
2. Estimated graywater flow = 5 x 15 = 75 gallons per day [5 x 57 = 285 liters per day]

Design Estimates for Graywater Irrigation Systems

Graywater irrigation system design and selection depend on a variety of elements: location, soil type, water supply source, type of treatment facility, and application of reuse. Additional requirements are noted for the reuse of graywater systems for irrigation systems. Some of the parameters are groundwater level, geological stability of the region, plot plan, distance of irrigation from adjacent properties, lakes, lot lines, drainage channels, water supply lines, surface slope, wells, and the interaction of graywater systems with private sewage disposal systems. Inspection and testing are an inherent part of the design.

System components must be securely installed, and the manufacturer must be properly identified. The holding tanks must be installed in dry levels, and, if underground, contamination issues must be taken into consideration. The authority having jurisdiction shall review all plans, and qualified and experienced contractors shall install the system in accordance with the contract documents.

Table 2-2 LEED 2009 Baseline for Plumbing Fixtures

Fixture	LEED 2009 Baseline
Toilets	1.6 gpf (3.5 gpf for blowout closets)
Urinals	1.0 gpf
Lavatory faucets, privatea	2.2 gpm at 60 psig
Lavatory faucets, public	0.5 gpm at 60 psig
Lavatory faucets, metering	0.25 gallons per cycle
Residential kitchen faucets	2.2 gpm at 60 psig
Showerheads	2.5 gpm at 80 psig
Pre-rinse spray valves	1.6 gpm (no psig specified)

[a]Private lavatory faucets include both residential and private commercial applications such as hotel guest rooms and hospital patient rooms.

Table 2-3 Design Criteria for Graywater Irrigation of Six Typical Soils

Soil Type	Minimum Irrigation Area per 100 Gallons of Estimated Graywater Discharge per Day, square feet
Coarse sand or gravel	20
Fine sand	25
Sandy loam	40
Sandy clay	60
Clay with considerable sand or gravel	90
Clay with small amounts of sand or gravel	120

To design a graywater system, you must estimate the water supply source. Separate design parameters become important for reuse in buildings or in irrigation systems. For irrigation systems, the required area of subsurface must be designed based on soil analysis.

Table 2-3 gives an example of the design criteria for the use of graywater systems in various soil types (coarse sand or gravel, fine sand, sandy loam, sandy clay, and mixed clay). As the soil weight decreases and the soil becomes less porous, the minimum square feet (square meters) needed for leaching increases. Coarse sand or gravel needs a 20-square foot irrigation area per 100 gallons (1.86 square meters per 379 liters) of estimated graywater discharge per day. Clay with a small amount of sand or gravel requires 120 square feet per 100 gallons (11.15 square meters per 379 liters) of estimated graywater per day.

The area of the irrigation field shall be equal to the aggregate length of the perforated pipe sections within the valved zone times the width of the proposed irrigation field. Each proposed graywater system shall include at least three valved zones. No excavation for an irrigation field shall extend within 5 vertical feet (1.5 meters) of the highest known seasonal groundwater table, and it shall not extend to a depth where graywater may contaminate the groundwater or ocean water.

The design of the graywater distribution in subsurface drip systems is based on the emitter manufacturer's recommendations. The soil type and loading criteria from Table 2-3 are also applicable to drip irrigation systems.

Table 2-4 identifies the location and separation distance from a variety of structures and environments. For example, any building or structure shall be a minimum of 5 feet (1.5 meters) from a graywater surge tank. The minimum distance from any property line to a graywater surge tank is also 5 feet (1.5 meters). Critical areas such as streams, lakes, seepage pits, and cesspools shall be a minimum of 50 feet (15.2 meters) from surge tanks and 100 feet (30.5 meters) from irrigation fields. Similarly, the distance from the public water main to a surge tank shall be a minimum of 10 feet (3.1 meters). The table also identifies additional restrictions.

Graywater Treatment Systems

The graywater treatment system conditions the recovered water to a level consistent with both the intended use of the conditioned water and the design requirements of the design engineer, applicable code, or responsible code official—whichever is the most stringent. Typical wastewater (graywater and black water) treatments used for various types of projects include sedimentation, aeration, filtration, and disinfection.

The size of the treatment systems available vary from those installed for individual private dwellings to those serving multiple facilities. As the treatment facility becomes more complex, the number of treatment activities increases, and the quality of the water improves. Some of the treatment activities are basic screening, flow equalization, biological treatment, filtration, coagulation, sedimentation, disinfections, reclaimed water tank, membrane filtration, and activated carbon filtration.

The selection of a treatment system also depends on the quality and type of the influent water. To decide which treatment method is most appropriate, the type of fixture discharge to be reclaimed and the treatment requirements of the authority having jurisdiction must be determined.

Table 2-5 describes the types of filtration and water treatment processes most commonly used for graywater treatment. Depending on the type of filtra-

Table 2-4 Minimum Horizontal Distances for Graywater System Elements

Element	Distance from Treated Graywater Holding Tank, feet	Distance from Untreated Graywater Holding Tank, feet	Distance from Treated Graywater Irrigation System, feet	Distance from Untreated Graywater Irrigation System, feet
Buildings with below grade foundations	5	5	2	2
Buildings with no below grate foundations	5	5	None	None
Property line	5	5	2	2
Water supply wells	8	25	8	25
High water level of water body	8	25	8	25
Sanitary private on-site infiltration system (drain field)	25	25	None	None
Sanitary treatment tank or lift station (septic tank)	25	8	None	None
Water service	10	25	None	None

Table 2-5 Graywater Treatment Processes for Normal Process Efficiency

Process	Suspended Solids	Biological Oxygen Demand	Chemical Oxygen Demand	Phosphates, P0-4	Nitrogen	Total Dissolved Solids
Filtration	80	40	35	0	0	0
Coagulation/filtration	90	50	40	85	0	15
Chlorination	0	20[a]	20[a]	0	0	0
Tertiary treatment	95	95	910	15–60	50–70	80
Absorption (carbon filtration)	0	60–80	70	0	10	5

[a] Nominal, additional removals possible with super chlorination and extended contact time.

Table 2-6 Comparison of Graywater System Applications

System	Piping	Treatment	Potential Gray Water Uses	Water Savings[a]	Savings[a]
Conventional	Base	None	N/A	0	0
Type A (minimal treatment)	Separate gray-water riser/separate WC stack	Filtration, chlorination, color	Water closets	20,000 gal/day (75,708 L/day) 17% (inc. irrigation), 22% (without irrigation)	20,000 gal/day (75,708 L/day) 26%
Type A (enhanced treatment)	Separate gray-water riser/separate WC stack	Chemical filtration, chlorination, color	Water closets cooling towers, irrigation (pos.)	35,000 gal/day, (132,489 L/day) 30% (incl. irrigation), 38% (without irrigation)	35,000 gal/day, (132,489 L/day) 46%
Type B	Separate gray-water riser	Tertiary sewage treatment	All nonpotable uses	61,000 gal/day, (230,909 L/day) 52% (incl. irrigation)	

[a] Values for savings noted are based on the 250-room resort hotel example. Percentages are based on normal usage of 117,850 gal/day, including irrigation, and 91,150 gal/day, without irrigation.

tion, the degree and types of components filtered vary. Basic filtration concentrates on reducing suspended solids, but it does not absorb nitrogen or phosphates. Coagulation helps solids filtration and also absorbs phosphates. Chlorination is significant only in oxygen demand issues. Tertiary treatment includes filtration of all categories. Absorption, or carbon filtration, concentrates primarily on biological and chemical oxygen demands.

Economic Analysis

Any alternative plumbing system will pose an additional cost. Thus, an economic and energy analysis should be performed prior to committing to the project (see Table 2-6).

Precautions

Since graywater poses a potential health hazard, a great deal of care must be exercised once such a system is installed. One of the greatest dangers is the possibility that the graywater will be inadvertently connected to the potable water system. To avoid this possibility, the water itself and the piping must be made easily distinguishable, cross-connection precautions must be taken, and appropriate alarms must be installed.

To maintain water quality, alarms and monitors are important components of the reuse system. Frequent monitoring may replace alarms on low-risk installations; however, alarms and automatic solenoids may be critical for high-risk installations.

Treated water could be colored by biodegradable food dye. Fixtures can be purchased in the color of the water if the color of the water is found objectionable.

The piping system itself must be clearly identified with labels placed visibly along the run of the pipe. If possible, the piping material should be different so that the possibility of mistaking and interconnecting the two systems is unlikely. The color of reuse piping is frequently purple to alert future installers.

The most important consideration is educating the occupants and staff of a facility with a graywater system. An explanation of the dangers and proper operating instructions helps ensure that an informed staff will operate and maintain the system in the correct manner. A plan to transfer information from one employee to the next should be included in the maintenance plan for the system.

Public Concerns and Acceptance

Although graywater systems have been approved for general use in different parts of the world and have been designed in a variety of forms, they are still unfamiliar to many city and county governments, plumbing and facility engineers, and the general public. An exception is the Bahamas, where the local code mandates dual or graywater systems in all occupancies.

Although the use of graywater is a proven, cost-effective alternative to the use of potable water in various systems, many authorities are reluctant to approve these systems. Some reasons include the following:

- No generally accepted standard currently exists for the quality of recycled water. Several U.S. states, Japan, and the Caribbean have adopted codes and guidelines, but no nationally or internationally recognized standard has been created. This has resulted in rejection of the systems or long delays during the approval process of projects while the quality of the water is in question.
- Many regulatory and plumbing codes do not have any specific restrictions against using graywater or have ambiguous language that could be interpreted for its use, but whose officials impose special standards due to their lack of experience.

Table 2-7 Contaminant Concentration in Urban Storm Water

Contaminants Found in Runoff	Units	Average Concentrations[a]
Total suspended solids	mg/L	80
Total phosphorus	mg/L	0.30
Total nitrogen	mg/L	2
Total organic carbon	mg/L	12.7
Fecal coliform bacteria	MPN/100 mL	3,600
E. coli bacteria	MPN/100 mL	1,450
Petroleum hydrocarbons	mg/L	3.5
Cadmium	ug/L	2
Copper	ug/L	10
Lead	ug/L	18
Zinc	ug/L	140
Chlorides (winter only)	mg/L	230
Insecticides	ug/L	0.1 to 2
Herbicides	ug/L	1 to 5

[a]Concentrations represent mean or median storm concentrations measured at typical sites and may be greater during individual storms. Also note that mean or median runoff concentrations from storm water hotspots are two to 10 times higher than those shown here.
Units: mg/L = milligrams per liter; ug/L = micrograms per liter; MPN = most probable number

Table 2-8 Water Balance Worksheet

	Rainfall Available, gallons*	Anticipated Water Usage, gallons	Carryover, gallons
January	23,541	24,000 (800 gpd)	-459
February	18,925	24,000	-5,000
March	47,313	24,000	23,313
April	71,546	50,000	21,546
May	71,550	50,000	21,550
June	87,933	50,000	37,933
July	74,316	50,000	24,316
August	74,100	50,000	24,100
September	87,933	50,000	37,933
October	54,698	24,000	30,698
November	40,158	24,000	16,158
December	25,387	24,000	1,387

Although the use of graywater is ideal in certain circumstances, the success of graywater systems depends solely on public acceptance, and that requires an adequate educational effort. The use of colored water in water closets may not be attractive to the occupants of a newly occupied high-rise. Thus, educating the users of graywater is imperative. An understanding of the source and the associated dangers and limitations of graywater is essential to acceptance by the general public. To draw a parallel, the general public is now fully aware of the dangers of electricity, yet life without electricity is considered to be abnormal.

An economic analysis of graywater systems in healthcare facilities may favor dual-plumbing systems. However, the presence of viruses, bacteria, and biological contamination in healthcare graywater systems (through lavatories, bathtubs, showers, and sinks) may increase the cost of water treatment. Also, there is legitimate concern regarding the spread of disease through graywater systems that must not be overlooked. Therefore, the application of graywater systems in healthcare facilities may be a less-attractive option because of the possibility of biological contamination.

STORM WATER HARVESTING

Storm water harvesting and use for plumbing purposes is an additional option for sustainable design. The storm water harvesting system design frequently requires cooperation between the civil and mechanical design specialist. Storm water typically requires less treatment than graywater for toilet and urinal flushing and for irrigation.

Table 2-7 contains an example of storm water contaminant constituents.

The runoff in different geographical areas is affected by building patterns, salt or sand usage on roads and sidewalks, traffic, land use, building materials (such as lead flashings, galvanized roofs, or galvanized gutters and downspouts) and connected imperviousness.

A water balance can be conducted of the expected storm water collection by using the information from the National Oceanic and Atmospheric Administration's website (noaa.gov). This information will provide water balance inputs. More detailed information may be obtained from regional or local climate centers.

Table 2-8 provides an example of a water balance worksheet.

To determine the amount of rainfall available, use the following steps:

1. Divide the rainfall depth by 12 to convert the depth in inches to feet.
2. Multiply this number by 0.85 to take into account some loss over the impervious area.
3. Multiply this figure by the number of acres and then by 43,560 to convert the acreage to square feet.
4. Multiply this figure by 7.48 to convert to gallons.

The pervious area rainfall available will be based on the soil type.

Storm water harvesting is becoming an economical alternative in some areas. Treatment options may be similar to graywater for plumbing systems.

Frequently, a cartridge or bag filter and UV light system are adequate for storm water use for toilet and urinal flushing and lawn irrigation.

The economic analysis of storm water harvesting or graywater reuse systems can become the decisive issue that determines whether a system is even considered for a project. This analysis can be extrapolated for any other projects and variations.

Water shortages, government subsidies, tax incentives, the facility limitations of local governments, and population growth will be the primary motiva-

tors for designers and project engineers to consider reuse or storm water harvesting system selections in their designs.

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3 Vents and Venting

A component of a gravity drainage system, venting is a parallel arrangement of piping that limits the air pressure within the drain. By definition, venting is a separate piping system joined to the drainage system at certain connection points and sized to keep the air pressure in the drain from disturbing the water seals of fixture traps. Generally, the air pressure limit is 1 inch (25.4 millimeters) of water column, above or below atmospheric pressure. When the vent piping is of a sufficient diameter or limited in length, the permissible air pressure can be achieved.

Venting also allows air circulation, which prevents the accumulation of volatile substances in a drainage system. Such circulation is necessary for the installation of an interceptor, and some municipalities that have sewer problems warranting a house trap for each building require it.

Venting is not limited to sanitary drainage systems. Venting design principles are applicable to other drainage systems such as those for chemical waste, graywater waste, and clear water waste.

The design of a venting system is closely tied to the design of the drainage system. That is, the permissible velocities in the drainage system and its peak flow rates affect the diameters in the venting system. If sink drains are nonstandard or if the vertical distance between a fixture outlet and its trap outlet is excessive, then velocities in the entire drainage system will be greater than those assumed when vent sizing tables were tabulated.

Because they have no moving parts, vent systems are quiet, and they generally operate flawlessly for decades. However, these two virtues can disguise a fault in a drain and vent system if particular errors in the venting are unknown. These errors typically are related to the elevation of the horizontal portion of the venting.

The development of plumbing occurred across many broad geographical areas and at a time when communication was slow. Hence, a variety of interpretations exist regarding the details of venting, and the venting portions of plumbing codes vary greatly. Typically, vent sizing requirements are expressed as ratios of a vent diameter to the drain diameter. This design handbook, however, presents the engineering basis for venting, as well as the sizing tables of some model plumbing codes commonly enforced in the United States. Nonetheless, local plumbing codes should be consulted for the final requirements of a vent system design.

TRAP DESIGN

A fixture trap provides a water seal without significantly impairing flow. Figure 3-1 illustrates a sink trap with three pressure levels within a drain system, with no drainage occurring from the sinks and a fully open sink outlet. The principles of its trap design can apply to most other fixtures, except those with an intentional siphon action, such as a water closet.

In the first trap in Figure 3-1, the water level is even on both sides of the trap. That is, the air above the water on the drain system side has an atmospheric pressure identical to the air inside the room. The next trap shows the effect on the water levels if the atmospheric pressure on the drain system side increases by an amount that displaces the water downward by a ½ inch (12.5 millimeters). The water level rises on the room side by an equal amount, giving a 1-inch (25-millimeter) pressure difference. If the pressure increases to more than 2 inches (50.8 millimeters), air and other sewer gases will pass into the room.

The last trap in the figure shows the effect of negative pressure in the drainage system, which allows the atmospheric pressure of the room side of the trap to depress the water level by 1 inch (25 millimeters). The 1 inch of water on the other side is lost down the drain. When the pressure in the drainage system returns to neutral, the water levels will be 1½ inches (38 millimeters) above the dip point. If the negative pressure is subsequently more than 1½ inches (38 millimeters), air will be pulled from the room.

Another trap issue occurs when the momentum of water flowing from the sink causes most of the water to evacuate from the trap. When the pressure in the

drain returns to neutral, the water level may be below the dip point, and sewer gases will move freely from the drain system to the room. The loss of a trap seal is prevented by providing a fixture vent.

The pressure difference that causes a 1-inch (25.4-millimeter) deflection of water is 0.0361 pounds per square inch (psi) (0.249 kilopascals [kPa]).

In a good vent system design, the orientation of the vent pipe at its connection to a fixture drain is generally vertical or, at most, 45 degrees from vertical.

TYPES OF FIXTURE VENTS

Individual fixture vents and various alternative vent designs are commonly employed in plumbing systems. Some are mechanical; others use larger-than-normal drain diameters; and one recognizes the use pattern of private bathrooms. Still another addresses the vent connection limitations of island sinks.

Traditional alternative vent designs are generally part of most plumbing codes, while other alternative vent designs require a technical submission to the authority having jurisdiction (AHJ).

Common Vent

Figure 3-2 shows a common vent. It is suitable for lavatories, sinks, and floor drains. A similar design may serve water closets. The two fixtures connect at the same elevation with a vertical double-wye fitting. Some codes permit a double-sanitary tee, and others permit a horizontal branch with a horizontal double-wye whereby the vent connects downstream of the double-wye.

The vent is sized for the combined drainage fixture units of both fixtures. If two wall-outlet fixtures connect at different elevations, rather than what is shown in Figure 3-2, venting of the lower fixture is compromised. However, some codes permit this design, called a vertical wet vent, if the diameter between the two fixture connections is increased.

Wet Venting

Another wet vent design recognizes the usage of private fixture groups. That is, compared to public restrooms, a private bathroom is less likely to have two or three fixtures discharging into the drainage system simultaneously. Restricted to a water closet, a lavatory, and a bathtub or shower, the fixture branch of the water closet is downstream of the other fixtures and upstream of a stack or fixtures unrelated to the wet venting. An individual vent is connected only to the lavatory, and its drain is the vent for the other fixtures.

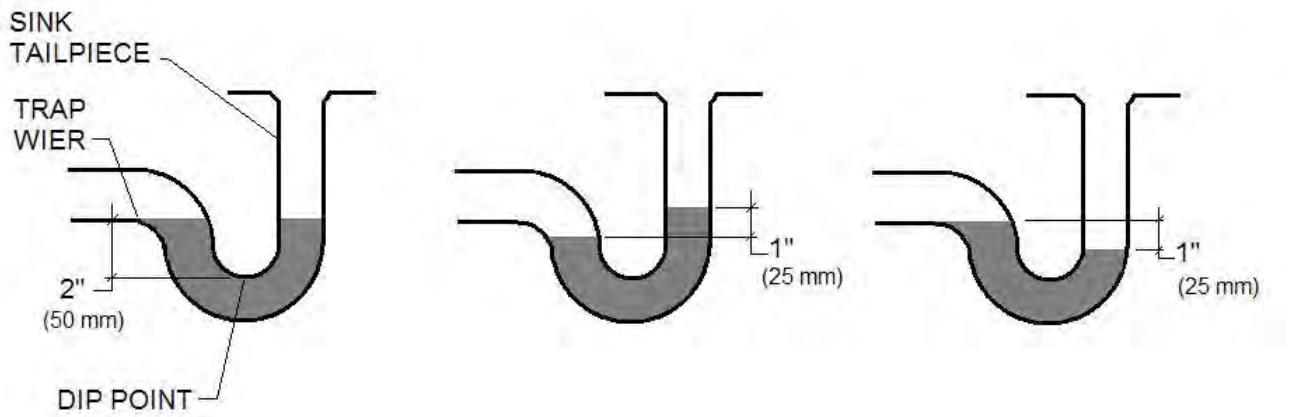
Various codes regulate the size of the wet vent, and some codes permit two bathroom groups with back-to-back lavatories connected with a common vent. Other codes permit a sink connection to the group, and others require a relief vent downstream of two bathroom groups.

Circuit Vent

Through a horizontal branch, many fixtures can be vented by one or two vents as shown in Figure 3-3. The branch is of uniform size for its distance between the connected fixture drains. Public toilet rooms typically use this design for venting floor-outlet water closets and floor drains. Various names are used for such venting, including circuit venting, loop venting, and battery venting. Typically, one vent connects between the two upstream fixtures, and the other vent connects downstream of the last fixture.

Codes vary in the details of the permissible design, usually with a limit of eight floor-outlet fixtures. Some codes permit a lavatory fixture branch to serve as either or both of the vent connections; hence, the fixtures of the circuit vent are also wet vented. With a generous diameter, the upper half of the cross-sectional area of the common horizontal branch is sufficient to prevent excessive pressures from affecting the trap seal of any non-flowing fixture in the group.

Figure 3-1 Sink Trap with Three Different Pressure Levels



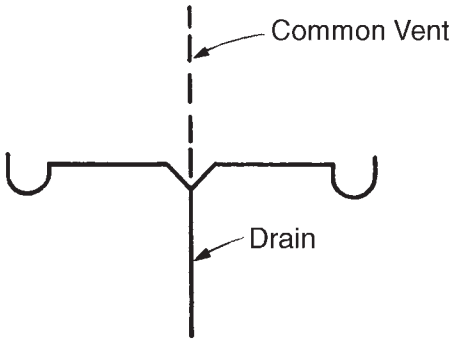


Figure 3-2 Common Vent for Two Sinks or Lavatories

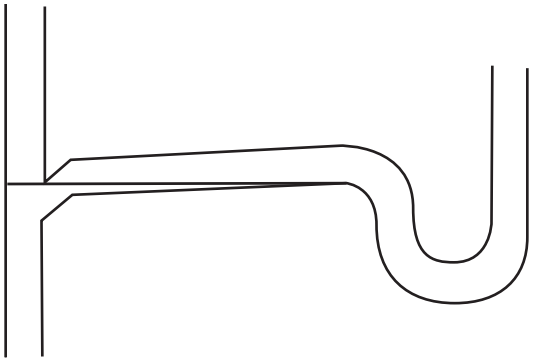
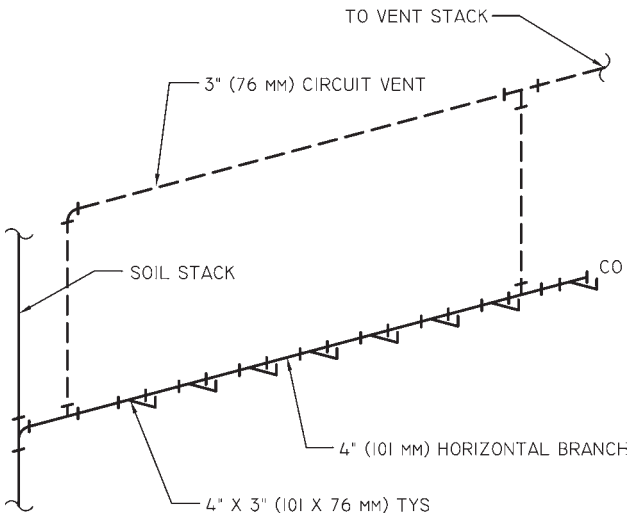
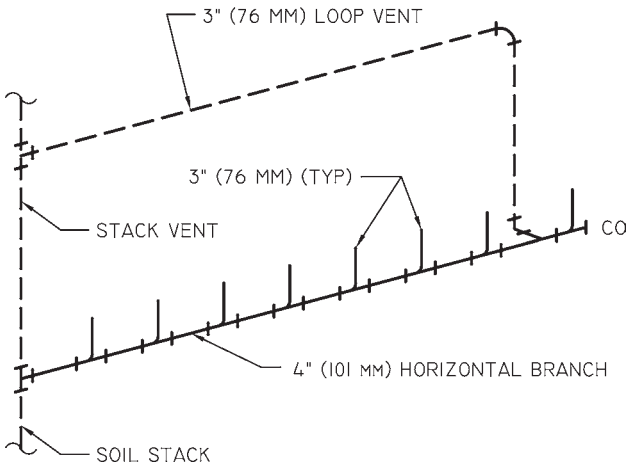


Figure 3-4 Vent Blocked by a Wye Fitting



Circuit Vent



Loop Vent

Figure 3-3 Circuit Vent Designs

Waste Stack

For circumstances with limited walls or little opportunity to provide a vertical vent pipe, other traditional venting designs are devised by employing a larger drain diameter. Called a waste stack, a vent is required only at the top of the drain stack. However, the advantages of a larger stack diameter, which limits air pressure within the core of air inside the stack, are not possible if the stack contains offsets.

The waste stack serves building designs that have identical wall layouts on multiple floors, but it does not accommodate varying wall locations between floors. Codes usually require each fixture to connect individually to the stack and the diameter to be constant from the base to the stack vent. Codes usually prohibit a water closet from being connected to a waste stack.

Combination Drain and Vent

Another design employed for circumstances with limited walls is called the combination drain and vent. Vent pipes at the upstream ends of a building drain are the only requirement. Unlike a drainage system served by individual vents, the building drain diameter in the combination waste and vent generally is increased by one commercial pipe size. Depending on the code, the vent pipe may be a drain stack, a single wall-outlet fixture, or a vent stack as a vertical extension from the building drain. The design is ideal for a column-free warehouse and for a basement that only has floor drains. The design is commonly used for venting the basement floor drain in residential construction.

Diameters, connection points, floor drain branch lengths, and possible downstream relief vents are prescribed in plumbing codes. Some codes permit a combination drain and vent in systems other than the building drain; other codes limit the types of fixtures connected to it, but some permit a limited number of water closets.

Island Vent

Similarly, a sink in casework that is not located near a wall requires an island sink vent. Unlike an individual vent that rises above the sink rim level before turning horizontal, an island vent turns horizontal just below the rim and drops below the floor. Depending on the code, it connects to a building drain that serves the sink. Other codes require a connection to the horizontal drain branch that serves the sink and to a vent stack in the nearest wall. Codes usually prescribe cleanouts and a pipe slope in the vent piping.

VENT SYSTEMS

The connection of a vent to a fixture drain should not be so close as to become clogged with debris washed through the trap, nor should it be so far away that it becomes blocked by water that will accumulate if downstream piping is obstructed. Figure 3-4 shows a vent blocked by backed-up water and a wye fitting. The vent is not blocked, for various connection orientations, if the location of the vent connection is less than the distances listed in Table 3-1.

From the vent connection, the vent pipe in a conventional system extends to the outdoors generally through a network of vent pipes. The open end of the pipe at the outdoor location, called a vent terminal, is generally above the roof, about 1 foot (300 millimeters) from its surface, and its diameter is of a generous size to prevent closure caused by frost buildup. A vent terminal location generally is restricted away from air intakes, doors, windows, and promenades. In addition, provision is made for expansion and contraction of the vent terminal relative to the roof membrane.

Where two vent pipes are connected, the horizontal pipes joining them are called vent headers or vent branches. The connection of two or more stack vents is called a vent header, while the connection of two or more fixture vents is called a branch vent.

Drainage basins that are pumped of their contents require a vent to replenish the lost volume with air that is at atmospheric pressure. This vent pipe allows the basin to be sealed from the building's air. Interceptors also may require an individual vent.

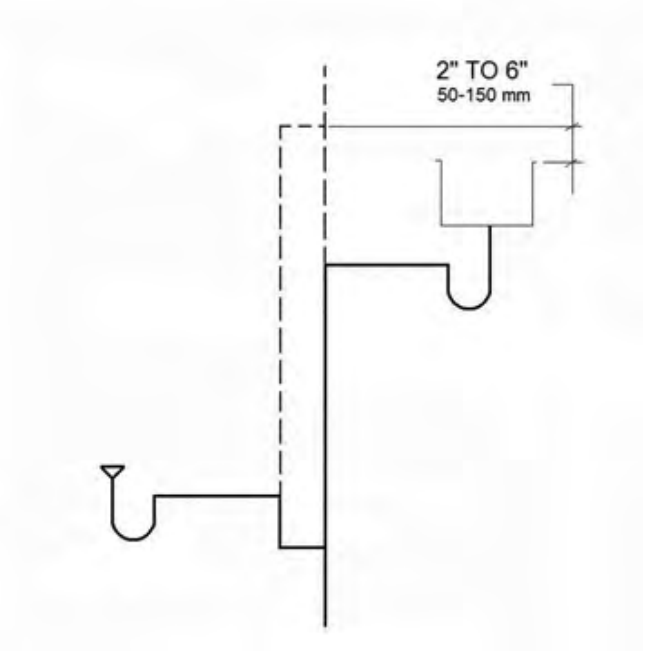


Figure 3-5 Two Vent Pipes Joined Above the Sink Rim

These vents may be combined to the other vents unless the interceptor requires isolation such as with chemical wastes.

All parts of a vent system, including the vent terminal, are independent of similar vent system types. That is, the sanitary vent system does not share its parts with the vent system of a chemical waste system, clear water system, graywater system, or steam vent system.

The piping material for vent systems can be identical to the drain system. The pressure test for the drain system often is applied to the vent system at the same time, with a few differences. Insulation that may be applied on drain piping that is prone to condensation is not applied to the vent piping, and the radii of elbows and tees are usually sharper than on drainage fittings.

For a fixture drain, the elevation of the horizontal portion of its vent is generally 2 to 6 inches (50.8 to 152 millimeters) above the rim of the fixture. Similarly, the elevation of a branch vent is 2 to 6 inches (50.8 to 152 millimeters) above the rim elevation of the highest connected fixture (see Figure 3-5). This elevation restriction prevents the fixture from functioning correctly when an obstruction occurs downstream of its vent connection. If the vent branch were at or below the fixture rim, drainage flow would divert to the vent of the lower fixture, and the obstruction would continue to be unnoticed.

Table 3-1 Maximum Distance of a Fixture Trap from a Vent Connection

Fixture Drain Diameter, in. (mm)	Slope, inch per foot (%)	Distance with Sanitary Tee, ft (m)	Distance with Wye Fitting, ft (m)
1.25 (32)	¼ (2)	3.5 (1.0)	1.5 (0.4)
1.5 (38)	¼ (2)	5 (1.5)	4 (1.2)
2 (51)	¼ (2)	6 (1.8)	4.5 (1.4)
3 (76)	¼ (2)	8 (2.4)	6 (1.8)
3 (76)	⅛ (1)	10 (3.0)	8 (2.4)
4 (102)	¼ (2)	10 (3.0)	8 (2.4)
4 (102)	⅛ (1)	12 (3.6)	10 (3.0)

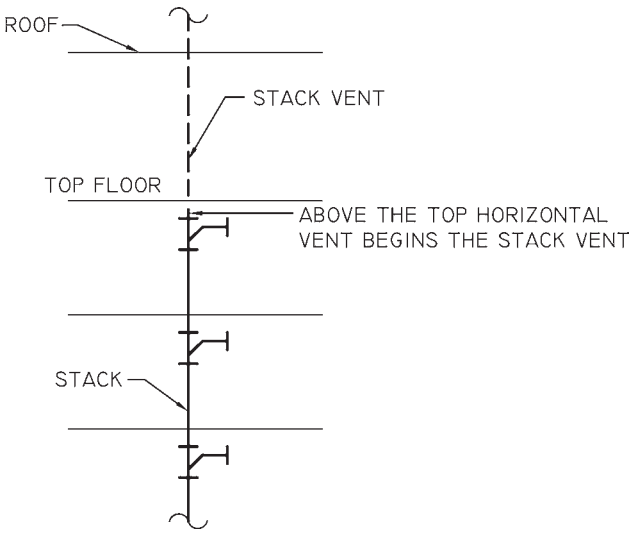


Figure 3-6 Stack Vent Joined to a Drain Stack

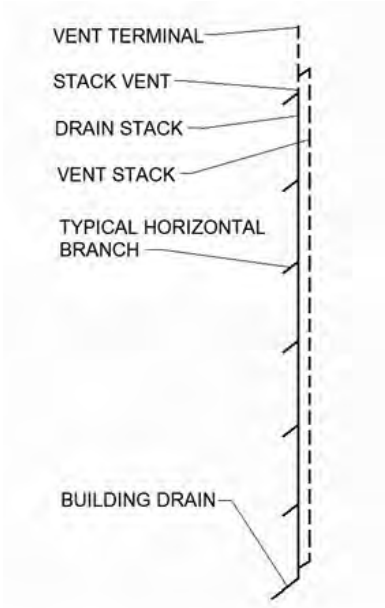


Figure 3-7 Vent Stack Joined to a Drain Stack

A horizontal vent pipe is installed with its slope, if any, favoring the drain stack so water is never trapped within the vent. Various restrictions on the horizontal length were based on an earlier belief that continuous airflow was required in venting to maintain trap seals. However, this has been disproven. Continuous airflow is required only if volatile substances are present, such as with certain interceptors or in city sewers.

VENT STACK DESIGN

Recall that the flow in a vertical drain stack consists of solids, a film of water around its interior surface, and a hollow core of air in the center. In approximately 50 feet (15 meters), the velocity reaches a maximum and remains constant for the remaining descent. At the base, the film transitions into an open channel flow in the lower half of the building drain, and air occupies the upper half of the building drain pipe. The major portion of the transition consists of a rapid shallow channel that abruptly converts to a deeper channel. This abrupt elevation change is called a hydraulic jump. Before the jump, the film dropping from the inside portion of the pipe bend creates a curtain that isolates the core of air in the stack from the air in the building drain. The hydraulic jump also may isolate the core of air. Hence, air pressure builds up in the core unless it's relieved.

In plumbing, the distance between floors can be regarded as an interval between branches connected to the drain stack. Such branch intervals are used as the basis for venting requirements, and the term allows some liberty regarding floors not having a connection to the stack.

For buildings with four branch intervals or less, a vent is connected at the top of each drain stack and extends upward to a vent terminal or a vent header (see Figure 3-6). This top connection is sufficient to relieve the air pressure in the core.

In a high-rise building, those with five or more branch intervals, a vent pipe is placed parallel to each drain stack to relieve the core air pressure. It connects at the base of the drain stack before the drain sweeps to a horizontal plane. The top end of the vent stack joins the vent that extends from the drain stack (see Figure 3-7). For buildings with 10 branch intervals or more, intermediate vent connections, called yoke vents, are made at every 10 branch intervals.

Sizing a Vent Stack

To size a vent stack, the vent diameter and length are determined from the maximum flow rate of the water and air flowing in the drain stack and passing toward its base. The downward moving air velocity in the core is equal to the terminal velocity of the water film. From the ratio of the cross-sectional area of the water to the entire pipe diameter, the flow rate of the air passing into and up the vent stack can be determined. When the vent stack is of a sufficient diameter, the pressure change due to friction along its length is no more than 1 inch (25.4 millimeters) of water column.

Example 3-1

For a 4-inch (102-millimeter) drain stack with water flowing at terminal velocity and covering 7/24 of the stack cross-sectional area, find the flow rates of water and air in the drain stack.

The ratio of the cross-sectional area is 7/24 = 0.292. From Chapter 1, Sanitary Drainage Systems, derive the water flow rate in the stack from the stack flow capacity equation. Thus, the water flow rate is $27.8 \times 0.2917^{1.667} \times 4^{2.67} = 144$ gpm. (From the stack capacity table in Chapter 1, the stack flow of water is 9.14 liters per second.)

From the same chapter, the terminal velocity is $3 \times (144 \div 4)^{0.4} = 12.6$ feet per second (fps). The cross-sectional area of the air core is found by subtracting the area of the water from the total area. Thus:

Total cross-sectional area = $4^2 \times \text{pi} \div 4 = 12.6$ square inches ($100^2 \times \text{pi} \div 4 = 7{,}854$ square millimeters)

Cross-sectional area of water = $12.6 \times 0.292 = 3.66$ square inches ($7{,}854 \times 0.292 = 2{,}291$ square millimeters)

Cross-sectional area of air = $12.6 - 3.66 = 8.93$ square inches ($7{,}854 - 2{,}291 = 5{,}563$ square millimeters)

The flow of air is the product of velocity and cross-sectional area. Thus, the airflow rate is $12.6 \times 8.93 \times 12 \times 60 \div 231 = 349$ gallons per minute (gpm) ($9.14 \times 5{,}563 \div 2{,}291 = 22.2$ liters per second).

A vent stack is sized based on the conservation of energy of the air circulating in a drain stack and a vent stack. Recall the following from Bernoulli's equation for an ideal flow between any two points along a flow stream, applicable in any consistent units of measurement:

Equation 3-1

$$\frac{P_1}{d} + h_1 + \frac{v_1^2}{2g} = \frac{P_2}{d} + h_2 + \frac{v_2^2}{2g}$$

where
P = Pressure
d = Specific weight
h = Height
v = Velocity
g = Gravitational acceleration

In an actual flow stream, a friction term, h_f, is added to the right side of the equation to represent the friction between the two points. For Point 1 of a vent stack being at the lower connection of a drain stack and Point 2 being at the top of the vent stack, the equation can be revised as follows:

Equation 3-2

$$\frac{P_1}{d} + \frac{v_1^2}{2g} = h_2 + \frac{v_2^2}{2g} + h_f$$

If the vent diameter is unchanged along the length of the vent stack, the velocity terms can be omitted. For the friction term expressed as $h_f = f \times ([v_2^2 \div 2g] \times [L \div D])$, the equation is:

Equation 3-3

$$\frac{P_1}{d} = h_2 + f \times \left(\frac{v_2^2}{2g} \times \frac{L}{D} \right)$$

where
f = Darcy-Weisbach friction factor
L = Pipe length, Point 1 to Point 2
D = Pipe diameter of the vent stack

Rearranging the terms to find the maximum length of a vent stack for a given diameter, we find Equation 3-4, which is for an adequate pipe length and diameter for the given air velocity and the permissible pressure drop.

Equation 3-4

$$L = \frac{(P_1/d - h_2) \times D}{f v_2^2/2g}$$

This general equation is applicable in U.S. customary units and SI units.

Alternatively, Equation 3-4 may be expressed in terms of the flow rate of air, q. Recall that $v = q \div (D^2 \text{pi} \div 4)$. Thus, for $h_2 = 0$, we have:

Equation 3-5

$$L = \frac{(P_1/d) \times D}{f \times (q/D^2 \text{pi}/4)^2/2g)}$$

Simplify this equation by recalling the density of standard air as 0.000044 pounds per cubic inch (0.0119 Newton per liter), 231 cubic inches = 1 gallon, and $P_1 = 0.0361$ psi (248.8 pascals). Thus,

$L = (0.0361 \div 0.000044) \times 2 \times 32.2 \times D^5 \times (\text{pi} \div 4)^2 \times (60 \div 231)^2 \div (fq^2)$

[$L = (248.8 \div 0.0119) \times 2 \times 9.824 \times D^5 \times (\text{pi} \div 4)^2 \times (1{,}000) \div (fq^2)$]

or

Equation 3-6

$$L = \frac{2{,}226\ D^5}{fq^2} \left[\frac{2.53 \times 10^8\ D^5}{f\ q^2} \right]$$

The unit for length is in feet (meters), diameter is in inches (millimeters), air flow is in gpm (liters per second), and f is dimensionless.

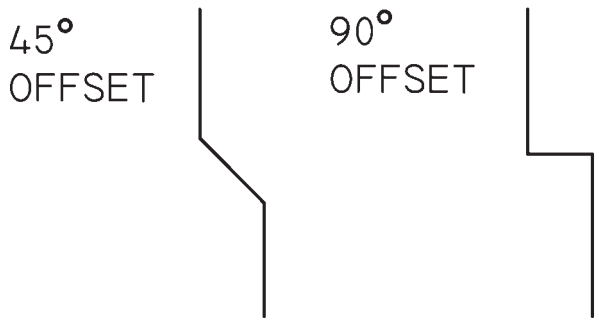


Figure 3-8 Drain Stack Offsets

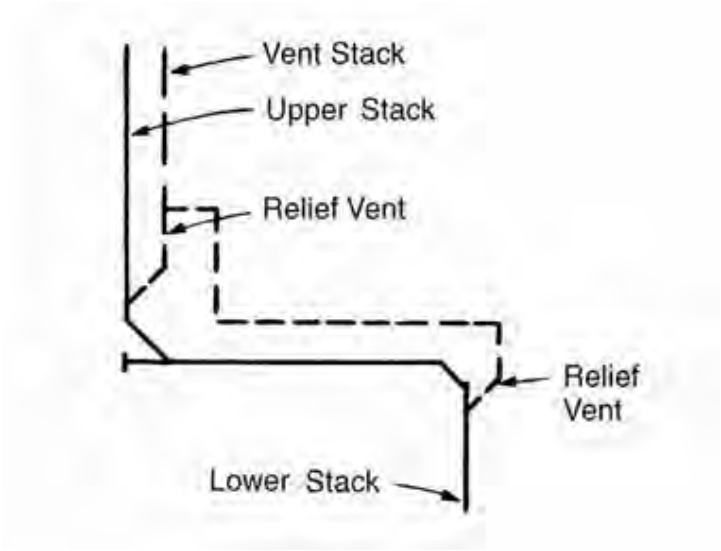


Figure 3-9 Relief Vents at a Drain Stack Offset

Example 3-2

For a 4-inch (102-millimeter) vent pipe with terminal air velocity flowing at 349 gpm (22 liters per second), find the friction factor, f, for a rough steel interior surface and find the maximum length of the vent pipe for 1 inch (25.4 millimeters) of water column between the two end points of a vent stack. Assume air at standard pressure and a temperature of 50°F (10°C).

At standard pressure, the specific weight of air is 0.0760 lbf/ft^3 (and its density is 1.218 kg/m^3). At 50°F (10°C), the viscosity of air is 0.0000004 lbf-s/ft^2 (0.000019 N-s/m^2). The velocity is 0.4085 x 349 ÷ 4^2 = 8.91 fps (2.68 meters per second). Thus, the Reynolds number, R, is:

$$R = 4 \times 8.91 \times 0.0760 \div (0.0000004 \times 32.2 \times 12) = 17{,}500$$

$$[R = 0.102 \times 2.68 \times 1.218 \div (0.000019) = 17{,}500]$$

The roughness to diameter ratio is:

$$0.00030 \div 0.333 = 0.00090 \; [0.000091 \div 0.102 = 0.00090)$$

From the Moody diagram, f = 0.029. Thus:

$$L = 2{,}226 \times 4^5 \div (0.029 \times 349^2) = 645 \text{ feet}$$

$$[L = 2.53 \times 10^8 \times 0.102^5 \div (0.029 \times 22.0^2) = 195 \text{ meters}]$$

Assumptions for this solution are as follows:

- The properties of air are at standard pressure and with a temperature of 50°F (10°C).
- Pressure drop is 0.0361 psi (248.8 pascals) or 1 inch (25.4 millimeters) of water column.
- A terminal velocity is occurring.
- Pipe is straight and of uniform diameter, there are no fittings, and the interior roughness is 0.00030 (0.000091) (twice that of new steel pipe).
- Pipe diameter is a nominal value rather than the actual inside diameter. An actual diameter will greatly affect length determinations since the diameter is raised to the fifth power in Equation 3-6.
- The air velocity in the vent stack is the same as in the drain stack. Actually, the air velocity in the vent stack may vary from the velocity in the drain stack.
- The circulation of air is down the drain stack and up the vent stack. Other changes in the volume of air in the drain stack, from transient water flows, will involve airflow in or out of the vent terminal.
- Stack height is negligible relative to the permissible pressure drop.

In a technical submission to the authorities having jurisdiction, these assumptions may be adjusted to the actual conditions to provide a more accurate determination of the vent length.

Offsets

If the drain stack is not vertical from its top branch to the building drain, other air pressure-restricting conditions will occur where the stack changes direction. Figure 3-8 illustrates several types of offsets of a drain stack. At the upstream end of each offset, the air is blocked in the same way it is blocked at the base of a drain stack. Hence, a vent connection point, called a relief vent, is added to the drain stack if there are drain branch connections below the offset.

For 90-degree offsets, a relief vent is provided upstream and downstream of the horizontal portion of the offset as shown in Figure 3-9. For 30- and 45-degree offsets, a vent relief is provided upstream of the offset. The diameter of the relief vent matches the vent stack. The connection of the upper end of the two reliefs generally is prescribed to be a certain distance above the floor.

Suds Pressure Zones

Another air restriction in plumbing occurs from detergents whose suds collect at the base of a drain stack, in a stack offset, and in a bend of the building drain. The affected areas are called suds pressure zones as shown with double lines over the pipes in Figure 3-10. The suds are displaced by water and solids, but not by air. Hence, for stacks loaded with laundry discharges, branches should not be connected to these zones, and an additional vent connection is required at the base of the stack above the suds-pressure zone.

Main Vent

A vent for the building drain is referred to as the main vent. Connecting from the building drain to a vent terminal or vent header, it relieves any pressure variation in the building drain. In some codes, a drain stack or vent stack qualifies as the main vent.

FIXTURE VENT DESIGN

The nature of water flow in a drain system is transient regarding which fixtures are flowing and the pattern of the flow with respect to time. However, the concern of the designer is the maximum flow rate. This rate is generally at the start of a fixture discharge.

At each fixture, air pressure at the vent connection increases as a discharge of water and solids approaches the connection. When the bulk of the water passes, air pressure drops below ambient and the air flow rate matches that of the water flow rate. This behavior pattern of the water and air is recognized especially in long horizontal branches. The water flow stabilizes into a steady flow occupying the lower half of the drain pipe. The upper half is occupied with air moving at the same velocity. Hence, the flow rates are identical.

As in vent stack sizing, the size of an individual fixture vent is determined from the air flow rate, the vent pipe diameter, and the vent pipe length to the vent terminal. For venting with changes in direction, equivalent lengths of straight pipe are added for each vent fitting. Hence, its actual length plus the equivalent lengths is the developed length.

Example 3-3

Find the maximum length of a 1.5-inch (38.-millimeter) vent serving a water closet connected to a 3-inch (10-millimeter) horizontal drain branch. Assume that the drain branch is sloped at 1 percent and its flow rate is no more than 45 gpm (2.84 liters per second).

Since the drain branch is half full, the water flow rate and air flow rate are identical at 45 gpm (2.84 liters per second). The velocity of the air in the vent is $0.4085 \times 45 \div 1.5^2 = 8.17$ fps (2.49 meters per second). The Reynolds number, at properties similar to Example 3-2, is:

$$R = 1.5 \times 8.17 \times 0.0760 \div (0.0000004 \times 32.2 \times 12) = 6{,}000$$

$$[R = 0.0381 \times 2.49 \times 1.218 \div (0.000019) = 6{,}000]$$

The roughness to diameter ratio is:

$$0.00030 \div 0.125 = 0.0024 \; [0.000091 \div 0.0381 = 0.0024].$$

From the Moody diagram, $f = 0.0385$. Thus, the maximum developed length of the vent pipe, before its air pressure exceeds 1 inch (25.4 millimeters) of water column, is:

$$L = 2{,}226 \times 1.5^5 \div (0.0385 \times 45^2) = 210 \text{ feet}$$

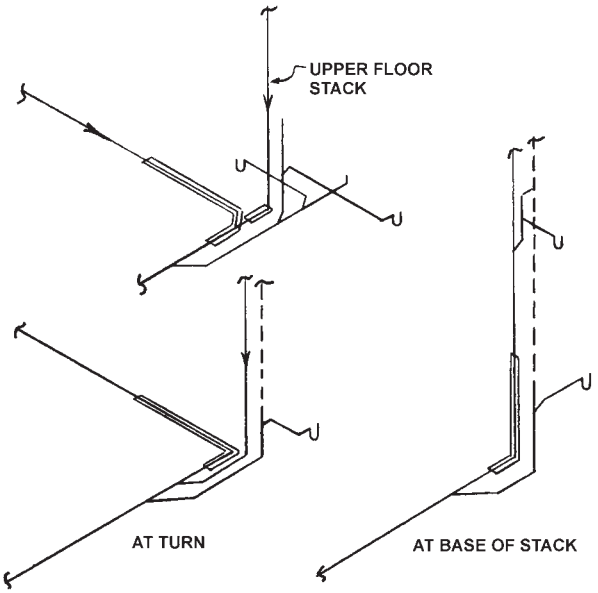
$$[L = 2.53 \times 10^8 \times 0.0381^5 \div (0.0385 \times 2.84^2) = 65 \text{ meters}]$$

Vent pipes on fixtures connected to the building drain are not different than those connected to a horizontal branch. Like the horizontal branch, the water flow in the building drain branch stabilizes into a uniform pattern occupying the lower half of the pipe. Air in the upper half flows at the same velocity as the water in the lower half. If the fixture in Example 3-3 were connected to the building drain rather than a horizontal branch, the determination of the vent length, by using Equation 3-6, is found in the same way.

For two fixtures with individual vents, the airflow in the vent branch serving them is determined from combining the air flow rates of each fixture. The vent length is selected for the fixture furthest from the vent terminal.

The composite effect of multiple fixtures for any part of the drain system generally is decided on a 99 percent probability, assuming such a rare event is random. The tabulation of drainage fixture units from each connected fixture provides an easy determination of drain loading. It can be applied to any grouping of fixtures or the entire building.

A corresponding load on the vent system is determined in the same way. That is, drainage fixture units can be noted at each section of vent piping from the accumulation of fixture units served by that section of vent piping. A capacity table for fixture venting can be formulated with drainage fixture units, vent diameters, and vent lengths. Equation 3-6 provides the relationship between airflow, vent diameter, and vent length. Building drain pipe diameters are selected based on drainage fixture units. Drain capacities, in gpm (liters per second), are calculated by the Manning formula. Hence, for each commercial pipe diameter, drainage fixture units can be matched to the gpm (liters per second) values of water flow and equal amounts of airflow.



Note: Double lines represent suds pressure zones. Shown are connections outside the pressure zones.

Figure 3-10 Suds Pressure Zones

For example, a 5-inch (12-millimeter) building drain sloped at 1 percent is permitted no more than 390 drainage fixture units. The Manning formula, with n = 0.013, determines the stabilized water flow rate and air flow rate to be 77 gpm (4.86 liters per second). Thus, the vent branch for all of the fixtures contributing to the 390 drainage fixture units can be sized at 77 gpm using Equation 3-6.

ALTERNATIVE VENT SYSTEMS

Nonstandard alternative vent designs require a technical submission to the authority having jurisdiction. The submission may be a one-time submission of a product, or it may be a submission of each building using the alternative design. The submission includes all of the technical engineering requirements that are necessary for the intent of the code to be recognized by the authority.

Air-admittance Valves

A design method employing a special check valve at an individual vent connection and a pressure attenuator near the base of a drain stack is an alternative vent system. The check valve, or air-admittance valve, allows air into the drain branch when negative pressure conditions occur. When positive or neutral pressure occurs, the check valve closes. The location of an air-admittance valve is at each fixture or group of fixtures, similar to traditional venting. The vent can be located within casework but not within a wall without a louver. Manufacturers and code officials have various other specific installation limitations.

When positive pressure occurs at the base of a drain stack, a pressure attenuator momentarily absorbs the pressure increase before any nearby fixture trap is affected. A butylene bladder expands inside the device up to 1 gallon (3.78 liters), which effectively relieves the pressure surge. Pressure attenuators also are installed every three to five floors for buildings with more than 10 floors.

For vent systems using air-admittance valves, a main vent with a vent terminal and a connection to the building drain are required to relieve positive vent pressure. Drainage sumps also require traditional venting. Otherwise, individual vents are eliminated from the design. A stack vent with a vent terminal also is eliminated for stacks of six branch intervals or less.

For chemical waste systems, the compatibility of the chemicals must be within the recommendations of the admittance valve manufacturer.

Sovent Systems

The high velocity in a drain stack is prevented significantly in the Sovent design through special fittings. This proprietary design is suitable for a multistory building. The fittings eliminate the vent stack and many of the individual vents. The aerator fitting, spaced at each floor, prevents the occurrence of a terminal velocity and allows a water closet flow stream to join the stack flow without disrupting the air core. A deaerator fitting at the bottom allows the air core pressure to be relieved into the building drain. The deaerator fitting also is installed at the upstream end of a horizontal offset. Where a water closet is not connected to a stack, the terminal velocity is controlled at that floor level by installing two 45-degree stack offsets or an inline offset.

Fixtures connected to the building drain require individual vents, and fixtures on horizontal branches require individual vents if they are beyond the limits of the *Sovent Design Manual*. However, these individual vents can connect to the Sovent drain stack rather than a vent stack. The design manual also has various other requirements including fixture unit assignments, stack capacities, branch capacities, vent header sizing, and building drain sizing.

Table 3-2 IPC Sizes of Individual Vents and Vent Branches

Drainage Fixture Units	Minimum Permitted Vent Diameter, in. (mm)	
	Developed Length Less than 40 ft (12 m)	Developed Length More than 40 ft (12 m)
1	1.25 (32)	1.5 (38)
2	1.25 (32)	1.5 (38)
3	1.25 (32)	1.5 (38)
6	1.25 (32)	1.5 (38)
12	1.25 (32)	1.5 (38)
20	1.5 (38)	2 (51)
160	2 (51)	2.5 (64)
360	2.5 (64)	3 (76)

Single Stack

The design of the single stack, or Philadelphia stack, provides an installation economy and saves space in multistory buildings. Vent stacks and many individual vents are eliminated. Through larger stack diameters, the air core is relieved inside the stack and, through larger branches and traps, fixture trap seals are maintained. Other features include fixture fittings that replenish water in the trap.

JURISDICTIONS

Vent requirements vary geographically depending on the authority having jurisdiction. In the United States, two model codes predominate. The International Plumbing Code (IPC) is published by the International Code Council, and the Uniform Plumbing Code (UPC) is published by the International Association of Plumbing and Mechanical Officials.

Vent stacks can be sized to IPC requirements using a table in the code when you know the drain

stack diameter, drainage fixture units at the base of the stack, and developed length of the vent. Stack vents are sized similarly. For ease of sizing a vent for an individual fixture or a branch vent for a group of fixtures, Table 3-2 provides a convenient reference. It was created by relating drainage fixture units to drain diameters and the IPC requirement for vent diameters to be one-half of the drain diameter but no less than 1.25 inches (32 millimeters). The third column shows a one-increment pipe size increase, per IPC, when the developed length is greater than 40 feet (12 meters).

Vent piping can be sized to UPC requirements using Table 3-3, given the drainage fixture units, developed length, and horizontal length. Columns four and five are derived from specific UPC requirements. The cross-sectional area of the pipes in column five are provided in column six as a convenience to meeting the additional UPC requirement that the sum of the area of all vents of a building shall not be less than the area of the sewer serving the building.

Example 3-4

For a vent branch serving a group of fixtures with 12 drainage fixture units, find its minimum diameter in the IPC code and the UPC code given a developed total length of 100 feet of which 45 feet are horizontal.

From Table 3-2, for 12 drainage fixture units, the minimum vent diameter is 1.5 inches (38 millimeters). From Table 3-3, the values for 24 drainage fixture units must be used since the row above is less than 12. Because the permitted horizontal length is less than 45 feet, refer to column five for the minimum vent diameter of 2.5 inches (64 millimeters).

CONCLUSION

As part of a gravity drainage system, venting is a parallel arrangement of piping that limits the air pressure within the drain system. It is a separate pipe joined to the drain at certain connection points and generally is sized to avoid an air pressure in the drain system beyond 1 inch (25.4 millimeters) of water column above or below atmospheric pressure. When the vent piping is of sufficient diameter or its length is limited, the range of air pressure can be achieved in the drainage system. Vent pipe sizing varies between vent stacks and fixture vents.

Economy in the amount of vent piping is achieved by alternative designs such as a common vent, wet vent, circuit vent, waste stack, and combination waste and vent. Other alternative vent systems include air-admittance valves, Sovent systems, and the single-stack system.

Particular requirements in a vent system design vary greatly with local plumbing codes, which should be consulted in a final design.

Table 3-3 UPC Sizes of Any Vent

Drainage Fixture Units	Vent Size with Length Restrictions			Minimum Vent Diameter Without Length Restrictions, in. (mm)	Cross-sectional Area of Pipe, in.^{2} (mm^2)
	Minimum Diameter, in. (mm)	Maximum Length, ft (m)	Maximum Horizontal Length, ft (m)		
1	1.25 (32)	45 (13.7)	15 (4.5)	1.5 (38)	1.77 (1,140)
8	1.5 (38)	60 (18.2)	20 (6.1)	2 (51)	3.14 (2,030)
24	2 (51)	120 (36.6)	40 (12.2)	2.5 (64)	4.91 (3,170)
48	2.5 (64)	180 (54.9)	60 (18.2)	3 (76)	7.07 (4,560)
84	3 (76)	212 (64.6)	70 (21.3)	4 (102)	12.57 (8,110)
256	4 (102)	300 (91.4)	100 (30.5)	5 (127)	19.6 (12,600)
600	5 (127)	390 (119)	130 (39.6)	6 (152)	28.3 (18,200)
1,380	6 (152)	510 (155)	170 (51.8)	8 (203)	50.3 (32,400)
3,600	8 (203)	750 (229)	250 (76.2)	10 (254)	78.6 (50,700)

4 Storm Drainage Systems

Storm water systems may convey rainwater from building roof drains, area drains, subsoil drains, and foundation drains to a point of discharge, subsurface dispersal, or reuse. Some jurisdictions allow (or require) the discharge from clear water drainage systems to be included in the storm water system. These discharges should not include contaminants that exceed applicable ground or surface water standards established by the authority having jurisdiction (AHJ).

Building sites may be provided with conveyance piping for draining paved areas, parking lots, vegetated areas, and all other areas where the storm water could damage a structure or present a health or safety hazard to the public.

Storm water subsurface dispersal is controlled to protect groundwater quality and sometimes to enhance groundwater quantity (aquifer recharge).

The Clean Water Act, implemented by the U.S. Environmental Protection Agency (EPA), impacts construction site owners where one or more acres of land are disturbed during a construction project or where the land disturbance is part of a common plan of development. These owners are required to file a Notice of Intent to obtain a National Pollutant Discharge Elimination System (NPDES) permit prior to land disturbance. The NPDES permit includes the erosion control requirements to be used during the construction phase until final stabilization of the building is achieved. During the construction period, all storm water inlets are protected from construction site sediment.

The NPDES permit language includes a requirement for a post-construction storm water management plan. The plan must address the control of overland runoff from the site and of storm water within the storm water conveyance and infiltration systems (as these systems also provide a means for the storm water to exit the property). Some AHJs require a system to be provided to safely pass the 100-year, 24-hour storm, so the plumbing engineer must verify and review any local requirements during the design phase of the project. For more information on the NPDES system and the Clean Water Act, contact the AHJ or visit the EPA websites (cfpub.epa.gov/npdes and epa.gov/watertrain/cwa).

The AHJ also regulates the discharge point (municipal sewer, combined sewer, ground surface, subsurface, etc.) for storm water systems. Storm water systems may be designed for gravity flow to a point of discharge. Where this is not possible, elevating the storm water for discharge (using a pump, ejector, etc.), on-site infiltration, or storm water harvesting may be considered. Depending on the AHJ's requirements, a redundant (or backup) pump system may be mandatory. Some AHJs allow depressed areas on the site where the storm water is collected and allowed to remain until evaporation, transpiration, or infiltration allows the storm water to disperse into the environment. Detention basins, tanks, roof systems, or piping also are used to store rainfall and release the storm water over a designed period. Frequently these releases are required to replicate the hydrograph for the pre-construction site.

CODES AND STANDARDS

Storm water system design is one area of plumbing engineering that relies on several different types of laws, codes, and standards. The environmental protection laws establish authority for groundwater and surface water protection. Environmental agencies regulate watersheds based on specific local conditions. Local ordinances and the design of the municipal sewer, as well as approved management plans, may impact storm water designs. Building codes and the architectural design of the structure are limiting factors in the storm water design. The plumbing engineer is part of a design team that uses all of the codes and standards to comply with site-specific conditions and rules.

The model plumbing codes establish a minimum acceptable standard for the design and installation of storm water systems. Some states and large cities have adopted plumbing codes other than those usually associated with the region, and because of this

lack of standardization, the actual plumbing code used for each specific project must be obtained from the AHJ.

The applicable local codes, ordinances, and laws are the primary sources used for the storm water design. The tables and charts appearing in this chapter are used only to illustrate and augment this discussion and may not be appropriate for actual design purposes.

MATERIALS

Materials include piping, fittings, bedding, supports and hangers, fixtures, and treatment devices. Materials must be acceptable to the AHJ.

While creating the material specifications, research and follow all manufacturer requirements and limitations. Exposed leaders or downspouts should be capable of withstanding all anticipated abuses, corrosion, weather, and expected expansion and contraction.

See other *Plumbing Engineering Design Handbook* chapters on materials and joining methods for more information.

SITE DRAINAGE AND INFILTRATION

In the past, one of the basic plumbing principles required system designs to conduct storm water quickly from the site inlet to the point of discharge. However, that principle does not adequately address current storm water issues. Codes are being revised to change the drain system requirement from "quickly" to "efficiently."

The plumbing engineer's involvement with storm water management has been expanded to address the evaluation of the precipitation and runoff from the site. Thus, to design infiltration, detention, or small-diameter piping systems, the science of hydrology and the calculation of runoff for each particular site are necessary considerations.

The hydrology of a storm event is the basis for all storm system designs including pipe sizing, treatment devices and methods, detention systems, infiltration systems, and every combination imaginable. Webster's defines hydrology as "a science dealing with the properties, distribution, and circulation of water." The hydrology of a storm event limits this study to a particular precipitation event and the fate of the water that falls during that event.

All methods used to determine volumes and peak flows use historical data. Such precipitation and frequency information can be found on the National Oceanic and Atmospheric Administration's National Weather Service website (nws.noaa.gov).

Rainfalls and snowstorms occur as a series of events that have characteristics including rainfall amount, intensity, and duration. To design a storm water system, a particular storm event must be chosen. This is known as the design storm. Fortunately, most plumbing codes provide pipe sizing charts based on geographic area and time of concentration, so the designer does not need to calculate the peak flow rate. However, infiltration and reuse systems require the volume of the storm event to be determined.

When no typical conditions exist, a design frequency of 10 years typically is used for an average site. For the purpose of system design, when recommending a 10-year storm, it's necessary to also specify the duration of the storm. For example, an intensity-duration-frequency curve for Madison, Wisconsin, may show that a 10-year, 60-minute storm has a rainfall intensity of 2 inches per hour. In the same city, a 10-year, 15-minute storm has a rainfall intensity of approximately 4 inches per hour. For small sites, this is probably a logical number for estimation, as the time of concentration for a small site may be 10 to 20 minutes. However, many design manuals recommend a smaller time of concentration for small sites, such as 5 minutes.

Different design storms also are used for varying situations or purposes. For instance, the *Minnesota Urban Small Sites Best Management Practice Manual* states that two- and 10-year storms are used for subdivisions, industrial, and commercial design. One- and two-year storms are used to protect channels from sedimentation and erosion. Five- and 10-year events are used for adequate flow conveyance and minor flooding consideration. The 100-year storm defines the limits and flood plains and is used to consider the impacts of major floods.

Table 4-1 Coefficients for Use with the Rational Method

Type of Surface or Land Use	Coefficient of Runoff (c value)
Individual soil covers	
Forest	0.1 – 0.3
Turf or meadow	0.1 – 0.4
Cultivated field	0.3 – 0.4
Steep grassed area (2:1)	0.5 – 0.7
Bare earth	0.2 – 0.9
Gravel or macadam pavement	0.35 – 0.7
Concrete or asphalt pavement	0.8 – 0.9
Composite land uses	
Flat residential, about 30% impervious	0.40
Flat residential, about 60% impervious	0.55
Sloping residential, about 50% impervious	0.65
Flat commercial, about 90% impervious	0.80

The Rational Method

Many jurisdictions accept the Rational Method for calculating peak flow rates. The Rational Method was developed to identify peak flow for pipe and culvert sizing. It translates peak intensity of rainfall directly into peak intensity of runoff. When using the Rational Method for pipe sizing on small sites, the time of concentration should equal the intensity, as those parameters create the highest peak flow rate.

For a small site, a rate in cubic feet per second (cfs) can be calculated once the intensity is entered into the Rational Method formula.

The Rational Method is illustrated in Equation 4-1.

Equation 4-1

$$Q = Aci$$

where
Q = Runoff, cfs
A = Drainage area, acres (1 acre = 43,560 square feet)
c = Coefficient of runoff, a dimensionless number
i = Rainfall intensity, inches per hour

(There's a hidden correction factor of 1.008 cfs per a-in./hr.)

Example 4-1

As an example, consider a 1.5-acre site with a concrete or pavement cover (0.90 runoff coefficient) and a 4-inches/hour rainfall. The equation would be:

Q = 1.5 x 0.90 x 4 = 5.4 cfs (448.8 x 5.4 = 2,423.5 gallons per minute [gpm])

The Rational Method provides a peak flow rate. Using it, a designer can size a piping system to safely carry the peak flow to a treatment device or to a point of dispersal or discharge. The Rational Method was not intended to be used to calculate volume, so it does not provide any information for the designer of a detention or infiltration system.

Runoff Patterns

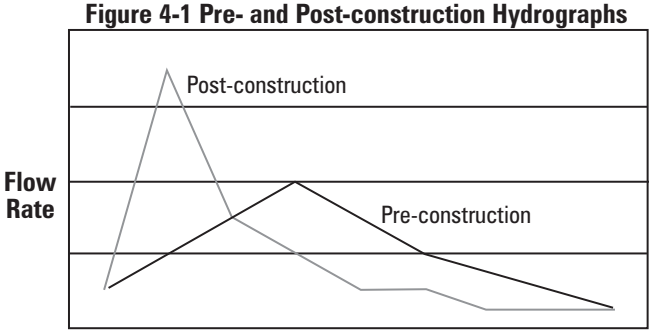
The runoff coefficient, or c value, can be found in the applicable local code or design manual. Table 4-1 is an example of such a table.

Figure 4-1 illustrates two hydrographs. One shows the runoff pattern prior to construction, and the other shows the runoff pattern after development on the same site. It's evident that the flow rate increases and decreases more quickly in areas that have been developed. It's also evident in Figure 4-1 that the peak flows are higher in a developed area than in predevelopment conditions.

Typically, these changes in hydrology affect the local environment in the following ways:

- The frequency and severity of flooding increases because peak flows are two to five times higher than before development.

Figure 4-1 Pre- and Post-construction Hydrographs



- Nearby streams become "flashy," or tend to flash flood because high flows occur quickly and affect stream levels.
- Base flow is reduced because the infiltration of storm water into shallow aquifers that provide the dry period feed for small streams is reduced. Streams that once flowed year-round disappear.

Flooding occurs downstream at higher elevations than prior to urbanization. Under normal conditions, a stream develops a channel to accommodate a two-year storm (a storm that usually occurs no more than once every two years). Development along the stream increases impervious area and runoff. As peak flows increase, the banks of the stream widen.

Storm Water Quality

Impervious areas such as roofs, parking lots, and roads accumulate contaminants from vehicles, the atmosphere, and animals. Rainfall washes these contaminants from the impervious surface and deposits them into the groundwater, surface water, or soil unless a treatment device is used.

Table 4-2 lists common urban contaminant levels in runoff. The runoff in a specific geographical area is affected by building patterns, salt or sand usage on roads and sidewalks, traffic, land use, building materials (such as lead flashings, galvanized roofs, or galvanized gutters and downspouts), and connected imperviousness. For example, Table 4-3 contains mean values that are specific to the state of Wisconsin.

As illustrated by Tables 4-2 and 4-3, the number of bacteria in storm water is lower than the number in domestic wastewater. However, storm water does contain pathogenic (disease-causing) bacteria such as Shigella (causes bacillary dysentery), Pseudomonas aeruginosa (causes swimmer's ear and skin infections), and pathogenic E. coli. Viruses also can travel in storm water runoff. In fact, according to *Groundwater Contamination from Storm Water Infiltration,* viruses have been found in groundwater below infiltration ponds where no indicator bacteria are present.

Estimating Time of Concentration and Rainfall Intensity

As previously stated, the Rational Method assumes that a storm duration matching a drainage area's time of concentration produces the greatest runoff rate, so to be more accurate than simply assuming a number, the time of concentration could be estimated by using an appropriate procedure. The FAA (Federal Aviation Agency) has developed a simple formula for use with the Rational Method that can be used to define the time of concentration for a site.

Equation 4-2

$$t_c = [1.8(1.1 - c)L_h^{1/2}]G^{-1/3}$$

where
t_c = Time of concentration, minutes
c = Cover factor in the Rational Method formula
L_h = Hydraulic length, feet
G = Slope along the hydraulic length, percentage

This formula was further simplified by Bruce Ferguson in his text *Introduction to Storm Water.*

Equation 4-3

$$t_c = L_h^{1/2} c_g$$

where
t_c = Time of concentration, minutes
L_h = Hydraulic length, feet
c_g = Factor combining everything except hydraulic length

These time of concentration equations are depicted in chart format in Figure 4-2.

After the time of concentration has been calculated, it must be applied to the design storm for the site. Frequently the 10-year storm is used; however, as stated before, the length of the design storm is based on the control intent.

Another way to estimate figures in the Rational Method equation is to use rainfall intensity-duration-frequency curves. For instance, Figure 4-3 shows the intensity-duration-frequency curves for Madison, Wisconsin. Using a time of concentration of approximately seven minutes and a 10-year storm, the rainfall intensity that would be used in the Rational Method is approximately 5.5 inches per hour. If one were designing for the two-year storm, the intensity would be about 4 inches per hour.

Other Resources for Calculating Runoff

Technical Release 55 (TR-55): *Urban Hydrology for Small Watersheds* by the U.S. Department of Agriculture's Natural Resources Conservation Service was designed to provide a simplified procedure to calculate storm water runoff volume, peak flow, hydrographs, and storage volumes required for storm water management structures.

TR-55 is a model. The new Windows version has specific capabilities and limitations, including those shown in Table 4-4.

Table 4-2 Contaminant Concentrations in Urban Storm Water

Contaminant	Unit[a]	Average Concentration[b]
Total suspended solids	mg/L	80
Total phosphorus	mg/L	0.30
Total nitrogen	mg/L	2.0
Total organic carbon	mg/L	12.7
Fecal coliform bacteria	MPN/100 mL	3,600
E. coli bacteria	MPN/100 mL	1,450
Petroleum hydrocarbons	mg/L	3.5
Cadmium	ug/L	2
Copper	ug/L	10
Lead	ug/L	18
Zinc	ug/L	140
Chlorides (winter only)	mg/L	230
Insecticides	ug/L	0.1 – 2.0
Herbicides	ug/L	1 – 5.0

[a] Units: mg/L = milligrams/liter, ug/L = micrograms/liter, MPN = most probable number
[b] Concentration represents the mean or median storm concentration measured at typical sites and may be greater during individual storms. Also note that mean or median runoff concentrations from storm water hotspots are two to 10 times higher than those shown here.
Source: *Manual on the Design and Construction of Sanitary and Storm Sewers,* American Society of Civil Engineers

Figure 4-2 Time of Concentration

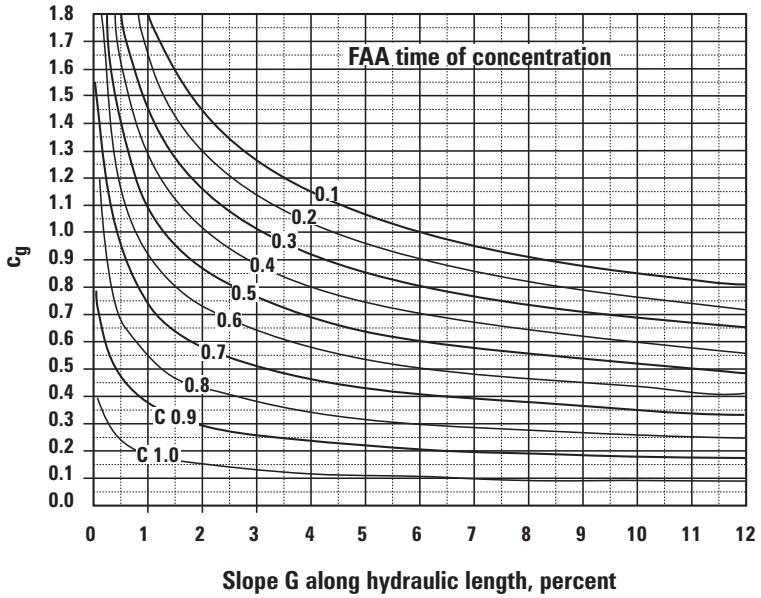
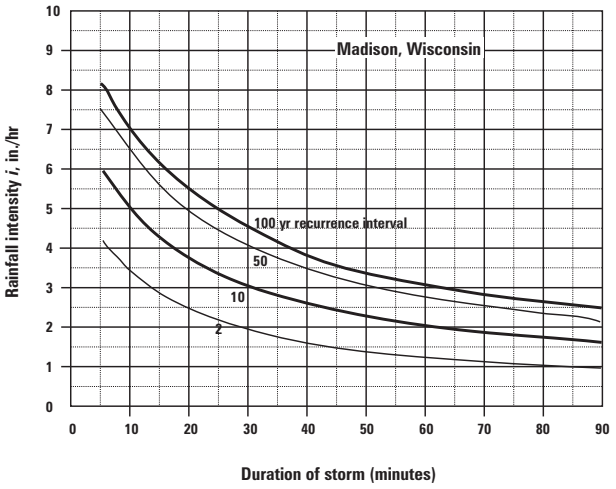


Figure 4-3 Intensity-Duration-Frequency Curve



Certain data requirements must be entered into the TR-55 main window. These data include:

- Identification information (user, state, county, project, and subtitle)
- Dimensionless unit hydrograph
- Storm data
- Rainfall distribution
- Sub-area data

A user of TR-55 must be familiar with the entry information. To learn more about TR-55, visit the website at wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models/WinTR55.html.

As another resource, the Wisconsin Department of Natural Resources provides a simple worksheet that may be used on 5-acre or smaller sites. This worksheet can be found in Appendix 4-A.

Table 4-3 Sources of Pollutants in Wisconsin Storm Water
Geometric mean concentrations of contaminants in runoff from source area and storm sewer outfalls

Contaminant	Feeder Streets	Collector Streets	Arterial Streets	Lawns	Driveways	Roofs	Parking Lots	Outfall
	Residential Source Areas							
Total solids (mg/L)	796	493	-[a]	600	306	91	-	369
Suspended solids (mg/L)	662	326	-	397	173	27	-	262
Total phosphorus (mg/L)	1.31	1.07	-	2.67	1.16	0.15	-	0.66
Total recoverable copper (ug/L)	24	56	-	13	17	15		16
Total recoverable lead (ug/L)	33	55	-	- -	17	21	-	32
Total recoverable zinc (ug/L)	220	339	-	59	107	149	-	203
Fecal coliform (cfu/100mL)	92,061	56,554	-	42,093	34,294	294	0	175,106
	Commercial Source Areas							
Total solids (mg/L)	-	---	373	-	-	112	127	---
Suspended solids (mg/L)	-	---	232	-	-	15	58	---
Total phosphorus (mg/L)	-	---	0.47	-	-	0.20	0.19	---
Total recoverable copper (ug/L)	-	---	46	-	-	9	15	---
Total recoverable lead (ug/L)	-	---	50	-	-	9	22	---
Total recoverable zinc (ug/L)	-	---	508	-	-	330	178	---
Fecal coliform (cfu/100 mL)	-	---	9,627	-	-	1,117	1,758	---
	Industrial Source Areas							
Total solids (mg/L)	-	958	879	---	-	78	531	267
Suspended solids (mg/L)	-	763	690	---	-	41	312	146
Total phosphorus (mg/L)	-	1.5	0.94	---	-	0.11	0.39	0.34
Total recoverable copper (ug/L)	-	76	74	---	-	6	41	28
Total recoverable lead (ug/L)	-	86	60	---	-	8	38	25
Total recoverable zinc (ug/L)	-	479	575	---	-	1,155	304	265
Fecal coliform (cfu/100 mL)	-	8,338	4,587	---	-	144	2,705	5,114

Units: mg/L = milligrams/liter, ug/L = micrograms/liter, cfu = colony forming unit

[a] Single dash indicates source area is not in the land use; double dash indicates insufficient data; triple dash indicates values are shared with those above for the same source area.

Note: The relatively large concentrations of zinc in roof runoff indicate that galvanized roofing materials were a source of the zinc. One-third of the residential roofs had galvanized downspouts. Roofing materials also might be a source of copper and lead in the runoff from residential roofs. Concentrations of dissolved copper and total recoverable copper and lead were slightly larger in the residential roof runoff than in runoff from driveways and lawns.

Source: "Sources of Pollutants in Wisconsin Storm Water," Wisconsin Department of Natural Resources

Table 4-4 Windows TR-55 Capabilities and Limitations

Variable	Limits
Minimum area	No absolute minimum is included in the software. The user should carefully examine results from sub-areas less than 1 acre.
Maximum area	25 square miles (6,500 hectares)
Number of sub-watersheds	1 – 10
Time of concentration for any sub-area	0.1 hour $< t_c <$ 10 hours
Number of reaches	0 – 10
Type of reaches	Channel or structure
Reach routing	Muskingum-Cunge
Structure routing	Storage-Indication
Structure type	Pipe or weir
Structure trial size	1 – 3
Rainfall depth	Default or user-defined; 0 – 50 inches (0 – 1,270 mm)
Rainfall distribution	RNCS Type I, IA, II, III, NM60, NM65, NM70, NM75, or user-defined
Rainfall duration	24 hours
Dimensionless unit hydrograph	Standard peak rate factor of 484 or user-defined
Antecedent moister condition	2 (average)

Figure 4-4 Inlet Control Shown for a Pipe or Culvert

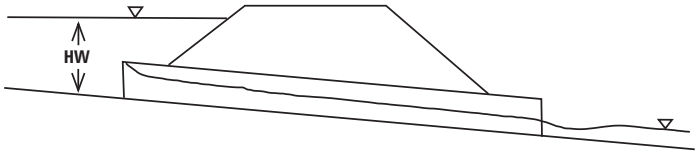
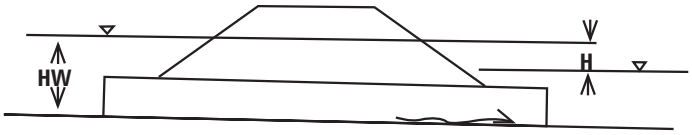


Figure 4-5 Outlet Control Shown for a Pipe or Culvert



Collection Systems

It is possible for a person to get sucked into, entrapped by, or drown in a storm water collection system due to a vortex or high-velocity flow. The designer can help eliminate high-velocity, high-volume safety hazards by separating flow into inlets rather than concentrating flow at the surface.

At the very start of any storm water collection system is the inlet. Inlets come in many shapes and sizes and are critical to a responsible storm water system design. They come in many types, including manhole grates, curb inlets, gutter inlets, combination inlets, and multiple inlets.

Some codes require inlet calculations, and several hydraulic issues must be considered when designing inlets—not only the design of the inlet itself, but also the surface condition where the piping is installed.

Inlet control occurs where water is backed up at the pipe or culvert entrance. The submerged inlet behaves like an orifice, with the increased head creating an increased pressure that increases the discharge rate. Figure 4-4 shows an illustration of inlet control.

Outlet control occurs where the pipe outlet is submerged due to ponding or a slow flow rate, which also affects the capacity of the system. Figure 4-5 depicts one type of outlet control. Other conditions may exist that affect flow when an outlet is submerged.

Advanced Plumbing Technology by Dr. Alfred Steele, PE, includes an equation for calculating the capacity of a catch basin or manhole-style inlet.

Equation 4-4

$$Q = {}^{2}/_{3}AC(2gh)^{1/2}$$

where
Q = Inlet capacity, cfs
$^{2}/_{3}$ = A factor to correct for assumed blockage of one-third of the inlet's net open area
A = Net open area of the inlet, square feet
C = Orifice coefficient, usually taken as 0.60
g = A constant, 32.2 feet/second/second
h = Head, in feet on the inlet or depth of water on top of the inlet, usually not more than 2 or 3 inches

Manufacturers of manholes, catch basins, and curb inlets can provide the designer with more accurate information on the volume of flow through inlets when the variable of water height about the inlet is known.

Conveyance

According to *Introduction to Storm Water,* storm conveyance systems were the exclusive approach to storm water management until about 1965. A conveyance system was designed to handle the peak flow rate during a design storm.

Today, it seems strange that some codes state: "Drain systems shall be designed, constructed, and maintained to conduct the wastewater or sewage quickly from the fixture to the place of disposal, with

velocities which will prevent clogging, fouling, and the depositing of solids, and shall have adequate cleanouts so arranged that the drain pipes may be readily cleaned." At the time that basic plumbing principle was written, the drainage system had one purpose: to drain water quickly from a site. In fact, even *Advanced Plumbing Technology,* written in 1984, references the design of "site drainage." Dr. Steele wrote: "The primary objective of a site drainage system is to collect and convey all excess storm water from the site to a convenient and safe discharge point."

What's changed in collection systems since the earlier codes? Most importantly, the storm water system's primary objective isn't always to collect and convey storm water quickly to a discharge point. In fact, today's storm water systems have many objectives.

Some systems are designed to detain storm water in the conveyance piping so the post-construction runoff hydrograph closely resembles the pre-development hydrograph of the site. This is called "peak shaving." The detention system may include controlled-flow roof drainage systems, oversized piping grids, tank systems, or subsurface gravel beds that are lined to prohibit infiltration. Because such systems are meant to detain storm water, the required slopes for most plumbing drainage piping aren't required for detention systems.

Many codes state: "All horizontal drain piping shall be installed at a pitch which will produce a computed velocity of at least 1 foot per second when flowing full." Piping designed to "drain" is required to be installed to produce the minimum velocity of 1 foot per second (fps). Piping systems designed to "detain" storm water may be designed to create less than the 1-fps velocity.

Although currently most codes have no stated velocity maximums, manufacturers of pipe materials have permitted maximum velocities. The velocity of water from discharge points also is frequently controlled by environmental protection agencies.

Other plumbing systems perform the joint function of collection-infiltration systems. As the requirements of municipal storm water plans and NPDES permits become more widely used, more of these systems will be designed and installed.

Sizing Conveyance Piping

The designer may use the tables in the local code or a formula such as Manning's (Equation 4-5) to calculate flow velocity, and that information can be used to calculate the capacity of the conveyance piping.

Equation 4-5

$$V = 1.486/n \times R^{2/3} \times S^{1/2}$$

where
V = Velocity of flow, fps
n = A coefficient representing roughness of pipe surface, degree of fouling, and pipe diameter
R = Hydraulic radius (hydraulic mean depth of flow), feet
S = Hydraulic slope of flow surface, feet per foot

The quantity rate of flow is equal to the cross-sectional area of flow times the velocity of flow. This can be expressed as:

Equation 4-6

$$Q = AV$$

where
Q = Quantity of rate of flow, cfs
A = Cross-sectional area of flow, square feet
V = Velocity of flow, fps

By substituting the value of V from Manning's formula, one obtains the following:

Equation 4-7

$$Q = A \times 1.486/n \times R^{2/3} \times S^{1/2}$$

Once velocity and capacity are known, the following equations and methods are acceptable for sizing conveyance piping:

- FlowMaster
- Manning's equation for gravity flow
- Hazen-Williams equation for pressurized flow

Piping Alignment

When a change in pipe diameter occurs at a manhole or catch basin, the alignment of the incoming and the outgoing pipes should be such that the crowns of the pipes, not the inverts, line up. This installation promotes a smooth water flow and helps prevent backwater in the upstream piping. Figure 4-6 illustrates this rule.

Detention

Detention systems are designed to modify the conveyance system to slow the rate of flow from an area. Detention systems may be designed using piping systems, tanks, reservoirs or surface ponds, or paved areas. Several arrangements may be used as subsurface detention.

A detention system poses no risk to the groundwater, as the groundwater and the storm water do not interact in a detention system.

Piping systems designed to detain storm water may be installed with a slope of less than that required for drainage piping. If the velocity is less than 1 foot per second, the system must have access ports for cleaning or an equivalent method for removing solids. A downstream restriction should occur in a manhole or be accessible.

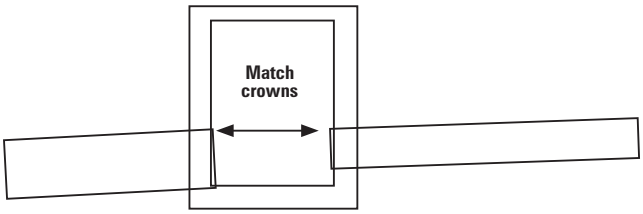
Detention on parking lots by restricted piping systems or inlets should not allow ponding more than a height of 6 inches and should not allow water to

enter the building. The AHJ may have more stringent requirements for detention.

Detention Tanks

Several designs including tanks currently are used, and many more designs most likely will appear in the future. A lined, subsurface, gravel-filled void is one example. Another is the concrete structure.

Figure 4-6 Crown Alignments on Storm Sewer Piping



Infiltration

A subsurface infiltration system could look like a conventional gravity dispersal system (septic system) or it may resemble a subsurface created wetland. Many options are available for these designs.

Considerations for Infiltration System Design

A soil and site evaluation should be performed by a person acceptable to the AHJ. No substances should be discharged into the infiltration system that would exceed groundwater standards.

Load rates should be based on Table 4-5. Note that Table 4-5 assumes rooftop quality. Total suspended solids (TSS) must be treated to less than 35 milligrams per liter, or the suspended solids must be reduced by 80 percent prior to infiltration. Other treatment requirements for runoff from parking lots or other contaminated areas prior to infiltration may be required by the AHJ.

The load rate as shown on Table 4-5 is suggested for infiltration, and it is recommended to load at less than 5 inches per hour for basins or trenches. This is a groundwater quality consideration. Although storm water and its impact on the environment is a fairly new concept, the groundwater laws in many states require groundwater protection.

Vertical setbacks to zones of seasonal soil saturation are 5 feet for water from any source other than rooftops and 1 foot for rooftop runoff. This restriction for rooftop runoff applies only to saturated-flow systems. It does not apply to subsurface drip irrigation or surface spray irrigation. The design also should take hydraulic restrictions into account, even though there is no setback for quality, regardless of the source. Groundwater mounding, or the local rise of the water table above its natural level, should be taken into account when designing an infiltration system more than 15 feet wide.

A sand blanket consisting of engineered soils to treat storm water may be added to an in situ soil that doesn't meet the vertical setback requirements. Also, the AHJ should be consulted for the established setback to wells.

The draindown time should be less than 24 hours for surface ponding and 72 hours for subsurface drainage.

Check with the U.S. EPA for requirements for class V injection wells.

Treatment

Catch basins, detention basins, manufactured filters, and even grass filter strips can provide storm water treatment. The U.S. EPA provides a list of best management practices and assigns treatment values to some common practices. Other treatment performance may be documented by manufacturers.

Accessibility and Maintenance

All plumbing systems require maintenance. It seems to be a given that when the toilet doesn't flush, someone fixes it. When a storm water detention system becomes filled with silt or groundwater contamination occurs when an infiltration system fails, it's a more complicated situation, but it still needs repair and maintenance.

Designers must plan for that maintenance. All devices and safeguards that are discussed in this chapter shall be maintained in good working order.

Table 4-5 Design Infiltration Rates for Soil Textures Receiving Storm Water

Soil Texture[a]	Design Infiltration Rate Without Measurement (inches/hour)[b]
Coarse sand or coarser	3.60
Loamy coarse sand	3.60
Sand	3.60
Loamy sand	1.63
Sandy loam	0.50
Loam	0.24
Silt loam	0.13
Sandy clay loam	0.11
Clay loam	0.03
Silty clay loam	0.04[c]
Sandy clay	0.04
Silty clay	0.07
Clay	0.07

[a]Use sandy loam design infiltration rate for fine sand, loamy fine sand, very fine sand, and loamy fine sand soil textures.

[b]Infiltration rates represent the lowest value for each textural class presented in Table 2 of Rawls, 1998.

[c]Infiltration rate is an average based on Rawls, 1982 and Clapp and Hornberger, 1978.

As velocity decreases or contaminant load increases, more cleanouts or accessibility ports (e.g., manholes) could be included in the design.

Vector Control

Vector control is an important issue that's tied to maintenance. The most dangerous vector related to storm water is currently the mosquito.

In 1998, the California Department of Healthcare Services Vector-borne Disease Section conducted a study to learn whether storm water practices supported vector populations. The results proved that mosquitoes use the standing water in storm water devices as homes. It was evident that requiring storm water devices has allowed many species to greatly expand their range and increase their numbers. Even small breeding areas combine to make big problems.

There are two types of mosquitoes: the permanent water species and the flood water species. The former lays its eggs in quiet water, and the latter lays eggs on damp soil where the next flooding event will allow a hatch. The research done in California shows that the Aedes, Culex, and Anopheles mosquitoes are most often associated with storm water devices.

With recent concerns about the West Nile virus and continuing issues with LaCrosse encephalitis, the industry and storm water regulators should keep in mind that the construction of new habitats has the potential of making a bad situation worse. Maintenance schedules that ensure a system's operation as designed is critical for vector control. The book *The Coming Plague* says: "For most insect experts it came as no surprise that even a one-year slackening in mosquito control efforts could result in a surge in the bugs and the microbes that they carried."

How can plumbing designs be modified to reduce mosquito breeding sites? First of all, draindown times should be reduced to less than 72 hours. A current proposal for infiltration devices is a maximum draindown time of 24 hours. Secondly, subsurface system inlets can be sealed or screened to prevent mosquito entry. A third way to prevent surface standing water is to fill the area with rock to eliminate the mosquito habitat.

INTERIOR BUILDING DRAINAGE SYSTEM DESIGN

The design of storm water drainage systems shall be based on local code requirements and sound engineering judgment. Special local conditions, building and site characteristics, and code requirements may necessitate a unique design. The designer should keep in mind that the codes are minimum standards only. All designs must meet or exceed the local code requirements.

General Design Criteria

The following items should be considered when establishing the storm water system.

- Rainfall rate, snow depth, freezing conditions, snowmelt, frost line, and other conditions usually can be found in NWS or NOAA publications. Also, the AHJ can provide the required information for local conditions.
- The building's construction, including roof type, drainage slope patterns, vertical wall heights, parapet heights, scupper sizes and locations (if provided), emergency drain requirements and locations, pipe space allocations in the ceiling space, and wall and chase locations must be determined.
- Minimum pipe size and slope, overflow requirements, extent of overflow pipe and discharge requirements, and method of connection to the public sewer are all code-related items. If such requirements are not available, use good engineering practices as outlined in this chapter. Methods of detention are usually code-mandated requirements. Several available methods, such as controlled-flow roof drainage, siphonic roof drainage, rain gardens, green roofs, detention basins, infiltration basins, and infiltration trenches could be used.
- Site conditions, including location, proximity to surface water, topography, elevation, soils, groundwater table, location and pipe material of public storm sewer, location of existing manholes, and location of other utilities within the site, must be determined.
- The local code shall be consulted to determine the rainfall rate that is applicable for the design area. If the code is not available or if a longer rainfall period is permitted, the design should be for a 10-year, five-minute storm for the building roof and site unless other factors are involved that require greater protection from flooding. Rarely is a shorter minimum economically justifiable.
- Expansion and improper anchoring of the vertical pipe have caused roof drains to be pushed above the roof deck, destroying the integrity of the roof waterproofing by tearing the flashing and the waterproofing membrane. This problem can be more apparent in high-rise buildings and buildings where the exposed leader is subject to cold rainwater or melting snow and ice that enter piping at the ambient temperature of the building. An expansion joint at the roof drain or a horizontal section of the branch line should be considered to

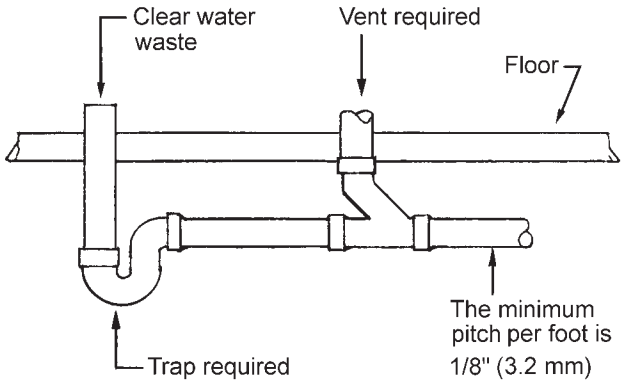


Figure 4-7 Clear Water Waste Branches for Connection to Storm System

Source: Reprinted, by permission, from *The Illustrated National Plumbing Code Design Manual* (Ballanco & Shumann 1987)

accommodate the movement of the leader without affecting the roof drain.

- The horizontal section of the pipe and the roof drain body should be insulated, per cold water installations with a vapor barrier, to control condensation. Low-temperature liquid flow in the piping causes condensation to form on the outside of the piping, possibly causing stain damage to the ceilings or, where exposed, drip marks on the flooring. This condensation usually extends 15 feet from the roof drain. Past this distance, the water is no longer cold enough to cause condensation.
- Locating the vertical leaders within the building has several advantages: convenience, safety, appearance, and freeze protection. However, leaders located on the exterior can be installed at a much lower cost and do not take up valuable floor space.
- The piping layout must be coordinated with other design team disciplines that are affected, such as the architect providing chase locations at proper columns for vertical leaders (also known as conductors or downspouts) and the structural engineer for pipe support and footing depths. Other utilities, such as ductwork and conduit runs, also may be affected.
- If interior floor/hub drains, drains from lower roofs, clear water wastes, or areaway drains are connected to the storm system inside the building (if allowed by the AHJ), the drains must connect at least 10 pipe diameters (10 feet [3.05 meters] minimum) downstream of the last offset fitting. Clear water wastes should be properly trapped and vented. Traps must be the same size as the horizontal drain to which they are connected and should be provided with at least 4-inch (102-millimeter) deep-seal P-traps. See Figure 4-7.
- Because of the excessive pressure that may exist in the leader, drains sometimes connect to a stack at a lower level. Above an offset, the drain becomes the vent to relieve the pressure, blowing water, and air. These drains are subject to backflow and should be routed separately to tie to the system 10 feet (3.05 meters) beyond the elbow or offset. If backwater valves are used, they can cause the areas affected to not drain, and a buildup of water may occur. Horizontal piping of clear water wastes and vents should be sized as a sanitary drainage branch. When such piping is tied to a leader, an upright wye should be utilized if possible. See Figure 4-8
- To keep the number of leaders to a minimum, combine flows from more than one roof drain, clear water wastes, or any combination thereof. The plumbing engineer must include the additional flows when calculating the leader size. This method is especially beneficial in keeping the costs of high-rise buildings contained.
- If leaders are to be located at building columns, the column footing design must be coordinated with the structural engineer to take into consideration the leader location. The base elbow should be a long sweep bend to help alleviate any excess pressures in the downstream pipe, and the elbow should be properly supported. The elbow may rest directly on the column footing, which acts as a support.
- A riser clamp should be provided at each floor line to support the leader. Also, a cleanout shall be provided at the base of all stacks (although caution must be exercised when opening these cleanouts because full leaders create a high hydraulic pressure situation).
- If blockage occurs in the drainage system and backs up in the vertical leader, the piping system may be subject to a head pressure greater than the joining system is designed to withstand. To prevent joint failure, pressure pipe may be considered for the piping system. At the lower floors, all exterior leaders that may be damaged, such as occurs in parking or truck-loading areas, should be protected by metal or concrete guards or recessed in the wall and constructed of a ferrous alloy pipe, such as cast iron, to 5 feet (1.5 meters) above the paving or loading platforms.
- If an offset is 45 degrees or less, the leader can be sized as a vertical pipe. If the offset is greater than 45 degrees, the pipe must be sized as a horizontal pipe. To avoid stoppages,

the leader cannot be reduced in size in the direction of flow throughout its length. For example, an 8-inch (203-millimeter) horizontal line must tie to an 8-inch (203-millimeter) vertical leader, even if Table 4-6 requires a smaller size for the vertical leader. Vertical leaders should be tied to the horizontal main with single-wye fittings. Double-wye fittings should be avoided.

Roof Drainage

Coordination

The building roof transfers the combined weight of live and dead loads (with the proper additional safety factor) to the supporting structure. Live loads include snow, rain, wind, and water on the roof. Dead loads include all mechanical and electrical equipment and the roof deck.

Locating the roof drains should be a cooperative effort among the architect, structural engineer, and plumbing engineer. The architect is familiar with the building construction, parapets, walls, chase locations, available headroom for pipe runs, roof construction, and waterproofing membrane. The structural engineer is familiar with the structural support layout, roof slopes, column orientation, footing sizes and depths, and maximum allowable roof loading. The plumbing engineer can provide information concerning the maximum roof areas per drain, wall, and column furring-out requirements, headroom requirements, ceiling space requirements, minimum footing depths, and the possible benefits of ponding. The plumbing engineer also should ensure that the drains are located in the low points of the roof to limit deflection, which could cause ponding and shifting of the roof low point, and to minimize the horizontal piping runs.

Table 4-6 Sizes of Roof Drains and Vertical Pipes

Diameter of Leader, in. (mm) Dimensions of Leader, in. (mm)	Cross-Sectional Area, in.^{2} (cm^2)	Water Contact Area, in.^{2} (cm^2)	Maximum Discharge Capacity, gpm (L/s)[a]
2 (50.8)	3.14 (20.3)	6.28 (40.5)	30 (1.2)
2 × 2 (50.8 × 50.8)	4.00 (25.8)	8.00 (51.6)	30 (1.2)
1½ × 2½ (38.1 × 63.5)	3.75 (24.2)	8.00 (51.6)	30 (1.2)
2½ (63.5)	4.91 (31.7)	7.85 (50.6)	54 (3.4)
2½ × 2½ (63.5 × 63.5)	6.25 (40.3)	9.00 (58.1)	54 (3.4)
3 (76.2)	7.07 (45.6)	9.42 (60.8)	92 (5.8)
2 × 4 (50.8 × 101.6)	8.00 (51.6)	12.00 (77.4)	92 (5.8)
2½ × 3 (63.5 × 76.2)	7.50 (48.4)	11.00 (71.0)	92 (5.8)
4 (101.6)	12.57 (81.1)	12.57 (81.1)	192 (12.1)
3 × 4¼ (76.2 × 107.6)	12.75 (82.3)	14.50 (93.6)	192 (12.1)
3½ × 4 (88.9 × 101.6)	14.00 (90.3)	14.00 (90.3)	192 (12.1)
5 (127)	19.06 (123.0)	15.07 (97.2)	360 (22.7)
4 × 5 (101.6 × 127)	20.00 (129.0)	18.00 (116.1)	360 (22.7)
4½ × 4½ (114.3 × 114.3)	20.25 (130.6)	18.00 (116.1)	360 (22.7)
6 (152.4)	28.27 (183.4)	18.85 (121.6)	563 (35.5)
5 × 6 (127 × 152.4)	30.00 (193.5)	22.00 (141.9)	563 (35.5)
5½ × 5½ (139.7 × 139.7)	30.25 (195.2)	22.00 (141.9)	563 (35.5)
8 (203.2)	50.27 (324.3)	25.14 (162.2)	1,208 (76.2)
6 × 8 (152.4 × 203.2)	48.00 (309.7)	28.00 (180.6)	1,208 (76.2)

[a] With approximately 1¾-in. (45-mm) head of water at the drain

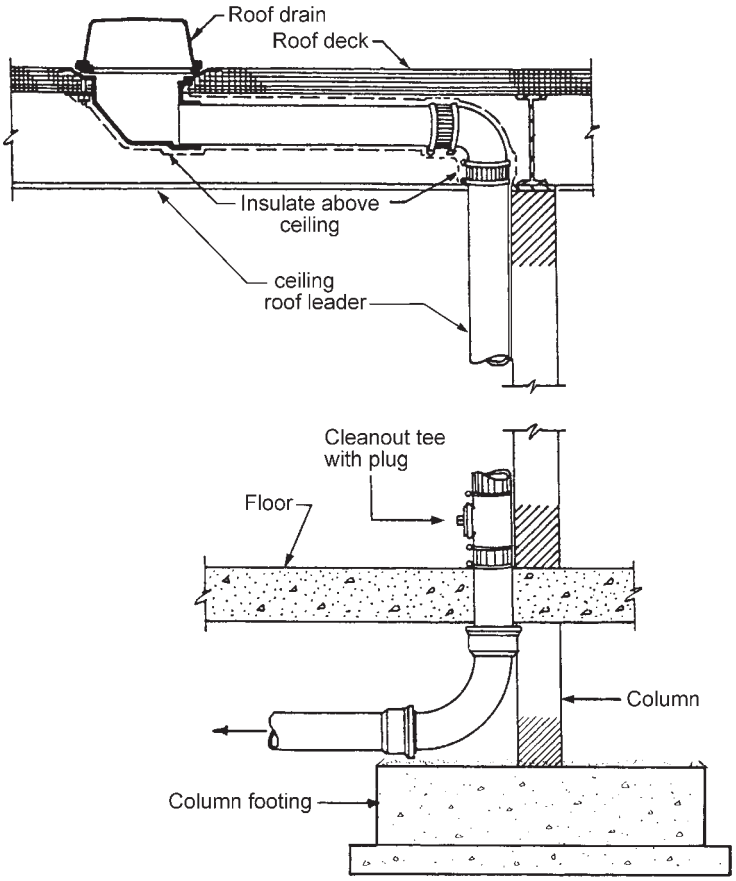


Figure 4-8 Typical Roof Drain and Roof Leader

Source: Reprinted, by permission, from *Cast Iron Soil Pipe and Fittings Engineering Manual* (Cast Iron Soil Pipe Institute, 1976)

Drain Location

Drain location must be coordinated with the architectural design of the building. The roof structure must be able to support the weight of ponded water by design or by nature. The roofing material and roof structure must be designed in accordance with the local code in force. Most codes require the installation of two roof drains to serve each roof.

Some things to consider include the following:

- Roof decks should be covered with an approved roof covering.
- Flashings must be installed to prevent moisture from damaging the structure.
- Accessible inlets may need protection from vandalism.

Adjacent Surfaces

Roof drains also receive rainwater from other roof areas such as penthouses that discharge onto the roof area being calculated and from the adjacent vertical walls. Some codes require 50 percent of two adjacent vertical wall areas to be added to the horizontal roof area. Other codes use complex formulas for various wall configurations. These formulas typically are excessive for roof areas that have more than one vertical wall or multiple-story walls with runoff directed to the horizontal roof surface.

Rain seldom falls in a totally vertical direction. Depending on wind conditions, the angle of rainfall could be as much as 60 degrees to the vertical or more. Wind, particularly with high-rise buildings, can blow rain off a vertical wall and away from building surfaces.

Roof Drain Design

Standard roof drains have three basic parts: strainer, flashing ring with gravel stop, and drain body or sump. Strainers may be coated with cast iron, have a polyethylene dome (for use where leaves may accumulate), or be flat (for sunroofs, areaways, and parking decks).

When selecting the type of drain to use, the engineer must know the roof construction and thickness. For instance, the roof may be flat or pitched, used to retain water for cooling purposes, have a sprinkler system for cooling purposes, used as a terrace, used as a parking deck with heavy traffic, or used to retain rainwater to limit the effluent to the storm sewer system.

Roof drains, other than for flat decks, should have dome strainers that extend a minimum of 4 inches (101.6 millimeters) above the roof surface immediately adjacent to the drain. Strainers for roof drains shall have available inlet areas not less than 1.5 times the area of the leader that serves the drain. Dome-type strainers are required to prevent the entrance of leaves, debris, birds, and small animals. Flat-deck strainers, for use on sun decks, promenades, and parking garages where regular maintenance may be expected, shall have available inlet areas not less than two times the area of the leader that serves the drain. Heel-proof strainers may be required if the roof is subject to pedestrian traffic. This will require larger grates to compensate for the smaller drainage holes in the strainers.

The flashing ring is used to attach the roof waterproofing membrane to the drain body to maintain the watertight integrity of the roof. An underdeck clamp should be utilized to secure the drain to the metal or wood decking. Poured concrete roofs do not require these clamps, but drain receivers should be used on drains for concrete roofs. Drains that may receive sand and grit should be provided with sediment buckets.

Secondary Roof Drainage Systems

Secondary (emergency) roof drainage often is mandated by the local AHJ in case the primary drains becomes blocked. This drainage system can consist of either scuppers through the sides of the building or separate roof drains installed at a higher elevation than the primary roof drain. If scuppers are utilized, they should be placed ½ inch (12.7 millimeters) above the maximum designated head or 4 inches (101.6 millimeters) above the roof level. One scupper or secondary drain should be provided for each roof drain. The structural engineer shall be advised that scuppers will be installed to be able to accommodate for the additional weight of the water.

The design, size, and placement of secondary roof drains are mandated by local code requirements. The primary drainage system must be designed for the local code value based on the roof area (in square feet). The secondary drainage system shall handle any overflow that occurs when the primary drain is clogged. Some codes may require secondary drainage systems to be designed for more stringent values, such as those required when the primary drainage system is clogged. Additionally, if a rainfall heavier than the design rainfall occurrs, the two systems should work together to carry the increased load.

Secondary drainage systems may be either scuppers, which allow the entrapped rainwater to overflow the roof, or a separately piped drainage system. The secondary piping system shall be designed similarly to the primary drainage system, but these drains shall be installed separately from the primary system as mandated by code requirements and discharge to several possible disposal points. One disposal point should be above grade so building personnel can see that the primary drainage system is blocked. Another should discharge directly into the main drainage system adjacent to the primary drain. A third possibility is connecting a separate system to the main house drain before or after it leaves the building.

Controlled-flow Storm Drainage System

Controlled-flow systems collect rainwater on the roof and release the flow slowly to the drainage system. These systems can provide significant installation savings because they require smaller roof drains, smaller-diameter piping, and smaller-diameter storm sewers. These systems also help alleviate flooding in overtaxed public storm sewers or drainage canals during heavy rainfalls. The impact on the sewage treatment plant for a combined storm/sanitary sewer (where allowed) is considerably lessened by the use of controlled-flow roof drainage systems.

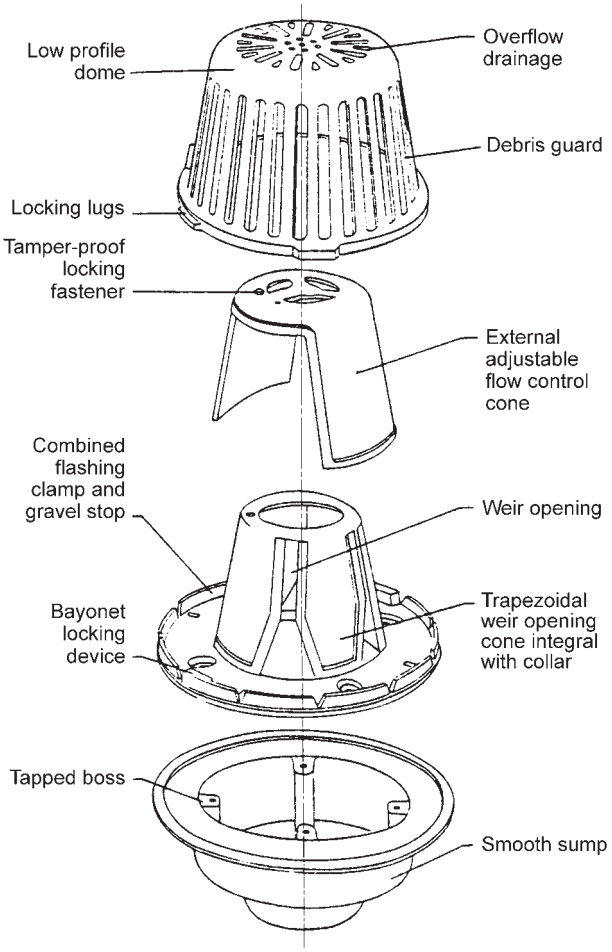


Figure 4-9 Example of a Controlled-flow Drain

Source: Reprinted, by permission, from the Jay R. Smith catalog

Controlled-flow systems should not be used if the roof is used for functions precluding water storage, such as a sundeck or a parking level, or if not allowed by the AHJ. Holding the water on the roof increases structural costs and may require a different roof-covering material.

The flow-control device should be installed on the drain so the rainwater discharge rate does not exceed the rate calculated to discharge into the site system. This means that rainwater will pond on the roof. A typical controlled-flow roof drain is illustrated in Figure 4-9.

The roof design for controlled-flow roof drainage should be based on a minimum 30-pound-per-square-foot (1.44-kilopascal [kPa]) loading to provide a safety factor above the 15.6 pounds per square foot (0.75 kilograms per square meter) represented by the 3-inch (76.2-millimeter) design depth of water. The roof should be level, and 45-degree cants should be installed at any wall or parapet. The flashing should extend at least 6 inches (152.4 millimeters) above the roof level. Doors opening onto the roof must be provided with a curb at least 4 inches (101.6 millimeters) high. Flow-control devices should be protected by strainers, and in no case should the roof surface in the vicinity of the drain be recessed to create a reservoir.

Roof drain manufacturers have done much research on the engineering criteria and parameters regarding the head of water on the roof for the weir design in controlled-flow roof drains, and they have established suggested design procedures with flow capacities and charts.

Siphonic Roof Drains

A siphonic roof drain contains a baffle that allows and sustains negative atmospheric pressure in the drainage piping and inhibits the admission of air, causing full-bore flow and higher flow volumes and velocities. The hydraulic balance in a siphonic roof drain system is achieved by employing engineering calculations to ensure that the piping system fills automatically when there is moderate to heavy rainfall. The resulting flow or siphonic action requires the installation of level drainage manifold pipes serving multiple roof drains. This is an advantage for large buildings where the traditional slope of the drains is problematic.

The depth of the water on the roof depends only on the resistance value assigned to the drain by the manufacturer.

Rainfall Rates

The rainfall rate for roof drain sizing shall be established by the local code, AHJ, or the NOAA. The rates for various rainfall intensities that often are used without calculation—duration, length, and return period—also are listed. Using available tables, a designer can select a precipitation frequency value for a 10- or 100-year return period with durations of five, 15, and 60 minutes. Other return periods and durations can be interpolated between the values listed.

The selection of the duration and frequency of a storm for the site as a whole is discussed later in this chapter under the site drainage requirements. If the code for roof drains provides this information, first establish the closest city and determine the rainfall intensity in inches per hour. Then go to the code chart and use this figure for sizing purposes. If exact figures are not found, either mathematically interpolate between the figures shown or refer to recommendations by the local code officials. It also may be possible to find a rate one-half of the value of the actual rainfall as provided in the code for roof drains.

Interior Pipe Sizing and Layout Criteria

Interior storm drainage systems are designed utilizing architectural and engineering design information. The following points should be considered.

- The contributing area of each roof drain shall be calculated and noted.

- Roof drains and vertical pipe are sized as indicated in code requirements, depending on the square footage of the contributing roof area. Manufacturers provide sizing and flow rate information for their products on their websites.
- Where there is an adjacent vertical wall, the drain size is based on the horizontal collection area plus a percentage of the two adjacent vertical wall areas. The vertical wall area is referred to as sidewall flow.
- The sizes of the horizontal mains are based on the accumulated flow of the drains and leaders upstream as indicated in code requirements. A minimum 2-fps (0.61-meter per second) velocity should be maintained to properly scour the pipe of grit, sand, and debris. (Some authorities recommend a minimum 3-fps [0.91-meter per second] velocity to keep the sediment suspended.) The sizes of a typical horizontal storm drain for various slopes are given in Table 4-7.
- The sizes of mains downstream of sump pumps are based on the accumulated flow of gravity drains upstream plus the discharge capacity of any sump pumps upstream. Often the code assigns a square foot equivalent for each gpm of discharge to be used in sizing mains.
- The pipe size of the sump pump discharge is based on the capacity of the pump, but is normally the same as the discharge pipe size of the pump. The code assigns a square foot equivalent for each gpm for sizing purposes. For duplex pumps operating simultaneously, the combined discharge capacity should be used. The discharge pipe should connect to the horizontal storm main at least 10 feet (3.05 meters) downstream of the base of any stack, as high pressure can exist in this zone due to hydraulic jump.
- When a separate secondary system is required, the size of the building storm drain is based on the accumulated flow from the drain leaders upstream. The method used to dispose of the overflow drain discharge must meet local code requirements. Local codes may not allow open discharge onto the street, especially in northern climates; therefore, it may be necessary to tie the secondary system into the public storm sewer separately from the primary drainage system. Both may be routed to the same manhole, but with separate inlets. Local code dictates the size. Some areas of the country require the secondary drainage system to spill onto grade to indicate that the system is operating.
- Horizontal piping must be supported properly, with bell holes provided for underground bell-and-spigot piping. Cleanouts should be provided at any change in direction exceeding 45 degrees and at any change in pipe size and to meet any applicable local code requirements for distances between cleanouts. The cleanouts should be extended up to grade, to the floor above, or out to the wall face with a wall plate. Locating cleanout plugs above ceilings may cause damage to the ceiling when the pipe must be cleaned.
- Avoid running horizontal piping above the ceilings of computer rooms, kitchens, and food-preparation areas. A pipe rupture above one of these areas could cause major damage and contamination. Piping under building slabs should be avoided if feasible, as pipe leaks could erode the fill below the slab and cause the slab to crack.
- If the storm-drainage system receives continuous or intermittent flow from sump pumps, air-conditioning units, or similar devices, the flow should be added to the drainage system, either on the roof if the discharge is onto the roof or in the piping if the discharge ties directly into the drainage system.

After layout and sizing, the designer should review the proposed system to determine if revisions to the layout would improve the system from the standpoint of ease of installation, cost of materials, and/or coordination with other trades.

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Table 4-7 Size of Horizontal Storm Drains

Diameter of Drain, in.	Maximum Projected Roof Area for Various Slopes of Drains, ft²		
	⅛-inch slope	¼-inch slope	½-inch slope
2	250	350	500
2½	357	505	714
3	690	930	1,320
4	1,500	2,120	3,000
5	2,700	3,800	5,320
6	4,300	6,100	8,700
8	9,300	13,000	18,400
10	16,600	23,500	33,000
12	26,700	37,500	53,000
15	47,600	67,000	95,000

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APPENDIX 4-A

Runoff Volume Calculation for Typical Wisconsin Commercial Sites

The purpose of this worksheet is to calculate runoff volumes from pervious and impervious areas using a simplified TR-55 approach. The complete version of TR-55 (210-VI-TR-55, Second Ed., June 1986) can be obtained at the NRCS website.

Step 1

Select the runoff values from Table 1 for the municipality closest to the site. Impervious areas have one value while pervious areas have three different values depending on the hydrologic soil group. Pick the hydrologic soil group that best represents the site.

Step 2

Determine the impervious and pervious contributing areas. (Note: For conversion purposes, 1 acre equals 43,560 square feet.)

Impervious Area: _____ (square feet)

Pervious Area: _____ (square feet)

Step 3

Determine runoff volumes.

Impervious area (ft^2) x Impervious runoff (feet) = Impervious volume (ft^3)

_____ x _____ = _____

Pervious area (ft^2) x Pervious runoff (feet) = Pervious volume (ft^3)

_____ x _____ = _____

Total = Impervious volume + Pervious volume = _____ (ft^3)

Note: Per NR 151.12, the infiltration device must infiltrate 10 percent of the total runoff volume for commercial sites and 25 percent for residential sites as calculated using a two-year, 24 hour design storm.

Definitions

Impervious area constitutes rooftops, parking lots, and other paved areas where water is unable to effectively infiltrate. For these calculations, impervious areas are assigned a curve number of 98.

For these calculations, pervious areas are characterized by urban grass cover in fair condition overlaying soils from one of the hydrologic soil groups listed below.

- A–B: Soils characterized as sand, loamy sand, or silt loam and having low runoff conditions and moderate infiltration rates. Due to compaction, type A soils are rarely encountered on construction sites.
- C: Soils characterized as loamy or sandy clay loams that have moderate runoff potential and low infiltration rates.
- D: Soils consisting chiefly of clays, silt clays, sandy clays, and clay loams that have high runoff potential and very low to no infiltration capacity.

Information on a soil's specific hydrologic soil class can be obtained from soil surveys. However, the textural class listed above provides an adequate means of determining the hydrologic soil group.

Contributing areas are areas from which runoff enters the device via overland flow, ditched flow, or piped flow. Areas that are offsite that contribute runoff also must be accounted for during the design, but may not be needed when determining the amount of water required to infiltrate.

Assumptions and Notes

This worksheet is based on TR-55 and provides a simple and quick method to calculate runoff volumes from commercial sites. Calculation of runoff peaks and flow times (time of concentration) requires use of TR-55.

This worksheet assumes the following conditions:

- Pervious areas are assumed to be under average antecedent moisture conditions.
- Pervious areas are characterized as grass under fair conditions modified by the soil class. Curve numbers of 69, 79, and 84 are used to characterize A–B, C, and D soils respectively. If an alternate land use is required, refer to TR-55 to calculate the runoff volume. For most commercial applications, the numbers utilized in this worksheet will adequately characterize grassed areas and small planting areas.
- To help account for the effects of soil compaction, group A soils have been combined with group B soils and utilize group B curve numbers.
- This worksheet assumes that impervious areas are directly connected. Impervious areas are considered connected if runoff from them flows directly into the drainage system. Unconnected impervious is defined by runoff that flows over pervious areas before discharging to the drainage system.
- Rainfall values for the two-year, 24-hour storm were obtained from TP-40 for seven municipal areas to account for the variation in rainfall patterns across the state.

Table 1 Rainfall (inches) for Selected Municipalities

Parameters	Municipality						
	Madison	Milwaukee	Green Bay	Eau Claire	Duluth	La Crosse	Wausau
Rainfall (2-year, 24-hour)	2.8	2.6	2.4	2.7	2.5	3.0	2.8
Corresponding Runoff Quantities (feet)							
Runoff impervious area	0.214	0.198	0.181	0.206	0.189	0.231	0.214
Runoff pervious area (A–B soils)	0.048	0.039	0.032	0.043	0.035	0.056	0.048
Runoff pervious area (C soils)	0.087	0.076	0.064	0.081	0.070	0.099	0.087
Runoff pervious area (D soils)	0.113	0.099	0.087	0.106	0.093	0.127	0.113

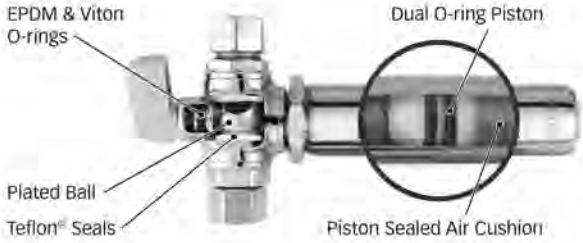
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ASSE 1010

US Patent 5735307
NSF/ANSI 61
†**NSF/ANSI 61-G**



Description	Pattern	Finish	C360 Brass Alloy	dahl-ECO†
COPPER - *Female Solder*				
1/2 C (Female Solder) x 3/8 OD Comp x WHA	Straight	Plated	116-13-31-14WHA	516-13-31-14WHA
1/2 C (Female Solder) x 3/8 OD Comp x WHA	Angle	Plated	216-13-31-14WHA	616-13-31-14WHA
COPPER - *Compression*				
5/8 OD Comp x 3/8 OD Comp x WHA	Straight	Plated	116-33-31-14WHA	516-33-31-14WHA
5/8 OD Comp x 3/8 OD Comp x WHA	Angle	Plated	216-33-31-14WHA	616-33-31-14WHA
Iron - *Female NPT*				
3/8 FIP x 3/8 OD Comp x WHA	Straight	Plated	116-52-31-14WHA	516-52-31-14WHA
3/8 FIP x 3/8 OD Comp x WHA	Angle	Plated	216-52-31-14WHA	616-52-31-14WHA
1/2 FIP x 3/8 OD Comp x WHA	Straight	Plated	116-53-31-14WHA	516-53-31-14WHA
1/2 FIP x 3/8 OD Comp x WHA	Angle	Plated	216-53-31-14WHA	616-53-31-14WHA
CPVC - *Female*				
1/2 Female CPVC x 3/8 OD Comp x WHA	Straight	Plated	116-46-31-14WHA	516-46-31-14WHA
1/2 Female CPVC x 3/8 OD Comp x WHA	Angle	Plated	216-46-31-14WHA	616-46-31-14WHA
PEX - *Crimp*				
1/2 Crimpex x 3/8 OD Comp x WHA	Straight	Plated	116-PX3-31-14WHA	516-PX3-31-14WHA
1/2 Crimpex x 3/8 OD Comp x WHA	Angle	Plated	216-PX3-31-14WHA	616-PX3-31-14WHA

The 3rd digit in our part number indicates the type of valve operation:
"6" = lockshield operation (as shown), also available: "1" = chrome plated handle, "4" = red handle, or "5" = blue handle.

†Environmentally friendly dahl-ECO products average less than 0.1% lead on wetted surfaces, and are made of alloy C69300 American ECO BRASS®, which offers the best stress corrosion crack and dezincification resistance available.

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5 Cold Water Systems

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.

This chapter presents the major flow and pressure-related components of a cold water distribution system, from the utility water meter and backflow prevention to inadequate or excessive pressures, velocity and sizing issues, and final testing and cleaning.

CODES AND STANDARDS

Plumbing codes establish a minimum acceptable standard for the design and installation of various systems, including cold water. There are various model codes, but some states and large cities have adapted plumbing codes other than the ones usually associated with the region. Because of this non-standardization, the actual plumbing code used for each specific project must be obtained from a responsible code official.

The information pertaining to cold water design appears in the approved local plumbing code and must be the primary method used for the accepted methods and sizing. 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.

DOMESTIC COLD WATER METERS

Many major municipalities furnish and/or install a particular type of water meter. In such locations, the meter characteristics (type, size, flow, pressure drop, remote readouts, costs, etc.) can be obtained from the local water department. Depending on the type of project being contemplated, a utility may request 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 want the meter immediately adjacent to the tap to prevent illegal connections between the meter and the tap. Where job conditions mandate such a location, a meter in an outside pit or manhole should be watertight against both surface and groundwater conditions. Electric tape heating 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 use usually are classified as the positive-displacement type, which indicates direct flow and records water passage in gallons (liters) or square feet (square meters).

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 (16, 19.1, 25, 40, and 50 millimeters) in size; are manufactured to have a 150-pounds-per-square-inch (psi) (1,034-kilopascal [kPa]) 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 millimeters) 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 millimeters). 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 millimeters). Propeller meters are used where low flows never occur.
- Fire-line meter or detector-check meter: One of these types of meter 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.

Various types of meter 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.

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])
- Water pressure available at meter
- Size of building service
- Piping, valve, and elevation pressure losses
- Meter costs and tap fees
- Maintenance costs and fees

Tables 5-1 through 5-3 from AWWA M22: *Sizing Water Service Lines and Meters* are provided here as additional guidelines for water meter sizing and selection.

CROSS-CONNECTION CONTROLS

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 back-siphonage), the control device may be a vacuum breaker. If pressure immediately downstream of the device is greater than atmospheric (a situation defined as back-pressure), 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 Controls

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 strainers typically are bronze, and valves 2½ to 10 inches are stainless steel or cast iron with an FDA coating.) For ½- through 2-inch strainers, the screen should be 20 mesh, and the perforated screen for 2½- to 10-inch strainers should be no larger than ⅔inch. 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 (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. The discharge from a typical RPZ can be found in Figure 5-1. 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 5-4. 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. A wide variety of air gap designs are available, including both funnel and sink styles.

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.

The pressure losses through often-used RPZs are given in Table 5-5.

Table 5-1 Displacement-type Meters Meeting AWWA Specifications—Flow Pressure Loss Averages

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)	
5/8 × 3/4 (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
3/4 (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

Source: AWWA Standard M22

Table 5-2 Compound-type Meters Meeting AWWA Specifications—Flow Pressure Loss Averages

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)	
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)	(80.75)	7.8 (53.82)	800 (50.46)	4.0 (27.60)	3

Source: AWWA Standard M22

Table 5-3 Turbine-type Meters Meeting AWWA Specifications—Flow Pressure Loss Averages

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)	
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 Standard M22

BOOSTER PUMP SYSTEMS

When it is determined that the city water pressure or well pump pressure is not sufficient to meet the water supply demands of a building, a booster pump system is 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 (meters)
p = Flow stream's static pressure, pounds per square foot (kPa)
d = Flow stream's density, pounds per cubic foot (kilograms per cubic meter)
v = Flow stream's velocity, feet per second (meters per second)
h_p = Pump head (total dynamic head)
g = Acceleration of gravity, 32.2 feet/second^2 (meters/second^2)
h_f = Friction head loss between Points 1 and 2, feet (meters)

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, you can omit the two velocity terms. 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, meters, 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 meters) and up to 18 feet (5.49 meters) respectively.

Table 5-4 BFP Flow Rate

Drain Size Flowing Full					
Drain size		Maximum Flow Rate, GPM, l/m			
In	Dn	⅛"/ft	(0.5 cm/m)	¼"/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	1670	314	2385
8	200	494	3755	696	5290
10	250	934	7100	1300	9900

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 meters) 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 meters), and the uniform pressure loss of this length is 5 psi (35 kPa) per 100 feet (30 meters).

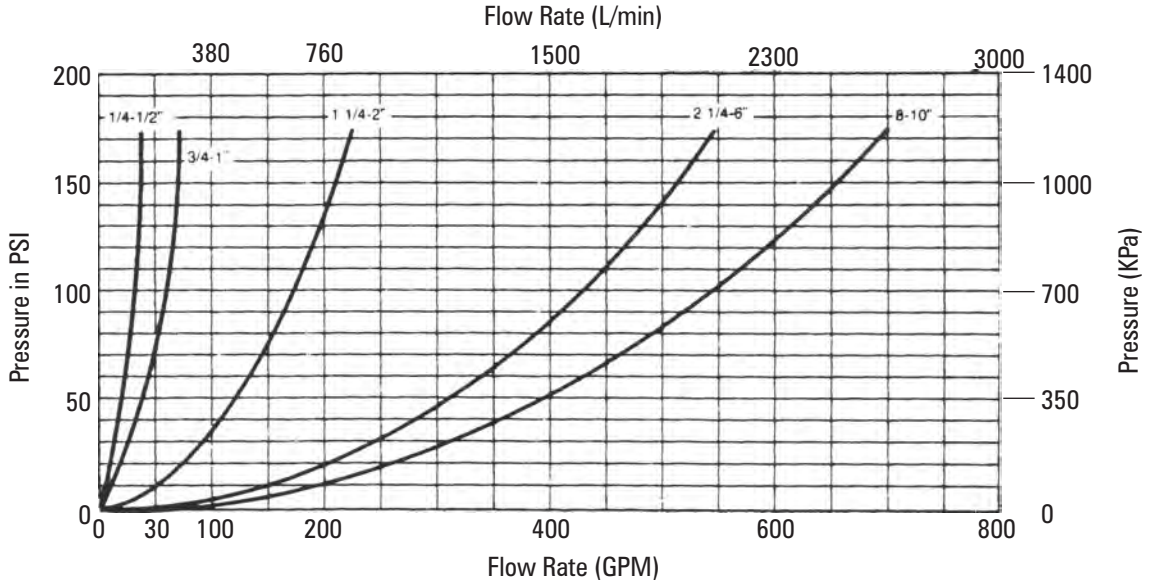


Figure 5-1 RPZ Discharge Flow Rate

Table 5-5 Pressure Losses Through RPZs

3" RPZ – Friction Loss Through Device							
GPM	WTTS	AMES	CONB	FEBB	CLAV	HERS	WILK
100	11.5	9.2	12.3	10.9	7.4	11.2	11.0
200	11.9	8.9	12.6	11.1	5.9	11.7	12.6
300	13.1	10.6	13.9	12.6	6.1	12.9	14.8
4" RPZ – Friction Loss Through Device							
GPM	WTTS	AMES	CONB	FEBB	CLAV	HERS	WILK
200	8.6	8.5	9.7	10.5	7.4	11.0	10.3
300	9.0	10.0	9.6	8.9	7.0	11.4	10.9
400	10.1	11.3	9.8	8.5	7.5	12.3	11.2
500	11.3	12.2	10.1	8.8	8.0	13.5	12.2
6" RPZ – Friction Loss Through Device							
GPM	WTTS	AMES	CONB	FEBB	CLAV	HERS	WILK
300	10.0	6.9	10.7	10.3	7.3	10.4	10.2
400	9.2	7.0	10.7	10.1	7.1	10.6	10.5
500	9.8	7.7	10.8	10.0	7.0	10.7	10.8

Figures denote psi friction losses for specific flows. Do not interpolate between flows; manufacturer's pressure loss curves must be consulted.

Key
WTTS: Watts model #909
AMES: Ames model #4000-ss
CONB: Conbraco model #40-200
FEBB: Febco model #860
CLAV: Cla-Val model #RP-1
HERS: Hersey model #6CM
WILK: Wilkins model #975

- 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:
- $(p_2 - p_1) \div d = (20 - 25) \times 144 \div 62.4 = -11.5$ feet [(138 – 172) ÷ 9.8 = -3.50 meters]
- Building friction head = (400 x 0.05 + 6 + 9) x 144 ÷ 62.4 = 80.8 feet [(120 x 35 ÷ 30 + 41 + 62) ÷ 9.8 = 24.6 meters]
- Pump system friction head = 4 + 18 = 22 feet [1.22 + 5.49 = 6.70 meters]
- Total dynamic head = 48 – 11.5 + 80.8 + 22 = 139 feet [14.6 – 3.50 + 24.6 + 6.70 = 42.4 meters

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 meters) on a 7.5-horsepower (hp) (5.60-kilowatt [kW]) 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 set point 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 set point, 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, overcurrent 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 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. 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. 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. Typically the flexible partition is

Table 5-6 Hydropneumatic Tank Volume Ratios

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

Table 5-6(SI) Hydropneumatic Tank Volume Ratios

Max. Pressure, kPa	Minimum Pressure, kPa									
	69	138	207	276	345	414	483	552	621	690
138	0.288									
207	0.447	0.224								
276	0.548	0.366	0.183							
345	0.618	0.464	0.309	0.155						
414	0.669	0.536	0.402	0.268	0.134					
483	0.708	0.590	0.472	0.354	0.236	0.118				
552	0.739	0.634	0.528	0.422	0.317	0.211	0.106			
621	0.764	0.669	0.573	0.478	0.382	0.287	0.191	0.096		
690	0.785	0.697	0.610	0.523	0.436	0.349	0.262	0.174	0.087	
758	0.802	0.722	0.642	0.561	0.481	0.401	0.321	0.241	0.160	0.080
827	0.817	0.742	0.668	0.594	0.520	0.445	0.371	0.297	0.223	0.148
896	0.829	0.760	0.691	0.622	0.553	0.484	0.415	0.346	0.276	0.207
965	0.840	0.776	0.711	0.646	0.582	0.517	0.453	0.388	0.323	0.259
1034	0.850	0.789	0.729	0.668	0.607	0.546	0.486	0.425	0.364	0.304
1103	0.859	0.801	0.744	0.687	0.630	0.572	0.515	0.458	0.401	0.343
1172	0.866	0.812	0.758	0.704	0.650	0.596	0.541	0.487	0.433	0.379
1241	0.873	0.822	0.770	0.719	0.668	0.616	0.565	0.514	0.462	0.411
1310	0.879	0.830	0.782	0.733	0.684	0.635	0.586	0.537	0.489	0.440
1379	0.885	0.838	0.792	0.745	0.699	0.652	0.606	0.559	0.512	0.466

a rubber diaphragm, which moves as pressure varies. It effectively isolates the air from the water.

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 5-3 (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 (cubic meters)
V_t = Total tank volume, cubic feet (cubic meters)
dV/dt = Average flow over time period t_p during low system demand

Then, when you define $(dV/dt)(t_p)$ as the drawdown volume V_d, you can examine the tank volume between two pressure levels in the tank and equate it 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, you have:

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

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

Rearranging and combining this with the average low flow, you get the tank volume formula:

Equation 5-4

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

The pressure ratio is a convenient volume ratio of drawdown volume to tank volume. For average near-sea-level conditions, Table 5-6 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 liters).

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 5-7, an example of a four-story building with a 10-gpm (37.8-liter-per-minute) 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, such as that illustrated in Figure 5-2, 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 meter) 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 preset levels
- Alarms, which alert operating personnel that a malfunction exists
- Safety devices, which operate when a malfunction occurs to avoid potential accidents

The piping arrangements between the various components of an elevated water tank system are illustrated in Figure 5-3.

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

- It is less complex than either of the other two 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 the other systems.
- A smaller pump capacity is required than for either of the other two systems.
- Pressure fluctuation in the system is minimal.
- Maintenance requirements are minimized.

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

- An exposed tank (or the enclosure around it) may be considered unsightly.

Table 5-7 Tank Size Varying by Its Location in a Building

Minimum Pressure, psi (kPa)	Maximum Pressure, psi (kPa)	$(p_2-p_1)/(p_2)$	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 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 5-8 to find a recommended minimum domestic storage volume of gravity tanks for various building types. For multiple dwellings, refer to Figure 5-4.

To use Table 5-8, 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 5-9. If the building's occupants are predominantly women, add 15 percent to the water storage requirement.

For multiple dwellings, use Figure 5-4 to find the number of gallons of storage per person depending on the number of apartments. If the actual number of people is not available, an approximate number can be found by using two people per bedroom or four people per apartment, whichever is larger, and multiplying by that number. Then multiply the number of people by the gallons (liters) required per person to find the domestic storage capacity of the house tank. To this, add 10 percent for constant uses of water, such as HVAC makeup. Add an additional number of gallons for fire protection water storage, if any. Then select a standard storage tank size equal to or larger than the required amount.

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.

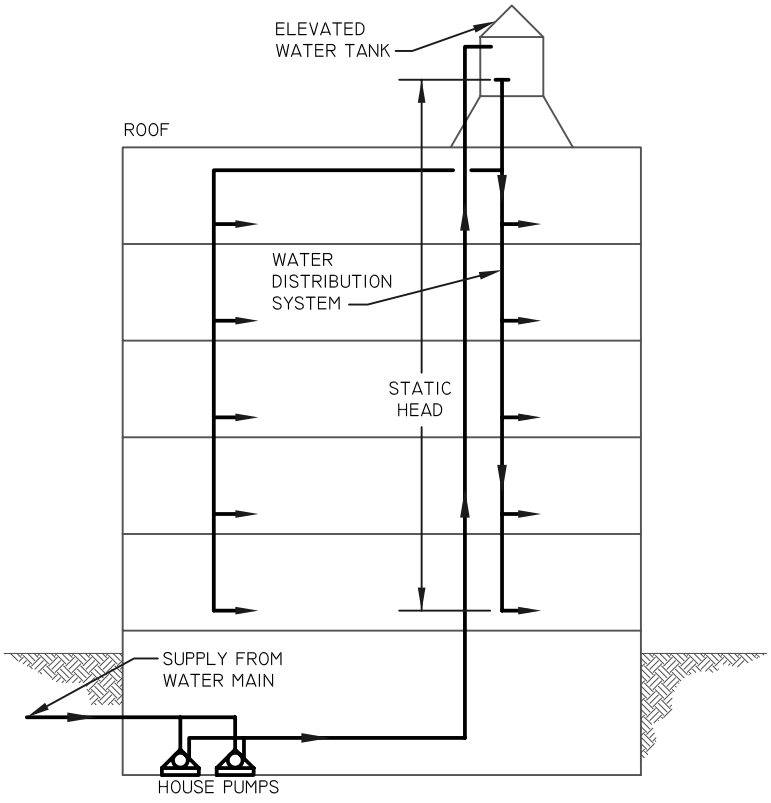


Figure 5-2 Simplified Downfeed Water Supply System with Simplified Elevated Water Tank

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 rise up to a temperature set point 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 5-5

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

where

V_{S1} = Volume of system at density d_1 (cubic feet [cubic meters]), pounds per cubic foot (kilograms per cubic meter)

V_{S2} = Volume of system at density d_2 (cubic feet [cubic meters]), (kilograms per cubic meter)

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 [cubic meters]), psia (kPa)

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

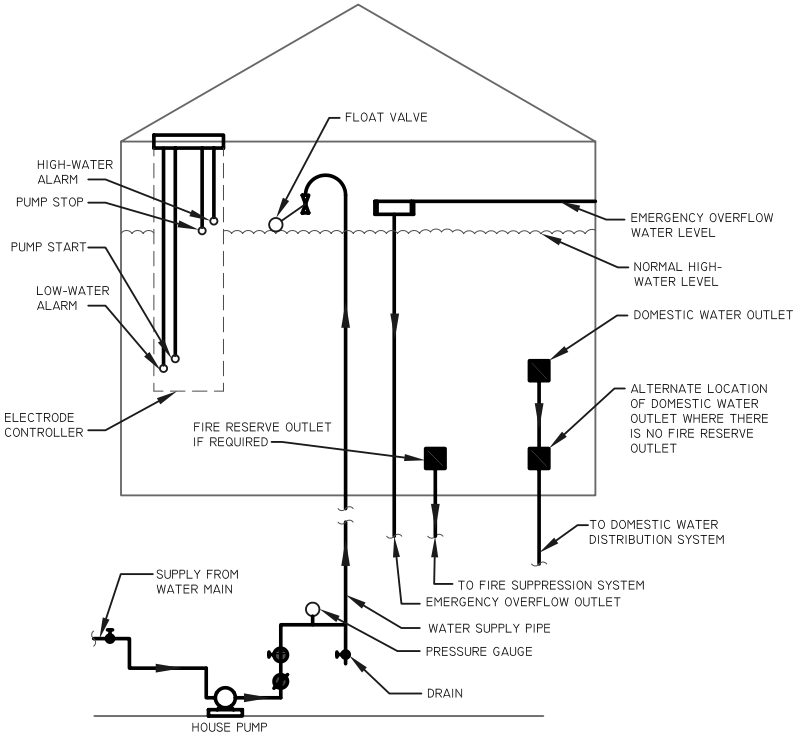


Figure 5-3 Piping Arrangement of an Elevated Water Tank

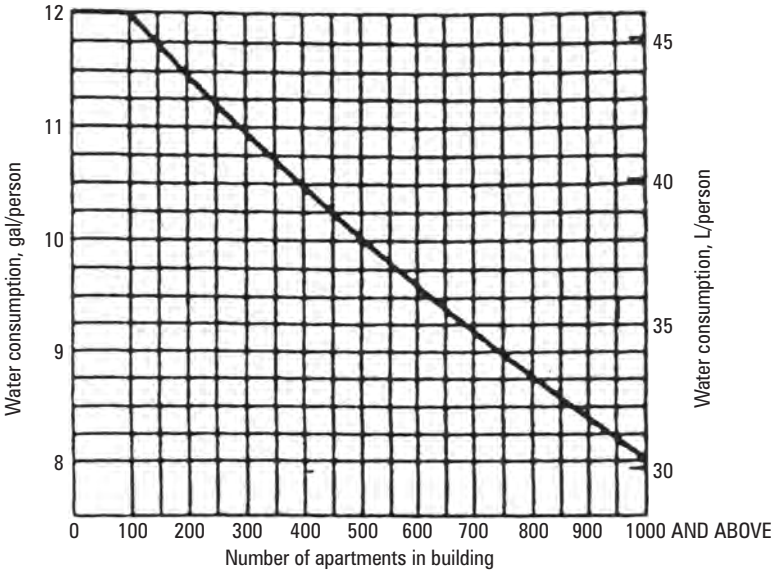


Figure 5-4 Estimated Water House Tank Storage Capacity, Multiple Dwellings

Table 5-8 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

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 you choose 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 expansion tank will be $V_t = V_1$, or:

Equation 5-6

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

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 5-6, Table 5-10 shows water density ratios for several maximum temperatures, and Table 5-11 shows pressure ratios for average sea-level conditions.

Table 5-9 Standard Wood House Tanks

Capacity, gal*	Dimension, ft+ Diameter × Stave	Number of dunnage beams	Dunnage, in++
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	11½ × 10	6	4 × 6
7,500	12 × 10	6	4 × 6
7,500	11 × 12	6	4 × 6
8,000	12½ × 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	13½ × 16	8	4 × 6
20,000	16 × 16	8	6 × 6
25,000	17½ × 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

* 1 gal = 3.8 L
\+ 1 ft = 0.3 m
++ 1 in = 25.4 mm
Source: Isseks Bros. Co.

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), $(d_1 - d_2) \div d_2$ is (62.425 – 61.38) ÷ 61.38 = 0.0171 ([1 – 0.9832] ÷ 0.9832 = 0.0171). Manufacturers regard $V_1 - V_2$ as an acceptable volume.

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.

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.

Table 5-10 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 5-11 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

For example, where initial pressures exceed 200 psi (1,379 kPa) or 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. It is recommended where the initial pressure is 200 psi (1,379 kPa) or more and where the ratio of initial to reduced pressure is more than 4 to 1 (e.g., 200 to 50 psi [1,379 to 344.7 kPa]), or where the initial pressure fluctuates greatly.

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. This type of installation should be employed wherever there is a wide variation of reduced-pressure requirements and where it is vital to maintain a continuous water supply. It also 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 liters per second) and the set pressure required is 50 psi (344.7 kPa). Select two valves, each rated at 200 gpm (12.6 liters per second), 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 millimeters) 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 liters per second) at a 60-psi (413.7-kPa) set pressure. The selection might be a 4-inch (100-millimeter) PRV rated for 240 gpm (15.1 liters per second) (80 percent of total maximum flow rate) and set at 60 psi (413.7 kPa) and a 1½-inch (40-millimeter) PRV rated for 60 gpm (3.8 liters per second) 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 (see Figure 5-5), 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 5-7, known as Joukowsky's formula:

Equation 5-7 (Joukowsky's formula)

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

where
P_r = Pressure rise above flow pressure, psi (kPa)
w = Specific weight of liquid (water = 62.4 pounds per cubic foot [1,000 kilograms per cubic meter])
a = Velocity of pressure wave, feet per second (fps) (meters per second)
v = Change in flow velocity, fps (meters per second)
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 5-8:

Equation 5-8

$$a = \frac{A_w}{(1 + KB)^{½}}$$

where
A_w = Velocity of sound in water (at room temperature approximately 4,900 fps [1,490 meters per second])
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

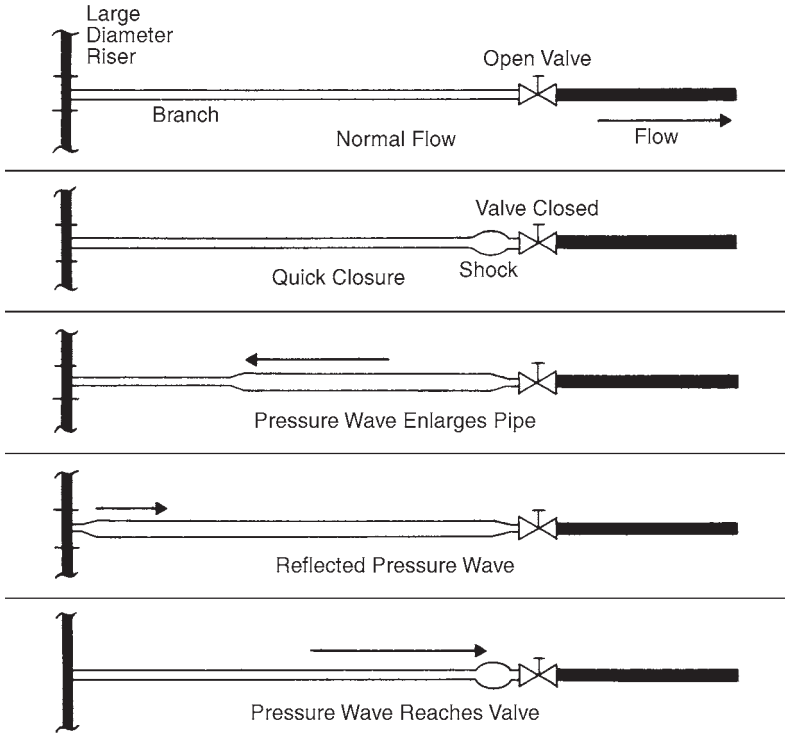


Illustration adapted from Plumbing & Drainage Institute, Standard PDI-WH201.

Figure 5-5 Illustrations of a Shock Wave

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 meters per second). Using Equation 5-7, the maximum pressure rise is approximately 60 times the change in velocity, and at a typical maximum design velocity of 8 fps (2.4 meters per second), 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 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 is the 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) and a is the velocity of a pressure wave as already defined. 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, say, 20 feet (6 meters), a 4,000-fps (1,200-meter-per-second) pressure wave would complete this oscillation at a rate of 200 hertz, definitely within the audible range.

As can be seen by reviewing Equation 5-7, 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-liter-per-flush) flushometer, with a beginning static pressure of 25 psi (170 kPa), the maximum instantaneous flow reaches 40 gpm (150 liters per second) with full closure about 12 seconds after peak flow. At 80 psi (550 kPa), the same flushometer will deliver 75 gpm (280 liters per second) 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 5-7 and 5-8, 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 5-7 and 5-8 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 up-sized, 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-millimeter) pipe is about 2.5 times that of a 1-inch (25-millimeter) pipe. This larger size branch line to a water closet flushometer, for example, would decrease the water velocity and therefore shock wave intensity P_r by 60 percent. A set of 1½-inch (38-millimeter) 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. Figure 5-6 shows some examples of air chambers. Air chamber capacity requirements are shown in Table 5-12, taken from Dawson and Kalinske, Iowa Institute of Hydraulic Research.

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, as illustrated in Figures 5-7(a) and 5-7(b).

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 American Society of Sanitary Engineering (ASSE) 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 5-13 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 5-13 were taken from a certain edition of the National Plumbing Code. As plumbing codes evolve, fixture unit values change. Without diminishing the value of Table 5-13, 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 5-13.
- 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 meters) 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.

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 kilogram per liter), which holds nearly constant through a temperature range of 32–60°F (0–15.6°C).

For calculations involving high temperature (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 formulae 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:

Equation 5-9 (Hazen-Williams Formula)

$$f = 0.2082\left(\frac{100}{C}\right)^{1.85}\left(\frac{q^{1.85}}{d^{4.8655}}\right)$$

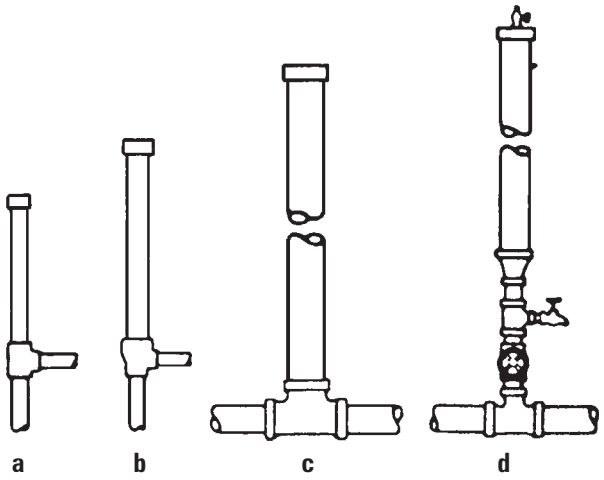


Figure 5-6 (a, b) Plain Air Chambers, (c) Standpipe Air Chamber, (d) Rechargeable Air Chamber

where

f = Friction head, feet of liquid per 100 feet of pipe (meters of liquid per 100 meters of pipe)
C = Surface roughness constant (dimensionless, see Table 5-14)
q = Fluid flow, gpm (liters per second)
d = Inside diameter of pipe, inches (millimeters)

This formula is most accurate for water flow in pipes larger than 2 inches (50.8 millimeters) and at velocities less than 10 fps (3 meters per second).

Equation 5-9 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). Values of C, for various types of pipes, are shown in Table 5-15 with the corresponding multipliers that should apply to the values of the head loss, f, for various temperatures.

Figure 5-8 is a copy of N 1.85 graph paper used to analyze water flow at various velocities. If you know two points on the graph and connect a line between them, you can determine 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.

Table 5-12 Required Air Chambers

Nominal Pipe Diam., in. (mm)	Pipe Length, ft (m)	Flow Pressure, psi (kPa)	Velocity, fps (m/s)	Required Air Chamber	
				Volume, in.^{3} (cm^3)	Phys. 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 × 12 7/10 (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)

Table 5-13 Water Hammer Arrester Sizing

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

Source: Plumbing and Drainage Institute

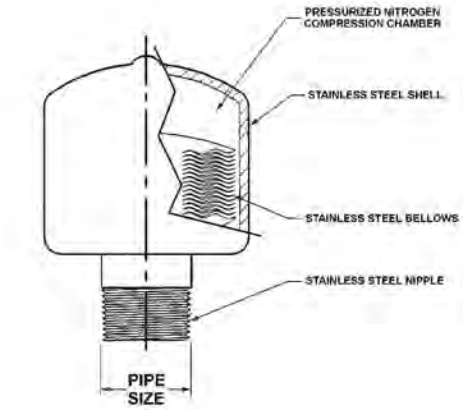


Figure 5-7(a) Bellows

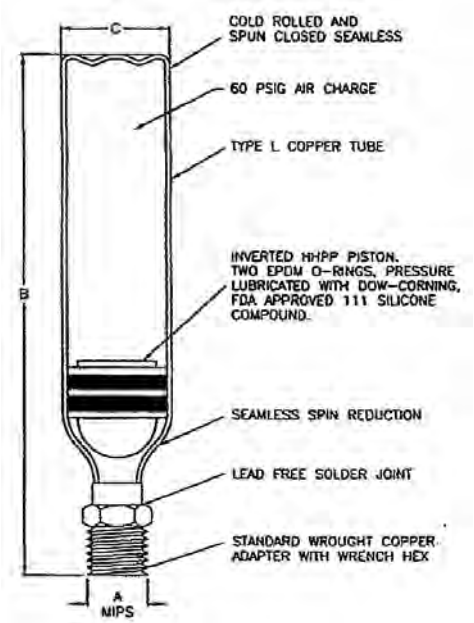


Figure 5-7(b) Piston

Table 5-14 Densities of Pure Water at Various Temperatures

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

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 5-10 (Darcy-Weisbach Formula)

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

To convert to psi, the equation is:

Equation 5-10a

$$\text{Also, } p = h_f \times \left(\frac{\varphi}{144}\right)$$

where
hf = friction head loss, feet (meters) 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 (meters)
D = inside diameter of pipe, feet (meters)
V = average velocity of flow, fps (meters per second)
g = gravitational acceleration, 32.2 ft/sec/sec
φ = pounds per cubic foot (kilograms per cubic meter)

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 factor f takes into account viscosity (temperature), pipe roughness, and 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, f can be determined by the C.F. Colebrook formula, Moody diagrams, or from manufacturer data or various handbooks.

Equation 5-11 (Colebrook Formula)

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

To get the Reynolds number, the equation is:

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

where
R = Reynolds number, from Figure 5-9
f = Friction factor, dimensionless
ε = Absolute roughness, in ft
D = Inside diameter of pipe, ft
V = Average pipe velocity, ft/sec
v = Kinematic viscosity, ft2/sec

Since the Colebrook equation is complicated, f may be obtained from a graph developed by L.F. Moody (see Figure 5-10). This graph shows the relation

between the friction factor f, 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 5-16 for some values of ε (absolute roughness) and Table 5-17 for some values of f.

For domestic plumbing, design tables or graphs can be found in local code documents or various ASPE publications or obtained from the pipe manufacturers (see Figure 5-11 through 5-14). 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 your design. When picking a product for your design, you must use the latest manufacturer literature. Also, you must use 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 [liters per second]), maximum velocity desired (fps [meters per second]), and the pressure available for piping friction loss per 100 feet (psi [kPa]).

Demand

To size piping, you must know the maximum gpm (liters per second) 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 5-18, which was taken from the International 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

Table 5-15 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

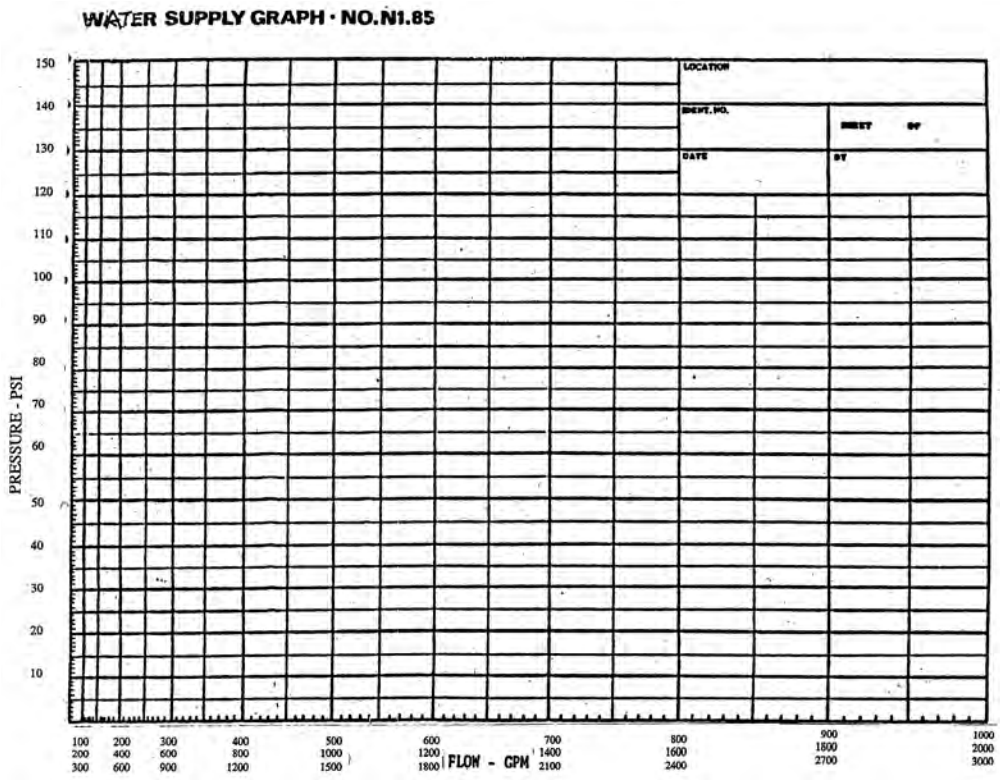


Figure 5-8 Water Supply Graph

(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 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.

You must 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, you must use the predominant fixture type. (For gpm conversions, see Table 5-19 or Figure 5-15). Add all the WSFU (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 you know the gpm of all branches and mains as well as the pressure drop per 100 feet to be allowed (to size the pipe), you then can go to the pipe graphs. Most codes tell you the minimum pipe size to the final fixture connection and also its maximum length (see Table 5-20). They also tell you the minimum flow rate and the minimum flow pressure (see Table 5-21). You must check this information with the manufacturer's requirements for the fixtures that are being used on the project.

As stated previously, you must use the plumbing code that applies to your project's location. The IPC table examples are used in this chapter for no particular reason. The IPC currently uses the Hunter's curve fixture unit conversion to gpm, which was developed in 1924. If you are designing a facility where this code requirement is in effect, the information must be used. Since that time, however, many authorities have determined that use of the curves leads to oversized piping, mainly due to the reduced water flow and different life patterns of modern fixtures. If this code is not the approved code for the local area, the use of modern fixture units to gpm conversions is recommended.

Figure 5-16 shows a form you can use to keep track of WSFU and other data. Figure 5-17 illustrates a piping sketch showing the typical code definitions of a domestic water piping system.

Velocity

The second factor affecting the sizing of a water line is velocity. A maximum velocity of 10 fps (3 meters per second), which is suggested by some model plumbing codes, is much too high for domestic plumbing installations. Even 8 fps (2.4 meters per second), as listed in other codes, is very high for many types of domestic water piping and subject to water hammer.

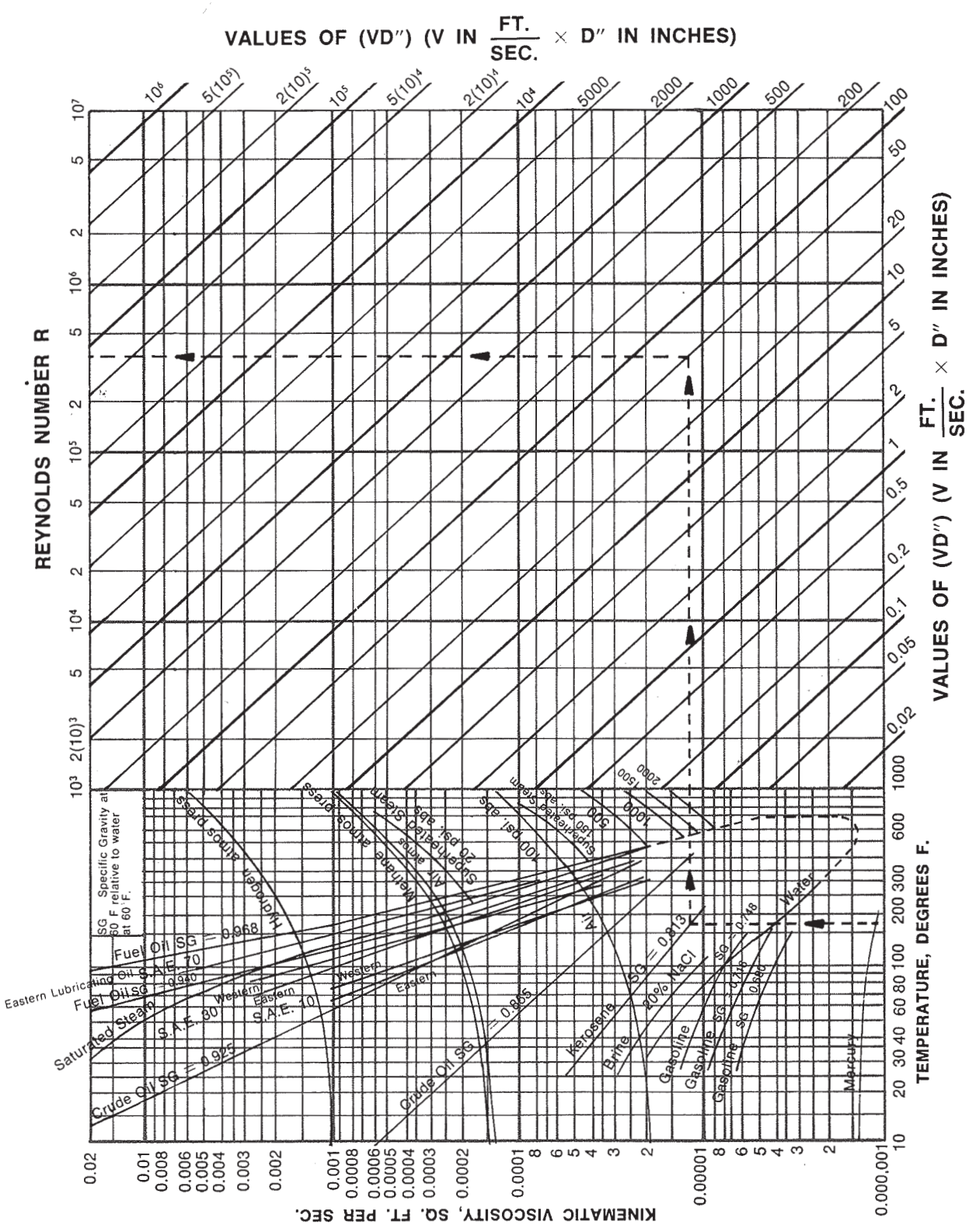


Figure 5-9 Kinematic Viscosity and Reynolds Number Chart

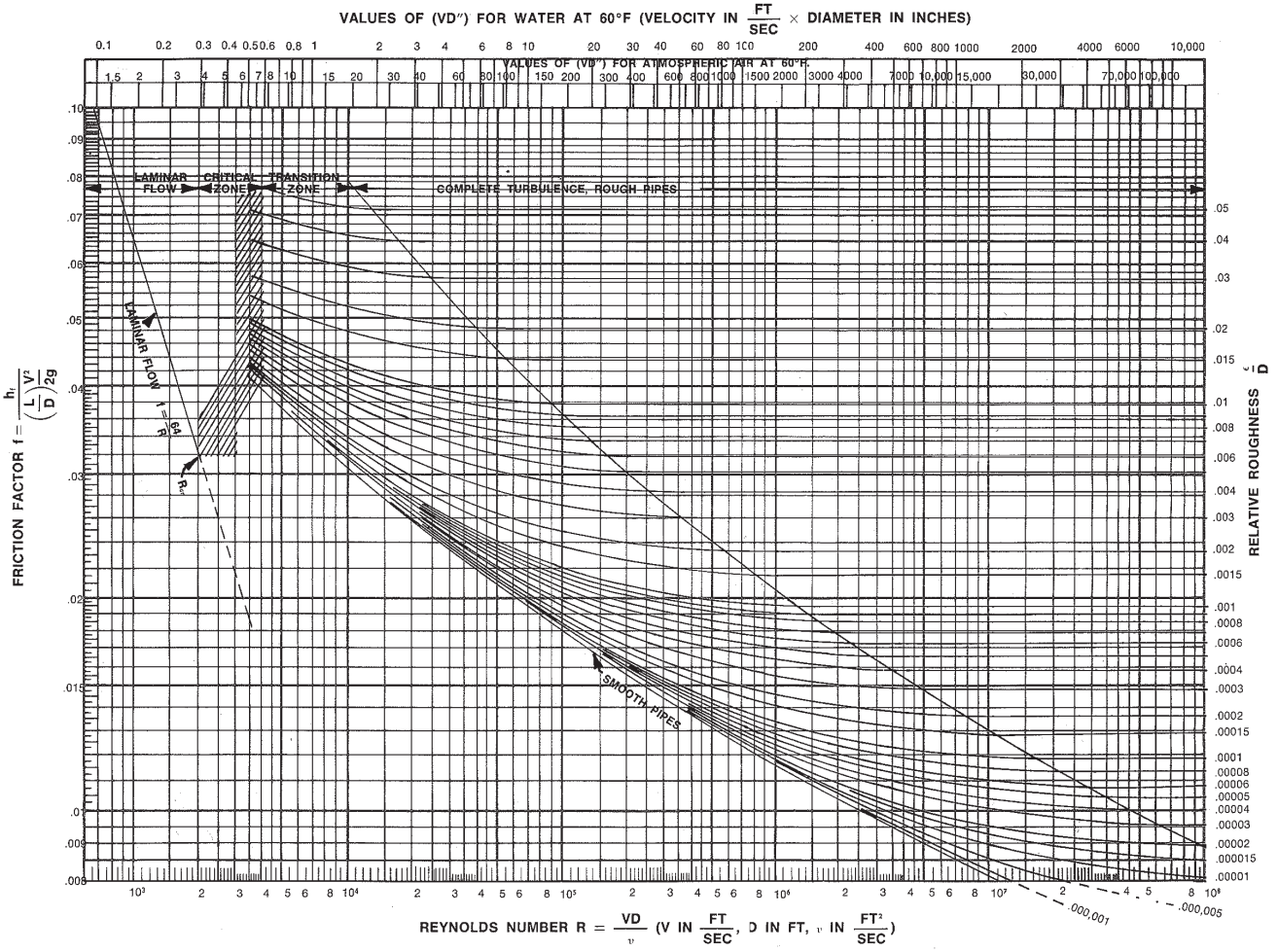


Figure 5-10 Friction Factors for Any Kind and Size of Pipe

Table 5-16 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 5-17 Average Values for Coefficient of Friction, f

Nominal Pipe Size, inches	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

A velocity above 6 or 7 fps (1.8 or 2.1 meters per second) 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 meters per second) 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
Copper (K, L): 5–8 fps cold
2–3 fps > 140°F
4–5 fps < 140°F
PVC: 4–6 fps
CPVC: 5 fps
Polyethylene: 6–8 fps
RFP: 4–6 fps

Pressure

The third factor affecting the sizing of a water line is the pressure available for piping friction loss. The first step in ascertaining pressure available for friction loss

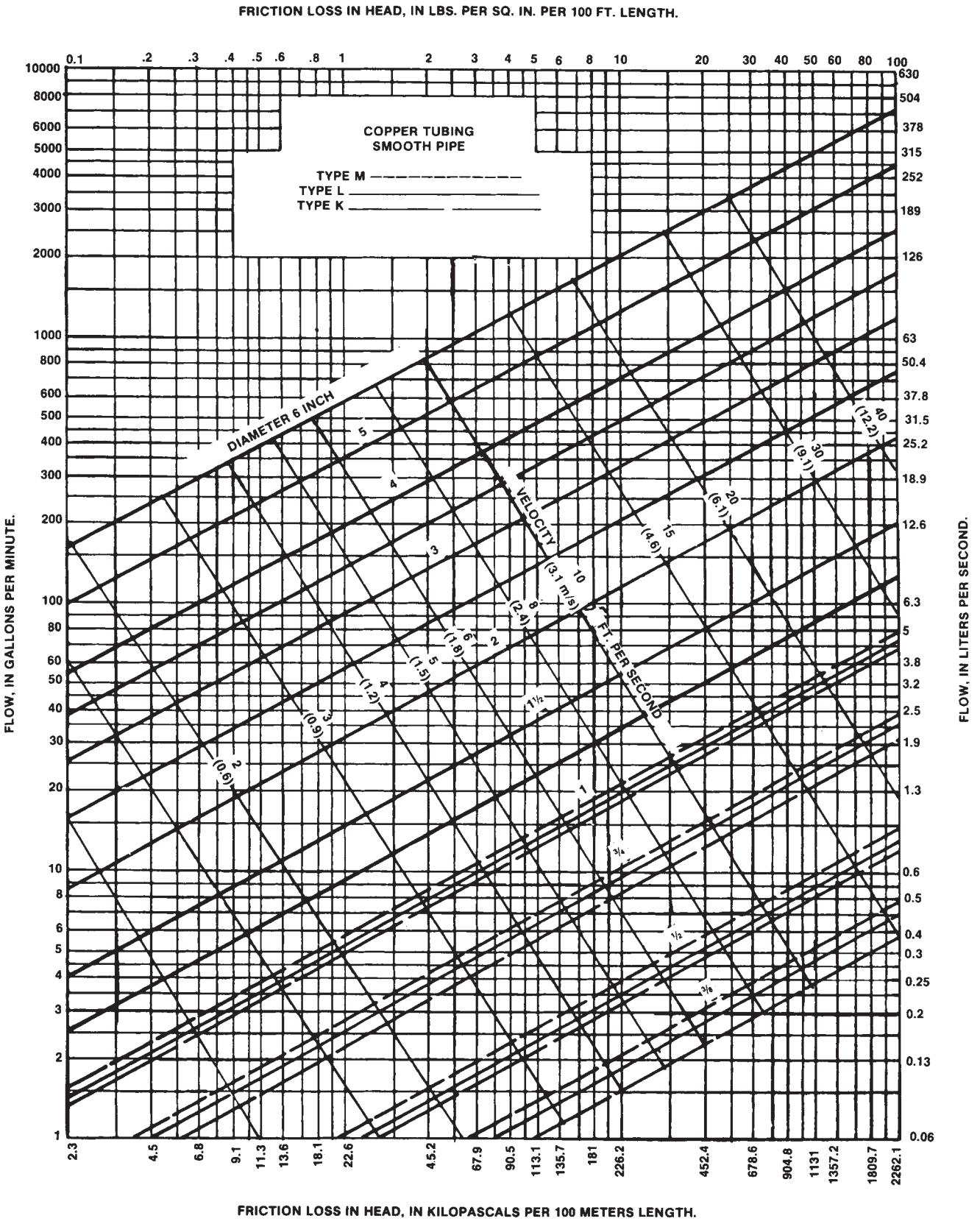


Figure 5-11 Pipe Sizing Data, Smooth Pipe

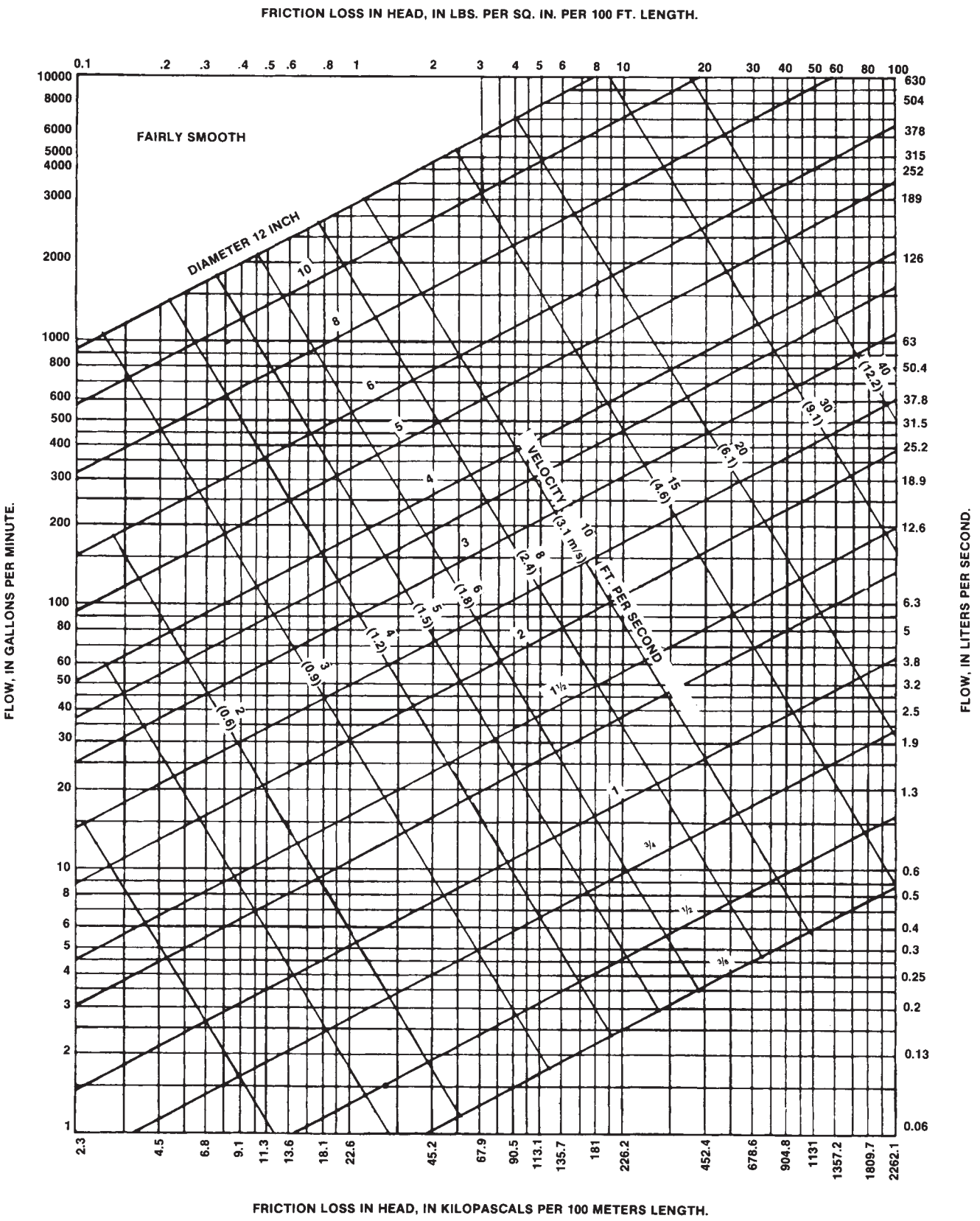


Figure 5-12 Pipe Sizing Data, Fairly Smooth Pipe

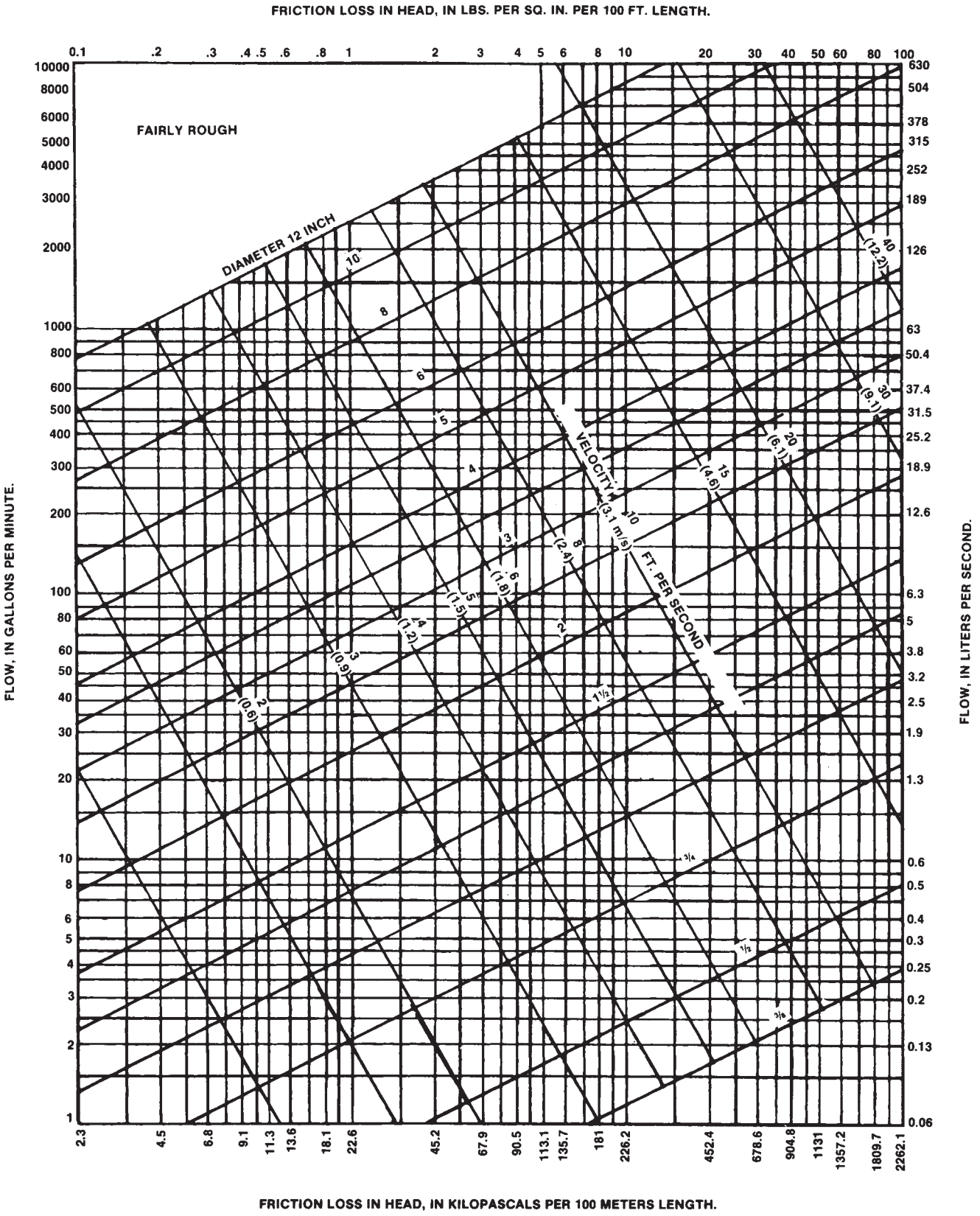


Figure 5-13 Pipe Sizing Data, Fairly Rough Pipe

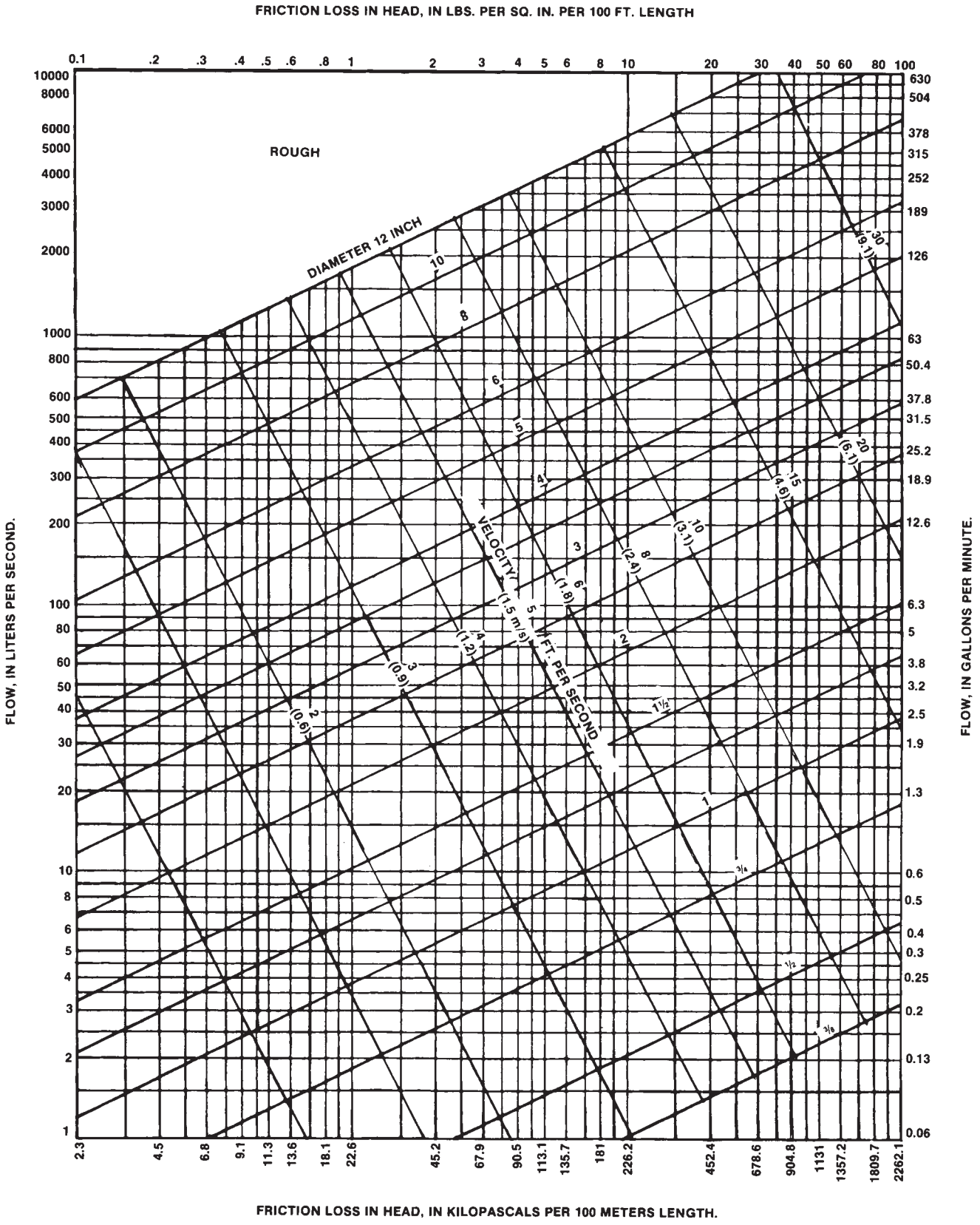


Figure 5-14 Pipe Sizing Data, Rough Pipe

Table 5-18 Load Values Assigned to Fixtures[a]

Fixture	Occupancy	Type of Supply Control	Load Values, in Water Supply Fixture Units (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.	⅜″ 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″ flush valve	10.0	—	10.0
Urinal	Public	¾″ 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.

Source: International Plumbing Code

Table 5-19 Estimating Demand

Supply Systems Predominantly for Flush Tanks			Supply Systems Predominantly for Flush Valves		
Load	Demand		Load	Demand	
Water supply Fixture units	Gallons per minute	Cubic feet per minute	Water supply fixture units	Gallons per minute	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	5	15.0	2.0052
6	10.7	1.430376	6	17.4	2.326032
7	11.8	1.577424	7	19.8	2.646364
8	12.8	1.711104	8	22.2	2.967696
9	13.7	1.831416	9	24.6	3.288528
10	14.6	1.951728	10	27.0	3.60936
11	15.4	2.058672	11	27.8	3.716304
12	16.0	2.13888	12	28.6	3.823248
13	16.5	2.20572	13	29.4	3.930192
14	17.0	2.27256	14	30.2	4.037136
15	17.5	2.3394	15	31.0	4.14408
16	18.0	2.90624	16	31.8	4.241024
17	18.4	2.459712	17	32.6	4.357968
18	18.8	2.513184	18	33.4	4.464912
19	19.2	2.566656	19	34.2	4.571856
20	19.6	2.620128	20	35.0	4.6788
25	21.5	2.87412	25	38.0	5.07984
30	23.3	3.114744	30	42.0	5.61356
35	24.9	3.328632	35	44.0	5.88192
40	26.3	3.515784	40	46.0	6.14928
45	27.7	3.702936	45	48.0	6.41664
50	29.1	3.890088	50	50.0	6.684
60	32.0	4.27776	60	54.0	7.21872
70	35.0	4.6788	70	58.0	7.75344
80	38.0	5.07984	80	61.2	8.181216
90	41.0	5.48088	90	64.3	8.595624
100	43.5	5.81508	100	67.5	9.0234
120	48.0	6.41664	120	73.0	9.75864
140	52.5	7.0182	140	77.0	10.29336
160	57.0	7.61976	160	81.0	10.82808
180	61.0	8.15448	180	85.5	11.42964
200	65.0	8.6892	200	90.0	12.0312
225	70.0	9.3576	225	95.5	12.76644
250	75.0	10.026	250	101.0	13.50168
275	80.0	10.6944	275	104.5	13.96956
300	85.0	11.3628	300	108.0	14.43744
400	105.0	14.0364	400	127.0	16.97736
500	124.0	16.57632	500	143.0	19.11624
750	170.0	22.7256	750	177.0	23.66136
1,000	208.0	27.80544	1,000	208.0	27.80544
1,250	239.0	31.94952	1,250	239.0	31.94952
1,500	269.0	35.95992	1,500	269.0	35.95992
1,750	297.0	39.70296	1,750	297.0	39.70296
2,000	325.0	43.446	2,000	325.0	43.446
2,500	380.0	50.7984	2,500	380.0	50.7984
3,000	433.0	57.88344	3,000	433.0	57.88344
4,000	535.0	70.182	4,000	525.0	70.182

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. The maximum and minimum pressures may be nearly the same or they may vary greatly depending on the time of year, hour of the day, type of adjacent buildings, etc. Care must be taken to handle the high pressure as well as the low pressure. If the maximum pressure is more than 80 psi 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.

The city water pressure should be determined from a fire hydrant flow test, which is taken as close to the site as possible and includes static and residual pressures at the desired flow rate (above normal use with your building added) (see Figure 5-18). The residual pressure, with all of the above considerations taken into account, 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.

If a pressure-regulating device is installed, the available pressure after the falloff pressure must be used (on outlet side of meter or backflow preventer).

The water meter creates a loss of pressure, and the pressure drop is available from the manufacturer's flow charts. See samples of such charts in Figures 5-19(a), 5-19(b), and 5-19(c). You must decide if you want to lose or preserve the water pressure available at the street.

You also must determine 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. Some iteration will be required to find the one place with the highest pressure drop. For example, see the system shown in Figure 5-20. To find the critical circuit, determine which final fixture or device requires the most pressure (from the meter outlet). The flush valve water closet needs 15 psi (103.4 kPa) and has no static loss. The backflow preventer has a 16-psi (110.3-kPa) pressure drop and a 8.66-psi (59.7-kPa) static loss for a total loss of 24.66 psi (170 kPa). The dishwasher has a total loss of 40 psi (275.8 kPa)—25 psi (172.4 kPa) for the dishwasher plus a 5-psi (34.5-kPa) loss through the water heater plus a 10-psi (69-kPa) loss through the softener. Therefore, the piping to the dishwasher is the governing critical circuit because it has the highest total pressure required when the needed flow pressures and static losses are added.

The pressure required at each fixture or appliance can be determined from the applicable code and/or the manufacturer's information (refer back to Table 5-21). 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 per meter) 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 you calculate the meter outlet pressure. You must account for the elevation difference between the city main and the meter.

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. (Do you want the drop to be high or low?) 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. (Do you want the drop to be high or low?)
4. Determine the outlet pressure at the meter from the values obtained in Steps 1 through 3.
5. You now must determine the most hydraulically remote point (the piping main and branch) using the greatest amount of needed end pressure and the total pressure drops 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. Examples include the water softener or other water treatment devices, water heater, PRV, control valve or solenoid, and reduced-pressure backflow preventer.
6. Determine the pressure needed at the final fixture or appliance, as well as the static pressure drop or increase due to elevations.
7. Calculate the pressure drop allowed for the piping using the values obtained in Steps 5 and 6.

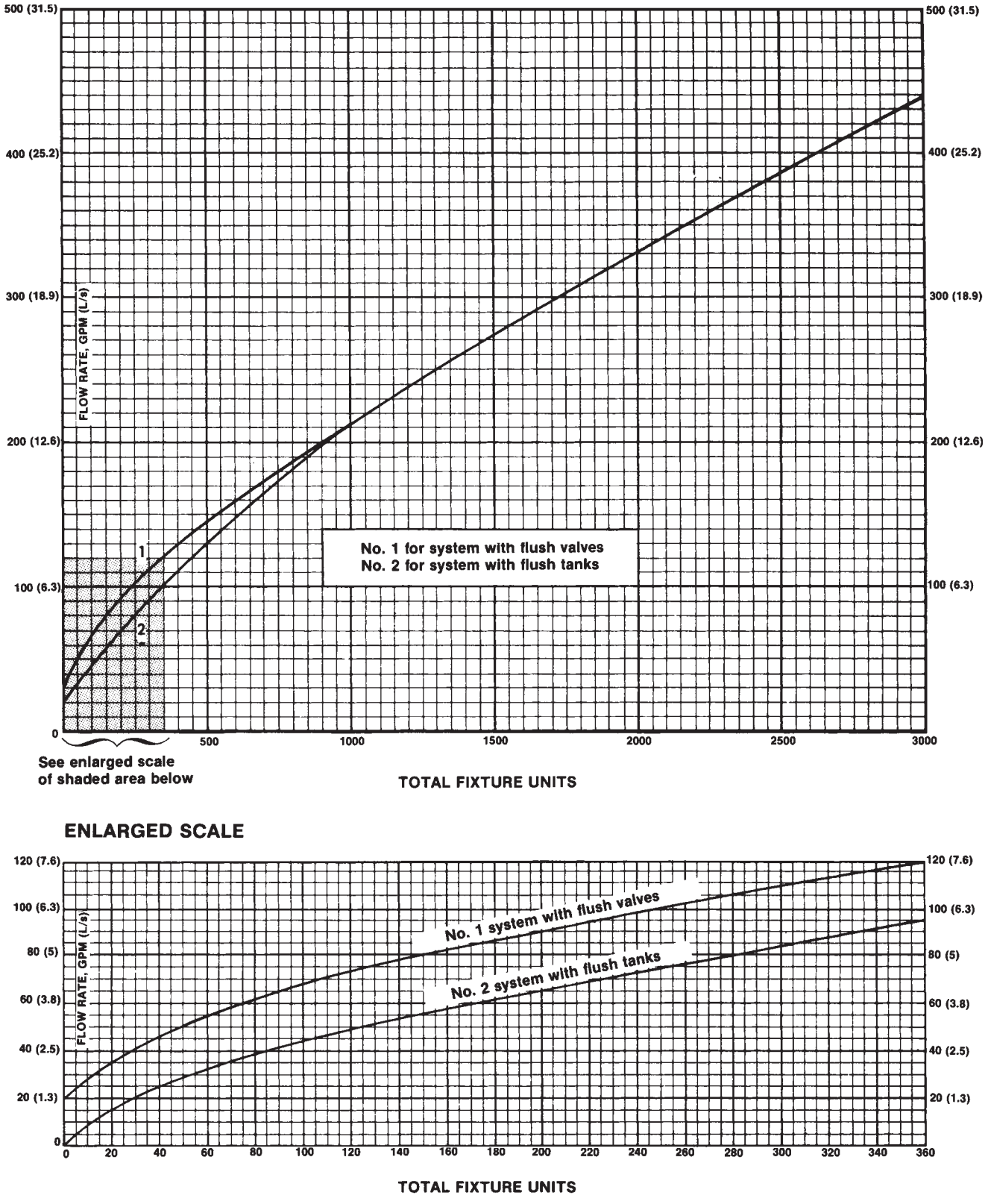


Figure 5-15 Conversion of Fixture Units, fu, to gpm (L/s)

Table 5-20 Minimum Sizes of Fixture Water Supply Pipes

Fixture	Minimum Pipe Size, in.
Bathtubs[a] (60" × 32" and smaller)	½
Bathtubs[a] (larger than 60" × 32")	½
Bidet	⅜
Combination sink and tray	½
Dishwasher, domestic[a]	½
Drinking fountain	⅜
Hose bibbs	½
Kitchen sink[a]	½
Laundry, 1, 2 or 3 compartments[a]	½
Lavatory	⅜
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	⅜
Water closet, flush valve	1
Water closet, flushometer tank	⅜
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 5-21 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	15	15
Water closet, blow out, flushometer valve	35	25
Water closet, flushometer tank	1.6	15
Water close;, siphonic, flushometer valve	25	15
Water closet, tank, close coupled	3	8
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

Fixture or Group	Public or Private	Quantity	Fixture Units for Individual Fixtures			Total Fixture Units			Min gpm	Min Pressure	Min Pipe
			Hot	Cold	Total	Hot	Cold	Total			
Total Fixture unit count											

Figure 5-16 Form to Track WFSU and Other Data

8. You now must determine the equivalent length (sometimes called 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.
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 gpm totals, starting from the farthest connection back to the meter, and using the allowable pressure drop per 100 feet, refer to the pipe graphs (Figures 5-11 through 5-14) and select the pipe sizes for the most hydraulically remote point. Don't go above the maximum desired velocity. When you get to the maximum velocity line, follow it to the left (the maximum flow rate).

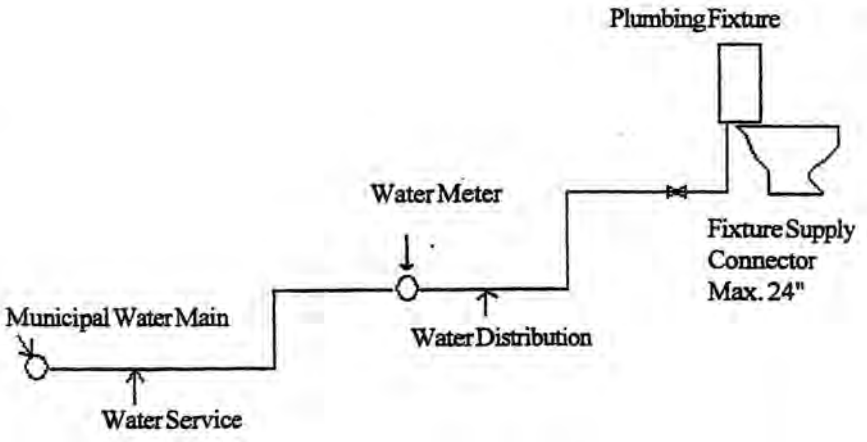


Figure 5-17 Domestic Water Piping Sketch

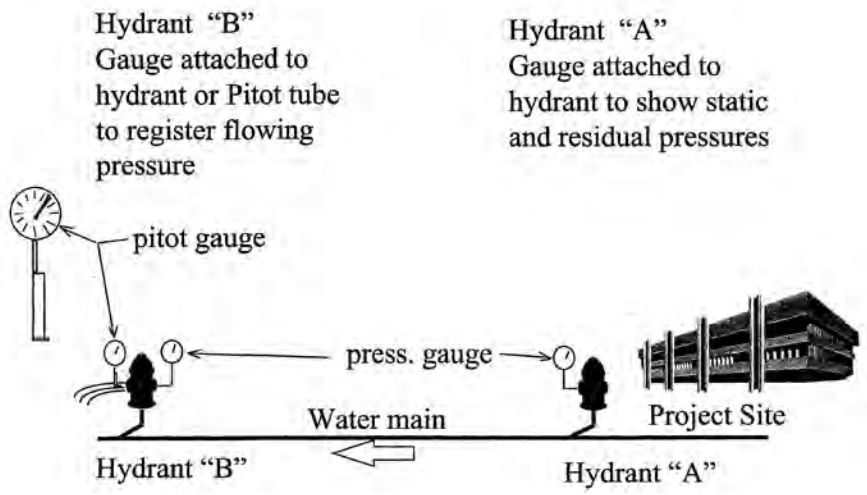


Figure 5-18 Method for Conducting a Water Flow Test

11. You now must determine how to size all 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 ([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).

Example 5-2

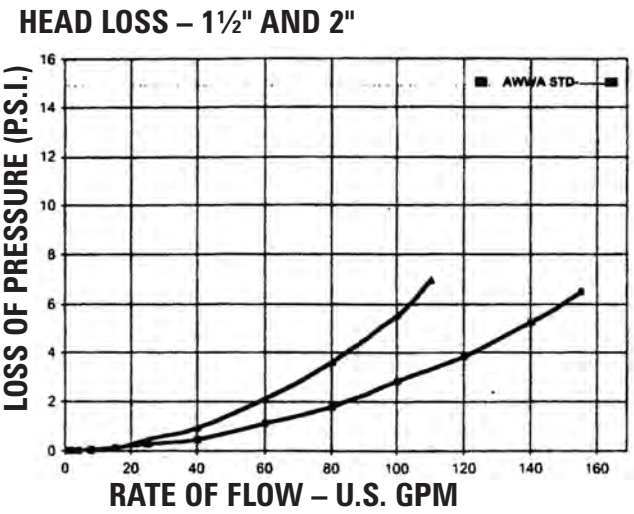
Figure 5-21 illustrates how to determine the pressure available for friction.

In the system shown (with a main line running from the meter, point A, to the governing fixture or appliance, point L—the critical circuit), each section of the line is 10 feet (3.1 meters) in equivalent length, for a total of 100 feet (30.5 meters) from A to L. This includes an allowance for fittings. The allowable pressure drop for pipe friction is 10 psi (69 kPa). The first tabulation is the friction loss in the system.

Section A–B has an equivalent length of 10 feet (3.1 meters). The uniform pressure drop is 10 psi per 100 feet (226.2 kPa per 100 meters). Assuming that precisely sized pipe is selected (for this theoretical case) to give a pressure loss (due to friction) of exactly

Figure 5-19(a) Disc-type Positive Displacement Magnetic Drive Meter





NOTE: Performance curves are typical only and NOT a guarantee of performance.

Flow Characteristics

Meter Size	Typical Low Flow (95%) Minimum)	Typical Operating Range (100% ± 1.5%)	Maximum Continuous Operation
1½"	1½ GPM	5 to 100 GPM	50
2"	2 GPM	8 to 160 GPM	80

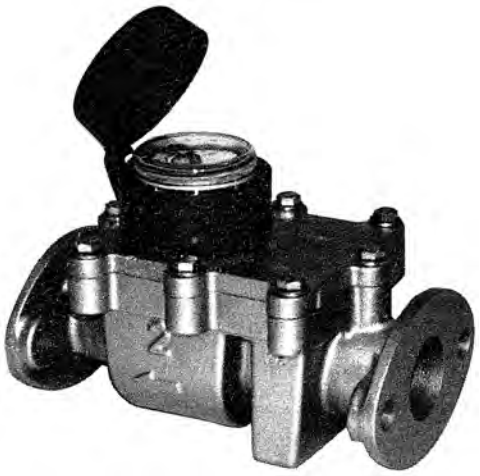
Figure 5-19(b) Compound Magnetic Drive Meter



Flow Characteristics

Meter Size	Typical Low Flow (95%) Minimum)	Typical Operating Range (100% ± 1.5%)	Maximum Continuous Operation	Maximum Intermittent Flow
1½"	2 GPM	4 to 120 GPM	120 GPM	120 GPM
2"	2½ GPM	4 to 160 GPM	160 GPM	160 GPM

Figure 5-19(c) Horizontal Turbine Meter



Flow Characteristics

Meter Size	Typical Low Flow (95%) Minimum)	Typical Operating Range (100% ± 3%)	Maximum Continuous Operation
2"	¼ GPM	1 to 160 GPM	80 GPM
3"	½ GPM	4 to 320 GPM	160 GPM
4"	¾ GPM	6 to 500 GPM	250 GPM
6"	1½ GPM	10 to 1000 GPM	500 GPM
8"	2 GPM	16 to 1600 GPM	800 GPM

10 psi per 100 feet (226.2 kPa per 100 meters), the pressure loss in this section (A–B) is 1 psi (6.9 kPa), and the pressure for friction at point B is 9 psi (62.1 kPa). In section K–L, at point L, there is no pressure left for friction. This is the governing fixture (and the critical circuit).

Method A uses the same uniform pressure loss in the branches as was used in the critical circuit line to the governing fixture. The pressure available for friction at the end of each branch is not zero. At point M it is 1 psi (6.9 kPa); at point R it is 5 psi (34.5 kPa); and at point U it reaches a maximum of 8 psi (55.2 kPa). Unless the pressure to each of the other fixtures is used up as piping friction loss or fixture pressure drop, more water than necessary flows through the branches nearest the meter to use the excess available

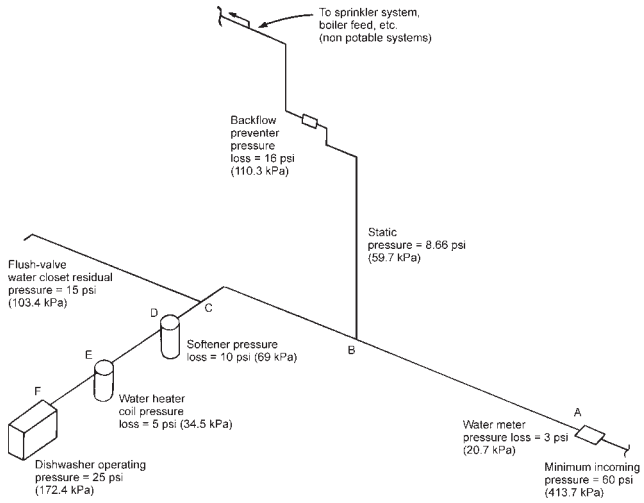


Figure 5-20 Establishing the Governing Fixture or Appliance

pressure. However, in a complex piping system this is the typical method used. It is the most common method for design purposes.

Method B illustrates the total pressure loss method. All the available friction piping pressure in each of the branches is used. In actual practice, this method cannot be utilized. The average pressure loss in each section closer to the meter is very high, far higher than normally is accepted. Many engineers and designers would be concerned with the high pressure loss as well as with the resulting high velocity in the small pipe. The next-to-last column shows the pressure drop that must be used for each branch.

Method C is the branch length method. The critical circuit is sized on the uniform pressure drop of the critical system (Method A), and the branches are sized on their own allowable friction pressure drop. At section M–J, the total allowable pressure drop over the entire system (point A to point M) is 10 psi (69 kPa). Point M has an equivalent length of 90 feet (27.4 meters) from point A. This gives an allowable pressure drop of 11.1 psi (7.6 kPa), (10/90) per 100 feet (30.5 meters), and an unused frictional pressure of 0.9 psi (6.2 kPa). By going through all the branches in the same manner and working out the pressure drop for the new equivalent length, the branches can be sized. You can see that the unused frictional pressure varies from 0.9 psi (6.2 kPa) to a maximum of 4.66 psi (32.1 kPa). These pressures are less than those resulting from Method A, and the average pressure drops are less than those resulting from Method B. Consequently, Method C frequently is used by designers. In actual practice, it is not necessary to calculate the average pressure drop for each branch. Usually the branches are close together, and the changes in the average pressure drop are very small.

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 meters), the lines are sized on the basis of a 4- to 6-fps (1.2- or 1.8-meters-per-second) 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, you can determine the pressure drop in all piping from the piping graphs (Figures 5-11 through 5-14). By measurement or other manufacturer information, you can 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 5-22). Note that these are not affected by the flow velocity and therefore are very inaccurate.

For a more accurate pressure drop, you should use K values or C_v values (design coefficients), which can be calculated using Equation 5-12.

Equation 5-12

$$\Delta h = KV2/2g$$

$$\text{Also, } Q = Cv\ \sqrt{(\Delta P/SG)}$$

$$\Delta P = (Q/Cv)2\ S.G.$$

$$\Delta h = \text{Fluid head (ft)}$$

where

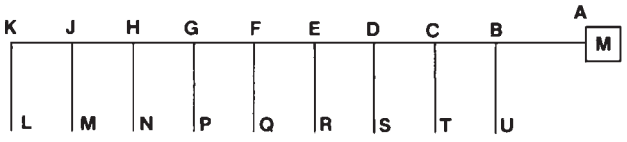
V = Velocity, fps (meters per second)
g = Acceleration of gravity
ΔP = Pressure, psi (kPa)
Q = Flow, gpm (liters per second)
S.G. = Specific gravity, water = 1.0 (for water, Δh x 0.43 = psi)
K = Coefficient
Cv = Flow through a valve where a pressure loss of 1 psi occurs

See Figure 5-22 for the K values to typical valves and fittings. See Figure 5-23 for the Cv values for valves. They take into account the effect of velocity on the pressure drop through the fitting or valve. For the approximate pressure loss through 3-, 4-, and 6-inch reduced-pressure-zone backflow preveters, refer back to Table 5-5.

METHOD A						
Section	Developed Length in Section, ft (m)	Developed Length from Point A, ft (m)	Friction Loss, psi/100 ft (kPa/100 m)	Friction Loss in Section, psi (kPa)	Total Pressure Loss from Friction, psi (kPa)	Pressure at End of Section for Friction, psi (kPa)
A–B	10 (3.1)	10 (3.1)	10 (226.2)	1 (6.9)	1 (6.9)	9 (62.1)
B–C	10 (3.1)	20 (6.1)	10 (226.2)	1 (6.9)	2 (13.8)	8 (55.2)
C–D	10 (3.1)	30 (9.1)	10 (226.2)	1 (6.9)	3 (20.7)	7 (48.3)
D–E	10 (3.1)	40 (12.2)	10 (226.2)	1 (6.9)	4 (27.6)	6 (41.4)
E–F	10 (3.1)	50 (15.2)	10 (226.2)	1 (6 9)	5 (34.5)	5 (34.5)
F–G	10 (3.1)	60 (18.3)	10 (226.2)	1 (6.9)	6 (41.4)	4 (27.6)
G–H	10 (3.1)	70 (21.3)	10 (226.2)	1 (6.9)	7 (48.3)	3 (20.7)
H–J	10 (3.1)	80 (24.4)	10 (226.2)	1 (6.9)	8 (55.2)	2 (13.8)
J–K	10 (3.1)	90 (27.4)	10 (226.2)	1 (6.9)	9 (62.1)	1 (6.9)
K–L	10 (3.1)	100 (30.5)	10 (226.2)	1 (6.9)	10 (69)	0 (0)

METHOD B						
Section	Developed Length in Section, ft (m)	Developed Length from Point A, ft (m)	Pressure at Start, psi (kPa)	Friction Loss, psi/100 ft (kPa/100 m)	Friction in Section, psi (kPa)	Pressure at End, psi (kPa)
M–J	10 (3.1)	90 (27.4)	2 (13.8)	10 (226.2)	1 (6.9)	1 (6.9)
N–H	10 (3.1)	80 (24.4)	3 (20.7)	10 (226.2)	1 (6.9)	2 (13.8)
P–G	10 (3.1)	70 (21.3)	4 (27.6)	10 (226.2)	1 (6.9)	3 (20.7)
Q–F	10 (3.1)	60 (18.3)	5 (34.5)	10 (226.2)	1 (6 9)	4 (27.6)
R–E	10 (3.1)	50 (15.2)	6 (41.4)	10 (226.2)	1 (6.9)	5 (34.5)
S–D	10 (3.1)	40 (12.2)	7 (48.3)	10 (226.2)	1 (6.9)	6 (41.4)
T–C	10 (3.1)	30 (9.1)	8 (55.2)	10 (226.2)	1 (6.9)	7 (48.3)
U–B	10 (3.1)	20 (6.1)	9 (62.1)	10 (226.2)	1 (6.9)	8 (55.2)

METHOD C						
Section	Friction Loss, psi/100 ft (kPa/100 m)	Friction Loss in Section, psi (kPa)	Pressure at Start, psi (kPa)	Friction Loss, psi/100 ft (kPa/100 m)	Friction in Section, psi (kPa)	Pressure at End, psi (kPa)
M–J	20 (452.4)	2 (13.8)	0 (0)	11.1 (251.1)	1.1 (7.6)	0.90 (6.2)
N–H	30 (678.6)	3 (20.7)	0 (0)	12.5 (282.8)	1.25 (8.6)	1.75 (12.1)
P–G	40 (904.8)	4 (27.6)	0 (0)	14.3 (323.5)	1.43 (9.9)	2.57 (17.7)
Q–F	50 (1131)	5 (34.5)	0 (0)	16.6 (375.5)	1.66 (11.5)	3.34 (23)
R–E	60 (1357.2)	6 (41.4)	0 (0)	20 (452.4)	2 (13.8)	4 (27.6)
S–D	70 (1583.5)	7 (48.3)	0 (0)	25 (565.5)	2.5 (17.2)	4.5 (31)
T–C	80 (1809.7)	8 (55.2)	0 (0)	33.3 (753.3)	3.33 (23)	4.66 (32.1)
U–B	90 (2035.9)	9 (62.1)	0 (0)	50 (1131)	5 (34.5)	4 (27.6)



PLAN OF SYSTEM

Figure 5-21 Determining Pressure Available for Friction

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. The aforementioned 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 authority having jurisdiction, 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 administrative authority).

- 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 completion of disinfection.

- 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 (mg/L) 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; the material used for disinfection; the retention period of the disinfectant in 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; the name and location of the job and the date the samples were obtained; the 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.

Table 5-22 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 (9.5)	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 (12.7)	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 (19.1)	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 (25.4)	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 (31.8)	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 (38.1)	5 (1.5)	3 (0.9)	7 (2.1)	1.5 (0.5)	1 (0.3)	45 (13.7)	22 (6.7)
2 (50.8)	7 (2.1)	4 (1.2)	10 (3.1)	2 (0.6)	1.3 (0.4)	55 (16.8)	28 (8.5)
2½ (63.5)	8 (2.4)	5 (1.5)	12 (3.7)	2.5 (0.8)	1.6 (0.5)	65 (19.8)	34 (10.4)
3 (76.2)	10 (3.1)	6 (1.8)	15 (4.6)	3 (0.9)	2 (0.6)	80 (24.4)	40 (12.2)
4 (101.6)	14 (4.3)	8 (2.4)	21 (6.4)	4 (1.2)	2.7 (0.8)	125 (38.1)	55 (16.8)
5 (127)	17 (5.2)	10 (3.1)	25 (7.6)	5 (1.5)	3.3 (1)	140 (42.7)	70 (21.3)
6 (152.4)	20 (6.1)	12 (13.7)	30 (9.1)	6 (1.8)	4 (1.2)	165 (50.3)	80 (24.4)

Note: Allowances based on nonrecessed threaded fittings. Use ½ the allowances for recessed threaded fittings or streamline solder fittings.

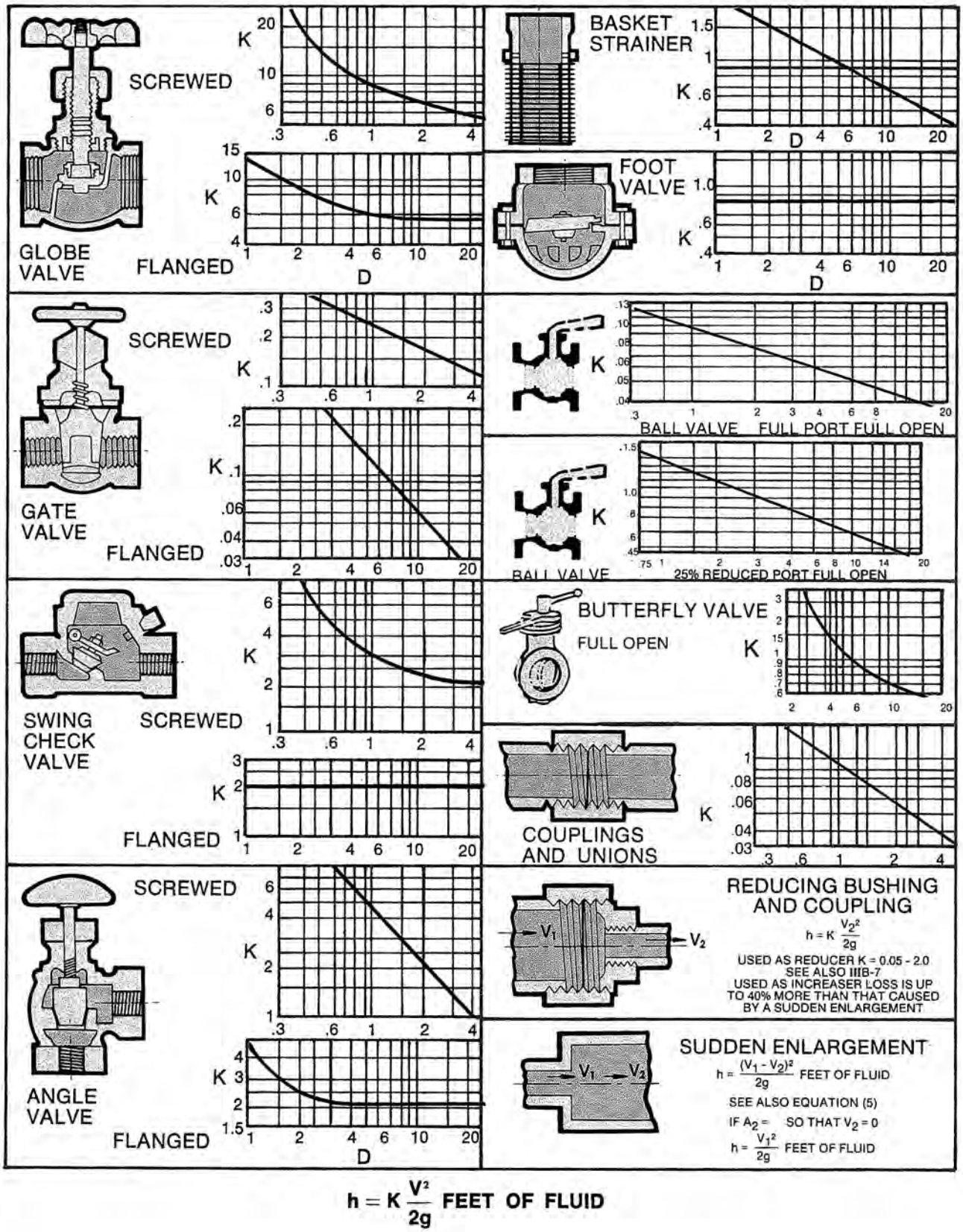


Figure 5-22 Typical Resistance Coefficients for Valves and Fittings

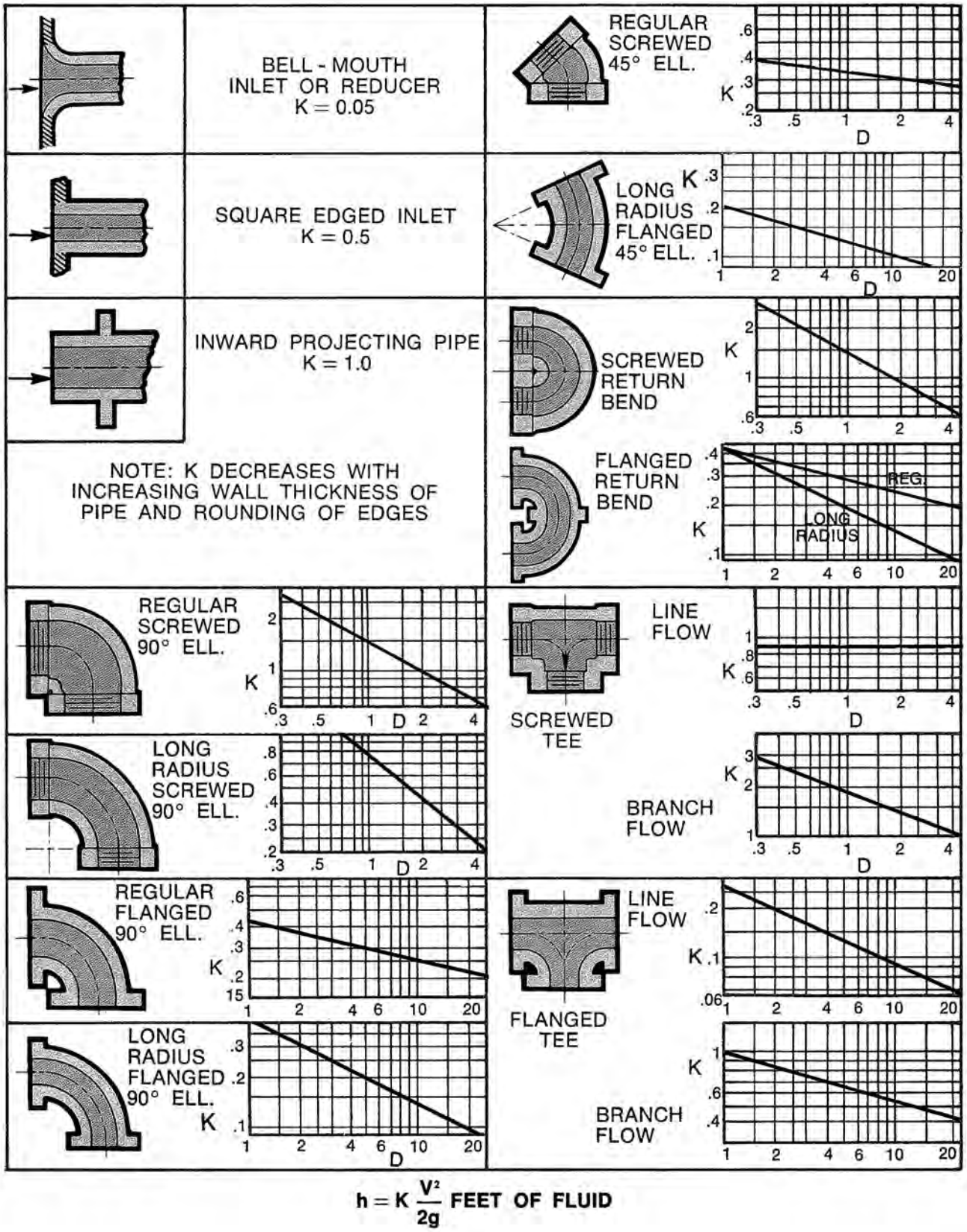


Figure 5-22 (cont.) Typical Resistance Coefficients for Valves and Fittings

- 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 (engineer) for his 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 above suggested procedures, shall be included in the specifications.

GLOSSARY

Accuracy (regarding pressure-regulating valves) 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.

AWWA Acronym for the American Water Works Association.

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

Back-siphonage 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 size the branches (not the critical circuit) based on the new equivalent length pressure drop 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).

CPVC Abbreviation for Chlorinated polyvinyl chloride.

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 (137.9 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.

PRV Abbreviation for pressure-regulating valve.

PVC Abbreviation for polyvinyl chloride.

Reduced-flow pressure The pressure maintained at the pressure-regulating valve outlet when water is flowing. The no-flow (closed), set-point 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 (regarding pressure-regulating valves) The capability of a pressure-regulating valve to respond to changes in outlet pressure.

RFP Abbreviation for reinforced fiberglass plastic.

RPZ Abbreviation for reduced pressure zone backflow preventer.

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 (regarding pressure-regulating valves) 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 dif-

Figure 5-23 Flow Data, C_V Values for Valves

Fig. Nos.	Valve Size ⅛	¼	⅜	½	¾	1	1¼	1½	2	2½	3	3½	4	5	6
GATES															
S & T-22	.5	2	4.9	9.1	22	40	65	95	175						
S & T-180	—	5.6	10.7	17.6	32	50	95	130	220						
S & T-111-113-131-133 134-135-136-174-176	—	5.6	10.7	17.6	32	54	97	135	230	337	536	710	960	1,525	2,250
(T & F-617-619-667-669 607-609) (CS-102-103 302-303-602-603) (F-637-639-DI-102)									215	335	510	710	945	1,525	2,250
GLOBES															
S & T-211 (BWY)-235Y 275Y	.61	1.16	2.2	3.64	6.65	11.1	20	28	48	70	111	—	198		
T-275-B	—	1.16	2.21	3.64	6.65	11.1	20	28	48	70	111				
F-718-(CS-132-133 332-333-632-633 (738)									45	70	105	—	195	315	465
CHECKS															
S & T-413-433-473 (Swing)	—	1.3	2.5	4.8	14.3	24	43	60	102	150	238	315	435	675	1,000
S & T-480 (Poppet)			3.70	6.86	16.3	30	49	72	130						
F-908 (Swing)									150	243	356	—	665	1,073	1,584
T & F-918-968-938 (Swing)									137	221	327	—	605	975	1,440
W-900-W (Wafer)												—	505	806	1,200
W-F-910-960 (Poppet)											330	—	595	950	1,400

(THROTTLING FACTORS)
For throttling use with disc partially open. Multiply C_V by factor.
Note: Gate valves are not throttled.

Percent Open										
0	10	20	30	40	50	60	70	80	90	100
0	.35	.65	.90	.93	.96	.98	.99	1.00	1.00	1.00
0	.03	.035	.06	.1	.16	.24	.32	.47	.68	1.00
0	.35	.65	.90	.93	.96	.98	.99	1.00	1.00	1.00

ficult 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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6 Domestic Water Heating Systems

Proper design of the domestic hot water supply system for any building is extremely important. Careful planning on the basis of all available data will ensure a safe and adequate supply of hot water. A properly designed system must, of course, conform to all applicable codes plus the regulations of the authority having jurisdiction (AHJ).

The objectives for a domestic hot water design and distribution system include the following:

1. Provide adequate amounts of water at the prescribed temperature to all fixtures and equipment at all times of use.
2. Provide a system that will perform its function safely.
3. Utilize an economical heat source.
4. Provide a cost-effective, efficient, and durable installation.
5. Provide an economical operating system with reasonable maintenance.

A well-designed system should deliver hot water at the prescribed temperature to the outlet with very little delay, thereby satisfying the users plus avoiding the wasteful running of water until the desired temperature is achieved. The hot water should be available at any time of use, day or night, and during low-demand periods as well as peak flows. Plumbing codes provide some guidance here—for example, uncirculated hot water dead-end legs should be 100 feet or shorter. However, meeting this code minimum may be unsatisfactory to users. The balance between near-instantaneous hot water delivery and incremental project cost must be maintained.

Safety must be built into any hot water system, and the plumbing codes require specific methods that must be used to achieve certain levels of safety. National standards recommend additional methods, which, while not having the force of law, nevertheless are accepted as good engineering design practices.

The three paramount dangers to be guarded against are excessive pressure, excessive temperature, and contamination. Excessive temperatures and pressures are avoided by using correctly sized temperature and pressure (T&P) relief valves at water heaters. Where check valves are present, as on hot water circulation systems and backflow preventers, thermal expansion tanks are to be used. The risk of scalding and thermal shock can be reduced by using many types of mechanical, pressure-balanced, or thermostatic mixing valves, installed at the hot water source and/or the point of use.

As with the domestic cold water system, water hammer arresters should be used to mitigate anticipated pressure spikes at quick-closing solenoid-operated valves. Strategically placed pressure gauges and thermometers, perhaps wired back to the building automation system (BAS), allow easy monitoring of the system.

Contamination of the domestic hot water system is prevented by many of the same methods used with the domestic cold water system. Cross-contamination is prevented by using appropriately selected backflow preventers for both hazard type and temperature. Double-wall heat exchangers are required for use with indirect-fired water heaters.

Warm water, such as that present in dead-end legs, low-temperature circulating loops, and storage-type water heaters at low temperatures, provides the ideal environment for waterborne bacterial growth, most notably Legionella pneumophila. Health concerns from waterborne bacterial growth must be considered in all hot water designs. Waterborne bacterial control measures should be included in the design whenever hot water is supplied to high-risk occupancies, such as hospitals or nursing homes. It is also good engineering practice to address waterborne bacterial control in hotels. Again, the designer must balance the need for reasonable public safety with excessive project costs.

An economical heat source will save money. Typical energy sources include natural gas, liquefied petroleum gas, oil, electricity, steam, boiler hot water (hydronics), waste heat, and solar thermal. The availability and cost of any of these sources or combinations of these sources dictate equipment and

system selection. Where an especially economical energy source is available but not adequate to satisfy the total demand, it might be used to preheat the cold water supply to the heater.

A cost-effective and durable installation begins with the judicious selection of the proper materials and equipment. As with the domestic cold water system, the pipe materials and layout, joining methods, hangers, and insulation all must match the project's needs and will determine the cost as well as the ease of replacement and repair.

An economical operating system with reasonable maintenance depends on all of these considerations. The location of piping, ease of circulation, bypasses around pumps and tanks, adequate valving, accessibility and provisions for the future all are items affecting the operation and maintenance of a system.

Finally, extra capacity and redundancy need to be tailored to each application.

DOMESTIC WATER HEATER SIZING

Sizing a domestic water heater is as much an art as a science. For anything other than a small residential system, it's not reasonable to simply go to a table or chart and make a selection. Codes do not indicate how much hot water is required. Instead, they contain only generalizations such as "Provide adequate amounts of hot and cold water to all sinks, lavatories, showers, etc." Codes do, however, provide information about minimum and maximum flow rates to fixtures and address safety concerns such as maximum temperatures and required water heater safety devices.

The design of a domestic water-heating system begins with estimating the facility's load profile and identifying the peak demands. To accomplish these steps, you must talk to the users of the space, determine the building type, and learn any owner requirements. The information thus gathered will establish the required capacity of the water-heating equipment and the general type of system to be used.

A number of factors must be considered when sizing a system, and experience plays a big part. Every system is different, so the path that leads to final selection varies for each system. Two buildings might have the same number and type of fixtures, but the water requirements could be vastly different. For instance, an apartment building for retired people would have different hot water needs than one that primarily houses families or college students.

To help with sizing, water heater manufacturers maintain substantial water heater sizing guidelines and instructional manuals, all kept current with industry standards and trends. ASPE's *Domestic Water Heating Design Manual* covers virtually every type of facility and heating system available.

Information Gathering

The first step to sizing a domestic hot water heater system is to collect the information needed to define the system parameters. Some of the information will be readily available, already gathered as part of the domestic cold water system design, but some may require further investigation. Following is a partial list of sample questions.

- In what type of building will the system be installed?
- Where is the building located?
- What codes should be followed?
- Do any local code amendments apply?
- Does the owner or operator of the building have any unusual requirements?
- Does the owner or operator of the building prefer a particular type of system?
- Are there any other hot water systems in the building?
- What area of the building will the system serve?
- What is the area used for?
- How many plumbing fixtures will there be?
- Who will be using the plumbing fixtures?
- Are there any high-usage fixtures, such as hot tubs?
- Are there plans to expand the facility in the future?
- Will there be laundry, food service, or health club areas?
- How many areas will be used simultaneously?
- How much space is available for the system?
- What energy sources are available?
- Where in the building will the equipment be placed?
- Will flues or combustion air be a problem due to the location?
- What is the building cold water source?
- What are the water hardness, pH, total dissolved solids and other water quality parameters?
- Will the system be inactive for long periods?
- How far from the heater will the furthest fixture be?
- How many showers will be used simultaneously and for what duration?

Water Heater Sizing Methods

With the correct information gathered, the load profile and peak demand can be calculated. Once again, this is not necessarily a straightforward process. Several methods for calculating the load of a building are available, and one method is not always better than another. Two methods from the American Society of Plumbing Engineers (ASPE) are outlined here. Other

Table 6-1 Hot Water Demand per Fixture for Various Types of Buildings (gallons [liters] of water per hour per fixture, calculated at a final temperature of 140°F [60°C])

Fixture	Apartment	Club	Gymnasium	Hospital	Hotel	Industrial Plant	Office Building	Private Residence	School	YMCA
Basins, private lavatory	2 (7.6)	2 (7.6)	2 (7.6)	2 (7.6)	2 (7.6)	2 (7.6)	2 (7.6)	2 (7.6)	2 (7.6)	2 (7.6)
Basins, public lavatory	4 (15)	6 (23)	8 (30)	6 (23)	8 (30)	12 (45.5)	6 (23)		15 (57)	8 (30)
Bathtubs	20 (76)	20 (76)	30 (114)	20 (76)	20 (76)		20 (76)		30 (114)	
Dishwashers[a]	15 (57)	50-150 (190-570)		50-150 (190-570)	50-200 (190-760)	20-100 (76-380)		15 (57)	20-100 (76-380)	20-100 (76-380
Foot basins	3 (11)	3 (11)	12 (46)	3 (11)	3 (11)	12 (46)		3 (11)	3 (11)	12 (46)
Kitchen sink	10 (38)	20 (76)		20 (76)	30 (114)	20 (76)	20 (76)	10 (38)	20 (76)	20 (76)
Laundry, stationary tubs	20 (76)	28 (106)		28 (106)	28 (106)		20 (76)		28 (106)	
Pantry sink	5 (19)	10 (38)		10 (38)	10 (38)		10 (38)	5 (19)	10 (38)	10 (38)
Showers	30 (114)	150 (568)	225 (850)	75 (284)	75 (284)	225 (850)	30 (114)	30 (114)	225 (850)	225 (850)
Service sink	20 (76)	20 (76)		20 (76)	30 (114)	20 (76)	20 (76)	15 (57)	20 (76)	20 (76)
Hydrotherapeutic showers				400 (1,520)						
Hubbard baths				600 (2,270)						
Leg baths				100 (380)						
Arm baths				35 (130)						
Sitz baths				30 (114)						
Continuous-flow baths				165 (625)						
Circular wash sinks				20 (76)	20 (76)	30 (114)	20 (76)		30 (114)	
Semicircular wash sinks				10 (38)	10 (38)	15 (57)	10 (38)		15 (57)	
Demand factor	0.30	0.30	0.40	0.25	0.25	0.40	0.30	0.30	0.40	0.40
Storage capacity factor[b]	1.25	0.90	1.00	0.60	0.80	1.00	2.00	0.70	1.00	1.00

a Dishwasher requirements should be taken from this table or from manufacturers' data for the model to be used, if this is known.

b Ratio of storage tank capacity to probable maximum demand per hour. Storage capacity may be reduced where an unlimited supply of steam is available from a central street steam system or large boiler plant.

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Figure 6-1 Occupant Demographic Classifications

No occupants work	High Demand
Public assistance and low income (mix)	
Family and single-parent households (mix)	
High number of children	
Low income	
Families	Medium Demand
Public assistance	
Singles	
Single-parent households	
Couples	Low Demand
High population density	
Middle income	
Seniors	
one person works, 1 stays home	
All occupants work	

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methods are available from other societies, government sources, or water heater manufacturers, and they are valuable resources as they include building types not addressed by the following two methods. Some owners, and notably government projects, prescribe which method should be used.

Method 1: Average Hourly Demand

The first method utilizes average hourly data in gallons per hour (gph) for various types of buildings and occupancies. The sizing chart is shown on Table 6-1.

To calculate using this method, count the fixtures, multiply the number of fixtures by the gallons per hour for the fixture in the particular type of building, and add them. Then multiply this total by the simultaneous usage factor to get the maximum hourly demand for the system. The minimum recommended storage volume then is calculated by multiplying the total demand by the storage factor. This is a simple method, but it has limitations:

- It can be applied only to the types of facilities listed.
- It is to be used only for the sizing of storage tank systems.
- It does not consider the types of occupants.
- It does not address high-use or high-volume fixtures.

Method 2: Occupancy Type

The second method of calculating hot water usage is outlined in *Domestic Water Heating Design Manual*. It addresses specific occupancies (see Figure 6-1 and Table 6-2) and tailors the calculation process to the type of building. There is a separate method for calculating the load for each building type, based on its individual operating characteristics. Not all types of facilities are addressed, but those that are can be accurately calculated using this method. It can be used to establish the sizing for systems using a storage tank, instantaneous, or semi-instantaneous heater. It also addresses additional concerns such as high-usage or high-volume fixtures.

BASIC FORMULAE AND UNITS

The equations in this chapter are based on the principle of energy conservation. The fundamental formula for this expresses a steady-state heat balance for the heat input and output of the system.

Equation 6-1

$$q = r\,w\,c\,\Delta T$$

where

q = Time rate of heat transfer, British thermal units per hour (Btuh) (kilojoules per hour)
r = Flow rate, gph (liters per hour)
w = Weight of heated water, pounds (kilograms)
c = Specific heat of water, Btu per pound per °F (kilojoules per kilograms per °K)
ΔT = Change in heated water temperature (temperature of leaving water minus temperature of incoming water, represented as Th – Tc, °F [°K])

For purposes of this discussion, the specific heat of water is constant, c = 1 Btu/lb/°F (c = 4.19 kJ/kg/K), and the weight of water is constant at 8.33 lb/gal (999.6 kg/m^3).

Equation 6-2

$$q = gph\left[\left(\frac{1\ \text{Btu}}{\text{lb/°F}}\right)\left(\frac{8.33\ \text{lb}}{\text{gal}}\right)(\Delta T)\right]$$

$$\left\{ q = \frac{m^3}{h}\left[\left(\frac{4.188\ \text{kJ}}{\text{kg/K}}\right)\left(\frac{999.6\ \text{kg}}{m^3}\right)(\Delta T)\right]\right\}$$

Example 6-1

Calculate the heat output rate required to heat 600 gph from 50°F to 140°F (2.27 m^3/h from 283.15°K to 333.15°K).

From Equation 6-2,

$$q = 600\ gph\left[\left(\frac{8.33\ \text{Btu}}{\text{gal/°F}}\right)(140–50°F)\right] = 449{,}820\ \text{Btu/h}$$

$$\left\{ q = \frac{2.27\ m^3}{h}\left[\left(\frac{4188.32\ \text{kJ}}{m^3/K}\right)(333.15–283.15\ K)\right] = 475\ 374\ \text{kJ/h}\right\}$$

Note: You should be aware that water heaters installed in high elevations must be derated based on the elevation. The water heater manufacturer's data should be consulted for information on the required modifications.

HEAT RECOVERY—ELECTRIC WATER HEATERS

It takes 1 Btu of energy to raise 1 pound of water 1°F. Since 1 kilowatt is equal to 3,413 Btu and 1 gallon of water weighs 8.33 pounds, then it would take 1 kilowatt of electrical power to raise 410 gallons (1,552.02 liters) of water 1°F. This can be expressed in a series of formulae, as follows:

Equation 6-3

$$\frac{410\ \text{gal}}{\Delta T} = \text{gal of water per kW at } \Delta T$$

$$\left(\frac{1552.02\ \text{L}}{\Delta T} = \text{L of water per kW at } \Delta T\right)$$

Equation 6-4

$$\frac{gph \times \Delta T}{410\ \text{gal}} = \text{kW required}$$

$$\left(\frac{1552.02\ \text{L}}{\Delta T} = \text{kW required}\right)$$

Equation 6-5

$$\frac{gph}{\text{gal of water per kW at } \Delta T} = \text{kW required}$$

$$\left(\frac{\text{L/h}}{\text{L of water per kW at } \Delta T} = \text{kW required}\right)$$

where

ΔT = Temperature rise (temperature differential), °F (°C)
gph = Gallons per hour of hot water required
L/h = Liters per hour of hot water required

Equation 6-3 can be used to establish a simple table based on the required temperature rise.

Temperature Rise, ΔT, °F (°C)	Gal (L) of Water per kW
110 (43)	3.73 (14.12)
100 (38)	4.10 (15.52)
90 (32)	4.55 (17.22)
80 (27)	5.13 (19.42)
70 (21)	5.86 (22.18)
60 (16)	6.83 (25.85)
50 (10)	8.20 (31.04)
40 (4)	10.25 (38.8)

Table 6-2 Low, Medium, and High Guidelines: Hot Water Demand and Use for Multifamily Buildings

Demand	Peak 5-min, gal (L)/person	Peak 15-min, gal (L)/person	Peak 30-min, gal (L)/person	Maximum per hour, gal (L)/person
Low	0.4 (1.5)	1.0 (4.0)	1.7 (6.5)	2.8 (10.5)
Medium	0.7 (2.6)	1.7 (6.4)	2.9 (11.0)	4.8 (18.0)
High	1.2 (4.5)	3.0 (11.5)	5.1 (19.5)	8.5 (32.5)

Demand	Maximum 2 Hours, gal (L)/person	Maximum 3 Hours, gal (L)/person	Maximum Day, gal (L)/person	Average Day, gal (L)/person
Low	4.5 (17.0)	6.1 (23.0)	20.0 (76.0)	14.0 (54.0)
Medium	8.0 (31.0)	11.0 (41.0)	49.0 (185.0)	30.0 (113.6)
High	14.5 (55.0)	19.0 (72.0)	90.0 (340.0)	54.0 (205.0)

Note: These volumes are for domestic hot water delivered to the tap at 120° F (49° C).

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This table can be used with Equation 6-5 to solve for the electric element (in kilowatts) needed to heat the required recovery volume of water.

Example 6-2

An electric water heater must be sized based on the following information:

40 gph (151.42 liters per hour) of hot water at a temperature of 140°F (60°C) is required.

The incoming water supply during winter is 40°F (4°C).

Using Equation 6-5 and the above table, we find the following:

$$\frac{40 \text{ gph}}{4.1 \text{ gal } (100°\text{F})} = 9.8 \text{ kW required}$$

$$\left(\frac{151.42 \text{ L/h}}{15.52 \text{ L } (38°\text{C})} = 9.8 \text{ kW required}\right)$$

HOT WATER TEMPERATURE

The generally accepted minimum hot water temperatures for various plumbing fixtures and equipment are given in Table 6-3. Both temperature and pressure should be verified with the client and checked against local codes and the manuals of equipment used.

MIXED WATER TEMPERATURE

Frequently, higher-temperature hot water must be blended with cold or cooler-temperature water to obtain a desired mixed water temperature. In such a case it is useful to have a quick method for determining the relative volumes of all three water temperatures involved.

In Equation 6-6, P is a hot water ratio or multiplier, and it can be used to determine the percentage of supply hot water that will blend with the cooler water to produce a desired mixed water temperature.

Equation 6-6

$$P = \frac{T_m - T_c}{T_h - T_c}$$

where

P = Hot water ratio, unitless

T_h = Supply hot water temperature, ˚F (˚C)

T_c = Inlet cold water temperature, ˚F (˚C)

T_m = Desired mixed water temperature, ˚F (˚C)

Values of P for a range of hot and cold water temperatures are given in Table 6-4.

Example 6-3

A group of showers requires 25 gallons per minute (gpm) (1.58 liters per second) of 105°F (41°C) mixed water temperature. Determine how much 140°F (60°C) hot water must be supplied to the showers when the cold water temperature is 50°F (10°C).

$$P = \frac{105 - 50°\text{F}}{140 - 50°\text{F}} = 0.61$$

$$\left(P = \frac{41 - 10°\text{C}}{60 - 10°} = 0.61\right)$$

Table 6-3 Typical Hot Water Temperatures for Plumbing Fixtures and Equipment

Use	Temperature °F (°C)
Lavatory:	
Hand washing	105 (40)
Shaving	115 (45)
Showers and tubs	110 (43)
Therapeutic baths	95 (35)
Surgical scrubbing	110 (43)
Commercial and institutional laundry	140–180 (60–82)
Residential dishwashing and laundry	120 (48)
Commercial, spray-type dishwashing (as required by the NSF): Single- or multiple-tank hood or rack type:	
Wash	150 min. (66 min.)
Final rinse	180–195 (82–91)
Single-tank conveyor type:	
Wash	160 min. (71 min.)
Final rinse	180–195 (82–91)
Single-tank rack or door type:	
Single-temperature wash and rinse	165 min. (74 min.)
Chemical sanitizing glassware:	
Wash	140 (60)
Rinse	75 min. (24 min.)

Note: Be aware that temperatures, as dictated by codes, owners, equipment manufacturers, or regulatory agencies, occasionally will differ from those shown.

Therefore, 0.61 (25 gpm) = 15.25 gpm of 140°F water required[0.61 (1.58 L/s) = 0.96 L/s of 60°C water required].

Table 6-2 also may be used to determine P.

WATER HEATERS

Many types of domestic water heaters are available. The most commonly used type of water heater for homes, office buildings, multiple-unit dwellings, and similar establishments is the direct-fired automatic storage water heater. Such heaters are simple, inexpensive to install, and low maintenance. They generally have a low Btu input, with the heating of the water spread over the design hour. Commonly used energy sources include electricity, fuel oil, and gas.

Instantaneous-type water heaters must have sufficient capacity to provide the maximum instantaneous flow rate of hot water. Historically, a gas-fired instantaneous heater finds its best application where water-heating demands are constant, such as swimming pools, certain dishwasher booster requirements, and industrial processes, or where space conditions are a prime consideration, but currently available models have much improved electronic modulating control. Instantaneous water heaters have near zero standby losses.

Table 6-4 Hot Water Multiplier, P

T_h = 110°F Hot Water System Temperature

T_c, CW Temp. (°F)	T_m, Water Temperature at Fixture Outlet (°F)			
	110	105	100	95
45	1.00	0.92	0.85	0.77
50	1.00	0.92	0.83	0.75
55	1.00	0.91	0.82	0.73
60	1.00	0.90	0.80	0.70
65	1.00	0.89	0.78	0.67

T_h = 120°F Hot Water System Temperature

T_c, CW Temp. (°F)	T_m, Water Temperature at Fixture Outlet (°F)					
	120	115	110	105	100	95
45	1.00	0.93	0.87	0.80	0.73	0.67
50	1.00	0.93	0.86	0.79	0.71	0.64
55	1.00	0.92	0.85	0.77	0.69	0.62
60	1.00	0.92	0.83	0.75	0.67	0.58
65	1.00	0.91	0.82	0.73	0.64	0.55

T_h = 130°F Hot Water System Temperature

T_c, CW Temp. (°F)	T_m, Water Temperature at Fixture Outlet (°F)							
	130	125	120	115	110	105	100	95
45	1.00	0.94	0.88	0.82	0.76	0.71	0.65	0.59
50	1.00	0.94	0.88	0.81	0.75	0.69	0.63	0.56
55	1.00	0.93	0.87	0.80	0.73	0.67	0.60	0.53
60	1.00	0.93	0.86	0.79	0.71	0.64	0.57	0.50
65	1.00	0.92	0.85	0.77	0.69	0.62	0.54	0.46

T_h = 140°F Hot Water System Temperature

T_c, CW Temp. (°F)	T_m, Water Temperature at Fixture Outlet (°F)									
	140	135	130	125	120	115	110	105	100	95
45	1.00	0.95	0.89	0.84	0.79	0.74	0.68	0.63	0.58	0.53
50	1.00	0.94	0.89	0.83	0.78	0.72	0.67	0.61	0.56	0.50
55	1.00	0.94	0.88	0.82	0.76	0.71	0.65	0.59	0.53	0.47
60	1.00	0.94	0.88	0.81	0.75	0.69	0.63	0.56	0.50	0.44
65	1.00	0.93	0.87	0.80	0.73	0.67	0.60	0.53	0.47	0.40

T_h = 150°F Hot Water System Temperature

T_c, CW Temp. (°F)	T_m, Water Temperature at Fixture Outlet (°F)										
	150	145	140	135	130	125	120	115	110	105	100
45	1.00	0.95	0.90	0.86	0.81	0.76	0.71	0.67	0.62	0.57	0.52
50	1.00	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50
55	1.00	0.95	0.89	0.84	0.79	0.74	0.68	0.63	0.58	0.53	0.47
60	1.00	0.94	0.89	0.83	0.78	0.72	0.67	0.61	0.56	0.50	0.44
65	1.00	0.94	0.88	0.82	0.76	0.71	0.65	0.59	0.53	0.47	0.41

T_h = 160°F Hot Water System Temperature

T_c, CW Temp. (°F)	T_m, Water Temperature at Fixture Outlet (°F)										
	160	155	150	145	140	135	130	125	120	115	110
45	1.00	0.96	0.91	0.87	0.83	0.78	0.74	0.70	0.65	0.61	0.57
50	1.00	0.95	0.91	0.86	0.82	0.77	0.73	0.68	0.64	0.59	0.55
55	1.00	0.95	0.90	0.86	0.81	0.76	0.71	0.67	0.62	0.57	0.52
60	1.00	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50
65	1.00	0.95	0.89	0.84	0.79	0.74	0.68	0.63	0.58	0.53	0.47

Table 6-4 Hot Water Multiplier, P (continued)

T_h = 180°F Hot Water System Temperature

T_c, CW Temp. (°F)	T_m, Water Temperature at Fixture Outlet (°F)										
	180	175	170	165	160	155	150	145	140	135	130
45	1.00	0.96	0.93	0.89	0.85	0.81	0.78	0.74	0.70	0.67	0.63
50	1.00	0.96	0.92	0.88	0.85	0.81	0.77	0.73	0.69	0.65	0.62
55	1.00	0.96	0.92	0.88	0.84	0.80	0.76	0.72	0.68	0.64	0.60
60	1.00	0.96	0.92	0.88	0.83	0.79	0.75	0.71	0.67	0.63	0.58
65	1.00	0.96	0.91	0.87	0.83	0.78	0.74	0.70	0.65	0.61	0.57
110	1.00	0.93	0.86	0.79	0.71	0.64	0.57	0.50	0.43	0.36	0.29
120	1.00	0.92	0.83	0.75	0.67	0.58	0.50	0.42	0.33	0.25	0.17
130	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10	—
140	1.00	0.88	0.75	0.63	0.50	0.38	0.25	0.13	—	—	—
150	1.00	0.83	0.67	0.50	0.33	0.17	—	—	—	—	—
160	1.00	0.75	0.50	0.25	—	—	—	—	—	—	—

T_h = 43°C Hot Water System Temperature

T_c, CW Temp. (°C)	T_m, Water Temperature at Fixture Outlet (°C)			
	43	41	38	35
7	1.00	0.92	0.85	0.77
10	1.00	0.92	0.83	0.75
13	1.00	0.91	0.82	0.73
16	1.00	0.90	0.80	0.70
18	1.00	0.89	0.78	0.67

T_h = 49°C Hot Water System Temperature

T_c, CW Temp. (°C)	T_m, Water Temperature at Fixture Outlet (°C)					
	49	46	43	41	38	35
7	1.00	0.93	0.87	0.80	0.73	0.67
10	1.00	0.93	0.86	0.79	0.71	0.64
13	1.00	0.92	0.85	0.77	0.69	0.62
16	1.00	0.92	0.83	0.75	0.67	0.58
18	1.00	0.91	0.82	0.73	0.64	0.55

T_h = 54°C Hot Water System Temperature

T_c, CW Temp. (°C)	T_m, Water Temperature at Fixture Outlet (°C)							
	54	52	49	46	43	41	38	35
7	1.00	0.94	0.88	0.82	0.76	0.71	0.65	0.59
10	1.00	0.94	0.88	0.81	0.75	0.69	0.63	0.56
13	1.00	0.93	0.87	0.80	0.73	0.67	0.60	0.53
16	1.00	0.93	0.86	0.79	0.71	0.64	0.57	0.50
18	1.00	0.92	0.85	0.77	0.69	0.62	0.54	0.46

T_h = 60°C Hot Water System Temperature

T_c, CW Temp. (°C)	T_m, Water Temperature at Fixture Outlet (°C)									
	60	58	54	52	49	46	43	41	38	35
7	1.00	0.95	0.89	0.84	0.79	0.74	0.68	0.63	0.58	0.53
10	1.00	0.94	0.89	0.83	0.78	0.72	0.67	0.61	0.56	0.50
13	1.00	0.94	0.88	0.82	0.76	0.71	0.65	0.59	0.53	0.47
16	1.00	0.94	0.88	0.81	0.75	0.69	0.63	0.56	0.50	0.44
18	1.00	0.93	0.87	0.80	0.73	0.67	0.60	0.53	0.47	0.40

Table 6-4 Hot Water Multiplier, P (continued)

T_h = 66°C Hot-Water System Temperature

T_c, CW Temp. (°C)	T_m, Water Temperature at Fixture Outlet (°C)										
	66	63	60	58	54	52	49	46	43	41	38
7	1.00	0.95	0.90	0.86	0.81	0.76	0.71	0.67	0.62	0.57	0.52
10	1.00	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50
13	1.00	0.95	0.89	0.84	0.79	0.74	0.68	0.63	0.58	0.53	0.47
16	1.00	0.94	0.89	0.83	0.78	0.72	0.67	0.61	0.56	0.50	0.44
18	1.00	0.94	0.88	0.82	0.76	0.71	0.65	0.59	0.53	0.47	0.41

T_h = 71°C Hot-Water System Temperature

T_c, CW Temp. (°C)	T_m, Water Temperature at Fixture Outlet (°C)										
	71	68	66	63	60	58	54	52	49	46	43
7	1.00	0.96	0.91	0.87	0.83	0.78	0.74	0.70	0.65	0.61	0.57
10	1.00	0.95	0.91	0.86	0.82	0.77	0.73	0.68	0.64	0.59	0.55
13	1.00	0.95	0.90	0.86	0.81	0.76	0.71	0.67	0.62	0.57	0.52
16	1.00	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50
18	1.00	0.95	0.89	0.84	0.79	0.74	0.68	0.63	0.58	0.53	0.47

T_h = 82°C Hot-Water System Temperature

T_c, CW Temp. (°C)	T_m, Water Temperature at Fixture Outlet (°C)										
	82	79	77	74	71	68	66	63	60	58	54
7	1.00	0.96	0.93	0.89	0.85	0.81	0.78	0.74	0.70	0.67	0.63
10	1.00	0.96	0.92	0.88	0.85	0.81	0.77	0.73	0.69	0.65	0.62
13	1.00	0.96	0.92	0.88	0.84	0.80	0.76	0.72	0.68	0.64	0.60
16	1.00	0.96	0.92	0.88	0.83	0.79	0.75	0.71	0.67	0.63	0.58
18	1.00	0.96	0.91	0.87	0.83	0.78	0.74	0.70	0.65	0.61	0.57
43	1.00	0.93	0.86	0.79	0.71	0.64	0.57	0.50	0.43	0.36	0.29
49	1.00	0.92	0.83	0.75	0.67	0.58	0.50	0.42	0.33	0.25	0.17
54	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10	—
60	1.00	0.88	0.75	0.63	0.50	0.38	0.25	0.13	—	—	—
66	1.00	0.83	0.67	0.50	0.33	0.17	—	—	—	—	—
71	1.00	0.75	0.50	0.25	—	—	—	—	—	—	—

Booster heaters are used to raise the temperature of the regular hot water supply to some higher-than-normal temperature needed to perform special functions. Booster heaters are utilized in applications such as commercial dishwashers with a limited use of very hot water. They can be located near their point of intended use and have simple controls.

Semi-instantaneous heaters contain approximately 10 to 20 gallons of storage, varying according to their rated heating capacity. This small quantity of water is adequate to allow the temperature control system to react to sudden fluctuations in water flow and to maintain the outlet water temperature within ±5°F (2.7°C). The temperature control system is almost always included with this type of heater as a package.

Indirect-fired water heaters, including solar thermal systems, have the advantage of physically separating the production of the necessary heating energy (e.g., boiler or solar collector) from the hot water storage tank. This modular design permits efficient and economical servicing. Copper-type heat exchanger boilers can be used in conjunction with a storage tank when a high-temperature circulating loop is used to prevent condensation, taking advantage of copper's superior thermal efficiency. Steam indirect-fired water heaters generally are used where large quantities of hot water are needed and are able to efficiently tap into the building steam supply.

Controls

The purpose for having controls on a hot water generator is to ensure a safe and sufficient volume of hot water at the desired temperature. Water heater controls are provided by the equipment manufacturer. The control components for water heaters differ depending on the type of heater and the manufacturer, and acceptable outlet temperature variations differ as well. Also, the various regulatory and testing agencies have requirements for controls that depend on the size and type of equipment used.

The distinction between water heater outlet temperature and plumbing fixture delivery temperature is critical. ASSE 1017: *Temperature-actuated Mixing*

Valves for Hot Water Distribution Systems addresses source distribution temperature requirements, and other ASSE standards apply to the various plumbing fixtures. Three primary ASSE standards addressing fixture delivery temperature include ASSE 1016: *Performance Requirements for Automatic Compensating Valves for Individual Showers and Tub/Shower Combinations,* ASSE 1069: *Performance Requirements for Automatic Temperature Control Mixing Valves,* and ASSE 1070: *Performance Requirements for Water Temperature Limiting Devices.* (Listings for ASSE 1016-1996 were deactivated and are superseded by the above standards.) ASSE 1071: *Temperature-actuated Mixing Valves for Plumbed Emergency Equipment* was established for emergency eyewashes, face washes, and drench showers.

Stratification in Storage-type Heaters and Tanks

Because of its lighter density, warm water rises to the top of a storage tank. The result of this rising action, known as stratification, occurs in all uncirculated tanks. It has been found that the amount of usable water in stratified horizontal and vertical tanks could be as low as 65 percent and 75 percent respectively, depending on design.

Stratification during recovery periods can be reduced significantly by mechanical circulation of the water in the tank. During periods of high demand, however, it might be useful to have stratification since this increases the availability of water at a usable temperature. For example, if a tank were equally stratified between 140°F (60°C) at the top and 40°F (4°C) at the bottom, this tank, in theory, still could deliver half its volume at 140°F (60°C). If the two layers were completely mixed, the tank temperature would drop to 90°F (32°C), which in most cases is an unusable temperature.

HOT WATER TEMPERATURE MAINTENANCE

Hot water of a desired temperature should be readily available at any fixture. Hot water supply piping transmits heat to the surrounding lower-temperature air by conduction, convection, and radiation. Insulation reduces but does not eliminate this heat loss. In large systems, if the heat loss is not addressed, users may become frustrated waiting for the desired temperature water. Water is wasted, and the associated energy and wastewater utility costs are incurred. This is particularly true in systems using low-flow and electronic faucets where the wait time can be very long.

Two common methods used to achieve satisfactory remote temperature maintenance include a hot water circulation system or a self-regulated electrically heated system.

Hot Water Circulation Systems

The sizing of the hot water circulation system includes selecting the pump, sizing the supply and recirculation piping, and selecting the insulation type and thickness. Proper sizing of the hot water circulating system is essential for the efficient and economical operation of the hot water system. Oversizing will cause the system to lose additional heat and result in unnecessary expenditures on equipment and installation. Undersizing will hamper circulation and thus starve the fixtures of the desired water temperature.

The procedure for sizing the hot water circulating piping is as follows:

1. Calculate the heat loss rates of the hot water supply piping.
2. Calculate the heat loss rates of the hot water circulating piping.
3. Calculate the circulation rates for all parts of the circulating piping and the total circulation rate required.
4. Determine the allowable uniform friction head loss and the total head required to overcome friction losses in the piping when the water is flowing at the required circulation rate.
5. Calculate the rates of flow for various pipe sizes that will give the uniform pressure drop established in Step 4, and tabulate the results.
6. Size the system based on the tabulation set up in Step 5.
7. With the sizes as established in Step 6, repeat Steps 2 through 6 as a check on the assumptions made.

As a guide to sizing circulation piping and circulation pumps, the following empirical methods are given, but they are not recommended in lieu of the more accurate procedures outlined above.

1. An allowance of 0.5 gpm (1.8 liters per minute) is assigned for each small hot water riser (¾–1 inch [1.9–2.54 centimeters]), 1 gpm (3.8 liters per minute) for each medium-size hot water riser (1¼–1½ inches [3.2–3.8 centimeters]), and 2 gpm (7.6 liters per minute) for each large-size hot water riser (2 inches [5 centimeters] and larger).
2. An allowance of 1 gpm (3.8 liters per minute) is assigned for each group of 20 hot water-supplied fixtures.

Self-regulating Heat Trace Systems

A heat trace system is used for hot water temperature maintenance. This type of system utilizes self-regulating cable installed on the hot water supply pipes underneath the standard pipe insulation. The cable adjusts its power output to compensate for variations in water and ambient temperatures. It produces more heat if the temperature drops and less heat if

the temperature rises. The heating cable replaces supply pipe heat losses at the point where heat loss occurs, thereby providing continuous hot water temperature maintenance and eliminating the need for a recirculating system. Heat trace systems are practical for small systems, systems where added flexibility of terminal runs is needed, or situations where recirculation piping is impractical. Hybrid circulation and heat trace systems are possible.

Selection variables affecting the performance of the heat trace system include the system temperature range, time to tap, water wastage, and energy efficiency. Installation and life-cycle costs also should be considered.

All heating cable components are UL listed for use as a part of the system to maintain hot water temperature. Component enclosures are rated NEMA 4X to prevent water ingress and corrosion. Electronic control modules are available, permitting programmed temperature profiles, including bacteria-killing high-temperature nighttime programs.

RELIEF VALVES

Water-heating systems shall be protected from excessive temperatures and pressures by relief valves. Temperature and pressure relief valves are available either separately or combined. A combination T&P relief valve offers economical and effective protection.

A relief valve on a water supply system is exposed to elements that may affect its performance, such as corrosive water that attacks materials and deposits of lime that close up waterways and flow passages. For these reasons, the minimum size of the valve should be ¾ inch (19 millimeters) for inlet and outlet connections, with the waterways within the valve of an area not less than the area of the inlet connection. Relief valves should be tested on a regular basis to ensure safe and proper operation.

All relief valves should have a discharge pipe connected to their outlets and terminate at a point where the discharge will cause no damage or injury. The discharge pipe size shall be at least the size of the valve discharge outlet, be as short as possible, and run down to its terminal without sags or traps.

Typically, T&P relief valves are tested to comply with the standards of the American Society of Mechanical Engineers (ASME), American Gas Association (AGA), or National Board of Boiler and Pressure Vessel Inspectors (NBBPVI) and are so labeled. The designer should verify which agency's standards are applicable to the water-heating system being designed and follow those standards for the sizes, types, and locations of required relief valves.

Sizing Pressure and Temperature Relief Valves

The following information applies to heaters with more than 200,000-Btu (211,000-kilojoule) input:

Temperature relief valves shall have the capacity to prevent water temperature from exceeding 210°F (99°C). They shall be water rated on the basis of 1,250 Btu (1,319 kilojoules) for each gph of water discharged at 30-pounds (13.6-kilograms) working pressure and a maximum temperature of 210°F (99°C).

The temperature rating is the maximum rate of heat input to a heater on which a temperature relief valve can be installed and is determined as follows:

Equation 6-7

$$\frac{\text{gph water heated} \times 8.33 \times \Delta T(°F)}{0.8} = \text{Btu valve capacity required}$$

$$\left(\frac{\text{L/h water heated} \times 1\ \text{kg/L} \times \Delta T(°C)}{0.8} = \text{kJ valve capacity required}\right)$$

Pressure relief valves shall have the capacity to prevent a pressure rise in excess of 10 percent of the set opening pressure. They shall be set at a pressure not exceeding the working pressure of the tank or heater.

The pressure rating is the maximum output of a boiler or heater on which a pressure relief valve can be used and is determined as follows:

Equation 6-8

$$\text{gph water heated} \times 8.33 \times \Delta T(°F) = \text{Btu valve capacity required}$$

$$\left[\text{L/h water heated} \times 1.0\ \text{kg/L} \times \Delta T(°C) = \text{kJ valve capacity required}\right]$$

Determine the Btu capacity required and then refer to the manufacturer's catalog for valve size selection. Note that on high Btu systems, multiple T&P relief valves may be required at the storage tank.

THERMAL EXPANSION

Water expands when heated, and this expansion must be accommodated in a domestic hot water system to avoid damage to the piping, fixtures, and accessories. Use of a properly sized thermal expansion tank will accomplish this. Plumbing codes require some type of thermal expansion compensation, especially when there is either a backflow prevention device on the cold water service to the building or a check valve in the system.

Relying only on the T&P relief valve to relieve the pressure is not good practice. Most local codes now require expansion tanks for systems more than 4 gallons (8.8 liters) in capacity.

The relevant properties of water are shown in Table 6-5.

Table 6-5 Thermal Properties of Water

Temperature		Saturation Pressure		Specific Volume		Density		Weight		Specific Heat	
°F	°C	psig	kPa	ft^3/lb	m^3/kg	lb/ft^3	kg/m^3	lb/gal	kg/m^3	Btu/lb-°F-h	J/kg-°C-h
32	0.0	29.8	3,019.6	0.01602	0.00100	62.42	999.87	8.345	1,001.40	1.0093	4,225.74
40	4.4	29.7	3,009.5	0.01602	0.00100	62.42	999.87	8.345	1,001.40	1.0048	4,206.90
50	10.0	29.6	2,999.4	0.01603	0.00100	62.38	999.23	8.340	1,000.80	1.0015	4,193.08
60	15.5	29.5	2,989.2	0.01604	0.00100	62.34	998.59	8.334	1,000.08	0.9995	4,184.71
70	21.1	29.3	2,969.0	0.01606	0.00100	62.27	997.47	8.325	999.00	0.9982	4,179.26
80	26.7	28.9	2,928.4	0.01608	0.00100	62.19	996.19	8.314	997.68	0.9975	4,176.33
90	32.2	28.6	2,898.0	0.01610	0.00100	62.11	994.91	8.303	996.36	0.9971	4,174.66
100	37.8	28.1	2,847.4	0.01613	0.00101	62.00	993.14	8.289	994.68	0.9970	4,174.24
110	43.3	27.4	2,776.4	0.01617	0.00101	61.84	990.58	8.267	992.04	0.9971	4,174.66
120	48.9	26.6	2,695.4	0.01620	0.00101	61.73	988.82	8.253	990.36	0.9974	4,175.91
130	54.4	25.5	2,583.9	0.01625	0.00101	61.54	985.78	8.227	987.24	0.9978	4,177.59
140	60.0	24.1	2,442.1	0.01629	0.00102	61.39	983.37	8.207	984.84	0.9984	4,180.10
150	65.6	22.4	2,269.8	0.01634	0.00102	61.20	980.33	8.182	981.84	0.9990	4,182.61
160	71.1	20.3	2,057.0	0.01639	0.00102	61.01	977.29	8.156	978.72	0.9998	4,185.96
170	76.7	17.8	1,803.7	0.01645	0.00103	60.79	973.76	8.127	975.24	1.0007	4,189.73
180	82.2	14.7	1,489.6	0.01651	0.00103	60.57	970.24	8.098	971.76	1.0017	4,193.92
190	87.8	10.9	1,104.5	0.01657	0.00103	60.35	966.71	8.068	968.16	1.0028	4,198.52
200	93.3	6.5	658.6	0.01663	0.00104	60.13	963.19	8.039	964.68	1.0039	4,203.13
210	98.9	1.2	121.6	0.01670	0.00104	59.88	959.19	8.005	960.60	1.0052	4,208.57
212	100.0	0.0	0.0	0.01672	0.00104	59.81	958.06	7.996	959.52	1.0055	4,209.83
220	104.4	2.5	253.3	0.01677	0.00105	59.63	955.18	7.972	956.64	1.0068	4,215.27
240	115.6	10.3	1,043.7	0.01692	0.00106	59.10	946.69	7.901	948.12	1.0104	4,230.34
260	126.7	20.7	2,097.5	0.01709	0.00107	58.51	937.24	7.822	938.64	1.0148	4,248.76
280	137.8	34.5	3,495.9	0.01726	0.00108	57.94	928.11	7.746	929.52	1.0200	4,270.54
300	148.9	52.3	5,299.6	0.01745	0.00109	57.31	918.02	7.662	919.44	1.0260	4,295.66
350	176.7	119.9	12,149.5	0.01799	0.00112	55.59	890.47	7.432	891.84	1.0440	4,371.02
400	204.4	232.6	23,569.4	0.01864	0.00116	55.63	891.11	7.172	860.64	1.0670	4,467.32
450	232.2	407.9	41,332.5	0.01940	0.00121	51.55	825.75	6.892	827.04	1.0950	4,584.55
500	260.0	666.1	67,495.9	0.02040	0.00127	49.02	785.22	6.553	786.36	1.1300	4,731.08
550	287.8	1030.5	104,420.6	0.02180	0.00136	45.87	734.77	6.132	735.84	1.2000	5,024.16
600	315.6	1528.2	154,852.5	0.02360	0.00147	42.37	678.70	5.664	679.68	1.3620	5,702.42

Example 6-4

Using Table 6-5, determine the thermal expansion of a typical residence. Assume the initial heating cycle has incoming water at 40°F (4°C) and a temperature rise of 100°F (38°C). The water heater has 50 gallons (189 liters) of capacity, and the piping system volume is 10 gallons (38 liters).

1. Specific volume of water at 40°F (4°C) = 0.01602 cubic foot per pound (0.00100 cubic meter per kilogram)
2. Specific volume of water at 140°F (60°C) = 0.01629 cubic foot per pound (0.00102 cubic meter per kilogram)
3. 0.01602 ÷ 0.01629 (0.00100 ÷ 0.00102) = 1.66 percent increase in volume
4. Total volume = 50-gallon (189-liter) tank + 10-gallon (38-liter) system = 60 gallons (227 liters)
5. 60 gallons (227 liters) x 1.66 percent volume increase = 1-gallon (3.79-liter) expansion
6. 1 gallon (3.79 liters) x 8.33 pounds per gallon (1 kilogram per liter) x 0.01628 cubic foot per pound (0.0010 cubic meter per kilogram) = 0.1356 cubic foot (0.0038 cubic meter) = 19.5 cubic inches (380 cubic centimeters)

THERMAL EFFICIENCY

No water heating process is 100 percent efficient. The actual input energy is always higher than the usable, or output, energy. The four primary measurements of water heater efficiency (among the common 12 to 15 measurements) are combustion efficiency, thermal efficiency, energy factor, and annual fuel utilization efficiency (AFUE).

Combustion efficiency (for fuel-fired water heaters) is a misnomer, as it has little to do with the efficiency of the combustion process. Rather, combustion efficiency is simply the total input energy minus the flue losses.

Thermal efficiency is a refinement of combustion efficiency, also accounting for jacket losses. In equation form, thermal efficiency = combustion efficiency – jacket losses.

Energy factor and AFUE are continued refinements, attempting to bring real-world meaningful values to consumers. Not every efficiency measurement is applicable to every water heater. For example, AFUE only applies to water heaters with input of 300,000 Btuh or less. Similarly, the testing protocol used to obtain an energy factor rating includes a 19-hour standby period, obviously benefiting instantaneous and tankless water heaters.

New government-mandated energy-efficiency rules are issued through the Environmental Protection Agency (EPA) and the Department of Energy (DOE). The American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) is an industry leader in promoting part-load efficiency ratings for modulating equipment and seasonal efficiency information. The Air-conditioning, Heating, and Refrigeration Institute (AHRI) is the primary testing and certifying organization.

Direct-fired gas water heaters lose part of their total energy capabilities to heated flue gases, inefficiencies of combustion, and radiation at heated surfaces. Their thermal efficiency, E_t, is defined as the heat actually transferred to the domestic water divided by the total heat input to the water heater. Expressed as a percentage, this is:

Equation 6-9

$$E_t = \frac{q - B}{q} \times 100\%$$

where

E_t = Thermal efficiency ratio, unitless

B = Internal heat loss of the water heater, Btuh (kilojoules per hour)

q = Time rate of heat transfer, Btuh (kilojoules per hour)

Refer to Equations 6-1 and 6-2 to determine q. Many water heaters and boilers provide input and output energy information.

Example 6-5

Calculate the heat input rate required for the water heater in Example 6-1 if this is a direct gas-fired water heater with a thermal efficiency of 80 percent.

From Example 6-1, q = 449,820 Btuh (475,374 kilojoules per hour). Thus, the heat input is:

$$\frac{q}{E_t} = \frac{449{,}820 \text{ Btu/h}}{0.80} = 562{,}275 \text{ Btu/h}$$

$$\left(\frac{q}{E_t} = \frac{475{,}374 \text{ kJ/h}}{0.80} = 594\ 217.5 \text{ kJ/h} \right)$$

LEGIONNAIRES' DISEASE

Legionnaires' disease is a potentially fatal respiratory illness. The disease gained notoriety when a number of American Legionnaires contracted it during a convention. That outbreak was attributed to the water vapor from the building's cooling towers. The bacteria causing Legionnaires' disease are widespread

Table 6-6 Recommended Water System Temperatures

	CDC	ASHRAE	FREIJE	ASHE/JCAHO	CCBC/ ISPC	IDPH	ASPE
Store DCW (maximum)		68˚F	68˚F				
Favorable for Legionella Growth	90–105˚F	77–108˚F	68–122˚F	77–108˚F			
Maximum DHW Discharge Temperature (patient care areas)					115˚F	110˚F	115˚F
Maximum DHW Discharge Temperature (behavioral health)						100˚F	
Recirculating DHW (minimum)		124˚F	122˚F	124˚F			
Store DHW (minimum)		140˚F	140˚F	140˚F			
Flush (thermal shock treatment) Minimum Time	150˚F @ 5 minutes	160–170˚F @ 5–30 minutes					158˚F @ 5 minutes

CDC = Centers for Disease Control and Prevention
ASHRAE = American Society of Heating, Refrigerating, and Air-conditioning Engineers Guideline 12–2000: *Minimizing the Risk of Legionellosis Associated with Building Water Systems*
FREIJE = Matthew R. Freije, *Legionella Control in Healthcare Facilities: A Guide for Minimizing Risk*
ASHE = American Society for Healthcare Engineering
JCAHO = Joint Commission on Accreditation of Healthcare Organizations
CCBC = City of Chicago Building Code
ISPC = Illinois State Plumbing Code
IDPH = Illinois Department of Public Health
ASPE = American Society of Plumbing Engineers

in natural sources of water, including rivers, lakes, streams, and ponds. In warm water, the bacteria can grow and multiply to high concentrations.

Prevention and control of Legionella bacteria is a major concern in healthcare facilities. While there are several potential sources of the bacteria in hospitals, for the purposes of this section, only Legionella in domestic hot water systems is addressed.

The Legionella bacteria can be found in many domestic hot and cold water systems in trace amounts. There are no health concerns with the bacteria until it colonizes (forming higher concentrations), and the bacteria are atomized and inhaled or aspirated. In most documented cases of Legionnaires' disease, transmission occurred when water containing the organism was aerosolized in respirable droplets (1–5 micrometers in diameter) and inhaled or aspirated by a susceptible host. No data indicates that the bacteria are of concern when swallowed, and no data supports Legionella being spread through person-to-person transmission. Legionella has been shown to most greatly affect immunosuppressed people. In a hospital, the following patients are most susceptible to Legionella infection: organ transplant patients, cancer patients receiving radiation or chemotherapy, patients with HIV, and surgical patients.

Varying Standards

Many different temperature ranges for Legionella bacterial growth are published. The Centers for Disease Control and Prevention (CDC) lists a favorable bacterial growth range of 90–113°F (32–45°C). ASHRAE lists a favorable bacterial growth range of 77–108°F (25–42°C), and Matthew Freije, author of *Legionellae Control in Healthcare Facilities,* lists the optimal temperature range for bacterial growth at 68–122°F (20–50°C) (95–115°F [35–46°C] ideal). The American Society for Healthcare Engineering (ASHE) and the Joint Commission list a range of 77–108°F (25–42°C). Combining these ranges would indicate a potential range of growth of 68–122°F (20–50°C).

All available information indicates that almost all bacteria die at temperatures above 130°F (54°C). The higher the temperature, the faster the bacteria die. Table 6-6 lists domestic water system temperatures as they relate to Legionella from the various agencies and organizations. Included on the table are three additional sources of temperature information: the City of Chicago Building Code, State of Illinois Plumbing Code, and ASPE. These were included as a sample of additional requirements from local jurisdictions and recommendations from plumbing organizations.

Legionella Hot Spots

As mentioned, available information indicates almost all Legionella bacteria die at temperatures above 130°F (54°C). Therefore, a common method of Legionella control is to maintain the domestic hot water system temperature above 130°F (54°C), with a preferable distribution system temperature of 140°F (60°C) and a return hot water temperature of at least 124°F (51°C).

However, on older piping systems not having thermostatic mixing valves at all outlets, a system cannot be operated at 130°F (54°C) or above and still maintain code compliance. As mandated by most local codes, the maximum hot water temperature to plumbing fixtures in patient care areas is 115°F (46°C). This is to minimize scalding potential due to excessive water temperature. Often, the shower valves in a hospital facility are not of the thermostatic mixing valve type, which would allow the system to be operated at an elevated temperature. As a result, a hospital's domestic hot water systems are operated at approximately 115°F (46°C), with a return hot water temperature of 105–110°F (41–43°C). Unfortunately, no matter what code you use, this temperature range is in the Legionella bacteria growth temperature range.

Bacterial growth is most prominent in stagnant areas such as storage tanks and dead ends of piping. Bacteria typically grow in the biofilm, scale, slime, and sediment found in these locations. It tends to not grow in sections of the piping distribution system that are actively flowing and have little biofilm or sediment buildup. Increased water velocity in a piping system can help reduce biofilm, but excessive water velocity can be detrimental to a piping system. Care should be taken to not exceed 7 feet per second of velocity in the pipe, or erosion could take place, causing pipe failure.

Legionella bacteria also can reside in the scale buildup on showerheads. The showerhead provides a sieve effect, and the additional rough surface of the scale provides additional area for biofilm. Other locations of bacterial growth include spas and whirlpools. There also have been reports of bacterial growing on natural rubber washers.

Controlling Legionella

Many methods of controlling the colonization of Legionella bacteria are available. These include elevated temperature maintenance, heat and flush cycles, copper-silver ionization, chlorine dioxide injection, halogenization, ultraviolet (UV) radiation, ozonation, hyper-chlorination, filtration/rechlorination, and combinations of these.

Elevated Temperature Maintenance

This involves keeping the system temperature continually at or above 140°F (60°C), as recommended by several of the agencies noted previously. However, it is frequently impractical in large, old facilities.

Heat and Flush

This is a method of disinfecting the piping system by elevating the system temperature to 150°F (66°C) or higher and flushing the high-temperature water through every outlet for at least 30 minutes. This method has proven effective in killing the bacteria present in most domestic hot water systems. Large quantities of biofilm in the piping system might require additional contact time with the high-temperature water.

The advantages of this method are that it involves no capital expenditures for equipment and can be implemented immediately. Disadvantages include increased labor, difficulty coordinating the flushing of the system without risking a scalding injury to patients, and inefficiency on fixtures having thermostatic mixing valves. There is no residual protection, so this is a non-permanent solution to Legionella contamination. The bacteria will eventually return and colonize in the system.

Copper-silver Ionization

This method involves installing a flow-through ionization chamber containing copper-silver electrodes. As electrical current is applied to the electrodes, positively charged copper and silver ions are released into the water system. The positively charged ions bond to the microorganisms, causing them to die. The optimal concentration of copper-silver ions is said to be 400 parts per billion (ppb) for copper and 40 ppb for silver.

The advantages of this alternative are that the equipment is relatively easy to install and maintain and it provides permanent, continuous disinfection. The disadvantages are the initial equipment costs and continuing operating and maintenance costs. Copper-silver ionization often is recommended as an option for use on domestic hot water systems serving immunodeficient patient care areas.

Chlorine Dioxide Gas Injection

This is effective in the control of Legionella bacteria in domestic hot water systems. It penetrates biofilm and slime and kills bacteria at its growth sites. Its advantages are that it stays in solution for long periods, and since it requires low concentrations, it minimizes chlorine-induced corrosion concerns. The disadvantages are that the equipment is best suited for use in small to medium-size applications; the equipment is fairly expensive; a chlorine dioxide gas generator is required for each hot water system; and water chemistry must be monitored closely. For large facilities, it might be necessary to install multiple injectors. Chlorine dioxide is a viable option for use on domestic hot water systems serving immunodeficient patient care areas if closely monitored.

Halogenization

The use of halogens (chlorine, bromine, and iodine) at dosages ranging from 0.3–1 part per million (ppm) is a viable option only if the water pH is controlled precisely. As the water pH drops, so does the efficiency of the halogen as a biocide. A final but critical consideration is the issue of carcinogenic halogenated compounds being dumped into the waterway. A byproduct of chlorine treatment of water is total trihalomethanes (TTHM), which may elevate the risk of certain cancers. While the risk may be small, the EPA is attempting to reduce TTHM concentrations in U.S. water systems. Halogens therefore are seldom recommended for use in healthcare facilities.

Ultraviolet Radiation

UV radiation is effective in killing the bacteria as it flows through a single point in the system. It is effective only for use on small, localized systems and short runs of pipe. It is ineffective in large systems and does not eliminate the growth of existing colonies in other portions of the system. The effect of UV on Legionella within protozoan vesicles (protozoan bodies loaded with Legionella cells) is also not known.

Ozonation

Ozone is effective in killing the bacteria in the immediate vicinity of the ozone generator. Its advantage is that TTHMs are not produced by ozone treatment. Its disadvantages are that decomposition of the ozone in the system quickly dissipates the concentrations required to kill bacteria; it can cause corrosion problems in old piping; it is ineffective in large systems; and it does not eliminate the growth of existing colonies in other portions of the system. This is also an expensive option.

Hyper-chlorination

This method is effective in killing the bacteria, but it has several very important negative aspects. First, high chlorine concentrations are required to kill the bacteria. Second, chlorine byproducts are TTHMs, which are potential carcinogens. Third, chlorine is corrosive and can cause degradation leading to potential failure of the piping. It therefore is not recommended for regular use in most hospital facilities.

Filtration/Rechlorination

This involves the use of 5-micron filters in conjunction with a rechlorination system. It first filters foreign matter being introduced into the piping system from an unfiltered water supply, thus reducing the scale and sediments in which the biofilm can propagate. Rechlorination then is used to maintain a chlorine level more conducive to inhibiting biofilm growth. Chlorine concentrations should be closely monitored to prevent over-chlorination. This type of system typically is used on non-municipal-type water systems

and does not apply to hospitals receiving a central water supply.

Legionella Control Recommendations

For hospitals, Joint Commission Environment of Care Standard EC.1.7 requires the facility to develop a management plan establishing and maintaining a utility systems management program to "reduce the potential for organizational illness." This management plan shall provide processes for "managing pathogenic agents in…domestic water and aerosolizing water systems."

Two approaches are recommended in the CDC guidelines for Legionella prevention and control. The first approach involves periodic, routine culturing of water samples from the hospital's potable water system. For large hospitals, the CDC does not recommend random sampling. For large hospital facilities, the second approach listed is more practical to implement. The recommended approach follows:

1. Educate the hospital staff to increase their awareness of the symptoms of Legionellosis. Maintain a high index of suspicion for Legionellosis and appropriately use diagnostic tests for Legionellosis in patients with nosocomial pneumonia who are at risk of developing the disease and dying from the infection.
2. Initiate an investigation for a hospital source of Legionella upon identification of one case of definite or two cases of possible nosocomial Legionella disease.
3. Routinely use only sterile water for filling and terminal rinsing of nebulization devices.

For high-risk areas such as operating rooms, ICU, AIDS, and cancer treatment areas, it often is recommended that the hospital install chlorine dioxide or copper-silver ionization equipment on the domestic hot water systems feeding these areas.

Following is a checklist for existing domestic hot water piping systems to help minimize system-wide Legionella growth.

1. Remove dead legs in the domestic hot water system. Establish a policy of removing leftover piping.
2. Replace heavily scaled showerheads.
3. Extend hot water recirculation lines to the furthest point from the supply to ensure full system circulation.
4. All new piping should be copper, which is more corrosion resistant than galvanized iron piping. The formation of rust pockets is conducive toward biofilm proliferation and Legionella growth. Corrosion also leads to slime and scale buildup.
5. Change the water and sanitize the integral piping in whirlpools and spas frequently.

If the disease is detected and confirmed, disinfection of the piping system will be required. Of the above methods, the most immediately available form of disinfection is usually the heat and flush method. This will involve the least capital investment; it can be quickly implemented; and when properly executed it is effective in eradicating most existing bacteria colonies. After disinfection, a Legionella control system should be installed, and a program should be instituted to monitor bacteria levels in the piping. It is also advisable to get concurrence from the medical facility's relevant committees, such as the infection control committee.

SCALDING

A research project by Moritz and Henriques at Harvard Medical College looked at the relationship between time and the water temperature necessary to produce a first-degree burn, which is the least serious type of burn and results in no irreversible damage. The results of the research show that it takes a 3-second exposure to 140°F (60°C) water to produce a first-degree burn. At 130°F (54°C), it takes approximately 20 seconds, and at 120°F (49°C) it takes 8 minutes to produce a first-degree burn.

The normal threshold of pain is approximately 118°F (48°C). A person exposed to 120°F (49°C) water would immediately experience discomfort, so it's unlikely that the person would be exposed for the 8 minutes required to produce a first-degree burn. However, people in some occupancies (e.g., hospitals), as well as those over the age of 65 and under the age of one, may not sense pain or move quickly enough to avoid a burn once pain is sensed. If such a possibility exists, scalding protection should be considered, and it often is required by code. (For more information on skin damage caused by exposure to hot water, see Table 6-7.)

Table 6-7 Time/Water Temperature Combinations Producing Skin Damage

Water Temperature		
°F	°C	Time, seconds
Over 140	Over 60	Less than 1
140	60	2.6
135	58	5.5
130	54	15
125	52	50
120	49	290

Source: Tom Byrley. 1979. "130 degrees F or 140 degrees F." *Contractor Magazine* (September). First published in *American Journal of Pathology.*

Note: The above data indicate conditions producing the first evidence of skin damage in adult males.

CODES AND STANDARDS

The need to conform to various codes and standards determines many aspects of the design of a domestic hot water system as well as the selection of components and equipment.

Some of the most often used codes and standards follow:

- Regional, state, and local plumbing codes
- ANSI/ASHRAE 90.1: *Energy Standard for Buildings Except Low-rise Residential Buildings*
- ASME Boiler and Pressure Vessel Code
- ANSI Z21.22: *Relief Valves for Hot Water Supply Systems*
- Underwriters' Laboratories (UL) listings for electrical components
- National Sanitation Foundation (NSF) listings
- AGA listings for gas-burning components
- National Fire Protection Association (NFPA) standards
- National Electrical Code
- U.S. Department of Health and Environmental Control
- American Society of Sanitation Engineers (ASSE) standards

In addition, the federal government, agencies with jurisdiction over public schools and public housing, and many other agencies have specific requirements that must be observed when designing projects and selecting equipment for them.

7 Fuel Gas Piping Systems

This chapter describes low- to medium-pressure fuel gas systems on consumer sites from the property line to the final connection of the most remote gas appliance or piece of equipment, with supply pressures of 7 inches of water column to 5 pounds per square inch gauge (psig). This system is intended to provide sufficient pressure and volume for all uses. Since natural gas is a nonrenewable energy resource, you should design for its efficient use. The direct utilization of natural gas is preferable to the use of electrical energy when electricity is obtained from the combustion of coal, nuclear, natural gas, or oil. However, in many areas, the gas supplier and/or local governmental agencies may impose regulations that restrict the use of natural gas. Refer to the chapter "Energy and Resource Conservation in Plumbing Systems" in *Plumbing Engineering Design Handbook, Volume 1* for information on appliance efficiencies and energy conservation recommendations.

The composition, specific gravity, and heating value of natural gas vary depending on the well (or field) from which the gas is extracted. Natural gas is a mixture of gases, most of which are hydrocarbons, and the predominant hydrocarbon is methane. Some natural gases contain significant quantities of nitrogen, carbon dioxide, or sulfur (usually as hydrogen sulfide). Natural gases containing sulfur or carbon dioxide typically are corrosive. These corrosive substances usually are eliminated by treating the natural gas before it is transmitted to the customers. In addition, readily condensable petroleum gases usually are extracted before the natural gas is supplied to the pipeline to prevent condensation during transmission.

The physical properties of natural gas and liquefied petroleum gas are given in Table 7-1. Natural gas and liquefied petroleum gas both are colorless and odorless, so an additive called mercaptan is injected into both types of gases for leak-detection purposes.

Many types of gases are used as a fuel gas. Natural gas and liquefied petroleum gas are preferred where easily and cheaply obtained. (These are the two predominately used types.) However, other gases may be used based on availability. For the properties of gases commonly available throughout the world, refer to Table 7-2.

TYPES OF GAS SERVICE

Natural gas is obtained from a franchised public utility obligated to provide gas to all who request this service. There are different types of services a utility may provide, each with a different cost. They include the following:

Table 7-1 Average Physical Properties of Natural Gas and Propane

	Propane	Natural Gas (methane)
Formula	C_3H_8	CH_4
Molecular weight	44.097	16.402
Melting (or freezing) point, °F	– 305.84	– 300.54
Boiling point, °F	– 44	– 258.70
Specific gravity of gas (air = 1.00)	1.52	0.60
Specific gravity of liquid 60°F/60°F (water = 1.00)	0.588	0.30
Latent heat of vaporization at normal boiling point, Btu/lb	183	245
Vapor pressure, lb/in^2, gauge at 60°F	92	
Pounds per gallon of liquid at 60°F	4.24	2.51
Gallons per pound of liquid at 60°F	0.237	
Btu per pound of gas (gross)	21591	23000
Btu per ft^3 gas at 60°F and 30 in mercury	2516	1050 ±
Btu per gallon of gas at 60°F	91547	
Cubic feet of gas (60°F, 30 in Hg)/gal of liquid	36.39	59.0
Cubic feet of gas (60°F, 30 in Hg)/lb of liquid	8.58	23.6
Cubic feet of air required to burn 1 ft^3 gas	23.87	9.53
Flame temperature, °F	3595	3416
Octane number (isooctane = 100)	125	
Flammability limit in air, upper	9.50	15.0
Flammability limit in air, lower	2.87	5.0

Table 7-2 Physical and Combustion Properties of Commonly Available Fuel Gases

No.	Gas	Heating value				Heat release, Btu		Specific gravity	Density, lb per ft³	Specific volume ft³/lb
		Btu/ft³		Btu/lb						
		Gross	Net	Gross	Net	Per ft³ air	Per lb air			
1	Acetylene	1,498	1,447	21,569	20,837	125.8	1677	0.91	0.07	14.4
2	Blast furnace gas	92	92	1,178	1,178	135.3	1804	1.02	0.078	12.8
3	Butane	3,225	2,977	21,640	19,976	105.8	1411	1.95	0.149	6.71
4	Butylene (hutene)	3,077	2,876	20,780	19,420	107.6	1435	1.94	0.148	6.74
5	Carbon monoxide	323	323	4,368	4,368	135.7	1809	0.97	0.074	13.5
6	Carburetted water gas	550	508	11,440	10,566	119.6	1595	0.63	0.048	20.8
7	Coke oven gas	574	514	17,048	15,266	115.0	1533	0.44	0.034	29.7
8	Digester (sewage) gas	690	621	11,316	10,184	107.6	1407	0.80	0.062	16.3
9	Ethane	1,783	1,630	22,198	20,295	106.9	1425	1.05	0.080	12.5
10	Hydrogen	325	275	61,084	51,628	136.6	1821	0.07	0.0054	186.9
11	Methane	1,011	910	23,811	21,433	106.1	1415	0.55	0.042	23.8
12	Natural (Birmingham, AL)	1,002	904	21,844	19,707	106.5	1420	0.60	0.046	21.8
13	Natural (Pittsburgh, PA)	1,129	1,021	24,161	21,849	106.7	1423	0.61	0.047	21.4
14	Natural (Los Angeles, CA)	1,073	971	20,065	18,158	106.8	1424	0.70	0.054	18.7
15	Natural (Kansas City, MO)	974	879	20,259	18,283	106.7	1423	0.63	0.048	20.8
16	Natural (Groningen, Netherlands)	941	849	19,599	17,678	111.9	1492	0.64	0.048	20.7
17	Natural (Midlands Grid, U.K.)	1,035	902	22,500	19,609	105.6	1408	0.61.	0.046	21.8
18	Producer (Wellman-Galusha)	167	156	2,650	2,476	128.5	1713	0.84	0.065	15.4
19	Propane	2,572	2,365	21,500	19,770	108	1440	1.52	0.116	8.61
20	Propylene (Propane)	2,332	2,181	20,990	19,030	108.8	1451	1.45	0.111	9.02
21	Sasol (South Africa)	500	443	14,550	13,016	116.3	1551	0.42	0.032	31.3
22	Water gas (bituminous)	261	239	4,881	4,469	129.9	1732	0.71	0.054	18.7

- Firm service: This service provides a continuous supply of gas under all conditions.
- Interruptible service: This service allows the utility to stop the gas supply under certain conditions and proper notification and to restart service when the conditions no longer exist. The most common reason for this interruption is when the ambient temperature falls below a predetermined point.
- Light or heavy process service: This service is provided for process or other industrial use. The quantity of gas must meet specific utility company requirements.
- Commercial or industrial service: This service is used for heating and/or cooling loads for commercial and industrial building classifications.
- Transportation gas service: This is used when the gas is purchased directly from the producer (or wellhead) and not directly from the utility company. The gas is actually carried in the utility company's mains, and there is a charge for the use of the piping system.

APPROVALS

The American Gas Association (AGA), National Fire Protection Association (NFPA), and American National Standards Institute (ANSI) do not approve, inspect, or certify fuel gas installations, procedures, equipment, or materials. All such items must comply with the authority having jurisdiction (AHJ). Although certain model codes provide information with respect to natural gas and liquefied petroleum gas requirements and regulations, local utility suppliers and administrative authorities having jurisdiction may have established their own set of guidelines and requirements. Therefore, they should be consulted at the start of any design. It is up to the plumbing engineer to determine the various agency requirements to design a code-compliant system, while incorporating any additional governing requirements and regulations.

In some municipalities, the plumbing engineer may be required to provide a letter of service request to the utility supplier at the beginning stages of the project. Such a letter contains information the supplier may require such as supply pressures, lengths of piping, and equipment load information that will be anticipated for use in a facility. The utility supplier then may dictate the necessary parameters for the design based on the information provided by the plumbing engineer. (Refer to the "Interior Natural Gas Pipe Sizing" section later in this chapter for additional information.)

SYSTEM OPERATING PRESSURE

The gas pressure in the piping system downstream of the meter is usually 5 to 14 inches (125 to 356 millimeters) of water column, but in some cases it can be as much as 2 to 5 pounds per square inch (psi) (13.8 to 34.5 kilopascals [kPa]). Under certain conditions, engineering practice will limit the pressure losses due to friction in the piping system to a range between 0.2 and 0.5 inch (5 and 13 millimeters) of water column, but all model codes allow the engineer the opportunity to take a greater pressure drop. However, local codes may vary, and the engineer should consult the local AHJ prior to the design of any system.

Most appliances typically require approximately 3.5 inches (89 millimeters) or water column, but certain appliances such as water heaters and boilers may require higher gas pressures to operate properly. Where appliances require higher operating pressures and/or where long distribution lines are encountered, it may be necessary to select a higher pressure at the meter outlet to satisfy the appliance requirements or allow for greater pressure losses in the piping system, thereby allowing economy of pipe size.

Systems often are designed with meter outlet pressures of 2 to 5 psi (13.8 to 34.5 kPa), combined with pressure regulators to reduce the pressure for appliances as required. In most cases, the utility company will reduce the incoming pressure to a figure that is requested by the design engineer at the start of the project or to conform to local code requirements. In some areas of the country, gas pressures on both sides of the meter are in inches of water column.

The maximum allowable operating pressure for natural gas piping systems inside a building is based on NFPA 54: *National Fuel Gas Code,* except when approved by the AHJ or when insurance carriers have more stringent requirements. Natural gas system pressures generally are not permitted to exceed 5 psig (34.5 kPa) unless all the following are met:

1. The AHJ will allow a higher pressure.
2. The distribution piping is welded. (Note: Some jurisdictions also may require welded joints to be x-rayed to verify continuity.)
3. Pipe runs are enclosed for protection and located in a ventilated place that will not allow gas to accumulate.
4. The pipe is installed within areas used specifically for industrial processes, research, warehousing, or mechanical equipment rooms.

A maximum liquefied petroleum gas pressure of 20 psig (138 kPa) generally is allowed, provided the building is used specifically for research or industrial purposes and is constructed in accordance with NFPA 58: *Liquefied Petroleum Gas Code,* Chapter 7.

EFFICIENCY

The difference between the input and the output of any equipment is the heat lost in the combustion process (burner), heat exchanger, and flue gases. Water-heating and space-heating equipment is usually 75 to 85 percent efficient (although high-efficiency equipment in the upper 90 percent range is also available), and ratings are given for both input and output. Cooking and laundry equipment is typically 75 to 85 percent efficient, with input ratings that take into consideration internal losses. When only the output required for an appliance is known, it will be necessary to increase the volume of gas to account for the loss of its listed efficiency.

CODES AND STANDARDS

At the beginning of any given system design, the plumbing engineer shall determine the primary model code that will be referenced, along with the specific year edition of that code. The following model codes should be viewed for provisions regarding natural gas and liquefied petroleum gas regulations, requirements, and standards:

- Uniform Plumbing Code, promulgated by the International Association of Plumbing and Mechanical Officials (IAPMO)
- International Fuel Gas Code, promulgated by the International Code Council (ICC)
- National Standard Plumbing Code, promulgated by the National Association of Plumbing-Heating-Cooling Contractors

The primary code may reference NFPA 54. Other codes and standards that may be applicable are ANSI/NFPA 30: *Flammable and Combustible Liquids Code,* ANSI/NFPA 58, ANSI Z83.3: *Gas Utilization Equipment for Large Boilers,* ANSI/UL 144: *Pressure-regulating Valves for Liquefied Petroleum Gas*, NFPA 88A: *Standard for Parking Structures,* and American Gas Association standards.

Insurance carriers such as Industrial Risk Insurers and FM Global also may impose standards and requirements that may be more stringent than the applicable code.

GAS METERS

Meters are required in all services. To achieve optimal accuracy, the pressure into the meter must be regulated. Requirements for various utility suppliers differ regarding the placement and arrangement of the meter assembly. The assembly could consist of filters, valves, regulators, and relief valves. It could be placed indoors or on a slab outdoors either aboveground or underground in a vented pit. The plumbing contractor is usually responsible for a pit, slab, telephone outlet, and electrical outlet adjacent

Table 7-3 Approximate Gas Demand for Common Appliances[a]

Appliance	Input, Btuh	Input, mJ/h
Commercial kitchen equipment		
Small broiler	30,000	(31.7)
Large broiler	60,000	(63.3)
Combination broiler and roaster	66,000	(69.6)
Coffee maker, three-burner	18,000	(19)
Coffee maker, four-burner	24,000	(25.3)
Deep fat fryer, 45 lbs (20.4 kg) of fat	50,000	(52.8)
Deep fat fryer, 75 lbs (34.1 kg) of fat	75,000	(79.1)
Doughnut fryer, 200 lbs (90.8 kg) of fat	72,000	(76)
Two-deck baking and roasting oven	100,000	(105.5)
Three-deck baking oven	96,000	(103.3)
Revolving oven, four or five trays	210,000	(221.6)
Range with hot top and oven	90,000	(95.0)
Range with hot top	45,000	(47.5)
Range with fry top and oven	100,000	(105.5)
Range with fry top	50,000	(52.8)
Coffee urn, single, 5 gal (18.9 L)	28,000	(29.5)
Coffee urn, twin, 10 gal (37.9 L)	56,000	(59.1)
Coffee urn, twin, 15 gal (56.8 L)	84,000	(88.6)
Stackable convection oven, per section of oven	60,000	(63.3)
Residential equipment		
Clothes dryer (Type I)	35,000	(36.9)
Range	65,000	(68.6)
Stove-top burners (each)	40,000	(42.2)
Oven	25,000	(26.4)
30-gal (113.6-L) water heater	30,000	(31.7)
40- to 50-gal (151.4 to 189.3-L) water heater	50,000	(52.8)
Log lighter	25,000	(26.4)
Barbecue	50,000	(52.8)
Miscellaneous equipment		
Commercial log lighter	50,000	(52.8)
Bunsen burner	5,000	(5.3)
Gas engine, per horsepower (745.7 W)	10,000	(10.6)
Steam boiler, per horsepower (745.7 W)	50,000	(52.8)
Commercial clothes dryer (Type II)	See manufacturer's data	

[a] The values given in this table should be used only when the manufacturer's data is not available.

to the meter if required. In most cases, the utility company provides the meter.

The utility company typically runs the service on the consumer's site up to the meter location, terminating with a shutoff valve. The utility company also may install wireless radio frequency or encoder-type meter-reading equipment at the meter so that gas consumption data can be obtained remotely by utility company personnel. Remote reading is becoming more common and is most often done through an electronic pulse output assembly mounted on the meter. Different styles are available, consisting of radio frequency (RF) and fixed networks, portable/handheld devices, mobile systems, Wi-Fi, and direct power line transmission types. Manufacturers have developed pulse or encoder registers that produce electronic outputs for radio transmitters, reading storage devices, and data-logging devices. Pulse meters typically send a digital or analog electronic pulse to a recording device. Encoder registers have an electronic means for an external device to question the meter register for either the position of the odometer wheels or a stored electronic reading.

In most cases, remote meter reading is advantageous to the local utility company because it allows utility personnel to obtain meter information without the expense of actually having to travel to the meter location. Nevertheless, the plumbing engineer should always investigate the different options that may be offered by the local utility company for remote meter reading, as a particular facility might specifically desire this option such as where submetering of individual areas or tenants within a larger facility may be necessary or where meter information might need to be obtained from a meter located in a secure area. Another advantage is that customer billing can be based on near real-time consumption rather than on estimates based on previous or predicted consumptions.

Meter Types

The three basic types of meters are diaphragm, rotary, and turbine.

Diaphragm meters are positive-displacement devices that have fixed-volume measurement compartments formed by a two-sided convoluted diaphragm. A small pressure drop across the meter causes it to cycle, so the compartments alternately fill with gas at the inlet and then empty at the outlet. By counting the number of cycles, the meter provides a measure of gas volume.

Rotary meters are also positive-displacement measurement devices. In their case, however, a pair of hourglass-shaped impellers forms the fixed-volume compartments. When downstream demand initiates the flow of gas, the impellers rotate to receive a fixed volume of gas at the inlet and then discharge it at the outlet.

A turbine meter is classified as an inferential meter. It has a rotor in the gas stream in lieu of fixed volume compartments. As gas flows through the meter, the rotor turns at a speed that is proportional to the rate of gas.

Meter Selection

Deciding which type of meter is the best choice for a particular application depends on the following:

1. The pressure of the gas being metered
2. The maximum flow rate of the gas being metered

3. The minimum flow rate of the gas to be metered

Depending on the specific model, diaphragm meters have pressure ratings up to 100 psig. Rotary meters can operate up to 285 psig. For applications more than 285 psig, a turbine meter should be selected.

Ratings for these meter types may overlap with respect to capacities and pressures. This overlap allows for versatility when selecting the correct meter for certain applications. For example, a project's maximum flow rate may fit into the "typical" range indicated in a manufacturer's product data listing for a diaphragm meter, but the pressure of the gas being metered may be more than 100 psig. In this case, a small rotary meter would be selected.

For most projects, the following meter choices are typical:

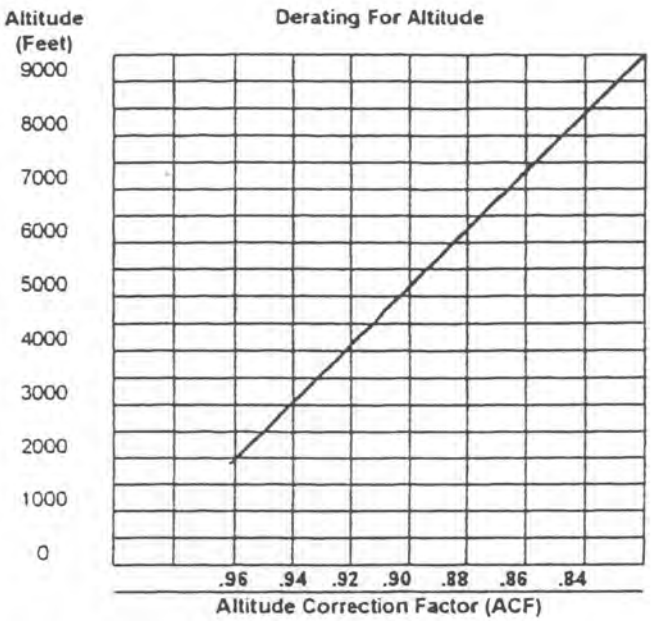
- Diaphragm meters: 10 to 1,000 cubic feet per hour (cfh), 100 psig or less
- Diaphragm, rotary, and turbine meters: 1,000 cfh to 50,000 cfh, 100 psig or less
- Rotary or turbine meters: 50,000 to 325,000 cfh, 100 to 285 psig
- Turbine meters: 325,000 to 18,000,000 cfh, 285 to 1,440 psig

Range ability is another consideration when selecting a gas meter for a given project. Range ability is the ratio of maximum flow rate to minimum flow rate that can be measured within the specified accuracy of the meter. For example, most diaphragm meters provide an accuracy of ±1 percent of reading with a range ability of more than 100:1. Therefore, a meter with a maximum rating of 250 cfh will provide ±1 percent accuracy for flow rates from 2.5 to 250 cfh.

PRESSURE-REGULATING VALVES

A pressure regulator is a device used to reduce a variable high inlet pressure to a constant lower outlet pressure. The line regulator is used to reduce supply line pressures. If used, this regulator usually is installed outside, upstream of the meter assembly, and it is provided by the utility company. If installed inside a building, a dedicated relief vent pipe will need to be connected at the regulator's vent connection and routed to the exterior of the building per the local AHJ. An intermediate regulator located downstream of the meter assembly may be used to further reduce pressure from 2 to 5 psig (13 to 35 kPa) or to a pressure suitable for use by terminal equipment of approximately 7 inches (178 millimeters) of water column.

An appliance regulator connects the supply to equipment at the point of use and may be provided by the equipment manufacturer, specifically on equipment that may include a gas train. Types of appliance regulators are zero governor, backpressure regulator, and a differential regulator.



The Altitude Correction Factor (ACF) should be multiplied by the gas input at sea level to determine the corrected input. Sizing of the equipment is then performed utilizing this corrected input multiplied by the full load efficency.

Figure 7-1 Altitude Correction Factor

When regulators are installed inside a building and require venting, these vents must be routed to the atmosphere. The vents from individual regulators may not be combined. However, a vent to the outdoors is not required for regulators equipped with and labeled for utilization with an approved vent-limiting device installed in accordance with the manufacturer's instructions. Regardless, incorporating vent-limiting devices should be evaluated carefully for each specific project design to ensure that the proper safety measures have been accounted for and that local jurisdictional requirements have been met. Regulators with vent-limiting devices are in many cases allowed only within ventilated spaces to ensure that any gas escaping from the vent is dissipated safely.

When bottled gas is used, the tank can have as high as 150-psi (1,034.6-kPa) pressure to be reduced to the burner design pressure of 11 inches (279.4 millimeters) of water column. The regulator typically is located at the tank for this pressure reduction.

Gas Regulator Relief Vents

Guidelines for the use of relief vents from pressure regulators, also referred to as gas-train vents, can be found in the latest editions of NFPA 54 and *FM Global Loss Prevention Data Sheet 6-4: Oil- and Gas-fired Single-burner Boilers,* as well as in other publications of industry standards, such as those issued by Industrial Risk Insurers and the American Gas Association.

It should be noted that when pressure regulators discharge (or the diaphragm in the regulator ruptures), large amounts of fuel gas may be released. It is not uncommon for a local fire department to be summoned to investigate an odor of gas caused by a gas-train vent discharge. Every attempt should be made to locate the terminal point of the vents above the line of the roof and away from doors, windows, and fresh-air intakes. They should be located on a side of the building that is not protected from the wind. Refer to NFPA 54, local utility supplier requirements, and local codes for the exact requirements for vent termination locations.

CONTROL VALVES

Excess Flow Valves

An excess flow valve is a device that shuts off the flow of gas if there is a much larger flow through the pipe or service than that for which it was designed. In some parts of the country, particularly in areas where earthquakes may occur, excess flow valves are necessary to guard against the possibility of a break during such an event. In other cases, where danger exists for equipment such as large boilers, installation should be considered.

A low-pressure cutoff shall be installed between the meter and the appliance where the operation of a device, such as a gas compressor, appliance, or boiler, could produce a vacuum or dangerous vacuum condition in the piping system.

Appliance Control Valves

An appliance shutoff valve shall be installed at all gas appliances. Valves at flexible hose connections are to be installed prior to the flexible connection that is used to connect the appliance to the building gas supply.

Interlocks and Solenoid Valves

An automatic interlock or gas solenoid valve can be interconnected with the automatic fire extinguishing system when required to shut off the gas supply to all equipment in a kitchen when sprinklers discharge in the event of a fire. These valves typically are provided by the fire suppression equipment contractor and installed by the plumbing or mechanical contractor. (Note: Laboratories may utilize similar automatic shutoff capabilities. Refer to the "Laboratory Use" section further in this chapter for more information.)

In earthquake-prone areas, a seismic shutoff valve is necessary to shut off the supply of gas if a seismic event is of sufficient magnitude to potentially rupture the gas supply pipe or separate the pipe from equipment.

APPLIANCES

Most manufacturers of gas appliances rate their equipment with gas consumption values in British thermal units per hour (Btuh), which is used in determining the maximum gas flow rate to be supplied to the appliance via the piping system. Table 7-3 shows the approximate gas consumption for some common appliances (listed in Btuh). To find the flow rate of the gas required, always use the consumption data listed by the manufacturer and divide it by the Btu per cubic feet content of the gas as provided by the utility supplier. (Note: Natural gas is nominally rated at 1,000 Btu per cubic feet for design purposes. However, it is very important to verify the actual Btuh content or rating to be used, as well as the altitude/elevation necessary for deration purposes for a specific project design.)

VENTING

Integral to the design of any natural gas system are the venting and combustion air requirements required for appliances to operate properly and efficiently. Appliances are listed by types and categories that shall be used in the design of flue/vent systems. Along with the requirements for natural gas systems, appliance venting requirements also are stipulated in NFPA 54, the International Fuel Gas Code (IFGC), and any specific requirements dictated by the local gas supplier as applicable. Although not within the scope of this chapter, it is mentioned here for reference purposes due to the fact that the plumbing engineer may be required to provide design input with respect to venting even though not responsible for the actual design of these systems.

It generally is not the plumbing engineer's responsibility to design and specify gas vents. This is done by either the HVAC engineer or the manufacturer. However, water heater technologies that are currently available, such as non-condensing, high efficiency, and forced combustion, may require specific venting consideration, which in turn should be coordinated with the HVAC engineer to ensure that all aspects of the venting design have been coordinated.

The products of combustion from an appliance must be safely exhausted to the outside. This is accomplished with a gas vent system in most cases. Where an appliance has a very low rate of gas consumption (e.g., Bunsen burner or countertop coffee maker) or where an appliance has an exhaust system associated with the appliance (e.g., gas clothes dryer or range) and the room size and ventilation are adequate, a separate gas vent system may not be required. Current practice usually dictates the use of factory-fabricated and listed vents for small to medium-size appliances. Large appliances and equipment may require specially designed venting or exhaust systems.

For reference purposes, a general description of venting categories is as follows:

- Category I: Appliance operates with a negative vent static pressure and a flue gas temperature that avoids condensation (negative pressure/non-condensing).
- Category II: Appliance operates with a negative vent static pressure and a flue gas temperature that may cause excessive condensation within the vent (negative pressure/condensing).
- Category III: Appliance operates with a positive vent static pressure and a flue gas temperature that avoids condensation (positive pressure/non-condensing).
- Category IV: Appliance operates with a positive vent static pressure and a flue gas temperature that may cause excessive condensation within the vent (positive pressure/condensing).

Where the rating of the appliance is not known, it shall comply with the typical demand of the type of appliance as indicated in NFPA 54.

ALLOWABLE GAS PRESSURE

The gas pressure in the piping system downstream of the meter is usually 5 to 14 inches (125 to 356 millimeters) of water column, but in some cases it can be as much as 2 to 5 psi (13 to 35 kPa). Under certain conditions, engineering practice will limit the pressure losses due to friction in the piping system to a range between 0.2 and 0.5 inch (5 to 13 millimeters) of water column, but all model codes allow the engineer the opportunity to take a greater pressure drop. However, local codes may vary, and you should consult the local AHJ prior to sizing any system.

Most appliances require approximately 3.5 inches (89 millimeters) of water column; however, be aware that large appliances, such as boilers, may require higher gas pressures to operate properly. Where appliances require higher operating pressures and/or where long distribution lines are encountered, it may be necessary to select a higher pressure at the meter outlet to accommodate the appliance requirements or allow for greater pressure losses in the piping system. If a greater pressure at the meter outlet can be attained, a greater pressure drop can be allowed in the piping system. If the greater pressure drop design can be used, a more economical piping system is possible. This scenario generally involves designing a system that utilizes multiple regulators. In a situation with an extreme distance between the meter and the appliance location, a multi-regulator system is often the best option. Reasons for this involve distribution pipe size, length of run, and appliance Btuh demand.

For example, a 700-foot equivalent length of distribution piping from the meter to an appliance located at the far end of a building with a total load of more than 1,000,000 Btuh, at a delivery pressure of 7 to 11 inches (177.8 to 279.4 millimeters) of water column likely would benefit from a multi-regulator system because one single regulator (set at 7 inches [177.8 millimeters] of water column and located at the gas meter) would require a fairly large distribution pipe for that distance at the appliance demand. Therefore, a main distribution system regulator (located at the

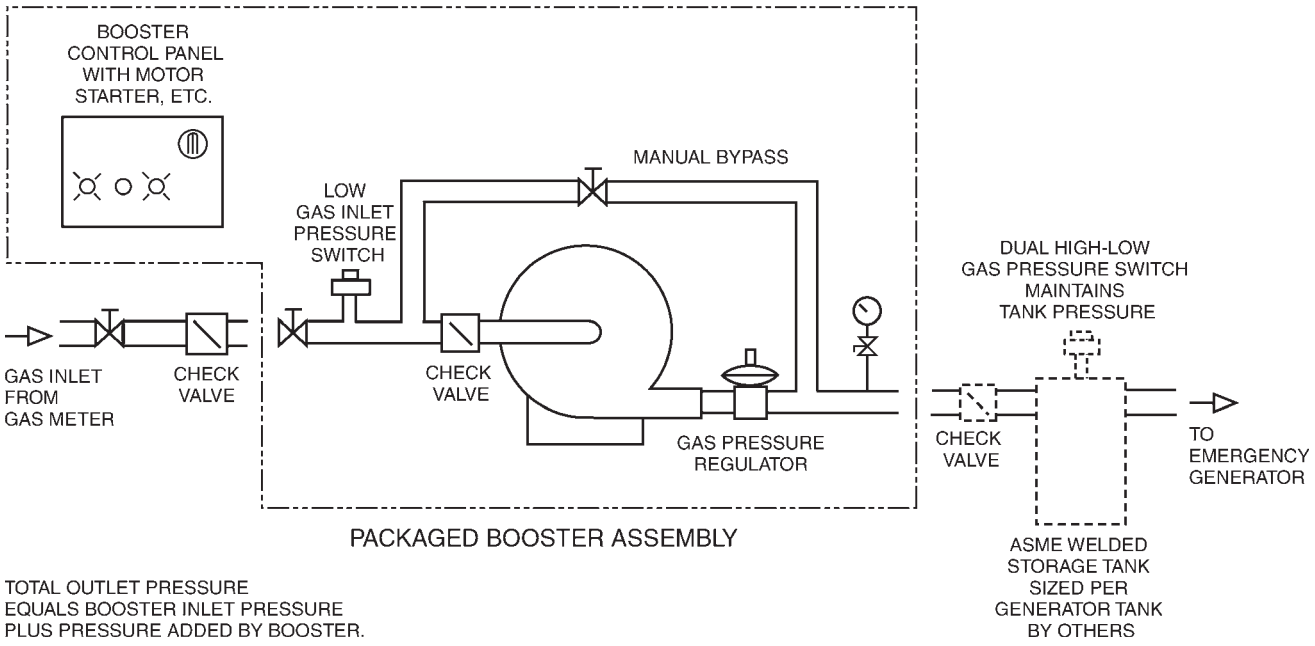


Figure 7-2 Variations of a Basic Simplex Booster System: (Standby Generator Application with Accumulator Tank Having a Limitation on Maximum Pressure

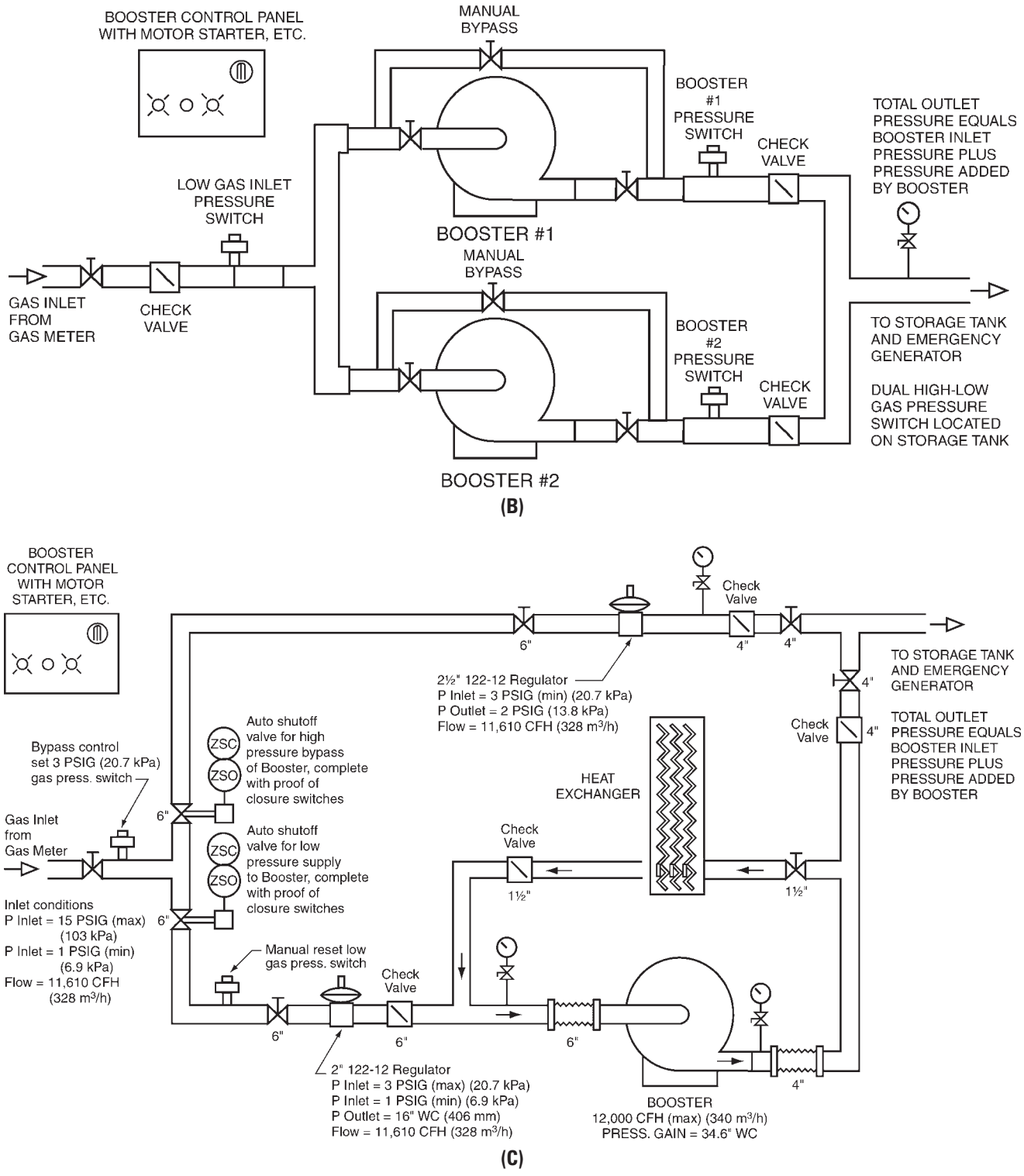


Figure 7-2 (cont.) Variations of a Basic Simplex Booster System: (B) Dual Booster System for Critical Systems Like Those in Hospitals; (C) Heat Exchanger Loop Example—Required for High Flow Range with Low Minimum Flow

meter and set at 5 psig [34.47 kPa]) would be used to supply a higher system pressure to the appliance, thus utilizing a smaller pipe size than would be required for a low-pressure delivery at the same length of pipe. The secondary, or step-down, regulator (located at the appliance) then would lower the gas supply pressure sufficient to supply the appliance.

Some additional issues need to be considered with respect to designing multi-regulator systems. Where most appliances are located within interior building spaces, secondary regulators need to be strategically located so they can be properly vented to the outdoors and be maintained efficiently. Other facilities may have a mix of both interior appliances and gas-fired rooftop equipment that is exposed to the outside. These systems can be designed such that secondary regulators are located at the roof, eliminating the need for associated vent piping and providing easy access for maintenance or replacement. Also, secondary regulators can be located in a manner in which they can supply several appliances within a specific zone or area, minimizing the number of secondary regulators needed for use, although requiring more low-pressure gas supply piping downstream of the secondary regulator. Simply stated, there are tradeoffs for every given situation, and you need to address all possible scenarios to design the most efficient system and accommodate the owner's requirements as much as possible.

LABORATORY USE

Natural gas is the primary gas used in laboratories at lab benches and within fume hoods for Bunsen burners. Where natural gas is not available, liquefied petroleum gas (propane) is used, but this generally requires the manufacturer to be advised due to the Bunsen burner requiring a smaller orifice. Typical Bunsen burners consume either 5 cfh (0.15 cubic meters per hour) for small burners or 10 cfh (0.30 cubic meters per hour) for larger burners. The maximum pressure at the burner should not exceed 14 inches (355.6 millimeters) of water column. The 10-cfh (0.30-cubic-meters-per-hour) capacity is most commonly used for design purposes.

Flow diversity can be applied (relative to determining system pipe sizes) where natural gas is supplied to Bunsen burners. However, both the acceptance and methodology for determining flow diversities for this purpose must be obtained by the local AHJ or utility supplier prior to the design of any system. Where flow diversity factors are allowable for implementation, they shall be done so with careful judgment and sound engineering principles, based on each individual facility type and operational characteristics. Note that each type of facility contains its own unique operational characteristics and, with respect to natural gas, should not be assigned a global or standard set of diversity guidelines typically seen in various charts and graphs for other services such as compressed air and vacuum. Prior to the start of any system design, you should consult with a facility's owners (and users) to help determine the proper diversities that could be implemented, based on the facility's unique programming requirements and use by its occupants.

Certain local jurisdictions may require laboratory natural gas systems, especially those in schools or universities, to be provided with emergency gas shutoff valves located at the main supply piping to each laboratory. NFPA standards (45, 72 and 101) also contain requirements regarding emergency and automatic shutoff of gas systems. Valves for these applications should be normally closed and opened only when the gas is being supplied. They should be located inside the laboratory and used in conjunction with shutoff valves at the benches or equipment (which may be required by other codes). You should ensure that locations meet local code requirements.

Utility controllers and laboratory service panels are manufactured, pre-assembled safety devices that regulate the control of various services and devices such as domestic water, natural gas, and electrical outlets within science classrooms and instructional, research, and medical facilities. They typically contain solid-state electronic controllers with relays that activate these services. A keyed service switch integrated into the design of the utility controller restricts the ability to activate services by unauthorized persons, resulting in a safe environment for students or other occupants. Utility controllers also typically are equipped with a panic button that would deactivate the gas service upon being pressed.

ALTITUDE DERATING FACTOR

Natural gas has a lower density at higher altitudes than at lower altitudes, which must be considered when a project location is more than 2,000 feet above sea level. This altitude correction factor shall be multiplied by the gas input ratings at sea level to determine the corrected input at full-load capacity. Refer to Figure 7-1 to determine the derating factors for natural gas.

PIPING SYSTEM MATERIALS

The International Fuel Gas Code (IFGC), model plumbing codes, and standards published by NFPA (54 and 58) list the approved materials for use in natural gas and liquefied petroleum gas (propane) piping systems. The most commonly used materials for these systems (along with additional notes and cautionary statements) are listed below for reference purposes.

Metallic Pipe

Cast Iron

Cast iron pipe shall not be used.

Steel and Wrought Iron

Steel and wrought-iron pipe shall be at least of standard weight (Schedule 40) and shall comply with one of the following standards:

- ANSI/ASME B36.10: *Welded and Seamless Wrought-Steel Pipe*
- ASTM A53: *Standard Specification for Pipe, Steel, Black and Hot-dipped, Zinc-coated Welded and Seamless:* Black or carbon steel piping is generally the most commonly selected steel pipe material for natural gas and propane piping systems. Galvanized steel pipe is covered with a protective coating of zinc that greatly reduces its tendency to corrode and extends its life expectancy. However, it should be noted that galvanized steel piping is not approved for use in many jurisdictions for natural gas service. In general, it should not be used in natural gas systems because corrosivity levels in natural gas can vary over time and can cause the zinc to flake off and clog the system.
- ASTM A106: *Standard Specification for Seamless Carbon Steel Pipe for High-temperature Service*

Copper and Brass

Copper and brass pipe is approved for use, but they shall not be used if the gas contains more than an average of 0.3 grains of hydrogen sulfide per 100 standard cubic feet (SCF) of gas (0.7 milligrams per 100 liters).

Threaded copper, brass, or aluminum alloy pipe is approved for use, but shall not be used with gases that are corrosive to such material.

Aluminum Alloy

Aluminum alloy pipe shall comply with ASTM B241: *Specification for Aluminum-alloy Seamless Pipe and Seamless Extruded Tube* (except that the use of alloy 5456 is prohibited) and shall be marked at each end of each length indicating compliance. Aluminum alloy pipe shall be coated to protect against external corrosion where it is in contact with masonry, plaster, or insulation or is subject to repeated wettings by such liquids as water, detergents, or sewage. Aluminum alloy pipe shall not be used in exterior locations or underground.

Metallic Tubing

Seamless copper, aluminum alloy, or steel tubing shall not be used with gases corrosive to such materials.

Steel

Steel tubing shall comply with ASTM A254: *Standard Specification for Copper-brazed Steel Tubing*.

Copper and Brass

Copper and brass tubing shall not be used if the gas contains more than an average of 0.3 grains of hydrogen sulfide per 100 SCF of gas (0.7 milligrams per 100 liters). Copper tubing shall comply with standard Type K or Type L of ASTM B88: *Standard Specification for Seamless Copper Water Tube* or ASTM B280: *Specification for Seamless Copper Tube for Air-conditioning and Refrigeration Field Service*.

Aluminum

Aluminum alloy tubing shall comply with ASTM B210: *Standard Specification for Aluminum and Aluminum-alloy Drawn Seamless Tubes* or ASTM B 241. Aluminum alloy tubing shall be coated to protect against external corrosion where it is in contact with masonry, plaster, or insulation or is subject to repeated wettings by such liquids as water, detergent, or sewage. Aluminum alloy tubing shall not be used in exterior locations or underground.

Corrugated Stainless Steel Tubing

Corrugated stainless steel tubing (CSST) shall be listed in accordance with ANSI LC 1/CSA 6.26: *Fuel Gas Piping Systems Using Corrugated Stainless Steel Tubing*. The standard requires a contractor to be certified by the manufacturer before installing CSST. CSST is approved by all national plumbing and gas codes. However, some local jurisdictions and authorities may restrict its use.

As an alternative to the installation of rigid steel or copper piping systems, CSST systems can be used from ⅜-inch up to 2-inch tube sizes. CSST systems consist of a continuous, flexible, stainless steel pipe with an exterior polyethylene (PE) jacket, which is ASTM E84: *Standard Test Method for Surface Burning Characteristics of Building Materials* rated (smoke and fire rated 25/50) to be installed in a plenum. The piping is produced in coils that are air-tested for leaks. It most often is installed in a central manifold configuration (also called parallel configuration) or extended from steel pipe mains with home run lines that extend to gas appliances (also called a hybrid system).

Flexible gas piping is lightweight and requires fewer connections than conventional gas piping because it can be bent easily and routed around obstacles. This can amount to a substantial reduction in labor costs as compared to a conventional rigid piping system installation. CSST piping systems can be a good choice for a retrofit or renovation project where existing conditions could render a rigid piping system installation very costly or disruptive to existing building occupants.

Precautions are necessary when designing, sizing, and installing CSST. Although you can design a CSST system the same way you design a rigid system, it is not the most efficient way to use this material. It's necessary to understand that the CSST industry is very proprietary, and all manufacturers have configured their systems differently. Consequently, once a CSST manufacturer is chosen either by the contractor or engineer, it would be prudent to stay the course for that project. Given the different flow characteristics between CSST and rigid pipe systems, it's important to understand that you cannot size CSST the same way you size rigid pipe systems. By using the chosen manufacturer's design and installation guide, which will include sizing criteria, you will be able to size the system properly. Installation, as with all natural gas and propane systems, should be done with care, but due to the flexible nature of this system, it's important to follow the strict guidelines set forth in the ANSI standard for safe routing and strike protection.

Plastic Pipe and Tubing

Plastic pipe, tubing, and fittings used to supply fuel gas shall conform to ASTM D2513: *Standard Specification for Thermoplastic Gas Pressure Pipe, Tubing, and Fittings.* Pipe to be used shall be marked "gas" and "ASTM D2513."

Table 7-4 Equivalent Lengths for Various Valve and Fitting Sizes

	Pipe Size, in. (mm)									
Fitting	**¾ (19.1)**	**1 (25.4)**	**1½ (38.1)**	**2 (50.8)**	**2½ (63.5)**	**3 (76.2)**	**4 (101.6)**	**5 (127)**	**6 (152.4)**	**8 (203.2)**
	Equivalent Lengths, ft (m)									
90° elbow	1.00 (0.3)	2.00 (0.61)	2.50 (0.76)	3.00 (0.91)	4.00 (1.22)	5.50 (1.68)	6.50 (1.98)	9.00 (2.74)	12.0 (3.66)	15.0 (4.57)
Tee (run)	0.50 (0.15)	0.75 (0.23)	1.00 (0.3)	1.50 (0.46)	2.00 (0.61)	3.00 (0.91)	3.50 (1.07)	4.50 (1.37)	6.00 (1.83)	7.00 (2.13)
Tee (branch)	2.50 (0.76)	3.50 (1.07)	4.50 (1.37)	5.00 (1.52)	6.00 (1.83)	11.0 (3.35)	13.0 (3.96)	18.0 (5.49)	24.0 (7.32)	30.0 (9.14)
Gas cock (approx.)	4.00 (1.22)	5.00 (1.52)	7.50 (2.29)	9.00 (2.74)	12.0 (3.66)	17.0 (5.18)	20.0 (6.1)	28.0 (8.53)	37.0 (11.28)	46.0 (14.02)

Note: The pressure drop through valves should be taken from manufacturers' published data rather than using the equivalent lengths, since the various patterns of gas cocks can vary greatly.

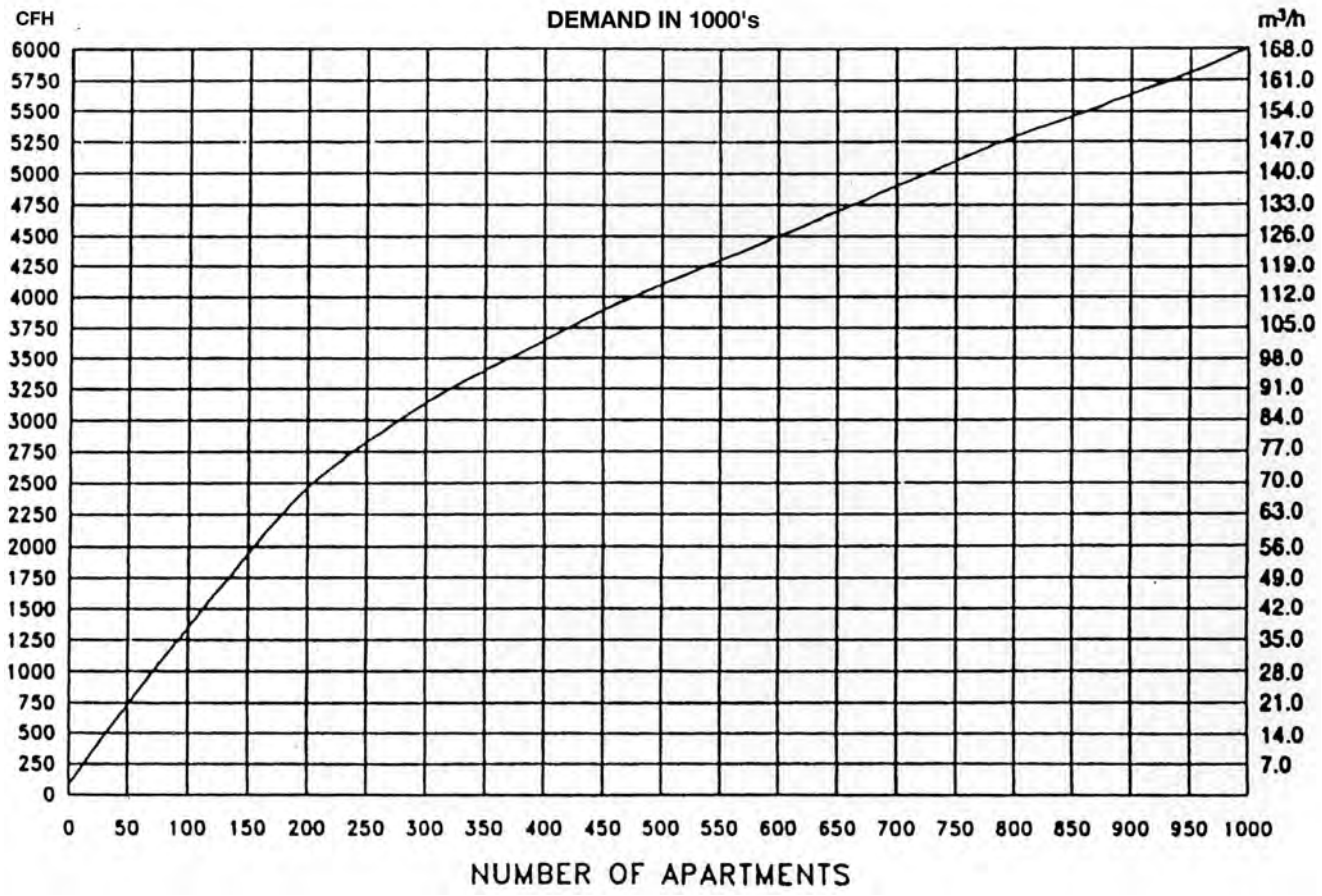


Figure 7-3 Gas Demand for Multiple-unit Dwellings with More than 50 Apartments

Polyethylene plastic pipe may be used outside for underground installations only. In addition, PE pipe installations typically require warning tape and/or tracer wire to be installed above the installed pipe for locating purposes and to protect the pipe from damage from digging equipment.

Fittings and Joints

Steel pipe joints shall be threaded, flanged, brazed, or welded. Threaded connections are most commonly used for piping up to 3 inches. Welded or flanged joints become more practical above this size range as it is difficult to maneuver assembled sections of large screwed piping due to weight and space constraints. Where nonferrous pipe such as copper or brass is brazed, the brazing materials shall have a melting point in excess of 1,000°F (538°C). Brazing alloys shall not contain more than 0.05 percent phosphorus.

Steel pipe and fittings 4 inches (100 millimeters) and larger shall be welded. In some jurisdictions the size of the piping determines whether the piping is required to be welded and, in some cases, x-rayed at the welding points. Always verify the exact requirements with the local AHJ.

Tubing joints shall be made with approved gas tubing fittings, brazed with a material having a melting point in excess of 1,000°F (538°C), or made by press-connect fittings complying with ANSI/CSA LC4: *Press-Connect Copper and Copper Alloy Fittings for Use in Fuel Gas Distribution Systems*. (Brazing alloys shall not contain more than 0.05 percent phosphorus.)

Flexible Hose Connections

Indoor hose connectors shall be a listed connector in compliance with ANSI Z21.24/CSA 6.10: *Connectors for Gas Appliances*. The connector shall be used in accordance with the manufacturer's installation instructions and shall be located in the same room as the connected appliance. Only one connector shall be used per appliance. Indoor gas hose connectors may be used with laboratory, shop, and food service equipment. A shutoff valve must be installed where the connector is attached to the building piping. The connector must be of minimal length, but shall not exceed 6 feet (1.8 meters). The connector must not be concealed, must not extend from one room to another, and must not pass through wall partitions, ceilings, or floors.

Outdoor hose connectors shall be a listed connector in compliance with ANSI Z21.75/CSA 6.27: *Connectors for Outdoor Gas Appliances and Manufactured Homes*. Only one connector shall be used per appliance. They may be used to connect portable outdoor gas-fired appliances if the hose connections and appliances are listed for such applications. A shutoff valve or listed quick-disconnect device must be installed where the connector is attached to the supply piping, with piping installed in such a manner as to prevent the accumulation of water or foreign material. This connection must be made only in the outdoor area where the appliance is to be used.

Non-stationary (mobile) commercial cooking appliances and other types of appliances that may be moved for cleaning and sanitation purposes shall be connected in accordance with the connector manufacturer's installation instructions using a listed appliance connector complying with ANSI Z21.69/CSA 6.16: *Connectors for Movable Gas Appliances*. Movement

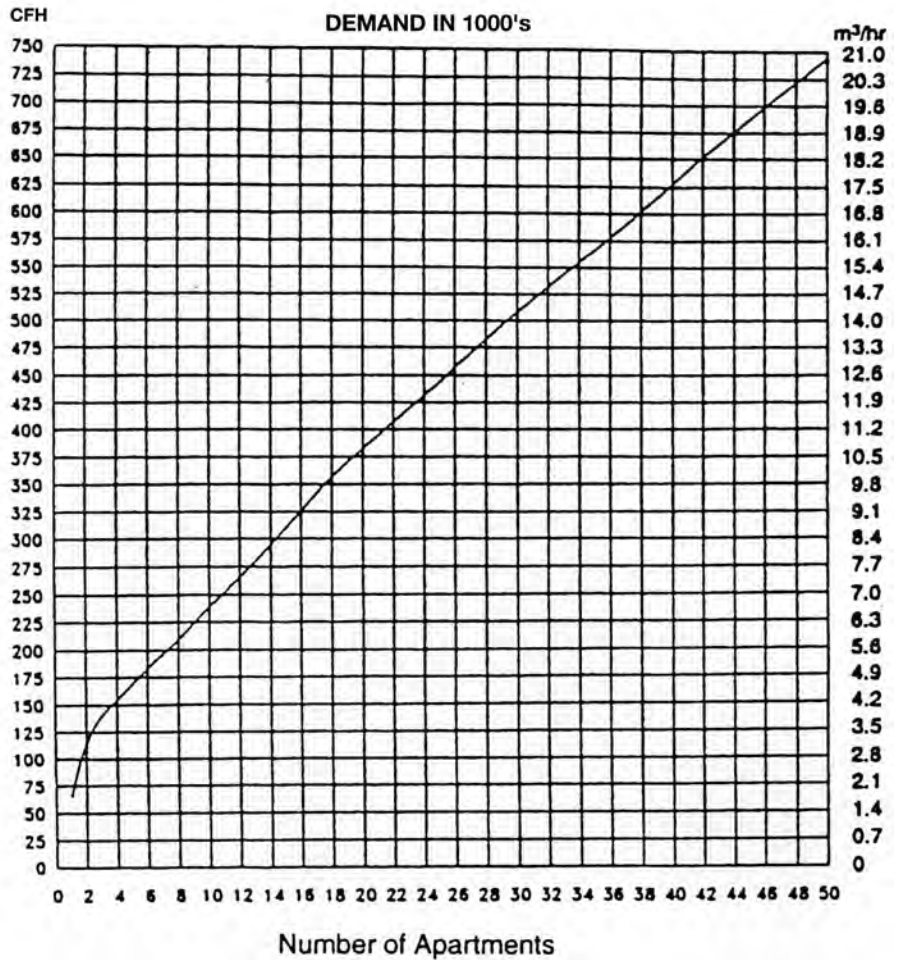


Figure 7-4 Gas Demand for Multiple-unit Dwellings with Less than 50 Apartments

of appliances with casters (in all cases) shall be limited by a restraining device installed in accordance with the connector and appliance manufacturers' installation instructions to prevent damage if the appliance should move while the gas supply is connected.

Grounding

Bonding and electrical grounding of all natural gas piping systems are required by NFPA 70: *National Electrical Code* and the International Fuel Gas Code. Additional consideration should be exercised where installations are located in regions prone to lightning. Electrical bonding is required to prevent damage that could occur during an electrical storm.

NATURAL GAS BOOSTERS

A gas booster is a mechanical device that increases natural gas pressure. It is used when the gas utility does not provide adequate pressure. It is important to note that the gas service must be capable of the volumetric flow rate required at the boosted pressure level. A gas booster cannot supplement quantity where an inadequate volumetric supply of gas may exist.

Gas boosters for natural gas are hermetically sealed and are equipped to deliver a specific volumetric flow rate (within the booster's rated capacity) to an increased gas pressure beyond the supply pressure. The outlet pressure usually remains at a constant differential above the supply pressure within a reasonable range. The discharge pressure is the sum of the incoming gas pressure and the booster-added pressure at the selected flow rate. The incoming gas pressure typically has an upper safety limit as stipulated by the hermetic gas booster manufacturer. Therefore, you may encounter cautions or warnings about the upper limits of incoming pressure, approximately 5 psi (34.5 kPa). Installation of gas boosters must be closely coordinated with the utility company or gas supplier.

Materials and Construction

Housing and Rotor

Boosters used for fuel gas must be Underwriters Laboratories (UL) listed for the specific duty intended and shall be hermetically sealed. Casings on standard boosters usually are constructed of carbon steel, but they also are available in stainless steel and aluminum. Inlet and outlet connections are threaded or flanged, depending on the pipe connection size and manufacturer selected, and the casings are leak-tight. Drive impellers are contained within the casing and always manufactured of a spark-resistant material such as aluminum.

Discharge check valves are furnished at the booster inlet and at the booster bypass. It is important that all valves used are listed and approved for use on gas piping systems. The fan, control panel, valves, piping, and inter-electrical connections can be specified as a skid-mounted package at the discretion of the designer. This allows for a UL listing of the entire package, rather than of individual components.

Electrical Components

Motor housings for gas booster systems are designed for explosion-proof (XP) construction and are rated per National Electrical Manufacturers Association (NEMA) Class 1, Division 1, Group D classification with thermal overload protection. A factory UL-listed junction box with a protected, sealed inlet is necessary for wiring connections.

Other Electrical Ancillary Equipment

Boosters are equipped with low-pressure switches that monitor the incoming gas pressure. The switch is designed to shut down the booster should the utility-supplied pressure fall below a preset limit. The set point is usually about 3 inches (76 millimeters) of water column, but you should verify the limit with the local gas supplier. The switch must be UL listed for use with the gas service supplied. When the switch opens, it de-energizes the motor control circuit and simultaneously initiates both audible and visual signals, which require manual resetting.

The booster can be equipped with an optional high/low gas pressure switch. This feature allows the booster to run only when adequate supply pressure is available. The switch shuts down the booster when it reaches the maximum discharge set-point pressure at the output line pressure.

Minimum Gas Flow

Gas boosters normally require a minimum gas flow that serves as an internal cooling medium. For example, a booster sized at a flow rate of 10,000 cfh (283.2 cubic meters per hour) has an inherent minimum turndown based on the minimum flow required to cool the unit. This rate, for the booster in this example sized at 10,000 cfh, may be 2,000 cfh (566.3 cubic meters per hour). Should the unit be required to run below this turndown rate, additional supplemental cooling systems must be incorporated within the gas booster design. The heat exchangers normally rated for this use are water cooled.

Intrinsic Safety

Electrical connections are made through a sealed, explosion-proof conduit to the XP junction box on the booster unit. Control panels are rated NEMA 4 for outdoor use and NEMA 12 for indoor use, unless the booster system is to be located in a hazardous area, which may have additional requirements. The panel (as an assembly) must display a UL label specific for its intended use.

Table 7-5 Pipe Sizing for Pressure Less than 2 psi (14 kPa) and Loss of 0.3 inch (7.5 mm) of Water Column

	Pipe Size, in.								
Nominal	½	¾	1	1¼	1½	2	2½	3	4
Actual ID	**0.622**	**0.824**	**1.049**	**1.380**	**1.610**	**2.067**	**2.469**	**3.068**	**4.026**
Length, ft	**Capacity in Cubic Feet of Gas per Hour**								
10	131	273	514	1,060	1,580	3,050	4,860	8,580	17,500
20	90	188	353	726	1,090	2,090	3,340	5,900	12,000
30	72	151	284	583	873	1,680	2,680	4,740	9,660
40	62	129	243	499	747	1,440	2,290	4,050	8,270
50	55	114	215	442	662	1,280	2,030	3,590	7,330
60	50	104	195	400	600	1,160	1,840	3,260	6,640
70	46	95	179	368	552	1,060	1,690	3,000	6,110
80	42	89	167	343	514	989	1,580	2,790	5,680
90	40	83	157	322	482	928	1,480	2,610	5,330
100	38	79	148	304	455	877	1,400	2,470	5,040
125	33	70	131	269	403	777	1,240	2,190	4,460
150	30	63	119	244	366	704	1,120	1,980	4,050
175	28	58	109	224	336	648	1,030	1,820	3,720
200	26	54	102	209	313	602	960	1,700	3,460
250	23	48	90	185	277	534	851	1,500	3,070
300	21	43	82	168	251	484	771	1,360	2,780
350	19	40	75	154	231	445	709	1,250	2,560
400	18	37	70	143	215	414	660	1,170	2,380
450	17	35	66	135	202	389	619	1,090	2,230
500	16	33	62	127	191	367	585	1,030	2,110
550	15	31	59	121	181	349	556	982	2,000
600	14	30	56	115	173	333	530	937	1,910
650	14	29	54	110	165	318	508	897	1,830

Table 7-6 Specific Gravity Multipliers

Specific Gravity	Capacity Multiplier	Specific Gravity	Capacity Multiplier	Specific Gravity	Capacity Multiplier
0.35	1.310	0.75	0.895	1.40	0.655
0.40	1.230	0.80	0.867	1.50	0.633
0.45	1.160	0.85	0.841	1.60	0.612
0.50	1.100	0.90	0.817	1.70	0.594
0.55	1.040	1.00	0.775	1.80	0.577
0.60	1.000	1.10	0.740	1.90	0.565
0.65	0.962	1.20	0.707	2.00	0.547
0.70	0.926	1.30	0.680	2.10	0.535

Gas Laws for Boosters

The gas laws apply to the relationship of the incoming gas supply and the boosted service. The standard law for compressed gas relationships is as follows:

Equation 7-1

$$PV = RT$$

where
P = Pressure, psi or inches of water column (kPa or millimeters of water column)
V = Volume, cfh (cubic meters per hour)
R = Constant for the gas/air mixture used
T = Temperature, °F (°C)

Usually the temperature of the gas remains relatively constant and can be ignored in the relationship. Therefore, the pressure multiplied by the volume is proportional to a constant R. Further, the pressure/volume ratios before and after the booster are proportional. That is:

Equation 7-2

$$P_1V_1 = P_2V_2$$

where
P_1 = Pressure at a point prior to the booster
P_2 = Pressure at a point after the booster

In most cases, the volumetric rating of gas-fired equipment is listed in Btuh, which can readily be converted to cfh. In the booster application, sizing criteria should be approached from a standard cfh (scfh) rating, not an actual cfh (acfh) rating.

The temperature of the gas is usually constant. However, in the event the gas is to be heated or cooled, the previously mentioned gas laws are affected by temperature. Gas density changes affect the constant, but usually do not affect the relationship since the same mixture is boosted across the fan.

High-rise Building Issues

Consideration must be given to the rise effect in available gas pressure as gas rises within the piping located in a high-rise building. Therefore, if the gas system supplies a kitchen on the first level and a boiler in a penthouse of a 50-story building, it may be necessary to boost the supply pressure to the kitchen but not to the boiler. Gas rises to the penthouse through the piping system because of the density differential; its rising is dependent on this stack effect, which is directly related to the piping system layout.

Design Considerations

Although a gas booster is a basic piece of mechanical equipment, significant design considerations should be taken into account when considering its use.

- Indoor vs. outdoor location: This may be driven by the local code or the end user. An indoor location involves a lower initial cost and lower costs for long-term maintenance. Outdoor locations are inherently safer.

Table 7-7 Conversion of Gas Pressure to Various Designations

	Equivalent inches		Pressure per square inch		Equivalent inches		Pressure per square inch		
kP	Water	Mercury	Pounds	Ounces	Water	Mercury	Pounds	Ounces	kP
0.002	0.01	0.007	0.0036	0.0577	8.0	0.588	0.289	4.62	2.0
0.05	0.20	0.015	0.0072	0.115	9.0	0.662	0.325	5.20	2.2
0.07	0.30	0.022	0.0108	0.173					
0.10	0.40	0.029	0.0145	0.231	10.0	0.74	0.361	5.77	2.5
					11.0	0.81	0.397	6.34	2.7
0.12	0.50	0.037	0.0181	0.239	12.0	0.88	0.433		3.0
0.15	0.60	0.044	0.0217	0.346	13.0	0.96	0.469	7.50	3.2
0.17	0.70	0.051	0.0253	0.404					
0.19	0.80	0.059	0.0289	0.462	13.6	1.00	0.491	7.86	3.37
0.22	0.90	0.066	0.0325	0.520	13.9	1.02	0.500	8.00	3.4
					14.0	1.06	0.505	8.08	3.5
0.25	1.00	0.074	0.036	0.577					
0.3	1.36	0.100	0.049	0.785	15.0	1.10	0.542	8.7	3.7
0.4	1.74	0.128	0.067	1.00	16.0	1.18	0.578	9.2	4.0
0.5	2.00	0.147	0.072	1.15	17.0	1.25	0.614	9.8	4.2
0.72	2.77	0.203	0.100	1.60	18.0	1.33	0.650	10.4	4.5
0.76	3.00	0.221	0.109	1.73	19.0	1.40	0.686	10.9	4.7
1.0	4.00	0.294	0.144	2.31					
					20.0	1.47	0.722	11.5	5.0
1.2	5.0	0.368	0.181	2.89			0.903	14.4	6.2
1.5	6.0	0.442	0.217	3.46	25.0	1.84	0.975	15.7	6.7
1.7	7.0	0.515	0.253	4.04	27.2	2.00	1.00	16.0	6.9
					27.7	2.03			

- Access: The location should be accessible for installation, inspection, and maintenance, but the unit should not be so accessible as to create a security issue. Keep the equipment out of traffic patterns and protect it from heavy equipment.
- Minimum and maximum flow rates: Boosters typically have a minimum flow rate that must be maintained so the booster's motor remains cool. When specifying a booster, always indicate the minimum flow required in addition to other design parameters. Cooling devices and bypass loops may be required if the application requires a turndown in flow (lowest flow expected) that is higher than the boosters' minimum flow rate.
- Controls and interlocking: Determine how the application should be controlled and what demands the application will put on the system. The control philosophy, method of electrically interlocking the system to the gas-fired equipment, and physical hardware will vary based on the application.

For some specific examples, see the schematics in Figure 7-2, which indicate variations of a basic simplex booster system for an emergency generator. In Figure 7-2(A), the regulator controls the maximum delivered pressure, and a combination high/low pressure switch on the tank cycles the booster to ensure emergency startup pressure for the generator. Oversized piping (in this case) could be substituted for the tank itself. Provide adequate volume so the generator can activate and deliver standby power back to the booster system to continue operation during main power interrupt.

In Figure 7-2(B), a dual booster system, the booster is controlled in a lead/lag control scenario. Should one booster fail, the second is started automatically. Unit operation is rotated automatically via the control panel to share the duty and to keep both units in operating order.

The booster with a heat exchanger loop shown in Figure 7-2(C) has a potential of up to 15 psi (103.4 kPa) and down to 28 inches (711.2 millimeters) of water column supply pressure. The system automatically diverts gas around the booster if sufficient supply pressure is available.

While these illustrations obviously do not cover all the potential applications, they are provided to give the system designer some guidance.

Sizing a Gas Booster

A gas booster's main purpose is to increase the pressure of a volume of gas to overcome a supply pressure deficiency. When sizing a booster, an engineer needs to understand the following terms and issues.

Maximum Design Flow

The maximum design flow (Q_{max}) is the sum of all gas loads at the maximum capacity rating (MCR) for all equipment downstream of the booster that could possibly be required to operate simultaneously.

Minimum Design Flow

The minimum design flow (Q_{min}) is the minimum volumetric flow that could exist while the booster is operating. This flow is not always associated with the smallest Btuh-rated piece of equipment. For example, when evaluating a 75,000,000-Btuh (22-megawatt) boiler with a 10:1 turndown ratio in comparison to a 1-Btuh (0.3-watt) hot water heater that is on/off in operation, the larger Btuh- (watt-) rated boiler has the smaller flow of 0.75 Btuh (0.2 watt) at its minimum firing rate.

Turndown Ratio

The turndown ratio (TD) is the ratio of the MCR input to the equipment's minimum, or low-fire, input. For

example, a 100-Btuh (29.3-watt) burner that can fire at a minimum rate of 20 Btuh (5.9 watts) has a TD ratio of 5:1.

Pressure Droop and Peak Consumption

Pressure droop is the inability of a supply system to maintain a steady or consistent inlet pressure as an increase in volumetric flow is demanded. Often, in areas where boosters are applied, the supply pressure in off-peak months when gas is not in such demand can be sufficient to run a system. As the local demand for gas increases, the supply system no longer can provide the gas efficiently, and the pressure falls off, or droops. It is the booster's function to overcome the droop (or excessive pressure drop) of the supply system during such times.

Flow Rate Relationships

It is important that the flows for the separate pieces of equipment relate to each other. In other words, do the three boilers always operate in unison while another process machine always operates off peak and alone? Relationships among the equipment can significantly affect both maximum and minimum flow rates.

Test Block

The test block is a factor of safety added to the design criteria. Typically, a minimum 5 percent added volume and 10 percent added static pressure should be applied to the design criteria. When specifying the equipment, ensure that you note both the design and test block conditions. This ensures that safety factors are not applied to criteria that already include safety factors.

Minimum and Maximum Inlet Pressure

The minimum inlet pressure ($P_{I\text{-}min}$) is the minimum supply pressure in inches (millimeters) of water column gauge. This must be evaluated during peak flow demands for both the equipment and the local area. Always evaluate during flow, not static, conditions. It is also important to know how high the inlet pressure is expected to rise during off-peak periods. A booster is typically rated to about 5 psi (34.5 kPa). It may be possible to exceed this rating during off-peak demand periods; therefore, a bypass system or other means of protection is required. Often this pressure can be specified by the local gas company as the minimum guaranteed gas pressure from their supply system. Also, the maximum inlet pressure ($P_{I\text{-}max}$) must be determined.

Maximum Outlet Pressure

The maximum outlet pressure ($P_{O\text{-}max}$) includes all maximum and required supply pressures for the various pieces of equipment being supplied with gas from the booster. Determine the differential between the highest expected gas pressure supply to the booster (e.g., 8 inches [203.2 millimeters] of water column) and the lowest maximum supply pressure rating to a piece of equipment (e.g., 18 inches [457.2 millimeters] of water column). The booster's pressure gain should not exceed this differential (for the above example, 18 – 8 = 10 inches [457.2 – 203.2 = 254 millimeters] of water column) unless other means of protecting the downstream equipment are provided.

Outlet Pressure Protection

Several methods to protect equipment downstream of a booster are available if over-pressurization during off-peak periods occurs. If all the equipment being serviced operates at nominally the same pressure, install a regulator on the inlet or outlet of the booster to maintain a controlled maximum outlet pressure. If the equipment being serviced operates at various inlet pressures, it may be best to supply a regulator for each piece of equipment. Most often, packaged equipment is supplied with its own regulator. If this is the case, review the equipment regulator's maximum inlet pressure.

To perform an evaluation of system requirements, the following procedure is suggested:

1. Establish the design Q_{min} and Q_{max} per the previously discussed definitions while evaluating TD requirements.
2. Establish $P_{I\text{-}min}$ and $P_{I\text{-}max}$ per the previously discussed definitions.
3. Define the maximum inlet pressure requirements to the equipment ($P_{I\text{-}eq}$).
4. Define piping pressure losses (P_{PL} in psi [kPa]) from the gas booster location to each piece of equipment.
5. Determine the design flow rate (Q_D): Q_{min} to Q_{max} in cfh (cubic meters per hour).
6. Determine the design pressure boost (DP): $P_{I\text{-}eq} + P_{PL} - P_{I\text{-}min}$.
7. Calculate the test block flow (Q_{TB}): $(1.05 \times Q_{min})$ to $(1.05 \times Q_{max})$.
8. Test the block pressure boost: $1.10 \times DP = P_{I\text{-}eq} + P_{PL} - P_{I\text{-}min}$.

INTERIOR NATURAL GAS PIPE SIZING

Data to Be Obtained

To accurately size all elements of the piping system, calculate or obtain the following information:

1. Information needed by both the utility company and the engineer
2. Gas pressure available after the meter assembly
3. Allowable friction loss through the piping system
4. Pressure required at the equipment and or appliance

5. A piping layout that indicates all connected equipment, allowing determination of the measured length of piping to the furthest connection
6. The maximum demand
7. A pipe sizing method acceptable to the AHJ or local code

Information Needed by the Utility Company and the Engineer

The following are intended to be complete lists of items. Not all items will be necessary for all projects.

The following criteria and information shall be obtained in writing from the public utility company and provided to the engineer:

- Actual Btu content of the gas provided
- Minimum pressure of the gas at the outlet of the meter
- Extent of the installation work done by the utility company and the point of connection to the meter by the facility construction contractor
- The location of the utility supply main and the proposed run of pipe on the site by the utility company, in the form of a marked-up plan or description of the work, including the expected date of installation if no gas is available
- Acceptable location of the meter and/or regulator assembly or a request to locate the meter at a particular location
- Any work required by the owner/contractor to allow the meter assembly to be installed (such as a meter pit or slab on grade)
- Types of gas service available and the cost of each

For the utility company to provide this data, the following information must be provided to them:

- Total connected load. The utility will use its own diversity factor to calculate the size of the service line. For the design of the project's interior piping, the design engineer will select the diversity factor involved (as allowable by the governing code and/or local jurisdiction).
- Minimum pressure requirements for the most demanding equipment
- A site plan indicating the location of the proposed building orientation on the site and the specific area of the building where the proposed natural gas service will enter the building
- Preferred location of the meter/regulator assembly
- Expected date for the start of construction
- All specific requirements for pressure
- Two site plans, one to be marked up and returned to the engineer
- The hours of operation for the different types of equipment
- A list of all future or anticipated equipment and capacities

Pressure Available After the Meter

This shall be established in writing from the utility at the start of the project. All gas–fired equipment and devices proposed for use on the project are to be submitted, and the pressure requirements and flow rates for each piece of equipment must be provided to the utility.

Allowable Friction Loss Through the Piping

This shall be established by the engineer and shall be determined by the following criteria:

- Pressure provide by the utility company (from 5 inches (125 millimeters) of water column to 5 psi (34.5 kPa)
- Required pressure at the equipment and or appliance (typically a minimum 3.5 inches (89 millimeters) of water column for residential appliances and as much as 11 inches (280 millimeters) of water column for some rooftop equipment)
- Allowable pressure drop either by code or the AHJ

After receiving the necessary criteria, the engineer can determine the allowable pressure drop for a particular system. This conceivably could be from 0.3 inch (7.6 millimeters) of water column to 6 inches (152.4 millimeters) of water column (for a low-pressure system) and from 1 psi (7 kPa) to 3.5 psi (24.1 kPa) for medium- to high-pressure systems)

Piping Layout

The equivalent length of piping is necessary to indicate the layout of the entire piping system and all connected appliances and equipment. The equivalent length of piping is calculated by measuring the actual length of the proposed piping from the meter to the furthest connection and then adding 50 percent (for fittings) of the measured length to obtain the total equivalent length. If a very accurate determination of the equivalent length is required, you must tabulate the fittings and valves and add those to the measured length. Refer to Table 7-4 for the equivalent amount of pipe length to be added for various valves and fittings.

It is common practice to omit the vertical length because natural gas is lighter than air. It expands at the rate of 1 inch (25.4 millimeters) of water column for each 15 feet (4.6 meters) of elevation as the gas rises. The increase in pressure due to the height will offset any friction loss in the piping. For example, if a high-rise building contained 100 feet of equivalent

horizontal pipe length and 200 feet of equivalent vertical pipe length, only the horizontal portion of piping (100 feet) would be considered for establishing the total equivalent length of pipe for design purposes, even though the actual equivalent pipe length in this example is 300 feet.

Maximum Demand

The maximum demand is calculated by the engineer with input from the owner if necessary. For residential use, Figure 7-3 (large multiple-unit residential projects) and Figure 7-4 (small multiple-unit residential projects) give a direct reading of the usage in cfh (cubic meters per hour). These direct reading tables give flow rate use by using the number of apartments. For schools, use no diversity factor for individual classrooms. Use no diversity factor for groups of classrooms if information on the proposed use is not conclusive or available from the owner. For industrial use, a diversity factor generally is not used due to the possibility of simultaneous use by all connected equipment.

For a listing of input requirements for common appliances, refer to Table 7-3.

Natural Gas Pipe Sizing Methods

A number of formulae can be used to calculate the capacity of natural gas piping based on such variables as delivery pressure, pressure drop through the piping system, pipe size, pipe material, and length of piping. These formulae are referenced in numerous model codes as well as NFPA 54.

The most commonly referenced formula for gas pressures below 1½ psi (10.3 kPa) is the Spitzglass formula. Another commonly referenced equation for pressures of 1½ psi (10.3 kPa) and above is the Weymouth formula. Using these formulae for sizing can be very tedious and time consuming, so they are rarely used. However, they were used as a basis for the sizing tables that are included in the model codes and NFPA standards. These tables are regarded as the most conservative method for sizing natural gas piping systems and should be referenced specifically for each project as dictated by the governing code.

The *Plumbing Engineering and Design Handbook of Tables,* published by the American Society of Plumbing Engineers, contains pipe sizing tables for many systems, including natural gas and liquified petroleum gas (propane) systems. These tables contain sizing information for most of the commonly used piping materials including pipe sizes at various pressures and cfh requirements.

In addition, proprietary tables and calculators are available from various organizations, and popular spreadsheet programs currently available on the market also can be used.

The methods used for sizing natural gas piping systems are as follows.

Longest Length Method

This is the traditional method used to determine the longest equivalent piping length (from the meter or delivery point to the farthest outlet), which then is used in conjunction with the pipe sizing tables to determine the appropriate pipe diameter for all other sections of piping in the system. In simple terms, only the cfh quantities listed in the tables for this pipe length are used to size each and every branch and section of pipe. This method is the simplest to use, and it generally yields the most conservative sizing because the short runs of piping located close to the meter can be somewhat oversized. One advantage to using this method is that it can provide some cushion in the branch piping, allowing for future reconfiguration of the piping system without replacing entire branch lengths.

Branch Length Method

This is an alternate sizing method that could permit slightly smaller pipe diameters in some segments of a piping system when compared with the longest length method. The pipe size of each section of the longest pipe length (from the meter or delivery point to the farthest outlet) shall be determined using the longest equivalent length of piping and the associated cfh quantity listed in the tables for that section. Then, the pipe sizes of each section of branch piping not previously sized shall be determined using the equivalent lengths of piping from the point of delivery to the most remote outlet of each individual branch and the associated cfh quantity listed for that particular section.

Hybrid Pressure Method

This method is used when it is necessary to design a piping system that utilizes multiple supply pressures within a single distribution system. The pipe size for each section of high-pressure gas piping shall be determined using the longest equivalent length of piping from the meter or delivery point to the farthest pressure regulator. The pipe size from the pressure regulator to each outlet shall be determined using the length of piping from the regulator to the most remote outlet served by that regulator. With this method, medium-pressure gas tables (up to 5 psig) are used to size the piping upstream of the pressure regulators, and low-pressure gas tables (7 to 11 inches of water column) are used to size the piping downstream of each pressure regulator.

Sizing Tables

Table 7-5 is based on Schedule 40 steel pipe, cubic feet per hour of gas, and a specific gravity of 0.60. The friction loss allowable is indicated. The table

has been provided as a supplement to the pipe sizing methods indicated, using the longest length method of pipe sizing.

To determine the size of each section of pipe in a gas supply system using the gas pipe sizing table, the following steps should be used:

1. Measure the length of the pipe from the gas meter location to the most remote outlet on the system. Add a fitting allowance of 50 percent of the measured length. This represents the total equivalent length of pipe. (For natural gas, the vertical portion of piping is not considered due to the pressure gained as gas rises. This very closely approximates the friction loss in the piping.)
2. Select the row showing the distance that is equal to or greater than the equivalent length calculated. (In Table 7-6, the entire 600-foot row has been highlighted as an example.) Once chosen, it is the only row to use throughout the sizing process for all individual branches and cumulative sections of pipe.
3. Use the columns in conjunction with the row previously selected to locate all gas demand figures for this particular system. Starting at the most remote outlet, find in the table the calculated gas demand for that design point. If the exact figure is not shown, choose the figure closest to or greater than the calculated demand and select the associated pipe size.
4. With the demand figure (and corresponding length) selected, find the associated pipe size.
5. Proceed for each design point and each branch of pipe. For each section of pipe, determine the cumulative gas demand supplied by that section.

If the gas used for the system has a different specific gravity than natural gas, obtain that figure from Table 7-6 and use this as a multiplier for the specific gas selected.

To convert gas pressure to various designations, refer to Table 7-7.

LIQUEFIED PETROLEUM GAS

Liquefied petroleum gas (propane) is a refined natural gas developed mainly for use beyond the utility's gas mains, but it has proven to be competitive in areas not covered by mains in rural areas. It is primarily a blend of propane and butane, with traces of other hydrocarbons remaining from the production method. The exact blend is controlled by the liquefied petroleum gas distributor to match the climatic conditions of the area served. For this reason, you must confirm the heating value of the supplied gas. Unlike natural gas, 100 percent propane has a specific gravity of 1.53 and a nominal rating of 2,500 Btu per cubic foot (93 megajoules per cubic meter).

Easy storage for relatively large quantities of energy has led to widespread acceptance and use of liquefied petroleum gas in all areas previously served by utilities providing natural gas to users, including for automotive purposes. In addition, a principal use is for heating in industrial projects. It is not a substitute for natural gas, but it provides an alternative energy source when owners want to use a low, interruptible rate for heating purposes. When used for this purpose, experience has shown that the mixing with air should produce a gas with the heating value of 1,500 Btu per cubic foot (a specific gravity of 1.30) for ease of burning and ignition. Use Table 7-6 for the factor to be used for sizing.

Environmental Effects of Propane

From an environmental standpoint, propane is nontoxic and non-caustic and will not create an environmental hazard if released as a liquid or vapor into water or soil. If spilled in large quantities, the only environmental damage that may occur is the freezing of any organism or plant life in the immediate area. There are no long-term effects following a propane spill, even in large quantities. Potential damage and danger occur only if the vapor is ignited following a spill. Even then, there are no long-term effects of ignited propane that can be damaging to the environment. Propane liquid and vapor are both environmentally sound and friendly in their unused states (prior to combustion) if released.

Following are some environmental facts about propane:

- Propane is not considered a greenhouse gas.
- Propane is not damaging to freshwater or saltwater ecosystems or underwater plant or marine life.
- Propane is not harmful to soil if spilled on the ground. It will not cause harm to drinking water supplies.
- Propane vapor will not cause air pollution, and it is not considered air pollution.
- Propane vapor is not harmful if accidentally inhaled by animals or people.
- Propane will cause bodily harm only if the liquid comes in contact with skin (boiling point -44°F).

Propane is listed as an approved clean fuel by U.S. energy policymakers and energy administrative bodies. Propane engine exhaust is clean and continues to power forklifts operated inside warehouses throughout the world.

Propane Storage Tanks

Propane storage tanks typically are provided by the vendor for the customer and are subject to the regula-

tions of the U.S. Department of Transportation (DOT) and the local authority, as well as NFPA standards. Tank manufacturers are required to adhere to ASME (American Society of Mechanical Engineers) regulations for construction of propane pressure vessels intended for use within the United States. ASME is the governing authority for all stationary propane tanks manufactured and used in the United States.

Propane tanks are considered either portable or stationary. Portable tanks, known as bottles or cylinders, are used as a fuel source for items such as gas grills and forklifts. Stationary propane tanks are located on facility sites and commercial businesses supplying multiple propane-powered appliances within the structures. Propane tanks, regardless of their size, store liquefied petroleum gas in liquid form until it is used as either a liquid or vapor. Propane tanks can be filled to only approximately 80 percent of total tank capacity and are for storing propane only.

Basic Propane Tank Function

The withdrawal of propane vapor from a tank lowers the contained pressure within the tank itself. This causes the liquid to boil, or vaporize, in an effort to restore pressure by generating vapor to replace the quantity that was removed. The required latent heat of vaporization is given up by the liquid and causes the liquid temperature to drop as a result of the expended heat.

The heat lost due to the vaporization of the liquid is replaced by the heat in the air surrounding the tank. This heat is transferred from the air, through the metal surface of the tank, into the liquid. (The area of the tank in contact with the vapor is not considered because the heat absorbed by the vapor is negligible.) The surface area of the tank that is immersed in the liquid is referred to as the wetted surface. The greater this wetted surface (or amount of liquid in the tank), the greater the vaporization capacity of the tank. Consequently, tanks that have large wetted surface areas have greater vaporization capacities. If the liquid in the tank receives heat for vaporization from the outside air, the higher the outside air temperature, the higher the vaporization rate of the tank. The worst conditions for vaporization rate occur when the tank contains a small amount of liquid, and the outside air temperature is low.

Propane Tank Requirements

Listed below are tank-related safety and compliance items:

- Manufacturer's nameplate: Containers without nameplates are not permitted to be filled. The nameplates are for identification and information concerning ASME propane tanks.
- Tank color: All propane tanks are required to be painted a reflective color. It is not uncommon for facility owners to want to paint their propane tanks a color that aesthetically blends with their facility. However, this can present a safety problem (as well as a serviceability problem) if the desired tank color is dark or non-reflective. Dark colors absorb heat, while lighter colors reflect it. Therefore, propane tanks need to be painted with colors that reflect heat. Also, rust is color and will contribute to the absorption of heat. Tanks that are rusted often need to be sanded or scraped with a wire brush before they can be repainted.

Propane Tank Regulators

Propane tank pressures can range from less than 10 psig to more than 200 psig. The purpose of the regulator is to reduce the propane gas down to safe and usable system pressures.

A propane regulator must be covered and protected or pointed vertically down. Regulators generally are found under the tank dome (located on top of the storage tank). If located outside the tank dome, the regulator vent must be pointed down to prevent rain, ice, and debris from entering the regulator. In addition, the vent should have a screen that keeps insects out of the regulator.

Types of regulators include the following:

- High-pressure regulators are propane liquid or vapor service regulators designed to reduce the pressure from the tank to a lower pressure in excess of 1 psig. These regulators often are used in combination with a second-stage regulator in a two-stage regulator system. However, they also can be used independently in systems where appliance or gas equipment demands are high and the only way to satisfy demand requirements is with a high-pressure regulator.
- First-stage regulators sometimes are referred to as high-pressure regulators, but they do not reduce variable tank pressures to appliance-level pressure. They simply lower the tank pressure before it enters the gas service line. The purpose of a first-stage regulator is to deliver propane at an adequate pressure to a downstream second-stage regulator. A first-stage regulator in a two-stage regulator system is installed at the propane tank and is connected directly to the service valve with a pigtail. If a first-stage regulator is used in a propane piping system, a second-stage regulator must be installed downstream (usually at the building entrance). A first-stage regulator cannot be installed independently in a propane piping system (reference NFPA 58: *Liquefied Petroleum Gas Code*). A second-

stage regulator also must be installed where the piping system enters the facility. The first-stage regulator will compensate for fluctuating tank pressures and will deliver into the propane gas line at a pressure of 10 psig or less. First- and second-stage regulators must be properly matched to ensure that the entire gas system is safe and functional.

- Second-stage regulators work with propane at a pressure supplied by the first-stage regulator (10 psig) and further decrease it to a pressure that can be used by the appliances (typically 11 inches of water column). Second-stage regulators are not used to decrease tank pressure and always must be installed downstream of a first-stage regulator for safe and proper operation. A regulator located at the propane entrance into a facility is always a second-stage regulator. Second-stage regulators are designed only to operate in combination with first-stage regulators. One cannot be used without the other.
- Integral two-stage regulators are a combination of both first- and second-stage regulators assembled into one unit. Integral two-stage regulators are always installed at the tank and compensate for varying tank pressures on the inlet side, while delivering steady service-line pressure and compensating for varying appliance demand on the outlet side. Integral twin-stage regulators are used in propane vapor service only and are the most common type of regulators used in residential propane gas installations. These are used primarily when the gas service line to the facility or appliance is a relatively short distance and Btuh load requirements are not extremely high.
- Adjustable high-pressure regulators: Propane gas flow pressure adjustment in high-pressure propane systems is made possible by direct-operated regulators, another name for adjustable high-pressure regulators. The primary purpose of an adjustable regulator is to ensure that the required pressure is delivered to the appliance when the liquid level of the tank is such that vaporization is not fast enough to meet the gas demands of the appliance. Simply stated, an adjustable regulator compensates for the lack of vaporization by allowing more pressure through the outlet and into the downstream gas line. Adjustable high-pressure regulators are commonly seen attached to bottles and tanks supplying roofing tar kettles, asphalt mixers, and propane-powered torches. Direct-operated regulators are not designed to act as a service valve, but rather to allow for the manual intervention in the regulation of delivery pressures as needed by the appliance.

Similar to natural gas systems, the reasoning behind having two separate regulators in a propane system is strictly for economy of the piping installation as previously explained in the natural gas section of this chapter.

Propane Tank Parts

All of the parts listed below are attached to the tank by the manufacturer with threaded fittings. These specialized propane tank parts consist of the following replaceable fittings and connections:

- Fill valve: The point at which a hose from a delivery truck is attached to the tank for refueling
- Relief valve: A safety relief assembly designed to vent propane in an over-pressure situation
- Service valve: The point at which propane is converted to vapor for use with appliance(s). The propane service valve is the controlling mechanism allowing propane gas to flow into the facility by way of the gas piping system. Although other gas valves may be present throughout the gas piping system, the service valve on the propane tank is the valve that controls 100 percent of the gas flow into the piping system. Propane service valves are for vapor service only.
- Fixed liquid level gauge: A gauge indicating that the level of propane is at or above 80 percent capacity
- Float gauge: A gauge that presents a visible indication of the propane volume in the tank (also referred to as a dial gauge)
- Vapor return valve: A connection used during propane delivery to remove excess tank pressure. When propane companies fill tanks in hot weather, they often will connect the vapor hose to the vapor return valve. This allows vapor to be safely recovered and contained in the delivery truck.
- Liquid withdrawal valve: A valve used to withdraw liquid propane from the tank.

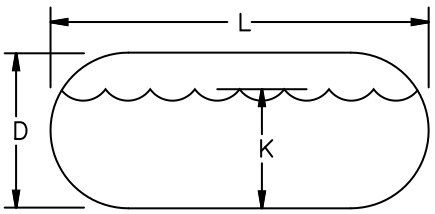
Storage Tank Location

Small tanks (those for residential cooking and heating) are allowed to be located in close proximity to buildings. However, large tanks (for industrial or multiple building uses) have strict requirements governing their location in relation to buildings, public-use areas, and property lines. If large leaks occur, the heavier-than-air gas will accumulate close to ground level and form a fog, creating the potential for a hazardous condition.

Proper safety precautions and equipment, as well as good judgment, must be utilized when locating large liquefied petroleum gas storage tanks. The lines also have to be purged of air prior to the startup of the facility. Guideline for proper clearances and placement of large, stationary propane tanks are listed in NFPA 58.

Propane Vaporization Requirements

Vaporization is the process of a liquid being converted into a gas (or vapor). Vaporization is related directly to the actual size of the propane tank as previously explained. For a propane appliance to work, vaporization must occur, and the amount of vaporization must be sufficient to deliver the required amount of propane.



Where:
D=Outside diameter (inches)
L=Overall length, (inches)
K=Constant for percent volume of propane liquid in tank

Percentage of Container Filled (%)	K Equals	*Propane Vaporization Capacity at 0° F (BTU/H)
60-18	100	DxLx100
50	90	DxLx90
40	80	DxLx80
30	70	DxLx70
20	60	DxLx60
10	45	DxLx45

*This formula allows for the temperature of the propane liquid to refrigerate to -20°F (below zero), producing a temperature differential of 20°F for the transfer of heat from the surrounding air, to the tank's "wetted" surface, and then into the propane liquid. (The vapor space area of the tank is not considered, as its effect is negligible).

Vaporization Capcities for Other Air Temperatures			
Prevailing Air Temperature	Multiplier	Prevailing Air Temperature	Multiplier
-15°F	0.25	+5°F	1.25
-10°F	0.50	+10°F	1.50
-5°F	0.75	+15°F	1.75
0°F	1.00	+20°F	2.00

Figure 7-5 Determining the Vaporization Capacity of a Propane Tank

Commercial and industrial propane applications using high-demand propane gas equipment need propane vaporizers to satisfy Btuh demand requirements. Vaporizers are used when equipment or appliance demands exceed the vaporizing capacity of the tank. Simply stated, vaporizers are used to supply the required amount of propane gas when the tank can't keep up with the downstream demand on its own and placing a much larger tank or multiple tanks with higher vaporization capacity would be impractical. Propane gas vaporizers work with liquid propane at a location separate from the tank, with liquid propane being piped to the vaporizing equipment for gas vaporization.

Types of propane vaporizers are as follows.

Direct-fired Vaporizers

Direct-fired propane vaporizers contain a flame that directly heats the liquid propane, which converts it to gas for use in downstream, high vapor demand equipment. Liquid propane is piped from the tank to the vaporizer where it then is heated and, in turn, the propane gas vaporization is accelerated. What makes a direct-fired vaporizer unique is that the gas used as the heat source is supplied by the same tank(s) supplying the liquid to be vaporized.

Note: Some jurisdictions may have regulations that prevent the installation of a direct-fired vaporizer due to location constrains and/or concerns about surrounding activities or structures. You must verify such restrictions prior to the start of system design.

Indirect-fired Propane Vaporizers

Indirect-fired propane vaporizers use heat from a supplemental source to heat liquid propane for its accelerated vaporization. Unlike direct-fired vaporizers, this type of vaporization equipment heats the liquid propane with an external source of heat, not with the propane gas from the same propane tank. However, if the liquid were heated with a flame generated from another propane tank, the equipment would still technically be an indirect-fired vaporizer. It is not the type of fuel being used that defines whether or not a vaporizer is direct or indirect—it is the fuel source that defines a vaporizer's classification.

Design Considerations

Liquefied petroleum gas systems should be located in such a manner that the hazard of escaping gas is kept to a minimum.

Since the heavier-than-air gas tends to settle in low places, the vent termination of relief valves must be located at a safe distance from openings into buildings that are below the level of such valves. With many gas systems, both the gas pressure regulator and fuel containers are installed adjacent to the buildings they serve. This distance should be at least 3 feet (0.91

meter) measured horizontally. However, the required clearances vary according to the tank size and adjacent activities. Refer to local code requirements and NFPA 54 for these clearances.

When liquefied petroleum gas piping is proposed for installation within crawl spaces or utility pipe tunnels, you may consider secondary containment for the supply piping, whereby the gas pipe is installed within a larger pipe that is sealed and vented at both ends. A sniffer system also could be considered, which automatically shuts down the gas supply, sounds an alarm, and activates an exhaust system to purge the escaping gas from the area upon detection of gas in the space due to a breach in the piping system.

Liquefied Petroleum Gas Sizing

Propane gas piping systems shall be sized in accordance with the tables that have been developed by the model codes and NFPA 54 and 58. Tables based on an outlet pressure of 11 inches (280 millimeters) of water column would be suitable for interior piping. Tables based on higher outlet pressures are more suitable for site mains and distribution piping from the tank to the building entry point. Obtain or request the pressure provided by the supplier and determine the pressure drop in the piping system that would be appropriate. The AHJ shall be consulted regarding the acceptance of the pressure(s) selected.

1. For stationary propane tanks, sizing is accomplished via the following steps:
2. The total Btuh demand must be determined. The total Btuh demand is the sum of all propane gas usage in the system, determined by adding all of the Btu input ratings of the connected appliances. Future appliances also must be considered during this process and added to the system demand.
3. Once the Btuh input quantities for all appliances are obtained, determine the Btu quantity used per day for each appliance. Then add up the total. The result will represent the Btu per day total for the system.
4. Using the total Btu per day established in Step 2, divide by approximately 91,502 (Btu per gallon of gas at 60°F) to obtain the gallons per day of propane required.
5. The gallons per day quantity then is used to establish the tank sizes in relation to tank filling schedules. Typically, 14 days between tank fillings is acceptable; however, you will need to evaluate this figure based on the individual project requirements.
6. Finally, once the tank sizes have been established, use the information contained in Figure 7-5 to determine (and verify) the vaporization capacity for the tank sizes proposed for use. If the tanks proposed for use cannot provide sufficient vaporization, more tanks will need to be added or a vaporizer will need to be incorporated to accommodate the appliance demands. (Note: This step can be performed first and, in conjunction with the Btuh demand, can be used to establish an estimation of the required tank size.)

For sizing propane piping distribution systems, the process is similar to natural gas as previously explained in the natural gas section of this chapter. Unlike natural gas systems, however, propane is heavier than air. Therefore, vertical sections of piping must be considered in the calculation of equivalent pipe lengths for determining allowable pressure drops.

GLOSSARY

Boiling point The temperature of a liquid at which the internal vapor pressure is equal to the external pressure exerted on the surface of the liquid.

Btu Abbreviation for British thermal units, the quantity of heat required to raise the temperature of 1 pound of water by one degree Fahrenheit.

Burner A device used for the final conveyance of gas, or a mixture of gas and air, to the combustion zone.

Butane (C_4H_{10}) A saturated aliphatic hydrocarbon existing in two isomeric forms and used as a fuel and a chemical intermediate.

Caloric value See heating value.

Chimney A vertical shaft enclosing one or more flues for conveying flue gases to the outside atmosphere.

Condensate The liquid that separates from a gas (including flue gas) due to a reduction in temperature.

Cubic foot (meter) of gas The amount of gas that would occupy 1 cubic foot (cubic meter) at a temperature of 60°F (15.6°C), saturated with water vapor, and under a pressure equivalent to that of 30 inches of mercury (101.3 kPa).

Demand The maximum amount of gas per unit time, usually expressed in cubic feet per hour (liters per minute) or Btu (watts) per hour, required for the operation of the appliance(s) supplied.

Dilution air Air that enters a draft hood or draft regulator and mixes with the flue gases.

Diversity factor The ratio of the maximum probable demand to the maximum possible demand.

Draft hood A device built into an appliance, or made a part of the vent connector from an appliance, that is designed to provide for the ready escape of the flue gases from the appliance in the event of no draft, back draft, or stoppage beyond the draft hood; prevent a back draft from entering the appliance; and neutralize

the effect of stack action of the chimney or gas vent upon the operation of the appliance.

Excess air Air passes through the combustion chamber and the appliance flues in excess of that which is theoretically required for complete combustion.

Flue gases The products of combustion plus the excess air in appliance flues or heat exchangers (before the draft hood or draft regulator).

Fuel gas A gaseous compound used as fuel to generate heat. It may be known variously as utility gas, natural gas, liquefied petroleum gas, propane, butane, methane, or a combination of the above. It has a caloric value that corresponds to the specific compound or combination of compounds. Care must be exercised in determining the caloric value for design purposes.

Gas log An unvented, open-flame room heater consisting of a metal frame or base supporting simulated logs designed for installation in a fireplace.

Gas train A series of devices pertaining to a fuel gas appliance located on the upstream side of the unit. Typically, it consists of a combination of devices and may include pipe, fittings, fuel, air-supervisory switches (pressure regulators), and safety shutoff valves.

Gas-train vent A piped vent to atmosphere from a device on a gas train.

Gas vent Factory-built vent piping and vent fittings listed by a nationally recognized testing agency, assembled and used in accordance with the terms of their listings, used for conveying flue gases to the outside atmosphere.

Type B gas vent A gas vent for venting gas appliances with draft hoods and other gas appliances listed for use with type B gas vents.

Type B-W gas vent A gas vent for venting listed gas-fired vented wall furnaces.

Type L gas vent A gas vent for venting gas appliances listed for use with type L vents.

Heating value (total) The number of British thermal units produced by the combustion, at constant pressure, of 1 cubic foot (cubic meter) of gas when the products of combustion are cooled to the initial temperature of the gas and air, the water vapor formed during combustion is condensed, and all the necessary corrections have been applied.

LPG Liquefied petroleum gas, a mixture of propane and butane.

Loads connected The sum of the rated Btu input to individual gas utilization equipment connected to a piping system. It may be expressed in cubic feet (cubic meters) per hour.

Meter set assembly The piping and fittings installed by the gas supplier to connect the inlet side of the meter to the gas servi ce and the outlet side of the meter to the customer's building or yard piping.

Pipe, equivalent length The resistance of valves, controls, and fittin gs to gas flow, expressed as equivalent length of straight pipe. In some cases, it is referred to as the developed pipe length.

Pressure drop The loss in static pressure due to friction or obstruction during flow through pipe, valves, fittings, regulators, and burners.

Propane (C_3H_8) A gaseous hydrocarbon of the methane series, found in petroleum.

Regulator, gas pressure A device for controlling and maintaining a uniform gas pressure. This pressure is always lower than the supply pressure at the inlet of the regulator.

Safety shutoff device A device that is designed to shut off the gas supply to the controlled burner or appliance if the source of ignition fails. This device may interrupt the flow of gas to the main burner only or to the pilot and main burner under its supervision.

Specific gravity The ratio of the weight of a given volume of gas to that of the same volume of air, both measured under the same conditions.

Vent connector The portion of a venting system that connects the gas appliance to the gas vent, chimney, or single-wall metal pipe.

Vent gases The products of combustion from a gas appliance plus the excess air and the dilution air in the venting system above the draft hood or draft regulator.

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8 Private On-site Wastewater Treatment Systems

Private on-site wastewater treatment systems (POWTS) provide an alternative to public sewers. The primary emphasis of this chapter is on residential, anaerobic treatment (septic) tanks; effluent and gravity-soil absorption systems; soil evaluation; anaerobic treatment tank selection; and the design of the dispersal cell.

Most areas of the country have local regulations that must be followed regarding the design of sewage treatment and dispersal systems. Most areas have extension offices that may provide valuable information, including soil surveys and soil maps. The examples given in this chapter are only general guidelines and illustrations of the criteria and methods and are not to be used for actual project design purposes.

The wastewater discharge to POWTS must be controlled. These systems are not designed to handle solids, such as disposable diapers, feminine products, food disposal wastes, or excessive oils, fats, and greases.

PRIMARY TREATMENT

The two types of primary treatment generally used in residential on-site treatment are aerobic and anaerobic. The purpose of both is to collect sewage effluent, decompose organic matter, and separate other solids from the effluent stream. The effluent from either process is a liquid, and variations in the effluent quality directly affect the design of the soil absorption component.

SOIL ABSORPTION SYSTEMS

The soil absorption system receives the effluent from the primary treatment tank by means of gravity or via a pump system.

In-ground soil absorption component operation is a two-stage process involving both wastewater treatment and dispersal. Treatment is accomplished predominately by physical and biochemical processes within the treatment/dispersal zone. The physical characteristics of the influent wastewater, influent application rate, temperature, and the nature of the receiving soil affect these processes.

Physical entrapment, increased retention time, and conversion of pollutants in the wastewater are important treatment objectives accomplished under unsaturated soil conditions. Pathogens contained in the wastewater eventually are deactivated through filtering, retention, and adsorption by in-situ soil.

Dispersal primarily is affected by the depth of the unsaturated receiving soil, the soil's hydraulic conductivity, influent application rate, land slope, and the area available for dispersal.

The in-ground soil absorption component consists of a distribution cell. Influent is discharged to the distribution cell, where it flows through the void area formed by stone aggregate and perforated pipe or leaching chambers and then passes into the underlying in-situ soil for treatment and dispersal to the environment. The soil beneath the distribution cell, to the prescribed depth and known as the treatment/dispersal zone, is considered part of the cell.

Cover material over the geotextile fabric or leaching chamber provides frost protection and a barrier to excess precipitation or runoff infiltration, prevents erosion protection, and allows oxygen transfer. The in-situ soil within the treatment/dispersal zone provides the physical and biochemical treatment for the influent.

The successful operation of a soil absorption system requires a comprehensive site evaluation, good design criteria, and careful installation. Every in-ground soil absorption component design ultimately is matched to the given soil and site.

When evaluating a site, you must consider the lot size, soil characteristics, slope, topography, surface water, and the seasonal high-water table. Residential lots must be large enough to accommodate the projected area of the dispersal cell and primary treatment device while maintaining minimum setbacks from surface waters, wells, and property lines as mandated by local codes. In the absence of code specifications, Table 8-1 may be used as a guide when using the morphological

evaluation of the soil, while Table 8-2 may be used for the percolation test.

Estimating Soil Absorption Rates

Soil Maps

The capacity of a soil to absorb and transmit water is an important consideration in agriculture, particularly in relation to irrigation, drainage, and other land management practices. Through careful studies in these fields, a variety of aids have been developed for determining the absorption and water-transmission properties of soil that could be helpful in the sewage field. Considerable information on the relative absorption capacities of specific soils in many areas has been accumulated. Much of this information is included in soil survey reports and maps published by the U.S. Department of Agriculture. However, although the soil maps may be used for initial discussion, the suitability of a soil for effluent treatment and dispersal should not be assigned based on these maps.

Clues to Infiltrative Capacity

Information about the relative absorption capacities of soils also may be obtained by a close visual inspection of the soil. This is known as a soil profile description. The value of such an inspection depends on the interpreter's knowledge of the pertinent soil properties. The main properties indicative of infiltrative capacity are soil texture, structure, color, depth, consistence, boundary characteristics, and redoximorphic features.

- Texture: Soil texture generally is defined as the relative proportion of sand, silt, and clay in the soil. It is the first clue to the soil's infiltrative capacity. Generally large soil particles create large pores and a faster infiltration rate.
- Soil texture can best be judged by feeling. Lighter or sandier soils have a gritty feel when rubbed between the thumb and forefinger. Silty soils have a floury feel and, when wet, have no cohesion. Heavier, clay-type soils are dense and hard when dry and have a slick, greasy feel when wet.
- The use of soil texture in determining infiltrative capacity has its limitations. It is usually reliable

Table 8-1 Maximum Soil Application Rates Based on Morphological Soil Evaluation (in gals./sq.ft./day)

Soil Characteristics			Maximum Monthly Average			
Texture	Structure		BOD_5 30-≤220mg/L TSS>30≤150mg/L		BOD_5≤30mg/L TSS≤30mg/L[c]	
COS, S, LCOS, LS	—	0	0.7[a]	0.5 [b,c]	1.6[a]	0.5[b]
FS, LFS	—	0	0.5		1.0	
VFS, LVFS	—	0	0.4		0.6	
	—	OM	0.2		0.6	
		1	0.4		0.6	
	PL	2,3	0.0		0.2	
		1	0.4		0.7	
COSL, SL	PR, BK, GR	2,3	0.6		1.0	
	—	OM	0.2		0.5	
	PL	2,3	0.0		0.2	
	PL, PR, BK, GR	1	0.2		0.6	
FSL, VFSL	PR, BK, GR	2,3	0.6		0.8	
	—	OM	0.0		0.2	
	PL	1	0.4		0.6	
	PL,PR,BK,GR	1	0.4		0.6	
L	PR, BK, GR	2,3	0.6		0.8	
	—	OM	0.0		0.2	
	PL	2,3	0.0		0.2	
	PL,PR,BK,GR	1	0.4[c]		0.6	
SIL	PR, BK, GR	2,3	0.6		0.8	
SI	—	—	0.0		0.0	
	—	OM	0.0		0.0	
	PL	1,2,3	0.0		0.2	
		1	0.2		0.3	
SCL, CL SICL	PR, BK, GR	2,3	0.4		0.6	
	—	OM	0.0		0.0	
	PL	1,2,3	0.0		0.0	
		1	0.0		0.0	
SC, C, SIC	PR, BK, GR	2,3	0.2		0.3	

Note a: With ≤ 60% rock fragments
Notes b: With > 60 < 90% rock fragments
Note c: Requires pressure distribution
Note d: **C** – Clay, **COS** – Coarse Sand, **COSL** – Coarse Sandy Loam, **FS** – Fine Sand, **FSL** – Fine Sandy Loam, **LFS** – Loamy Fine Sand, **LVFS** – Loamy Very Fine Sand, **LS** – Loamy Sand, **S** – Sand, **SC** – Sandy Clay, **SCL** – Sandy Clay Loam, **SI** – Silt, **SICL** – Silty Clay Loam, **SIL** – Silt Loam, **VFSL** – Very Fine Sandy Loam , **VFS** – Very Fine Sand, **VFSL** – Very Fine Sandy Loam
Note e: **BK** – Blocky, **GR** – Granular, **M** – Massive, **PL** – Platy, **PR** – Prismatic,
0 – Structureless, 1– Weak, 2 – Moderate, 3 – Strong

Table 8-2 Maximum Soil Application Rates Based on Percolation Rates

Percolation Rate (minutes per inch)	Maximum Monthly Average	
	BOD_5 > 30 mg/L < 220 mg/L TSS > 30 mg/L < 150 mg/L (gals/sq ft/day)	BOD5 < 30 mg/L TSS < 30 mg/L (gals/sq ft/day)
0 to less than 10	0.7	1.2
10 to less than 30	0.6	0.9
30 to less than 45	0.5	0.7
45 to less than 60	0.3	0.5
60 to 120	0.2	0.3
Greater than 120	0.0	0.0

for lighter soils. However, with heavier soils (including sandy soils containing appreciable amounts of silt or clay), you must look for additional clues, such as structure and soil color.

- Structure: Soil structure is characterized by the aggregation (or grouping together) of textural particles to form secondary particles of a larger size. The structure can be recognized by the manner in which a clod, or lump, breaks apart. If a soil has well defined structure, a clod will break with very little force, along well-defined cleavage planes, into uniformly sized units. If a soil has no structure, or is structureless, it may flow like beach sand or hold together like a massive block of clay.
- In general, the four fundamental structural types, named according to the shape of the aggregate particles, are platy, prism-like, block-like, and spherical. The spherical structure tends to provide the most favorable infiltrative properties, and the platy structure tends to provide the least favorable. Although other factors, such as the size and stability of the aggregates in water, also influence the infiltrative capacity of the soil, recognition of the type of structure is probably sufficient for a general appraisal.
- Color: Another clue to the infiltrative capacity of soil is its color. Most soils contain some iron compounds, which, if alternately exposed to air and water, oxidizes and takes on a reddish-brown or yellow color. Thus, if the soil has a uniform reddish-brown to yellow oxidized color, air and water most likely have been freely and alternatively moving in and through the soil. Such a soil has some desirable infiltrative characteristics. At the other extreme, a dull gray or mottled soil coloring indicates a lack of oxidizing conditions or a very restricted movement of air and water through the soil. Mottled soils may indicate poor infiltrative characteristics.
- Depth (or thickness) of permeable strata: The quantity of water that may be infiltrated into the soil frequently is proportional to the thickness (or volume) of the soil horizon. With a soil having 1 foot (0.3 meter) or more of permeable material above tight clay, the infiltrative capacity is far greater than it is in a soil having the same kind of material lying within 2 inches (50.8 millimeters) of tight clay.

Procedure for Percolation Tests

Although the requirement for a percolation test is being replaced by the soil evaluation report, you should consult the authority having jurisdiction (AHJ) to ascertain whether the perc test is required. (Note: The procedure for percolation tests described in this chapter was developed at the Robert A. Taft Co.)

Several types (procedures) of percolation test may be acceptable to the AHJ, or there may be no standards. In the absence of standards, the following method of conducting a percolation test may be used.

Six or more tests should be made in separate test holes, spaced uniformly over the proposed absorption field site.

Dig or bore a hole with horizontal dimensions varying from 4 to 12 inches (101.6 to 304.8 millimeters) and vertical sides to the depth of the proposed absorption trench. To save time, labor, and water per test, the holes can be bored with a 4-inch (101.6-millimeter) auger.

Carefully scratch the bottom and sides of the hole with a knife blade or a sharp-pointed instrument to remove any smeared soil surfaces and provide a natural soil interface into which water may percolate. Remove all loose material from the hole. Add 2 inches (50.8 millimeters) of coarse sand or fine gravel to protect the bottom from scouring and sediment.

To conduct the test, carefully fill the hole with clear water to a minimum depth of 12 inches (304.8 millimeters) over the gravel. In most soils, it is necessary to refill the hole by supplying a surplus reservoir of water, possibly by means of an automatic siphon, to keep water in the hole for at least four hours and preferably overnight. This procedure ensures that the soil is given ample opportunity to swell and to approach the condition it will have during the wettest season of the year. Thus, tests of the same soil give comparable results, whether they are made in a dry or wet season.

It is important to distinguish between saturation and swelling. Saturation means that the void spaces between soil particles are full of water. This can be accomplished in a short period. Swelling is caused by the intrusion of water into individual soil particles. This is a slow process, especially in clay-type soils, and it is the reason that a prolonged soaking period is required.

In sandy soils containing little or no clay, the swelling procedure is not essential. Therefore, in these soils there is no need to refill the hole with water.

With the exception of sandy soils, the percolation rate measurement should be made on the day following the procedure described above, 24 hours after water is first added to the hole. For sandy soils, the percolation rate measurement may be taken after the water from one filling of the hole has completely seeped away.

If the water remains in the test hole after the overnight swelling period, adjust the depth to approximately 6 inches (152.4 millimeters) over the gravel.

From a fixed reference point, measure the drop in the water level over a 30-minute period. This drop is used to calculate the percolation rate.

If no water remains in the hole after the overnight swelling period, add clear water to bring the depth of the water in the hole to approximately 6 inches (152.4 millimeters) over the gravel. From a fixed reference point, measure the drop in the water level at approximately 30-minute intervals for four hours, refilling to 6 inches (152.4 millimeters) over the gravel as necessary. The drop that occurs during the final 30-minute period is used to calculate the percolation rate of the soil. Any drop during the prior period provides the information for a possible modification of the procedure to suit local circumstances.

In sandy soils—and in types of soil in which the first 6 inches (152.4 millimeters) of water seep away in fewer than 30 minutes after the overnight swelling period—the time interval between the measurements should be 10 minutes and the test should be run for one hour. The drop that occurs during the final 10 minutes is used to calculate the percolation rate.

Soil Absorption System Selection

For areas where the percolation rates and/or soil characteristics are acceptable, the next step after conducting a soil and site evaluation is to determine the absorption system suitable for the site.

For unsuitable sites, the installation of a traditional soil absorption system is impossible, and you must consider alternative types of absorption systems, such as mounds, at-grades, or shallow subsurface irrigation. If none of these alternatives is acceptable, you may have to consider the use of a sewage lift station to pump the wastewater to a public sewer system or wastewater treatment plant, a holding tank, or a private wastewater treatment plant.

Selection of the appropriate absorption system depends to some extent on the location of the system in the area under consideration. A safe distance should be maintained between the system's site and any water supply source or other physical feature that may be impacted by the POWTS or may impact the operation of the POWTS. Since the distance that pollution may travel underground depends on numerous factors, including the characteristics of subsoil formations and the quality of the sewage discharged, no specified distance is absolutely safe in all localities. Ordinarily, a greater distance means greater safety provided. The location of the components of sewage disposal systems shall be as required by local codes. In their absence, Table 8-3 may be used as a guide.

Table 8-3 Recommended Setbacks for Soil Absorption Systems

Physical Feature	POWTS Soil Absorption System	Exterior Subsurface Treatment Tank or Holding Tank	Servicing, Suction Lines and Pump Discharge Lines
Building	10 feet	5 feet	None
Property Line	5 feet	2 feet	2 feet
Swimming Pool	15 feet	None	None
High Water Mark of Navigable Water	50 feet	10 feet	10 feet
Water Service or Private Water Main	10 feet	10 feet	10 feet
Public Water Main	8 feet	8 feet	8 feet
Public Well	400 feet	400 feet	200 feet
Private Well	50 feet	25 feet	25 feet

Details pertaining to local water wells—such as depth, type of construction, and vertical zone of influence—and data on geological formations and the porosity of the subsoil strata should be considered when determining the allowable distance between wells and subsurface disposal systems.

In-ground Conventional Soil Absorption System

An in-ground soil absorption system routinely consists of a bed constructed of aggregate or placed within a chamber. In either installation, a void is created to allow for storage of the partially treated effluent. Piping may be installed within the void to serve as a

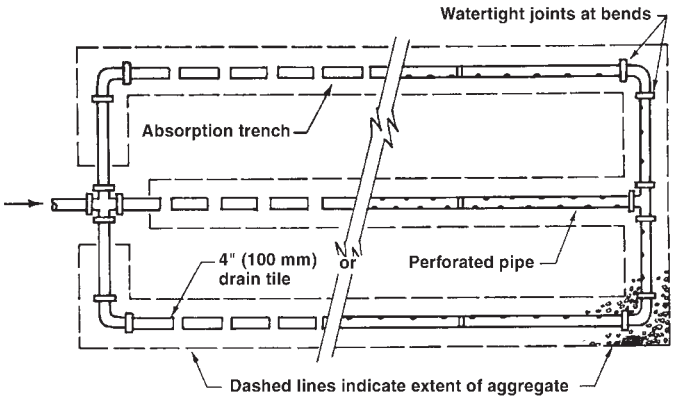


Figure 8-1 Three Legs of Disposal Field Fed from Cross Fitting Laid on Its Side

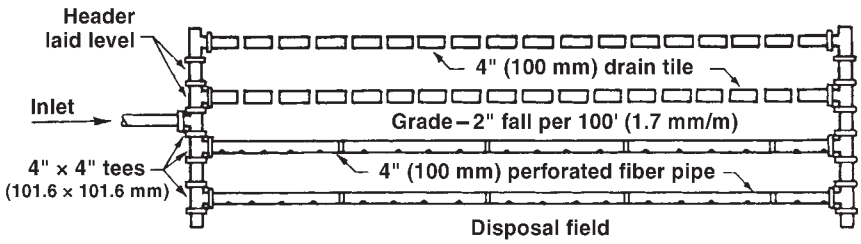


Figure 8-2 Disposal Lines Connected by Headers to Circumvent Stoppages

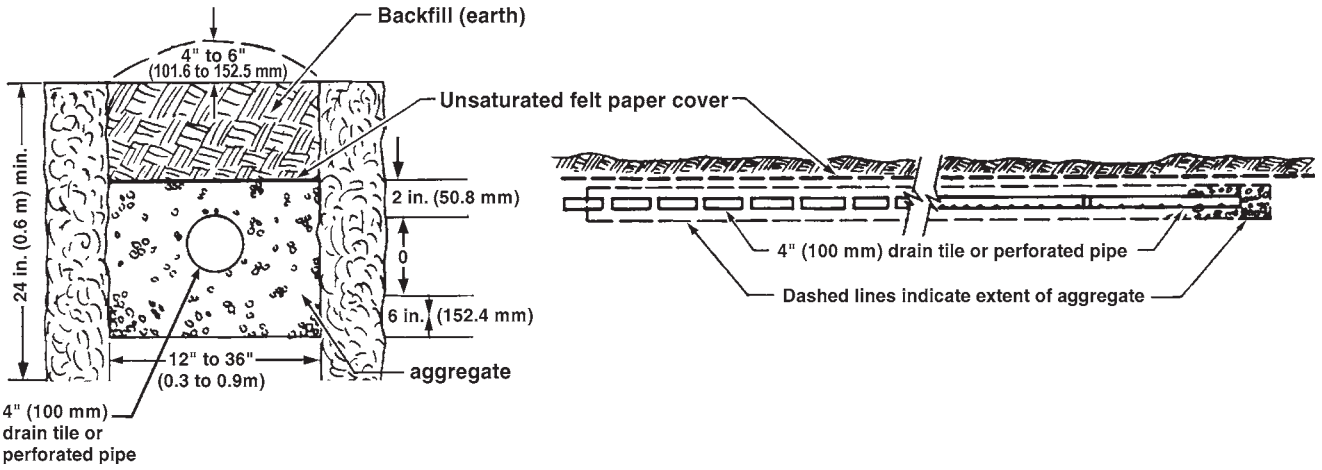


Figure 8-3 Transverse and Lineal Sections of Drain Field Showing Rock and Earth Backfill around Drain Tile

distribution system for the effluent. Perforated plastic is the piping material typically used.

Many different designs may be used when laying out a subsurface absorption field. Typical layouts of absorption trenches are shown in Figures 8-1, 8-2, and 8-3. The choice may depend on the size and shape of the available disposal area, the capacity required, or the topography of the installation site.

Absorption trench depths are based on the suitable soil depth on the site. A minimum depth of 12 inches (304.8 millimeters) from the original grade will help reduce the ponding of partially treated wastewater near the system.

The required absorption area is predicated on the results of the soil profile description or the percolation tests and may be obtained from Table 8-1 or 8-2. The wastewater discharged from a home may be calculated using the following equation:

Equation 8-1

Estimated flow per day = 100 gallons x Number of bedrooms

The estimated flow per day is multiplied by a 150 percent safety factor, and the resulting design flow is used to calculate soil application rates.

The area of the lot on which the system is to be constructed should be large enough to allow room for a replacement system. For example, for a three-bedroom house the design flow is 450 gallons per day (150 gallons per bedroom per day x 3 bedrooms). If the soil application rate is 0.5, the size of the system is calculated by dividing the design flow by the application rate:

$$\frac{\text{450 gallons per day}}{\text{0.5 gallon per square foot per day}} = \text{900 square feet}$$

The spacing of the trenches generally is governed by local regulations or practical construction considerations such as the type of equipment and safety. For serial distribution on sloping ground, the trenches should be separated by at least 3 feet (0.9 meter) to allow for the maximum infiltration area. Refer back to Table 8-3 for the recommended distances to be kept between the disposal system and various site features, such as wells and dwellings.

The width of the trenches on sloping sites is governed by two factors: the depth of suitable soil and the vertical separation distance required between the bottom of the absorption system and the limiting condition and the minimum depth of the system in in-situ soil. On a flat site, limiting the width of the trenches to 6 ft (1.8 m) allows for a conservative use of surface area and reduces groundwater mounding caused by excessively wide systems.

Using the previous example, on a site that would permit a system to be 100 feet (30.5 meters) in length, the following assumptions are made:

- 900 square feet ÷ 100 feet = 9 feet
- Two trenches, each 4.5 feet wide and 100 feet long
- 6 feet separating the trenches to allow for machine access
- 15-foot width required for the system
- 3 feet between the system and the replacement of equal dimension

Thus, 33 feet (15 feet + 3 feet + 15 feet) is required for the width. With the width replacement area, 33 feet + 33 feet + 3 feet separation = 69 feet is required for the width.

Site Preparation and Construction

Procedures used in the construction of an in-ground soil absorption component are just as critical as the design of the component. A good design with poor construction results in component failure. The soil shall be worked only when the moisture content is low to avoid compaction and smearing. Consequently,

installations are to be made only when the soil is dry enough to prevent compaction and smearing of the infiltrative surface. Proper equipment includes tractors or other equipment that will not compact the infiltrative surface. Foot traffic on the infiltrative surface should be minimal, and equipment traffic on or over the infiltrative surface should be avoided.

The construction plan to be followed includes the following procedures:

1. Check the moisture content and condition of the soil. If the soil at the infiltrative surface can be rolled into a ¼-inch wire, the site is too wet. Smearing and compaction will result, thus reducing the infiltrative capacity of the soil. If the site is too wet, do not proceed until it dries out. If the soil at or below the infiltrative surface is frozen, do not proceed.
2. Set up a construction level or similar device and determine all relative elevations in relationship to the benchmark. It is necessary to determine the bottom elevation of the distribution cell, land surface contour lines, and approximate component elevations critical to the installation.
3. Lay out the absorption area within the tested designated area. Where possible, lay out the absorption areas on the site so that the distribution cell runs parallel with the land surface contours. Reference stakes offset from the corner stakes are recommended in case corner stakes are disturbed during construction.
4. Excavate the distribution cells to the correct bottom elevations, taking care not to smear the infiltrative surface. If the infiltrative surface or sidewalls are smeared, loosen them with the use of a rake or similar device. The infiltration surface can be left rough and should not be raked smooth.
5. Install observation pipes with the bottom 6 inches (152.4 millimeters) of the pipe slotted for components using stone aggregate. When leaching chambers are installed, the observation pipe connects to the top of the leaching chamber. The observation pipes are located at opposite ends of the distribution cell. Each observation pipe is located one-fifth to one-tenth the length of the distribution cell measured from the end of the cell. Installation of the observation pipe includes a suitable means of anchoring so the pipes are not dislodged during inspections.
6. If stone aggregate is used, place it into the excavated area until the top of the stone aggregate is at the elevation of the distribution piping. Placement of the stone aggregate is done in such a manner as not to compact the infiltrative surface. If leaching chambers are used, install the leaching chambers in accordance with the manufacturer's installation instructions.
7. Place the distribution pipes, as determined from the design, on the stone aggregate. Connect the distribution box, drop box, or manifold to the pipe from the treatment or dosing chamber.
8. Install a vent pipe, if one is to be installed.
9. If stone aggregate is used, place stone aggregate over the distribution pipe and the entire distribution cell until the elevation of the stone aggregate is at least 2 inches (50.8 millimeters) above the top of the distribution pipe.
10. If stone aggregate is used, place geotextile fabric over the stone aggregate.
11. Place the cover material on top of the geotextile fabric and/or leaching chamber. Avoid backfilling the first 12 inches (304.8 millimeters) with cobbles, stones, or frozen material that could damage the pipe, chamber, or fabric.

COLLECTION AND TREATMENT ALTERNATIVES

Alternatives to Gravity Collection and Distribution

If a gravity piping system is not possible, pumped systems are used. Alternatives to the typical gravity collection and distribution system that should be evaluated include small-diameter gravity sewers, pressure sewers, and vacuum sewers.

If the septic tank receives effluent other than raw wastes, small-diameter pipe (4 inches [101.6 millimeters] nominal) may be used to reduce the cost of conventional gravity sewers. The individual septic tanks should partially treat the wastewater by decomposition of the larger particles and permit sand and grit to settle. The 4-inch (101.6-millimeter) mains should be installed at a minimum gradient of 0.67 percent based on a minimum velocity of 1.5 feet per second (0.5 meter per second) at half-pipe flow capacity. Under these conditions, using the Manning Formula, a 4-inch (101.6-millimeter) pipe can carry more than 2,000 gallons per hour (gph) (2.1 liters per second), sufficient to serve 670 people (assuming a peak flow of 3 gph [3.2 milliliters per second] per person).

Pressure sewer systems generally consist of septic tanks at each facility, a small submersible pump, and small-diameter plastic mains. Grinder pumps may be placed in the septic tank. Construction costs are reduced because the sewer main can follow the contour of the land just below the frost line.

Vacuum transport systems consist of a vacuum pump, a receiving tank (held at approximately 7.5 pounds per square inch absolute (psia) [51.7 kilopascals

(kPa)]), and a vacuum valve. When there is sufficient sewage in the lateral and the vacuum is at the proper level, the valve will open, and the sewage will enter as a slug. The slug of wastewater will move toward the receiving tank until the dispersal of the slug results in a break in the seal, thus ending the vacuum effect. Traps should be placed at regular intervals in the mains to reshape the slugs. When the trap fills, the vacuum effect is reestablished, causing the slug to continue toward the receiving tank with the next operation of the valve. Vacuum sewers flow full and provide many of the advantages of pressure sewers.

Alternatives to Conventional Primary and Secondary Treatment

The alternatives to conventional primary and secondary treatment include sand filtration and evapotranspiration. Sand filters have been used in sewage treatment for many years. More recently, standard systems have been modified to recirculating sand filter systems, which have demonstrated that, if properly designed, installed, and operated, they can produce effluents that meet stringent effluent and stream-quality standards. Evapotranspiration as a means of disposing of domestic wastes has been researched at several locations, and its use has been accepted by various local jurisdictions. However, this type of system is rarely used.

The use of self-contained sewage treatment plants, particularly the tertiary treatment type, has found wide acceptance for facilities. Though this method is outside the scope of this chapter, it is discussed briefly in the section on individual aerobic wastewater treatment plants.

SEPTIC TANKS

If the lot is large enough to accommodate one of the previously discussed types of absorption system and construction of the system is permitted by the AHJ, the next step is the selection of a suitable septic tank.

Functions of the Septic Tank

Untreated liquid household effluent consists of both solids and liquids. If both were discharged directly into the seepage beds or trenches, the beds or trenches eventually would clog. The septic tank is a device that protects the beds by separating solids from liquids. The solids are retained in the septic tank so that only liquid is discharged to be percolated into the ground.

To provide this protection, two functions take place within the septic tank:

1. Biological treatment: Sewage effluent (fecal matter) is subjected to decomposition by natural, bacterial processes. The bacteria present in the liquid are anaerobic (i.e., they thrive in the absence of free oxygen). This decomposition, or treatment, of the sewage under anaerobic conditions is termed septic, hence the name of the tank.
2. Solids removal: Sludge is defined as an accumulation of solids at the bottom of the septic tank. Scum is a partially submerged mat of floating solids that forms at the surface of the fluid in the septic tank. Some sludge and scum are decomposed. The residual material, composed of inert solid materials, remains. After a period of time, these solids, including all types of grease, must be pumped out. Space must be provided in the septic tank to store this residue between cleanings; otherwise, sludge and scum eventually will be scoured from the septic tank and may clog the disposal field.

The heavier sewage solids settle to the bottom of the septic tank, forming a blanket of sludge. The lighter solids, including fat and grease, rise to the surface and form a layer of scum. A considerable amount of the sludge and scum is liquefied through decomposition or digestion. During this process, gas is liberated from the sludge and carries some solids to the surface, where they accumulate with the scum. Ordinarily, they undergo further digestion in the scum layer, and a portion settles again to the sludge blanket at the bottom. This action is retarded if a considerable amount of grease is in the scum layer. The settling also is retarded in small septic tanks because of the gasification due to fluctuations of flow, which are relatively wider in smaller septic tanks than in larger ones. This effect is reflected in Table 8-4, which shows the recommended minimum liquid capacities of household septic tanks.

As wastewater enters the septic tank, effluent is forced out of the tank into the drain field. Although the effluent is liquid, some solids remain in suspension. These solids are digested further by the soil as the liquid effluent trickles out of the drain piping into trenches and the surrounding absorption field.

Septic Tank Materials

Septic tanks should be watertight and constructed of materials not subject to excessive corrosion or decay. Concrete, fiberglass, and coated metal commonly are used. Properly cured, precast, and cast-in-place reinforced-concrete septic tanks are acceptable by most jurisdictions. Special attention should be given to job-built septic tanks to ensure that they are watertight. Heavyweight concrete block should be laid on a solid concrete foundation. Mortar joints should be surfaced with two ¼-inch (6.4-millimeter) coats of portland cement/sand plaster.

Precast septic tanks should have a minimum wall thickness of 3 inches (76.2 millimeters) and should be adequately reinforced to facilitate their handling. When precast slabs are used as covers, they should be watertight, have a thickness of at least 4 inches

(101.6 millimeters), and be adequately reinforced. All concrete surfaces should be coated with an acceptable compound to minimize corrosion, as approved by the AHJ.

Septic Tank Construction, Installation, and Operation

Backfill

Backfill around septic tanks should be made in thin layers thoroughly tamped in a manner that will not produce undue strain on the septic tank. Settlement of the backfill may be done with the use of water, provided the material is thoroughly wetted from the bottom upward and the septic tank is first filled with water to prevent floating.

Access

Adequate access to each compartment of the septic tank should be provided for inspection and cleaning. Both the inlet and the outlet devices should be accessible. Access to each tank compartment should be provided by means of a removable cover or a 20-inch (0.5-meter) manhole. Where the top of the septic tank is located more than 18 inches (0.46 meter) below the finished grade, manholes and inspection holes should extend to the finished grade. In most instances, the extension can be made using a clay or concrete pipe, but proper attention must be given to any potential hazard involved (such as yard maintenance equipment) when manholes are extended close to the ground surface.

Inlet Invert

The inlet invert should enter the septic tank at least 3 inches (76.2 millimeters) above its liquid level to allow for any momentary rises in the liquid level during discharges to the unit. This free drop prevents backwater and stranding of solid material in the house sewer leading to the septic tank.

A vented inlet tee or baffle should be provided to divert the incoming sewage downward. This device should penetrate at least 6 inches (152.4 millimeters) below the liquid level of the septic tank, but in no case should the penetration be greater than that allowed for the outlet device.

Outlet

It is very important for the outlet device to penetrate just far enough below the liquid level of the septic tank to provide balance between the sludge and scum storage volume. Otherwise, part of the advantage of the capacity is lost. A vertical section of a properly operating septic tank would show it divided into three distinct layers: scum at the top, a middle zone free of solids (called clear space), and a bottom layer of sludge. The outlet device retains scum in the septic tank, but at the same time it limits the amount of sludge that can be accommodated without scouring (which results in the sludge discharging in the effluent from the septic tank).

Table 8-4 Liquid Capacity of Tank[a]

Number of Bedrooms[b]	Recommended Minimum Tank Capcity, gal (L)	Equivalent Capacity per Bedroom, gal (L)
2 or fewer	1,000 (3,785)	300 (1,135.6)
3	1,000 (3,785)	375 (1,419.5)
4	1,500 (5,678.1)	350 (1,324.9)

a Provides for use of garbage grinders, automatic clothes washers, and other household appliances.
b For each additional bedroom beyond four, add 350 gal (1,324.9 L).

Observations of sludge accumulations in the field indicate that the outlet device should be extended to a distance below the surface equal to 40 percent of the liquid depth. For horizontal, cylindrical septic tanks, this distance should be reduced to 35 percent. For example, in a horizontal, cylindrical septic tank having a liquid depth of 42 inches (1.1 meters), the outlet device should penetrate 14.7 inches (0.4 meter) below the liquid level.

The outlet device should be extended above the liquid line to approximately 1 inch (25.4 millimeters) from the top of the septic tank. The space between the top of the septic tank and the baffle will allow any gas to pass through the septic tank into the house vent.

Tank Proportions

Available data indicates that, for septic tanks of a given capacity, shallow units function as well as deep ones. Also, for septic tanks of a given capacity and depth, the shape of the unit is not important. However, it is recommended that the smallest plan dimension be a minimum of 2 feet (0.6 meter) in length. Liquid depths may range between 30 and 60 inches (0.8 and 1.5 meters).

Storage Above Liquid Level

Capacity is required above the septic tank liquid line to provide for the portion of the scum that floats above the liquid. Although some variation is to be expected, on average about 30 percent of the total scum accumulates above the liquid line. In addition to the provision for scum storage, 1 inch (25.4 millimeters) usually is provided at the top of the septic tank to permit free passage of gas back to the inlet and house vent pipe.

For septic tanks having straight, vertical sides, the distance between the top of the septic tank and the liquid line should be equal to approximately 20 percent of the liquid depth. In horizontal, cylindrical tanks, approximately 15 percent of the total circle should be provided above the liquid level. This condition is met if the liquid depth (the distance from the outlet invert to the bottom of the tank) is equal to 79 percent of the diameter of the septic tank.

Use of Compartments

Although a number of arrangements is possible, the term "compartments" refers to the number of units in series. These compartments can be separate units linked together or sections enclosed in one continuous shell, with watertight portions separating the individual compartments.

A single-compartment septic tank provides acceptable performance. Available data indicates, however, that a two-compartment septic tank (with the first compartment equal to one-half to two-thirds of the total volume) provides better suspended-solids removal, which may be especially valuable for the protection of the soil absorption system. Septic tanks with three or more equal compartments are at least as good as single-compartment septic tanks of the same total capacity. Each tank compartment should have a minimum length of 2 feet (0.6 meter) with a liquid depth ranging from 30 to 60 inches (0.8 to 1.5 meters).

An access manhole to each tank compartment shall be provided. Venting between the tank compartments should be provided to allow the free passage of gas. Inlet and outlet fittings in the septic tank should be proportioned (as they are for a single tank). The same allowance should be made for storage above the liquid line (as is made for a single tank).

Grease Interceptors

Grease interceptors (grease traps) ordinarily are not considered necessary on household sewage disposal systems. The discharge from a garbage grinder should not be passed through these units. With the capacities recommended in this chapter, septic tanks can receive the grease normally discharged from a residence.

Chemicals

The operation of a septic tank is not improved by the addition of disinfectants or other chemicals. In general, the addition of chemicals to a septic tank is not recommended and actually may have an adverse effect on the bacterial processes necessary for digestion. Use of commercial products containing sodium hydroxide or potassium hydroxide as the active agent may result in the sludge bulking. A large increase in the alkalinity may interfere with digestion. The resulting effluent may damage the soil structure severely and cause accelerated clogging, though temporary relief may be experienced immediately after application of the product.

Frequently, however, the harmful effects of ordinary household chemicals are overemphasized. Small amounts of chlorine bleaches, added ahead of the septic tank, may be used for odor control and will have no adverse effects on the system. Small quantities of lye or caustics commonly used in the home, added to the plumbing fixtures, are not objectionable as far as the operation of the septic tank is concerned. If the septic tanks are as large as recommended, the dilution of the lye or caustics in the unit will offset any of the harmful effects that otherwise might occur.

Many commercial products containing enzymes have been placed on the market for use in septic tanks. As far as is known, none have proved, in properly controlled tests, to have an advantage.

Soaps, detergents, bleaches, drain cleaners, and other materials commonly used in households have no appreciable adverse effects on the sewage system. However, both the soil and essential organisms might be susceptible to large doses of chemicals, resulting from a hobby or an industry, discharged into the sewage system.

Bulk quantities of chemicals (paints, varnishes, pesticides, herbicides, etc.) should not be introduced to the system, as these may cause significant problems by overloading the system, interrupting the digestion process, or placing harmful or toxic chemicals into the soil or waterways.

Miscellaneous

All sanitary wastes from a household should discharge into a single septic tank and disposal system. For household installations, it is usually more economical to provide a single disposal system rather than two (or more) with the same total capacity. Normal household waste, including that from the laundry, bath, and kitchen, should pass into a single system.

Roof drains, foundation drains, and drainage from other sources producing large intermittent or constant volumes of clear water should not be piped into the septic tank or absorption area. Such large volumes of water will exceed the tank capacity, stir up the contents of the septic tank, and carry some of the solids into the outlet line. The disposal system following the septic tank likewise will become flooded or clogged or both and may fail. Drainage from garage floors or other sources of oily waste also should be excluded from the septic tank.

Toilet paper substitutes should not be flushed into a septic tank. Paper towels, newspaper, wrapping paper, rags, and sticks may not decompose

Table 8-5 Allowable Sludge Accumulation

Liquid Capacity of Tank,[a] gal (L)	Liquid Depth, ft (m)			
	2½ (0.8)	3 (0.9)	4 (1.2)	5 (1.5)
	Distance from bottom of outlet device to top of sludge, in. (mm)			
750 (2838.8)	5 (127)	6 (152.4)	10 (254)	13 (330.2)
900 (3406.5)	4 (101.6)	4 (101.6)	7 (177.8)	10 (254)
1000 (3785.0)	4 (101.6)	4 (101.6)	6 (152.4)	8 (203.2)

[a] Tanks smaller than the capacities listed require more frequent cleaning.

in the septic tank and are likely to lead to clogging of the plumbing and disposal systems.

Waste brines from household water softener units may have an adverse effect on the action of the septic tank, shortening the life of a sewage disposal field installed in a structured clay-type soil.

Adequate venting is obtained through the building plumbing system if the septic tank and the plumbing system are designed and installed properly. A separate vent on a septic tank is not necessary.

A chart showing the location of the septic tank and disposal system should be placed in a suitable location in the buildings served by the system. Whether furnished by the builder, septic tank installer, or local health department, the chart should contain instructions on the inspection and maintenance required for the septic tank. This chart will help acquaint homeowners with the necessary maintenance procedures that septic tanks require, thus forestalling failures of the unit by ensuring satisfactory operation. Extension of the septic tank's manholes or inspection holes to within 8 inches (203.2 millimeters) of the ground surface will simplify maintenance and cleaning. Records must be retained, including all performed maintenance.

Abandoned tanks should be filled with earth or rock.

Cleaning Septic Tanks

Septic tanks should be cleaned before too much sludge or scum accumulates. If the sludge or scum approaches the bottom of the outlet pipe, solids will be discharged through the outlet device into the sewage disposal field and will clog the system. When this condition occurs, eventually the liquid may break through to the ground surface, and the sewage may back up the plumbing fixtures. When a disposal field is clogged in this manner, it is necessary to clean the septic tank, and it also may be necessary to construct a new disposal field.

The tank capacities recommended in Table 8-4 provide a reasonable period of good operation before cleaning becomes necessary. However, due to the wide range in the rates at which sludge and scum accumulate, the tank should be inspected at least once per year and cleaned as necessary.

Although it is a difficult task for most homeowners, actual inspection of sludge and scum accumulations is the only way to determine when a septic tank needs to be pumped. When a septic tank is inspected, the depth of the sludge and scum should be measured in the vicinity of the outlet baffle. The septic tank should be cleaned if the bottom of the scum mat is within 3 inches (76.2 millimeters) of the bottom of the outlet device or the sludge comes within the limits specified in Table 8-5.

Scum can be measured with a stick to which a weighted flap has been hinged or with a device used to feel the bottom of the scum mat. The stick is forced through the scum mat, and the hinged flap falls into a horizontal position. The stick then is raised until resistance from the bottom of the scum is felt. With the same tool, the distance to the bottom of the outlet device can be determined.

A long stick wrapped with rough, white toweling and lowered to the bottom of the septic tank will show the depth of sludge and the liquid level of the septic tank. The stick should be lowered behind the outlet device to avoid scum particles. After several minutes, if the stick is carefully removed, the sludge line can be distinguished by the sludge particles clinging to the toweling.

In most communities where septic tanks are used, companies are engaged in cleaning septic tanks. The local health department can make suggestions on how to obtain this service. (In some communities, the service is offered on a limited basis and paid for by property taxes.) Cleaning typically is accomplished by pumping the contents of the septic tank into a truck. Septic tanks should not be washed or disinfected after pumping. A small residue of sludge should be left in the septic tank for seeding purposes. The material removed from the septic tank is a regulated waste requiring proper handling according to laws and rules imposed by federal or state agencies. The tank should never be emptied into storm drains or discharged directly into any stream or watercourse. All methods of sewage disposal must be approved by the local health authority.

When a large septic tank is cleaned, the tank should not be entered until it has been ventilated thoroughly and all gases have been removed to prevent the possibility of explosion or asphyxiation. Anyone who must enter the septic tank should wear a self-contained breathing apparatus and be attached to the surface by a stout rope.

Distribution Boxes

It is recommended that distribution boxes not be used for individual sewage disposal systems for the following reasons:

1. The distribution boxes may be eliminated from septic tank soil absorption systems for other methods of distribution without inducing an increased possibility of failure of the disposal field. Evidence indicates that distribution boxes may be harmful to a system.
2. Data indicates that, on level ground, equal distribution is unnecessary if the system is designed so that an overloaded trench drains back to other trenches before a failure occurs.
3. On sloping ground, a method of distribution is needed to prevent an excessive buildup of

head and the failure of any one trench before the capacity of the entire system is reached. It is doubtful that distribution boxes can provide an equal distribution.

SEWAGE DISPOSAL SYSTEMS FOR INSTITUTIONS AND SMALL ESTABLISHMENTS

Septic tank systems are used to provide sewage treatment and disposal in many types of small establishments—such as schools, institutions, motels, hotels, restaurants, trailer parks, housing projects, large private estates, and camps—where the quantities of sewage involved are larger than those discharged from an individual home. In general, the usefulness of a septic tank system decreases as the size of the facility served increases.

A lack of sanitary engineering advice during the design of such a system generally leads to failures, excessive costs, and a multitude of other problems. Anyone contemplating the use of such a system should employ an engineer qualified to design it. The first item to be determined from the AHJ is whether or not this method of sewage disposal is suitable for the type of establishment under consideration.

Any institutional septic tank system should incorporate appurtenances and supplemental design features to meet the requirements of the establishment and the varying site conditions. Such systems can be successful when appropriate experience, study, and planning are employed in their choice and development. This section describes the most generally successful procedures and practices as a guide for designing institutional systems. For occupancies covered by this section, under the federal Clean Water Act and related state water-quality regulations, it is common that applications must be made for discharge requirements in addition to obtaining the normal approvals. For instance, for restaurants, supermarkets, and other establishments producing appreciable amounts of grease, grease interceptors commonly are required, either as a central grease trap located outside the building or, preferably, as separate grease interceptors located at each grease-producing fixture. Because regulations at all levels changing frequently, requiring greater clarity of effluent, you should be sure to contact all of the agencies that may be involved.

Water Conservation

In most institutional systems, an important factor in preventing overload of wastewater disposal systems is water conservation. Means of conserving water include automatically closing faucets on all public wash basins; flow restrictors, where applicable; water closet and urinal fixtures designed to minimize water consumption; preventive maintenance; and user education programs aimed at wastewater reduction. The use of 1.6-gallon- (6.1-liter-) per-flush water closets is certainly a major factor in wastewater reduction.

Numerous states and localities are implementing, or studying the implementation of, water (gray and/or black) recycling programs.

Special Fixtures

A number of failing septic tank systems at highway safety rest stops, parks, and service stations have been corrected by installing water closets that use 2 quarts (2.3 liters) per flush or less. This option should be evaluated in system design, especially for occupancies where water closets and urinals produce the majority of wastewater at sites where soil porosity is limited.

Some service stations and similar occupancies utilize specially designed units to effectively recycle wastewater so health officials permit its reuse for toilet flushing.

Alternative Systems

Institutional wastewater management for sites without sewers presents unusual challenges. Jurisdictional authorities should develop policies whereby innovative, alternative systems can be evaluated to determine the conditions under which such systems may be accepted, based on the various factors involved.

Some effective alternatives to soil absorption-based systems are hydromechanical and membrane-based systems. Depending on the exact institutional or regional treatment requirements, the treatment options are clarification, aerobic digestion, anaerobic digestion, microfiltration, ultrafiltration, disinfection, reverse osmosis, and discharge/dispersal. Special consideration should be given to the maintenance and operational needs of these systems as part of the selection process.

Special Design

Special design features are desirable for large institutional-type systems. Consideration should be given to providing larger-than-required tanks, and two or more properly designed baffles often are preferred over a dual-tank system. Openings should be conveniently accessible for tank cleaning and maintenance.

Seepage systems also must be properly designed. For gravity flow, each seepage trench should not exceed 100 feet (30.5 meters) in length. For systems designed for more than 2,000 gallons (7,570 liters) per day, automatic dosing by a siphon or pump is desirable to ensure that the whole system is effectively used. Special dosing should be designed to fill the entire seepage trench piping to about three-fourths capacity.

Allowing for 100 percent expansion or having two separate absorption areas for alternating between seepage systems also is a possibility for institutions.

Individual Aerobic Wastewater Treatment Plants

Where surface discharge is authorized by the AHJ, individual treatment plants can be used. Approval under NSF/ANSI Standard 40: *Residential Wastewater Treatment Systems* may be required. This standard requires compliance with Class 1 effluent standards to meet U.S. Environmental Protection Agency secondary treatment guidelines.

Septic tanks may require the installation of intermittent, conventional, or recirculating sand filters. Stabilization ponds or lagoons, either conventional or aerated, may be accepted by some jurisdictions when soil absorption systems are contemplated.

It is essential to determine the characteristics and suitability of the area reserved for the subsurface disposal system, including, as required, room for future expansion. This includes checking the required separation from wells and surface waters, the topography, data on groundwater levels and impermeable layers, the soil evaluation, and percolation tests as required. You should fully explore all technical and legal aspects of securing approval of an acceptable method of sewage disposal before the site is developed. To do so, it is necessary to make a somewhat detailed plan of the total contemplated site occupancy to determine the sizes and capacities of the disposal units.

When soil absorption systems are contemplated, it is essential to determine the characteristics and suitability of the soil as a first step toward design. The builder of the establishment should explore this feature of a proposed site before the site is purchased. After the percolation tests are completed, the quantity of the sewage to be discharged should be estimated to determine the size and capacity of the disposal units.

Table 8-6 Average Wastewater Flows from Residential Sources

Source	Unit	Flow, gal (L)/unit/day	
		Range	Typical
Apartment	Person	53–90 (200–340)	69 (260)
Hotel, residential	Resident	40–58 (150–220)	50 (190)
Individual dwelling			
Average home	Person	50–92 (190–350)	74 (280)
Better home	Person	66–106 (250–400)	82 (310)
Luxury home	Person	79–145 (300–550)	100 (380)
Semi-modern home	Person	26–66 (100–250)	53 (200)
Trailer park	Person	32–53 (120–200)	40 (150)

Table 8-7 Typical Wastewater Flows from Commercial Sources

Source	Unit	Wastewater Flow, gal (L)/unit/day	
		Range	Typical
Airport	Passenger	2.1–4.0 (8–15)	2.6 (10)
Automobile service station	Vehicle serviced	7.9–13.2 (30–50)	10.6 (40)
	Employee	9.2–15.8 (35–60)	13.2 (50)
Bar	Customer	1.3–5.3 (5–20)	2.1 (8)
	Employee	10.6–15.8 (40–60)	13.2 (50)
Hotel	Guest	39.6–58.0 (150–220)	50.1 (190)
	Employee	7.9–13.2 (30–50)	10.6 (40)
Industrial building	Employee	7.9–17.2 (3–65)	14.5 (55) [excluding industry and cafeteria]
Laundry (self-service)	Machine	475.0–686.0 (1800–2595)	580.0 (2195)
	Wash	47.5–52.8 (180–200)	50.1 (190)
Motel	Person	23.8–39.6 (90–150)	31.7 (120)
Motel with kitchen	Person	50.2–58.1 (190–220)	52.8 (200)
Office	Employee	7.9–17.2 (30–65)	14.5 (55)
Restaurant	Meal	2.1–4.0 (8–15)	2.6 (10)
Rooming house	Resident	23.8-50.1 (90–190)	39.6 (150)
Store, department	Toilet room	423.0–634.0 (1600–2400)	528.0 (2000)
	Employee	7.9–13.2 (30–50)	10.6 (40)
Shopping center	Parking space	0.5–2.1 (2–8)	1.1 (4)
	Employee	7.9–13.2 (30–50)	10.6 (40)

ESTIMATING SEWAGE QUANTITIES

Disposal systems typically are designed prior to the actual construction of a facility. In estimating the quantity of sewage, the first consideration must be given to local code requirements. These requirements usually result in design flows that are considerably above average. If there are no code requirements, the most reliable criteria are readings from water meters at similar existing buildings, which can be obtained from the water utility company. It is recommended that a safety factor of 10 percent be added to the quantity of water obtained to account for any additional unknown requirements. However, water flows that do not pass through the sewage system (e.g., irrigation) should be excluded.

Where codes and actual usage data are not available, it is necessary to use other methods of estimating the amount of sewage to be discharged. For residential facilities, refer to Table 8-6 for average daily wastewater flows, including minimum and maximum flow and frequency distribution. This data is useful for the design of systems for apartments, mobile home parks, and similar residential facilities. Refer to Tables 8-7

Table 8-8 Typical Wastewater Flows from Institutional Sources

Source	Unit	Wastewater Flow, gal (L)/unit/day	
		Range	Typical
Hospital, medical	Bed	132.0–251.0 (500–950)	172.0 (650)
	Employee	5.3–15.9 (20–60)	10.6 (40)
Hospital, mental	Bed	79.3–172.0 (300–650)	106.0 (400)
	Employee	5.3–15.9 (20–60)	10.6 (40)
Prison	Inmate	79.3–159.0 (300–600)	119.0 (450)
	Employee	5.3–15.9 (20–60)	10.6 (40)
Rest home	Resident	52.8–119.0 (200–450)	92.5 (350)
	Employee	5.3–15.9 (20–60)	10.6 (40)
School, day			
With cafeteria, gym, showers	Student	15.9–30.4 (60–115)	21.1 (80)
With cafeteria only	Student	10.6–21.1 (40–80)	15.9 (60)
Without cafeteria, gym, showers	Student	5.3–17.2 (20–65)	10.6 (40)
School, boarding	Student	52.8–106.0 (200–400)	74.0 (280)

Table 8-9 Typical Wastewater Flows from Recreational Sources

Source	Unit	Wastewater Flow, gal (L)/unit/day	
		Range	Typical
Apartment, resort	Person	52.8–74.0 (200–280)	58.1 (220)
Cabin, resort	Person	34.3–50.2 (130–190)	42.3 (160)
Cafeteria	Customer	1.1–2.6 (4–10)	1.6 (6)
	Employee	7.9–13.2 (30–50)	10.6 (40)
Campground (developed)	Person	21.1–39.6 (80–150)	31.7 (120)
Cocktail lounge	Seat	13.2–26.4 (50–100)	19.8 (75)
Coffee shop	Customer	4.0–7.9 (15–30)	5.3 (20)
	Employee	7.9–13.2 (30–50)	10.6 (40)
Country club	Member present	66.0–132.0 (250–500)	106.0 (400)
	Employee	10.6–15.9 (40–60)	13.2 (50)
Day camp (no meals)	Person	10.6–15.9 (40–60)	13.2 (50)
Dining hall	Meal served	4.0–13.2 (15–50)	7.9 (30)
Dormitory, bunkhouse	Person	19.8–46.2 (75–175)	39.6 (150)
Hotel, resort	Person	39.6–63.4 (150–240)	52.8 (200)
Laundromat	Machine	476–687 (1,800–2,600)	581.0 (2,200)
Store resort	Customer	1.3–5.3 (5–20)	2.6 (10)
	Employee	7.9–13.2 (30–50)	10.6 (40)
Swimming pool	Customer	5.3–13.2 (20–50)	10.6 (40)
	Employee	7.9–13.2 (30–50)	10.6 (40)
Theater	Seat	2.6–4.0 (10–15)	2.6 (10)
Visitor center	Visitor	4.0–7.9 (15–30)	5.3 (20)

through 8-9 for typical wastewater flows from commercial, institutional, and recreational sources.

Where measurements of water consumption are not possible, it is necessary to use other methods of estimating the amount of sewage to be discharged. One method is to base the estimated flow on the number of bedrooms. A second method is to calculate the flow on the basis of the number and kinds of plumbing fixtures. If the building is used as a restaurant, the number of meals served may be the best criteria. Refer to Table 8-10 to estimate sewage quantities for general establishments. The quantities given in the table are merely the best averages available at this time, and they should be modified in localities or establishments where experience indicates a need to do so.

It is sometimes economically wise to construct separate disposal systems for different types of waste at a given establishment. The decision regarding the number of disposal systems may be influenced by topography, conditions of terrain, and the locations of the buildings contributing to the waste. For example, at large camps and some resorts, the kitchen and central dining facilities may be located at appreciable distances from the living quarters, cottages, and cabins. Under such circumstances, the kitchens may be provided with separate disposal systems designed especially for kitchen waste. A major factor is grease interception.

Also, while many authorities discourage the use of garbage disposal units or disposals for occupancies served by on-site disposal systems, such disposers are still used. For such occupancies where disposers are used and for food processing and poultry or animal slaughtering establishments and other units producing special types of liquid waste, separate interceptors and pretreatment should be designed to meet the particular requirements of the establishment.

Separate systems also may be used for community bathhouses. When this is done, the total per-capita flow must be broken down into its component parts, and some allowance should be made for the amount of sewage tributary from the different disposal systems. Table 8-11 illustrates how this may be done where no definite data regarding exact distribution flow is available.

For a certain number of new establishments, you may not be able to obtain from the client accurate estimates of the number of patrons to be served by the disposal system. This is particularly true in the case of restaurants and recreational facilities, such as picnic areas and country clubs. In such cases, the following data should be considered. For restaurants, seating capacity, type of menu, hours of operation per

Table 8-10 Quantities of Sewage Flows

Type of Establishment	gpd/Person (L/D/Person)[a]
Airports (per passenger)	5 (20)
Apartments—multifamily (per resident)	60 (225)
Bathhouses and swimming pools	10 (40)
Camps	
Campground with central comfort stations	35 (130)
With flush toilets, no showers	25 (95)
Construction camps (semipermanent)	50 (190)
Day camps (no meals served)	15 (60)
Resort camps (night and day) with limited plumbing	50 (190)
Luxury camps	100 (380)
Cottages and small dwellings with seasonal occupancy	50 (190)
Country clubs (per resident member)	100 (380)
Country clubs (per nonresident member present)	25 (95)
Dwellings	
Boarding houses	50 (190)
additional for nonresident boarders	10 (40)
Luxury residences and estates	150 (570)
Multifamily dwellings (apartments)	60 (225)
Rooming houses	40 (150)
Single-family dwellings	75 (285)
Factories (gal [L] per person, per shift, exclusive of industrial wastes)	35 (130)
Hospitals (per bed space)	250 (945)[b]
Hotels with private baths (2 persons per room)	60 (225)
Hotels without private baths	50 (190)
Institutions other than hospitals (per bed space)	125 (475)
Laundries, self-service (gal [L] per wash, i.e., per customer)	50 (190)
Mobile home parks (per space)	250 (945)
Motels with bath, toilet, and kitchen wastes (per bed space)	50 (190)
Motels (per bed space)	40 (150)
Picnic parks (toilet wastes only) (per picnicker)	5 (20)
Picnic parks with bathhouses, showers, and flush toilets	10 (40)
Restaurants (toilet and kitchen wastes per patron)	10 (40)
Restaurants (kitchen wastes per meal served)	3 (10)
Restaurants, additional for bars and cocktail lounges	2 (8)
Schools	
Boarding	100 (380)
Day, without gyms, cafeterias, or showers	15 (60)
Day, with gyms, cafeteria, and showers	25 (95)
Day, with cafeteria, but without gyms or showers	20 (80)
Service stations (per vehicle served)	10 (40)
Swimming pools and bathhouses	10 (40)
Theaters	
Movie (per auditorium seat)	5 (20)
Drive-in (per car space)	5 (20)
Travel trailer parks without individual water and sewer hookups (per space)	50 (190)
Travel trailer parks with individual water and sewer hookups (per space)	100 (380)
Workers	
Construction (at semipermanent camps)	50 (190)
Day, at schools and offices (per shift)	15 (60)

[a] Unless otherwise noted.

[b] Includes cafeteria.

day and all available data can be considered in calculating wastewater quantities and characteristics. For recreational facilities such as picnic areas and country clubs, a review of all proposed buildings, campsites, and methods of operation can provide valuable data. Computations and estimates can be made from the number and types of fixtures installed, with data from similar facilities elsewhere.

Estimates of sewage quantities from golf clubs should be verified, and calculations should be based on the weekend population. Allowances of 10 gallons (37.9 liters) per person for showers and 7 gallons (26.5 liters) per person for toilet and kitchen wastes, both for the average weekend population, have been found reasonable.

Figure 8-4, taken from the *Manual of Septic Tank Practice,* has long been used to estimate the allowable rate of sewage application to a soil-absorption system. Where all pertinent factors are suitable for conventional soil absorption systems, Figure 8-4 and Table 8-12 may be used for sizing systems where the percolation test is selected. However, where local experience, soil analysis results, and other data are available, such data should be taken into consideration in the final design.

Table 8-12 and Figure 8-4 do not allow for waste from garbage grinders and automatic washing machines. Discharges from these appliances to an institutional waste disposal system call for special design considerations.

Generally, garbage disposal units are not recommended for institutional occupancies that have central kitchens. It is usually more efficient and economical to handle garbage through conventional garbage cans and disposal methods. However, where it is decided to use garbage disposal units in central kitchens or food-processing plants, you should design the grease interceptor or a separate garbage separation tank especially on the basis of the anticipated quantities of garbage to be produced between normal tank cleanings. Then, special provisions should be made for the removal and disposal of garbage and grease at sufficiently frequent intervals based on actual periodic inspection of such receptacles.

The amount of additional wastewater flow from garbage grinding can be estimated by determining the nature of the operation. Interpolating from data in the *Manual of Septic Tank Practice*, an average design flow of about 1 gallon (3.8 liters) per meal per day is estimated when garbage grinders are used.

For residential automatic laundries, the *Manual of Septic Tank Practice* gives about 40 gallons (151.4 liters) per wash. An estimate of the average number of wash loads per day multiplied by 40 (151.4) would, therefore, give the wastewater flow to attribute to an institutional laundry.

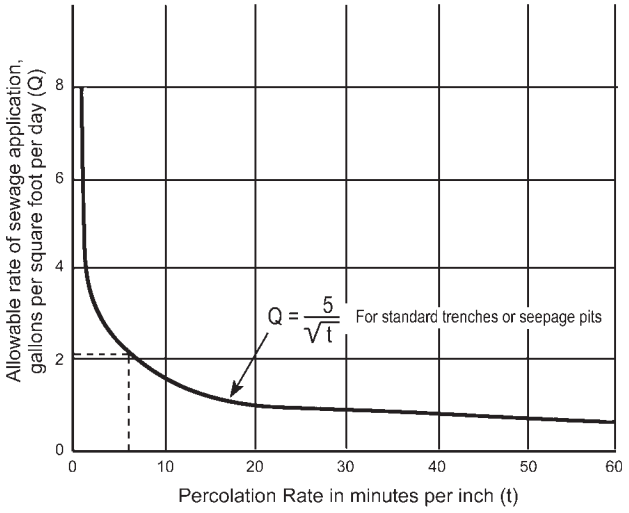


Figure 8-4 Graph Showing Relation Between Percolation Rate and Allowable Rate at Sewage Application

Source: *Manual of Septic Tank Practice*

INSPECTION

After a soil absorption system has been completely installed and before it is used, the entire system should be tested and inspected. The septic tank should be filled with water and allowed to stand overnight to check for leaks. If any leaks occur, they should be repaired immediately. The soil absorption system should be inspected before it is covered to be sure that the disposal system is installed properly. Prompt inspection before backfilling usually is required by local regulations, even where approval of plans for the subsurface sewage disposal system is required before issuance of a permit. Backfill material should be free of large stones and other deleterious material and should be overfilled a few inches (millimeters) to allow for settling.

Table 8-11 Estimated Distribution of Sewage Flows

Type of Waste	Volume, gpd/person (L/d/person)				
	30 (115)	40 (150)	50 (190)	75 (285)	100 (380)
Kitchen wastes	0[a]	7 (26)	10 (40)	10 (40)	15 (60)
Toilet wastes	15 (60)	15 (60)	20 (80)	25 (95)	30 (115)
Showers, washbasins, etc.	15 (60)	18 (70)	20 (80)	25 (95)	35 (135)
Laundry wastes	0[a]	0[a]	0[a]	15 (60)	20 (80)

[a] No waste from these uses.

Table 8-12 Allowable Rate of Sewage Application to a Soil Absorption System

Percolation Rate (time in min for water to fall 1 in. [25.4 mm])	Maximum Rate of Sewage Application for Absorption Trenches,[a] Seepage Beds, and Seepage Pits[b], g/ft²/d (L/m²/d)[c]	Percolation Rate (time in min for water to fall 1 in. [25.4 mm])	Maximum Rate of Sewage Application for Absorption Trenches, Seepage Beds, and Seepage Pits[b], g/ft²/d (L/m²/d)[c]
1 or less	5.0 (244.3)	10	1.6 (78.2)
2	3.5 (171.0)	15	1.3 (63.5)
3	2.9 (141.7)	30[d]	0.9 (44.0)
4	2.5 (122.2)	45[d]	0.8 (39.1)
5	2.2 (107.5)	60[d,e]	0.6 (29.3)

[a] Absorption area is figured as trench bottom area and includes a statistical allowance for vertical sidewall area.
[b] Absorption area for seepage pits is effective sidewall area.
[c] Not including effluents from septic tanks that receive wastes from garbage grinders and automatic washing machines.
[d] More than 30 is unsuitable for seepage pits.
[e] More than 60 is unsuitable for absorption systems.

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9 Private Water Wells

Private water wells are considered a type of private water supply because they are designed to provide potable water for a single building or facility of either residential or commercial construction. Normally, a water well that provides potable water to multiple buildings or facilities is considered a community water supply. Community water supply systems require more stringent design, a greater volume of reserve storage capacity, redundant pumping systems, a highly scrutinized permit process, and, for the most part, a full-time licensed water system operator. Conversely, a private water well system is installed, controlled, operated, and maintained by the user. Safe drinking water is the ultimate goal, and the methods described in this chapter are a means to that goal.

Engineering considerations in the design of private water wells include the following: the geology of the area, required demand, potential water quality, system elements, equipment, construction, initial operation, and maintenance procedures. In addition to addressing each of these areas, you should seek sources of local information and references, including drilling logs of previously constructed wells and their respective water quality test results. The regional governmental agency or health department responsible for water quality and protection is the preferred source of information for the quality of the water supply and approximate location of aquifers. This agency should be contacted as soon as possible to determine the adequacy and quality of the supply and any local regulations governing the construction of private water wells.

Wells often are classified as deep or shallow. A shallow well is considered to be 50 to 100 feet (15 to 30 meters) deep. A deep well generally is considered to be a superior source because the water is less susceptible to contamination and the depth of the aquifer usually fluctuates less than that in a shallow well.

CODES AND STANDARDS

The Safe Drinking Water Act governs the quality of water from wells. U.S. Environmental Protection Agency manuals include standards establishing maximum contamination levels. The Association of State Drinking Water Administrators provides potable water information. State, local, and regional regulations provide minimum construction standards.

SOURCES OF SUPPLY

The source of water for private water well systems is groundwater, which by definition is subsurface water stored in a saturated state within certain types of geological formations beneath the Earth's surface. The Earth's crust is comprised of multiple layers of various geological formations of different minerals and many different substrates. Water-filled voids occur in both bedrock and regolith formations. The glacial drift (sand and gravel) and sandstone regions are examples of shallow water-bearing zones, whereas shale and dolomite regions do not contain any saturated water properties.

The water-saturated voids or regions are considered aquifers, and it is possible to find multiple aquifers at various elevations at the same location. Aquifers store subsurface water that can be yielded in a usable quality and quantity through the use of water wells. The water quality and volume that can be obtained from aquifers substantially change from region to region and elevation to elevation. Groundwater supply is recharged through surface runoff that soaks into the ground and is not absorbed by surface agriculture. Commercial development and drought reduce the available recharge water for applicable aquifers. Thus, aquifer recharge is necessary to preserve the well's water source. Protecting our environment from pollution is critical to the quality of future groundwater supplies.

A further explanation of subsurface water is given in Chapter 4: "Storm Water Drainage," in this volume.

WELLS

A water well is a cased hole (usually vertical) that is drilled through the Earth's substrate to access water that is stored within the Earth's aquifers. Modern

wells generally are drilled using a machine that advances a bore hole to an aquifer, where a casing is installed to prevent collapse of the boring. This casing also prevents the well's aquifer from being contaminated by surface water or other sources of surface pollution at or near the surface of the ground.

The size of the well is determined by the building's water demand, equipment size (pump and pipe), and static pumping elevation. Deeper wells typically require larger-diameter pumps and impellers, thus requiring larger-diameter casings. Residential wells providing water for a single dwelling generally range from 2 to 6 inches (5 to 15 centimeters) in diameter and produce several hundred gallons of water per day. High-capacity wells, such as wells for industry or municipal water supplies, may range from 6 to 36 inches (15 to 91 centimeters) in diameter or larger and may produce several million gallons of water per day.

Shallow wells of 50 to 100 feet (15 to 30 meters) or less can be installed in loose formations of sand by driving or jetting (a high-pressure jet of water) a 2-inch (5-centimeter) pipe into the ground until an adequate depth is reached to provide the required water. Shallow wells more than 50 feet (15 meters) in depth generally are drilled using mud or air rotary. These techniques use a fluid, such as water, drilling mud, or compressed air, to clean the soil cuttings from the bore hole as the well is drilled. Water or drilling mud is used in loose formations of sand and gravel to stabilize the bore hole, whereas deeper wells through clay and bedrock formations generally are drilled using air and water to clean the bore hole since these formations are fairly stable.

The bore hole is advanced until either adequate water is encountered or bedrock is reached. In either case, the bore hole must be of a significant depth to isolate the well so it is not contaminated from surface water and pollutants. In porous formations of sand or gravel, casing is installed with a well screen to allow the water to easily enter the well from the aquifer. If bedrock is encountered before water, the bore hole is advanced into the bedrock a few feet, a casing is installed, and the well is advanced into the bedrock until water is encountered. The annulus between the casing and bore hole must be sealed with an impervious material to prevent infiltration of surface water into the aquifer.

Specific state, local, and regional regulations provide minimum construction standards for wells regarding potential sources of contamination, structures, surface features, and property lines. Additionally, state regulations may specify a minimum depth of the well, minimum amount of casing, type of casing, and grouting specifications for the annulus of the casing to prevent surface contamination. Typically, well permits are required before actual drilling can begin, with follow-up jurisdictional inspections.

Dug and Augered Wells

Depths of dug and augured wells can be 65 feet (20 meters) or more, depending on the position of the water table, while diameters are usually 3 to 30 feet (1 to 9 meters). Dug and augered wells can yield relatively large quantities of water from shallow sources. They are the most common type of well used for individual water supplies. Their large diameters permit storage of considerable quantities of water if the well extends some distance below the water table. Some large municipal wells called collectors are dug wells with lateral, screened horizontal pipes.

In the past, all dug wells were excavated by hand; today, the auger method is becoming more widely utilized. The auger pulls loose material to the surface for distribution as fill. Large dug wells can be constructed rapidly with portable excavating and augering equipment. For safety and to prevent caving, a lining of shoring or sheet piling should be placed in the hole to brace the walls.

A dug well must be permanently lined with a casing of wood staves, brick, rock, concrete, or metal to support it from cave-in. A properly constructed dug well penetrating a permeable aquifer can yield approximately 200 to 1,000 gallons per minute (gpm) (757 to 3,785 liters per minute), although most domestic dug wells yield less than 18,000 cubic feet per day (510 cubic meters per day). It is difficult to provide a proper sanitary seal on a dug well, whereas augering allows the installation of a welded steel casing to prevent ground source contamination. Construction of dug wells is prohibited or at least discouraged in some areas because of the increased possibility of surface contamination compared to deeper wells constructed by other means.

Bored Wells

Bored wells are constructed with hand-operated (shallow depths) or power-driven earth augers similar to those previously described. Augers are available in several shapes and sizes, all operating with cutting blades at the bottom that bore through the Earth's substrate in a rotary motion. Hand-boring operations rarely exceed 50 feet (15 meters) in depth, whereas power drilling/augering equipment can exceed 1,000-foot (305-meter) depths.

Deep well construction requires casing pipe insulation to contain and prevent contamination but also to protect the well shaft from collapsing. The drilling operation may pass through loose gravel or unstable strata before it reaches an aquifer to support the necessary water quality and quantity required for the project under design.

It is important to specify a proper compound of Portland cement and bentonite to grout and seal the well casing respective to its penetration through the various geological formations. This prevents surface contamination and prohibits contamination between the various layers between the Earth's geological formations.

Driven Wells

A driven well consists of a series of connected lengths of pipe driven by repeated impacts into the ground to below the water table. Water enters the well through a drive (or sand) point at the lower end of the well. This consists of a screened cylindrical section protected during driving by a steel cone at the bottom.

Diameters of driven wells are small, with most falling in the range of 2 to 4 inches (5 to l0 centimeters). Standard-weight steel and galvanized steel pipe having threaded couplings serve as casing. Most depths are less than 50 feet (l5 meters), although a few exceed 65 feet (20 meters).

As suction-type or jet pumps extract water from driven wells, the water table must be near the ground surface if a continuous water supply is to be obtained. The practical suction limit (i.e., the vertical distance between the suction intake of the pump and the pumping level in the well) for a single pipe installation is about 25 feet (7.6 meters). However, two-pipe venturi suction designs or multistaged turbine pumps can remove water from deeper depths.

Driven wells are suitable for single-home, residential water supplies, for temporary water supplies (such as those required on a remotely located construction project), and for exploration and observation. Driven wells are limited to unconsolidated formations containing no large gravel or rocks that might damage the drive point. Driving can be done with a manual sledge, ram driver, drop hammer, or air hammer. The important advantages of driven wells are that they can be constructed in a short time, at minimum cost, and by just one person.

Jetted Wells

Jetted wells are constructed by the cutting action of a downward-directed stream of water. The high-velocity stream washes the earth away, while the casing, which is lowered into the deepening hole, conducts the water and cuttings up and out of the well. Small-diameter holes of 2 to 4 inches (5 to l0 centimeters) to depths greater than 50 feet (l5 meters) can be formed in this manner. Jetted wells typically yield small amounts of water and are best suited to unconsolidated formations.

During the jetting operation, the drill pipe is turned slowly to ensure a straight hole. To complete a shallow jetted well after the casing extends below the water table, the well pipe with a screen attached is lowered to the bottom of the hole inside the casing. The outer casing then is pulled, gravel is inserted between the interior casing and the bore hole, and the well is ready for pumping.

The above procedure can be simplified by the use of a self-jetting well point. This consists of a tube of brass screen ending in a jetting nozzle, which is screwed to the well pipe. As soon as the well point is jetted to the required depth, the well is completed and ready for pumping. Gravel should be added around the drill pipe for permanent installation.

Construction of jetted wells is prohibited in some areas because of the inability to grout the annular space and the consequent exposure of the well to surface contamination.

HYDRAULICS OF WELLS

Figure 9-1 shows a well under two conditions: (A) static (non-pumping) and (B) pumping. Once the pumping of the well starts, the water table (or in the case of a confined aquifer, the potentiometric surface) is lowered in the vicinity of the well, and the resulting water table surface is known as the cone of depression. The decrease in the water level at and in the vicinity of the well is known as the drawdown.

The basic equilibrium equation for an unconfined aquifer can be derived using the notations indicated in Figure 9-1. In this case, the flow is assumed to be radial, the original water table is considered to be horizontal, the well is considered to fully penetrate the aquifer, which has an infinite area, and steady-state conditions must prevail. Using Darcy's law, this becomes:

Equation 9-1

$$Q = \frac{K_f (h_2^{\,2} - h_1^{\,2})}{1{,}055 \, \mathrm{Log_e}\left(\frac{r_2}{r_1}\right)}$$

where

Q = Discharge, gpm (liters per minute)
Kf = Permeability (flow velocity), gallons per day per square foot (liters per day per square meter)
h2 = Static head measured from the bottom of the aquifer, feet (meters)
h1 = Depth of water in the well while pumping, feet (meters)
r2 = Radius of the cone of depression, feet (meters)
r1 = Radius of the well, feet (meters)

This equation then may be solved for Kf, yielding:

Equation 9-2

$$K_f = \frac{1{,}055 Q \mathrm{Log_{10}}\left(\frac{r_2}{r_1}\right)}{(h_2^{\,2} - h_1^{\,2})}$$

In Equation 9-2, Loge has been converted to Logl0; Kf (flow velocity) is in gallons per day per square foot

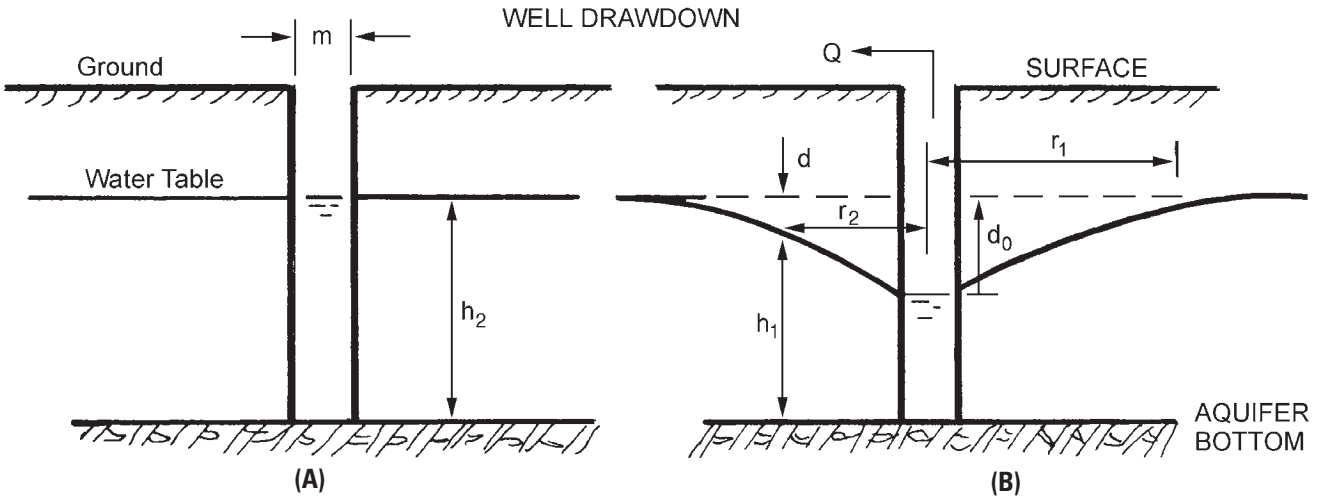


Figure 9-1 Well Under (A) Static and (B) Pumping Conditions

(liters per day per square meter); Q (discharge) is in gpm (liters per minute); and r and h are measured in feet (meters). If the drawdown is small compared to the total aquifer thickness, an approximate formula for the discharge of the pumped well can be obtained by inserting wall height (hw) for h1 and the height of the aquifer for h2 in Equation 9-l.

The basic equilibrium equation for a confined aquifer can be obtained in a similar manner, using the notation indicated in Figure 9-1. The same assumptions apply. Mathematically, the flow in cubic feet (cubic meters) per second may be determined as follows:

Equation 9-3

$$Q = \frac{2K_f m\,(h_2 - h_1)}{\mathrm{Log_e}\left(\frac{r_2}{r_1}\right)}$$

where

m = Inside diameter of the well shaft, feet (meters)

The coefficient of permeability may be determined by rearranging Equation 9-3 as follows:

Equation 9-4

$$K_f = \frac{528Q\mathrm{Log}_{10}\left(\frac{r_2}{r_1}\right)}{m(h_2^{\,2} - h_1^{\,2})}$$

PROTECTION OF WELLS

Whenever groundwater pumped from a well is intended for human consumption, proper sanitary precautions must be taken to protect the water quality. (See the following discussion of water quality.) Pollution sources may exist either above or below the ground surface. Submersible pump installations often are equipped with a pitless adapter, which provides an excellent sanitary seal as well as frost protection for the discharge piping. A cross-section of a typical pitless adaptor is illustrated in Figure 9-2.

Surface pollution can enter wells through either the annular space outside the casing or the top of the well itself. To close avenues of access outside the casing, the annular space should be filled with a sealing grout of cement, bentonite, or a combination thereof. Entry through the top of the well can be prevented by the provision of a water-tight cover to seal the top of the casing. Some pumps are available with metal bases that provide the necessary closure. For pumps with an open-type base or where the pump is not placed directly over the well, a seal is required for the annular opening between the discharge pipe and the casing.

It is desirable to provide a small (sealed) opening in or below the pump base to allow for periodic water level measurements. Covers around the well should be made of concrete, elevated above the level of the adjacent land, and slope away from the well. Where possible, pitless adapters should be used in preference to buried well seals or seals located in a concrete pit.

Subsurface pollution may be introduced by nearby septic systems, adjacent industry, surface runoff, or numerous types of current and past land uses. A contaminated plume can extend a long distance in an underground stream or aquifer. Regular bacteriological and chemical testing of the water quality is required to ensure potability. Whenever a new well is completed or an old well is repaired, contamination from equipment, well materials, or surface water may be introduced. The addition and agitation of a chlorine compound will disinfect the well, though this may corrode old steel-cased wells. Thus, following the disinfection, the well should be pumped to waste until all traces of chlorine are removed. As a final check on the potability of the water, two samples should be collected 24 hours apart and sent to a certified testing laboratory for bacteriological examination.

In regions where winter frost occurs, it is important to protect pumps and water lines from freezing. Pitless adapters are the most common method used to protect the well head from freezing and pollution.

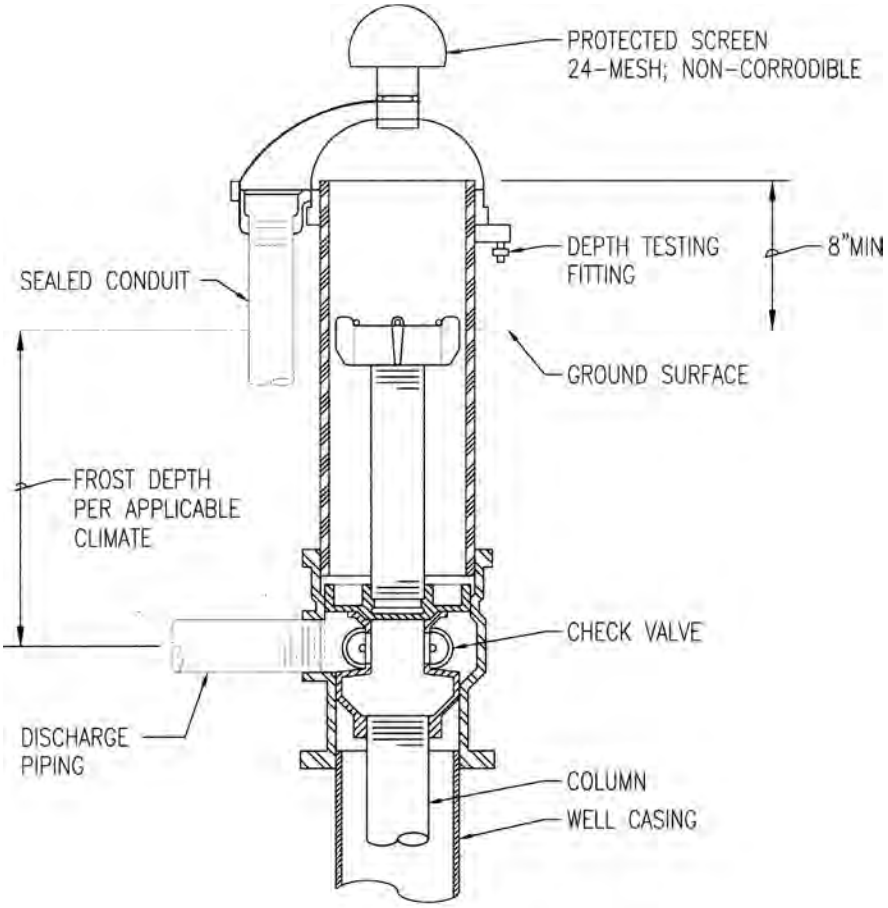


Figure 9-2 Typical Pitless Adaptor

Pitless adaptors allow for pump discharge below frost level and at the same time provide a check valve for backflow protection.

When a well is abandoned, it should be sealed properly by filling it with cement grout, bentonite, or a combination thereof. Sealing prevents surface contamination from entering the well, prevents accidents and the possible movement of inferior water from one aquifer to another, and conserves water in flowing wells. As necessary, other sealing measures may be needed to ensure that contaminants do not migrate within the aquifer by movement in the annular space between the well casing and the bore hole. To ensure that the well is completely sealed, the cement and/or bentonite should be pumped under pressure through a tremie pipe or other means to discharge at the bottom of the well, forcing its way upward until it reaches the surface.

WATER DEMAND

The demand for water in a new system is determined by the design engineer. The building's system dynamic and static requirements are utilized in determining the water demand. You should consult with the local administrative authority regarding local codes and regulations. Designing water systems for firefighting purposes requires knowledge of a building's construction, occupancy, and use. Nationally recognized standards, acceptable to the local administrative authority under the applicable code, should be followed.

The flow from a 1½-inch (3-centimeter) nominal size nozzle at 45 pounds per square inch gauge (psig) (310.3 kilopascals) can be as much as 250 gpm (l5.8 liters per second). It is recommended to install water meters on the non-domestic demands (such as irrigation, fire protection, and heating/cooling loads) to allow the building's owner to monitor consumption.

WATER QUALITY

The Safe Drinking Water Act of l974, subsequently amended in 1996, requires the administrator of the EPA to promulgate national standards for the purity of drinking water and corresponding regulations to enforce them. Current EPA manuals include standards establishing maximum contamination levels, and states have adopted these standards or more stringent standards. Efforts must be made to conform to these regulations in all systems.

Well water is usually satisfactory for drinking because of the natural filtration created as the water passes through the geological formations. However, when an excess of dissolved minerals or gases is present, the water must be treated. Selection of the appropriate treatment process must be made based on a thorough knowledge of the water and its chemical composition. The processes employed include filtration, softening, coagulation and flocculation, taste and odor control, prophylaxis, and disinfection. These treatment processes are described below.

Filtration

Where the water is not of an adequate purity and/or clarity, filters are required. Filters may be either gravity or pressure type and should include automatic controls for all functions. These devices may be sand or multimedia (provided that when aggressive or low-pH water is processed, the sand does not contain excessive

amounts of limestone or shells). The grade of the sand and/or type of media depends on local conditions.

Coarse sand is less effective in the removal of turbidity and bacteria, while fine sand requires a shorter period between washings. Filters may use layers of various grades of sand and gravel to minimize filter gravel upset and loss of sand. These units may include anthracite coal particles or activated carbon, both of which are often effective in removing objectionable tastes, odors, and other impurities. Filters should be backwashed and disinfected before being placed back in service. Parallel filtration prevents interruption of the supply water during backwash and/or cleaning.

Softening

The two methods of reducing any dissolved calcium and magnesium that are suitable for large water supplies are the zeolite process and the lime soda method. The zeolite process replaces the calcium and magnesium chlorides, and all residues (backwash) must be disposed of in locations where the groundwater will not be contaminated. Zeolite systems may be automated or manual. When iron is removed by this process, the oxides may clog the filter beds. Cleaning the beds requires high-velocity washing.

The lime soda method removes calcium, magnesium, manganese, iron, and carbon dioxide. The pH is raised, and most units effectively destroy any harmful organisms. This method produces considerable quantities of sludge, which require proper disposal. The lime soda method involves a large installation and skilled operation. Equipment is needed to mix and feed chemicals and for flocculation and settling, recarbonating and filtering. When iron is not removed, it may be held in solution in cool water up to 72 hours by the addition of hexametaphosphate. This chemical may prevent incrustation in water with a high pH.

Scale and Corrosion Control

Elimination of any excessive scale and corrosion of the piping system is important. This may be accomplished by the proper choice of piping materials or by chemical treatment of the water. Specifying a plastic distribution system will not protect the metallic piping and equipment in buildings. The control of hardness, dissolved oxygen and carbon dioxide, and acidity may be necessary. Sodium hexametaphosphate commonly is used for corrosion control, scale prevention, and removal of hardness.

Taste and Odor Control

Potassium permanganate oxidizes iron and manganese, forming a precipitate. This compound also acts as an algaecide. Oxygenation is another way to treat the water, which may (in some cases) be more effective than treating it with potassium permanganate. Activated carbon has been found to be effective in removing phenolic compounds as well as certain other undesirable materials. Sodium thiosulfate or sodium bisulfate has been used to remove chlorine from water, and copper sulfate will destroy living organic matter.

Prophylaxis

Fluoride sometimes is added to the water with the intent of reducing dental cavities. Where amounts of fluoride are excessive, tooth enamel will become mottled. Some waters have adequate or even excessive fluoride in their natural state.

Disinfection

Disinfection should be the last step in the water treatment process. Chlorination has been shown to prevent epidemics of waterborne disease, and it also destroys ammonia. It is an inexpensive method compared to ultraviolet radiation and ozone treatment. Gaseous chlorine is used in large installations, while calcium and sodium hypochlorite are satisfactory for small systems. Water from a properly constructed modern well seldom needs to be disinfected once the well and pumping equipment are initially disinfected.

Radon Contamination

In areas where radon (a radioactive gas) is present in low quantities in the ground, the water might be contaminated. Treatment may be necessary to eliminate radon from the water, and water softening often is used to accomplish this.

SYSTEM ELEMENTS

Pumps

The three most common well pump systems are vertical turbine pumps, jet pumps, and submersible pumps.

The vertical turbine pump is a centrifugal pump with the motor on the ground surface over the bore hole and the shaft and impeller suspended in the aquifer. It is well suited for large flow rates, deep wells, and high discharge heads.

The jet pump is a centrifugal pump with the motor and the impeller on the ground surface. It uses a jet of water flowing down the bore hole to create a partial vacuum at the bottom that, with a special fitting, draws an additional amount of water into the discharge pipe. This pump is used for small flow rates.

A submerged pump is a centrifugal pump that is entirely self-contained in a housing. It contains an electrical motor close-coupled with an impeller and an attached discharge pipe to the surface. This pump is well suited for a wide variety of flow rates and pressures.

The design of a pumping system should take into consideration maintenance and the possible failure of one pump in the system. It is sometimes necessary to have a backup (second) pump, which can be expensive.

However, if the system serves fire hydrants or fire protection equipment within a building without the use of a storage tank, it may be essential.

Pumps for residential or light commercial applications may be readily in stock at local supply companies in areas where many private water wells are prevalent. On the other hand, it is common to have large well drilling companies keep and maintain a large-diameter submersible well pump for large applications within their inventories for your emergency use at a cost.

A cross-section of a vertical turbine pump is illustrated in Figure 9-3. You should give more attention to the pump base (or foundation) than is shown in this figure. If the pump is in an unheated building, the foundation must be below the frost line to avoid any movement, and there must be sufficient mass to eliminate any vibration. Also, extreme care must be taken in setting the anchor bolts and aligning the pump and the shaft to prevent any misalignment.

The vertical turbine pump shown in Figure 9-3 is very practical for large-capacity, relatively straight and plumb shallow wells. Where deep wells or misaligned wells are encountered, it may be more practical to use a submersible pump. These units can be fitted with almost any number of stages (sections) and, depending upon the size of the well, can exceed the capacity and efficiency of the surface-mounted vertical turbine pump.

Submersible Well Pumps

Well pumps produce flow by transforming mechanical energy to hydraulic energy. Manufacturers produce a wide variety of pumps. The selection of a particular size and type of pump depends on several factors:

- Required pumping capacity
- Well diameter and depth
- Depth and variability of pumping level
- Straightness of the well
- Sand pumping
- Total pumping head
- Duration of pumping
- Type of power available
- Costs

The total pumping head, or total dynamic head, of a pump represents the total vertical lift and pumped distance of the water from the well. The total head consists of three components:

1. Drawdown inside the well (including aquifer and well losses)
2. Static head, or the difference between the static groundwater level and the static discharge elevation
3. Friction losses due to flow through the intake and discharge pipes. The total pumping head increases with the discharge rate.

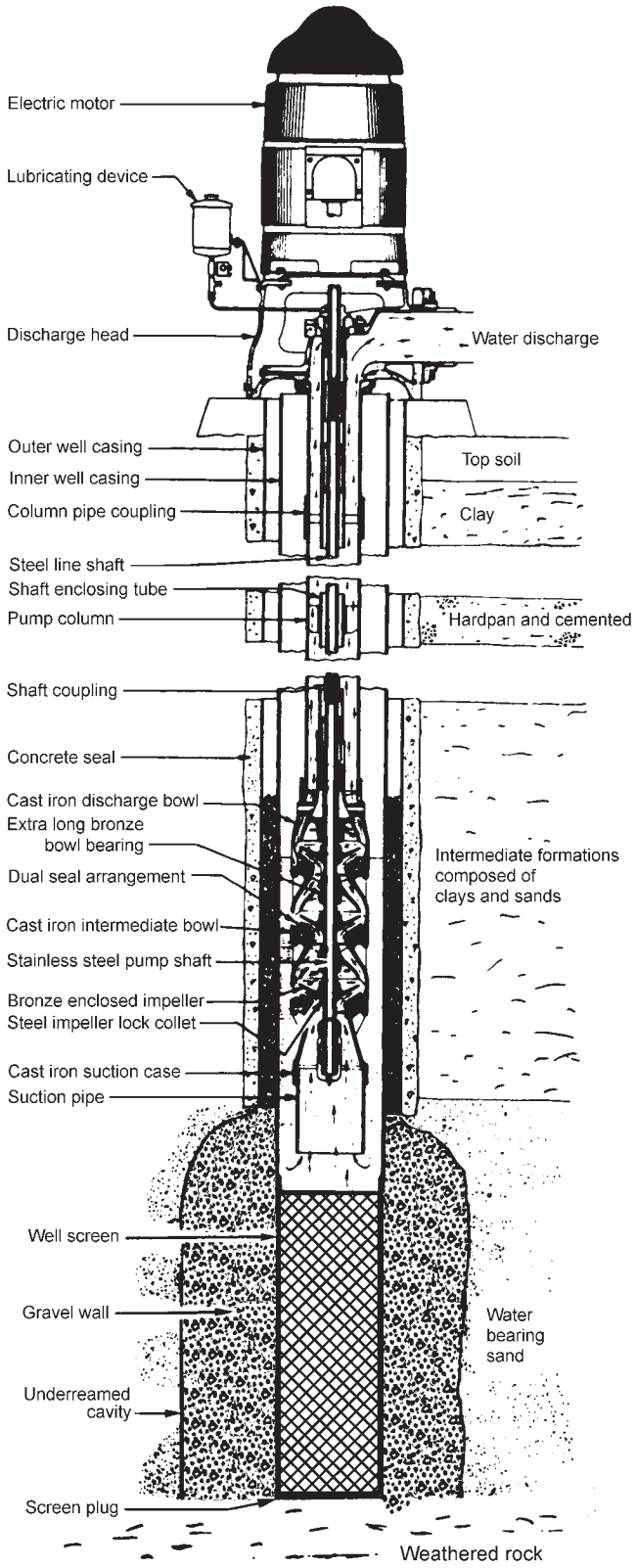


Figure 9-3 Typical Gravel Filter Well with a Vertical Turbine Pump (Note the concrete seal adjacent to the outer well casing)

For shallow wells where only small discharges are needed, submersible pumps, vertical turbine pumps (Figure 9-2), or gear pumps may be installed. Discharges range up to approximately 18,000 cubic feet per day (510 cubic meters per day). Suction lifts should not exceed approximately 23 feet (7 meters) for efficient and continuous service. (Available net positive suction head, or NPSH, for lift for the selected pump is critical in this determination.)

Where a large discharge is required from a shallow well, a centrifugal pump commonly is employed. The assembly may be mounted with a horizontal or vertical shaft. The horizontal design is efficient, easy to install and maintain, and usually connected directly to an electric motor. Because of the low suction head, the pump often is placed a short distance above the water level in a large-diameter well. (The NPSH must meet the design requirements.)

Storage Tanks

Storage tanks are useful as emergency sources and to prevent overtaxing the water supply system in firefighting situations. Elevated storage tanks provide uniform pressures and reduce energy and pump costs.

Storage tanks should be constructed of materials that are nontoxic and corrosion resistant. The detailed construction requirements for water storage tanks intended for firefighting purposes are outlined in National Fire Protection Association (NFPA) Standard 22: Water Tanks for Fire Protection. Storage tank supports usually are designed to resist seismic movement. The tanks must have provisions for cleaning. Rainwater cisterns also can be used for an emergency supply of drinking water if the water is appropriately filtered and treated prior to use.

Storage tank capacity and the size of the pump system are related. Without storage, the pumps must be large enough to supply instantaneous demand. This is impractical since instantaneous water demands are unpredictable, thus causing short-cycling of pump motors and reducing pump life expectancy. As the size of the storage tank increases, the fill rate of a gravity tank can decrease with the reduction, or elimination, of peak loads to reduce costs and equipment size. This also allows continuous operation of the pumps at maximum efficiency.

Ground-mounted storage tanks located on the side of a hill must be installed on a concrete foundation with the footing below the frost line and adequate support under the entire bottom of the storage tank. Taking soil-bearing tests prior to designing the foundation is extremely important. It is better to over-design than for a portion of the foundation to settle and allow the storage tank to become warped or possibly leak.

Prefabricated storage tanks are available in sections and constructed of steel with a glass lining. If a steel tank is field-erected, after its construction it must be coated on the inside with an FDA-approved epoxy-base paint, and it is suggested that the same coating be applied on the outside for weather protection. Underground tanks require coatings and cathodic protection. There are several different suppliers of this type of material, finish, and protection. It is recommended that you consult an expert before specifying the coating.

In flatland areas where the terrain does not allow for a ground-mounted storage tank, it is necessary to install an elevated tank on legs or to use a standpipe. The foundation in such installations is just as critical as it is with ground-mounted tanks. The installation of ground-level or aboveground storage tanks raises the question of ice forming in the storage tank itself. If the water level within the storage tank is allowed to fluctuate over a broad range, the changes in the water level will break up the ice so it is not necessary to heat the unit.

For a small residential system or light commercial system (e.g., a remotely located school), the use of a hydropneumatic storage tank is recommended because it is relatively inexpensive compared to an elevated storage tank. In sizing such a unit, you should assume that only one-third of the tank's capacity will be available as usable water, excluding the capacity of the well pump. Also, a compressed air supply with air-to-water balance controls to the top of the storage tank should be provided to recharge the unit, since the large water surface can gradually absorb the air and reduce the volume of the air cushion. Precharged hydropneumatic tanks eliminate the requirement for an air compressor for recharging. Unfortunately, the available sizes preclude their use to residential and light commercial applications. Generally, hydropneumatic tank systems do not provide sufficient storage for fire protection or for extended outages of the well pump.

The minimum size of storage, regardless of the type of tank, may be determined graphically (see Figure 9-4). The first diagram denotes the hourly water demand throughout a typical peak day. Also shown, as line A-B, is the average pumping rate, which is exceeded during the morning period from 5:00 to l0:00 a.m. and again in the afternoon from 2:00 to 3:00 p.m. During these periods, water is drawn from the storage tank. The second diagram denotes the cumulative water consumption for the day. Again, the pumping volume (a constant rate) is shown as line A-B. The quantity S represents the total storage volume required with the supply rate A-B. Alternate supply rates can be drawn to determine the corresponding storage volume requirement.

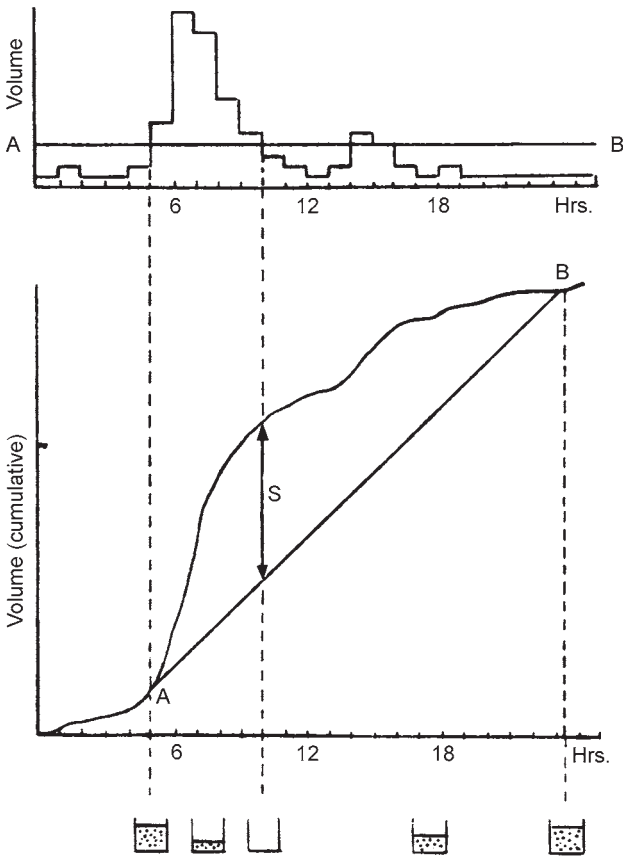


Figure 9-4 Graph Indicating Minimum Storage Tank Size

Storage Tank Suction Piping

The minimum distance below the water level that a suction inlet must be to avoid drawing any air into the suction pipe is illustrated in Figure 9-5. Minimum submergence is highly desirable to develop a full pump output. In addition, the suction pipe should be a few inches (centimeters) above the bottom of the storage tank to avoid drawing any sediment into the suction pipe. Gravity storage tanks must be screened and adequately vented. Anti-vortex plates also can be utilized at suction connections to storage vessels to prevent the pump from drawing air and cavitating.

Pressure Regulators

Pressures in excess of 80 psi (551.6 kilopascals) in private water well systems should be avoided whenever possible; in some cases, this is required by local codes. If this is so, pressure-regulating devices must be installed. Pressure regulators, as most devices, are subject to wear and may create noisy conditions, and relief valves are required to be used in conjunction with them, in the event of regulator failure.

This condition determines the height of the elevated storage tank from the lowest point of use. The fluctuation of the water level from the top of the storage tank to the bottom is not critical. If a well pump's starting and stopping is controlled by the storage tank level, the reduced-pressure condition of 80 psi (551.6 kilopascals) can be achieved by one of a number of acceptable means. You should consult with the local administrative authority to determine the approved methods.

Unfortunately, in northern latitudes, a float-type level control in the storage tank frequently is affected by icing and, therefore, is not a very reliable device. One of the more common ways of eliminating the problem is the use of an altitude valve, which is installed in the supply line to an elevated storage tank, basin, or reservoir for the purpose of preventing overflow. The altitude valve closes at the predetermined high-water level and opens for refilling when the water level recedes. A single-acting altitude valve is employed for filling purposes only. The dis-

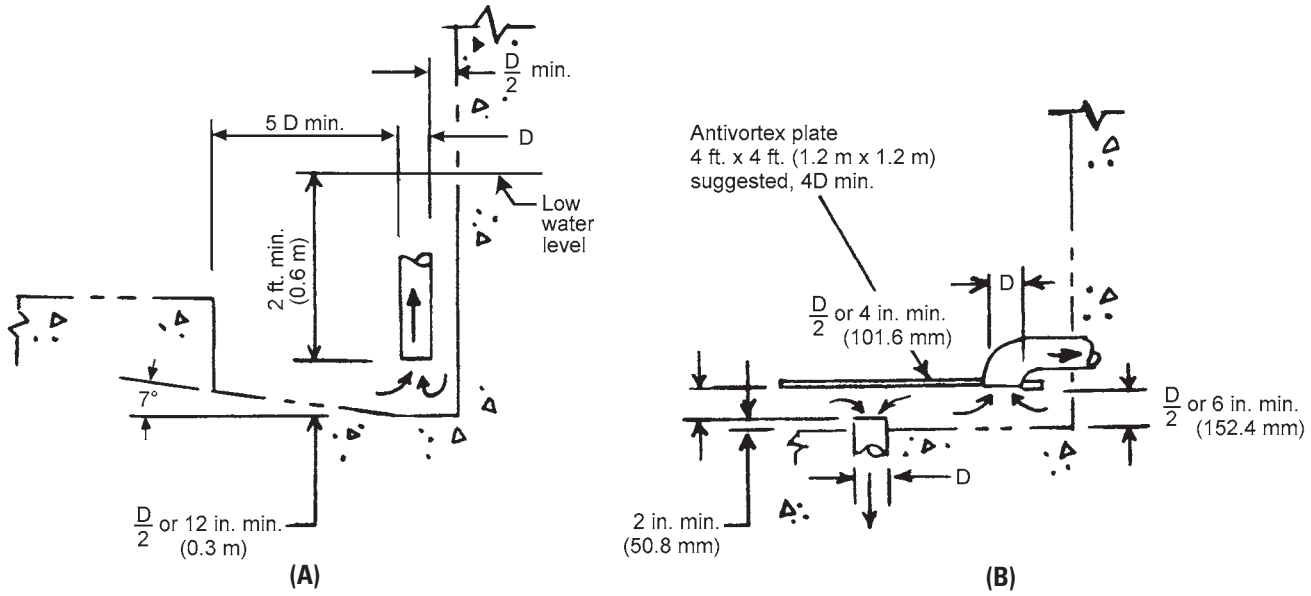


Figure 9-5 Storage Tank Suction Piping Detail: (A) Sump Suction Alternate, (B) Anti-vortex Alternate

charge from the storage tank is handled by a swing check valve in a bypass around the altitude valve. A double-acting altitude valve is designed for two-way flows and eliminates the need for a bypass. Without additional controls, the well pump or system pump will run continuously.

Another type of system currently available controls the well pump and the storage tank level by sensing the system's pressure at the point of pump discharge.

PERFORMANCE SPECIFICATIONS

The design and specification of private water wells is not an exact science. You can consult with all of the regulatory agencies and review previous well drilling logs within the region to find no place where X marks the spot. On the other hand, you may shift your drill hole 10 feet north and 30 feet west to find a sand and gravel vein that can be test-pumped at 200 gpm (757 liters per minute) for 24 hours and barely impact the elevation of the aquifer. On large-diameter wells, it may be prudent to drill an inexpensive, small-diameter (2-inch [5-centimeter]) test hole to determine if water is available at the proposed location. Test pumping on a small-diameter well will determine the availability of large volumes of water, as required for large-diameter wells, utilizing the equations listed within this chapter.

It is recommended to write your specifications on performance-based conditions. List estimated drilling depths through the various anticipated geographical formations, and require the installing well contractor to give a plus or minus unit cost basis for penetrating through these anticipated formations. In the event they penetrate through in a lesser depth, a legitimate credit can be received; if it is a greater depth, a prenegotiated cost already is established. It also is recommended to establish a unit cost basis for well test pumping (per-hour basis), installed casing pipe material (per-diameter and per-foot basis), installed grout or sealing material (per pound or bag), and hourly rates for well development and clearing using shots similar to nitroglycerine blasts. Bid-form unit pricing will keep all parties on a level playing field when unexpected circumstances arise, a periodic occurrence when digging or drilling private water wells.

CORROSION PROTECTION

Metallic piping generally is chosen because of the high pressure requirements. Plastic pipes, when used, usually are not subject to corrosion. The occurrence of corrosion depends on the soil and water conditions. Proper water treatment and pipe linings can minimize interior attack; exterior attack may be reduced by coatings, cathodic protection, and careful selection of the backfill. Coatings must remain intact, and protection must be inspected and maintained periodically.

Require a one-year warranty and a follow-up one-year inspection of all cathodic protection devices (anodes) and protective coatings by the installing contractor for additional quality control.

INITIAL OPERATION AND MAINTENANCE

After the well has been dug, it must be developed. Every type of drilling causes some disturbance to the aquifer by clogging the pores of the formation where it exists. After the bore hole has been completed, the casing is inserted, the intake attached, and the gravel packing installed.

Development is the process of removing loose material from the natural formation around the intake and enlarging it. This is the last stage of construction and is regarded as an art rather than a science.

Following development of a well, the next procedure is testing for yield by measuring the flow rate of pumping and observing the lowering of the water level. This is called drawdown and is the quantity of water that can be withdrawn on a continuing basis without depletion of the aquifer.

All private water wells and potable water piping must be disinfected prior to being placed in service. This process may be accomplished by introducing a solution of chlorine followed by a thorough flushing of the system with clear water. Well-kept records of the piping and connections will facilitate good operation and maintenance. Periodic flushing, particularly of dead ends and low-velocity branches, will prevent sedimentation and fouling. Regularly scheduled valve exercising will ready the system for shutdown during an emergency. Leakage may be controlled by inspection. Installation of approved backflow prevention devices will protect the private water supply from nonpotable sources. Inspections during and after construction will guard against cross-connections.

ADDITIONAL INFORMATION

For additional information on groundwater protection, contact the National Ground Water Association at ngwa.org. For additional information on safe drinking water standards, contact the Association of State Drinking Water Administrators at asdwa.org.

10 Vacuum Systems

This chapter describes the design criteria, source equipment, and piping distribution networks for vacuum systems used for general and laboratory applications and central vacuum-cleaning systems.

For the purposes of the discussion in this chapter, references to inch-pound (IP) units and international standard (SI), or metric, units shall follow the following conventions:

1. Flow-rate measurements referring to standard conditions shall be preceded by the prefix "s" for IP units and "n" for SI units.
2. Pressure designations using standard atmospheric conditions as the base shall be followed by the suffix "g" for gauge pressure in IP units. (No suffix is used with SI units.)
3. Pressure designations using absolute zero pressure conditions as the base shall be followed by the suffix "abs" in both IP and SI units.
4. Pipe sizes using nominal pipe-diameter dimensions in IP units shall be designated as nominal pipe size (NPS) and based on inches and fractions of an inch (e.g., 2 and 1½ inches). In SI units, the size shall be expressed as nominal diameter (DN), based on millimeters (e.g., 50 and 40 DN).

Unless otherwise noted, measurements used in this chapter are in inch-pound (IP) units, with metric (SI) units given in parenthesis.

FUNDAMENTALS

For the purposes of this discussion, vacuum is any air pressure lower than atmospheric pressure. Vacuum is created when air at atmospheric pressure enters a piping system that has a lower pressure. In most vacuum systems, the air becomes the transporting medium for any gas or suspended solids, and the negative pressure provides the energy for transportation. These two essential factors operate in inverse proportion: as the airflow increases, the vacuum pressure decreases.

Systems must be designed to produce the specific vacuum pressure and airflow levels that have been determined, often by experience and experimentation, to be most effective in performing their respective tasks. The exception is where vacuum pressure is intended to produce a force to lift objects or simply to evacuate and maintain a vacuum in an enclosed space. For these uses, airflow is only a function of how long it takes the system to achieve its ultimate vacuum pressure. Vacuum used for lift is outside the scope of this chapter.

The vacuum piping network is sized using the following four criteria: total connected load/flow rate, diversity factor, equivalent length of piping, and allowable friction loss.

The vacuum level is the difference in pressure between the evacuated system and the atmosphere. Vacuum pressures fall into four general categories:

1. Rough (or coarse) vacuum: 28 to 0.098 inches of mercury (711.2 to 25 torr; 3.326 to 94.8 kilopascals [kPa])
2. Medium (or fine) vacuum: 0.098 inches of mercury to 1 micrometer (μm) of mercury (25 to 0.0010 torr; 3.326 to 0.0075 kPa)
3. High vacuum: 1 to 1 x 10^{-6} micrometer of mercury (0.0010 to 1 x 10^{-9} torr; 0.0075 to 7.5 x 10^{-9} kPa)
4. Ultra-high vacuum: 1 x 10^{-6} to 1 x 10^{-9} micrometer of mercury (1 x 10^{-9} to 1 x 10^{-12} torr; 7.5 x 10^{-9} to 7.5 x 10^{-12} kPa)

PRESSURE MEASUREMENT

While defining vacuum is straightforward, measuring a vacuum level (or force) is not. Several methods of measurement are used, each depending on a different reference point.

Units of Measurement

The two basic reference points for measuring vacuum are standard atmospheric pressure and perfect vacuum. When the point of reference is standard atmospheric pressure, the measurement from that

to a specified vacuum pressure is called gauge pressure. If the pressure level is measured from a perfect vacuum, the term used for the measurement is absolute pressure. Local barometric pressure, which is the prevailing pressure at any specific location, should not be confused with standard atmosphere, which is mean barometric pressure at sea level.

To compute work forces and changes in volume, it is necessary to convert to negative gauge pressure, expressed as pounds per square inch gauge (psig) or kPa, or to absolute pressure, expressed as pounds per square inch absolute (psia) or kPa. The units used are inches of mercury (in. Hg) and the millibar (mbar). These units originate from the use of a barometer. The basic barometer is an evacuated vertical tube with its top end closed and the open bottom placed in a container of mercury open to the atmosphere. The pressure, or weight, exerted by the atmosphere on the open container forces the mercury up into the tube. At sea level, this pressure supports a column of mercury 29.92 inches high. In pressure units, this becomes 14.69 psi (0 kPa).

Standard Reference Points and Conversions

On the dials of most pressure gauges, atmospheric pressure is assigned the value of zero. Vacuum measurements must have a value of less than zero. Negative gauge pressure is the difference between the system vacuum pressure and atmospheric pressure. Absolute pressure is the pressure (in psia) above a perfect vacuum and is equal to atmospheric pressure less negative gauge pressure.

Other vacuum units are atmospheres, torr, and micrometers. To calculate atmospheres, divide absolute pressure in psia by 14.7. A torr is 1/760 of an atmosphere, and a micrometer is 0.001 torr.

Figure 10-1 gives conversion from and to various IP and SI pressure measurements. Table 10-1 gives numerical multipliers for converting torr into various other vacuum pressure units.

Flow Rate Measurement

The two types of flow rate measurement are mass flow measured by weight, used in chemical process industries, and volumetric flow measured in cubic feet per minute (cfm) (liters per minute). Only volumetric flow is used for calculations in this chapter.

The flow rate measurement for vacuum is exactly the opposite of that for compressed air. Using ambient, standard free air at atmospheric pressure (referred to as standard cubic feet per minute [scfm]) as a common reference, the ambient free air entering the vacuum pipe will expand to fill the vacuum in the piping system, creating a lower vacuum pressure. Standard air is dry (0 percent relative humidity), 14.7 psia (101.4 kPa), and 60°F (15.5°C).

Table 10-1 Conversions from Torr to Various Vacuum Pressure Units

0.0010 torr	=	1 micrometer of mercury (μm Hg)
0.0075 torr	=	1 pascal (Pa)
0.7501 torr	=	1 millibar (mbar)
1.000 torr	=	1 mm mercury (mm Hg)
1.868 torr	=	1 in. water at 4°C (in. H_2O)
25.40 torr	=	1 in. mercury (in. Hg)
51.71 torr	=	1 lb/in.^{2} (psi)
735.6 torr	=	1 tech. atmosphere (at)
750.1 torr	=	1 bar
760.0 torr	=	1 standard atmosphere (atm)

The flow in a vacuum pipe is expanded cfm and represents the flow under actual vacuum conditions, referred to as actual cubic feet per minute (acfm), which is greater than scfm. Another phrase used to indicate acfm is inlet cubic feet per minute (icfm).

The above designations are not universally used; therefore, it is important to ensure that the correct nomenclature for vacuum pump capacity specifications and flow rate is identified and understood prior to selection and sizing.

Converting scfm to acfm

The following formula is used to convert scfm to acfm.

Equation 10-1

$$\text{acfm} = \text{scfm}\,\frac{29.92}{\text{P}} \times \frac{\text{T} + 460}{520}$$

where

P = Actual pressure for the scfm being converted, inches of mercury (kPa)

T = Actual temperature for the scfm being converted, °F (°C)

For practical purposes, a numerical method for solving Equation 10-1 can be used if the temperature is 60°F (15.5°C). At that temperature, the second part of the equation becomes unity. Table 10-2 gives the numerical values for 29.92/P. To find acfm, multiply the scfm by the value found in the table opposite the vacuum pressure (P).

A direct ratio for converting scfm to acfm (sL/s to aL/s) for various pressures is given in Table 10-3. Multiply the scfm (sL/s) by the factor corresponding to the pressure in inches of mercury abs (kPa abs) to find acfm (aL/s).

GENERAL VACUUM CRITERIA

Adjusting the Vacuum Pump Rating for Altitude

The rating of a pump at altitude is a lower percentage of its rating at sea level. For each 1,000-foot (304.8-meter) increase in altitude, atmospheric pressure drops by approximately 1 inch of mercury (3.39 kPa) (see Table 10-4).

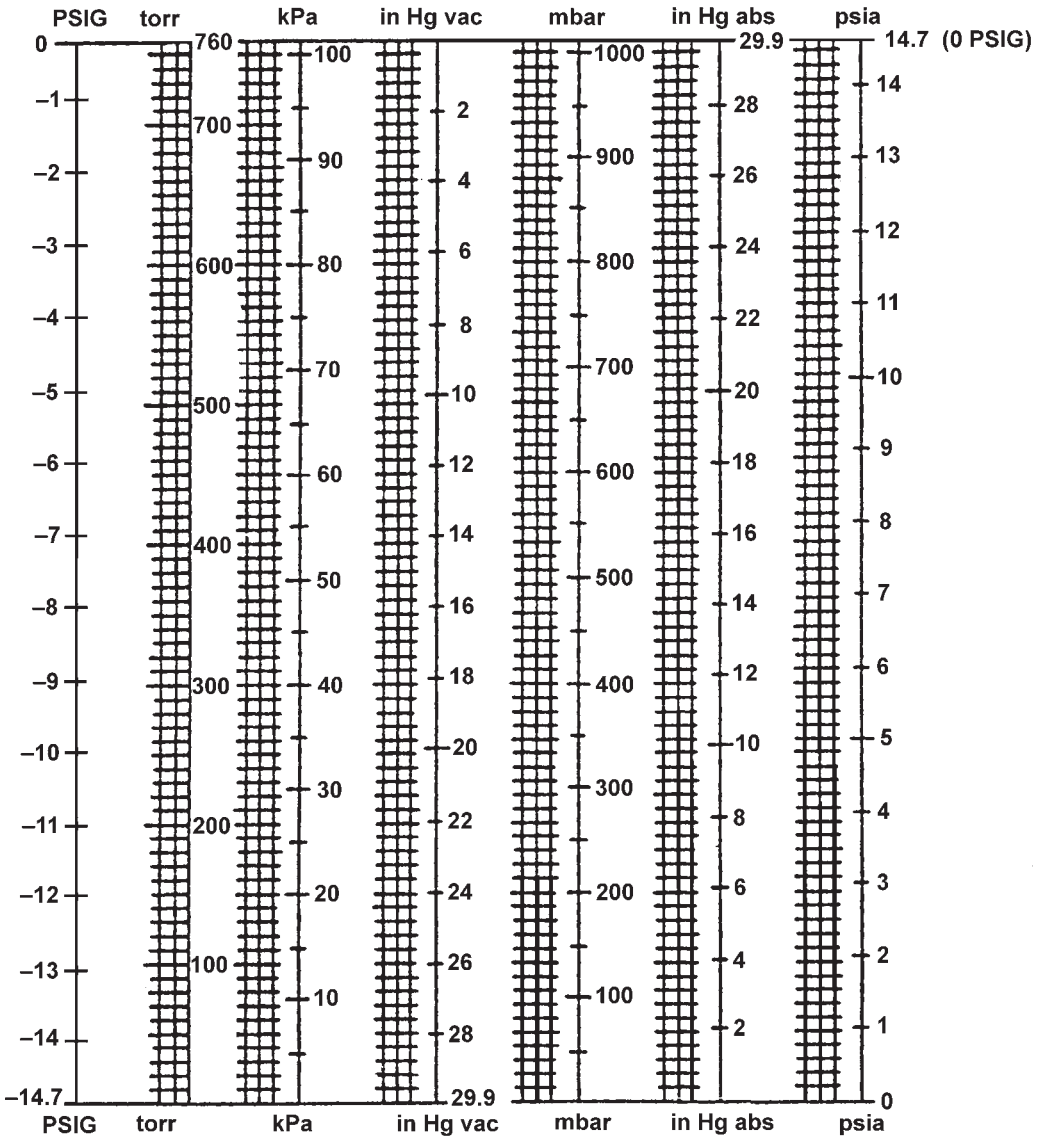


Figure 10-1 Conversion of Vacuum Pressure Measurements

To adjusting scfm for altitude, multiply the actual scfm by the factor found opposite the altitude where the project is located. Table 10-5 provides altitude multiplication factors to accomplish this.

For example, for the city of Denver (at 5,000 feet [1,524 meters]), the local atmospheric pressure is 24.90 inches of mercury (84.3 kPa). Dividing 30 inches of mercury (standard atmospheric pressure at sea level) into 24.90 gives a percentage of 83.3 percent. If a pump is rated at 25 inches of mercury (84.7 kPa) at sea level, 83.3 percent of 25 is 20.8 inches of mercury (70.4 kPa) at 5,000 feet (1,524 meters). This is the required vacuum pressure that would equal 25 inches of mercury (84.7 kPa) at sea level.

At altitudes above sea level, the scfm delivered is reduced because of the difference in local pressure compared to standard pressure. The scfm must be increased to compensate for this difference.

Time for a Pump to Reach the Rated Vacuum

The time a given pump will take to reach its rated vacuum pressure depends on the volume of the system in cubic feet (cubic meters) and the capacity of the pump in scfm (sL/s) at the vacuum-rated pressure. However, simply dividing the system volume by the capacity of the pump does not produce an accurate answer because the vacuum pump does not pump the same quantity of air at different pressures.

A logarithmic relationship can be approximated by the following formula:

Equation 10-2

$$T = \frac{V}{Q} N$$

where
T = Time, minutes
V = Volume of system, cubic feet (cubic meters)

Table 10-2 Expanded Air Ratio, 29.92/P, as a Function of Pressure, P (in. Hg)

P	29.92/P	P	29.92/P
29.92	1.00	10.92	2.7399
28.92	1.0346	9.92	3.0161
27.92	1.0716	8.92	3.3542
26.92	1.1114	7.92	3.7777
25.92	1.1543	6.92	4.3236
24.92	1.2006	5.92	5.0540
23.92	1.2508	4.92	6.0813
22.92	1.3054	3.92	7.6326
21.92	1.3650	2.92	10.2465
20.92	1.4302	1.92	15.5833
19.92	1.5020	0.92	32.5217
18.92	1.5814	0.80	37.40
17.92	1.6696	0.70	42.0742
16.92	1.7683	0.60	49.8667
15.92	1.8794	0.50	59.84
14.92	2.0054	0.40	74.80
13.92	2.1494	0.30	99.7334
12.92	2.3158	0.20	149.60
11.92	2.5101	0.10	299.20

Note: 1 in. Hg = 3.39 kPa

Table 10-3 Direct Ratio for Converting scfm to acfm (sL/s to aL/s)

In. Hg	kPa Abs.	Factor	In. Hg	kPa Abs.	Factor
1	97.9	1.05	16	47.09	2.15
2	94.5	1.1	17	43.71	2.3
3	91.15	1.1	18	40.33	2.5
4	87.77	1.15	19	36.95	2.73
5	84.39	1.2	20	33.57	3
6	81.01	1.25	21	30.20	3.33
7	77.63	1.3	22	26.82	3.75
8	74.19	1.35	23	23.37	4.28
9	70.81	1.4	24	19.99	5
10	67.43	1.5	25	16.61	6
11	64.05	1.55	26	13.23	7.5
12	60.67	1.62	27	9.85	10
13	57.29	1.75	28	6.48	15
14	53.91	1.85	29	3.10	30
15	50.54	2.0	29.92	0	60

Table 10-4 Barometric Pressure Corresponding to Altitude

Altitude[a]		Barometric Pressure	
m	ft	in. Hg	kPa
–3,040	–10,000	31.00	104.5
–152	–500	30.50	102.8
0	0	29.92	100.8
152	500	29.39	99.0
304	1,000	28.87	97.3
456	1,500	28.33	95.5
608	2,000	27.82	93.7
760	2,500	27.31	92.0
912	3,000	26.81	90.3
1,064	3,500	26.32	88.7
1,216	4,000	25.85	87.1
1,368	4,500	25.36	85.5
1,520	5,000	24.90	83.9
1,672	5,500	24.43	81.9
1,824	6,000	23.98	80.8
1,976	6,500	23.53	79.3
2,128	7,000	23.10	77.8
2,280	7,500	22.65	76.3
2,432	8,000	22.22	74.9
2,584	8,500	21.80	73.4
2,736	9,000	21.39	72.1
2,888	9,500	20.98	70.7
3,040	10,000	20.58	69.3

[a] Sea level = 0

Table 10-5 Factor for Flow Rate Reduction Due to Altitude

Altitude		Factor for Adjusted scfm
m	ft	
0	0	1.0
152	500	1.02
304	1,000	1.04
456	1,500	1.06
608	2,000	1.08
760	2,500	1.10
912	3,000	1.12
1,064	3,500	1.14
1,216	4,000	1.16
1,520	5,000	1.20
1,824	6,000	1.25
2,128	7,000	1.30
2,432	8,000	1.35
2,736	9,000	1.40
3,040	10,000	1.45
3,344	11,000	1.51

1scfm = 0.472 sL/s

Q = Flow capacity of pump, scfm (sL/s)
N = Natural log constant:

- For vacuum up to 10 inches of mercury (33.9 kPa), N = 1
- For vacuum up to 22.5 inches of mercury (76.2 kPa), N = 2
- For vacuum up to 26 inches of mercury (88.0 kPa), N = 3
- For vacuum up to 28 inches of mercury (94.8 kPa), N = 4

To obtain the most accurate answer, you should obtain pump curves from the manufacturer and substitute the N value for each scfm (sL/s) capacity at increments of 5 inches of mercury (16.9 kPa) and then add the N values to find the total time. Selection of the value for N depends on the highest level of system vacuum pressure and is constant for several calculations.

Adjusting Pressure Drop for Different Vacuum Pressures

When the available sizing chart uses a vacuum level different than that of the system being designed, the pressure loss for the scfm (sL/s) and pipe size for the system's vacuum pressure can be found by dividing the pressure drop in the chart by the ratio found from the following formula:

Equation 10-3

$$30 - \frac{\text{new vacuum pressure}}{\text{pressure used to create chart}}$$

Simplified Method of Calculating Velocity

The following formula can be used to find the velocity of a gas stream under a vacuum.

Equation 10-4

$$V = C \times Q$$

where

V = Velocity, feet per second (fps) (meters per second)
C = Constant for velocity based on pipe size (refer to Table 10-6)
Q = Flow rate based on an absolute vacuum pressure, acfm (aL/s)

Example 10-1

Calculate the velocity of 100 scfm (47.2 sL/s) through a 2-inch (50-DN) pipe with a pressure of 20 inches of mercury (67.7 kPa).

Find the equivalent absolute pressure of 20 inches of mercury (67.7 kPa). Using Table 10-7, read 9.92 inches of mercury abs (33.57 kPa abs).

Convert 100 scfm (47.2 sL/s) to acfm (aL/s) at a pressure of 9.92 inches of mercury abs (33.57 kPa abs) by using Table 10-3. Opposite 10 inches of mercury (33.9 kPa) is 1.5. Thus, 100 scfm x 1.5 = 150 acfm (70.8 aL/s).

Refer to Table 10-6 to obtain C. This table has been developed from the flow characteristics of air in Schedule 40 pipe. Opposite 2-inch (50-millimeter) pipe is 42.92.

Solving for velocity, V = 150 acfm x 42.92 = 6,438 fps (1,962 meters per second).

Vacuum Work Forces

The total force of a vacuum system acting on a load is based on the vacuum pressure and the surface area on which the vacuum is acting. This is expressed in the following formula:

Equation 10-5

$$F = P \times A$$

where

F = Force, pounds (Newtons)
P = Vacuum pressure, psig (Pa or Newtons per square meter)
A = Area, square inches (square meters)

Since the above formula is theoretical, it is common practice to use a safety factor in the range of three to five times the calculated force to compensate for the quality of the air seal and other factors such as configuration of the load and outside forces such as acceleration.

VACUUM PUMPS AND SOURCE EQUIPMENT

Vacuum is produced by a single or multiple vacuum pump drawing air from remote vacuum inlets or equipment. Except for some rare industrial applications, vacuum pumps withdraw air from a receiver to produce the vacuum in the system.

Table 10-6 Constant, C, for Finding Mean Air Velocity

DN	40 Sched. Pipe Size, in.	C	DN	40 Sched. Pipe Size, in.	C
12	⅜	740.9	65	2½	30.12
15	½	481.9	75	3	19.53
20	¾	270.0	90	3½	14.7
25	1	168.0	100	4	11.32
32	1¼	96.15	125	5	7.27
40	1½	71.43	150	6	5.0
50	2	42.92	200	8	2.95

1 in. = 25.4 mm

Air exhausted from the system must be discharged to the atmosphere by means of an exhaust piping system. The pipe size shall be large enough to not restrict operation of the vacuum pump. (See the separate discussions under the "Laboratory and Vacuum Systems" and "Vacuum Cleaning Systems" sections, which follow.)

Alarms are required for maintenance purposes or to annunciate trouble, generally inadequate vacuum pressure, in the system.

Vacuum Pumps

The majority of vacuum pumps are divided into two general groups: gas transfer and capture. Capture-type pumps are outside the scope of this chapter.

Gas-transfer pumps are essentially air compressors that use the vacuum system as their inlet and discharge compressed air to the atmosphere. The majority of pumps used for most applications are gas-transfer pumps. They operate by removing gas from the lower pressure of the system and conveying it to the higher pressure of the free-air environment through one or more stages of compression provided by a vacuum pump. These pumps also are known as mechanical rotary-type pumps and are the type used most often for industrial and laboratory purposes.

These pumps can be divided into two categories: liquid sealed and dry. Liquid-sealed pumps use liquid, typically water or oil, to create a seal between the rotor and casing to produce a vacuum. Examples of liquid sealed gas-transfer pumps include rotary vane, once-through oil (OTO); rotary vane, recirculating oil sealed; oil-sealed reciprocating (rotary) piston; and liquid ring.

Dry vacuum pumps use tight tolerances to seal the pump chamber to produce vacuum. This can be done using closely machined tolerances or replaceable wearing sealing elements. These types of pumps generally run hotter than liquid-sealed pumps. Examples of dry pumps are rotary sliding vane, oil-less; reciprocating (rotary) dry piston; rotary lobe (roots), ordinary lobe or claw; rotary screw; diaphragm; and centrifugal (turbo).

Table 10-7 IP and SI Pressure Conversion

kPa abs.	in. Hg	in. Hg abs.	psia
101.4	0	29.92	14.70
97.9	1	28.92	14.2086
94.5	2	27.92	13.7173
91.5	3	26.92	13.2260
87.77	4	25.92	12.7347
84.39	5	24.92	12.2434
81.01	6	23.92	11.7521
77.63	7	22.92	11.2608
74.22	8	21.92	10.766
70.84	9	20.92	10.275
67.45	10	19.92	9.7838
64.07	11	18.92	9.2926
60.68	12	17.92	8.8015
57.29	13	16.92	8.3129
53.91	14	15.92	7.8216
50.52	15	14.92	7.328
47.13	16	13.92	6.8369
43.75	17	12.92	6.3457
40.37	18	11.92	5.8546
36.98	19	10.92	5.3634
33.59	20	9.92	4.8722
30.21	21	8.92	4.3811
26.82	22	7.92	3.8911
23.43	23	6.92	3.3988
20.05	24	5.92	2.9076
16.66	25	4.92	2.4165
13.27	26	3.92	1.9253
9.89	27	2.92	1.4342
6.502	28	1.92	0.9430
3.12	29	0.92	0.4520
2.71	29.22	0.80	0.3930
2.37	29.52	0.70	0.3439
2.03	29.72	0.60	0.2947
0	29.92	0	0

The diaphragm and centrifugal pumps are used more for small benchtop applications and not for central systems.

It is best to buy a vacuum pump as a complete package assembled by the pump manufacturer, with all of the accessories included. This way, the pump or pumps, receiver, inlet filter, oil-mist filter, oil separator, heat exchangers, cooling fans, water reservoir tanks, sensors, gauges, piping, valves, starters, disconnects, and controls all can be factory tested prior to delivery on site. Once on site, all that remains is field connection to the utilities and system piping. The individual components can be purchased separately, field located, and interconnected, but this requires additional time.

Equipment can be tank mounted or skid mounted. Skid-mounted equipment can be made in stackable-modular sections to conserve space or allow expansion in the future.

Receivers

The piping distribution system is connected to the pumps through a tank called a receiver. The receiver balances the vacuum pressure extremes produced by operation of the pump and maintains the desired range of vacuum as the demand rises or falls depending on the number of inlets that open or close. When the system vacuum pressure drops to a predetermined level beyond the capacity of a single pump, additional pumps in a multiplex assembly are started. When the desired high level of vacuum is reached, the pumps could be shut off.

Larger units may be constantly operated—loading, unloading, or bypassing on demand. Often, a timer on the system allows the pumps to run longer than required by system pressure to prevent rapid cycling. If the vacuum level cannot be achieved or maintained, an audible or visual alarm indicates the shortage.

Factors that affect receiver sizing are pump capacity, operating range, and piping system volume. On small piping systems, the receiver size is more important to avoid short-cycling the pumps. On larger piping systems, the size of the receiver has little effect on actual system operation, and it is selected by the manufacturer based on experience.

For laboratory systems with a liquid-ring pump and known to handle liquids, the receiver and hence the pumps should be placed at the lowest level of the building or piping system with the piping pitched back to the receiver. The receiver should have a sight glass and drain valve to drain all liquid from the receiver.

In other laboratory and process systems, the receiver and pumps can be installed anywhere in the building. If they are installed above the laboratory spaces such as in a mechanical penthouse, make sure provisions for draining the piping system at the low points are considered.

Seal Liquids

For liquid-ring pumps, a circulating liquid in the pump casing is an integral part of the pump operation. This liquid, generally water or oil, is commonly known as seal liquid and is not intended to refer to shaft or any other kinds of sealing.

Water, commonly used for sealing purposes, must be continuously replaced. With no conservation, approximately 0.5 gallons per minute (gpm) per horsepower (1.9 liters per horsepower) is used. Manufacturers have developed proprietary water-conservation methods that typically reduce the usage to approximately 0.1 gpm per horsepower (0.4 liter per horsepower). Specific information about water usage and the additional space required must be obtained from the manufacturer.

Oil used for sealing purposes is recirculated and may have to be cooled. The pump does not require any water to operate. The oil eventually becomes contaminated and must be replaced on a regular basis. Typically, a running time of 1,500 to 2,000 hours is the useful life of seal oil. It may be desirable to install a running time meter on these pumps to aid in maintenance. Some pumps using oil, such as the once-through oil rotary vane, often require more

installation space than other types of pumps. Specific information about the additional space required shall be obtained from the manufacturer. Other recirculating oil-sealed units will fit within the space required for other types of vacuum systems.

For once-through oil-sealed pumps, an oil supply and collection system can be engineered to supply oil and collect the waste oil from the pumps. The disposal of the waste oil should be considered in evaluating the cost of the pump.

Additional types of liquids can be used for seal liquid in a vacuum pump. A liquid from the process can be used, and the pump materials selected to suit the application. Consult a manufacturer or vendor to select the materials and equipment to design such a system.

Vacuum Pressure Gauges

The two commonly used gauges are the Bourdon and the diaphragm.

The Bourdon gauge is a mechanical gauge used to measure the difference in relative pressure between the system and local barometric pressure. The most widely used type of gauge, it is simple, inexpensive, and rugged. The heart of the gauge is the Bourdon tube that is closed at one end and open to the vacuum at the other. As the vacuum pressure varies, the tube changes shape. A pointer attached to the tube moves, indicating the pressure on a dial.

The diaphragm gauge measures the pressure difference by sensing the deflection of a thin metal diaphragm or capsular element. Similar to the Bourdon gauge, its operation relies on the deformation of an elastic metal under pressure.

Ancillary Equipment

Control panels should be mounted by the manufacturer on the skid to avoid field wiring. They also can be remotely mounted on a wall near the equipment, preferably within line of sight. All equipment on the skid, including the control panel, shall be UL listed.

A coalescing, or oil-mist, filter should be used on the exhaust of any pump that uses oil to prevent the discharge of oil into the atmosphere. It also can be used to recover solvents from the discharge airstream.

A knockout pot is a device that prevents entrained liquid or slugs of liquid from entering the inlet of mechanical pumps used in industrial applications. It also can be combined with an inlet filter in one housing.

Inlet filters are used to remove solids or liquids that may be present in the inlet airstream prior to the air entering the pump. Various filter elements are available to remove particulates approximately 0.3 micrometer in size.

Cooling of the vacuum pumps must be considered in the layout of the system. Most units can be air cooled with radiators and cooling fans mounted on the skid. The heat rejection into the space must be considered by the HVAC engineer to prevent the space from becoming too hot. A temperature increase of 5 to 20°F is not uncommon, and a vacuum pump's performance decreases as the room temperature escalates, which can result in a shorter life-cycle of the equipment. Some manufacturers have room temperature requirements for proper operation of their equipment.

Other units can be furnished with heat exchangers and cooled with domestic water or chilled water. Means of obtaining year-round chilled water sources must be considered. Cooling with domestic water on a once-through basis, after which the water is sent to the drainage system, is discouraged. Storm water reuse and graywater systems can be utilized as a cooling media where climates and programs allow for a reliable means of cooling. However, if the supply from these alternative water sources is less than required, a backup cooling source must be considered. Systems also have been developed that use an aluminum reservoir tank to cool the water through convection and radiation using relatively little makeup water.

In cases where the system as a whole has a high vacuum pressure, it may be necessary to lower the vacuum pressure to a branch. For liquid-ring pumps, this is generally done with an air-bleed valve on the branch where the lower vacuum pressure is desired. When the valve is opened, air is allowed to enter the system. For precise control, a needle valve is used. Bleeding air into the system must be accounted for in the selection of the pump capacity.

For other mechanical pumps, lowering the vacuum pressure can be accomplished by using a throttling valve at the inlet. This creates a higher vacuum drop at the throttling valve, allowing a lower vacuum level on the user side of the valve while maintaining the high vacuum level on the system side. This way no additional load (bleed air) must be accounted for in the system.

Some laboratory and most process pump skids using oil-sealed pumps may use an air or nitrogen gas purge. A purge usually occurs at the end of a pump run cycle to evacuate any chemical vapors that may condense as the pump cools. It also can occur at startup to warm up the pump and remove any condensed liquids. The purge cycle may last from five to 15 minutes.

LABORATORY VACUUM SYSTEMS

Laboratory vacuum systems serve general chemical, biological, and physics purposes. Principal among such purposes are drying, filtering, fluid transfer, and evacuating air from apparatus. The usual working

pressure of standard vacuum systems is in the range of 12 to 21 inches of mercury (40.6 to 67.7 kPa).

Some cases, usually in chemistry laboratories, call for high vacuum in the range of 24 to 29 inches of mercury (81.3 to 98.2 kPa), which is usually produced with a separate point-of-use vacuum pump adjacent to the area of application. Central systems can be designed to accommodate high vacuum uses down to 29.64 inches of mercury (7 torr). With the use of a booster (blower), a vacuum level of 29.88 inches of mercury (1 torr) is possible, but this is not recommended for large systems. These ultra-high vacuum systems should be used only for closed-ended systems (i.e., closed vessels at the use points). If used for general drying and filtering, they will not maintain vacuum levels. The system should be designed using an extensive program or spreadsheet to size the piping. Pipe sizes tend to be large due to the expansion of the air and vapor from atmospheric pressure to deep vacuum.

Other types of systems serve light industrial and manufacturing purposes, such as those of the pharmaceutical and chemical industries.

Codes and Standards

No codes and standards are applicable to the design of laboratory and manufacturing vacuum systems. The most important requirements are those of the end user and good engineering practice. For laboratory work within healthcare facilities, conformance to NFPA 99: *Standard for Healthcare Facilities* is required. The standard addresses different levels of systems based on the use of the facility. Some laboratories may fall under one of the categories listed, so the code should be investigated for applicability to your system.

Laboratories conducting biological work where airborne pathogens could be released are required to follow the appropriate biological level criteria established by *Biosafety in Microbiological and Biomedical Laboratories* (BMBL) developed by the U.S. Department of Health and Human Services Public Health Services, Centers for Disease Control and Prevention (CDC), and the National Institutes of Health (NIH). For most biological installations, check valves should be installed in each branch line to every room or area to prevent cross-discharge. It is common to have separate pumps for areas with different biological levels. In addition, the vacuum pump exhaust shall be provided with duplex 0.02-micrometer (HEPA) filters on the exhaust to prevent all pathogenic particulates from being expelled to the outside air.

On higher biosafety laboratory levels (BSL-3 or higher), it is more common to use point-of-use vacuum pumps located in the laboratory. This eliminates the potential of contaminated air being transferred out of the containment area. When using a central vacuum system on higher-level BSL laboratories, it is recommended to locate the filters upstream of the pump in the containment area. This requires the filters to be changed by the users and eliminates the potential of contaminating clean areas during filter change. By locating the filters in the containment area, the pump can be located and serviced outside the biological containment area. Considerations for decontamination of the piping and equipment should be evaluated for maintenance purposes. Additional isolation, sampling, and vent valves may be required to successfully allow for decontamination of the piping and equipment.

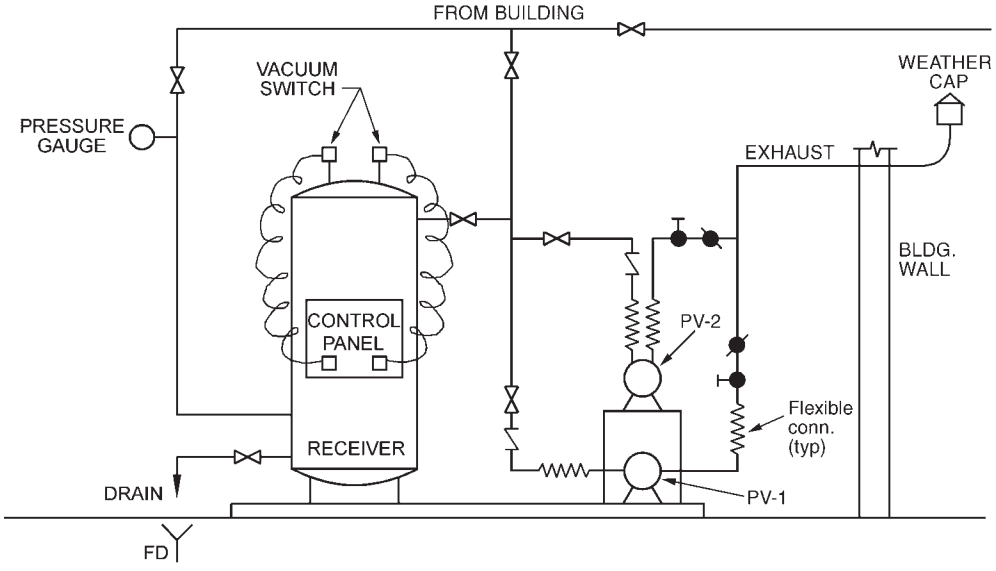


Figure 10-2 Schematic Detail of a Typical Laboratory Vacuum Pump Assembly

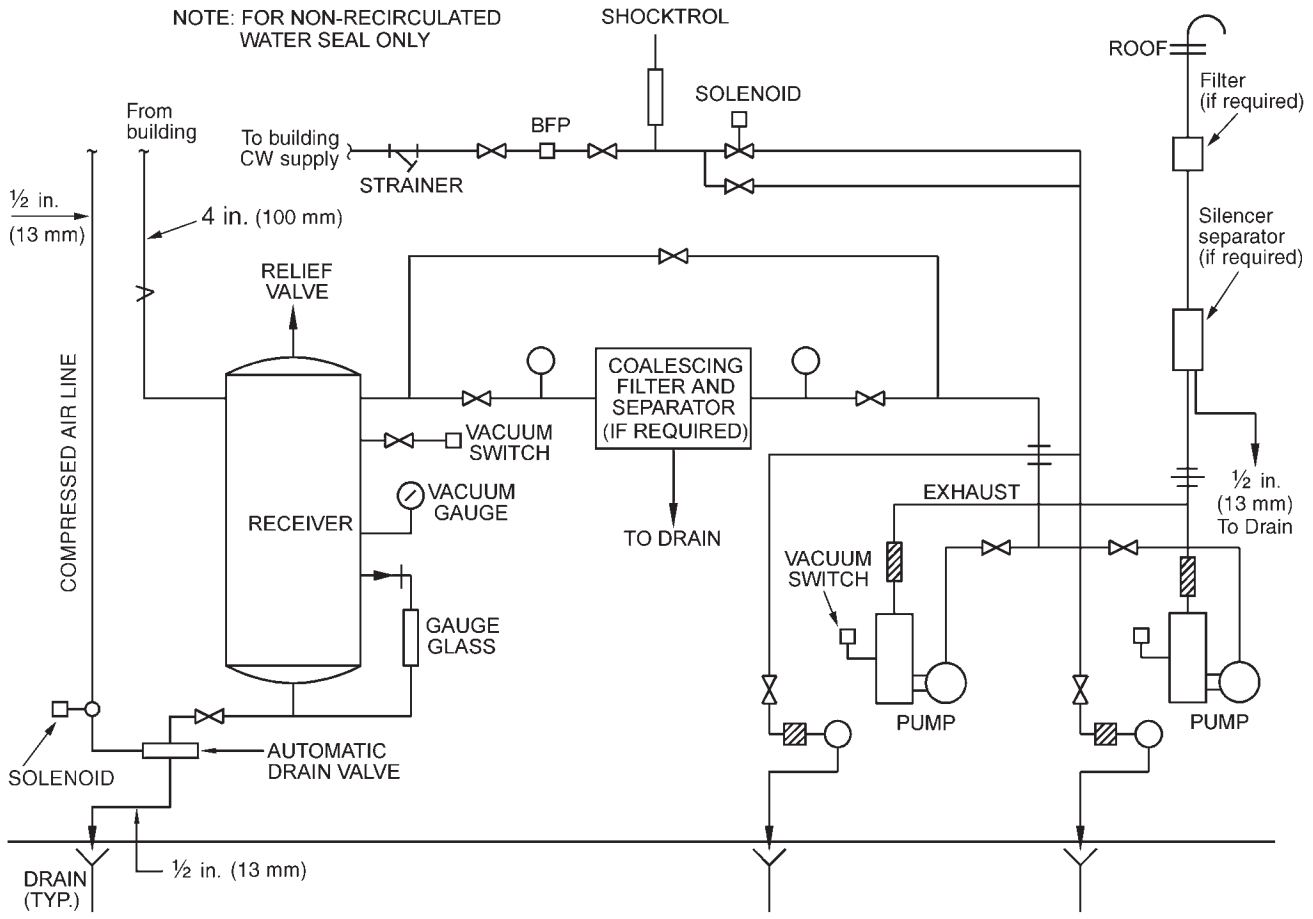


Figure 10-3 Typical Process Vacuum Pump Duplex Arrangement

Vacuum Source

The vacuum source usually consists of two or more pumps that are designed to operate as system demand requires, a receiver used to provide a vacuum reservoir and to separate liquids from the vacuum airstream, the interconnecting piping around the pumps and receiver, and alarms. A duplex system, with each pump capable of assuming the entire load, typically is selected if the system is critical to the operation of the laboratory. In some smaller installations where the vacuum system is not critical, it may be acceptable to have a single vacuum pump or two pumps designed to handle a percentage of the total load. This allows some level of capacity when one pump fails or needs to be maintained.

The pumps selection should be based on the anticipated design conditions consisting of vacuum level, process gases or liquids, first cost, maintenance cost, utility cost, and reliability. No single pump type will suit all applications; they each have strong and weak points.

The two most often used pump types in laboratories are liquid ring and sliding vane. A common configuration for more than one pump is a rack mounting one above the other and both pumps installed over the receiver for a compact footprint. A schematic detail of a typical laboratory vacuum pump assembly is illustrated in Figure 10-2. A schematic detail of a typical process vacuum pump duplex assembly is illustrated in Figure 10-3.

Dry pump technology has gained prominence over the past years due to water conservation concerns and waste oil disposal. These pumps have moved from strictly chemical duty into the laboratory and medical industry. Since they do run hot, they need to be evaluated for use on a laboratory or medical system so auto-ignition of the vapors does not happen.

Distribution Network

Piping for the distribution system shall be a corrosion-resistant material such as copper tube type K or L, stainless steel, galvanized steel pipe (usually Schedule 40 ASTM A53), or even plastic such as PVC, polypropylene, or high-density polyethylene. Copper tube shall be hard tempered except when installed underground, where soft tempered should be used. Although cost has a major influence on the selection of the piping material, the most commonly used is copper tube type L, ASTM B88, up to 4 inches (100

millimeters) in size, with soldered joints. Pipe 5 inches (125 millimeters) and larger is usually Schedule 40 galvanized steel pipe with malleable iron fittings and threaded joints.

Fittings shall have a long-turn drainage pattern so as to not impede the flow of fluids in the pipe. For high vacuum systems, steel pipe with welded joints should be considered to eliminate possible leaks.

General System Layout

It is recommended to locate the vacuum equipment at the lowest level of the system, so gravity will carry solids and liquids. The vacuum equipment may be at the top of the system such as in a penthouse, but heavy liquids and materials will collect at the low points. Proper clearances should be provided for maintenance and accessibility, including pump removal. Piping should be run with a slight slope back toward the receiver. Risers should have isolation valves. Provisions for cleanouts should be considered to allow cleaning of the vacuum piping. This is important since vacuum piping acts as a receiver and over the years will collect material along its walls.

Vacuum pump exhaust should vent outside, clear of any air intakes and windows. The routing should be as direct as possible and insulated for personnel protection near the pump since it may get hot depending on the pump selected. Provide a low-point drain valve since rainwater and condensed liquids in the exhaust stream may collect in the pipe.

Pipe Sizing Criteria

Number of Inlets

Using the project's plans, locate and count the number of inlets and determine the required flow rate for each. No codes or other mandated requirements specify the locations of vacuum inlets. The number of inlets is provided by the architect or lab programmer and determined by the end user, based on the requirements of all rooms, areas, and equipment used in the facility. Inlets for laboratory stations, fume hoods, etc. shall be appropriate for the intended use, based on the requirements of the end user.

Location of the Supply Source

Select the location of the supply source in conjunction with the architect, electrical department, and any others who are involved.

System Pressure

Determine the system operating pressure by discussing with the end user the type of research being performed and the function of the vacuum.

Flow Rate

The basic flow rate from each laboratory inlet shall be 1 scfm (0.47 sL/m). This flow rate is used in conjunction with the direct reading figure for the diversity factor. For manufacturing facilities, the flow rate shall be obtained from the manufacturer of the equipment being supported.

Allowable System Pressure Loss

A generally accepted criterion used to size a piping system is to allow a high-to-low pressure range of 3 to 5 inches of mercury (10.2 to 16.9 kPa) for the entire system (after the source assembly) and a maximum velocity between 4,000 and 5,000 feet per minute (1,219 to 1,524 meters per minute). If noise may be a problem, use 4,000 feet per minute (1,219 meters per minute). For smaller systems, use an allowable pressure loss of 1 inch of mercury (3.4 kPa) for each 100 feet (31 meters) of pipe. If dealing with high vacuum applications, the allowable high-to-low pressure loss is much less, in the range of 0.12 to 0.2 inch of mercury (3 to 5 torr). A generally accepted criterion is to use 10 percent of the highest pressure at the source.

Equivalent Run of Pipe

The equivalent length of piping is found by using the actual measured run of pipe and adding an associated length of pipe for various fittings and valves. Each fitting and valve has associated friction losses. To calculate this loss, you can use published tables that equate the losses seen in various fittings to the losses you would see in an equivalent length of pipe. Due to variations of pipe routings from the design to the contractor-completed installation, another common method used is to assume a percentage of the total length of piping to allow for fittings. The percentage of pipe length used to account for fittings can vary depending on the project. Some factors that need to be considered in assuming a percentage of total run for fittings are how much of the routing is long straight runs versus bends, the number of branch takeoffs, and the number of valves. All of these components can influence the equivalent length of pipe to account for fittings.

Common percentages to allow for fittings are between 15 and 50 percent of the measured run. The length of pipe run and the length of pipe to account for fittings is the total equivalent length.

Allowable Piping Pressure Loss

This is calculated using the allowable pressure loss for the system divided by the equivalent run of pipe in hundreds of feet. For example, if the measured run

Table 10-8 Diversity Factor for Laboratory Vacuum Air Systems

Number %	Use of Inlets Factor
1–2	100
3–5	80
6–10	66
11–20	35
21–100	25

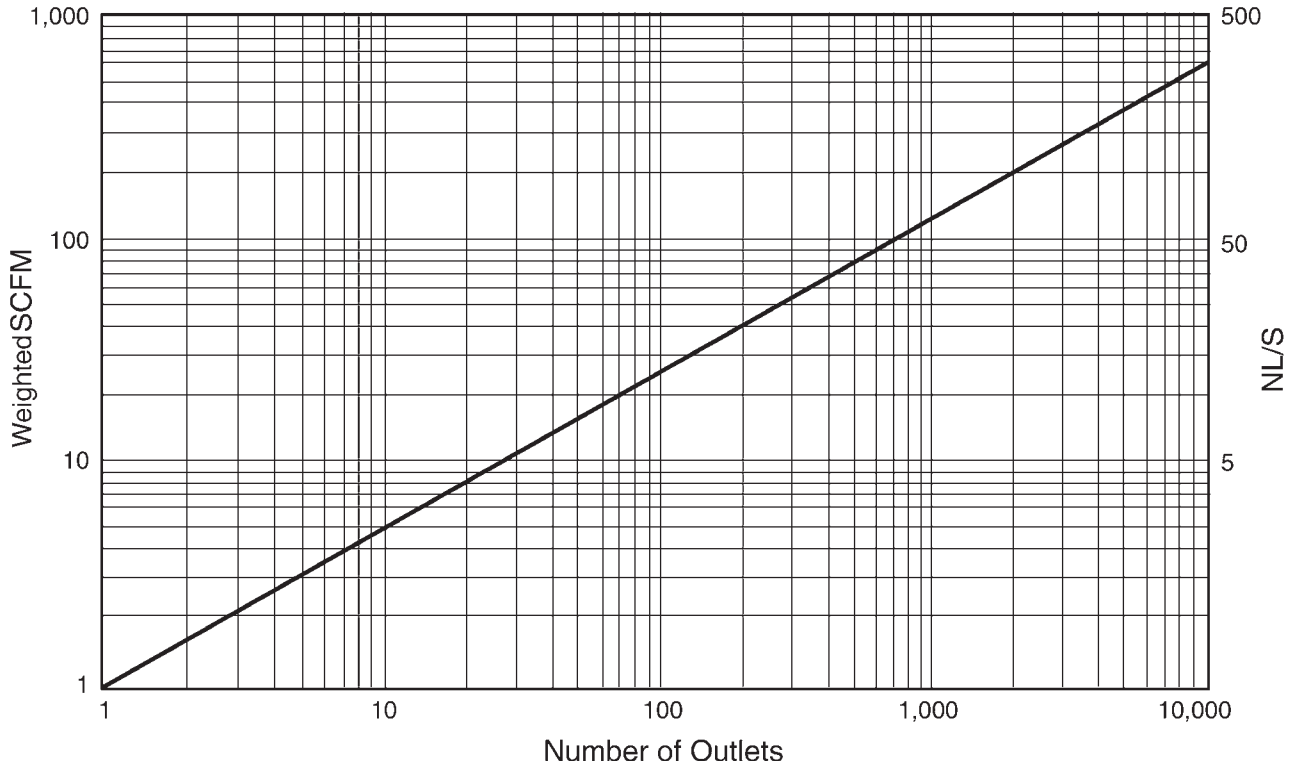


Figure 10-4 Direct Reading Chart Showing Diversity for Laboratory Vacuum

Table 10-9 Pressure Loss Data for Sizing Vacuum Pipe, Low Pressure Vacuum System

Standard Air Flow, cfm (L/min)	Pressure Drop per 100 ft (30 m) of Pipe, in. Hg (kPa) Nominal Pipe Size, in. (DN)							
	¾ (20)	1 (25)	1¼ (32)	1½ (40)	2 (50)	2½ (65)	3 (80)	4 (100)
1 (28.3)	0.15 (0.5)							
2 (56.6)	0.39 (1.3)	0.10 (0.3)						
3 (85.0)	0.77 (2.6)	0.19 (0.6)						
4 (113.3)	1.24 (4.2)	0.31 (1.1)	0.10 (0.3)					
5 (141.6)	1.78 (6.0)	0.44 (1.5)	0.14 (0.5)					
6 (169.9)	2.40 (8.1)	0.60 (2.0)	0.19 (0.6)					
7 (198.2)		0.77 (2.6)	0.24 (0.8)	0.12 (0.4)				
8 (226.6)		0.95 (3.2)	0.31 (1.1)	0.15 (0.5)				
9 (254.9)		1.17 (4.0)	0.38 (1.3)	0.18 (0.6)				
10 (283.2)		1.38 (4.7)	0.45 (1.5)	0.22 (0.7)				
15 (424.8)		2.80 (9.5)	0.88 (3.0)	0.44 (1.5)	0.12 (0.4)			
20 (566.4)			1.46 (4.9)	0.72 (2.4)	0.19 (0.6)			
25 (708.0)			2.20 (7.4)	1.09 (3.7)	0.29 (1.0)			
30 (849.6)				1.52 (5.1)	0.41 (1.4)	0.14 (0.5)		
35 (991.2)				2.00 (6.8)	0.54 (1.8)	0.18 (0.6)		
40 (1132.8)				2.50 (8.4)	0.67 (2.3)	0.22 (0.7)	0.10 (0.3)	
45 (1274.4)					0.81 (2.7)	0.27 (0.9)	0.12 (0.4)	
50 (1416.0)					0.99 (3.3)	0.33 (1.1)	0.14 (0.5)	
60 (1699.2)					1.34 (4.5)	0.45 (1.5)	0.19 (0.6)	
70 (1982.4)					1.79 (6.1)	0.60 (2.0)	0.26 (0.9)	0.07 (0.2)
80 (2265.6)					2.30 (7.8)	0.77 (2.6)	0.32 (1.1)	0.09 (0.3)
90 (2548.8)						0.96 (3.2)	0.41 (1.4)	0.11 (0.4)
100 (2832.0)						1.17 (4.0)	0.50 (1.7)	0.14 (0.5)
125 (3540.0)						1.71 (5.8)	0.74 (2.5)	0.20 (0.7)
150 (4248.0)						2.30 (7.8)	0.99 (3.3)	0.27 (0.9)
175 (4956.0)							1.28 (4.3)	0.35 (1.2)
200 (5664.0)							1.61 (5.4)	0.44 (1.5)

Source: Courtesy of Ohmeda.
Note: Based on copper pipe type L, ASTM B88.

Table 10-9(A) Pressure Loss Data for Sizing vacuum Pipe, High Vacuum Pressure System

Laboratory Vacuum Branch Piping – 26" Hg					
Total Outlets	Outlets Used	SCFM	Pipe Size	Velocity (FPM)	Pressure Drop (in Hg)
1	1.0	0.5	½	2,556	0.04
2	2.0	1.0	¾	2,454	0.02
3	3.0	1.5	¾	3,705	0.06
4	4.0	2.0	¾	4,998	0.12
5	5.0	2.5	1	3,617	0.05
6	5.7	2.9	1	4,209	0.07
7	6.4	3.2	1	4,657	0.08
8	7.1	3.6	1¼	3,412	0.04
9	7.9	3.9	1¼	3,701	0.05
10	8.6	4.3	1¼	4,088	0.05
11	9.3	4.6	1¼	4,380	0.06
12	10.0	5.0	1¼	4,771	0.07
13	10.5	5.2	1¼	4,967	0.08
14	11.0	5.5	1½	3,683	0.04
15	11.4	5.7	1½	3,819	0.04
16	11.9	6.0	1½	4,023	0.05
17	12.4	6.2	1½	4,160	0.05
18	12.9	6.4	1½	4,296	0.05
19	13.3	6.7	1½	4,502	0.06
20	13.8	6.9	1½	4,639	0.06
21	14.3	7.1	1½	4,777	0.06
22	14.8	7.4	1½	4,984	0.07
23	15.2	7.6	2	2,915	0.02
24	15.7	7.9	2	3,031	0.02

Velocity of 4,000 fpm,Type L copper, pressure drop in in. Hg/100 ft

is 300 feet and the building has a large percentage of fittings and valves versus long straight runs of pipe, add 50 percent of the total run for fittings (150 feet), which equals 450 feet of equivalent run. The allowable system pressure loss is calculated at 5 inches of mercury, so divide the allowable system pressure loss by the equivalent run times 100 to obtain the number in 100 feet of pipe. The result is a piping pressure loss of 1.1 inches of mercury per 100 feet. However, this calculation must be made in terms compatible with the chart or table for flow rate and pressure loss per length of pipe that you have selected for sizing.

Diversity Factor

The diversity factor established for general laboratories is based on experience. It has been found to be slightly more than that used for compressed air because the vacuum is often left on for longer periods of time. Refer to Figure 10-4 for a direct reading chart to determine the adjusted general laboratory vacuum flow rate based on the number of connected inlets regardless of type or location. Find the connected number of inlets along the bottom, and where the number crosses the reference line determine the scfm (sL/s) on the side of the chart.

For the design of classrooms, the diversity factor for one and two classrooms on one branch is 100 percent. For more than two classrooms, use a diversity factor double that found in Table 10-8, but never less than the largest scfm (sL/s) calculated for the first two rooms. Since the above flow rates and diversity factors are arbitrary, they must be used with judgment and modified if necessary for special conditions and client requirements. Always consult the user for definitive information regarding the maximum probable simultaneous usage of connected inlets. Table 10-8 has been prepared for a numerical calculation of the diversity factor, if desired.

Piping Network Sizing

The following method should be used to size the pipe at each design point. Use the previously calculated allowable piping pressure loss and adjusted scfm (sL/s) at each design point. For sizing a low vacuum distribution system, use the vacuum sizing chart in Table 10-9, which is based on scfm (sL/s) flow rate and friction loss in psi per 100-foot length of piping. For a high vacuum pressure, use Table 10-9(A). Proceed from the furthest point to the source. Enter Table 10-9 with the scfm (nL/m) and find the value equal to or less than the previously calculated allowable pressure loss for the system. Read the size at the top of the column where the selected value is found.

For industrial facilities, this information shall be obtained from the end user.

Source Vacuum Pump Sizing

The source pump for laboratories is selected using the flow rate of the gas at all inlets, the diversity factor for the whole facility, and a range of vacuum pressure. The source pumps for industrial facilities are sized using the total connected load reduced by a diversity factor determined from the duty cycle of the equipment and a diversity factor based on end-user requirements.

The pressure range usually extends from 5 inches of mercury (16.9 kPa) higher than the highest required vacuum pressure (the pump stopping point) to a low

Table 10-10 Vacuum Pump Exhaust Pipe Sizing

Total Vacuum Plant Capacity, All Pumps		Equivalent Pipe Length, ft (m)						
		50 (15.2)	100 (30.4)	150 (45.6)	200 (60.8)	300 (91.2)	400 (121.6)	500 (152)
scfm	nL/s	Pipe Size, in. (DN)						
10	4.72	2 (50)	2 (50)	2 (50)	2 (50)	2 (50)	2 (50)	2 (50)
50	23.6	2 (50)	2½ (65)	3 (75)	3 (75)	3 (75)	3 (75)	3 (75)
100	47.2	3 (75)	3 (75)	3 (75)	4 (100)	4 (100)	5 (125)	5 (125)
150	71	3 (75)	4 (100)	4 (100)	4 (100)	5 (125)	5 (125)	5 (125)
200	55	4 (100)	4 (100)	4 (100)	5 (125)	5 (125)	5 (125)	5 (125)
300	142	4 (100)	5 (125)	5 (125)	5 (125)	6 (150)	6 (150)	6 (150)
400	189	5 (125)	5 (125)	6 (150)	6 (150)	6 (150)	8 (200)	8 (200)
500	236	5 (125)	6 (150)	6 (150)	6 (150)	8 (200)	8 (200)	8 (200)

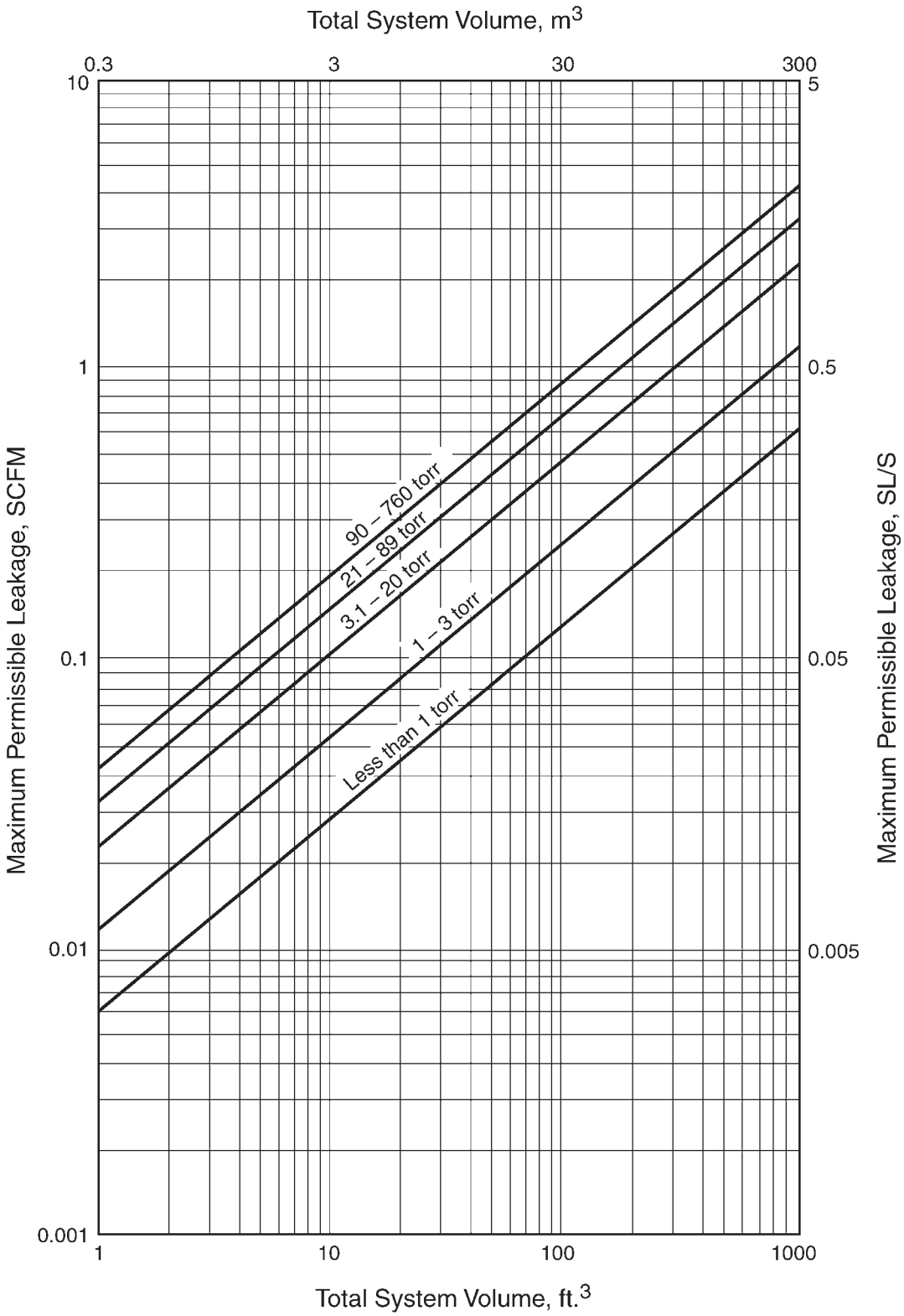


Figure 10-5 Acceptable Leakage in Vacuum Systems

Source: Courtesy of Becker Pumps

figure equal to the lowest acceptable system pressure (the pump starting point). For duplex and triplex pump arrangements, the intermediate vacuum settings for multiple pumps shall be adjusted accordingly.

Vacuum Pump Exhaust Pipe Sizing

For sizing the exhaust piping from the vacuum pump source assembly, refer to Table 10-10, using the equivalent length of exhaust piping as the length of piping. (See the "Piping Network Sizing" section below for a definition of equivalent length.)

System Leakage

There is a difference between desirable and acceptable leakage in a vacuum system. Ideally, no leakage should occur. It is common practice to test laboratory vacuum piping systems, section by section, at the rated maximum working pressure for 24 hours with no loss of pressure permitted. Yet it is almost impossible to install a large system that does not have small leaks. If such is the case, what is an acceptable amount of leakage?

There is no generally accepted value for allowable leakage in a vacuum system, which should be related to the volume of the piping network to be meaningful. However, the Heat Exchange Institute has developed a standard based on system volume. This formula, transposed to solve for leakage, is:

Equation 10-6

$$L = \frac{\frac{0.15 \times V}{T}}{4.5}$$

where

L = Leakage, scfm (sL/s)(To convert to metric, multiply L by 0.4719.)
V = Total piping system volume, cubic feet (cubic meters)
T = Time for vacuum pressure to drop 1 inch of mercury, minutes

After calculating the system volume and the leakage from the system, use Figure 10-5 to determine if the intersection of the two values falls within the acceptable portion of the chart.

VACUUM CLEANING SYSTEMS

Vacuum cleaning systems are used to remove unwanted dirt, dust, and liquids from floors, walls, and ceilings. This involves the use of either a permanent, centrally located system or portable, self-contained, electric-powered units. A central system transports the unwanted debris to a central location where it can be disposed of or recovered easily. Portable units can be moved throughout all areas of a facility. The design of portable units is outside the scope of this chapter.

Types of Systems and Equipment

The three types of permanent systems are dry, wet, and combination. The dry system is intended exclusively for free-flowing dry material. It is the most commonly used type of system, with cleaning capabilities ranging from cleaning carpets to removing potentially toxic and explosive product spills from the floors of an industrial facility. Equipment consists of a vacuum producer, one or more separators that remove collected materials from the airstream, tubing to convey the air and materials to the separator, and inlets located throughout the facility. A wide variety of separators is available to allow disposal and recovery of the collected materials.

The wet system is intended exclusively for liquid handling and pickup. It is commonly found in healthcare, industrial, and laboratory facilities where sanitation is important and frequent washings are required. Equipment consists of a vacuum producer, a wet separator constructed to resist the chemical action of the liquids involved, piping or tubing of a material resistant to the chemical action of the liquid, and inlets located throughout the facility.

A combination system is capable of both wet and dry pickup. Equipment consists of a vacuum producer, a wet separator constructed to resist the chemical action of the liquid mixtures involved, pipe or tubing of a material resistant to the chemical action of the combined solid/liquid, and inlets located throughout the facility.

Codes and Standards

No codes and standards directly govern the design and installation of vacuum cleaning systems. If dealing with explosive powders, NFPA 68: *Standard on Explosion Protection by Deflagration Venting* and NFPA 69: *Standard on Explosion Prevention Systems* may apply.

System Components

Vacuum Producer

Vacuum producers for typical vacuum cleaning systems consist of a single or multistage centrifugal-type unit powered by an electric motor. The housing can be constructed of various materials to handle special chemicals and nonsparking aluminum for potentially explosive dust. The discharge of the unit can be positioned at various points to accommodate the requirements of the exhaust piping system. Silencers, sound-attenuating enclosures, or rooms can be provided to attenuate the noise.

Separator

Separators are used to remove the solid particulates in the airstream generated by the vacuum producer. For dry systems, tubular-bag and centrifugal-type separators can be used.

If only dust and other fine materials are expected, a tubular-bag type is adequate. The bag is permanently installed and cannot be removed. It functions as an

air filter for fine particles and collects a majority of the dirt. This dirt eventually falls into a hopper or a dirt can at the bottom of the unit. To empty the entire unit, the system must be shut down. The bag must be shaken to remove as much of the collected material as possible and emptied into the dirt can. The dirt can is removed (or the hopper is emptied into a separate container) to clean out the unit. The dirt can should be sized to hold at least one full day's storage. Units are available with multiple bags to increase filter bag area. Shaking can be done either manually or by motor. The motor-operated shaker has adjustable timers to start operation after shut down of the system and to shake the bags. If continuous operation is required, compressed air can be blown through the bag to remove the dirt without requiring a shutdown.

The centrifugal-type separator is designed to remove coarse, dry particles from the airstream. It also is recommended when more than six simultaneous operators are anticipated to remove the bulk of the dirt. The air enters the separator tangential to the unit, and the air containing particulates is forced into a circular motion within the unit. Centrifugal force accomplishes separation.

The wet separator system collects the liquid, separates the water from the airstream, and discharges the waste to the drain. This type of separator can be equipped with an automatic overflow shutoff that stops the system if the water level reaches a predetermined high-water level and with automatic emptying features.

Immersion-type separators are used to collect explosive or flammable materials in a water compartment. If there is a potential for explosion, such as exists in a grain or flour-handling facility, the separator shall be provided with an integral explosion relief/rupture device that is vented to the outside of the building.

Filter

Vacuum producers typically are exhausted to the outside air and do not require any filtration. However, when substances removed from the facility are considered harmful to the environment, a HEPA filter must be installed in the discharge line to prevent contamination of the outside air. The recommended location is between the separator and the vacuum producer, but an alternate location immediately prior to penetration of the building wall or roof is also acceptable.

Silencer

When the exhaust from the vacuum producer is considered too noisy, a silencer shall be installed in the exhaust to reduce the noise to an acceptable level. Pulsating airflow requires special design considerations. The connection to the silencer shall be made with a flexible connection. Additional support for the silencer is recommended. Filters and silencers can be economically combined into a single, integral unit.

Inlets

Inlets are female inlet valves and are equipped with self-closing covers. They provide a quick connection for any male hose or equipment. The covers can be locked as an option. Many different inlet types are available, in sizes ranging from 1½ to 4 inches (40 to 100 millimeters) and of various materials.

Control and Check Valves

Valves for vacuum cleaning systems are different than standard valves. They are used to control the flow or stop the reverse flow of air in the system. When used only fully open or closed, they generally are referred to as blast gates. When used as regulating valves, they are called wafer butterfly valves. A less costly substitute for a blast gate is an air gate valve, which operates using a sliding plate in a channel. The plate has a hole that matches the size of the opening in the channel, with room to close off the opening completely. Air gates can be used only in low-pressure systems and are generally available in sizes from 2 to 6 inches (50 to 150 millimeters).

Check valves are typically spring-loaded, swing-type valves hinged in the center.

Air-bleed Control

If the exhauster is constantly operated with low or no inlet air, the exhauster motor might become hot enough to require shutdown due to overheating. To avoid this, an air-bleed device can be installed on the inlet to the exhauster that will automatically allow air to enter the piping system. If the facility indicates that this may be a possibility, the manufacturer of the unit should be consulted to determine the need for this device for the system selected.

Pipe and Fittings

The pipe material most often used is thin-wall tubing, generally in the range of 12 to 16 gauge. This tubing is available in plain carbon steel, zinc-coated steel, aluminum, and stainless steel. In some cases PVC can be used; however, you should verify with the pipe manufacturer that it can be used for the intended vacuum level of your system.

Fittings are specially designed for a vacuum cleaning system. Tubing typically is joined using shrink sleeves over the joints. Compression fittings and flexible rubber sleeves and clamps also are used. Tubing shall be supported every 8 to 10 feet (2.4 to 3.1 meters), depending on size, under normal conditions.

Standard steel pipe often is used in areas where the additional strength is required. In special areas where leakage prevention and strength are mandatory, the tubing joints can be welded if required.

Table 10-11 Recommended Sizes of Hand Tools and Hose

Nominal Size		Average Floor Cleaning and Moderate Spills	Close Hand Work	Removing Heavy Spills or Large Quantities of Materials	Overhead Vacuum Cleaning	Standard Hose Length	
DN	in.					ft	m
25	1	Not used	Yes	Inadequate	Not used	8	2.4
40	1½	Excellent	Yes	Fair	Preferred	25 and 50	7.5 and 15
50	2	Good	No	Good	Poor	25 and 50	7.5 and 15
65	2½	Not used	No	Excellent	Not used	25 and 50	7.5 and 15

Source: Courtesy of Hoffman

Detailed System Design

Inlet Location and Spacing

The first step in system design is to locate the inlets throughout the facility. The spacing of the inlets depends on the length of hose selected for use. After this is decided, the inlet locations shall be planned in such a manner that all areas can be reached by the selected hose length. This planning must take into account furniture, doorways, columns, and all other obstructions. Some small overlap must be provided to allow for hoses that cannot be stretched to the absolute end of their length. A 25-foot (7.5-meter) spacing should be provided in areas where spills are frequent, heavy floor deposits may occur, or frequent spot cleaning is necessary.

Generally, several alternate locations are possible for any given valve. Inlets should be placed near room entrances. Wherever possible, try to locate inlets in a constant pattern on every floor. This allows for the location of common vertical risers since the distance between floors is less than the distance between inlets. In any system, minimizing piping system losses by a careful layout will be reflected in reduced power requirements for the exhauster.

The inlets should be located between 24 and 36 inches (600 and 900 millimeters) above the floor.

Determining the Number of Simultaneous Operators

This is another major design consideration because an under-designed system will not produce the desired level of vacuum and an oversized system will be costly.

The maximum number of simultaneous operators is decided by the facility's housekeeping or maintenance department and depends on a number of factors:

- Is gang cleaning the preferred method? Is it possible to alter this practice to result in a less costly system?
- What is the maximum number of operators expected to use the system at the same time?
- Is the work done daily?

If no information is available for a commercial facility, the following guidelines are based on experience and can be used to estimate simultaneous use based on productivity. These figures consider the greater efficiency of using a central system compared to portable units, often in the order of 25 percent. However, they must be verified and based on the actual methods anticipated.

For carpets, one operator will be expected to cover 20,000 square feet (1,860 square meters) of area for regular carpeting in an eight-hour shift. For long or shag carpets, the figure is about 10,000 square feet (930 square meters). Another generally accepted figure for short time periods is 3,000 square feet per hour (280 square meters per hour) for standard floors, and 2,500 square feet per hour (233 square meters per hour) for shag and long carpets.

For hotels, an average figure of 100 rooms, including adjacent corridors, per eight-hour shift would be expected. For long or shag carpets, the figure is about 75 rooms.

For theaters, use the number of seats divided by 1,000 to establish the number of simultaneous operators.

For schools, 12 classrooms per day is an average figure for a custodian to clean in addition to other duties normally accomplished.

Inlet Valve, Tool, and Hose Sizing

The recommended sizes for hand tools and hose are given in Table 10-11.

Experience has shown that 1½-inch (40-DN) hose and tools for cleaning floors, walls, and ceilings is the most practical size to use. Smaller 1-inch (25-DN) tools are used for cleaning production tools, equipment, and benches. Larger hose and tools are used for picking up expected large spills and cleaning large tanks, boxcars, and the holds of ships.

Standard hoses are available in 25, 37.5, and 50-foot (7.5, 12, and 15-meter) lengths. For general cleaning, the location of inlet valves should allow for convenient cleaning, with a maximum of 50 feet (15 meters) of hose. This represents a labor savings by halving the number of times an operator has to change outlets. This length should not be exceeded, except for occasional cleaning, because of excessive pressure drop.

Table 10-12 Flow Rate and Friction Loss for Vacuum Cleaning Tools and Hoses

Use	Nominal Size of Tools and Hose	Minimum Volume and Pressure Drop[a]		Maximum Volume and Pressure Drop[a]	
		Volume, scfm	Pressure Drop, in. Hg	Volume, scfm	Pressure, in. Hg
Bench use	1-in. diam., 8-ft 1-in. flexible hose	40	1.20	50	1.90
White rooms or areas with very low dust content	1½-in. diam., 50-ft 1½-in. flexible hose	60	2.25	90	4.10
Usual industrial	1½-in. diam., 50-ft 1½-in. flexible hose	70	2.80	100[b]	4.80
Fissionable materials or other heavy metallic dusts and minute particles of copper, iron, etc.	1½-in. diam., 50-ft 1½-in. flexible hose	100	2.50	120	4.20
Heavy spills, Cleaning railroad cars and ship holds	2-in. diam., 50-ft 2-in. flexible hose	120	2.60	150	3.8

Source: Courtesy of Hoffman
Note: 1 scfm = 0.5 nL/s; 1 in. Hg = 3.4 kPa
[a] The pressure drop in flexible hose is 2½ times the pressure drop for the same length and size of Schedule 40 pipe.
[b] Can be exceeded by 10% if necessary.

Locating the Vacuum Producer Assembly

The vacuum producer assembly consists of the vacuum producer, commonly called an exhauster, and the separators. The following shall be considered when locating the vacuum equipment:

Provide enough headroom for the piping above the equipment and for the various pieces to be brought easily into the room or area where they are to be installed.

An ideal location is on the floor below the lowest inlet of the building or facility and centrally located to minimize the differences at remote inlet locations.

A convenient means to dispose of the collected debris should be available nearby. If a wet separator is used, an adequately sized floor drain is required.

Enough room around the separators shall be provided to allow for easy inspection, and, where dirt bins must be emptied, room must be provided for the carts needed to move them. Dry separators can be located outside the building for direct truck disposal of the dirt, if sufficiently protected.

Sizing the Piping Network

After the inlets and vacuum equipment have been located, the layout of the piping system accomplished, and the number of simultaneous operators determined, system sizing can begin.

Cleaning systems using hose and tools shall have sufficient capacity so that one pass over an area is all that is necessary for cleaning. With adequate vacuum, light to medium dirt deposits shall be removed as fast as the operator moves the floor tool across the surface. The actual cleaning agent is the velocity of the air sweeping across the floor.

Vacuum Pressure Requirements and Hose Capacity

To achieve the necessary air velocity, the minimum recommended vacuum pressure for ordinary use is 2 inches of mercury (7 kPa). For hard-to-clean and industrial-type materials, a vacuum pressure of 3 inches of mercury (10 kPa) is required. The flow rate must be sufficient to bring the dirt into the tool nozzle. Refer to

Table 10-13 Recommended Velocities for Vacuum Cleaning Systems

Nominal Tubing Size		Horizontal Runs of Branches and Mains and Vertical Downflow Risers		Vertical Upflow Risers	
in.	DN	Minimum Velocity (ft/min)	Recommended Max. Velocity (ft/min)	Minimum Velocity (ft/min)	Recommended Max. Velocity (ft/min)
1½	40	1,800	3,000	2,600	3,800
2	50	2,000	3,500	3,000	4,200
2½	65	2,200	3,900	3,200	4,700
3	75	2,400	4,200	3,800	5,100
4	100	2,800	4,900	4,200	6,000
5	125	3,000	5,400	4,800	6,500
6	150	3,400	6,000	5,000	7,200

Source: Courtesy of Hoffman
Note: 1 ft/min = 0.3 m/min

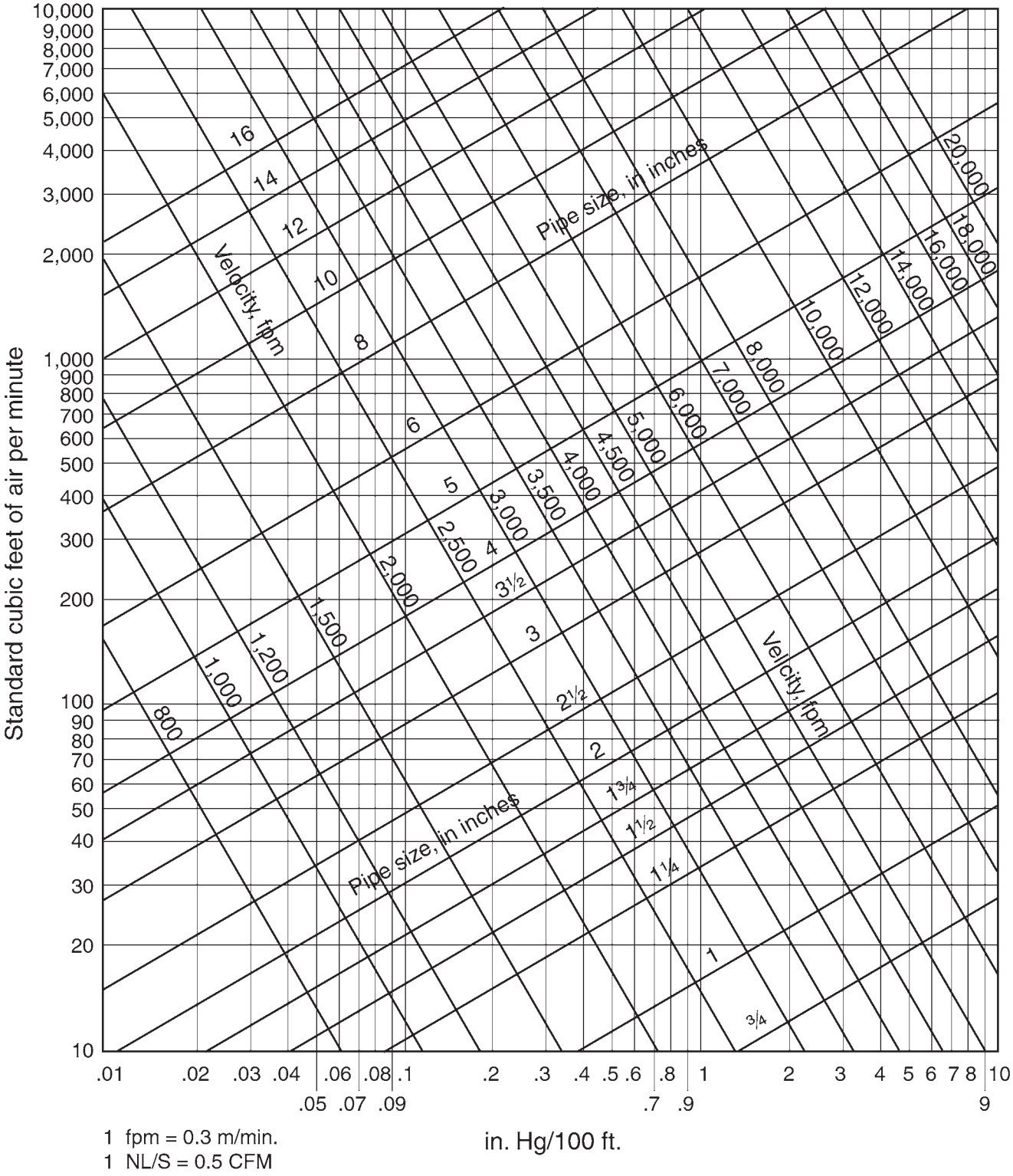


Figure 10-6 Vacuum Cleaning Piping Friction Loss Chart

Table 10-14 Pipe Size Based on Simultaneous Usage

Line Diameter		Number of Operators	
in.	DN	70 scfm, 1.5-in. hose	140 scfm, 2-in. hose
2	50	1	—
2½	65	2	1
3	75	3	2
4	100	5	3
5	125	8	4
6	150	12	6
8	200	20	10

Source: Courtesy of Spencer Turbine
Note: 1 scfm = 0.5 sL/s

Table 10-15 Equivalent Length (ft) of Vacuum Cleaning Pipe Fittings

Nominal Pipe Size		Equivalent Length of Pipe Fittings (ft)[a]	
in.	DN	90° Change in Direction	45° Change in Direction
1¼	32	3	1½
1½	40	4	2
2	50	5	2½
2½	65	6	3
3	75	7	4
4	100	10	5
5	125	12	6
6	150	15	7½
8	200	20	10

Notes: 1) For smooth-flow fittings, use 90% of these values.
2) 1 ft = 0.3 m
[a] Lengths based on use of cast-iron drainage fittings.

Table 10-12 to determine the minimum and maximum recommended flow rate of air and the friction losses of each hose size for the flow rate selected. For ordinary carpeting and floor-cleaning purposes, a generally accepted flow rate of 70 scfm (35 sL/s) is recommended.

Recommended Velocity

The recommended velocity in the vacuum cleaning piping system depends on the pipe's orientation (horizontal or vertical) and size. Since the velocity of the air in the pipe conveys the suspended particles, it should be kept within a recommended range. Refer to Table 10-13 for recommended velocities based on pipe size and orientation of the pipe.

The air velocity moves the dirt in the system. Oversizing the pipe will lead to low velocity and poor system performance.

Selecting the Number of Outlets Used Simultaneously

Facilities may have many inlet valves, but only a few inlet valves will be used at once. Under normal operating conditions, these inlets are chosen at random by the operators. To aid in the determination of simultaneous usage, the following conditions, which should be expected, are given:

- Adjacent inlet valves will not be used simultaneously.
- For the purposes of calculating simultaneous use, the most remote inlet on the main and the inlet closest to the separator will be assumed to be in use, along with other inlet valves between the two.
- Where mains and outlets are located on several floors, the use of inlets will be evenly distributed along a main on one floor or on different floors.
- For long horizontal runs on one floor, allow for two operators on that branch.

Sizing the Piping

Refer to Table 10-14 to select the initial pipe size based on the number of simultaneous operators. This table has been calculated to achieve the minimum velocity of air required for adequate cleaning. In this table, line refers to permanently installed pipe from the inlet to the separator, and hose is the hose connecting the tool to the inlet. A hose size of 1½ inches (40 DN) is recommended, except where the material to be cleaned will not pass through hose of this size or where a large volume of material is expected.

After the initial selection of pipe sizes, the actual velocity and friction loss based on the anticipated flow rates in each section of the piping system should be checked by using Figure 10-6. This chart provides a more accurate method of determining the pipe size, friction loss, and velocity of the system. To use it, enter the chart with the adjusted scfm and allowable pressure loss. Read the pipe size at the point where these two values intersect. If this point is between lines, use the larger pipe size. If any parameter is found to be outside any of the calculated ranges, the pipe size should be revised.

Pipe sizing is an iterative procedure, and the sizes may have to be adjusted to reduce or increase friction loss and velocity as design progresses.

Piping System Friction Losses

With the piping network sized, the next step is to calculate the precise worst-case total system friction losses, in inches of mercury (kPa), to size the exhauster. Friction losses are calculated by adding all of the following values, starting with the inlet most remote from the exhauster and continuing to the source:

Initial level of vacuum required: For average conditions, the generally accepted figure is 2 inches of mercury (6.8 kPa). For hard-to-clean material,

Table 10-16 Classification of Material for Separator Selection

Size of material	Very Fine		Fine		Granular		Lumpy		Irregular
	Recommended Sep. (S)	Ratio Vol. Bag Area	Recommended Sep. (S)	Ratio Vol. Bag Area	Recommended Sep. (S)	Ratio Vol. Bag Area	Recommended Sep. (S)	Ratio Vol. Bag Area	Separator Selection & Bag Area
Small	Cent.	Not appl.	Cent.	Not appl.	Cent.	Not appl.	Cent.	Not appl.	dependent on material
Medium	TB	6:1	Cent. and TB	6:1	Cent.	Not appl.	Cent.	Not appl.	
Large	Cent. and TB	3:1	Cent. and TB	6:1	Cent. and TB	6:1	Cent.	Not appl.	

Source: Courtesy of Spencer Turbine Co

Notes: 1. Centrifugal separators do not utilize bags.

2. Definition of terms:
   - Small: Light accumulations, such as those found in clean rooms, white rooms, laboratories, and so on.
   - Medium: Average accumulations, such as those found in classrooms, motels, assembly areas, and so on.
   - Large: Heavy accumulations, such as those found in foundries, spillage from conveyor belts, waste from processing machines, and so on.
   - Fine: 100 mesh to 8 in. (3.2 mm).
   - Very fine: Less than 100 mesh.
   - Granular: 8 to ½ in. (3.2 to 12.7 mm).
   - Lumpy: Lumps ½ in. (12.7 mm) and over.
   - Irregular: Fibrous, stringy, and so on.

3. Abbreviations: Cent. = centrifugal; TB = tubular bag.

industrial applications, and long shag-type carpet, the initial vacuum should be increased to 3 inches of mercury (10.2 kPa).

Pressure drop through the hose and tool: Refer to Table 10-12 for the friction loss through individual tools and hose based on the intended size and length of hose and the flow rate selected for the project.

Loss of vacuum pressure due to friction of the air in the pipe: Losses in the straight runs of the piping system are based on the flow rate of the air in the pipe at the point of design. (Refer to Figure 10-6.) Fittings are figured separately, using an equivalent length of pipe added to the straight run. Refer to Table 10-15 to determine the equivalent length of run for each type and size of fitting. Starting from the farthest inlet, use the cfm, pipe size, fitting allowance, and pipe length along the entire run of pipe to find the total friction loss.

Loss through the separator: A generally accepted figure is 1 inch of mercury (3.4 kPa) loss through all types of separators. However, the exact figure must be obtained from the manufacturer.

Exhaust line loss: This usually can be ignored except for long runs. Allow 0.1 inch of mercury (0.34 kPa) as an average figure for a run of 100 feet (30 meters).

Vacuum Producer Sizing

Exhauster Inlet Rating Determination

It is now possible to size the exhauster. The two exhauster ratings that must be known to select the size and horsepower are the worst-case piping system vacuum pressure losses and the flow rate, in scfm (sL/s), of air required by the system.

The vacuum pressure required from the exhauster is the total pressure necessary to overcome all piping system losses. This consists of the total pressure drop from all components in the piping network from the inlet farthest from the exhauster. Included are the initial inlet vacuum level required, pressure lost through the tool and hose selected, friction loss of air flowing through the piping system, pressure lost through separators, filters, and silencers, and finally the exhaust pressure to be overcome, if required. These values are added to establish the vacuum rating of the exhauster.

The flow rate of the air, in scfm (sL/s), entering the system is calculated by multiplying the number of simultaneous operators by the scfm (sL/s) selected as appropriate for the intended cleanup requirements. For smaller, less complex systems, using only the actual selected inlet cfm (L/s) is sufficient.

Exhauster Discharge

The discharge from the exhauster is usually steel pipe routed outside the building. It is also possible to route the exhauster discharge into an HVAC exhaust duct that is routed directly outside the building.

For a piped exhaust, if the end is elbowed down, it shall be a minimum of 8 feet (2.4 meters) above grade. If the end is vertical, an end cap shall be installed to prevent rain from entering the pipe. A screen should be used to prevent insects from entering. The size shall be equal to or one size larger than the size of the pipe into the exhauster. Use HVAC ductwork sizing methods to find the size of the exhaust piping while keeping the air pressure loss to a minimum.

The pressure loss through the exhaust pipe shall be added to the exhauster inlet pressure drop, the total of which will be calculated into the pressure that the exhauster must overcome. For short runs of about 20 feet (6 meters), this can be ignored.

To account for the various fittings comprising the exhaust system, an additional 30 percent should be added to the measured run to calculate the equivalent piping run.

Exhauster Rating Adjustments

For systems with very long runs or complex systems with both long and short runs of piping, some adjustment in the selected inlet flow rate (in cfm {liters per second]) shall be made. This is necessary because the actual flow rate at the inlets closest to the exhauster will be greater than the cfm at the end of the longest run due to the smaller friction loss. The adjustment will establish an average inlet flow rate for all inlets that will be used for sizing instead of the selected inlet flow rate.

To establish the adjusted flow rate, it is necessary to calculate separately the total system friction loss for each branch line containing inlets nearest and farthest from the exhauster. Following the procedures previously explained will result in minimum and maximum system friction loss figures.

The following formula can be used to calculate the adjusted cfm (liters per second):

Equation 10-7

$$\text{adjusted cfm} = \frac{\text{farthest inlet friction loss (in. Hg)}}{\text{closest inlet friction loss (in. Hg)}} \times \text{selected cfm}$$

The adjusted figure is used instead of the selected flow rate and multiplied by the number of simultaneous operators to size the exhauster.

All of the above calculations are based on scfm (sL/s) at sea level. If the location of the project is at an elevation higher than sea level, the figure should be adjusted to allow for the difference in barometric pressure. Refer back to Table 10-5 for the factor. This factor shall be multiplied by the figure to calculate the adjusted flow rate to be used in sizing the exhauster.

Another adjustment to the scfm (sL/s) figure used to size the exhauster is required if the equipment manufacturer uses icfm (iL/s) instead of scfm (sL/s). icfm (iL/s) is the actual volume of air at the inlet of

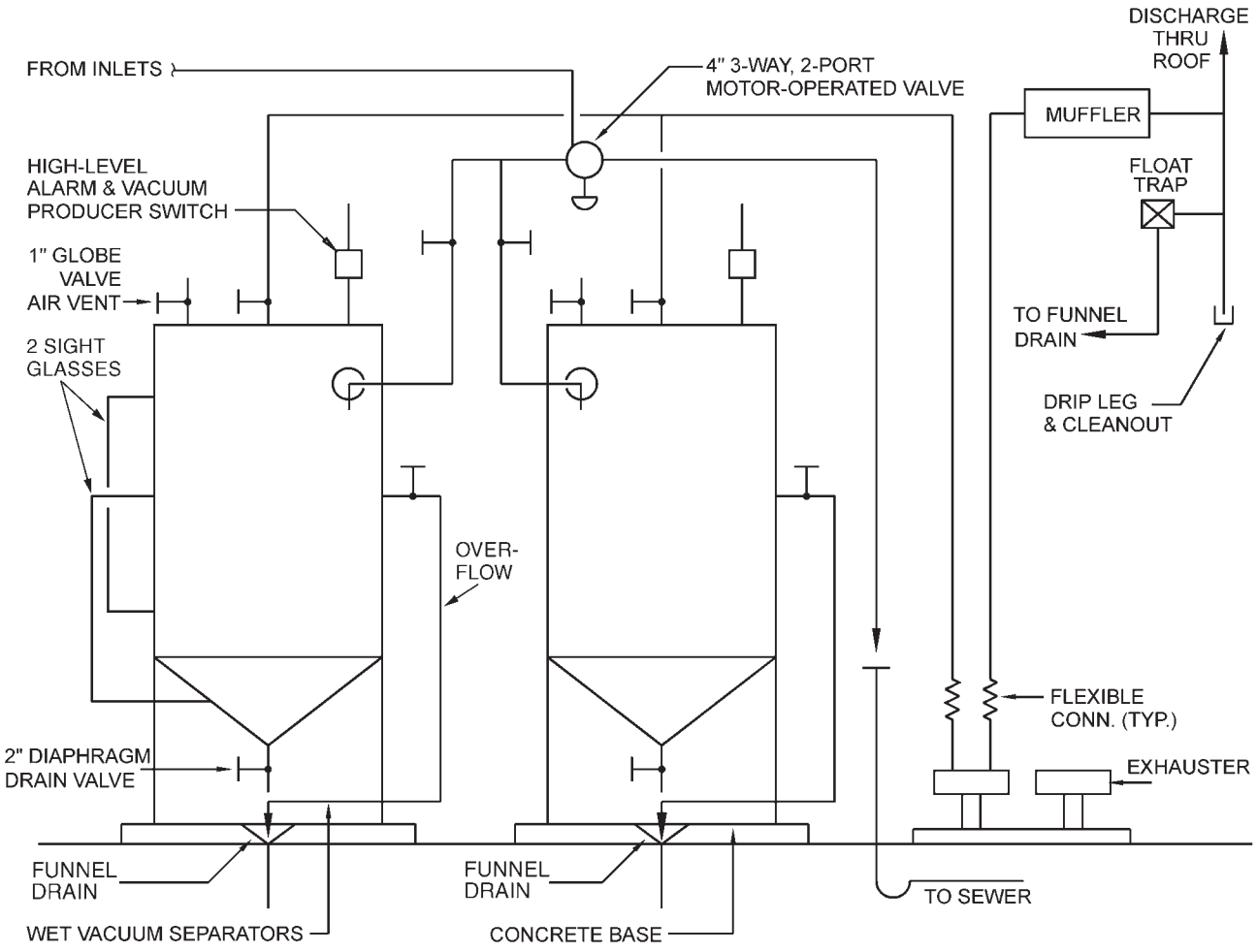


Figure 10-7 Schematic of a Typical Wet Vacuum Cleaning Pump Assembly

the exhauster using local temperature and barometric conditions. Previously discussed temperature and barometric conversions shall be used.

Separator Selection and Sizing

The separator is sized based on the cfm (liters per second) of the vacuum producer and the type of material expected to be collected. Refer to Table 10-16 for a classification of such material.

For dry separators, a starting point for sizing would provide a 6:1 ratio of filter bag area to bag volume for smaller volumes of coarse material and a 3:1 ratio for fine dust and larger quantities of all material. Wet and centrifugal separator sizing is proprietary to each manufacturer and depends on the quantity and type of material expected to be removed.

Some automatic separator cleaning systems use compressed air to aid in the dislodging of dust. The air pressure recommended is generally in the range of 100 to 125 psig (689 to 1,034 kPa).

General Design Considerations

Abrasion is the wearing away of the interior of the pipe wall by large, hard particles at the point where these particles strike the pipe. The effects are greatest at changes of direction, such as at elbows and tees and under the bag plates of separators. When abrasive particles are expected, it is recommended that either cast iron drainage fittings or Schedule 40 steel pipe fittings using sanitary pattern sweeps and tees be substituted for normally used tubing materials.

It is good practice to provide a safety factor to ensure that additional capacity is available from the exhauster without affecting the available vacuum. This should not exceed 5 percent of the total cfm (liters per second) and is used only when selecting the exhauster, not for sizing the piping system. The exhauster size should be selected and then the safety factor added. The unit selected should have that extra flow available.

The piping shall be pitched toward the separator. Plugged cleanouts should be installed at the base of all risers and at 90-degree changes in direction to allow any blockages to be easily cleared.

Piping geometry in the design of wet system piping could become critical. Every effort shall be made to keep the piping below the inlet valves to prevent any liquid from running out of the inlet after completion of the cleaning routines and to ease the flow of liquid into the pipe. Wet system pipe should pitch back to the separator at about 8 inches per foot (1 centimeter per meter). All drops should be no larger than 2 inches (50 millimeters) in size, and only one inlet shall be placed on a single drop. Each drop should terminate in a plugged tee facing down. This will allow any liquid still clinging to the sides of the pipe to collect at the bottom of the riser and be carried away the next time the system is used. A typical wet vacuum cleaning system is shown in Figure 10-7.

In facilities using controlled substances, there is always a possibility that a spill will occur. For cleaning this type of spill, a portable vacuum cleaning unit should be selected so that the filter can easily be weighed both before and after cleanup to account for the controlled substances picked up in the cleaning unit.

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11 Water Treatment, Conditioning, and Purification

For the purposes of discussion in this chapter, water treatment means the chemical or mechanical removal and/or replacement of ionic or nonionic substances in feed water to produce water for a predefined use. Water conditioning is the addition of chemicals to water to inhibit corrosion, chelate hardness, chelate trace metals, suspend colloids, and adjust pH. Pure water systems are systems designed to produce water pure enough for use in pharmaceutical plants, laboratories, high-density semiconductor manufacturing, and very high-pressure boilers. The explanations and definitions given are simplified but suffice for the purposes of this chapter.

CODES AND STANDARDS

Many codes and standards apply to the various water systems. Potable water treatment shall comply with the 1986 Safe Drinking Water Act and amendments. The U.S. Environmental Protection Agency (EPA) also has identified treatment technologies with given contaminant removal efficiencies for potable water.

Pure water treatment shall comply with one or more of the following, depending on the purity of the water desired.

- College of American Pathologists (CAP) and American Society for Testing and Materials (ASTM) reagent grade water
- U.S. Pharmacopeia (USP) standards for water purity
- Association for the Advancement of Medical Instrumentation (AAMI) standards
- Clinical and Laboratory Standards Institute (CLSI) standards
- Semiconductor Equipment and Materials International (SEMI) and ASTM electronics-grade water

BASIC WATER CHEMISTRY

Water to be treated is known generally as raw water, feed water, or source water. Water that has been treated is known as treated water, product water, and solute. Chemicals or substances that dissolve in water can be electrolytes or non-electrolytes. Electrolytes are chemicals that dissolve in water to form ions, such as sodium chloride ($NaCl$) and magnesium sulfate ($MgSO_4$). Non-electrolytes are chemicals that dissolve in water but do not break down, such as ethanol (C_2H_5OH), sugars, and many organics. The positively charged atoms are called cations because they migrate to the cathode electrode, and the negatively charged atoms are called anions because they migrate to the anode electrode. The ions in solution act almost independently. For example, magnesium sulfate dissociates to form positive magnesium ions and negative sulfate ions. Ions often are referred to as salts in reference to reverse osmosis water production.

When an electrolyte compound dissolves in water, the molecules of the compound separate, disperse among the water molecules, and are held in suspension, which is when colloids, particles, etc. are suspended in solution and do not settle under the influence of just gravity. When the limit of solubility is reached, those same compounds become suspended solids, and no chemical reaction occurs. Dissolved materials cannot be removed by filtration.

Some types of liquids cannot be dissolved. They break down into extremely small particles and then disperse into the water, even though they are not soluble. These liquids are called immiscible liquids. The resulting small particles are known as colloids. Colloidal material is at the upper end of the size range for ions and molecules, in the general range of 0.001 to 1.0 micrometer (μm). In most cases, other liquids, such as oil and grease, cannot separate into smaller-sized particles and become dispersed, but simply remain in suspension. If they are lighter than water, they float on top. If heavier, they sink below the surface.

All acid compounds referred to in water chemistry consist of hydrogen combined with an acid radical. Since the acid radical moves around as a unit, it is convenient to view the acid radicals as an integral anion unit. When a metal radical and an acid radical combine, they form a class of chemicals called salts.

If a metal cation and a hydroxide anion combine, a base results.

An acid is any compound capable of giving up a hydrogen ion (H^+) or proton. The acid's conjugate base, or anion, is the compound remaining after the loss of the H^+:

$$HCl \rightarrow \text{conjugate base} = Cl^-$$

A base is any compound capable of accepting a hydrogen ion or giving up a hydroxide (OH^-) ion:

$$NaOH \rightarrow \text{conjugate acid} = Na^+$$

The valence of any element is a measure of its chemical-combining power compared to that of a hydrogen atom, which has the assigned value of 1. The valence is the number of electrons in an atom that are free to share, give, or take from other atoms. An element with a value of +2 can replace two hydrogen atoms in a compound, or an element with a valence of -2 can react with two hydrogen atoms. When atoms combine to form compounds, a cation atom must combine with an anion atom, and in addition, the valence of the two basic elements must equal one another to form the compound.

Most of the basic chemical reactions in water treatment consist of rearranging cation and anion atoms using their valence. As can be seen in Table 11-1, hydrogen has a valence of 1, and sulfate has a valence of 2. When combined to form sulfuric acid, two hydrogen atoms are required to form the combination, resulting in the formula H_2SO_4. The chief exception is the case where carbonates and bicarbonates are destroyed by heating or aeration, giving off carbon dioxide.

Equivalent weight is the weight, in grams, of any element that could combine with or displace 1.008 grams of hydrogen or 8 grams of oxygen. Since the valence of an element is proportional to its combining power, the equivalent weight is based on its valence. This is illustrated in Table 11-1.

WATER IMPURITIES

Natural, or source, water is never chemically pure H_2O. Water dissolves ionic compounds as it comes in contact with the ground surface or mineral formations when it percolates through the earth. It also contains dissolved gases and dust picked up when falling through the air as rain, snow, or hail or when surface water is in contact with the air above the water level. Water is classified as surface water when obtained from sources such as lakes and rivers and groundwater when obtained from streams, wells, or other aquifers originating underground.

Turbidity

Turbidity (also called suspended solids) is a general term used to describe any form of insoluble matter suspended in water. Color is a chemical phenomenon often associated with turbidity. Color may be an indication of water containing decaying vegetation. However, the term "turbidity" is most often used when referring to mineral particulates because they are usually the most plentiful. Other commonly occurring impurities are liquids, such as oil, and the residue caused by decaying vegetation.

Coarse particles that settle rapidly when water is standing are referred to as sediment, and fine particles that mostly remain in suspension are called silt.

Microorganisms

Microorganisms are bacteria and viruses. They are living forms of particulate matter. Their unusual physiology allows them to grow and multiply in water containing only trace levels of nutrients. The presence of these nutrients in untreated water is an indicator of the presence of microorganisms, if the temperature is favorable for their growth. Although microorganisms are a suspended solid, the treatment required for their removal or neutralization puts them in a separate category.

Pyrogens cause fever, and pathogenic organisms (such as Legionella) cause diseases of all kinds. Endotoxins, which are fragments derived from the cell walls of gram-negative bacteria, are considered the most important and widely occurring group of pyrogen. Other organic growths include algae (a primitive form of plant life), fungi (plants lacking the chlorophyll required for photosynthesis), and bacteria, which exhibit both plant and animal characteristics. Bacteria are further subdivided into slime bacteria, which secrete slime; iron bacteria, which thrive on iron; sulfate-reducing bacteria, which live by consuming sulfate and converting it to hydrogen sulfide gas; and nitrifying bacteria, which use ammonia and whose by-product results in the formation of nitric acid.

Several methods of measurement are used, including viable-count essays, direct-count epifluorescent microscopy, scanning electron microscopy, and biochemical techniques. The most common means of measuring bacterial contamination is the viable-count method. This is done by passing the water being measured through a sterile nutrient medium and counting the number of colonies appearing on the medium after a period of time is allowed for growth. These are called colony forming units (cfu). Endotoxins are measured in endotoxin units per milliliter (eu/mL). An often-used form of measurement for endotoxins is the limulus amoebocyte lysate (LAL) test, wherein a blood extract of the horseshoe crab becomes turbid in the presence of bacterial endotoxins. This detection technique uses optical density (turbidity level) measured over a period of time.

Other Organisms

This term for biological life is applied to larger living things, such as clams, mussels, their larvae, and

Table 11-1 Important Elements, Acid Radicals, and Acids in Water Chemistry

Element	Symbol	Atomic Weight	Valence	Equivalent Weight
Aluminum	Al	27.0	3	9.0
Barium	Ba	137.4	2	68.70
Calcium	Ca	40.1	2	20.05
Carbon	C	12.0	Variable	—
Chlorine	Cl	35.46	Variable	35.46
Fluorine	F	19.0	1	19.0
Iron (ferrous)	Fe^{2+}	55.8	2	27.9
Iron (ferric)	Fe^{3+}	55.8	3	18.6
Hydrogen	H	1.0	1	1.0
Magnesium	Mg	24.3	2	12.15
Nitrogen	N	14.0	Variable	—
Potassium	K	39.1	1	39.1
Oxygen	O	16.0	2	8.00
Phosphorus	P	31.02	Variable	—
Sodium	Na	23.0	1	23.0
Sulfur	S	32.0	Variable	—
Silicon	Si	28.06	4	7.01

Acid Radicals	Formula	Molecular Weight	Valence	Equivalent Weight
Bicarbonate	HCO_3	61.0	1	61.0
Carbonate	CO_3	60.0	2	30.0
Chloride	Cl	35.46	1	35.46
Nitrate	NO_3	62.0	1	62.0
Hydroxide	OH	17.0	1	17.0
Phosphate	PO_4	95.0	3	31.66
Sulfite	SO_3	80.0	2	40.0
Sulfate	SO_4	96.06	2	48.03

Acid	Formula	Molecular Weight	Equivalent Weight
Carbonic acid	H_2CO_3	62.0	31.0
Hydrochloric acid	HCl	36.46	36.46
Phosphoric acid	H_3PO_4	98.0	32.67
Sulfuric acid	H_2SO_4	98.1	49.05
Sulfurous acid	H_2SO_3	82.1	41.05

Miscellaneous Compounds	Formula	Molecular Weight	Equivalent Weight
Aluminum hydroxide	$Al(OH)_3$	78.0	26.0
Calcium bicarbonate	$Ca(HCo_3)_2$	162	81.0
Calcium carbonate	$CaCO_3$	100	50.0
Calcium sulfate	$CaSO_4$	136	68.0
Carbon dioxide	CO_2	44.0	22.0
Ferric hydroxide	$Fe(OH)_3$	107	35.6
Magnesium carbonate	$MgCO_3$	84.3	42.1
Magnesium hydroxide	$Mg(OH)_2$	58.3	29.1
Magnesium sulfate	$MgSO_4$	120	60.1
Sodium sulfate	Na_2SO_4	142	71.0

other forms of life. They tend to clog water inlets from bodies of salt and fresh water and also may find their way into the piping system of a facility.

Dissolved Minerals and Organics

Dissolved organic substances typically found in water include both man-made and natural substances. Man-made chemical compounds, some of which are harmful to the environment, include herbicides, pesticides, trihalomethanes, surfactants, and detergents. Naturally occurring chemical compounds, which are typically not harmful in trace amounts, include lignins, tannins, humic and fulvic acid, and other bio-decomposition products.

Alkalinity

Alkalinity is a measurement of the quantity of dissolved earth minerals in water and the water's ability to neutralize acids. All natural water contains some measure of alkalinity. It is mainly the sum of carbonate, bicarbonate, and hydroxide ions in water, with borate, phosphate, and silicate ions partially contributing to the total. It is reported as parts per million (ppm) equivalent of calcium carbonate. Alkalinity is regarded as an important characteristic of water in determining its scale-forming tendency.

Alkalinity is measured using two end-point pH indicators in a titration with acid. The phenolphthalein alkalinity, or P alkalinity, measures the strong alkali in the solution. The methyl orange alkalinity, or M alkalinity, measures all of the alkalinity present in the solution. The M alkalinity is often called the total alkalinity because it also includes the P alkalinity. Alkalinity is not a measure of pH but is a contributor to the pH of the solution.

Hardness

Hardness is a measure of the total calcium, magnesium, iron, and other metallic elements that contribute to the "hard" feel of water. Carbonate, sulfate, and chloride salts of these elements are responsible for most of the scaling deposited on pipe and boiler walls. Generally accepted practice limits the term "hardness" to include only calcium and magnesium. Hardness usually is expressed in terms of milligrams per liter (mg/L) (grains per gallon [gpg]) as $CaCO_3$.

Often, water is characterized in general terms by the amount of hardness, as follows:

- Soft: 0–75 mg/L (0–4.4 gpg) as $CaCO_3$
- Moderate: 76–150 mg/L (4.5–8.7 gpg) as $CaCO_3$
- Hard: 151–300 mg/L (8.8–17.5 gpg) as $CaCO_3$
- Very hard: More than 300 mg/L (17.5 gpg) as $CaCO_3$

Iron

The most common form of iron is ferrous bicarbonate. Because this form of iron is soluble, it may be treated the same way as hardness.

Iron creates problems in ion-exchange processes where polymeric resins are predominant. Iron also creates problems on the surface of separation membranes. Soluble iron is called ferrous (Fe^{2+}), while insoluble iron is called ferric (Fe^{3+}). Iron in the ferrous form is subject to receiving an electron; it is said to be subject to oxidation. The presence of oxidation agents

in water with ferrous iron is the root of the problems. Common oxidants are oxygen and chlorine.

If it were possible for iron to stay in the ferrous form throughout the ion-exchange process, including regeneration of softening resin and the shutdown of membrane systems, it would not present a problem. However, for all practical purposes, it is impossible to prevent some of the ferrous substance from oxidizing to the ferric substance. During the oxidation process, other ionic substances are involved. Typically a long hydrocarbon chain results when resin or separation membranes are made. In these long chains are sites where the ferric iron connects to the polymer. The ferric connection point acts as a catalyst for further crystallization or chemical reactions with the iron or related substances, thereby creating a snowball effect for further chemical reactions.

Calcium

Calcium is a silver-white, bivalent, metallic element of the alkaline-earth group occurring only in combination. Common combinations are calcium carbonate, calcium chloride, calcium hydroxide, calcium phosphate, and calcium silicates.

Magnesium

The most common forms of magnesium are magnesium carbonate, magnesium bicarbonate, and magnesium chloride. These impurities tend to deposit scale on surfaces with which they come in contact.

Silica

The three common kinds of silica are soluble, colloidal, and particulate. Soluble silica often is referred to as reactive silica, and colloidal silica sometimes is called non-reactive or polymeric. The most common form in solution is silicon oxide, and in suspension it is found as a fine colloid. These impurities tend to deposit a scale on surfaces they come in contact with and form a gelatinous mass on reverse osmosis membranes.

Sodium and Potassium

Sodium and potassium form similar salts, with the most common being sodium or potassium chloride, sodium or potassium carbonate, and sodium or potassium bicarbonate.

Chlorides and Sulfates

The most common forms of chlorides and sulfates are dissolved salts of sodium, potassium, calcium, and magnesium. These impurities tend to deposit a scale on surfaces with which they come in contact.

Nitrates

The EPA has set drinking water limits for nitrates at 10 milligrams per liter. Though water with a high nitrate level is treatable, limits are placed on the discharge nitrate concentration if neutralized ion-exchange regeneration waste or membrane-separation concentrate is discharged directly into the environment or into a municipal treatment system. Thus, knowing the concentration of the supply and the local discharge limits is critical to the selection of the appropriate treatment equipment and system design.

Trace Elements

Trace elements are present in very small quantities and are considered problematic only if the amount is above an accepted level for the intended use of the water. Examples are lead, cadmium, copper, barium, silver, lithium, zinc, chromium, mercury, arsenic, and selenium.

When a supply-water treatment system is selected, the waste products must be considered. Many municipalities sell the sludge created by their process to local farms as fertilizer or cattle feed, so they place considerable restrictions on treatment discharges. Though elements may be identified as trace by analysis of the supply water, in concentration they may exceed local, state, and federal discharge limits.

Dissolved Gases

The most common dissolved gases in natural raw water are oxygen, carbon dioxide, nitrogen, and hydrogen sulfide. Potable water supplies usually also have chlorine and fluorides added for public health purposes. Of increasing concern is the presence of radon gas in many water supplies obtained from wells.

Oxygen is the basic factor in the corrosion process; it must be present for the corrosion of metals. Thus, its removal or reduction reduces the corrosiveness of the water. Carbon dioxide, nitrogen oxides, sulfur oxides, and hydrogen sulfide also contribute to corrosion by making water acidic.

No pretreatment is typically necessary for feed water with less than 1 part per million of chlorine. When more than 1 part per million of chlorine is present, an activated carbon filter is recommended.

Volatile Organic Compounds

Volatile organic compounds (VOCs) are those compounds that evaporate readily at ambient temperatures and pressures. Swamp gas is an example of a naturally occurring VOC. However, most of the compounds that are a concern regarding the production of chemically pure water are man-made. The EPA lists 21 regulated VOC compounds and 34 more unregulated VOC compounds.

Most of the VOCs that concern the user of chemically pure water originate from the treatment process itself. VOCs may originate from the following typical treatment components:

- Polyvinyl chloride (PVC) and chlorinated polyvinyl chloride (CPVC) pipe
- Polypropylene and polyethylene pipe

- Cation ion-exchange resin, the solvent used to make the polymer
- Anion ion-exchange resin, the solvent and the organic amines
- Reverse osmosis membrane, the solvent used to create the barrier polymer
- Ultrafiltration and nanofiltration membranes, the solvent used to create the polymer
- Fiberglass-reinforced plastic (FRP), polypropylene, and polyethylene-treated water-storage tanks
- Filter and ion-exchange vessel linings
- Pipe solvents, glues, and dopes
- Cross-flow filter media
- Other plastic wetted materials used in the construction of the system

Many of the items listed above can be substituted or treated to remove serious VOCs. To determine the best approach for avoiding serious contamination, contact the supplier of the treatment products considered. However, these organic compounds are volatile, meaning that with use they will dissipate dramatically. Flushing solutions used to rinse high-purity installations before they are commissioned are available. These solutions kill bacteria and rinse VOCs without severely damaging the system. To determine the best approach for the materials selected, always consult with the vendor before proceeding. Furthermore, consult the user to determine the impact of VOCs given off by the treatment. Consultation can save considerable effort, time, and money.

WATER ANALYSIS AND IMPURITY MEASUREMENT

Water samples are analyzed to determine the quantities of various impurities. The quantities must be presented in a logical and understandable manner to allow for easy and practical interpretation. The initial analysis of incoming water must be accurate and contain a worst-case scenario, and the desired output quality must be established prior to the selection of any treatment system.

The most accurate analyses of water samples are done by laboratories specializing in this type of work. Sterile containers must be used, and several samples must be taken over a period of time to ensure that peak readings and average values are obtained. Field tests of water samples, while not as accurate as laboratory tests, may provide accuracy levels acceptable to the user.

The results of the analysis are expressed in many ways. A common method used to report the concentration of ions in solution is the weight of an element or compound per liter of water, expressed as milligrams per liter of water. Another method is parts per million, which can be expressed either by the weight of an impurity compared to the weight of water (abbreviated w/w, weight to weight) or by the volume of the impurity to the volume of water (abbreviated v/v). Other units also are used, such as grains per gallon and equivalents per million (epm).

Milligrams per liter differs from parts per million in that it expresses a proportion in weight per volume. This finds specific use in the analysis of saline waters. For common supplies where the specific gravity of the liquid is approximately 1, milligrams per liter and parts per million are equal.

Grains per gallon often is used in discussion of ion-exchange equipment capabilities, where 1 grain per gallon equals 17.1 parts per million.

As previously explained, compounds break down into ions when dissolved. Although chemists can measure the amount of each ion present in a sample, it is not practical to find the total amount of each compound that actually went into solution. In practice, the actual method of analysis measures only ions. Using the ionic measurement when reporting impurities makes it easier and more convenient to interpret the results.

To further simplify reporting, it is desirable to reduce all ions present in solution to a common denominator, which is calcium carbonate. This is accomplished by comparing the equivalent weight of all ions present and expressing them as the part-per-million anion and cation equivalent of calcium carbonate. This method of expression is a widely accepted standard for reporting a water analysis, but it is not universal.

Table 11-2 presents the conversion factors used for major impurities. Figure 11-1 illustrates a typical water analysis report indicating impurities in parts per million, equivalents useful in calculating reacting chemicals, and a comparison of positive and negative ions.

pH

Potential hydrogen (pH) is a measurement of the hydrogen ion concentration in water and, therefore, a measure of the water's acidity. pH is calculated from the logarithmic reciprocal of the hydrogen ion concentration in water.

The pH scale ranges from 0 to 14, with values lower than 7 being acid, values higher than 7 being alkaline, and 7 being neutral. When an acid is added to water, the concentration of hydrogen ions increases, resulting in a lower pH. When an alkaline is added to water, the hydrogen ions decrease, resulting in a higher pH. The change of a pH unit represents a tenfold increase (or decrease) in strength. The pH is not a measure of alkalinity.

Specific Resistance

Specific resistance (measured in megohm-centimeters) is a measure of the amount of electrolytes in water. It measures the ability of 1 cubic centimeter of the sample solution at a given temperature to resist the flow of an electrical current. It is based on the activity of the compounds dissolved in water and is the most practical method of measuring ionic impurities from a given sample.

Resistance is given in ohms (Ω). The resistance is based on the amount of ionized salts only and varies with the temperature of the water.

Pure water has an electrical resistance of approximately 18.3 megohm-centimeters at 77°F (25°C). This maximum resistance value is based on

Table 11-2 Converting ppm of Impurities to ppm of Calcium Carbonate

Cations	Ionic ppm Multiplier	Anions	Ionic ppm Multiplier
Hydrogen	50.00	Hydroxide	2.94
Ammonium	2.78	Chloride	1.41
Sodium	2.18	Bicarbonate	0.82
Potassium	1.28	Nitrate	0.81
Magnesium	4.10	Bisulfate	0.52
Calcium	2.50	Carbonate	1.67
Ferrous iron	1.79	Sulfate	1.04
Ferric iron	2.69		
Cupric	1.57		
Zinc	1.53	**Other**	
Aluminum	5.55	Carbon dioxide	2.27
Chromic	2.89	Silica	1.67

WATER ANALYSIS REPORT

Collected _____

Sample No. 605

Analyzed _____

For ABC Co.

Reported _____

	Ion		epm	ppm as $CaCO_3$
Cations	Calcium as Ca	62 ppm	3.10	155
	Magnesium as Mg	31 ppm	2.54	127
	Sodium and potassium as Na	38 ppm	1.64	83
	Total cations		7.28	365
Anions	Bicarbonate as HCO_3	250 ppm	4.10	205
	Carbonate as CO_3	0 ppm	0	0
	Hydroxide as OH	0 ppm	0	0
	Chloride as Cl	11 ppm	0.31	15
	Sulfate as SO_4	138 ppm	2.87	145
	Nitrate as NO_3	_____ ppm		
	Total anions		7.28	365

Silica as SiO_2	5 ppm	Total hardness	282 ppm $CaCO_3$
Iron as Fe_2O_3	1.2 ppm	Methyl orange alkalinity	205 ppm $CaCO_3$
Total dissolved solids	536 ppm	Phenolphthalein alkalinity	0 ppm $CaCO_3$
Suspended solids (weight)	5 ppm		
Chloroform-extractable matter	_____ ppm		
Turbidity (after shaking)	5 ppm	pH 7.7	Color _____
Carbon dioxide as CO_2	10 ppm	Sp conductance _____	μmhos

Figure 11-1 Typical Water Analysis Report

the electrical resistance from the very small concentrations of hydrogen and hydroxide ions from the slight dissociation of water. This dissociation yields concentrations of 1 x 10^{-7} moles per liter for each hydrogen and hydroxide.

Temperature is a significant factor in the measurement of the electrical resistance of water, with warmer temperatures producing higher values. For example, the electrical resistance of water at 50°F (10°C) is 8.8 megohm-centimeters and at 104°F (40°C) is 43.3 megohm-centimeters.

Instruments, referred to as water resistivity meters, are available to accurately measure the electrical resistance of water. Because of the significant impact of temperature, these meters typically report electrical resistance normalized to 77°F (25°C). Resistivity meters typically are used as a measure of the total amount of electrolytes in purified water when the concentrations are very low. Resistivity conversions are given in Table 11-3.

Specific Conductance

Specific conductance (measured in micromhos per centimeter) measures the ability of 1 cubic centimeter of the sample solution at a given temperature to conduct an electrical current. It is the reciprocal of the resistance, in ohms. Since it is the opposite of resistance, it is given the name mho, which is ohm spelled backwards. The actual conductance is so small that it is measured in micromhos (μmho), which is one millionth of a mho.

As an example, at 70°F (19°C) demineralized water with 0.5 part per million dissolved salt has a conductance of 1 micromho. Pure water has a specific conductance of 0.055 micromho per centimeter at 77°F (25°C).

Conductivity conversions are given in Table 11-3. Specific conductance in actual practice typically is measured by probes suspended in the stream of water.

Total Suspended Solids

Total suspended solids is the sum of all the suspended material found in the water sample and commonly is measured in either parts per million or milligrams per liter.

Turbidity in water is classified by the size of the particulates in microns (1/1,000 inch [0.03 millimeter] diameter) and tested by a light interference method known as a nephelometric. This test compares the water sample by color to a standard color scale. This measurement is obtained by comparing the sample being tested with a known color reference, and the total suspended solids are indicated based on this comparison. The most common reporting method is the nephelometric turbidity unit, with higher units indicating increased turbidity.

Table 11-3 Resistivity and Conductivity Conversion

Grains/gal[a] as $CaCO_3$	ppm as $CaCO_3$	ppm NaCl	Conductivity, μmho/cm	Resistivity, MΩ/cm
99.3	1700	2000	3860	0.00026
74.5	1275	1500	2930	0.00034
49.6	850	1000	1990	0.00050
24.8	425	500	1020	0.00099
9.93	170	200	415	0.0024
7.45	127.5	150	315	0.0032
4.96	85.0	100	210	0.0048
2.48	42.5	50	105	0.0095
0.992	17.0	20	42.7	0.023
0.742	12.7	15	32.1	0.031
0.496	8.5	10	21.4	0.047
0.248	4.25	5.0	10.8	0.093
0.099	1.70	2.0	4.35	0.23
0.074	1.27	1.5	3.28	0.30
0.048	0.85	1.00	2.21	0.45
0.025	0.42	0.50	1.13	0.88
0.0099	0.17	0.20	0.49	2.05
0.0076	0.13	0.15	0.38	2.65
0.0050	0.085	0.10	0.27	3.70
0.0025	0.042	0.05	0.16	6.15
0.00099	0.017	0.02	0.098	10.2
0.00070	0.012	0.015	0.087	11.5
0.00047	0.008	0.010	0.076	13.1
0.00023	0.004	0.005	0.066	15.2
0.00012	0.002	0.002	0.059	16.9
0.00006	0.001	0.001	0.057	17.6
none	none	none	0.055	18.3[b]

[a] Grains per gal = 17.1 ppm ($CaCO_3$).
[b] Theoretical maximum.

An often-used standard for potable water is the method for the examination of water and wastewater developed by the American Public Health Service, which uses formazin to produce a known volume of turbidity. The standard color scale to which it is compared is derived from the platinum cobalt unit. Other methods less frequently used are the comparator tube determination using formazin, called the formazin turbidity unit, and the original test, the Jackson turbidity unit, named for the man who developed a method that compares the color of candlelight through a sample to a color standard. The most accurate method of measuring solids is gravimeterically, wherein a known quantity of water is evaporated and the resulting solids weighed.

The most effective method of removing turbidity is by the use of filters and strainers. The equipment chosen to accomplish this task depends for the most part on the sizes and types of the solids to be retained. Other factors include the materials of construction, the nature of the raw water, flow rate requirements, the particle removal target, initial and operating costs, and maintenance requirements.

Total Dissolved Solids

Often referred to as dissolved inorganics and mineral salts, total dissolved solids (TDS) is generally the sum of all dissolved minerals, including chlorides, sulfates, and carbonates. Dissolved solids contribute to scale deposit and corrosion of piping and equipment.

When dissolved in water, mineral salts form positively charged ions, mostly sodium and calcium, and negatively charged ions, mostly chlorides and sulfates.

Engineers designing ion-exchange systems consider total dissolved solids differently than those designing membrane-separation systems. Neither approach is incorrect, but if the approach is not defined, design errors will occur. Quantitatively, total dissolved solids is the difference in the weight between the tare weight of a crucible and the residue remaining after filtered water is evaporated. The quantitative chemical definition is used by membrane-separation system designers. The analytic, ionic definition is used by ion-exchange system designers. Since ion-exchange by definition is an ionic chemical process, the system designer must consider a balanced ionic solution when determining capacity and equipment size. When designing a treatment system consisting of both membrane separation and ion exchange, care must be taken when moving from the separation unit's product water analysis to that of the ion-exchange system.

Separation system analysis reports, as well as most laboratory water analysis reports, are shown as parts per million as $CaCO_3$. For example, sodium would be reported as Na^+, and calcium would be reported as Ca^{2+}. However, to simplify the task, when designing an ion-exchange system the "as ion" is converted to $CaCO_3$. The conversion is done by considering the equivalent weight of the ion, or the atomic weight divided by the ion's existing exchange valance. The equivalent weight then is converted to $CaCO_3$ by dividing the ion's equivalent by itself and multiplying the product by the equivalent weight of $CaCO_3$, or 50.

Total Organic Carbon

Total organic carbon (TOC) is a measurement of the organic carbon compounds found dissolved in water. These compounds contribute to corrosion, cause problems in manufacturing, and usually indicate the presence of endotoxins in water for pharmaceutical use. The test is requested to determine the contamination of water by trace organic compounds that could produce a residue or interfere in laboratory apparatus tests or provide trace contamination in a pharmaceutical product.

The measurement is generally complicated and depends on the expected level. For higher levels, the organic compound first is converted to carbon dioxide, which is measured by infrared absorption. Gas stripping is required to remove other forms of carbon ions from dissolved mineral compounds. For parts per billion (ppb) levels, photolytic oxidation is used, and the resulting carbon dioxide then is measured.

Silt Density Index

The silt density index (SDI) is a measure of the fouling potential of a feed water source. Since colloids and other solids can be any size in the sub-micrometer range, there is no direct method to measure their concentration in feed water. The silt density index is found by passing the feed water through a 0.45-micrometer filter at 30 pounds per square inch (psi) (207 kilopascals [kPa]). The silt density is found from the following formula:

Equation 11-1

$$SDI = \frac{1 - \frac{t_1}{t_2} \times 100}{T}$$

where

t_1 = Initial time needed to collect a 500-milliliter sample of water through a fresh 0.45-micrometer filter, 47 millimeters in diameter, in seconds

t_2 = Time to filter and collect a second 500-milliliter sample after exposing the same filter as above to the flow of feed water for 15 minutes, in seconds

T = Total test time, in minutes (typically 15 minutes, but may be less for high silt density index)

To obtain an accurate test, at the end of the elapsed time the filter should not become more than approximately 74 percent plugged. If this figure is exceeded, the test should be repeated using a shorter overall elapsed time.

(Note: A Millipore filter is the only membrane currently approved by ASTM International for determining silt density index.)

Many manufacturers of reverse osmosis (RO) cartridges recommend allowable silt density index figures for feed water. Typically, the maximum silt density index for hollow-fiber modules is 3, and for spiral-wound modules the allowable silt density index figure is 4. For continuous deionization, an silt density index of 4 or less is recommended. In practice, when water has a silt density index greater than 4, a prefilter with a 4-micrometer depth is recommended. In addition to the 4-micrometer filter, an additional 1-micrometer filter is recommended downstream. The use of a 4-micrometer filter on the feed water stream is always recommended as a precaution against fouling, regardless of the potential silt density index.

DEPOSITS AND CORROSION

The contaminants previously discussed will cause piping system fouling by depositing material on the walls of the pipe, thereby reducing the efficiency of the system, and reduce the thickness of the pipe wall by corrosion, which will cause failure of the piping system. Following is a brief discussion of these cat-

egories of problems and treatment methods as they generally apply to most systems.

Scale

Scale is a solid deposit on the walls of a pipe resulting from the precipitation of dissolved mineral solids in the fluid stream. This scale reduces heat transfer and interferes with the flow of water by increasing the friction of the fluid with the walls of the pipe. Boiler scale consists of calcium, magnesium, iron, and silica minerals. It can be substantially minimized by pretreating water prior to its entering the boiler to remove much of the scale-forming ingredients and adding effective chemicals to the feed water to adjust pH, prevent corrosion, and prevent deposits from occurring.

Condenser scale deposits consist of calcium carbonate, calcium sulfate, or silica minerals. They form when the minerals' concentration in water reaches a level where their solubility or the pH of saturation is exceeded and the minerals come out of solution. This can be prevented by controlling the pH, diluting the circulating water to prevent concentration, and adding chemicals to inhibit and prevent scale formation.

Sludge

Sludge is a sticky, adherent deposit in the feed water resulting from the settling out of suspended matter from several sources. One source is an excess of iron in the liquid, generally iron oxide (rust) and iron carbonate (a corrosion product). Other sources are mud, dirt, and clay that tend to collect and adhere in areas of low circulation. Sludge is prevented by filtering the incoming feed water and adding chemical dispersants to keep the solids in suspension, which then are removed by blowdown. Mud, dirt, and clay are rarely encountered except when the feed water is from surface sources.

Biological Fouling

Microbiological fouling is caused by the growth of bacteria, algae, fungi, and other organisms. Their growth is aided by a favorable water temperature, favorable pH, the presence of oxygen, and food. The buildup of microbes and their waste products, which also include dust and other suspended matter, is called slime.

Microbial control is achieved by sterilization, disinfection, and sanitation. Sterilization is the lethal disruption of all bacteria, mold, and yeast. It eliminates biofilm and spores, and numerically it is a 12 log reduction in bacteria. Disinfection is a 6 log reduction of microbials. Sanitation generally is considered a killing of the vegetative organisms. It minimizes the presence of bacteria and endotoxins, and numerically it is a 3 log reduction in bacteria.

There are different methods of controlling biofouling. Chemicals, ultraviolet radiation, heat, filtering, and ozone are the ones most commonly used. The method selected depends on the intended use of the treated water and the proposed materials of the system components.

Corrosion

Corrosion is the loss and eventual failure of metals and alloys from the electrochemical reaction between water and the pipe material. It is separated into two basic types: general and localized. General corrosion describes the potential dissolution of pipe over its entire exposed surface. Localized corrosion affects only a small area of the pipe surface. Conventional corrosion treatment of feed water for boilers and cooling water systems consists of pH control and the use of chemical corrosion inhibitors.

General Corrosion

General corrosion is a breakdown of the pipe material at a uniform rate over its entire surface by direct chemical attack. It is caused by the loss of the protective passive film that forms on the surface of a pipe coupled with a chemical reaction occurring between the pipe material and the chemicals in the fluid. Particular types of general corrosion include the following:

- Galvanic corrosion occurs in a liquid medium (called an electrolyte) when a more active metal (anode) and a less active metal (cathode) come in contact with one another and form an electrode potential. When this occurs, the more active (noble) metal tends to dissolve in the electrolyte and go into solution.
- Intergranular corrosion occurs in a pipe wall when material in the grain boundary of some alloys is less resistant to the corroding agent than the grains themselves, and the bonds between the grains are destroyed.
- Erosion corrosion is caused by a wearing of a pipe wall, usually as a result of excessive fluid velocity or constant wearing by solids in the water striking the walls of the pipe.

Localized Corrosion

Localized corrosion takes place on small areas of the surface, usually at high rates. It takes the following forms:

- Stress-corrosion cracking is a physical deterioration and cracking of a pipe wall caused by a combination of high operating temperature, tensile stress on the pipe, and chemicals in the fluid stream.
- Pitting is characterized by deep penetration of the metal at small areas of the surface, concentrating in small cells without affecting the entire surface.

- Crevice attack corrosion occurs at junctions between surfaces (often called crud traps) where a crack exists that allows an accumulation of a corroding agent.

PREDICTING SCALE FORMATION AND CORROSION TENDENCIES

A common and costly water-caused problem is the formation and deposit of mineral scale. Although scale deposits may contain a complex mixture of mineral salts, the primary constituent is calcium carbonate.

Most salts are more soluble in hot water than in cold water. Calcium and magnesium salts, on the other hand, dissolve more readily in cold water than in hot water. As a result, they tend to deposit on surfaces when a rise in temperature occurs. As the temperature rises, the tendency of dissolved solids to precipitate out of solution increases because of their property of inverse solubility. This is particularly true of calcium carbonate.

Alkalinity and pH are other factors that contribute to mineral scale formation. The pH value reflects the concentration of hydrogen protons (H^+) or hydroxyl ions (OH^-) in aqueous solutions. The level of this concentration, as indicated by pH, defines the ratio of bicarbonate to carbonate alkalinity. The measure of pH is made on a logarithmic scale. One end of the scale is the hydrogen proton, and the other end is the hydroxyl ion. When the pH is 7, there is an exact balance of hydrogen protons to hydroxyl ions in the water. A pH below 7 indicates an acid or a predominance of hydrogen protons. A pH above 7 indicates a basic solution or a predominance of hydroxyl ions. A pH below 5 indicates 100 percent carbonic and other mineral acids. A pH between 5.3 and 8.2 indicates a bicarbonate/carbonate relationship of the water. A pH above 8.2 indicates carbonate and hydroxyl alkalinity. As the pH proceeds upward from acidic to basic, the increase in carbonates increases the tendency for calcium and magnesium carbonates to precipitate out of solution.

Langelier Saturation Index

In the 1930s, W. F. Langelier studied the primary factors that affect the tendency of water to form deposits of mineral scale on heat-transfer equipment. As a result of this work, the Langelier Index, best known as the Langelier Saturation Index (LSI), was created. This index is based on numerical values given to the factors that affect deposits.

The index is actually a calcium carbonate saturation index. It is based on the assumption that water with a scaling tendency will deposit a corrosion-inhibiting film of calcium carbonate and thus be less corrosive. Water with a non-scaling tendency will dissolve protective films and thus be more corrosive. The interpretation of the LSI is based on the numerical values given in Table 11-4.

The LSI is calculated as follows:

Equation 11-2

$$LSI = pH - pH_s$$

where

LSI = Langelier Saturation Index number

pH = pH value obtained from testing the water in question

pH_s = Calculated pH of saturation for the calcium carbonate present in the water in question

The most accurate method is to use the following formula:

Equation 11-3

$$pH_s = (9.3 + A + B) - (C + D)$$

The numerical values of A, B, C, and D for substitution into Equation 11-3 are found in Table 11-5. A more empirical method to find pH_s is to use Figure 11-2.

Ryzner Stability Index

The Ryzner Stability Index (RI), often referred to as the stability index, is an empirical method used to predict the scale-forming tendencies of water. The RI is calculated from the following formula, applying the same definitions used for the LSI.

Equation 11-4

$$RI = 2\ pH_s - pH$$

The RI is always positive. When it falls below 6, scale formation is possible. Lower numbers of the index indicate more probable scale formation. For an interpretation of the RI, refer to Table 11-6.

Aggressiveness Index

Table 11-4 Prediction of Water Tendencies by the Langelier Index

Langelier Saturation Index	Tendency of Water
2.0	Scale-forming and for practical purposes noncorrosive.
0.5	Slightly corrosive and scale - forming.
0.0	Balanced, but pitting corrosion possible.
–0.5	Slightly corrosive and nonscale-forming.
–2.0	Serious corrosion.

Developed by the EPA, the Aggressiveness Index (AI) is used as a guideline parameter to find the corrosive tendency of potable water. This index is calculated as follows:

Equation 11-5

$$AI = pH + \text{Log } 10\ (\text{Alkalinity} \times \text{Hardness})$$

Values lower than 10 indicate an aggressive water; values between 10 and 12 indicate a moderately ag-

gressive water; and a value higher than 12 indicates a nonaggressive water.

TREATMENT METHODOLOGIES

Aeration

Aeration is a gas-transfer process in which water is brought into contact with air for the purpose of transferring volatile substances to or from the raw water. It is used most often to remove undesirable gases such as carbon dioxide, hydrogen sulfide, and methane. Aeration, by introducing oxygen, also is used to remove iron and manganese and to lower the amount of VOCs in ground water. The following are criteria for its use.

- Reduction of carbon dioxide by 90 percent is obtained by near saturation with oxygen. Carbon dioxide dissolved in ground water

Table 11-5 Numerical Values for Substitution in Equation 11-3 to Find the pH_s of Saturation for Water

Total Solids (ppm)	A	Ca as $CaCO_3$ (ppm)	C	M. Alkalinity (ppm)	D
50–330	0.1	10–11	0.6	10–11	1.0
400–1,000	0.2	12–13	0.7	12–13	1.1
		14–17	0.8	14–17	1.2
Temp., °F (°C)	B	18–22	0.9	18–22	1.3
32–34 (0–1.1)	2.6	23–27	1.0	23–27	1.4
36–42 (2.2–5.6)	2.5	28–34	1.1	28–35	1.5
44–48 (6.7–8.9)	2.4	35–43	1.2	36–44	1.6
50–56 (10–13.3)	2.3	44–55	1.3	45–55	1.7
58–62 (14.4–16.7)	2.2	56–69	1.4	56–69	1.8
64–70 (17.8–21.1)	2.1	70–87	1.5	70–88	1.9
72–80 (22.2–26.7)	2.0	88–110	1.6	89–110	2.0
82–88 (27.8–31.1)	1.9	111–138	1.7	111–139	2.1
90–98 (32.2–36.7)	1.8	139–174	1.8	140–176	2.2
100–110 (37.8–43.3)	1.7	175–220	1.9	177–220	2.3
112–122 (44.4–50)	1.6	230–270	2.0	230–270	2.4
124–132 (51.1–55.6)	1.5	280–340	2.1	280–340	2.5
134–146 (56.7–63.3)	1.4	350–430	2.2	350–440	2.6
148–160 (64.4–71.1)	1.3	440–550	2.3	450–550	2.7
162–178 (72.2–81.1)	1.2	560–690	2.4	560–690	2.8
178–194 (81.1–90)	1.1	700–870	2.5	700–880	2.9
194–210 (90–98.9)	1.0	880–1,000	2.6	890–1,000	3.0

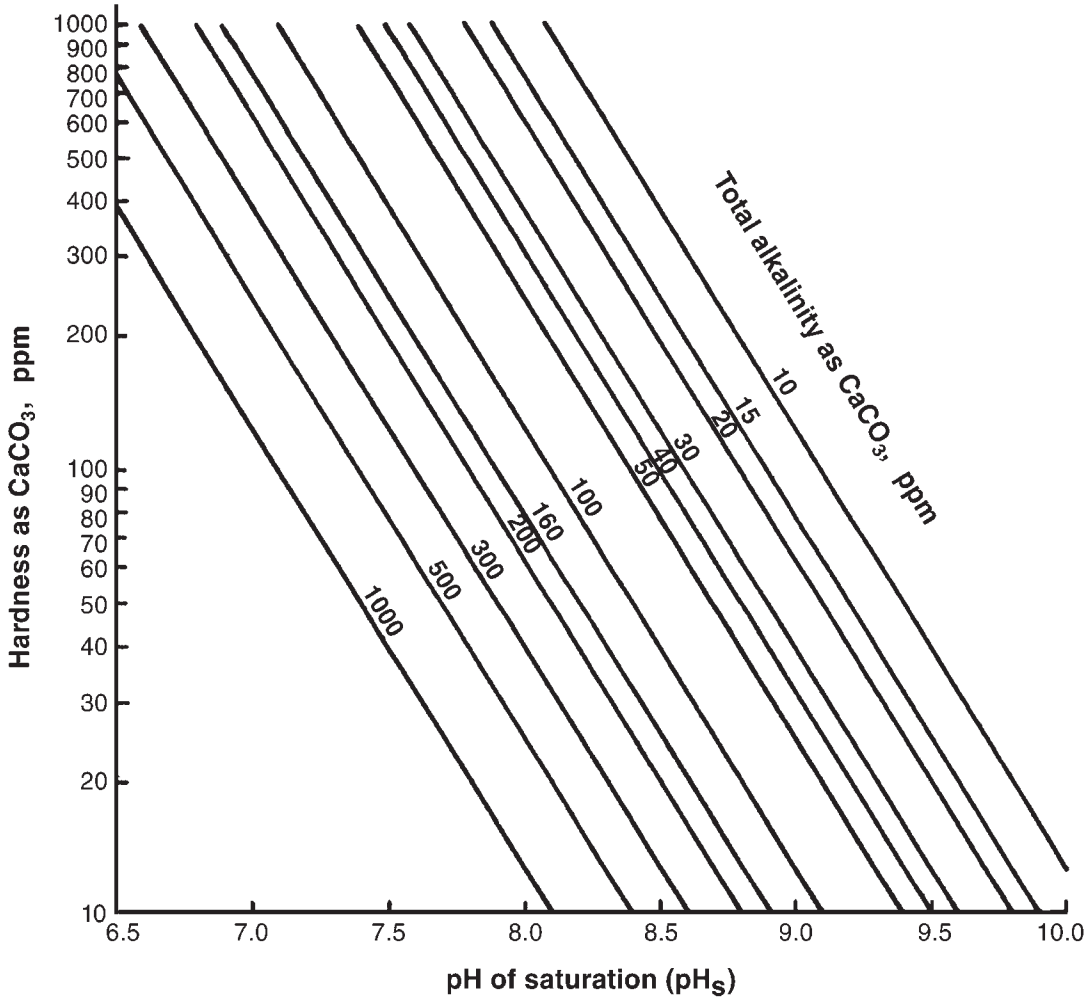


Figure 11-2 pH of Saturation for Water

Table 11-6 Prediction of Water Tendencies by the Ryzner Index

Ryzner Index	Tendency of Water
4.0–5.0	Heavy scale
5.0–6.0	Light scale
6.0–7.0	Little scale or corrosion
7.0–7.5	Significant corrosion
7.5–9.0	Heavy corrosion
9.0 and higher	Intolerable corrosion

will consume lime in the lime-soda softening process without any accompanying softening. Generally accepted practice indicates that aeration is not economical for carbon-dioxide concentrations in water of less than 10 milligrams per liter. The amount of lime saved should be compared to the cost of purchasing and operating the aerator before deciding on its use.

- Aeration will partially remove VOCs from raw water by oxidation, making them insoluble. They then are coagulated and removed from the water.
- Aeration alone could be used for the removal of hydrogen sulfide in concentrations of 2 milligrams per liter or less. Above this level, it could be used in conjunction with chlorination, which oxidizes hydrogen sulfide.
- Iron and manganese can be removed by aeration if this will not be done by other methods. These metals are oxidized to form insoluble hydroxides, which precipitate out at the proper pH levels. They then can be removed by settlement or filtered out of the water stream. Each part per million of dissolved oxygen will oxidize about 7 parts per million of iron or manganese.

The types of aerators commonly used are waterfall, diffusion (or bubble), and mechanical. Waterfall is used most commonly in utility water treatment.

Waterfall aerators are made in several types: cascade, spray nozzle, and multiple tray. Raw water enters the unit from the top and falls by gravity to the bottom, and various methods are used to evenly distribute and disperse the water throughout the unit. The type of waterfall aerator most commonly used is the naturally ventilated, multiple-tray type. This unit consists of a series of trays, one above the other, with perforated, slot, or mesh bottoms. The trays are filled with 2 to 6 inches (40 to 140 millimeters) of a medium, such as coke, stone, or ceramic balls, to improve water distribution and gas transfer as well as provide catalytic oxidation in the medium. The vertical opening between trays ranges between 12 and 30 inches (305 and 762 millimeters), depending on the number of trays required. Water loading on the trays is usually in the range of 10 to 20 gallons per minute per square foot (379 to 757 liters per minute per square meter). Efficiency can be improved by the use of enclosures and forced air blowers to provide counter-flow ventilation.

The simplest aerator is the diffusion type, which bubbles compressed air up through the water tank. The large volume of air required limits this to low flows of water. Air requirements vary from 0.1 to 0.2 standard cubic feet per minute (scfm) per gallon (0.003 to 0.006 cubic meters per minute per liter) of water aerated. A detention time, which ranges from 10 to 30 minutes, is necessary. Advantages of this type of aerator are the freedom from cold-weather operating problems, very low head loss, and the possibility of using this process for chemical mixing.

Mechanical aerators consist of an open impeller operating on the water surface of a tank. They are not as efficient as the waterfall or diffusion type, so longer retention times are necessary.

Clarification

Clarification reduces or removes turbidity, silt, and sediment in the raw water supply. The water could be treated with chemicals or filtered, depending on the amount of impurities present and the volume of water to be treated. If treated with chemicals, time is required for the solids to settle out of suspension. The chemical treatment process is usually reserved for large volumes of water.

Suspended and colloidal particles are normally in the range of 0.1 to 10 micrometers in size. They stay apart because negatively charged ionized matter is absorbed on their surfaces, and they repel each other. A measure of the charge surrounding the colloid is known as the zeta potential. These negative charges are reduced by the use of positively charged chemicals called coagulants, which, through a chemical reaction, reduce the zeta potential and allow the colloids to cluster to form a larger, jelly-like mass called floc. In a process called flocculation, colloidal particles, bacteria, and organic matter are mechanically brought together into larger and heavier particles. Too heavy to remain suspended, these particles now settle out of the water to the bottom. This process is called sedimentation.

Large volumes of water are clarified in a basin. First, the coagulant must be introduced with a strong action to completely disperse and mix the chemicals with the incoming water. Often, some of the sludge produced by flocculation is mixed with the coagulant. After coagulation is accomplished, the mixture is gently mixed to allow these larger particles to settle rapidly to the bottom of the tank. The particles and chemicals that settle out are called sludge, which

must be removed from the tank and disposed of. In most clarifier designs, these processes are done in the same operating unit.

The most frequently used chemical coagulant is aluminum sulfate, called alum or filter alum. Other frequently used coagulants are sodium aluminate and potash alum. Iron coagulants include ferric sulfate, ferris sulfate, and ferric chloride. Organic polyelectrolytes, which are polymers of high molecular weight, also are employed in low dosages to increase the effectiveness of treatment.

It is usually a matter of trial and error to find the correct amount of alum. This is because the amount depends on the size and quantity of the suspended solids in the raw water, retention time prior to flocculation, water temperature, and amount of mixing.

When the demand for water is low, one alternative flocculation method is to produce a finer floc, which can be removed by an appropriate filter system. By eliminating a large settling basin, high-quality water can be produced more quickly with smaller equipment.

Deaeration

Dissolved gases in the water supply, such as oxygen, carbon dioxide, hydrogen sulfide, and ammonia, can produce corrosion and pitting. They must be removed prior to using the water for most purposes. Although carbon dioxide and hydrogen sulfide can be removed by aeration, in many cases it is easier and less expensive to remove them by deaeration. In this process, the water temperature is raised to the saturation point for the existing pressure.

The two types of deaerators are steam and vacuum. When heated water is needed, such as for boilers, the steam type is preferred. When cold water is required, the vacuum type is used.

Steam deaerators break up water into a spray or thin film and then sweep steam across and through it to force out the dissolved gases. With this method, oxygen can be reduced to near the limit of detection. Design use is spread evenly among spray, tray, and combination units. Typical deaerators have a heating and deaeration section and a storage section for hot, deareated water. Often, a separate tank is provided to hold an additional 10-minute supply of deaerated water. The direction of steam may be crossflow, downflow, or countercurrent. The majority of the steam condenses in the first section of the unit. The remaining mixture of noncondensable gases is discharged to atmosphere through a vent condenser.

Vacuum deaerators use a steam jet or mechanical vacuum pump to develop the vacuum required to draw off the unwanted gases. The vessel has a packing material inside, and the inlet water is introduced to the top of the unit and passed down through this packing. Deaerated water is stored at the bottom of the vessel. The steam or vapor vacuum located at the top of the unit discharges the unwanted gases. The vacuum unit is far less efficient than the steam unit, and it most often is used in demineralizer systems to reduce the chemical operating cost and the demineralizer size and to protect anion-exchange resins from possible oxidation damage.

Dealkalizing

Dealkalizing is a process that reduces the alkalinity of feed water. This can be done either with or without the use of acid regenerant. Without the use of acid, the regenerant used is salt, and the process often is called salt splitting. The salt-splitting process exchanges all bicarbonate, sulfate, and nitrate anions for chloride anions. For best results, it is recommended that deionized water be used as feed water. Where hard, alkaline, and low-sodium water is available, the use of a weak acid resin should be considered.

The entire regeneration cycle is similar to water softening (described later in this chapter). It is not uncommon to use the same salt and regenerant piping to accommodate both the softener and the dealkalizer. Some caustic soda may be added (one part caustic soda to nine parts salt) to reduce the leakage of alkalinity and carbon dioxide. Since this can cause hardness leakage from the dealkalizer, a filter downstream of the processed water is necessary.

A weak acid resin also can be used. The process transfers the alkaline salts of calcium and magnesium to the weak acid resin and should include degasification if required by the product water. The weak acid process operates at a very high utilization factor, near the theoretically required amount. Hydrochloric acid, rather than sulfuric acid, is preferred for regeneration. This process is very sensitive to the flow rate, temperature, and contaminant level of the feed water. These changing conditions must be considered by the manufacturer in the design of the process. The entire regeneration cycle is similar to that of a cation ion-exchange column.

Decarbonation

Decarbonation is rarely used, but it should be considered if the bicarbonate level in the feed water is in the range of 14 to 20 milligrams per liter or higher. Decarbonation usually is accomplished in small systems by the use of filtered air flowing through the water stream and stripping out the carbon dioxide.

Distillation

In its basic form, distillation is the process of boiling feed water, condensing the steam produced from the feed water, and collecting the condensate, which yields product water theoretically free from nonvolatile impurities.

Three methods currently are used to produce distilled water: single-stage distillation, vapor compression, and multi-effect distillation.

Single-stage Distillation

The still used for single-stage distillation is the simplest type of still. Feed water enters the still and is evaporated and condensed in a single stage. Cooling water is required to condense the steam produced. This type of still produces water of approximately 1 megohm-centimeter, with higher purity possible with optional equipment that removes dissolved gaseous impurities. This method has a small footprint, is less labor intensive than the other methods, and tolerates feed water with a high level of impurity.

Vapor Compression

Sometimes called thermocompression distillation, vapor compression is a method of evaporation in which a liquid is boiled inside a bank of tubes. The vapor generated then passes through a mist eliminator that removes any water droplets. The pure vapor is withdrawn by a compressor in which the energy imparted results in a compressed steam with increased pressure and temperature. The higher-energy compressed steam is discharged into an evaporator. At this point, the steam gives up most of its energy (latent heat) to the water inside the tubes. More vapor is generated and the process is repeated. The condensate (distilled water) is withdrawn by the distillate pump and is discharged through a two-stream heat exchanger.

The excess feed water that did not evaporate also is pumped through an exchanger. Both the distillate and the blowdown are cooled, and the feed water is preheated prior to its entering the evaporator. These exchangers minimize the energy consumption of the system and eliminate the need for additional cooling water. The system operates continuously once it is started. Additional makeup heat, usually supplied by steam, is required for continuous operation. Vapor compression generally is considered more economical for large quantities of water and does not require high-quality feed water for proper operation. It has moderate first and operating costs.

Refer to Figure 11-3 for a typical flow diagram of a vapor compression unit.

Multi-effect Distillation

Multi-effect distillation units use staged evaporation and condensation to generate distilled water. Each stage is called an effect. Distilled water is produced in each effect when the steam generated by the evaporation of high-purity feed water in the previous stage is condensed. The initial driving force for the evaporation is power steam applied to the shell side of the first effect vessel. The multi-effect method has the highest initial cost and the lowest operating cost of the three distillation methods, and it requires the highest quality feed water.

The feed water enters the vessel, and its pressure is boosted by the feed pump. The feed water flows through a coil in the condenser, which allows it to pick up heat from the condensing steam. This preheated feed water flows through the feed control valve and into the tube side of the first effect. The first effect level controller senses the feed water level and signals the feed control valve to maintain the desired level. Power steam is introduced into the unit and flows through the steam control valve and into the shell side of the first effect.

Temperature sensors sense the temperature on the tube side of the first effect and signal the steam control valve to maintain the required temperature. This steam condenses on the outside of the tubes of the first effect, giving up its latent heat of vaporization to the feed water inside the tubes, causing it to boil and generate vapor.

The pure steam generated in the first effect is introduced into the shell side of the second effect. The pure steam condenses, producing distilled water while giving up its latent heat to the high-purity feed water inside the second effect tubes, causing the feed water to boil and generate vapor. Each effect operates at a lower pressure than the previous effect to provide the temperature difference that allows the transfer of heat. The pure steam generated in the tube side of the first effect by the condensing power steam passes through the mist eliminator to remove any entrained water droplets. Feed water from the first effect passes through an orifice and into the tube side of the second effect. The first effect pure steam enters the shell side of the second effect and is condensed on the outside of the tubes.

The condensate (distilled water) passes through an orifice and enters the shell side of the third effect. Feed water in the second effect passes through an orifice and into the tube side of the third effect.

After passing through the mist eliminator, the last effect, pure steam enters the condenser and condenses on the outside of the condenser coils. This distilled water from the last effect and the distilled water from the previous effects is cooled by the cooling water of the condenser. The distilled water exits the condenser and enters the distillate pump. The distillate is pumped through the distillate control valve and through the storage/dump valve. The condenser level controller senses the distillate level and signals the control valve to maintain the desired level.

Noncondensable gases in the condenser are vented to the atmosphere. The condenser temperature is maintained at a predetermined level by the cooling water flow. The unit is protected by pressure-relief valves along with high- and low-level alarms.

Refer to Figure 11-4 for a typical flow diagram of a multi-effect distillation unit.

Filtration

Deep-bed Sand Filtration

Deep-bed filters are designed to remove coarse suspended particulates larger than 10 micrometers. They are a pressure-type filter using either multi-graded sand or multimedia as the filter medium. Particulate removal in the range of 98 percent should be expected.

Sand-only filters for laboratory water systems generally operate at a velocity of about 4 gpm per square foot (192 liters per minute per square meter) of cross-sectional bed area. Multimedia filters operate at about 6 gpm per square foot (228 liters per minute per square meter) of cross-sectional bed area. Keep in mind that these values are general in nature, and it is important to operate these units at the velocities recommended by the individual manufacturer.

The multimedia filter achieves a more uniform distribution of filter media throughout the bed than the sand-only filter and is considered a more effective type of filter. A typical multimedia filter for laboratory use consists of a top layer of anthracite having a 1.1-millimeter-diameter grain size and a 1.5 specific gravity, a middle layer of sand having a 0.5-millimeter-diameter grain size and a specific gravity of 26, and a bottom layer of garnet having a 0.2-millimeter-diameter grain size and a 4.2 specific gravity. The normal operational flow rate ranges from 6 to 15 gpm per square foot (228 to 570 liters per minute per square meter) of bed area.

Backwashing is required to clean the filter, with the effluent discharged to the sanitary drainage system. A backwash flow rate of 10 to 15 gpm per square foot (380 to 570 liters per minute per square meter) generally is required for effective cleaning.

Cross-flow and Tangential-flow Filtration

In the past 10 years, a number of membrane filters have appeared on the market, and membrane systems have greatly expanded the field of mechanical filtration. Following are several typical media and membrane-filtration systems:

- Bag filter gross filtration, including limited membrane applications
- Standard cartridge depth filtration
- Hurricane (a trademark of the Harmsco Corp.), a cross between a standard tangential cartridge application and a cross-flow filter
- Horizontal and vertical pressure media filters, with or without a precoat
- Submicron cartridge filtration, including point-of-use ultrafiltration cartridges
- Cross-flow membrane systems designed for particulate removal in the concentrate
- Ultra-filtration to less than 10,000 molecular weight compounds
- Nano-filtration with a very low molecular weight filtration, to ionic levels of calcium sulfate
- Reverse-osmosis waste-treatment applications

These filtration systems typically are used in conjunction with ion-exchange and reverse-osmosis, high-purity systems to remove bacteria, pyrogens, and nonvolatile total organic carbon compounds. These filtration systems are used in waste-treatment applications, including the concentrated waste of reverse-osmosis systems and ion-exchange waste.

Activated Carbon Filtration

Activated carbon is used to remove residual chlorine, chloramine disinfectants, dissolved organics such as trihalomethanes, and a major portion of naturally occurring dissolved organic material from municipal water supplies. The nonionic organics tend to coat ion-exchange resins and all types of membranes.

Some system designers are reluctant to use the activated carbon filter in the generation of pure water because of the possible development of significant levels of bacteria in the unit itself. This can be controlled by periodically sanitizing the unit with pure steam or hot water with a temperature greater than 176°F (80°C). The need for sanitizing can be determined only by testing the water. Because of this need for sterilization, the interior of the filter housing should be lined or coated. When using pure water as feed water, stainless-steel housings should be avoided because of possible chloride stress corrosion and chloride pitting resulting from the chlorine in the feed water.

A typical detail of a packed-bed, activated-carbon unit is illustrated in Figure 11-5.

Ion Exchange and Removal

Ion exchange is the basic process in which specific ions in a feed water stream are transferred into an exchange medium called resin and exchanged for different ions of equal charge. When the ion-exchange process is used to treat water only for the removal of hardness, it generally is known as water softening. When the ion-exchange process is used to treat water for the removal of ions to produce pure water, it often is referred to as deionization (DI) or demineralization.

The deionization/demineralization process uses different types of resin to exchange first anions and then cations, resulting in the removal of all ions from feed water when the process is carried to completion. When all of the ionic components involved in water are removed by ion exchange, the water is said to be deionized or demineralized. The ion-exchange process also is used to remove dissolved inorganics. Water softening only exchanges some types of ions

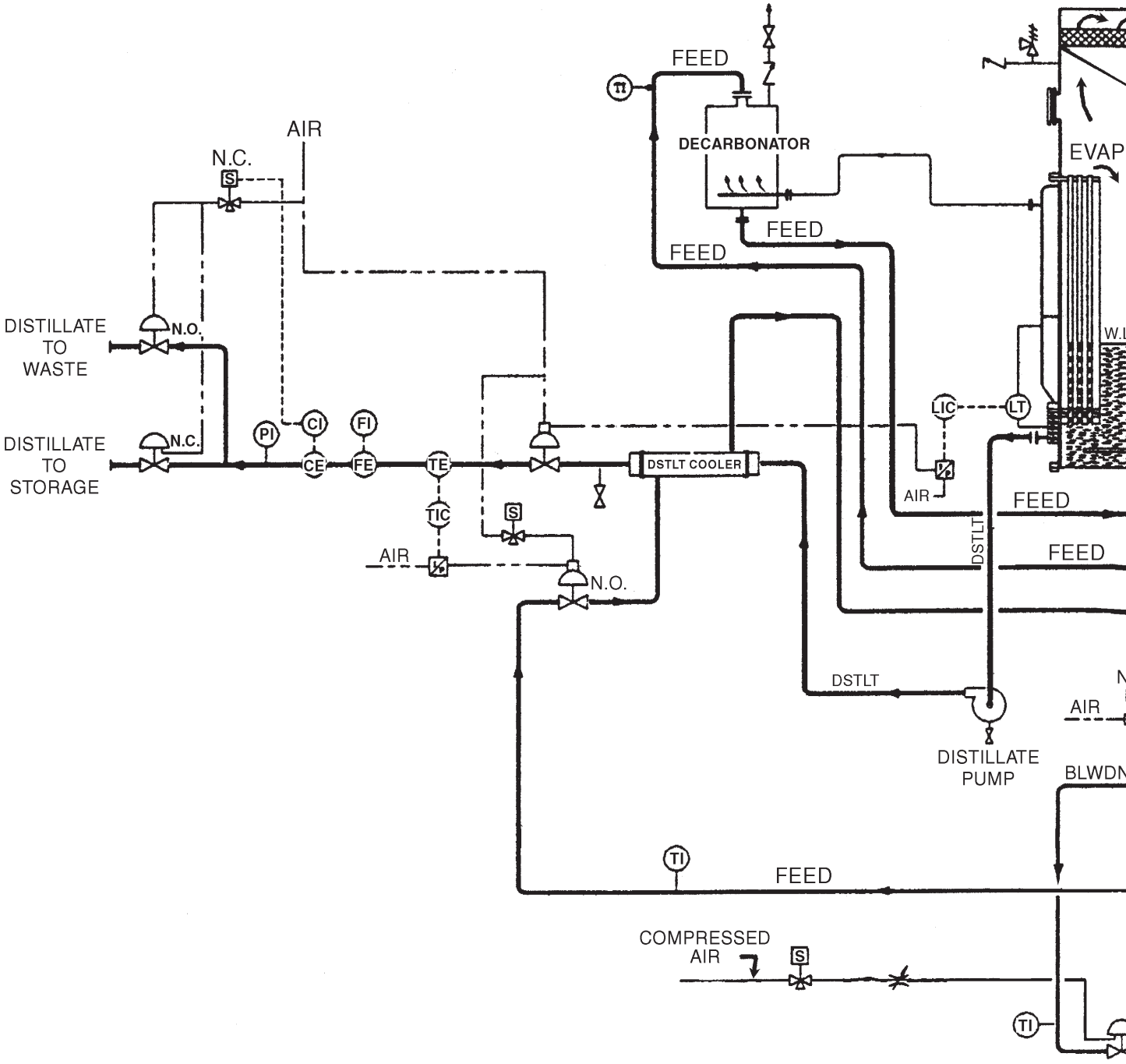
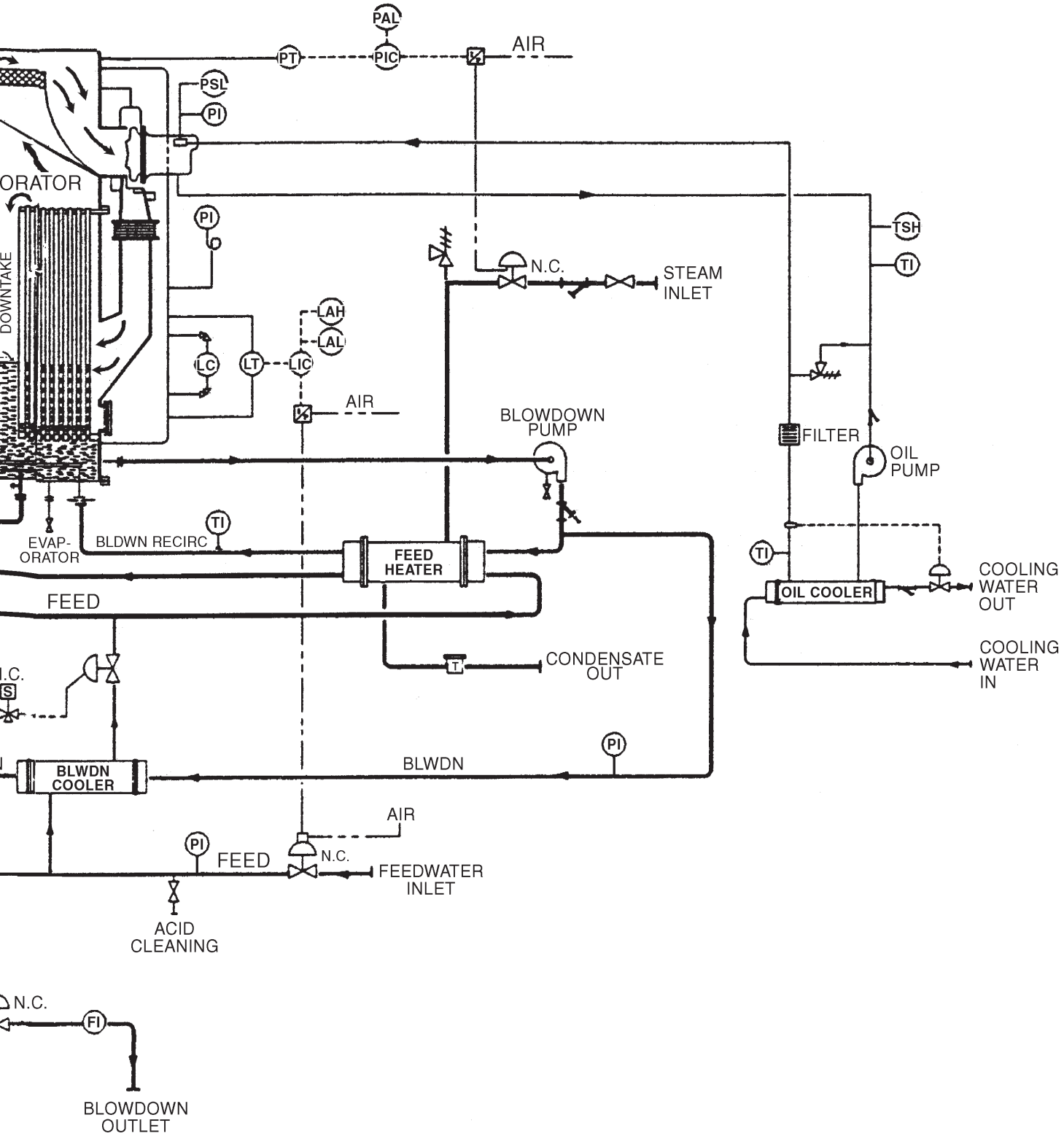


Figure 11-3 Detail of Vapor Compression Still


PAL
PT
PIC
AIR
PSL
PI
ORATOR
DOWNTAKE
PI
N.C.
STEAM
INLET
TSH
TI
LAH
LAL
LC
LT
LIC
AIR
BLOWDOWN
PUMP
FILTER
OIL
PUMP
EVAP-
ORATOR
BLDWN RECIRC
TI
FEED
HEATER
TI
OIL COOLER
COOLING
WATER
OUT
FEED
T
CONDENSATE
OUT
COOLING
WATER
IN
BLWDN
COOLER
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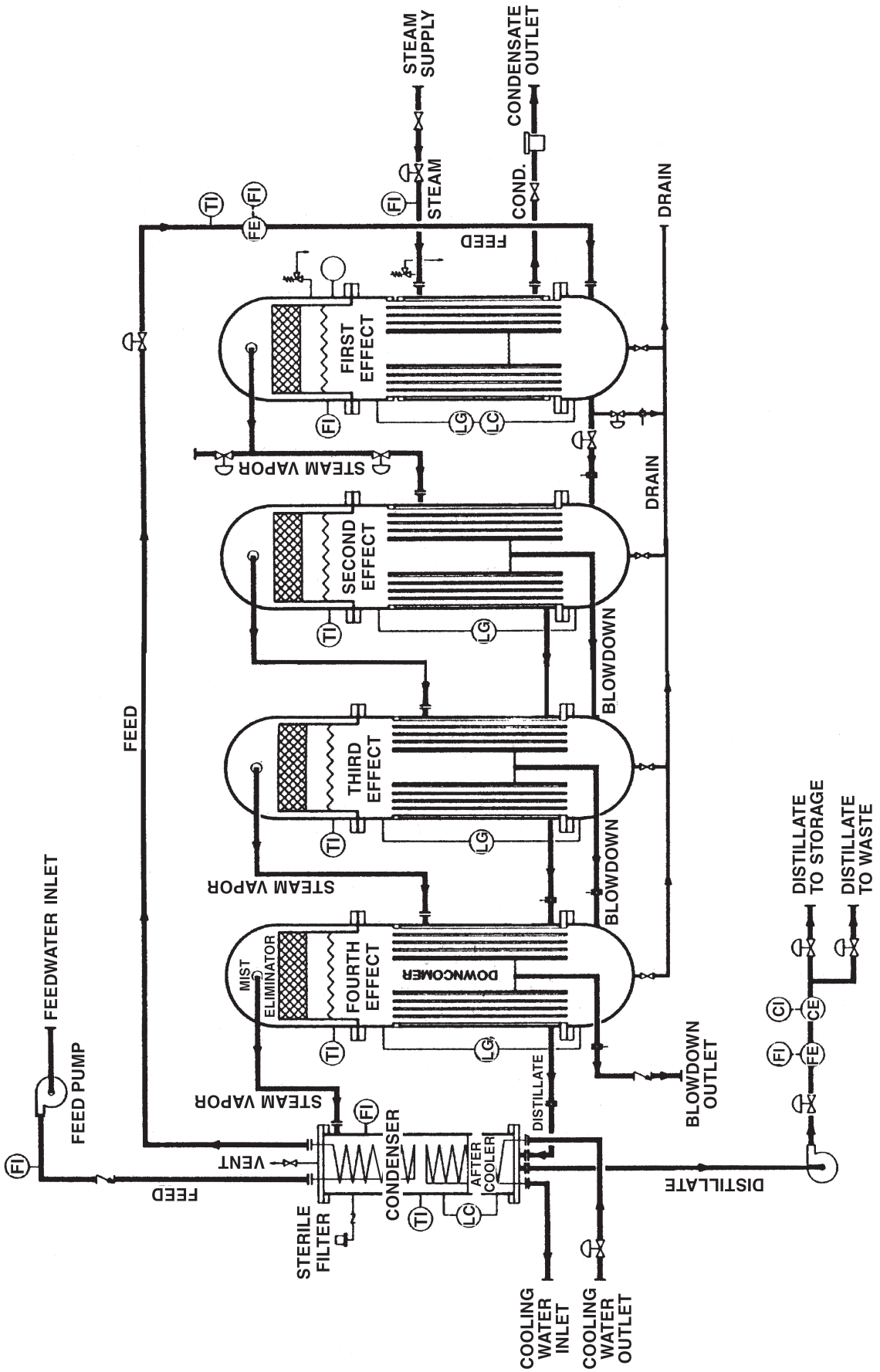


Figure 11-4 Detail of Multi-effect Still

for others that are less detrimental for the intended end use of the water.

Table 11-7 lists the common anions and cations typically found in water. Ion exchange does not remove significant amounts of organics, bacteria, particles, colloids, or turbidity.

Regenerable Ion Exchange

Regenerable ion exchange is a batch process in which ions in raw water are transferred onto a resin medium in exchange for other ions bonded to that medium as the raw water percolates through it. The ions in the raw water are adsorbed onto a bed of exchange resins and replaced with an equivalent amount of another ion of the same charge. This action continues until the medium has reached its exchange capacity and it no longer is capable of exchanging ions.

The two general types of deionizers are working and polishing. The working type is used for the initial removal of the bulk of ions from feed water or as only an ion-exchange process (such as hardness removal) if the purification is a single process. The polishing type is used to purify feed water after an initial run through a working ion-exchange system.

Resins

Resin-exchange media include natural inorganic aluminum silicates (sometimes called zeolites or green sands), bentonite clay, and synthetic, gelatinous and synthetic, organic resins. Most processes use the synthetic resins. Resins are graded by purity and consistency in size.

Table 11-7 Typical Cations and Anions Found in Water

Cations	Anions
Calcium	Carbonates
Magnesium	Bicarbonates
Sodium	Sulfates
Potassium	Chlorides
Iron	Nitrates
Manganese	Silica

Resin is manufactured in the form of a large number of spherical beads, typically about 0.4 millimeter in diameter. Weakly bonded ions on these beads' surfaces are used for the exchange process. Because the process must exchange ions of the same charge, ion-exchange resins are composed of either anion or cation exchange resins. Manufacturers are constantly making new resins for different ion-removal purposes.

Traditional deionization exchanges cations with hydrogen (H^+) ions (an acid) and anions with hydroxyl (OH^-) ions (a base). Although not 100 percent effective, these two exchange processes together remove cations and anions from water, and the remaining H^+ and OH^- ions combine to form water. When all of the ionized impurities are removed, the water is said to be deionized, which is also referred to as demineralized.

A large number of ion-exchange resins is available. Each resin is formulated to obtain optimum performance for different impurities. The affinity for different ions in solution is termed selectivity coefficients. The number of charges (valence) available on a particular ionic medium is a major factor in the selection of specific resins to remove the desired impurities and is based on an analysis of raw water. The resins are contained in a vessel, often referred to as a column. The actual resin bed could be supported by a mat of graded gravel, screen-wrapped pipe, or perforated plates, which also act to evenly distribute feed water over the entire resin bed. The resin beads in the vessel also create

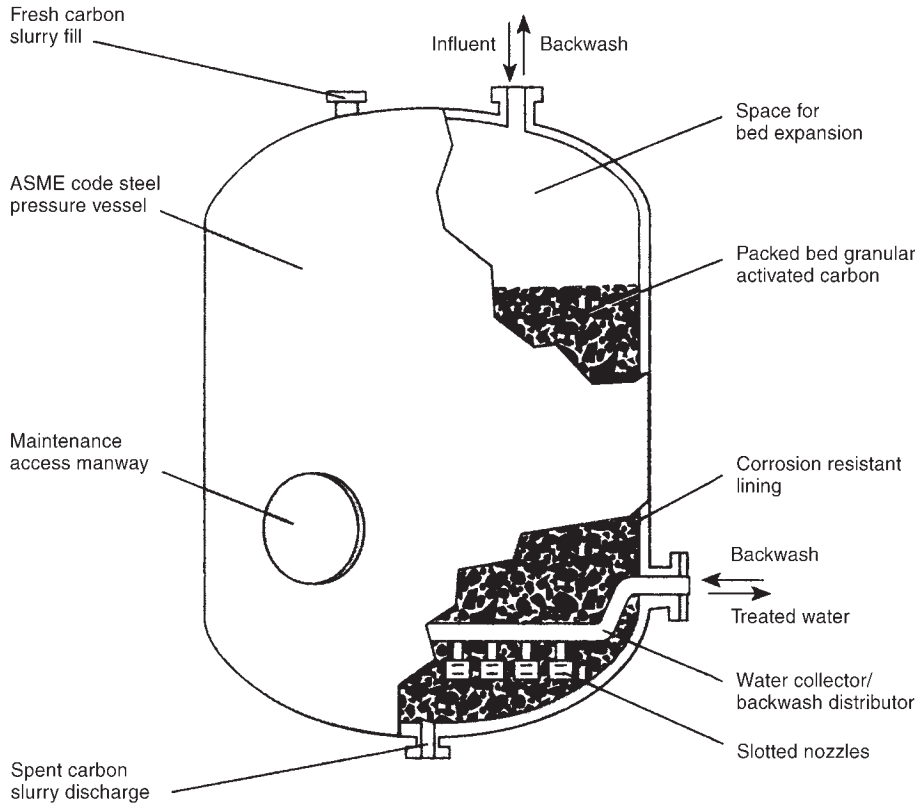


Figure 11-5 Schematic Detail of Large-scale, Granular-activated Carbon Filter

an effective depth filter. This filtering action leads to fouling and unpredictable operating runs because of an accumulation of particulates.

Anion resins could be either a strong or a weak base. An often-used anion resin is divinyl benzene, a gelatinous bead. Anion resin type 1 premium has a very small tolerance of bead size. Anion resin type 1 regular generally is used for maximum silica reduction. Resin type 2 is used most often, generally unless type 1 is requested specifically. The two resins have different costs and capacities. In general, the higher cost of the type 1 resin is considered acceptable to obtain a more efficient and longer-lasting resin. Weak-base exchangers are not effective in the removal of carbon dioxide or silica. They remove strong acids more by adsorption than by ion exchange. The end result is the same, and the efficiency of weak-base regeneration for acid-salt removal is far superior to that of strong-base material for the same job. Thus, weak-base units are superior when the feed water is high in sulfates and chlorides.

The two most often used cation-exchange resins are strong acid or weak acid. Strong cation resins remove all cations, regardless of the anion with which they are associated. These resins have a moderate exchange capacity and require a strong acid regenerant, such as hydrochloric or sulfuric acid.

The deionization process can be arranged as either a two-step (dual-bed) or single-step (mixed-bed) process. In the dual-bed process, one vessel contains the anion-exchange resins, and a second vessel contains the cation-exchange resins. In the mixed-bed unit, a single vessel contains a mixture of both resins. The dual-bed arrangement produces water less pure than that produced by a mixed bed, but it has a greater removal capacity. A typical mixed bed contains 40 percent cation resins and 60 percent anion resins. Dual beds are easier to regenerate. It is not uncommon to install a dual-bed exchanger, often referred to as a working exchanger, before a mixed bed to remove the bulk of the impurities, and then the mixed bed, often called a polishing exchanger, further purifies the water to the desired high purity.

Figures 11-6, 11-7, and 11-8 illustrate a typical single-bed ion-exchange unit, a typical dual-bed ion-exchange unit, and a typical mixed-bed ion-exchange unit respectively. The piping and valve arrangements of manufacturers may differ from those shown.

Regeneration Cycle

The ion-exchange process is reversible. As the water continues to pass through the ion-exchange resin beds over time, the number of ions on the resin beads available for exchange declines and gradually is exhausted. This process starts at the entry of the water to the vessel and progresses down the bed. When the resins have reached the limit of exchange, the bed is said to have reached its exchange capacity. It is then necessary to take the column out of service to be regenerated.

Regeneration, which is the reverse of deionization, is the term used for the displacement of the ions removed from the feed water. Regeneration generally consists of three steps: backwashing, application of regenerating solution, and rinsing. Regeneration can be performed either co-currently (in the same direction as the flow of feed water) or counter-currently (in the opposite direction of the flow of feed water). All of the water used for regeneration must be routed to a drain of adequate size. In addition, the acid and caustic must be neutralized prior to discharge into a public sewer system. It is common practice to combine the acid and caustic waste streams to neutralize the effluent to the greatest extent possible. Additional acid or caustic may have to be added to the final effluent to produce a pH acceptable to the local authorities. (Note: Sufficient safety precautions must be taken when handling regeneration chemicals.)

Backwashing is a counter-current operation accomplishing two purposes. The first is to remove any particulates that have accumulated in the resin bed and on the beads. The second is to regrade the resin beads so new beads are on top of the bed, which is where the heaviest duty from the beads is required. This is done by the resin bed expanding from its normal, packed condition by the reverse flow of wa-

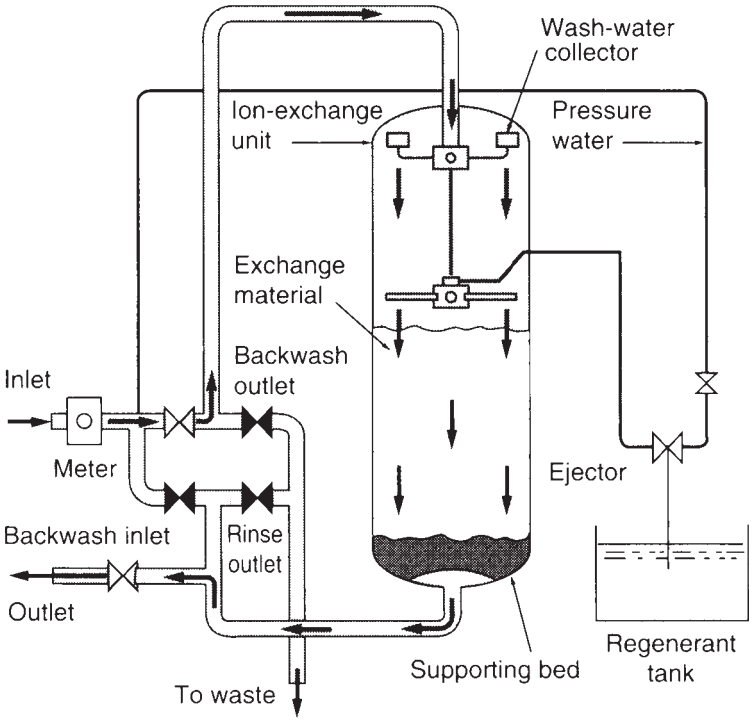


Figure 11-6 Typical Single-bed Ion Exchanger

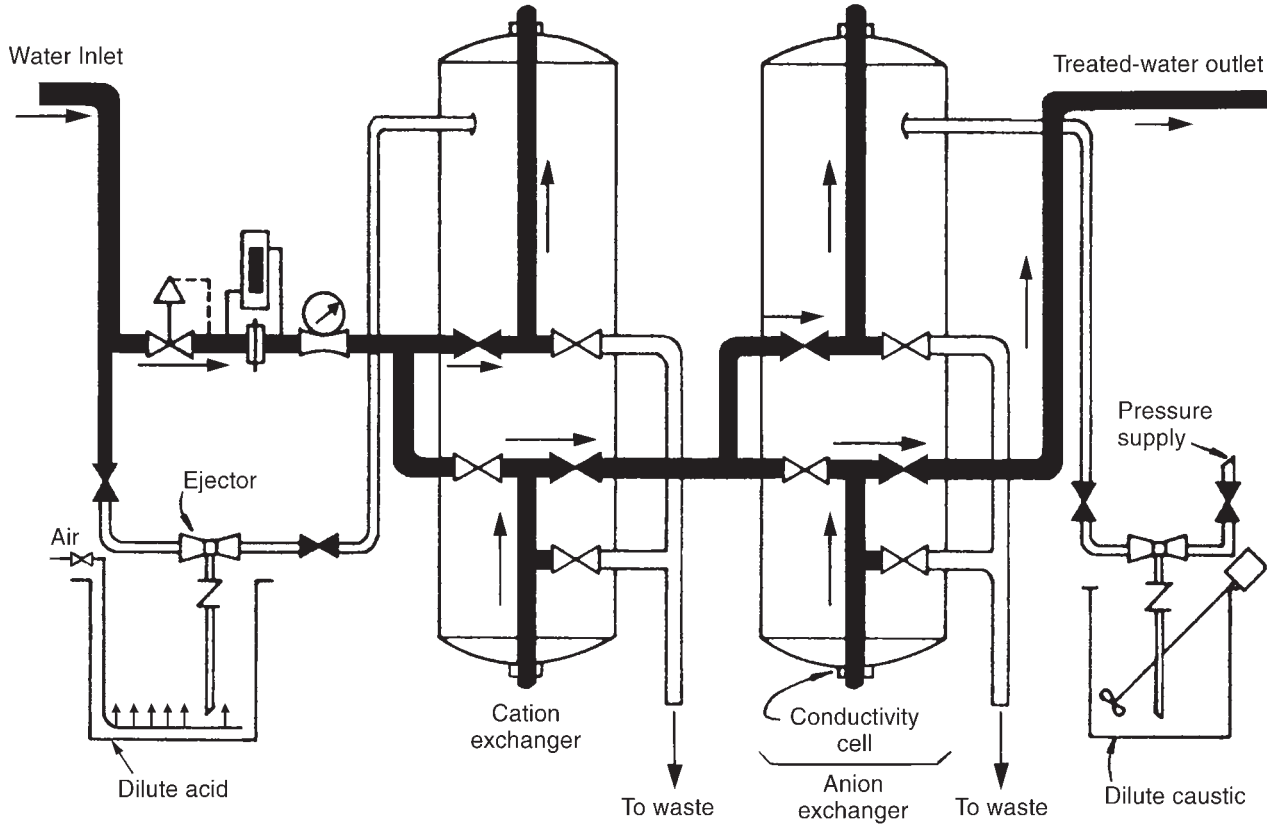


Figure 11-7 Typical Dual-bed Ion Exchanger

ter. The manufacturer establishes the required flow rate of backwash that should be maintained. A high flow rate will blow resin out of the tank and into the drain. The flow rate should be enough to scrub the beads together, increasing the cleaning action. A greater-than-recommended flow only wastes water and provides no additional benefits.

The two chemicals used to regenerate cation resin beds are either a 93 percent solution of sulfuric acid or a 30 to 32 percent solution of hydrochloric acid (HCl), also called muriatic acid. As they flow through the columns, they replace the retained cations with hydrogen ions from the acid. Hydrochloric acid is used most often because it has the greatest efficiency, and only one-quarter of the amount of sulfuric acid is used. Sulfuric acid is much lower in cost and is used when a large quantity of resin is to be regenerated, which makes its lower cost practical.

The chemical used most often for regenerating anion resins is a 40 percent mixture of sodium hydroxide, which replaces the retained anion ions with hydroxyl ions. For mixed-bed units, the resins must be separated prior to regeneration.

The quality of the chemicals used for regeneration has an important effect on the maintenance of exchange capacity. Although chemically pure ingredients are not required, some contaminants found in these chemicals collect on the resins and eventually cause difficulty in operation.

Technical-grade acids, which are free of oils and other organic materials, are acceptable for the regeneration of cation resins. They should be 66 Baume, free of suspended matter, and light in color. They should mix freely with water and not form any precipitate. Acid-containing inhibitors should not be used. Sulfuric acid is usually the most economical choice for large-scale use. Hydrochloric acid should be technical grade and a minimum of 30 percent hydrochloric acid by weight (18 Baume) and shall not contain excessive amounts of iron and organic materials. Hydrochloric acid obtained by the salt-aid or hydrogen-chlorine process has been found satisfactory. HCl obtained by the hydrolysis of chlorinated organic chemicals should be avoided, particularly if used to treat potable water.

Anion-exchange resins are regenerated with 76 percent sodium hydroxide, which shall be low in iron, chlorides, and silica to avoid fouling the strong-base anion exchangers. Weak-base anion exchangers are regenerated most economically with technical-grade, flake sodium hydroxide. Strong-base exchangers are best regenerated using nylon or rayon-grade sodium hydroxide, also 76 percent. If purchased in a 40 percent solution, the same grade previously indicated should be used. All caustic shall have a maximum of 2 parts per million chlorates.

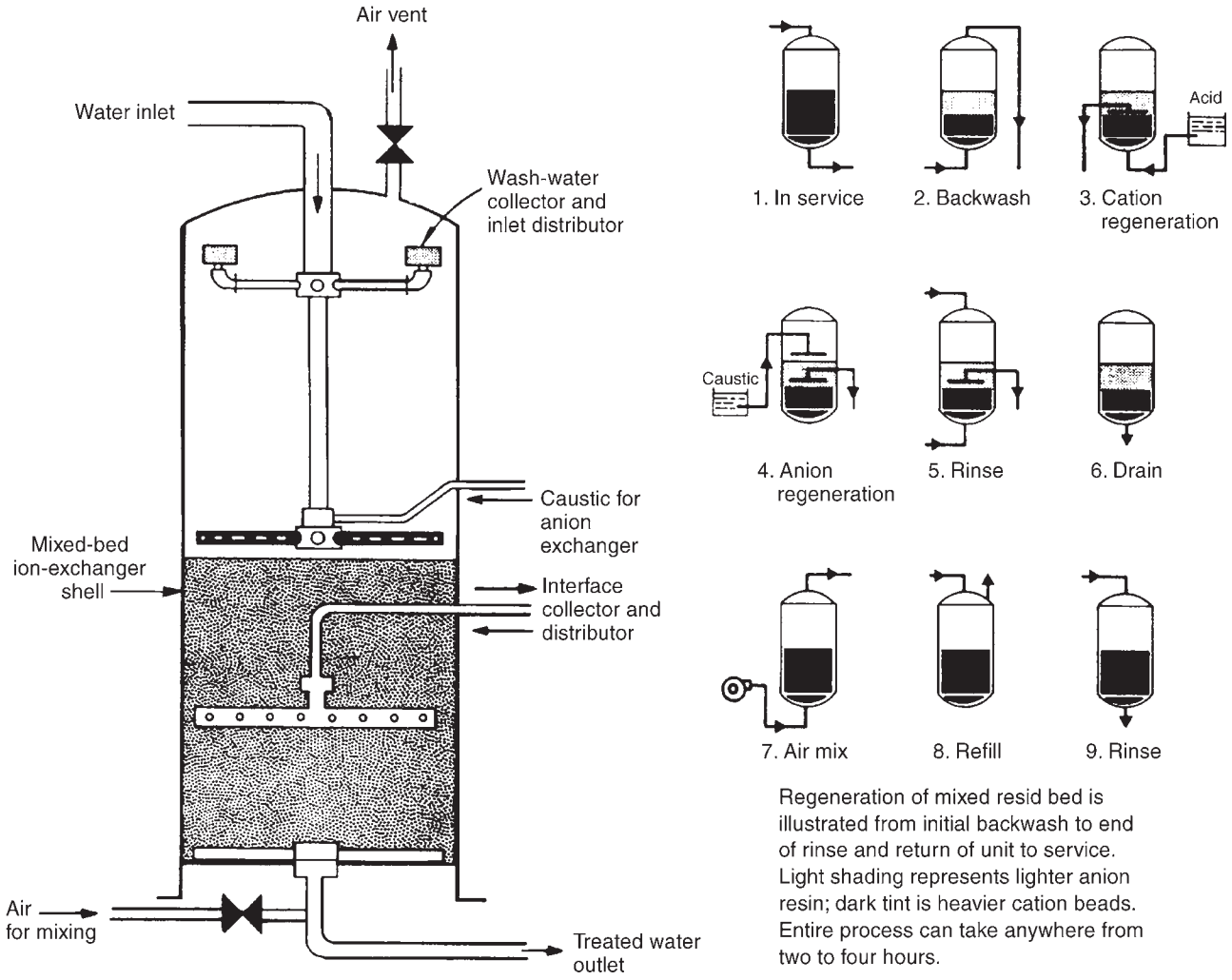


Figure 11-8 Typical Mixed-bed Ion Exchanger

The flush cycle is the shortest step. It is a co-current process whose purposes are to flush away any remaining residue of the regeneration liquids to drain and repack the bed in preparation for the new run.

The entire regeneration cycle typically takes about one hour. If the process requires continuous operation, a duplex set of equipment is installed so one is in use while the other is being regenerated.

To estimate the frequency of regeneration, first determine the exchange capacity, in grains, of the selected resin bed from literature provided by the manufacturer. Next, from the analysis of the raw water, find the average level of total dissolved solids and convert this figure into grains per gallon (liter). Dividing the flow rate, in gallons (liters), into the grain capacity of the resin bed gives the time it takes to saturate the resin bed before regeneration is required. As mentioned above, the designer must consider the ionic or molecular composition of the regeneration waste.

Service Deionization

Service deionization is not another form of deionization; it's a different type of equipment arrangement. With the regenerable type, the deionization equipment is permanent, and the regeneration is done on site by operating or maintenance personnel who must handle and store the chemicals used for regeneration. The service deionization system uses individual cartridges or tanks for the anion, cation, and mixed beds. When the individual cartridges are exhausted, they are replaced with recharged units on site by the supplier, and the exhausted cartridges are removed to be regenerated at the supplier's premises.

This arrangement considerably reduces the initial cost of the equipment, eliminates the need to store chemicals, and saves operating or maintenance personnel the time required to regenerate the units. In addition, it saves water that does not have to be used for backwash.

The operating costs to a facility for service DI equipment are higher than they are for the per-

manent bed type. However, when regeneration discharge and variable production costs are considered, the cost of point-of-operation demineralization becomes attractive.

Continuous Deionization

Continuous deionization, also known as electrodeionization, is a continuous water-purification process using direct current, an alternating arrangement of cation and anion-permeable membranes, and mixed-bed, ion-exchange resin. The cation and anion membranes form parallel, thin flow compartments, alternating between concentrating and diluting compartments. The diluting compartments contain a thin layer of ion-exchange resin. Some manufacturers also use ion-exchange resin in the concentrating compartments. A single set of these components is called a cell pair. Many sets of these cell pairs can be placed between sets of electrodes in a plate-and-frame device to achieve the desired flow output. More cell pairs allow higher flow. This arrangement is schematically illustrated in Figure 11-9.

Feed water enters into the top of all the compartments. Under the influence of a direct current electrical field, ions move from the water in the dilute stream, through the ion-exchange resin, toward the electrode with the opposite charge. Cations move toward the cathode, through the cation-permeable membrane, and into the adjacent concentrate stream. Anions move toward the anode, through the anion-permeable membrane, and into the adjacent concentrate stream. Deionized water exits from the bottom of the dilute stream. The alternating cation- and anion-permeable membranes trap and concentrate ions in the concentrate channels, and a small flow of feed water continuously rinses the concentrated ions to drain. The ion-exchange resin bed serves as a highly conductive medium through which ions flow because of the electric field. The various flow streams are hydraulically independent, allowing a high volume of high-purity water (product) and a low volume of concentrate (waste).

The resin-filled diluting compartment (cell) creates a low-level resistance path for ions. At the bottom of the diluting cell under the proper combination of flow, temperature, water conductivity, and voltage, the resins regenerate automatically without the use of added chemicals. This is commonly referred to as electroregeneration of the ion-exchange resins. This process is continuous and results in a steady supply of high-purity water from the diluting compartments. The continual ion removal and electroregeneration result in some significant advantages over conventional ion exchange, including no handling and disposal of

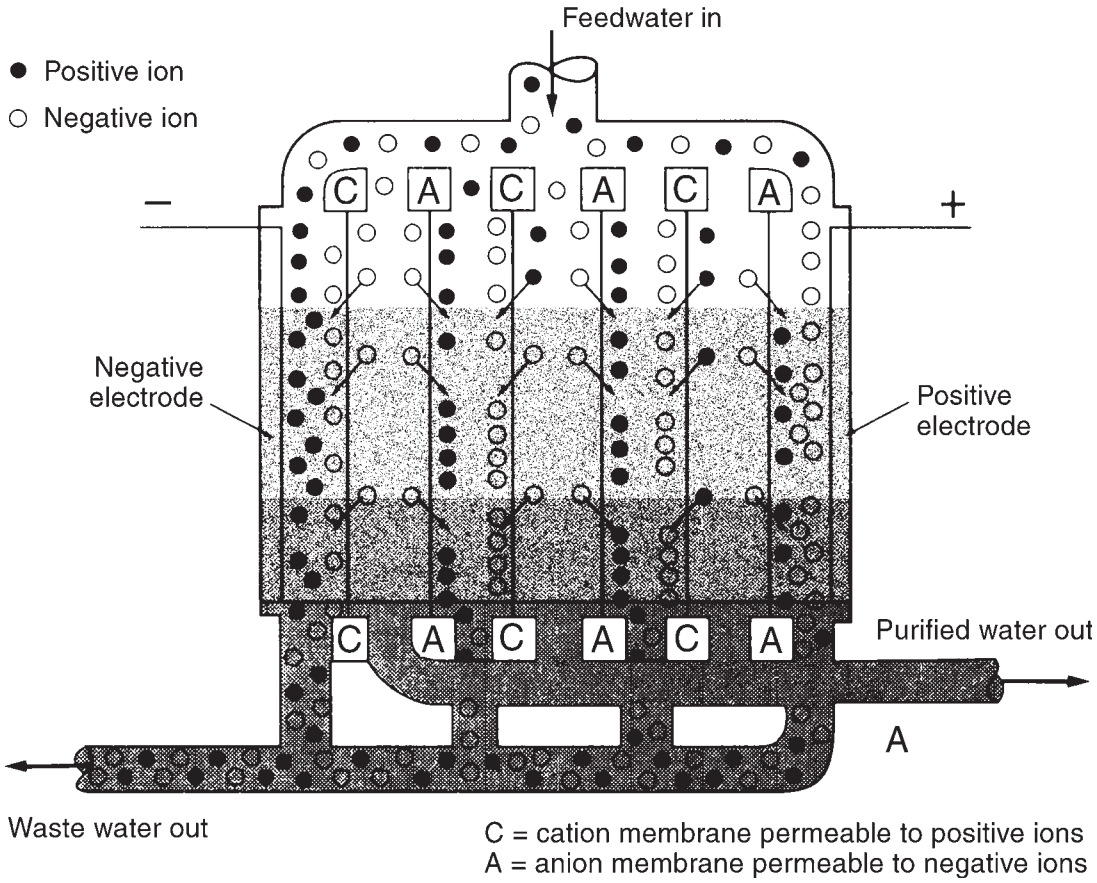


Figure 11-9 Schematic Operation of a Continuous Deionization Unit

hazardous regeneration chemicals, no interruptions due to exhaustion of the resins' ion-exchange capacity, and low operating costs.

Continuous deionization is sensitive to feed water impurities, and very few natural potable feed water supplies can meet the required feed water specifications without softening and additional pretreatment. Because of this limitation, most processes are now using continuous deionization for polishing purposes after reverse osmosis. The use of reverse osmosis and continuous deionization results in a complimentary combination of purification technologies, with the reverse osmosis removing the bulk of contaminants and the continuous deionization polishing the water to high purity levels.

Another disadvantage of continuous deionization is that the membranes and resins are incompatible with most sanitizing agents. Manufacturer specifications and guidelines should be checked and followed. However, when continuous deionization is used in combination with reserve osmosis, the reverse osmosis process effectively provides efficient removal of bacteria, and the sanitization of the reverse osmosis can reduce the risk of downstream bacteria growth. Furthermore, continuous deionization can provide water consistently low in bacteria, and the continuous deionization process can have a germicidal effect due to local pH shifts associated with electroregeneration.

Water Softening

Water softening is a process that reduces or removes dissolved impurities that cause hardness in water. This is done by one of two methods: adding lime-soda ash to the raw water for very large volumes or passing the raw water through an ion-exchange process.

The lime-soda ash method uses either hydrated lime or quicklime along with soda ash. When added to water, these chemicals react with the dissolved calcium and magnesium carbonate to form insoluble compounds. These compounds precipitate out of solution, are passed through a filter to be removed, and then are discharged to drain. This process usually is carried out during the clarification process rather than separately and is reserved for large volumes of water.

The ion-exchange method of water softening is a cation-exchange process used to remove insoluble and scale-forming iron and other multivalent cations, which are the primary causes of hardness, and to replace them with sodium ions, which do not contribute to hardness. The removal of these impurities prevents the buildup of insoluble scale precipitates on piping and the reverse-osmosis membrane. It is accomplished by passing the water through a bed of granular sodium cation-exchange resin. This process commonly is called sodium cycle ion exchange.

The resin bed typically occupies about two-thirds of the tank. The other one-third is needed for expansion of the resin bed during backwash. A generally accepted range of 0.4 to 3 gpm per cubic foot (50 to 380 liters per minute per cubic meter) of resin is used to determine the volume of resin and the cycle time of the unit.

Microbial growth inside the unit is a concern in softening systems used for pharmaceutical and some laboratory purposes. The water softener is regenerated with a brine solution, which does not destroy bacteria. The storage and regeneration equipment for the liquid brine solution also allows microbial growth in storage tanks exposed to the atmosphere. An alternative is to use a dry storage system, which generates a salt solution from water mixed with salt pellets only when necessary for regeneration. This controls microbial growth better than wet systems, but constant maintenance is required to monitor the brine tank. The quality of the salt in all systems should be determined periodically to ensure that no added substances are present.

The regeneration cycle is similar to that previously discussed. The difference is that salt is used to regenerate the resin bed. Industrial water softeners use rock salt for economy. Rock salt, because of its high mineral content, requires a special tank called a desolver to dissolve the rock salt in water prior to use. The water softener is similar to the schematic single-bed ion exchanger illustrated in Figure 11-6.

Ion-exchange System Design Considerations

Leakage is the presence of undesired ions in the final treated water. One of the major decisions that must be made when selecting an ion-exchange system is allowable leakage. The amount of leakage is a function of the completeness of regeneration of the resin. For water softening, generally accepted leakage amounts range between 0.1 and 1 part per million. Since total regeneration of the resin bed is inefficient and very costly, most water softeners operate at one-half to two-thirds of the ultimate capacity of the softener. There is sodium leakage from cation exchangers and silica leakage from anion exchangers. Normally, mixed-bed units have negligible leakage.

In general, for high-purity applications a single pass cannot give adequate purification of the water stream; therefore, a polisher is necessary. A mixed-bed ion-exchange system, when used as a polisher, in general has a 74 percent lower initial cost than a two-bed system. A single-pass reverse osmosis system is approximately equal to a two-bed ion-exchange system.

Usually, if the water demand for a facility is less than 40 gpm (151 liters per minute), the greatest benefit will be derived from the simpler, less costly equipment with higher operating costs. For this quantity, it is common to have a mixed-bed unit without a degasifier, which is not required. For systems with a requirement of 200 gpm (757 liters per minute) or

more, the majority of the systems installed will have multiple-bed units and a degasifier. Manufacturers must be contacted for specific system and resin selection and required equipment.

Where applicable, the use of weakly acidic and weakly basic resins minimizes chemical costs and reduces losses to waste because of the high regenerative capacity.

Some problems, such as microbial growth, are associated with water softeners. Sanitation usually is accomplished during regeneration. Iron buildup in the unit could pass through to downstream purification equipment unless operating personnel constantly monitor the water quality.

Membrane Filtration and Separation

Membrane filtration and separation is a general term for any water-purification process that removes contaminants from feed water by means of a thin, porous barrier called a membrane. When used as a filter, a membrane is capable of removing impurities of a much smaller size than other types of filters. Filters of this nature often are called ultrafilters and nanofilters. When membrane filtration and separation is used to produce pure water, the feed water flows parallel to the membrane (often called tangential flow), and not all of the feed water is recovered.

The two general categories of membrane filtration are reverse osmosis using a semipermeable membrane and filtration using ultrafiltration and nanofiltration membranes.

Reverse Osmosis

Reverse osmosis is a broad-based water-purifying process involving osmosis and ionic repulsion.

Osmosis is the spontaneous passage of a solvent (such as water) through a semipermeable membrane until there is an equal concentration of solute molecules (impurities such as sodium chloride) on both sides of the membrane. This membrane is called semipermeable because it allows the solvent to diffuse, or pass through, but it is impervious to the solute.

In the natural osmosis process, when two solutions of different concentrations are separated by a semipermeable membrane, water molecules from the less concentrated solution will spontaneously pass through the membrane to dilute the more concentrated solution. This occurs until a rough equilibrium is achieved. The driving force is a difference of pressure, called the osmotic pressure or concentration gradient, that exists across the membrane, and it is based on the degree of concentration of contaminants. This pressure is what drives the flow of the solvent. The flow (or flux) will continue until the osmotic pressure is equalized, which then results in a higher pressure on the concentrated solution side equal to the osmotic pressure.

Reverse osmosis is the flow of a solvent in the direction opposite the direction of flow of natural osmosis. If enough pressure is applied to the more concentrated solution, which in this discussion is water, pure water is diffused through the membrane, leaving behind the bulk of the contaminants. This concentration of contaminants is flushed to drain continuously and thereby removed from the system. The purified water is called permeate and the contaminant containing water reject or the reject stream. In some cases, the reject stream is referred to as salt. The performance characteristics of the selected membrane determine how large a system is required. The flow rate is measured in membrane flux, which is a measurement of the flow rate of permeate that will pass through a given area of the membrane at a specific temperature and pressure. The ratio of purified water flow to the feed water flow is called recovery. Most applications require a minimum 40 percent recovery rate to be considered practical. Rejection characteristics are expressed as a percent of the specific impurities removed and depend on ionic charge and size.

Four types of membrane module configuration are used for reverse osmosis applications: hollow fiber, spiral wound, tubular, and plate and frame. Spiral wound is the most commonly used configuration. In each design, maximum turbulence is necessary to avoid concentration polarization.

The hollow-fiber configuration, illustrated in Figure 11-10, consists of a perforated tube manufactured from ceramic, carbon, or porous plastic with inside diameters ranging from 1 to 6 inches (8 to 25 millimeter). It requires rigid support when mounted inside the pressure vessel. Feed water could be introduced into either the center or the outside, depending on the manufacturer of the module. Fouling resistance is low.

The spiral-wound configuration, illustrated in Figure 11-11, typically achieves a large surface area per unit volume. In this design, a flat membrane is formed around a fabric spacer closed on three sides, with the open side terminating in a perforated product water tube. The unit is placed in a pressure vessel. Feed water permeates through the membrane and flows radially inside the enclosure toward the product tube.

The tubular configuration, illustrated in Figure 11-12, consists of a perforated tube manufactured from ceramic, carbon, or porous plastic with larger inside diameters than the hollow-fiber configuration. The membrane is installed on the inside of the tube, and a number of tubes are installed inside a pressure vessel. Feed water enters the tube and permeates the membrane to be collected on the outside. The feed water channels are much more open than those of the spiral-wound configuration and less subject to fouling.

The plate and frame configuration, illustrated in Figure 11-13, consists of a membrane fixed to a grooved plastic or metal plate with several plates stacked together in a frame that includes feed water and drain ports. As the feed water flows across the membrane surfaces, the purified water penetrates the membrane and gathers along the frame for collection. The retentate continues to flow and could be recirculated or directed to drain. This configuration is used mostly for filtration and rarely for reverse osmosis systems. The packing density is low and the resistance to fouling is very high. It is used for small to medium volumes, generally less than 20 gpm (76 liters per minute).

System performance is determined by considering the following factors, which influence the capacity of the individual membranes selected:

- Operating pH
- Chlorine tolerance
- Temperature of the feed water
- Feed water quality, usually measured as silt density index
- Types of impurity and prior feed water treatment
- Membrane flux
- Number of operating hours
- Resistance to biodegradation and ability to be sanitized
- Rejection characteristics

Typical reverse osmosis systems remove the following contaminants to the following levels:

- Inorganic ions: 93 to 99 percent
- Dissolved organics: More than 99 percent (more than 300 molecular weight)
- Particulates: More than 99 percent
- Microorganisms: 99 percent

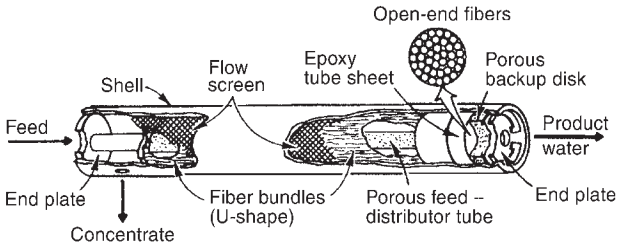


Figure 11-10 Hollow-fiber Reverse Osmosis Configuration

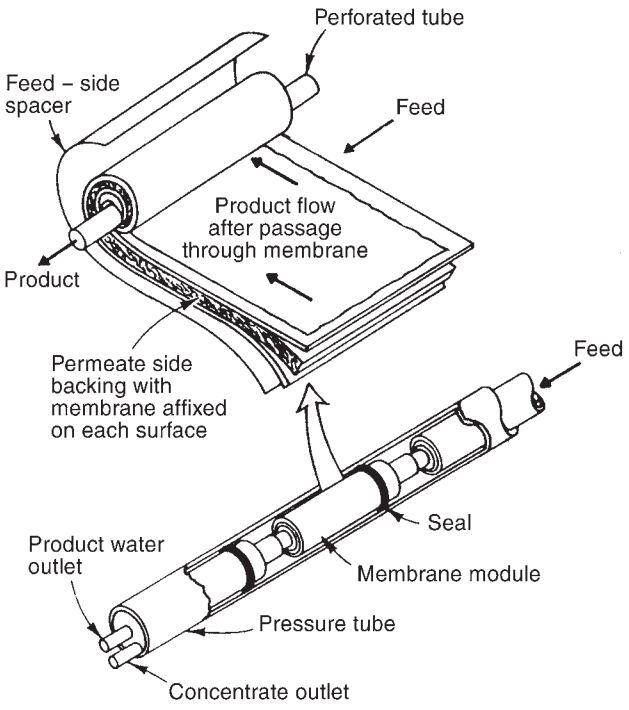


Figure 11-11 Spiral-wound Reverse Osmosis Configuration

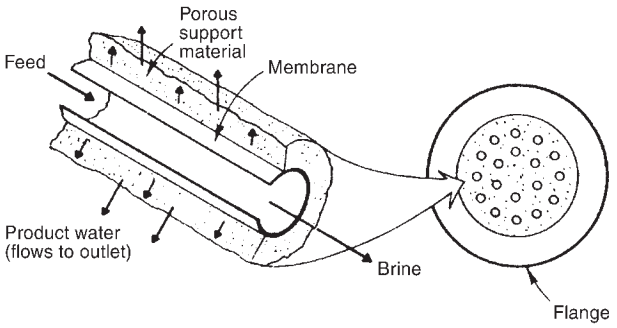


Figure 11-12 Tubular Reverse Osmosis Configuration

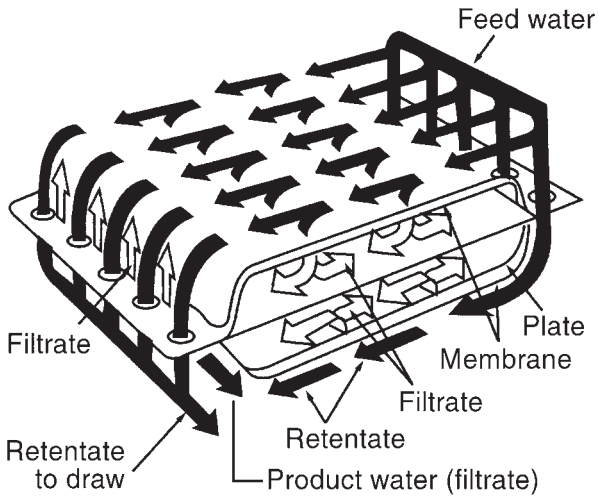


Figure 11-13 Plate-and-Frame Reverse Osmosis Configuration

Table 11-8 Comparison of Reverse Osmosis Polymers

	Thin Film Composite	Polyamide	Cellulose Acetate	Cellulose Triacetate	Polysulfone
pH stability	2–12	4–11	2–8	4–7.5	3–11
Chlorine tolerance	Fair–poor	Poor	Good	Fair–good	Good
Biological resistance	Good	Good	Poor	Fair–good	Good
Temperature limit for stability, °F (°C)	122 (45)	95 (35)	95 (35)	86 (30)	95 (35)
Typical rejection ionic species (%)	>90	>90	90	90	90
Flux	High	Low	Low–medium	Low–medium	High

The selection of a system configuration shall be based on the following considerations:

- Maximum recovery
- Fouling properties and resistance
- Production rate per unit volume

Only the following polymers have the necessary characteristics to function as a semipermeable membrane:

- Thin-film composite of various polymer materials
- Polyamide
- Cellulose acetate
- Cellulose tricetate
- Polysulfone

Typical characteristics and a comparison of these membranes are given in Table 11-8.

Cross-flow Filtration

Ultrafiltration and nanofiltration membranes are categorized by their pore size. Ultrafiltration membrane pore sizes range from 0.001 to 0.02 micrometer. Nanofiltration membranes have pore sizes allowing the passage of solids to 10,000 molecular weight, or daltons. The 10,000-dalton cutoff is recommended for the complete removal of pyrogens. Typical recovery rates for ultrafilters range between 95 and 98 percent, with the remainder flushed to drain.

The membranes are manufactured by bonding the membrane onto a porous, supporting substrate and then configuring it into elements. These filters usually are used as a pretreatment for the removal of colloids, bacteria, pyrogens, particulates, and high molecular-weight organics. Spiral wound and hollow fiber are the two most often-used configurations.

Microbial Control

Chemicals

The most often used disinfection method is the addition of oxidizing or nonoxidizing chemicals. Chemicals could be either biocides, which are substances that kill microbes, or biostats, which prevent the further growth of microbes. Commonly used chemicals are chlorine and chlorine compounds, hydrogen peroxide, and acid compounds.

To be effective, the chemical must have a minimum contact time in the water. In addition, a residual amount of the chemical must be present to maintain its effectiveness against organisms.

Chemicals add impurities to the water and generally are not suitable for a pure water environment. They mostly are used to disinfect potable and process water and equipment and are injected directly into the fluid stream by means of a metering pump. When present in the feed water used for purification, they must be removed. Chlorine may produce trihalomethanes.

Ultraviolet Radiation

Ultraviolet (UV) radiation is an in-line process, and UV light is generated using mercury vapor lamps. Two different wavelengths are available that produce the intensity and energy output necessary for the intended germicidal treatment requirements.

The 254-nanometer wavelength operates in the germicidal region, sterilizing by destroying bacteria, mold, viruses, and other microorganisms. This wavelength is preferred for pure water systems because it significantly reduces the multiplication of organisms.

The 185-nanometer wavelength operates in a high-energy spectrum of electromagnetic quantum-packet photon radiation (light) bands. The energy available can break down organic molecules and compounds to carbon dioxide and water by the photo-oxidation process. It slowly breaks the bonds in organic molecules by direct radiation and also oxidizes organisms by the formation of hydroxyl radicals. The UV spectrum is illustrated in Figure 11-14.

A flow rate of approximately 2 feet per second (0.6 meter per second) is a general industry standard for the effective sanitation of purified water. The flow rate through the UV device should be reduced compared to the circulation loop to extend the necessary contact time. The recommended location for the UV device is prior to the deionization equipment.

Problems with UV systems include the generation of ions that lower the resistivity of water and the possible leaching of silica from the quartz sleeve of the UV device. Glass, plastic, rubber, and similar materials exposed to UV radiation over time will crack, etch, discolor, and flake. Tests have shown that only 50 percent of the energy used by the bulb is actually transmitted to the water, and in time 25 percent of the output will be lost compared to a new bulb.

Filtering

A filter removes organisms from the fluid stream. Generally accepted practice is to use a 0.2-micrometer absolute filter for the removal of bacteria. Although the effectiveness of this practice is questioned by some authorities, recommended current practice is to use a membrane with an absolute rating (cutoff) of 10,000 daltons. Cartridge filtration is the most commonly used method of filtration.

Heat

Heating to 175°F (80°C) effectively sanitizes water under pressure. Heating can be accomplished by using steam, electric, or other types of heat exchangers. It is common practice to circulate purified water at this temperature and use heat exchangers to lower the water temperature at each point of use if necessary.

Ozone

Ozone (O_3) is an oxidizing gas generated from gaseous oxygen or catalytically from water. The most often used method of producing ozone is by a corona-discharge generator, which converts the oxygen in air to ozone. The air is passed between two electrodes, and an electrostatic discharge across the gap converts oxygen to ozone. A typical schematic drawing of a corona-discharge generator is illustrated in Figure 11-15.

It is a common misconception that the ozone created by the bulbs in mercury vapor lamps is imparted to the water. When 185-nanometer systems are employed as a treatment process, the bulbs are enclosed in quartz sleeves. Though it is true that the 185-nanometer bulbs are used to generate ozone, the bulbs are in a chamber where they are exposed to oxygen-rich air. The ozone created in that chamber then is induced into the aqueous stream as a method of stream sanitation.

The ozone system consists of a feed-gas treatment unit, an ozone generator, a water/ozone contact mechanism, and a destruction unit to eliminate any residual ozone.

The feed gas reaching the generator must not have any particles larger than 0.3 micrometers, and 95 percent of those larger than 0.1 micrometers must be removed. In addition, aerosols, moisture, and hydrocarbons shall be removed as required by the manufacturer. This purification usually is supplied as part of a package.

The three basic types of ozone generator are the Lowther plate unit, Otto plate unit, and tube unit.

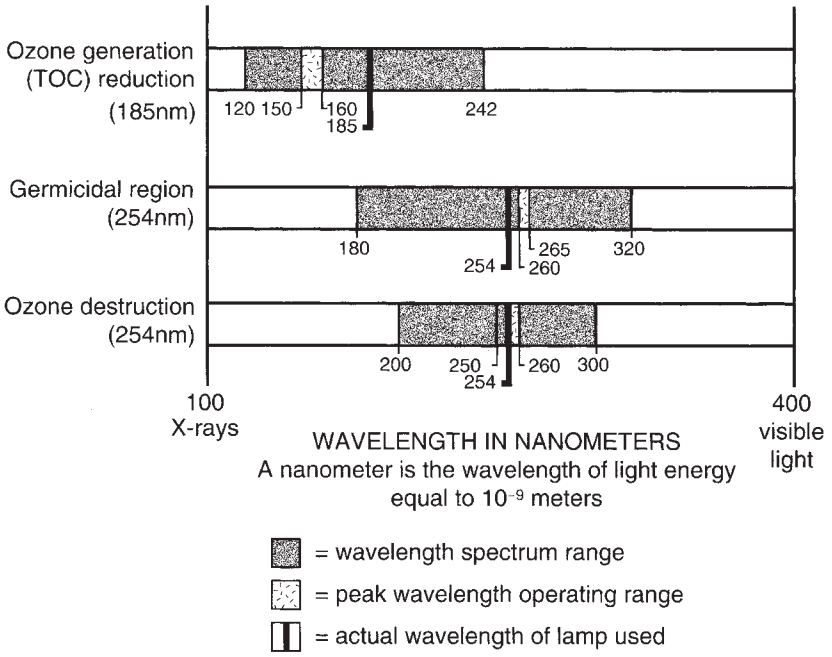


Figure 11-14 UV Wavelength Spectrum

They differ only in the manner in which they are cooled. Ozone generators use large amounts of electrical power, generally between 15 and 26 kilowatt-hours per kilogram of ozone.

Ozone and water are mixed in direct contact with one another by the use of static or mechanical mixers, injectors, or columns that optimize the dissolution of the gas.

Depending on the generator, ozone concentrations can vary from 100 to 3,000 parts per million. Because high concentrations are harmful to humans and metals, the ozone should not be allowed to escape to the atmosphere without being treated to a level below 0.1 part per million. Destruction can be accomplished by catalytic, thermal, and activated carbon. Thermal units operate at a temperature of 572°F (300°C) and generally require 3 to 5 minutes of contact time to be effective.

The mechanism for ozone oxidation is through generation of hydroxyl radicals. The gas is injected directly into the water stream.

Problems with ozone treatment include the ozone system's inability to oxidize all organic compounds. Also, the process is slow and in some cases will form stable and refractory compounds.

WATER TREATMENT

The following methods and equipment are used to condition water for various purposes.

Utility Water Treatment

Water from wells, rivers, lakes, and streams commonly is used for cooling and washing purposes, among others. Clarifying and treating such water to

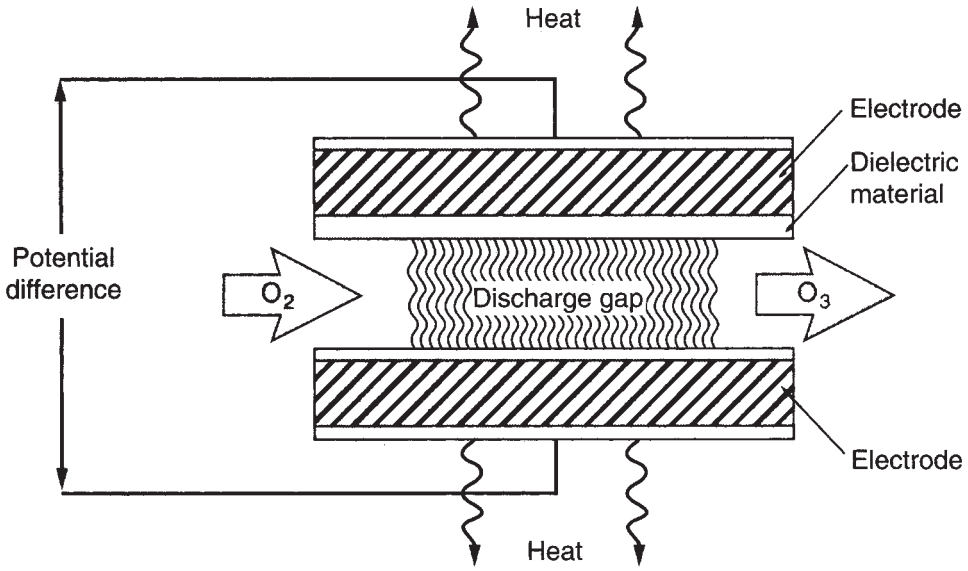


Figure 11-15 Principle of Corona Discharge Ozone Generator

meet the purity requirements of the proposed end use require good monitoring and quick reaction to raw and treated water fluctuations. If the water is going to be recirculated, the treatment methods are more stringent than if it is not going to be recirculated. If the water will be discharged into the environment, local codes must be followed regarding the allowable chemical amounts present in the wastewater to avoid the need for waste treatment.

Initial Filtering

If the supply is from surface water, a coarse or fine screen usually is placed at the intake to keep out fish and other large debris. Coarse screens are usually ½-inch (1.27-centimeter) diameter bars with a clear opening of 1 to 3 inches (2.54 to 7.62 centimeters). Fine screens could have openings of approximately $^3/_8$-inch (0.95-centimeter) square, with the water velocity through the screen limited to about 2 feet per second (0.6 meters per second). If the water quantity is small, basket strainers can be used. In climates where freezing may occur, the inlet should be placed far enough below the low water level to prevent freezing.

Clarification

After initial filtering, clarification is required to obtain water that meets the standards for the proposed use. The selection of the clarifier is based on the volume of water to be treated and the final quality desired. If the volume of water is small and the raw water is not very turbid, filters may be used.

Biological Control

To control microorganism fouling, microorganisms must be destroyed if possible, inactivated to keep them from reproducing, and removed from the water stream. This usually is accomplished by chlorination, filtration, ultraviolet radiation, ozone generation, and special adsorbents.

Chlorination is the least costly and most often-used method. The action of chlorine requires a specified contact time and the establishment of a residual chlorine amount. A range of 0.5 to 1 part per million generally is accepted for typical waters.

Water Softening

Water softening should be considered to reduce the hardness in the utility water system when the system is used for recirculated cooling purposes.

Boiler Feed Water Conditioning

In a boiler, energy in the form of heat is transferred across a heat-transfer surface from a fuel source to the water used for making steam. When subject to elevated temperature and pressure, the composition of the raw boiler water supply undergoes radical changes.

The effects of dissolved gases are magnified. The dissolved minerals may deposit a scale on the transfer surface that affects the heat-transfer process. The result is a reduction in the heat-transfer rate, a reduction in the flow rate, and increased damage from corrosion. A wide range of treatment methods is available, depending primarily on the impurities found in the raw water, the operating pressure of the boiler, and the makeup rate of water. These methods could be mechanical or chemical (the addition of chemicals to prevent deposits, inhibit corrosion, or neutralize impurities detrimental to the proposed end use of the water and the use of dispersants to keep particulates in suspension).

The treatment starts with an accurate feed water analysis, which is compared to the final treatment objectives established by the user and the boiler manufacturer. The degree of removal is determined by the difference in the two analyses. Recommended standards for boiler feed water and steam quality are given in Table 11-9.

A boiler water treatment program shall accomplish the following:

1. Reduce or remove hardness to control scale by either mechanical (external) or chemical (internal) treatment

2. Maintain the proper levels of alkalinity to ensure that proper chemical reactions can occur
3. Control dissolved oxygen and carbon dioxide through deaerating and the addition of an oxygen scavenger
4. Maintain the proper levels of conditioners so the suspended solids remain in suspension and can be eliminated easily through blowdown
5. Achieve optimum boiler blowdown

The mechanical removal of hardness is most often accomplished by water softening using an ion-exchange process, where the insoluble calcium and magnesium ions are replaced with highly soluble sodium ions. A commonly used resin is a strong acid resin in sodium form often referred to as zeolite. Real zeolite is a naturally occurring mineral no longer widely used because of its high cost. Its use introduces artificial resins that are more efficient for most uses.

The adjustment of pH is accomplished by the injection of dilute sulfuric or hydrochloric acid or sodium hydroxide or sodium carbonate. This requires close monitoring.

Feed water oxygen and carbon dioxide typically are removed with deaerators before the feed water enters the boiler. In addition to mechanical deaeration, a chemical oxygen scavenger can be added to the water to quickly eliminate any remaining traces of oxygen. Many scavengers are in use, but the most frequently used scavengers are sulfites (up to 1,000 pounds per square inch gauge [6,895 kilopascals]) and compounds of hydrazine. Hydrazine is being replaced by diethylhydroxylamine (DEHA), carbohydrazide, hydroquinone, and isoascorbic acid.

Chemicals can be added to the boiler feed water for two purposes. One is to keep the salts in solution so they will not cause scaling. The second is to precipitate salts out of solution to allow the particulates to be disposed of during blowdown. There are many effective materials, generally blends of component chemicals. Those most often used are polymers and phosphates and carbonates that are designed to optimize the precipitation of calcium, magnesium, and iron. Modern treatment has made hardness deposits much less common, but iron deposits have become more common because of the return of condensate to the boiler.

Boiler blowdown is the bleeding off of some water from the boiler. When steam is generated, impurities are left behind from the feed water converted to steam, and these accumulate over time. When the level of impurities becomes too high, a portion of the water is discharged to drain (blowdown). Blowdown could be intermittent or continuous.

Cooling Water Conditioning

The basic reason for the treatment of cooling water used in evaporative cooling towers and condenser systems is to keep any dissolved solids from depositing onto piping or equipment by preventing the dissolved solids from reaching the saturation point. This usually is expressed as the cycle of concentration of the water, which compares the dissolved solids in the feed water with the dissolved solids content of the circulating water. As an example, if the feed water has a total dissolved solids of 100 parts per million and the circulating water has a total dissolved solids of 300 parts per million, a cycle of concentration of 3 has been reached. The cycle of concentration is reduced by bleed off (blowdown) from the system.

Table 11-9 Recommended Boiler Feed Water Limits and Steam Purity

Drum Pressure, psig (kPa)	Range TDS[a] Boiler Water, ppm max.	Range Total Alkalinity[b] Boiler Water	Suspended Solids Boiler Water, ppm max.	Range TDS[c] Steam, ppm (max. expected value)
Drum-type Boilers[a]				
0–300 (0–2068)	700–3,500	140–700	15	0.2–1.0
301–450 (2,075–3,103)	600–3,000	120–600	10	0.2–1.0
451–600 (3,110–4,137)	500–2,500	100–500	8	0.2–1.0
601–750 (4,144–5,171)	200–1,000	40–200	3	0.1–0.5
751–900 (5,178–6,205)	150–700	30–150	2	0.1–0.5
901–1,000 (6,212–6,895)	125–625	25–125	1	0.1–0.5
1,001–1,800 (6,902–12,411)	100		1	0.1
1,801–2,350 (12,418–16,203)	50		n/a	0.1
2,351–2,600 (16,210–17,926)	25		n/a	0.05
2,601–2,900 (17,933–19,995)	15		n/a	0.05
Once-through Boilers				
1,400 and above	0.05	n/a	n/a	0.05

Source: American Boiler Manufacturers Association

Note: n/a = not available

[a] Actual values within the range reflect the total dissolved solids (TDS) in the feed water. Higher values are for high solids, lower values are for low solids in the feed water.

[b] Actual values within the range are directly proportional to the actual value of TDS of boiler water. Higher values are for the high solids, lower values are for low solids in the boiler water.

[c] These values are exclusive of silica.

Scale

The basic treatment for scale in cooling water systems is to add inhibitors that keep the scale from depositing on the walls of the pipe. They are similar to those used for boiler water treatment, but with the addition of surfactants, which change the surface characteristics of the pipe to prevent deposits and aid in removal if deposits occur.

Corrosion

Broadly defined as an electrochemical process, corrosion takes place when an electrical potential is possible between two surfaces common to an electrolyte. The factors impacting corrosion in aquatic systems include:

- Dissolved oxygen
- Total dissolved solids
- Alkalinity and pH
- Total hardness
- Temperature
- Flow velocity
- Types of metal used in the process
- Condition of the interior surface of the plumbing system
- Extraneous electrical current
- Bacteria

Simple tools used to predict the propensity of an aqueous solution to be corrosive are the Langelier, Stiff and Davis, and Ryznar indexes. Corrosion treatments consist of:

- pH control
- Chemical inhibitors
- Oxygen scavengers such as hydrazine, sodium bisulfate, and morphine
- Ensuring proper flow rates by correctly sizing metal pipe
- Sacrificial anodes
- Polishing and passivation of interior surfaces
- Biocide treatment

These shall be recommended by the manufacturer of both the chemicals and the equipment to ensure compatibility. The pH of the circulating water usually is controlled to a point near 7.5 to decrease its scale-forming tendency. The addition of a dilute acid is the most often-used method of control. A corrosion inhibitor often adds compounds that increase the tendency of scale to occur; therefore, a balance must be reached.

Biological Fouling

Microbial control is achieved with the addition of biocides, either oxidizing or nonoxidizing depending on their chemistry and killing action. Ozone also is commonly used.

Biocide treatment initially shocks microbes with a heavy dose, and then the concentration of the compounds is allowed to fall to a level of 25 percent of the initial dose. This is a generally accepted lower limit below which the biocide is not considered effective. Often, because of the presence of several different strains of microbes, more than one biocide may be required. A contact time approved by the chemical manufacturer is required.

These chemicals are added by means of a chemical feed pump discharging directly into the piping system. The levels must be closely monitored with alarms established by performance indicators based on operating experience.

Potable Water Treatment

Water used for human consumption or intended to be part of food products must be treated to comply with the Safe Drinking Water Act, the Surface Water Treatment Rule (which is part of the Safe Drinking Water Act), and local regulations. Substances that affect the quality of potable water are classified in four major headings.

1. Physical: Physical characteristics, such as color, turbidity, taste, and odor, often are related to the appearance of the water. Physical quality is corrected through the use of various types of filters.
2. Chemical: The chemical characteristics of water are related to dissolved minerals (mostly hardness), gases, and organics. The chemical quality of water is adjusted by the use of water softeners, ion exchange, reverse osmosis units, and activated charcoal units to remove organic impurities.
3. Biological: These characteristics are concerned with microorganisms that affect the health of the consumer. Biological treatment requires the use of biocides and biostats to eliminate and reduce the number of microorganisms present in the water and to create a residual amount of the chemical to maintain the required level of action required by code.
4. Radiological: This category is concerned primarily with radon in areas where the water may have come in contact with radioactive substances. Retention and aeration lower the radon count to acceptable limits in approximately eight hours.

A synopsis of general treatment methods for small potable water systems, including a discussion of general advantages and disadvantages, is given in Table 11-10.

WATER PURIFICATION

A total water treatment system for pure water used for laboratory and pharmaceutical purposes consists of three general, interrelated phases: pretreatment, purification, and distribution (including post-treat-

Table 11-10 Water Treatment Technology for Small Potable Water Systems

Technology	Advantages	Disadvantages
Filtration		
Slow sand	Operational simplicity and reliability, low cost, ability to achieve greater than 99.9% Giardia cyst removal.	Not suitable for water with high turbidity, requires large land areas.
Diatomaceous earth (septum filter)	Compact size, simplicity of operation, excellent cyst and turbidity removal.	Most suitable for raw water with low bacterial counts and low turbidity (<10 ntu), requires coagulant and filter aids for effective virus removal, potential difficulty in maintaining complete and uniform thickness of diatomaceous earth on filter septum.
Reverse osmosis membranes	Extremely compact, automated.	Little information available to establish design criteria or operating parameters, most suitable for raw water with turbidity <1 ntu, usually must be preceded by high levels of pretreatment, easily clogged with colloids and algae, short filter runs, concerns about membrane failure, complex repairs of automated controls, high percent of water lost in backflushing.
Rapid sand/direct filtration package plants	Compact, treat a wide range of water quality parameters and variable levels.	Chemical pretreatment complex, time-consuming; cost.
Disinfection		
Chlorine	Very effective, has a proven history of protection against waterborne disease, widely used, variety of possible application points, inexpensive, appropriate as both primary and secondary disinfectant.	Potential for harmful halogenated byproducts under certain conditions.
Ozone	Very effective, no THMs formed.	Relatively high cost, more complex operation because it must be generated on-site, requires a secondary disinfectant, other byproducts.
Ultraviolet radiation	Very effective for viruses and bacteria, readily available, no known harmful residuals, simple operation and maintenance for high-quality waters.	Inappropriate for surface water, requires a secondary disinfectant.
Organic Contaminant Removal		
Granular-activated carbon	Effective for a broad spectrum of organics.	Spent carbon disposal.
Packed-tower aeration	Effective for volatile compounds.	Potential for air emissions issues.
Diffused aeration	Effective for volatile compounds and radionuclides.	Clogging, air emissions, variable removal efficiencies.
Advanced oxidation	Very effective.	Byproducts.
Reverse osmosis	Broad spectrum removal, disposal.	Variable removal efficiencies, wastewater.
Inorganic Contaminant Removal		
Reverse osmosis	Highly effective.	Expensive waste removal.
Ion exchange	Highly effective.	Expensive waste removal.
Activated alumina	Highly effective.	Expensive waste removal.
GAC	Highly effective.	Expensive waste removal.

ment) of the purified water. Purification methods include distillation, deionization, continuous deionization, membrane filtration, and other approved processes. Water for injection can be produced only by distillation or membrane filtration. Ultra-pure water for specific applications often is made using pure water as feed water, which is then further purified to meet the specific requirements at the point of use. (Ultra-pure water systems used in the production of food products and electronic industries are considered process systems and are outside the scope of this chapter. For information on suggested guidelines for water purity in the electronics industry, contact Semiconductor Equipment and Materials International at semi.org.)

Codes and Standards

The required quality of purified water depends on the application. Various codes have defined water quality for use in specific industries. Among them are:

- 21 CFR 210: Current Good Manufacturing Practice in Manufacturing, Processing, Packing, or Holding of Drugs; General
- 21 CFR 211, Current Good Manufacturing Practice for Finished Pharmaceuticals
- *United States Pharmacopeia–National Formulary*
- Federal Food, Drug, and Cosmetic Act

Laboratory Systems

For laboratory work, all applications do not require the same quality of water. The American Society for

Testing and Materials, College of American Pathologists, Clinical and Laboratory Standards Institute, and Association for the Advancement of Medical Instrumentation have developed standards for water used in laboratories depending on the intended use. These standards are summarized in Tables 11-11, 11-12, and 11-13. The ASTM electronics-grade water standard is given in Table 11-14 for reference only.

Three pure water categories are included in the Clinical and Laboratory Standards Institute specifications:

1. Type I, called reagent grade water, is used for the analysis of trace matter and other critical applications. It is the purest water covered by any written standard. This water is free from organic and inorganic impurities, suspended solids, and microorganisms.
2. Type II, called analytical grade water, is suitable for all but the most critical procedures.
3. Type III, called general laboratory-grade water, is suitable for most qualitative analysis and equipment rinsing and as a supply for generating Type I water.

The four basic applications where high-purity water is needed in the biological laboratory are:

1. Water for media used in growing tissue cultures
2. Water used in media formulations for growing bacteria and other prokaryotes
3. Water used to make buffer solutions are used in enzymatic reactions
4. Water used to make solvent standards and reagents for various types of analysis

Another grade of water called organic free water often is required for trace analysis of various impurities. It has no formal specification and is required to have an organic purity greater than that required for Type I.

Pharmaceutical Systems

The type of water used for pharmaceutical purposes is called USP purified water. The name is derived from the United States Pharmacopoeia (USP) specifications for purified water, with revisions to the specification made from time to time based on current technology. The two categories of water referred to are purified water and water for injection. The standard for each is given in Table 11-15.

The four basic technologies used to produce pure water are ion exchange, distillation, membrane filtration and separation, and continuous deionization or electrodeionization. Some of these systems are often combined. The most common combination is called reverse osmosis/ deionization. The degree of treatment depends on end-user requirements, the amount and nature of the various contaminants present in the feed water stream, and the amount and nature of the various contaminants to be removed. Knowledge of the highest levels of contaminants and the highest-purity water required cannot be overemphasized. Unless these factors are well established, the selection of any treatment method is impossible. A typical pharmaceutical water purification flow diagram is shown in Figure 11-16.

Feed Water

Feed water quality, which is source dependent, is the first parameter to be identified in the design of a pure water system. The source strongly influences the pretreatment options and may dictate the treatment methods. A wide variation in types and concentra-

Table 11-11 CAP and ASTM Reagent-grade Water Specifications

	CAP Type			ASTM Type			
	I	II	III	I	II	III	IV
Spec. conductance (μmhos/cm)	0.1	0.5	10	0.056	1.0	0.25	5.0
Spec. resistance (M$\Omega \cdot$ cm)	10	2.0	0.1	18	1.0	4	0.2
Silicate (μg/L)	50	100	1,000	3	3	500	—
Heavy metals (μg/L)	10	10	10	—	—	—	—
Total organic carbon (μg/L)	—	—	—	100	50	200	—
Potassium permanganate reduction (min.)	60	60	60	—	—	—	—
Sodium (μg/L)	100	100	100	1	5	10	50
Chlorides (μg/L)	—	—	—	1	5	10	50
Hardness	neg	neg	neg	—	—	—	—
Ammonia	0.1	0.1	0.1	—	—	—	—
Bacterial growth (cfu/mL)	10	10^4	—	[a]	[a]	[a]	[a]
pH	—	—	5.0–8.0	—	—	—	5.0–8.0
CO_2 (μg/L)	3	3	3	—	—	—	—

[a] Microbiological contamination: When bacterial levels need to be controlled, reagent grade types should be further classified as follows:

	Type A	Type B	Type C
Maximum heterotropic bacteria count	10/1,000 mL	10/1,000 mL	100/10 mL
Endotoxin, endotoxin unit (EU)	<0.03	0.25	Not applicable

Table 11-12 NCCLS Reagent-grade Water Specifications

Characteristics	Type I	Type II	Type III
Bacterial content (colony-forming units per mL, maximum)	10[a]	1000	N/A
pH	N/A	N/A	5.0–8.0
Resistivity (25°C, MΩ/cm)	10	1.0	0.1
Silicate (mg/L max.)	0.05	0.1	0.1
Particulate matter[a]	0.22-μm filter	N/A	N/A
Organics[b]	Activated carbon	N/A	N/A

Source: Frankel 1996

[a] Preferably, type I water should be bacteria free.

[b] These specifications are process specifications and are not measured by the end user. Additional purification may be required for selected clinical laboratory procedures, such as:

1. Preparation of water with minimal pyrogen levels for cell culture.
2. Preparation of bacteria-free water for direct fluorescent detection of bacteria as in Legionella direct fluorescent antibody testing or direct fluorescent stains of mycobacteria.
3. Preparation of water with minimal organic content for HPLC.

Table 11-13 AAMI/ANSI Water Quality Standards

Contaminant	Suggested Maximum Level, mg/L
Calcium	2 (0.1 meq/L)
Magnesium	4 (0.3 meq/L)
Sodium	70 (3 meq/L)
Potassium	8 (0.2 meq/L)
Fluoride	0.2
Chlorine	0.5
Chloramines	0.1
Nitrate (N)	2
Sulfate	100
Copper, barium, zinc	0.1 each
Arsenic, lead, silver	0.005 each
Chromium	0.014
Cadmium	0.001
Selenium	0.09
Aluminum	0.01
Mercury	0.0002
Bacteria	200 (cfu/mL)

Source: Association for the Advancement of Medical Instrumentation (AAMI), 1990, Hemodialysis Systems Standard. Adopted by American National Standards Institute (ANSI), 1992.

Note: "meq/L" = mole equivalent/liter

tions of impurities is possible, depending on whether the feed water is obtained from a public utility or a private source, such as a well or other surface or groundwater source.

Surface waters are usually high in particulates, colloids, and organics. Underground waters tend to have low levels of particulates, colloids, and organics and relatively high levels of calcium and magnesium hardness and alkalinity (bicarbonates). Source water from agricultural areas often has high levels of nitrates, phosphates, and organic pesticides. Water from public utilities has residual chlorine, fluorides, and chloramines as well as iron oxides and other pipe-related impurities. It is important to establish or obtain historical water analysis data from different times and seasons to properly design a system with enough flexibility to obtain the required purity under worst-case conditions.

The U.S. Food and Drug Administration requires the feed water for USP purified water and water for injection systems to meet EPA guidelines for potable water. Of particular concern is the microbial level. The water should be virtually free of coliform, which is a pathogenic marker organism. The feed water also must meet the 400 colony-forming units per milliliter maximum value specified in *United States Pharmacopeia–National Formulary*.

The feed water also cannot contain added substances. This is an issue that appears to be interpreted differently by individuals and organizations involved in the design of purified water systems. Some systems presently in use appear, from an overall perspective, to violate this position. Items such as the chlorination of raw water supplies, acid addition to adjust pH, and the use of ozone to control microbial growth are subject to interpretation. All of the concerns are resolved during the application phase for U.S. Food and Drug Administration (FDA) approval and validation of the system.

Table 11-14 ASTM Electronics-grade Water Standard[a]

Assay	Grade			
	E-I	E-II	E-III	E-IV
Resistivity, minimum	>18.0[a]	17.5[b]	12	0.5
(MΩ · cm at 25°C)	> 17.0[a]	> 16.0[b]		
SiO_2 (total), max. (μg/L)	5	10	50	1,000
Particle count (per mL)	1	3	10	100
Particle size limit (μm)	0.10	0.5	1.0	10
Viable bacteria, max.	1/1000 mL	10/1000 mL	10/1 mL	100/1 mL
Copper, max. (μg/L)	1	1	2	500
Zinc, max. (μg/L)	0.5	1	5	500
Nickel, max (μg/L)	0.1	1	2	500
Sodium, max. (μg/L)	0.5	1	5	1,000
Potassium, max. (μg/L)	2	2	5	500
Chloride, max. (μg/L)	1	1	10	1,000
Nitrate, max. (μg/L)	1	1	5	500
Phosphate, max. (μg/L)	1	1	5	500
Sulfate, max. (μg/L)	1	1	5	500
Total organic carbon, max. (μg/L)	25	50	300	1,000
Endotoxins	0.03 EU[c]	0.25 EU[c]	N/A[d]	N/A[d]

Source: ASTM Standard D5127-90

[a] Above 18ΩD · cm 95% of the time, not less than 17

[b] 17.5 or greater 90% of the time, not less than 16

[c] EU = Endotoxin unit

[d] N/A = not applicable

Table 11-15 USP XXII Purified Water and WFI Water Purity Standards

Component	Purified Water	Water for Injection
pH	5.0–7.0	5.0–7.0
Chloride (mg/L)	0.5	0.5
Sulfate (mg/L)	1.0	1.0
Ammonia (mg/L)	0.1	0.1
Calcium (mg/L)	1.0	1.0
Carbon dioxide (mg/L)	5.0	5.0
Heavy metals (mg/L)	0.1 as Cu	0.1 as Cu
Oxidizable Substances	**Pass USP Permanganate Test**	
Total solids (mg/L)	10.0	10.0
Bacteria (cfu/mL)	100	50.0
—FDA action limit	100 cfu/mL	10 cfu/100 mL
Pyrogen (EU/mL by LAL)	—	0.25

Source:Numerical values are interpretations of procedures listed in the *Standards in United States Pharmacopoeia,* 24th. ed.

Purification System Design

Specific methods of purification are capable of removing various types of impurities better than others. None can be depended on to remove all the impurities necessary to achieve the purity level required for USP-purified water. It is accepted practice to use a combination of technologies, each of which is designed to remove a specific type of impurity.

The methods used to produce this water depend on the feed water supplying the facility. In most instances, feed water has a high level of some classes of contaminant. It is much more economical to pretreat that water to remove the bulk and/or the more concentrated of those impurities than use the purification equipment to polish the water to the desired purity level. In some cases, the removal of individual impurities is necessary to allow the use of specific types of purification equipment.

Pretreatment

Pretreatment is considered for two reasons:

1. To decrease potential damage to the membrane selected
2. To increase membrane filtration quality

The need for pretreatment is determined by an analysis of the raw water supply. The decision generally is governed by the cost efficiency of the pretreatment method and whether the cost of purchasing and installing the pretreatment equipment will reduce the initial cost of the main treatment equipment and lower the operating cost of the system as a whole enough to justify its installation.

Water Temperature

Membrane productivity (flux) usually is rated with feed water at 77°F (25°C) and is inversely proportional to the feed water viscosity.

When the water temperature is lower, additional membrane area is required. The flux increases with increased feed water temperature. Heating the feed water lowers the viscosity. The water could be heated with a separate water heater or with a blending valve using domestic hot water mixed with feed water to provide the necessary temperature.

pH Adjustment

The selected membrane should have an optimum pH operating range. To achieve it, a dilute acid is injected into the feed water if necessary. When using drinking water standards, this problem is rarely encountered.

Filtration

Filters are used to remove suspended solids originating from any source. If continuous production is required, a duplex arrangement should be installed so the filters can be backwashed or replaced with no interruption in service.

Sand and Multimedia Filters

A common initial method for gross particulate removal from source water is a pressure multimedia sand filter, used if the concentration of suspended solids is greater than 0.2 part per million. If the concentration is lower, a 5- to 10-millimeter cartridge filter often is used. Experience has shown that cartridge replacement is uneconomical compared to backwashing.

Cartridge Filters

These are used to remove lesser amounts of particulates prior to the central purification equipment. It is generally accepted practice to provide an in-line 5-millimeter cartridge depth filter to eliminate any particulates that would clog or interfere with the operation of the central purification equipment. This filter is recommended if the silt density index is less than 4 and generally required if the level is more than 4. If the level is more than 4, an additional 1-millimeter cartridge filter is recommended downstream of the main filter. In some locations, or on some feed waters, it is practical to use a sand, multimedia filter and a cartridge filter (with the sand filter first).

Carbon Filtration

Following the removal of gross particulates, a granulated carbon filter is provided to remove residual disinfectants (e.g., chlorine and chloramine), dissolved organics (oils, pesticides, surfactants), and suspended organics (humic and fulvic acids).

Flow rates through this filter are usually in the range of 1 to 4 gpm per square foot (3.78 to 15.14 liters per minute per square meter) of filter area, depending on the quantity of organics and chloramines in the entering water. Higher qualities of water require slower flow rates.

Problems with carbon filters are their tendency to harbor microbial growth due to the removal of chlorine. Frequent sanitizing is necessary, usually with potassium permanganate, sodium hydroxide,

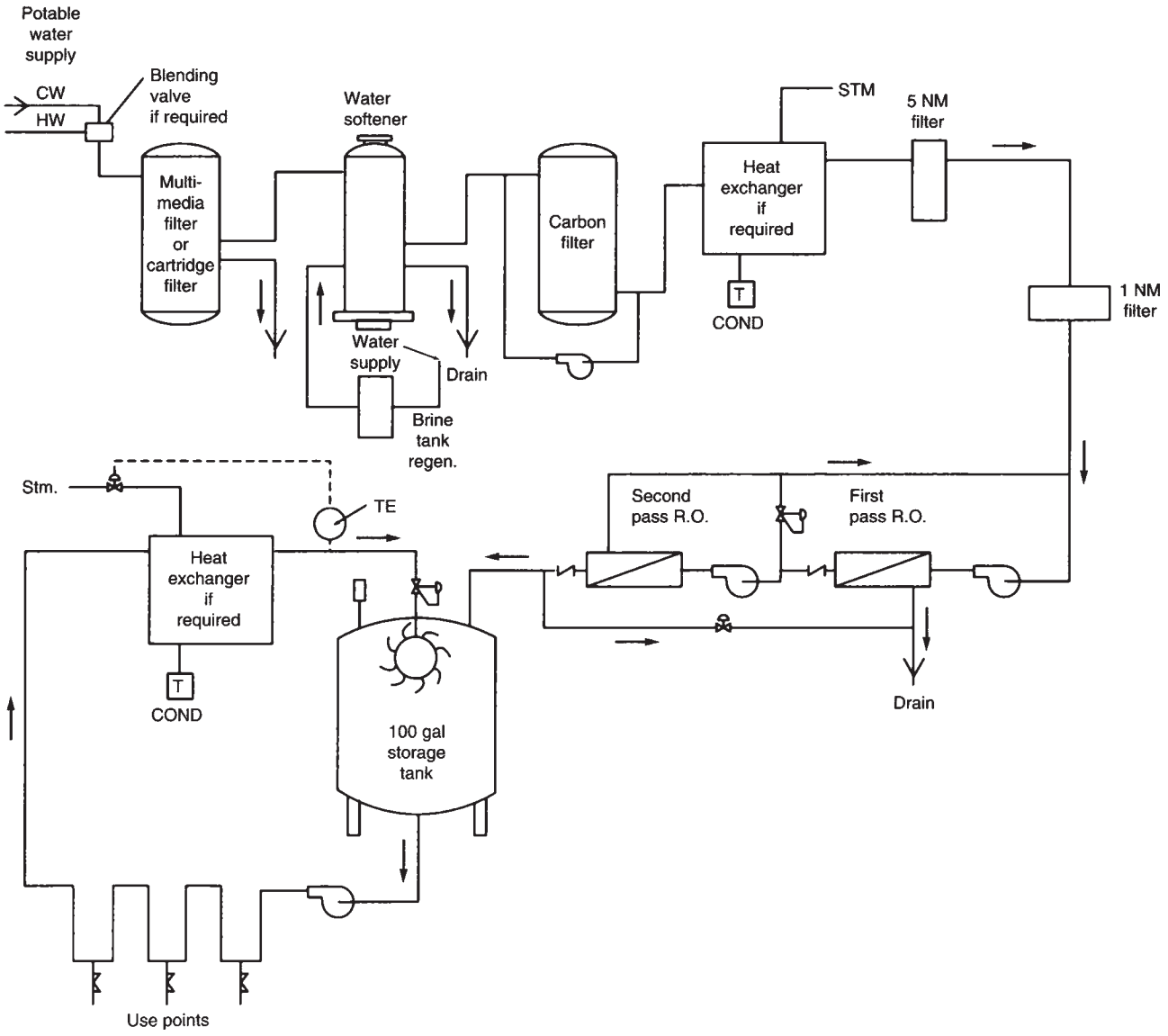


Figure 11-16 Typical Pharmaceutical Water Flow Diagram

or steam. If steam is selected, the tank should be constructed of 316L stainless steel.

Water Softening

If the hardness is high, it is necessary to provide a water softener to reduce the calcium and magnesium to a level required by the membrane selected. Water softening is recommended if the iron content exceeds 0.4 part per million.

The softener is another device harboring microbial growth. Sanitizing with potassium permanganate generally is used.

Biological and Total Organic Carbon Reduction

Ultraviolet units and ozone generators generally are used to remove microorganisms and total organic carbon from the feed water prior to its reaching the reverse osmosis units. Materials used in the system must be compatible with these units. There is a reluctance to use any chemical to remove microorganisms due to FDA restrictions regarding adding chemicals to the feed water. However, chlorine commonly is added to disinfect the feed water because it is cost effective and can easily be removed by granular activated carbon filters.

Biocide Removal

The most common source of feed water for most facilities is potable water. This water contains a residual amount of chlorine, which is necessary to comply with code for drinking water quality. To remove this residual chlorine, a granulated, activated-charcoal

filter is provided. An organic trap also may be required if organics are very high.

Central Purification Equipment

The basic methods used to produce high-purity water are distillation, ion exchange, continuous deionization or electrodeionization, and reverse osmosis. The method used will depend on the purity desired and limitations on initial or operating cost.

Storage

The storage of water reduces the size of the purification equipment. Storage tanks could be constructed from fiberglass-reinforced plastic with an internal vial suitable for the purpose, polypropylene (high-density or cross-linked with a minimum specific gravity of 1.5), polyethylene, or stainless steel (finish specified by user or process). The bottom of the tank shall be dished or conical to aid in complete drainage. It is an established fact that high-purity water degrades in storage because:

1. Water extracts contamination from any container.
2. Bacteria grow and secrete waste products.
3. Organics from solvents and the shedding of clothing can diffuse through the air and dissolve in the water.
4. Laboratory personnel secrete urea in perspiration and respiration that can cause the formation of ammonia in stored laboratory water.

The tank for USP water should be airtight and equipped with a non-shedding, 0.2-millimeter hydrophobic filter for venting. For water for injection systems, the tank should be type 304L or 316L stainless steel, pressure rated to a minimum of 35-psig (241-kilopascal) pressure and 3 inches (760 millimeters) of mercury vacuum, 180 grit, and electropolished. It is common practice to have a nitrogen gas blanket in the vapor space above the water in the storage tank to reduce the possibility of airborne contamination and reduce the formation of carbonic acid from the reaction of carbon dioxide and water in the tank. The tank shall have a jacket to maintain a temperature of 177ºF (80°C) and be insulated and provided with a rupture disk.

It should be noted that the design of a nitrogen blanket system is critical and should be specific to each individual situation. A special regulator is used in conjunction with a special tank vent to allow a very low flow rate of nitrogen to enter the tank as the tank is drawn down during a demand scenario. This keeps the tank from imploding as nitrogen is supplied to fill the empty portion of the tank caused by the stored water being removed. At the same time, as the demand for process water decreases and the tank fills, the regulator will close when the pressure in the tank reaches a predetermined level sufficient to provide the nitrogen blanket, while keeping the tank from bursting due to over-pressurization. Controlling the nitrogen blanket in this way helps conserve the amount of nitrogen needed to maintain the required blanket, which can be very costly depending on the size of the system. In addition, the storage tanks selected for this service should be pressure rated for the intended application in lieu of the atmospheric duty-rated tanks commonly selected for systems not requiring nitrogen blanket protection.

The discharge should be from the center bottom of the tank to allow complete circulation of the stored water. The water return should be at the top of the tank and be equipped with a spray ball or spray ring. This minimizes microbial growth by continuously washing the upper areas of the tank.

Sterilization

It is common practice to provide an in-line ultraviolet sterilization device to reduce microorganisms that may be present in the water. Another often-used method is to heat purified water to a temperature of 177°F (80°C) to prevent microorganism growth and then circulate it to maintain the sterile condition. Another possibility is the installation of a filter that will remove any organic particulates.

Piping Distribution Network

The piping material for USP water should be fabricated from either virgin polypropylene, polyvinylidene fluoride (PVDF), or stainless steel. Plastic pipe should be butt-joint heat-fused, and stainless steel pipe should be orbital welded.

Piping material for water for injection should be stainless steel, 180 grit, and electro-polished. Fittings shall have extended ends for orbital welding. All couplings shall be sanitary tri-clamp. Insulation shall be non-chloride bearing and designed for a temperature of 176°F (80°C).

Velocity in the distribution piping system should be sufficient to maintain turbulent flow, approximately 3 to 5 feet per second (0.91 to 1.5 meters per second). Piping system design and pump selection is critical to ensure the correct velocity throughout the entire loop. Following is a rule of thumb formula used to select the correct pipe diameter:

$$V = \frac{\text{gpm}\left(\frac{L}{s}\right) \times 0.4085}{ID^2}$$

or

$$ID = \left[\frac{\text{gpm}\left(\frac{L}{s}\right) \times 0.4085}{V}\right]^{1/2}$$

where

V = Velocity, feet per second (meters per second)
ID = Actual inside diameter, inches (millimeters)

(Note: Check for the actual inside diameter of various pipes based on schedules. Verify the impact of various linings. Know the impact of surface finish inside the pipe being considered.)

Pump selection can be made after pressure losses are calculated through the entire system. A booster pump may be required to keep the flow at the correct velocity.

Piping shall be sloped at a $^{1}/_{8}$-inch (3.2-millimeter) pitch per foot (meter) to allow complete drainage of the network. Dead legs of more than six pipe diameters should be avoided at all costs. Distribution loop piping also should be designed to incorporate sanitizing inlets, complete with fittings and a valve arrangement that would facilitate sanitizing of specific areas of the system, thus minimizing entire system shutdown or drainage in the event a piping repair or lab reconfiguration were to occur. To prevent future plastic pipe sagging and interference with drainage, continuous support of piping is recommended.

When comparing polypropylene, PVDF, and stainless steel from a cost standpoint, polypropylene is usually the least expensive, followed by PVDF, and stainless steel is the most expensive. In addition, while polypropylene and PVDF both have similar operating characteristics from a purity standpoint, PVDF can be selected in lieu of polypropylene in a condition where the piping may be required to meet ASTM E84: *Standard Test Method for Surface Burning Characteristics of Building Materials and UL 723: Test for Surface Burning Characteristics of Building Materials*, the standards for flame spread and smoke generation, such as in a return air plenum area.

Valves shall be consistent with the piping materials. Prior to the reverse osmosis or deionization units, full-bore ball valves are recommended. In the purified loop, use stainless steel diaphragm valves with an ethylene propylene diene monomer (EPDM) or Teflon diaphragm and a backing ring. Provide sample valves (usually needle type) at strategic points in the system to allow samples to be taken.

Pumps for purified water should be of sanitary design using a double mechanical seal with product water as the lubricant for the seals. Water for injection pumps should be type 316L stainless steel, 180 grit, and electro-polished. A casing drain should be provided.

System Design Considerations

USP water and water for injection are used in the pharmaceutical manufacturing process and often become part of the product. Because of this, all aspects of the purification system and distribution network are subject to inspection and validation by the FDA, which is responsible for determining if water quality used is adequate.

The FDA has specific guidelines for the selection of stills and reverse osmosis equipment used for production of water for injection. In contrast, purified water systems can utilize different types of purification equipment, since the microbial and chemical quality can vary depending on the proposed use of the water.

The purpose of any guidelines or standards is to verify that all pertinent purity requirements of the equipment and distribution system conform to current good manufacturing practice, are capable of consistently producing water of the required quality, and are capable of delivering water to the use point that meets the acceptance criteria for water coming in contact with the product. This investigation also includes verification that the purification equipment selected is capable of producing water of the required purity, the quality of installation for the distribution network produces a piping network capable of delivering water of the required quality to all outlets, and the continuing quality of system operation, maintenance, and ongoing testing will consistently provide water of the desired purity.

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12 Special Waste Drainage Systems

Special waste includes liquid effluent other than discharge from sanitary and storm water sources, such as acid waste, radioactive waste, biological and infectious waste, chemical waste, and fire suppression water drainage. This chapter describes the collection and criteria necessary for the design of various special waste drainage systems. Except for the neutralization of acid effluent, treatment methods for special waste are outside the scope of this chapter.

Each special waste system has unique properties that must be separately addressed. These systems generally route the waste from fixtures and equipment into a facility waste treatment system, with the treated effluent discharging directly into the public sanitary drainage sewer system. Very often, untreated waste is stored on site and collected by approved waste-removal contractors for disposal.

Unless specifically noted otherwise, all of the waste streams are assumed to have the approximate flow characteristics of water. Pipe sizing criteria are based on this assumption.

CODES AND STANDARDS

Two general jurisdictional bodies regulate different aspects of special waste systems. The first is the local or regional authority, which creates and enforces plumbing and health codes, including the local authorities charged with the review and approval of plumbing system designs and discharges into the public sewer system. Although such authorities are concerned with regulating the size and design of plumbing systems within a building, they also restrict the introduction of any type of waste into the sanitary sewer that may degrade the public sewer piping system or is incapable of being easily treated in the public waste treatment facility.

The second jurisdictional body, which has far more stringent regulations, includes the various agencies concerned with protecting workers, the public, and the environment from the discharge of toxic substances. Included in this group are federal, state, and local authorities responsible for preventing toxic discharge of any substances considered harmful into the general environment, public sewers, and public treatment systems. Such discharges can occur either as a result of spills and accidents or by deliberate, illegal discharge. To prevent such discharge, it is common practice for these agencies to inspect facilities, mandate on-site facility treatment systems, and require the use of double-wall piping and leak detection to prevent and mitigate any leakage from piping.

Other regulations, such as current good manufacturing practice (cGMP) from the U.S. Food and Drug Administration (FDA), the regulations of the federal Environmental Protection Agency (EPA), and facility validation protocols, are constantly being revised due to technological and design changes.

The services of an experienced environmental consultant who is familiar with the latest applicable rules and regulations and their interpretations should be consulted for system compliance with the maze of regulations.

SYSTEM APPROVAL REQUIREMENTS

Authorities make a distinction between drainage effluent that can be treated locally within a building (such as by biological waste sterilization, pH adjustment of chemical waste, or oil separation) and other effluent that requires a larger and more complex waste treatment system outside a building. Acceptance of such local treatment can be obtained only after conferences with the authorities responsible for issuing contamination limits for such discharge. If the local treatment system provides the appropriate level of contaminant removal, direct discharge into the public sanitary sewer is acceptable. If the levels of contaminant removal are beyond the capability of such local treatment, a more sophisticated system that demonstrates contaminant removal to the levels desired by the authority having jurisdiction (AHJ) must be chosen.

Any special drainage system effluent routed for treatment inside a facility or on site typically does

not require examination or approval by the local plumbing official. However, you should verify approval requirements with the governing code authority. If any effluent is routed to the public sewer system for eventual treatment, the discharge must conform to local regulations for the maximum concentration of any contaminant or pH level. If the only required method of treatment is pH adjustment prior to discharging into the building's sanitary drainage system or the public sewer system, most authorities require the installation of an acid drainage system. A pH value of 5 generally is viewed as the lowest acceptable level for direct discharge into a public sewer system, and a pH value of 10 is typically the highest acceptable level.

PIPE MATERIAL AND JOINT SELECTION CONSIDERATIONS

Important factors in the selection of the appropriate pipe material, gaskets, joining methods, and other piping components for any special waste drainage system are cost, temperature and composition of the effluent, the type of chemicals, and the concentration of each chemical that will enter the pipe. For some systems, the smoothness of the pipe interior or the lack of a crud trap is also an important factor. This also applies to any associated vent system.

Selection is accomplished by first establishing the flow rate, temperature range, and concentration and composition of all effluent and chemicals that are expected. All pipe manufacturers publish chemical compatibility charts that provide the effects of various chemicals on a particular pipe and include recommendations for acceptance using these chemicals. For conditions not listed on these charts, you should contact the manufacturer of the material and ask for technical assistance.

When the compatibility of various pipe systems is the same, the total installed cost and possible ease of assembly are the deciding factors. Even if a client's standard operating procedure (SOP) states that no chemicals or lab waste can be discharged down the drain, they still may require or benefit from a special waste piping system to protect the integrity of the drainage system in the event of an accidental spill or discharge.

PIPE SIZING CONSIDERATIONS

System design is concerned only with the adequacy of the pipe to carry away the design flow. System configuration usually requires traps to be provided on fixtures and floor drains and the venting system to conform to good plumbing design practice, which limits the pressure inside the system. All the elements of system design are left to the judgment of the design engineer.

The various plumbing codes generally use only satisfactory performance as a sizing guide for special waste system pipe sizing, compared to the specific drainage requirements mandated for sizing sanitary drainage systems. A common exception is for laboratory fixtures, in which case the drainage and vent systems may be required to be sized on a fixture unit basis. The reason for the lack of code requirements is that special drainage systems do not have a predictable or documented usage history, as do standard plumbing fixtures in sanitary drainage systems. Equipment drainage, spills, discharge from production facilities, and discharge from fixtures within the facilities are not always planned. They occur mostly at random intervals dictated by cleaning, production, maintenance schedules, and often accidents.

In addition, special drainage systems completely within the property of the facility do not fall under the plumbing code requirements for piping size or design, although they may fall under the jurisdiction of agencies such as the EPA or similar local environmental regulation bodies. Because of these factors, the special drainage piping system is sized on the basis of good engineering practice, which uses system slope, composition of the effluent, and expected flow rates rather than fixture units.

From each point in the system, the flow rate and pitch of the piping must be known to size the pipe. Pipe size should be determined based on the following criteria:

- Effluent has the characteristics of water. (If the effluent contains large concentrations of solids, the pitch should be adjusted accordingly.)
- The drainage system is sized on the basis of gravity drainage and maintenance of a minimum velocity of 2 feet per second (fps) (0.61 meters per second), using the anticipated maximum flow rate and pitch of the pipe at each point of design and a maximum velocity of 10 fps (3.05 meters per second) if the waste contains any solids.
- Gravity drainage pipe size is based on flow rate, slope, and velocity. Refer to Table 12-1 to find the velocity and size of pipe based on flow rate and slope. Depending on the system, piping should be sized to flow between one-half to three-fourths full to allow for unexpected large discharges, future changes, and accidents.

pH DEFINITION

Any dissolved impurity in water separates to form negatively and positively charged atoms called ions. Negative ions are called cations because they migrate

to the cathode, and positive ions are called anions because they migrate to the anode.

All acid compounds consist of hydrogen combined with an acid radical. In a mixture of acid and water, hydrogen ions result. pH is a measurement of the hydrogen ion concentration of a solution. Since the balance of hydroxyl (cation) and hydrogen (anion) ions must be constant, changes in one ion concentration produce corresponding changes in the other.

The pH value is calculated from the logarithmic reciprocal of the hydrogen ion concentration in water. The pH scale ranges from 0 to 14, with 0 being acid and 14 being alkaline; 7 is neutral. A change of one unit represents a tenfold increase (or decrease) in strength. pH is not a measure of alkalinity.

GENERAL SYSTEM DESIGN CONSIDERATIONS

It is good practice to separate each of the different systems inside the facility to a point outside the building so the individual services can be isolated and tested or sampled as may be required in the future by any local or national authority. Also, at some point in the future one system may require separate treatment because of a new substance that may be discharged.

One of the more constant aspects of special waste drainage systems is future change. In time, processes will change, equipment will be more efficient, facilities will become larger, and technology will be improved so the effluent will be different than it was at the time a system was originally designed. Thus, the design must allow for such change. It is common practice to size the drain one size larger than the design figures indicate or not to size the drainline to the exact point on the sizing chart indicated by the figures, especially where future expansion is probable. Thus, consideration should be given to selecting a pipe size slightly larger than required for the immediate flow rate or a material capable of resisting a greater selection of chemicals than necessary at the time of design. This must be verified with the client, of course, to ensure that the extra cost incurred by these options is acceptable.

ACID WASTE DRAINAGE AND VENT SYSTEMS

An acid waste drainage system collects and transports liquid wastes with a pH lower than 7 from laboratory fixtures, equipment, and all areas of a facility for discharge into an appropriate treatment facility or the sanitary drainage system after local treatment. The vent system equalizes flow in the drainage system in the same manner as in a sanitary drainage system.

For the purposes of this chapter, acid waste is divided into two general categories: laboratory waste and industrial waste. Laboratory waste consists primarily of dilute and concentrated mixtures of water and liquid chemical substances of mineral and organic origin. Many types of acid are usually present. Laboratory waste is discharged from sinks, cup sinks, fume hoods, and other similar fixtures and equipment. Discharge from floor drains, autoclaves, and glass washers and condensed water from various sources also are included.

Acid waste from industrial facilities consists of waste from accidental spills originating from tanks and piping and anticipated waste discharged from equipment into drains. Very often, the drainage piping must carry any of the acids used as part of the process. Where spills are directed into holding tanks, the drainage piping, tanks, pumps, and piping necessary to convey the effluent to treatment facilities is normally part of the plumbing engineer's responsibility.

The most important considerations in the selection of piping, valves, drains, and tanks for acid waste are the concentration and temperature of the acid. Acid wastewater from chemical and other facilities must be neutralized to a pH of 5 or higher prior to discharge into the sanitary system.

Health and Safety Concerns

All grades and concentrations of acids can severely damage the eyes and tissues of the body. Contact with the eyes can cause blindness. Contact with the skin causes irritation and burns. Inhaling the mist or vapors can cause lung irritation or burns. Ingestion destroys the tissues of the mouth, throat, and stomach.

Extreme care should be exercised in the handling and cleanup of all acids. Emergency drench equipment must be provided immediately adjacent to all hazards and locations where spills and other accidents could occur. If several people are normally present at a hazardous location, multiple pieces of drench equipment should be provided. Where fumes may be given off, emergency breathing apparatus must be provided.

For the laboratory environment, emergency showers shall be provided immediately inside or outside every room depending on travel distance. Some jurisdictions consider exiting the lab through a door an obstruction and will require an emergency shower inside the lab module. Where rooms are adjacent as in an open lab condition, a single shower is acceptable to serve multiple lab modules, provided it falls within the maximum allowable travel distance. Floor drains are not required in most jurisdictions, but the drain will help prevent the floor area surrounding the shower from becoming wet and slippery. Every room shall have an emergency eyewash, usually mounted on a sink or freestanding if sink mounting is not practical.

Table 12-1 Drainage Pipe Sizing

Pipe size, in.	Grade		½ Full			⅔ Full			Full		
			Discharge		Velocity	Discharge		Velocity	Discharge		Velocity
	in./ft	%	gpm)	cfs	ft/s	gpm	cfs	ft/s	gpm	cfs	ft/s
2	⅛	1.0	7	0.02	1.3	10	0.02	1.5	13	0.03	1.3
	¼	2.1	9	0.02	1.8	14	0.03	2.0	18	0.04	1.8
	½	4.2	14	0.03	2.9	22	0.05	3.2	28	0.06	2.9
	1	8.3	20	0.05	4.0	32	0.07	4.5	40	0.09	4.0
3	⅛	1.0	18	0.04	1.7	29	0.06	1.9	36	0.08	1.7
	¼	2.1	26	0.06	2.4	41	0.09	2.7	51	0.11	2.4
	½	4.2	40	0.09	3.7	64	0.14	4.1	80	0.18	3.7
	1	8.3	57	0.13	5.3	90	0.20	5.9	114	0.25	5.3
4	⅛	1.0	39	0.09	2.0	61	0.13	2.2	77	0.17	2.0
	¼	2.1	55	0.13	2.8	87	0.20	3.1	110	0.25	2.8
	½	4.2	87	0.20	4.5	138	0.31	5.0	174	0.39	4.5
	1	8.3	123	0.28	6.3	194	0.44	7.1	245	0.55	6.3
6		0.5	79	0.18	1.8	124	0.28	2.0	157	0.35	1.8
	⅛	1.0	1 10	0.25	2.5	174	0.39	2.8	220	0.49	2.5
		1.5	135	0.30	3.1	213	0.47	3.5	269	0.60	3.1
	¼	2.1	157	0.35	3.6	248	0.55	4.0	314	0.70	3.6
		2.5	175	0.39	4.0	277	0.62	4.5	350	0.78	4.0
	⅜	3.1	193	0.43	4.4	305	0.68	4.9	386	0.86	4.4
		3.5	207	0.46	4.7	327	0.73	5.3	413	0.92	4.7
	½	4.2	225	0.50	5.0	355	0.79	5.6	449	1.00	5.0
	⅝	5.2	247	0.55	5.6	391	0.87	6.3	494	1.10	5.6
	¾	6.3	270	0.60	6.1	426	0.95	6.8	539	1.20	6.1
	⅞	7.3	292	0.65	6.6	461	1.03	7.4	583	1.30	6.6
8		0.2	108	0.24	1.6	170	0.38	1.8	215	0.48	1.6
		0.4	153	0.34	2.0	241	0.54	2.2	305	0.68	2.0
		0.6	191	0.43	2.4	302	0.67	2.7	382	0.85	2.4
		0.8	236	0.53	2.9	372	0.83	3.2	471	1.05	2.9
	⅛	1.0	247	0.55	3.2	391	0.87	3.6	494	1.10	3.2
		1.5	303	0.68	3.8	479	1.07	4.3	606	1.35	3.8
	¼	2.1	348	0.78	4.5	550	1.22	5.0	696	1.55	4.5
		2.5	392	0.88	4.9	621	1.38	5.5	785	1.75	4.9
	⅜	3.1	427	0.95	5.4	674	1.50	6.0	853	1.90	5.4
		3.5	449	1.00	5.8	710	1.58	6.5	893	2.00	5.8
	½	4.2	494	1.10	6.2	780	1.74	6.9	987	2.20	6.2
	½	4.5	516	1.15	6.6	816	1.82	7.4	1,032	2.30	6.6
10		0.2	211	0.47	1.7	334	0.74	1.9	422	0.94	1.7
		0.4	303	0.68	2.4	479	1.1	2.7	606	1.35	2.4
		0.6	359	0.80	2.9	568	1.3	3.2	718	1.60	2.9
		0.8	438	0.98	3.5	692	1.5	3.9	875	1.95	3.5
	⅛	1.0	472	1.05	3.8	745	1.7	4.3	943	2.10	3.8
		1.5	561	1.25	4.5	887	2.0	5.0	1,122	2.50	4.5
	¼	2.1	651	1.45	5.3	1,029	2.3	5.9	1,302	2.90	5.3
		2.5	741	1.65	5.7	1,170	2.6	6.4	1,481	3.30	5.7
	⅜	3.1	808	1.80	6.4	1,277	2.8	7.2	1,616	3.60	6.4
		3.5	853	1.90	6.8	1,348	3.0	7.6	1,706	3.80	6.8

Where vapor is possible, fog nozzles using water to suppress the vapor and foam systems to prevent vapor from rising should be considered.

Common Types of Acid

Acids are widely used chemicals in the chemical processing industry. The most commonly used acids follow.

Sulfuric Acid

Sulfuric acid, among the most commonly used acids, is commercially available in many concentrations and as various percentages of oleum. Also called fuming sulfuric acid, oleums are sulfuric acids containing sulfur trioxide dissolved in the acid. Generally recommended piping materials for these acids at low temperatures (140°F [60°C] and lower) and up to 90 percent concentration are polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC), polypropylene (PP), polyvinylidene fluoride (PVDF), ethylene tetrafluoroethylene (ETFE), and high-density polyethylene (HDPE); glass; alloy 20; duriron; and fiberglass-reinforced plastic (FRP) piping with special resins. At 90 percent and higher concentrations, carbon steel Schedule 80 often is used. Stainless steel is generally unsuitable, except for oleums with less than 10.3 percent concentration. Vent lines should be of the same material used for the drain line.

Valve types include ball, gate, and diaphragm, with gate valves being the most commonly used. For low pressures and temperatures suitable for specific

Table 12-1(M) Drainage Pipe Sizing

Pipe size, mm	Grade		½ Full			⅔ Full			Full		
			Discharge		Velocity	Discharge		Velocity	Discharge		Velocity
	cm/m	%	L/s	m^3/s	m/s	L/s	m^3/s	m/s	L/s	m^3/s	m/s
50	1.04	1.0	0.44	0.57	0.40	0.63	0.57	0.46	0.82	0.85	0.40
	2.08	2.1	0.57	0.57	0.55	0.88	0.85	0.61	1.14	1.13	0.55
	4.16	4.2	0.88	0.85	0.88	1.39	1.42	0.98	1.77	1.70	0.88
	8.32	8.3	1.26	1.42	1.22	2.02	1.98	1.37	2.52	2.55	1.22
80	1.04	1.0	1.14	1.13	0.52	1.83	1.70	0.58	2.27	2.27	0.52
	2.08	2.1	1.64	1.70	0.73	2.59	2.55	0.82	3.22	3.12	0.73
	4.16	4.2	2.52	2.55	1.13	4.04	3.96	1.25	5.05	5.10	1.13
	8.32	8.3	3.60	3.68	1.62	5.68	5.66	1.80	7.19	7.08	1.62
100	1.04	1.0	2.46	2.55	0.61	3.85	3.68	0.67	4.86	4.81	0.61
	2.08	2.1	3.47	3.68	0.85	5.49	5.66	0.94	6.94	7.08	0.85
	4.16	4.2	5.49	5.66	1.37	8.71	8.78	1.52	10.98	11.04	1.37
	8.32	8.3	7.76	7.93	1.92	12.24	12.46	2.16	15.46	15.58	1.92
150		0.5	4.98	5.10	0.55	7.82	7.93	0.61	9.91	9.91	0.55
	1.04	1.0	6.94	7.08	0.76	10.98	11.04	0.85	13.88	13.88	0.76
		1.5	8.52	8.50	0.94	13.44	13.31	1.07	16.97	16.99	0.94
	2.08	2.1	9.91	9.91	1.10	15.65	15.58	1.22	19.81	19.82	1.10
		2.5	11.04	11.04	1.22	17.48	17.56	1.37	22.09	22.09	1.22
	3.12	3.1	12.18	12.18	1.34	19.25	19.26	1.49	24.36	24.36	1.34
		3.5	13.06	13.03	1.43	20.63	20.67	1.62	26.06	26.05	1.43
	4.16	4.2	14.20	14.16	1.52	22.40	22.37	1.71	28.33	28.32	1.52
	5.2	5.2	15.59	15.58	1.71	24.67	24.64	1.92	31.17	31.15	1.71
	6.3	6.3	17.04	16.99	1.86	26.88	26.90	2.07	34.01	33.98	1.86
	7.3	7.3	18.43	18.41	2.01	29.09	29.17	2.26	36.79	36.82	2.01
200		0.2	6.81	6.80	0.49	10.73	10.76	0.55	13.57	13.59	0.49
		0.4	9.65	9.63	0.61	15.21	15.29	0.67	19.25	19.26	0.61
		0.6	12.05	12.18	0.73	19.06	18.97	0.82	24.10	24.07	0.73
		0.8	14.89	15.01	0.88	23.47	23.51	0.98	29.72	29.74	0.88
	1.04	1.0	15.59	15.58	0.98	24.67	24.64	1.10	31.17	31.15	0.98
		1.5	19.12	19.26	1.16	30.22	30.30	1.31	38.24	38.23	1.16
	2.08	2.1	21.96	22.09	1.37	34.71	34.55	1.52	43.92	43.90	1.37
		2.5	24.74	24.92	1.49	39.19	39.08	1.68	49.53	49.56	1.49
	3.12	3.1	26.94	26.90	1.65	42.53	42.48	1.83	53.82	53.81	1.65
		3.5	28.33	28.32	1.77	44.80	44.75	1.98	56.35	56.64	1.77
	4.16	4.2	31.17	31.15	1.89	49.22	49.28	2.10	56.60	62.30	1.89
		4.5	32.56	32.57	2.01	51.49	51.54	2.26	65.12	65.14	2.01
250		0.2	13.31	13.31	0.52	21.08	20.96	0.58	26.63	26.62	0.52
		0.4	19.12	19.26	0.73	30.22	31.15	0.82	38.24	38.23	0.73
		0.6	22.65	22.66	0.88	35.84	36.82	0.98	45.31	45.31	0.88
		0.8	27.64	27.75	1.07	43.67	42.48	1.19	55.21	55.22	1.07
	1.04	1.0	29.78	29.74	1.16	47.01	48.14	1.31	59.50	59.47	1.16
		1.5	35.40	35.40	1.37	55.97	56.64	1.52	70.80	70.80	1.37
	2.08	2.1	41.08	41.06	1.62	64.93	65.14	1.80	82.16	82.13	1.62
		2.5	46.76	46.73	1.74	73.83	73.63	1.95	93.45	93.46	1.74
	3.12	3.1	50.98	50.98	1.95	80.58	79.30	2.19	101.97	101.95	1.95
		3.5	53.82	53.81	2.07	85.06	84.96	2.32	107.65	107.62	2.07

plastic pipes, plastic often is used. For higher temperatures and pressures, alloy 20 is preferred. In all cases, because of differences in manufacturing, pipe vendors should be consulted as to the suitability of materials for specific acid piping service.

Centrifugal pumps constructed of stainless steel alloy 320 with Teflon packing are in common use. Other manufacturers use FRP and plastic pumps. Also available are metallic pumps lined with plastic or glass. Temperature limits should be carefully checked for material suitability.

Spills of concentrated acids from tanks onto floors and equipment should be washed and flooded with water, which then must be routed to the acid drainage system for neutralization. Tanks used to contain this spillage should be of a suitable plastic. Since water reacts rapidly with acid and splatters, caution should be exercised. Heat and fumes also are given off, and breathing the fumes causes throat and lung injury. Where this situation is possible, suitable emergency breathing apparatus should be provided. An emergency shower should be provided in the immediate vicinity of acid storage and pipe routing.

Sulfuric acid is nonflammable, but it is highly reactive. Below a concentration of 75 percent it reacts with carbon steel and other metals to form hydrogen. It is particularly hazardous when in contact with carbides, chlorates, nitrates, fulminates, picrates, and powdered metals. In higher concentrations it will ignite combustible materials, such as oily rags

and sawdust. Dry chemicals or carbon dioxide are the fire-suppression methods of choice.

Because of the danger of fumes, oleum spills should be contained by curbs, and the liquid should be diverted from the area of a spill to a containment area, where it can be neutralized. The resulting liquid should be absorbed with diatomaceous earth, expanded clay, or other nonreactive material. This material should be carted away for suitable disposal.

Phosphoric Acid

Phosphoric acid is available in concentrations between 75 and 87 percent. Recommended pressure piping is stainless steel type 316 extra-low carbon (ELC) and CPVC Schedule 80. The drainage and vent piping, valves, and pumps are similar to those used for sulfuric acid. The Occupational Safety and Hazard Administration (OSHA) limits human exposure to this acid.

Precautions for spills and safety and health concerns are similar to those for sulfuric acid.

Hydrochloric Acid

Hydrochloric acid, also known as muriatic acid, is available in four strengths, designated as degrees Baume (an equivalent notation of specific gravity).

Piping materials for drainage and vent piping, valves, and pumps are PVC, CPVC, PP, PVDF, glass, high-silicon cast iron (HIS), or fiberglass-reinforced plastic. Precautions and procedures for spills and safety and health concerns are similar to those for sulfuric acid, except that caustic soda should not be used because hydrochloric acid reacts with this chemical.

Nitric Acid

Nitric acid is available in three grades designated by the percent of concentration by weight: 56–70 percent, 70–84 percent, and 97.5–100 percent. The recommended pressure piping material for concentrations up to 95 percent is 304L stainless steel. CPVC is acceptable up to 70 percent concentrations at 73°F (22.8°C). Above this concentration, aluminum piping is recommended. Pumps for concentrations up to 95 percent should be constructed of 304L stainless steel. Above this concentration, titanium, aluminum type 3003, or silicon iron are commonly used. The recommended materials for gate, ball, plug, and globe valves are 347 stainless steel or 304L stainless steel. Drain lines should be glass.

Precautions and procedures for spills and safety and health concerns are similar to those for sulfuric acid, except temperature and humidity affect the reaction of nitric acid on such metals as copper, brass, and zinc. Nitric acid reacts violently with organic substances, occasionally causing explosions. A self-contained breathing apparatus is required for approaching spills because of the emission of nitrogen oxides, commonly called nitrous fumes, which are extremely hazardous.

Hydrobromic Acid

Hydrobromic acid is commercially available in two concentrations: 70 and 99.95 percent.

Recommended pressure piping materials are glass and rubber-lined steel pipe, PVC, polyethylene (PE), and polytetrafluoroethylene (PTFE). In addition to the pressure piping, glass pipe could be used for drainage. Valves are often ball and plug type with a PVC, PE, or PTFE lining. Rubber-lined pinch valves are commonly used. Pumps are similar to those used for sulfuric acid, with the addition of Hastelloy B material.

Precautions and procedures for spills and safety and health concerns are similar to those for phosphoric acid, but the vapors are much more hazardous. This acid reacts with metals and produces explosive hydrogen gas.

Perchloric Acid

Perchloric acid is available in a concentration of 69–72 percent and is the strongest of all the inorganic acids.

Recommended pressure piping materials are glass, PTFE, and CPVC Schedule 80. Drainlines can be glass or CPVC. Valves are often ball-and-plug type manufactured from PTFE and duriron. Pumps manufactured from PTFE are the most commonly used.

Precautions and procedures for spills and safety and health concerns are similar to those for phosphoric acid, except when heated to 150°F (69°C), perchloric acid can cause objects not normally considered combustible, such as rubber gloves and human skin, to burst into flames.

Selection of Laboratory Waste Piping and Joint Material

The majority of the effluent from a typical laboratory consists primarily of water and acid. If toxic, chemicals used for experiments usually are confined to fume hoods. You should obtain information regarding the extent and concentration of all chemicals expected to be used in the laboratory from the end user.

The most cost-effective, above-the-floor piping from laboratory fixtures is generally fire-retardant polypropylene, with either heat-fused socket or screwed mechanical joints or CPVC drain waste and vent with special solvent cement. Other acceptable materials are glass with compression joints and high-silicon cast iron with caulked or compression gasket joints. Although PVC has the lowest initial cost, it also has a limited range of chemical compatibility and a low temperature rating. PVDF with fused or mechanical joints is also an acceptable material. It has a wide range of chemical compatibility and is a plenum-rated

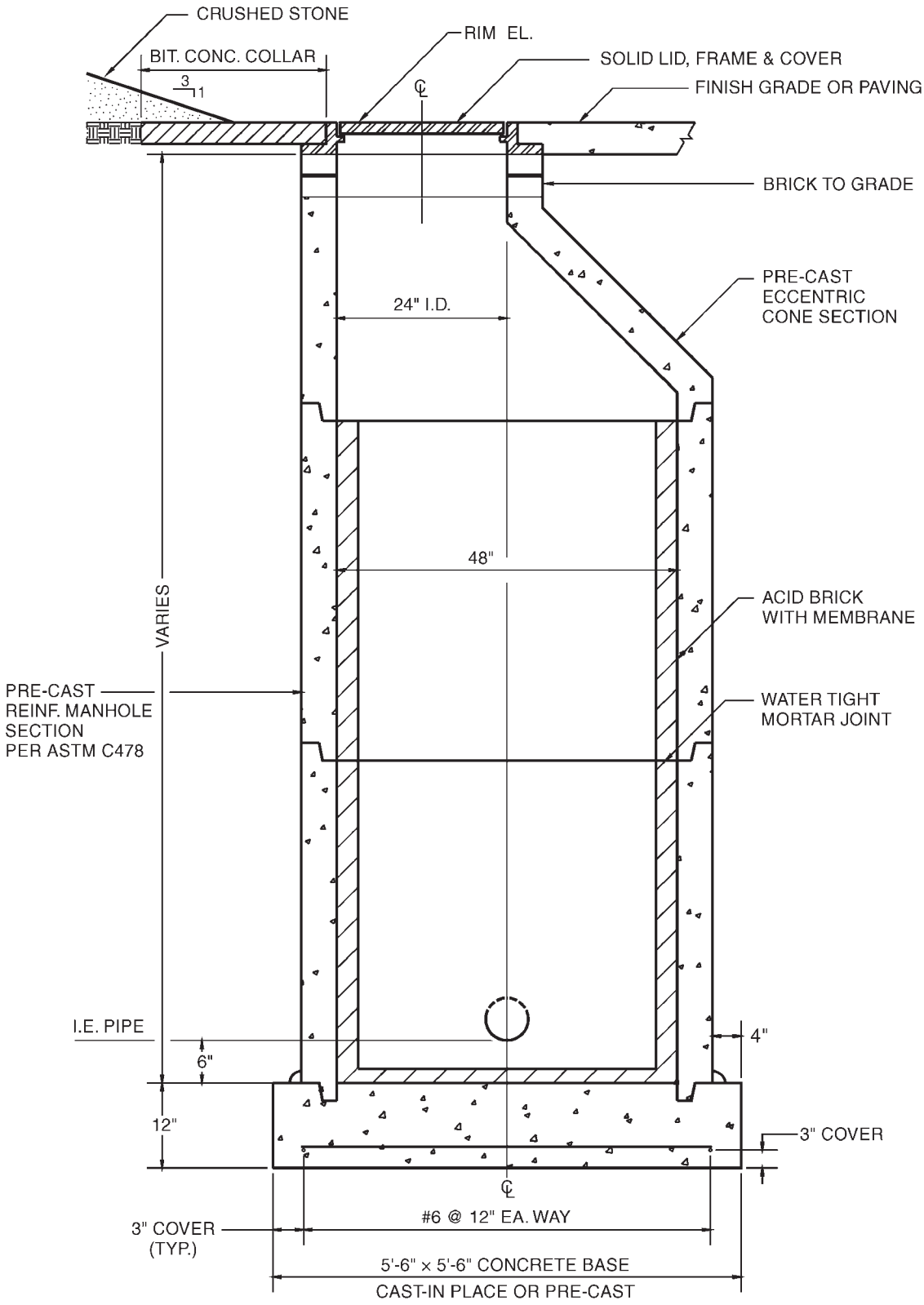


Figure 12-1 Typical Acid-resistant Manhole

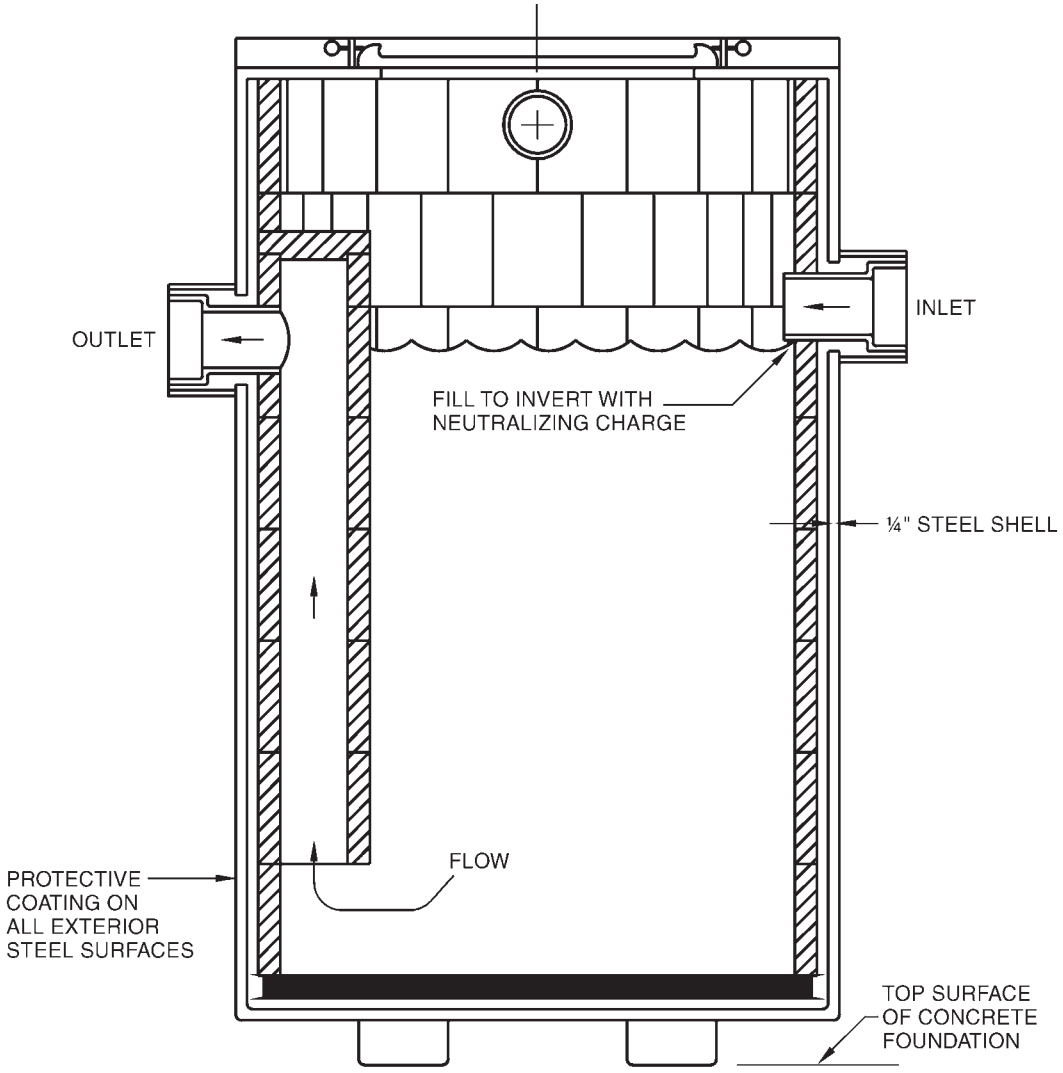


Figure 12-2 Typical Large Acid-neutralizing Basin

material; however, it is rarely used due to its higher cost versus PP. PTFE is resistant to the widest variety of chemicals and has the highest temperature rating and highest cost. CPVC is suitable to 210°F (98.9°C) and is resistant to a wide variety of chemicals.

Piping underground, subject to local codes, also could be polypropylene with heat-fused socket joints or high-silicon cast iron with compression gasket joints. Glass piping should be encased in a sleeve of polyethylene for protection.

Vent pipe shall be the same material as the drain pipe. The vent shall be carried above the roof level. Vent piping penetrating the roof shall not be glass. An adapter should be used and any other acceptable acid-resistant pipe material should be provided through the penetration.

System Design Considerations

General system design considerations for the laboratory drainage system shall be the same as those for the sanitary drainage system, including placement of cleanouts. Each fixture shall be individually trapped and vented. Clean water, such as that discharged from air compressors and other condensate drains, can spill into the laboratory drainage system when convenient and allowed per code. Because of possible stoppages that could flood all piping, the entire laboratory waste system shall be of the same acid-resistant piping material.

Where the only waste discharge is from laboratory fixtures, the use of fixture-unit schedules for pipe sizing is acceptable, but simultaneous use should be factored into the sizing process. When the effluent

is expressed in gallons per minute (gpm) (liters per second) from a known discharge, base the size on this value and the equivalent value from the fixtures. The pipe shall be sized using the pitch and a three-fourths-full pipe.

The laboratory drainage and vent system shall be separate from all other systems until the effluent is adequately treated. Then it may be combined on the site with other waste lines. If a manhole is required in the acid waste line, it should be acid resistant. A typical acid-resistant manhole is illustrated in Figure 12-1.

Acid Waste Treatment

All acid waste requires neutralization to a pH between 7.5 and 5 before it is permitted to be discharged into any public sewer for disposal. Commonly accepted practice permits local authorities to allow primary-treated effluent to discharge directly into the public sanitary sewer system after only pH treatment. The most often-used primary procedures are dilution, direct continuous contact with limestone chips in an acid-neutralizing basin, and continuous or batch treatment in an automated neutralization system utilizing chemical feed neutralizing.

A dilution basin dilutes chemicals to a neutral pH. This works if the facility has a large volume of water used for handwashing or other operations that do not introduce chemicals into the waste stream. If the volume of clean waste is low compared to the volume of acid waste, this method will not work sufficiently.

In an acid-neutralizing basin, a chemical reaction occurs between the acid and the limestone chips. Each basin shall be designed by the manufacturer to allow sufficient contact time for the chemical reaction to accomplish complete neutralization based on the maximum flow rate anticipated. Approximately 100 pounds (45 kilograms) of limestone chips treat 97 pounds (44 kilograms) of sulfuric acid and 75 pounds (34 kilograms) of hydrochloric acid. Effluent consisting primarily of sulfuric acid should be treated with dolomite limestone chips. This method of treatment requires periodic replacement and disposal of the spent limestone chips.

For general laboratory waste, several methods of treatment using limestone chips are available. For single isolated sinks, an acid-neutralizing trap should be considered. For a small number of sinks in a cluster, a shelf-mounted, small-diameter basin could be used. It should be confined to treating the discharge of acids from a small number of fixtures in remote locations or from individual sinks where the timely maintenance needed to fill the basin may not be possible. Larger basins, such as the one illustrated in Figure 12-2, are available to treat the effluent from a large number of laboratory sinks. If the discharge of oil or grease is expected in the laboratory waste stream, the installation of an interceptor basin before the acid sump is recommended. Some objectionable contaminants can coat individual chips and prevent the chemical action needed to neutralize the acid.

For a larger number of fixtures or equipment and where treatment by limestone chips alone is not practical, a continuous waste-treatment system consisting of a single or multiple basins and/or a mixing tank should be installed. This type of system automatically adds proper amounts of caustic to the incoming acid waste, thereby neutralizing the acid. A sophisticated arrangement of probes, chemical feed pumps, level indicators, and alarms is required. An agitator or mixer may be installed in the basin to mix the acid with the caustic, and the addition of a recorder may be desired. A probe is connected to an automatic caustic feed pump that introduces the proper amount of neutralizing liquid (commonly caustic soda) into the basin or mixing tank. Continuous treatment also may require additional downstream sensing probes and chemical additive locations to ensure that the discharge is within acceptable limits. If the system is located at a low level, a pump is required to bring the discharge up to the level of the sewer. Figure 12-3 illustrates a typical continuous waste-treatment system.

It is good engineering practice to route the discharge from the neutralizer separately into the sanitary house drain outside of the building for dilution prior to discharge into the public sewer. This also may be necessary for local authorities to monitor the waste stream without entering the building.

For preliminary determination of the number of sinks required for average laboratories, allow one sink for each 200 square feet (18.6 square meters) of laboratory area. Each sink will discharge 1 gpm (3.8 liters per minute). Cup sinks will discharge 0.5 gpm (1.9 liters per minute). For a maximum flow rate, assume that 50 percent of the sinks could discharge simultaneously.

RADIOACTIVE WASTE DRAINAGE AND VENT SYSTEMS

Many commercial facilities have low quantities and levels of radioactive waste. Because of the small amount of radioactive material present at these facilities, large storage and treatment systems and severe safety requirements are not necessary. Facilities with higher quantities of radioactive material and radiation levels fall under a different, much more stringent set of regulatory requirements. For such facilities, documentation regarding the protection of the public and workers in the event of an accident is considerably more complex.

The requirements for handling radioisotopes in laboratories are essentially no different than the requirements for handling toxic chemicals or pathogens, with the exception of providing radiation shielding if

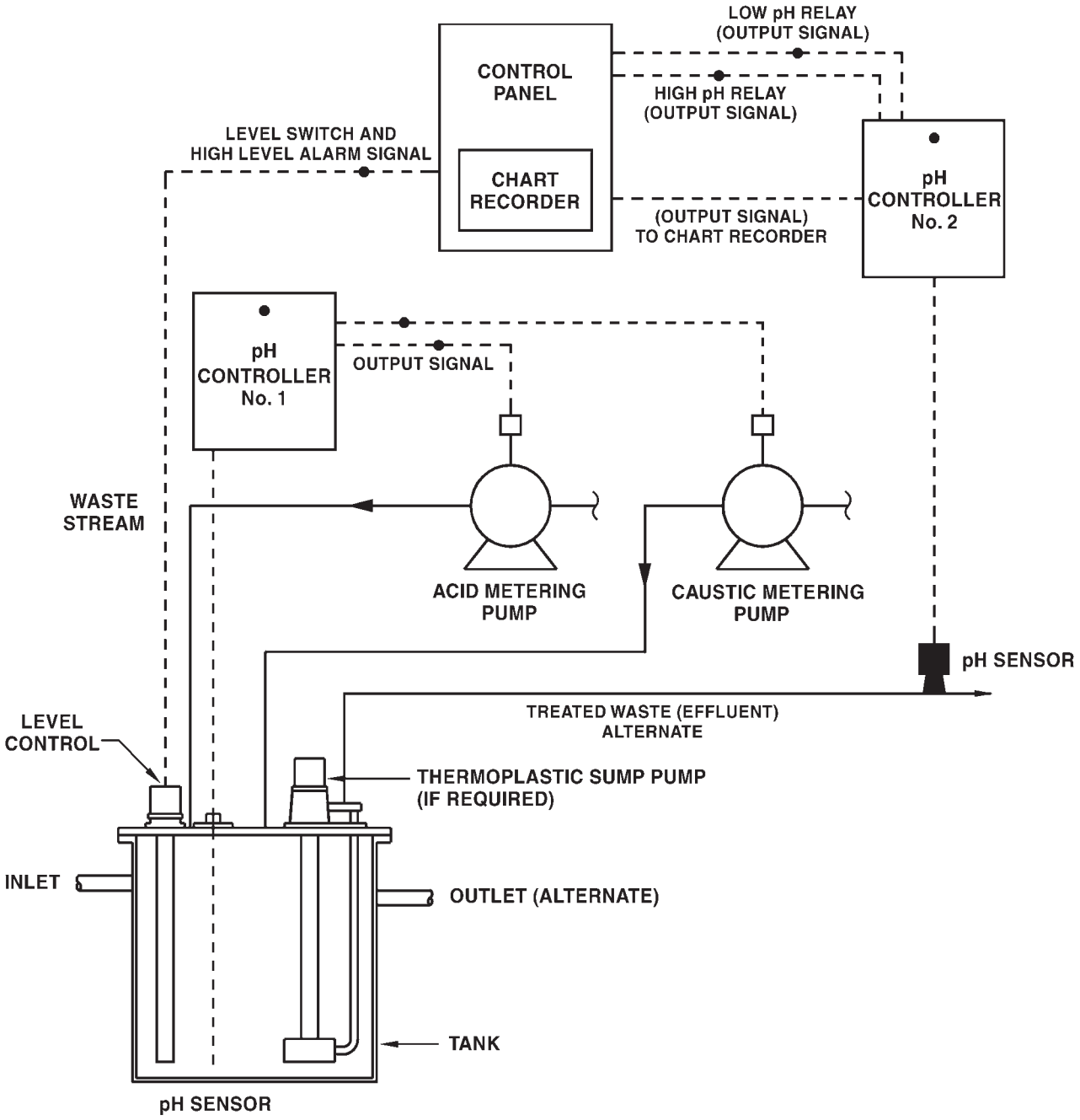


Figure 12-3 Typical Continuous Acid Waste Treatment System

necessary. The ideal goal is to totally eliminate the exposure of workers, staff, and the general public. Since this is not realistic, the design shall implement criteria that eliminate or reduce to allowable levels the radiation exposure of workers and maintenance personnel and prevent exposure of the general public to unacceptable amounts of radiation by waterborne radioactive waste (radwaste).

The Nature of Radiation

Radioactivity is the spontaneous emission of harmful particles from the unstable nucleus of an atom. There are many intermediate steps in the stabilization cycle, including the formation of other, less complex radioactive by-products called isotopes. These by-products, in turn, decay to form other unstable isotopes as the cycle continues. The end result is a highly stable element. For example, the end product of uranium is lead. One of the intermediate byproducts of uranium is radon.

Radiation is a general term meaning any or all of the following: alpha rays, beta rays, gamma rays, neutrons, x-rays, and other atomic particles. The three general classifications of radiation are alpha, beta,

and gamma. Alpha radiation is actually a helium atom with a high velocity. Beta radiation is an electron with a high velocity. Gamma radiation is a particle similar to a photon, which is light.

Alpha and beta radiation generally can be stopped by the skin or clothing, paper, or another similar, light material. Alpha loses energy very quickly in air and is no practical concern for distances greater than 12 inches (305 millimeters). High-energy beta radiation is commonly contained by only 1 inch (25 millimeter) of solid, dense plastic. Beta is denser and carries more energy greater distances than alpha, and it will burn bare skin and, in particular, damage the eye. However, it generally does not penetrate into the body to cause any internal damage. The greatest danger with beta radiation is to the eyes, particularly when the eye is directly exposed close to the source.

Gamma radiation is electromagnetic in nature. It carries the most energy and therefore is the most dangerous to humans. Its wavelength is shorter than light waves. When generated, it is similar to x-rays and behaves in a manner similar to light waves. When released from a source, gamma rays have a mass and velocity that are a measurable energy potential.

Radiation Measurement

Radioactivity is a general term used for the total release of radiation of all types from a source. Its measurement is in disintegrations per second (dps). This measurement is possible for gamma radiation because in most radioactive materials, it also produces a known amount of gamma radiation. However, the best manner of measuring gamma radiation is to measure the energy it produces per kilogram (pound) of air. Because the instruments needed to measure radiation in this way are very expensive, it is not widely used outside of the laboratory. The so-called Geiger-Mueller counter is the most common device for measuring radiation. It measures the penetration of the particles entering a tube, where the particles react with a gas to create a measurable electrical charge. If an amplification device is used, it can be heard in the form of static. The more modern instruments have a digital readout.

Units of Radiation

Particulate radiation is measured by the number of disintegrations per unit of time. A curie (c) is equal to 3.7 x 1010 disintegrations per unit. One millicurie (mc) is 0.001 curie, or 3.7 x 107 disintegrations per unit. One rad is defined as the dose corresponding to the absorption of 100 ergs per gram of tissue. A Roentgen measures ions carrying a total of 2.58 x 104 coulombs (C) of electrical energy.

Since the term radiation is a general one, a more specific method must be used to measure its effect on humans. The measurement is called a dose and is defined as the total quantity of radiation absorbed by the body or any portion of the body. Much of the time, the dose is modified by reference to a unit of time. This differs from radioactivity because all radiation is not absorbed by the body.

A rad is a measure of the dose to body tissue in terms of energy absorbed per unit mass. Gamma radiation is the type of radiation most commonly measured this way.

The most important measurement is the radiation equivalent to man, or rem. A rem is the measure of ionizing radiation passing through or absorbed by the body in terms of the biological effect relative to a dose of 1 roentgen of x-rays. The relation of the rem to other dose units depends on the actual biological effect to the particular part of the body being studied and the actual conditions and amount of time of the irradiation. One rem is the equivalent of 1 roentgen due to x-ray or gamma radiation, and also 1 rad due to x-ray or gamma or beta radiation. One rem of high-flux neutrons is roughly equivalent to 14 million neutrons per square centimeter incident to the body.

Allowable Radiation Levels

Many scientists believe that no exact radiation level is certain to cause permanent harm to an individual. Other scientists believe no level is harmless. A term called background level of radiation exists all over the world. The most common source of this is the sun, and it is called cosmic radiation. In addition, many substances, such as fly ash from burning organic fuels (particularly coal), granite, and many other natural substances contain trace isotopes of elements, emit radiation. One of the most common of these trace elements is carbon 14, used by scientists to date many materials.

The Nuclear Regulatory Commission (NRC) is a governmental body that establishes criteria for the field of radioactivity. These criteria appear in the federal government's Code of Federal Regulations.

All personnel working at any site where the possibility of exposure to radiation exists are required to wear some type of exposure-detection device that gives an accurate determination of their actual exposure. The photographic badge is the most common and is used where sensitivity is required. A pen-shaped device called a dosimeter is commonly used where there is less need for accuracy. It is used where instant determination of dose is necessary.

An unrestricted area is any area within a facility that is not specifically controlled for the purpose of protecting an individual from radiation or radioactive materials. A restricted area is access controlled. The term environs also may be used to describe areas adjacent to a restricted or high-radiation area, which is any accessible area within a facility capable of al-

lowing the body to receive 100 millirem (mrem) of radiation in one hour.

Shielding

The purpose of shielding is to reduce or eliminate radiation emanating from any source within the facility. The most effective material has the greatest density, so lead has been universally used for this purpose. Another commonly used material is concrete. In describing the shielding thickness between concrete and lead, 1/6 inch (4 millimeters) of lead is the equivalent of 12 inches (305 millimeters) of concrete. The use of concrete as a structural element of a building serves a supplementary purpose as a very good shielding material. It is up to the radiological safety officer, whose responsibilities are discussed later, to determine the type of shielding and its placement to lower radiation in specific areas. Radiation travels in a straight line; therefore, if a tank or a length of pipe must be shielded, the proper manner is to form a labyrinth, so the shine from the tank can't escape in a straight line.

The materials most commonly used for shielding purposes are concrete and sheet lead. Other materials that have proven effective are lead-lined concrete blocks, lead-lined lath for plaster, and lead-lined panels and gypsum boards.

The barriers set up to reduce radiation levels are primary barriers, which are the first line of defense, and secondary barriers, which are used to eliminate leakage radiation and scattered radiation where it may possibly exist.

Radioactive Materials

Radioactive materials are used for the following five general categories of work:

1. Imaging sciences
2. Diagnostic purposes
3. Treatment purposes
4. Industrial uses
5. Research

Almost all of the materials used are isotopes. An isotope is a form of an element with a different (or excess) number of neutrons in its nucleus. Because of this, the atom is unstable. Isotopes are identified by their atomic weight, which is the number of neutrons and protons in the nucleus.

A great number of isotopes are in use today. Some of the more common are:

- Iodine 131 (eight-day half-life)
- Phosphorus 32
- Technetium 99 (six-hour half-life)
- Calcium 45
- Carbon 14
- Strontium 90
- Radium 226

Since given amounts of radioactive material remain active for different periods, it is not possible to predict when any material will become completely stable. The method used to determine when a specific material loses half of its radioactivity is called its half life.

System Design Criteria

Approval Process and Application Requirements

The use of any radioactive material requires the licensing of the site for a specific purpose, quantity, and amount of radioactive material. Application for this license is made to either the Nuclear Regulatory Commission or a particular state. Those states that have elected to adopt NRC regulations and provide their own staff for the purpose of issuing and approving licenses are called agreement states. In some cases, these states make additional regulations of their own. Those states relying on the NRC to review and issue licenses are non-agreement states. In such states, the application is made to the appropriate party.

The duties of the radiological safety officer include administration, monitoring personnel exposure limits, and controlling any release of radionuclides to the sewer system. In addition, the radiological safety officer works with the engineers in the design phase of the facility to ensure that the piping runs and all other mechanical work will result in a low exposure to people within the facility. For the most part, this work is aimed at ensuring that facility personnel do not exceed the maximum permissible radiation dose allowed under the applicable codes for any particular type of radioactive material present and that non-staff members are not subject to unacceptable levels of radiation. The radiological safety officer is also responsible for the following:

- Teaching facility staff about potential dangers
- Keeping the necessary records for the facility
- Keeping an inventory of material and records disposal
- Maintaining the concentration of materials at the facility
- Designating areas within the facility to be restricted

General Design Criteria

The prime consideration in the design of any facility is controlling the exposure of personnel to radiation, a concept called ALARA, or as low as reasonably achievable. This requires every reasonable design method to limit the possible exposure of personnel inside the facility and to keep the presence of radioactivity in any unrestricted area to a figure as low

as reasonably achievable. Among the things that must be taken into account are the current state of technology, the economics of further improvements in relation to the benefits to the public's health and safety, and other socioeconomic considerations relating to the utilization of radioactive material in the general public interest.

The designer of the facility also must make a reasonable effort to eliminate residual radiation. One of the overriding concepts is the worst-case possibility, where the worst possible combination of circumstances is used to determine the possible level of radiation and the period of exposure. This concept should not be overused, and a general rule is to consider only one accident at a time. As an example, a serious spill and a fire would not be considered as likely to occur simultaneously.

Pipe Material Selection

The pipe selected for the radioactive drainage system depends on the type of radiation and the level of radioactivity expected, which, in turn, depend on the amount and type of radioactive material at the facility. In general, an ideal radwaste drainage pipe should have the following properties:

- It must be nonporous.
- It must be easy to clean and decontaminate.
- It should be acid resistant.
- It should be non-oxidizing.
- The joints should not form a crud trap.
- Joint materials must not be affected by radiation exposure.

In very high radiation areas, a pipe may be affected by the radiation present. The oxides of the pipe can become radioactive, or the pipe itself can be weakened. Plastic piping is not acceptable for radiation waste systems because the plastic may be affected by the radiation, causing weakening of elastomeric seals or gaskets. For this reason, Teflon is never used where anything more than a very low level of radiation is present. Other materials should be investigated regarding their suitability for use for the levels anticipated.

All of the commonly used materials (cast iron, ductile iron, copper, steel, and glass) and joints fall far short of the ideal. However, they are suitable for low-level waste and radioactive source materials found in facilities with low radiation levels. When the waste materials have a high radiation level, these materials and joints fail. As a result, stainless steel with welded joints has emerged as the material of choice for all industrial-type waste products. Type 316L is the type most commonly used.

A welded joint is the only type of joint that does not allow a crud trap to form. The orbital welding process often is used since it produces the cleanest interior weld surface. The proper weld end preparation is critical to proper welding and must be diagrammed or described in the specifications.

The two types of joint used for drainage pipe are butt welding and socket welding. Butt welding is when two pipes are placed end to end and joined with no overlapping. A socket weld is when one pipe is placed inside the other and only one end of the exposed pipe is actually welded around the exterior of the pipe. This is similar to a coupling, with only the joint on the outside of the pipe welded. In general, only pipe 2 inches (50 millimeters) and less is socket welded. Pipe this small is called small bore pipe.

Specifications for, and approval of, the entire welding process for both shop welding and field welding are necessary. Welding personnel must be qualified to ensure that they have sufficient training and knowledge to produce a weld of the required quality, but the qualifications of welding personnel are difficult to assess. High-temperature, high-pressure pipe is covered by ASME codes that specify the selection of successive welding type passes, filler metal composition, joint preparation, movement and handling of the pipe, tack welding and clamping, welding currents, metal deposit rates, and weld inspection. However, none of these code requirements apply to welded non-pressure drainage pipe. If the engineer does not have the knowledge to specify the minimum requirements for welders and the welding process, it could be left up to the contractor to determine the correct specifications for the project and recommend them to the engineer for approval. When this is done, the contractor establishes minimum criteria that will qualify any individual for welding on this particular project. It is then up to the contractor to test a welder's ability to make sound welds under the actual working conditions and using the same equipment expected to be used on the job and certify that person as being qualified. These criteria should be reviewed by the engineer for acceptability. It is common practice to use an outside, knowledgeable third party for this review process.

Any defects in welded piping, such as cracks or voids in a joint, must be found and corrected. All of them arise from the fact that the weld does not actually create a monolithic piece of pipe. The testing methods are of the non-destructive type, including visual inspection of the weld, dye penetration, magnetic testing, ultrasonic testing, and x-ray

Design Considerations

Human or animal waste, even that contaminated with radioactivity, is exempt from all Nuclear Regulatory Commission regulations, requiring only compliance with local codes as far as disposal, sizing, and all other criteria applicable to standard drainage systems. Many isotopes also are exempt from regulations regarding disposal into the public sewer.

Liquid radwaste to be discharged shall be diluted with the ordinary waste effluent from the rest of the facility before being discharged to the public sewer system. Thus, the radwaste piping first must be kept separate from the rest of the facility's effluent, but then combined before leaving the building for discharge into a public sewer. A method, such as a valved outlet from both the radwaste line and the combined discharge, should be provided for the radiological safety officer to sample the radwaste stream if desired. The pitch of the piping should be kept as steep as possible to empty the pipe quickly and to allow a scouring action to keep the radioactive solids in suspension.

It is common practice to confine high levels of radiation to glove boxes, protected fume hoods, or hot boxes. The small amount of liquid waste produced from this equipment should be stored in shielded containers below the equipment and removed periodically. If the storage of larger quantities of low-level radwaste is required, the waste is piped to a holding tank. A common holding time is ten half-lives of the effluent. Usually, radwaste is stored for disposal on the site, outside of the building and where easy transfer of the liquid is possible. The removal must be done by licensed waste-disposal contractors who transfer the waste from the holding tank into a special truck, which transports the liquid waste to a designated site suitable for disposal. Solid wastes such as gloves and wipes are stored in special containers, which are removed to the disposal area with the liquid radwaste.

Floor drains are normally not desired in laboratories using radioactive isotopes. If radioactive material spills, it is wiped up by hand using absorbent material, and the solid containing the spill is put in a special radwaste holding container within the lab. If a floor drain is installed, it should be constructed of stainless steel. For testing purposes and to close off a drain when it is not being used, each drain should be supplied with a closure plug. If a spill is possible, the floor must be pitched to the floor drain. A generally accepted value for the pitch of the floor is 1 inch per 20 feet (2.54 centimeters per 6.10 meters). The thickness of the slab must be closely coordinated because the slab is thinnest at the drain and made thicker at the ends of the area served to make up the pitch. It is not practical to cast the slab evenly and add a topping, because if the topping is chipped, a radioactive spill may get under the top coating. Since the slab depth is greater the longer the run to the drain, it is necessary to indicate the top of the drain elevation at each drain. This also makes it easier for the shop fabricator to make up accurate pipe spools.

Drains also require special treatment. They should be manufactured of stainless steel. Since different types of drains may be installed at different elevations and the piping may be made in spools (preassembled sections of piping), it is a good idea to number all of the individual drains on the design drawings. A box next to each drain can be used to provide information regarding type, number, and elevation.

Since fittings are a natural crud trap, running piping in, under, over, or adjacent to unrestricted areas in a facility should be avoided. If this is not possible, the line should be placed where additional shielding can be added, either at the time of construction or after the start of actual use, when the radiological safety officer may determine by survey where additional shielding is necessary. Much of the time, the ability to take the joint apart and flush out any crud is an advantage. Any of the popular joints for no-hub or grooved pipe are acceptable, as well as those for glass pipe if that is used in a laboratory for chemical resistance.

Cleanouts should be provided generously. They may be needed to flush out the line to reduce spots of high radiation rather than rodding out the entire line.

INFECTIOUS AND BIOLOGICAL WASTE DRAINAGE SYSTEMS

Biological waste has the same basic characteristics as other types of laboratory and production facility waste, but with the addition of biohazardous material, which is material suspended in the waste stream with live organisms that, if not contained, have the potential to cause infection, sickness, and very serious diseases. This waste may be discharged by gravity and under pressure from many sources, including:

- Fermentation tanks and equipment
- Process centrifuges
- Sinks, both handwashing and process
- Containment area floor drains
- Janitor closet drains
- Necropsy table drains
- Autoclave drains
- Contaminated condensate drains

Containment is the method used to isolate and confine biohazardous material. The facility equipment and design shall conform to acceptable and appropriate containment practices based on the hazard potential. A containment category is used to describe an assembly of both primary and secondary preventive measures that provide personnel, environmental, and experimental protection. Primary barriers are specific pieces of equipment such as the biological safety cabinet (which is the biologist's equivalent of the chemist's fume hood) and glove boxes. Secondary containment refers to features of the facility design surrounding and supporting the primary containment. These features are described and classified in Biosafety in Microbiological and Biomedical Laboratories (BMBL) developed by the U.S. Department of

Health and Human Services Public Health Services, Centers for Disease Control and Prevention (CDC), and the National Institutes of Health (NIH).

The classifications for biological containment in laboratories consist of four biosafety levels, BSL-1 through BSL-4. There are also corresponding BSL classifications for vivarium facilities depending on the agent and animal species used for research. The BMBL describes the work practices, equipment, and BSL selection criteria based on the activity of a particular laboratory. If the laboratory or production facility produces or uses greater than 2.6 gallons (10 liters) involving viable organisms, the facility may become large scale (LS). This is noted as BSL2 LS.

Manufacturing standards shall conform to good large-scale production (GLSP) standards. The same standards apply to both small and large-scale facilities.

Facility type of work is outlined later in this chapter in a very abbreviated and simplified form.

Codes and Standards

Mandated guidelines and regulations include the following:

- OSHA blood-borne pathogen regulations
- National Institutes of Health guidelines for the use of recombinant microorganisms
- FDA current good manufacturing practice regulations
- Centers for Disease Control and Prevention and National Institutes of Health guidelines for biosafety in microbiological and biomedical laboratories

Biological Safety Levels

The laboratory containment levels described in the BMBL are summarized as follows.

Biosafety Level 1

BSL-1 is the typical biological research facility classification for work with low-hazard agents. Viable microorganisms not known to cause disease in healthy adults are used at this level. Work is done on an open bench, and any hazard present can be controlled by using standard laboratory practice. Standard features consist of easily cleaned, impervious bench surfaces and handwash sinks, and the work area is separated from general offices, animal rooms, and production areas.

Contaminated liquid and solid waste shall be treated to remove biological hazards before disposal. Wastes containing DNA material or potentially infectious microorganisms shall be decontaminated before disposal. Facilities to wash hands are required in each laboratory.

Biosafety Level 2

Facility construction for BSL-2 is similar to that for BSL-1, except the microorganisms may pose some risk, and safety cabinets are often present. Equipment and work surfaces shall be wiped down with a suitable disinfectant. Sinks shall be scrubbed daily with a chlorine-containing abrasive and flushed with a suitable disinfectant. All liquid waste shall be immediately decontaminated by mixing it with a suitable disinfectant.

Nearly all laboratories operate under BSL-1 or BSL-2. At these levels, the facility is engaged in research, diagnostic, or production activities thought to pose little or minimal risk to workers.

Biosafety Level 3

BSL-3 activity involves organisms posing a significant risk or representing a potentially serious threat to health and safety. Biosafety cabinets are required, and all penetrations to the exterior the facility must be sealed to prevent leakage. These seals must be capable of being cleaned. Liquid waste is kept within the laboratory or facility and steam sterilized prior to discharge or disposal. Vacuum inlets must be protected by appropriate filters and/or disinfectant traps. Laboratory animals require special housing, or if conventional housing is used, personnel must be appropriately protected with full suits and respirators. A handwashing sink routed to sterilization shall be located adjacent to the facility exit. Vents from plumbing fixtures must be filtered.

Biosafety Level 4

BSL-4 is a rarely used classification because activities in this type of facility require a very high level of containment. The organisms present have life-threatening potential and may initiate a serious epidemic disease. All of the BSL-3 requirements apply. In addition, showers shall be provided for personnel at the airlock where clothes are changed upon entry or exit.

A biowaste treatment system shall be provided within the facility to sterilize liquid waste.

Effluent Decontamination System

A liquid-waste decontamination system collects and sterilizes (decontaminates) liquid waste. Effluent containing potentially hazardous bio-matter is collected in a dedicated drainage system, generally discharging by gravity into a collection tank below the floor level within the facility. From the collection tank, effluent is drained or pumped into a kill tank where the actual sterilization occurs. A kill tank is a vessel into which steam or chemical disinfectant is injected to kill any organism. The kill tank system shall be qualified to the same biosafety level as the facility from which it receives discharge. The kill tank system must be a batch process since time is needed to complete the sterilization and decontamination, based on the agent and sterilization process used.

System Components

The collection tank into which the effluent drains shall have a gasketed, waterproof manway for inspection and maintenance. The tank shall be capable of being chemically or steam sterilized. The sizing of the collection tank is done in conjunction with the sizing of the kill tank cycles and the estimated amount of biowaste being generated by the facility. The collection tank must be able to receive the projected waste being generated when the kill tank is in the decontamination cycle. If a pump is required to transfer biowaste from the collection tank to the kill tanks, it should be sized so it stays on for a minimum of one minute to avoid short-cycling and to protect the equipment.

The kill tank assembly commonly consists of a duplex tank arrangement, allowing one batch to be decontaminated while the other tank is filling. The size of the tanks varies based on the individual facility, but common practice is for each tank to be capable of containing one day's effluent plus the chemicals used for decontamination. The tanks must be large enough to hold a catastrophic spill and any potential sprinkler discharge that may result in the area. An agitator mixes the effluent with the deactivation chemicals.

In addition to the kill tanks, tanks containing disinfectant chemicals to be injected are required. A fully automatic control system must be provided to ensure the timely addition of the required chemicals in the correct amounts and for the required duration for deactivation of the bio-matter. Alarms and status shall be displayed in an appropriate panel located in a facility control room or other area.

The drainage system must be closed, which requires sealed floor drains and valved connections to equipment when not in use. Since the HVAC system maintains a negative pressure, the traps on all floor drains must have a seal 2½ inches (65 millimeters) deeper than the negative difference in air pressure. Floor drain traps shall be filled with a disinfectant solution when not used to eliminate the possibility of spreading organisms between different areas served by the same connected sections of the piping system.

The drainage piping material is based on the expected chemical composition of the effluent and the sterilization method. If the local authority considers the biowaste to be hazardous, a double-contained piping system with leak detection may be required. Stainless steel or PTFE pipe usually is chosen where high-temperature effluent may be discharged or steam sterilization may be required. PVC, CPVC, polypropylene, or lined FRP pipe can be used where effluent temperatures are low and also where chemicals will provide the method of sterilization.

If waste from pressurized equipment is discharged into a gravity system, the system must be adequately sized to carry away the waste at the proposed flow rate with pipe flowing one-half full, and adequate vents must be provided to equalize the internal pressure and ensure that the pipe is always at atmospheric pressure.

Valves shall be diaphragm type and capable of being sterilized using the same method as for the pipe. After appropriate decontamination, the kill tank effluent shall be discharged to drain. This effluent must be treated prior to discharge into a public sewer system for disposal.

Vents from pipe, fixtures, sealed sump pits, and kill tanks must be filter-sterilized prior to leaving the system using a HEPA or a 0.2-micrometer filter.

In the event of an accident, OSHA has rules to aid personnel responding to emergencies involving any hazardous material.

System Design Considerations

The treated discharge from any containment treatment shall be separately routed to the sanitary system outside the building to allow for monitoring and sampling.

CHEMICAL WASTE SYSTEMS

Industrial waste drainage systems can contain a wide variety of waterborne wastes, such as chemicals, solvents, suspended solids, and flammable liquids, as well as wastewater, many of which are considered hazardous. The purpose of the industrial waste drainage system is to collect and transport these wastes from inside a facility to a point on site where disposal or treatment can be accomplished.

Codes and Standards

A great body of regulations affects the design of any industrial drainage system. Among them are the federal Clean Water Act (CWA) and Resource Conservation and Recovery Act (RCRA), which are administered by the federal EPA as well as state and other local agencies. Local authorities also are empowered to create regulations that are stricter than federal regulations.

Where production and manufacturing facilities discharge waste, it is a general practice to engage the services of professionals experienced in wastewater treatment and environmental issues to ensure compliance with all of the latest applicable regulations. The major regulatory factor is whether or not any particular waste stream is hazardous. If so, protective measures, such as double-contained piping systems and leak detection, may be required.

Pipe Material and Joint Selection

Because of the vast diversity of manufacturing processes, it is impossible to make any general characterization of industrial wastewater. It is common for

various areas within a plant or industrial complex to be discharging different types of effluent with greatly varying characteristics.

The largest quantity of effluent in an industrial facility originates from drains. Drains receive discharge from production equipment, floor wash down, process and production machines, and other equipment such as compressors and boilers. The floor drain and the discharge pipe from the drain must be capable of resisting chemicals discharged from the production equipment. Selection of the most appropriate piping material can be accomplished only if the nature of the effluent, both present and future, is known.

An often-used material is vitrified clay sewer pipe because of its resistance to most chemicals. Manholes are lined, as shown in Figure 12-1.

System Design Considerations

The design of the drainage system depends on the location, composition, and quantity of discharged effluent from all sources. The layout and engineering of a piping network requires ingenuity and attention to detail.

Selection of the type and location of floor drains is a major aspect of drainage system design. Following are general guidelines for locating and selecting the drains:

- Wet floors are to be avoided. Drains should be located next to equipment and be large enough to allow multiple discharges to spill easily over them without requiring a run of pipe over the floor or the spill to run to the drain. If large flow rates are expected, a large drain should be selected.
- The use of long trench drains in areas where a number of pieces of equipment are placed creates easy access to the various drains from the equipment. This arrangement is usually less costly than multiple drains.
- In many cases, the discharge from equipment may be under pressure because of the head of water in the piece of equipment, such as occurs when a tank is emptied. The drain should be large enough in physical size to accept the largest expected flow. The size of the discharge pipe must be large enough to accept the maximum quantity flowing full by gravity without overflowing. An air gap shall be provided to prevent pressurizing the gravity drainage system.
- To accept the largest number of multiple, small-size drainage lines from equipment, a funnel type of drain should be provided. The top of the funnel should be as close to the floor as reasonable so an air gap can be provided between the top of the floor drain and the end of the equipment drain. This air gap shall be twice the diameter of the drainage line.
- Adequate cleanouts must be provided in drainlines. In lines that are at the ceiling of high floors, the cleanouts should be extended to the floor above to avoid the need for maintenance personnel to climb ladders to clean stoppages.
- The minimum size drainline under the slab or underground should be 2 inches (50 millimeters). Floor drains should be a minimum size of 4 inches (100 millimeters).
- Adequate venting of the drainage line must be provided to allow smooth flow. The vents shall be connected to the top of the drainline to either allow air at the top of the pipe to be vented out (when there is a slug of liquid) or admit air required by the flow of water or due to a partial vacuum created by the liquid flowing full. Vents shall be a minimum size of 2 inches (50 millimeters). If the room is pressurized to avoid contamination, the trap depth should be 2 inches (50 millimeters) longer than the amount of pressurization.
- Local regulations may require the use of double-contained piping to prevent potential leakage from discharging into the environment. A leak-detection system that annunciates leakage should be provided.

FIRE SUPPRESSION WATER DRAINAGE

For industrial facilities, the water used to suppress a fire could become contaminated with the products and raw materials with which it comes in contact. It is required for any water, such as sprinkler and firehose discharge, that could be contaminated in this manner to be routed to holding basins for analysis and possible treatment before being discharged into the environment. If no material is capable of causing contamination, no special consideration is necessary except to protect other areas of the facility from possible flooding.

System Description

The drainage system consists of the drains, located in such a manner to intercept the flow of fire water; drainage piping; a holding basin on site to contain and treat the total volume of water; and the necessary treatment system that will neutralize the water prior to its discharge into the environment.

The amount of water discharged from the fire suppression system is far greater than the amount of wastewater discharged from the facility under normal operating conditions. Overflow floor drains large enough to take the design flow rate shall be installed at points that will intercept the water before it flows

out of doorways or drive bays and route it to holding basins. The placement of these overflow drains shall be selected to intercept all of the water discharged and prevent it from damaging other parts of the facility or escaping from the property or into the ground.

The drainage piping is sized based on flow rate and pitch from the facility to the detention basin. The effluent is essentially clear water with a few solids, with possible contamination of the wastewater from whatever is stored in the area where the fire was present. The flow rate of water required to be disposed of is determined by first calculating the sprinkler water density over the area used for hydraulic calculations and then adding to this the flow rate from the number of fire standpipe hose streams possible. Velocity in the drainage pipe is not a major consideration because the system will be rarely used. A shallow pitch results in a low velocity, potentially causing the deposit of some material that could be flushed out after the event of a fire. A high velocity will not affect the life of the piping system because of the short amount of time the system will be in operation. Pipe size is selected based on the actual pitch of the pipe and the capacity flowing full. Refer to Table 12-1.

Venting of the system is required to allow the free flow of effluent. Each individual drain need not be vented, but each branch should have a loop vent of at least 2 inches (50 millimeters) in size. The vent could be connected to the sanitary vent system or carried through the roof independently.

The pipe material selected shall be compatible with the possible chemicals it may carry.

FLAMMABLE AND VOLATILE LIQUIDS

Federal, state, and local regulations have established standards for the discharge of volatile liquids, particularly oil, into storm water and sanitary sewers. These standards vary, and the responsible enforcement and code authorities must be consulted to determine the level of treatment required.

The most common flammable liquid is oil. The common characteristic of all volatile liquids is they are lighter than water. Their removal from water, therefore, is similar to the removal of oil outlined below.

OIL IN WATER

Oil is considered immiscible, which means it will not be dissolved in water. Since it cannot be dissolved, oil in water exists in several forms:

- Free oil
- Mechanically dispersed oil, which is fine droplets that are stable due to electrical charges and other forces but not due to the presence of surface active agents
- Chemically stabilized emulsions, which are fine droplets that are stable due to surface active agents
- Dissolved and dispersed oil, which is suspended in such a small size (typically 5 micrometers or smaller) that ordinary filtration is not possible
- Oil/wet solids, which are oils that adhere to the surfaces of solids such as particulates or sediment

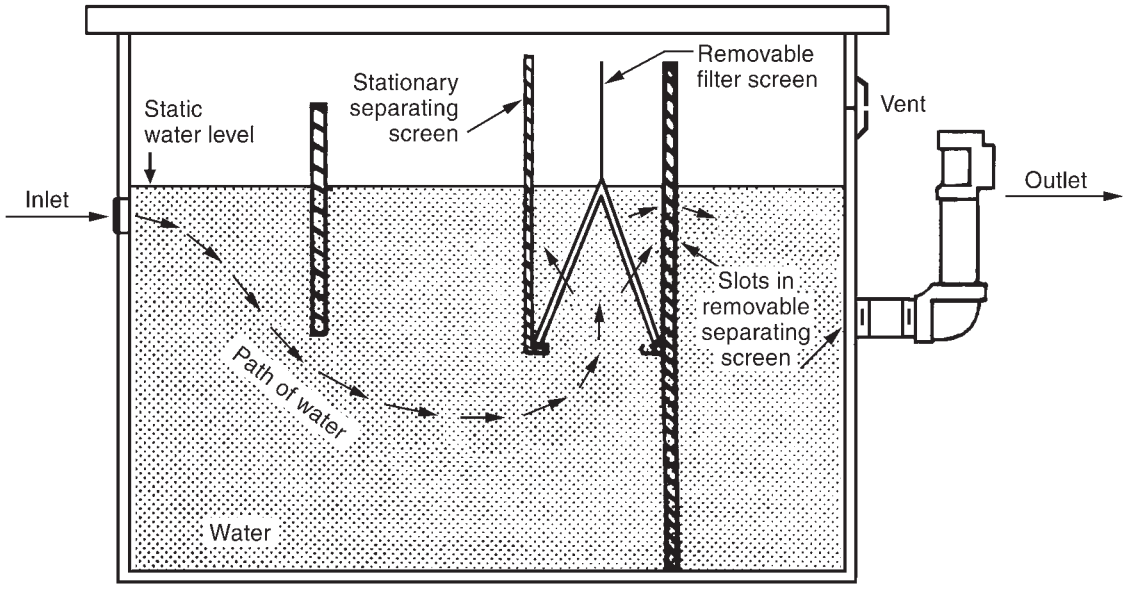


Figure 12-4 Typical Oil Interceptor

Source: Courtesy of Rockford Co.

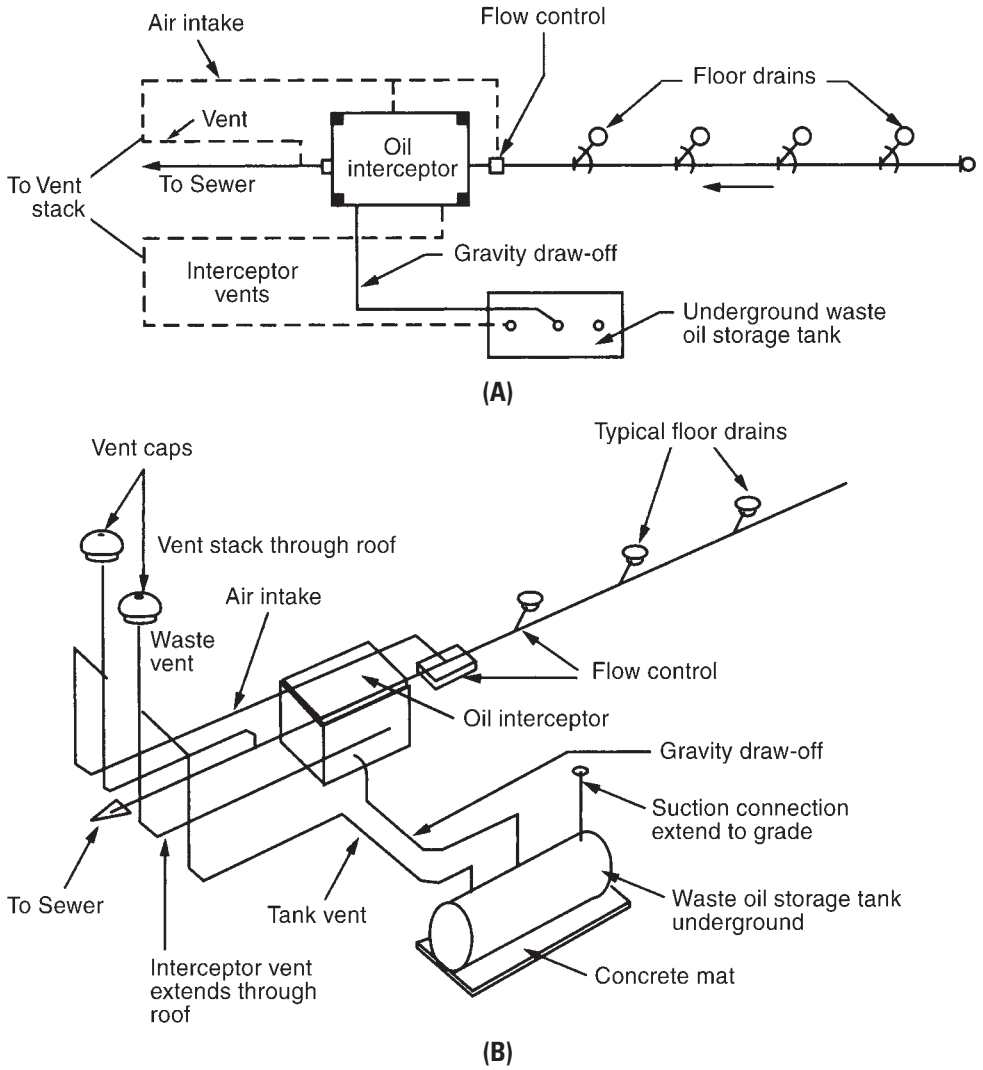


Figure 12-5 Typical Gravity Drawoff Installation: (A) Plan and (B) Isometric

Source: Frankel 1996

Methods of Separation and Treatment

Oil spills and leaks are best treated in their most concentrated state, which is at their source or as close to their source as reasonable. The primary methods used to separate and remove free oil and oil/wet solids are flotation and centrifugation. Secondary treatment, such as chemical treatment/coalescence and filtration, then is used to break up oil/water emulsions and remove dispersed oil. Finally, tertiary treatment, such as ultrafiltration, biological treatment, and carbon adsorption, removes the oil to required levels prior to discharge. This chapter discusses only the general principles of the primary and secondary separation methods and devices.

The American Petroleum Institute (API) has established criteria for the large-scale removal of globules larger than 150 micrometers. In abbreviated form, they are as follows.

- The horizontal velocity through the separator may be up to 15 times the rise velocity of the slowest-rising globule, up to a maximum of 3 fps (0.91 meters per second).
- The depth of flow in the separator shall be within 3 to 8 feet (0.9 to 2.4 meters).
- The width of the separator shall be between 6 and 20 feet (1.8 to 6.1 meters).
- The depth-to-width ratio shall be between 0.3 and 0.5.
- An oil-retention baffle should be located no less than 12 inches (305 millimeters) downstream from a skimming device.

Gravity Separators

Gravity separation is the primary and most often-used separation method. It is based on the specific gravity difference between immiscible oil globules and water. Since all volatile liquids are lighter than

an equal volume of water, gravity separators operate on the principle of flotation. As the water and oil flow through the unit, the oil floats to the top and is trapped inside by a series of internal baffles. Since the oil remains liquid, it is easily drawn off.

Flotation Devices

For larger-scale service, the flotation of oil and oil-wet solids to the top of the flotation chamber can be increased by the attachment of small bubbles of air to the surface of the slow-rising oil globules. This is done by adding compressed air to the bottom of the flotation chamber in a special manner creating small bubbles that mix with and attach to the oil globules.

Centrifugal Separators

For larger-scale service, the centrifugal separator is used. This device induces the combined oil and water mixture to flow around a circular separation chamber. The lighter oil globules collect around the central vortex, which contains the oil-removal mechanism, and the clear water collects at the outer radial portion of the separation chamber. Methods have evolved that produce effluent water with only 50 to 70 parts per million of oil, and proprietary devices exist that lower oil content to 10 parts per million.

Filtration

Chemical methods used to break oil/water emulsions followed by depth-type filters to remove the destabilized mixture have proven effective in the removal of oil globules between 1 and 50 micrometers. The velocity and flow rate of the mixture must be carefully controlled to allow optimum effectiveness of the system.

Oil Interceptors

Oil separators for small flows usually take the form of a single unit consisting of a drain grating into which the effluent flows, is trapped and separated by gravity, and then is diverted to an accumulator chamber to be drawn off manually or automatically. Another type of unit uses an overflow arrangement that sends the trapped oil to a remote oil-storage tank.

Because the vapor given off by the flammable liquid could ignite, it is important to provide a separator vent that terminates in the open air at an approved location above the highest part of the structure. Some codes require a flame arrestor to be installed on the vent.

Most commonly used for an oil interceptor is a coated steel vessel. Gratings, if used, must have the strength to withstand the type of vehicle expected to pass over the interceptor. A collection basket may be specified where debris, such as metal chips, can be intercepted before entering the interceptor.

Refer to Figure 12-4 for an illustration of a typical small oil interceptor. Figure 12-5 illustrates the installation of a typical oil interceptor with gravity oil drawoff for multiple-floor drain inlets.

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