

P · A · R · T · C

PIPING SYSTEMS

CHAPTER C1

WATER SYSTEMS PIPING

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INTRODUCTION

General Description

Water-distribution systems that serve populated areas and industrial complexes, including offices and light and heavy industry, are classified broadly as being of the loop, gridiron, or tree types. Figure C1.1 describes these three types. Within the broad concept, there may be a combining of all three types used as the building blocks for the overall system.

In the *loop system*, large feeder mains that surround areas many city blocks square serve smaller cross-feed lines connected at each end into the main loop. See Fig. C1.1a.

In the *gridiron (or grid) system*, the piping is laid out in checkerboard fashion, with piping usually decreasing in size as the distance increases from the source of supply. See Fig. C1.1b.

In the *tree system*, there is a single trunk main, reducing in size with increasing distance from its source of supply; branch lines are supplied from the trunk. See Fig. C1.1c.

The grid and loop systems provide better reliability because of their multiple paths. Grid and loop systems are often backed up with feeder pipes leading directly from the pumping station to remote distribution centers serving to bolster the supply to meet increased demands with growth of population.

Water distribution systems are made up of pipes, valves, and pumps through which water is moved from the source to homes, offices, and industries that consume the water. The distribution system may include facilities to store treated and un-

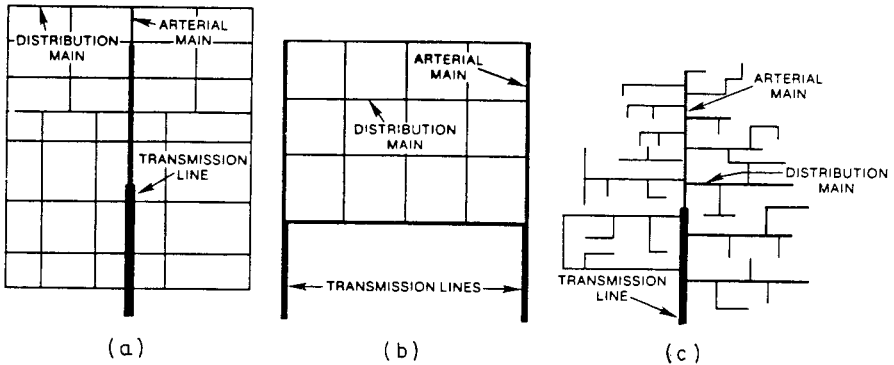


FIGURE C1.1 (a) Loop system, (b) grid system, (c) tree system.

treated water for use during periods when demand is greater than the source can supply and when special service requirements must be satisfied.

The distribution systems are subject to the requirements of local ordinances and state laws and health regulations. Two important requirements of any water distribution system are that it supply each user with a sufficient volume of water at adequate pressure; and for treated water systems, that the quality of the water be maintained by the treatment facility and distribution system.

Types of Water Piping Systems

There are four general types of piping systems in water distribution utilities: transmission lines, in-plant piping systems, distribution mains, and service lines. *Transmission lines* carry water from a source of supply to the distribution system. *Distribution mains* are the pipelines that carry water from transmission lines and distribute it throughout a service area, e.g., a community or industrial complex. *Service lines* are small diameter pipes that run from the distribution mains to the user.

The prime objective of a distribution network is to supply a sufficient quantity of water to all parts of the system, at pressures adequate for the requirements of the users at all times and under all conditions of their demands, including sufficient flow and pressure for fire-fighting purposes. Therefore, the selection of pipe sizes, material, geometry, and configuration in distribution networks is influenced more by the necessity of maintaining adequate water pressure than by the economics of pumping costs.

The common industrial or power applications of water systems are condenser-circulating water and service cooling-water systems. A condenser uses circulating water to condense steam exhausted from the plant's turbines. In a large steam-power plant this requires a considerable amount of water to be continuously circulated. Consequently, since the circulating water directly affects the plant's efficiency and reliability, an efficient, reliable, and economical circulating water system is required.

Service water systems provide cooling water to a plant's components, heat exchangers, and other services required by the plant. Due to current environmental regulations, recirculation-type systems in which the same water is used repeatedly must be applied in most cases. Means of cooling the water is provided in the form

of cooling towers, spray ponds, or cooling ponds. Initial fill and makeup water, to compensate for evaporation, leakage, and blowdown, has to be provided from a river, lake, sea, or other large natural body of water. Some service water systems and, in nuclear plants, emergency service water systems may be once-through-type systems.

A siphon system is one in which the siphon principle is employed to carry the water through elevated parts of the system, such as the condenser, in order to reduce the pumping power required. These elevated portions of the water system operate under a partial vacuum. A pressure system is one in which the water flows under a positive head throughout. This system is generally used with recirculating systems, such as with cooling tower installations.

Vertical pumps set in an intake basin are usually the most suitable for circulating water and service water applications. The complexity of the intake structure is naturally affected by the number of pumps necessary for the system. Reliability points to the use of at least two pumps. The design criteria for the plant will dictate the final choice, whether it will be two pumps at two-thirds capacity each, or one-half capacity each, or some other number of pumps and load distribution. The capacity selection is the subject of a careful analysis, taking into account site space and hydraulic conditions, water requirement, variation of pumping head, the best efficiency range of the pumps, and the costs of various layouts and options.

The intake chambers for vertical pumps require careful design for good pump operation. The design must bring about a uniform and undistributed flow of water to the pump without whirl. Most pump manufacturers and Hydraulic Institute have design suggestions for intake chambers for their particular pumps. There are no standard solutions to vertical-pump intake problems, so each vertical-pump installation should be studied individually.

Booster pumps may be required to ensure pressure to most distant higher elevation points without overpressurizing the lowest components. Horizontal pumps are generally suited for this application.

The intake piping to the suction of horizontal pumps should be designed so as to avoid air pockets. Also, the water-flow velocity should be made uniform over the suction inlet area by placing bends as far as possible from the pump inlet.

Discharge Structure. On the discharge end of once-through cooling water systems, an underwater (or sealed) discharge must be provided to prevent entry of air into the piping, which would otherwise break the siphon action at the condenser. For complex systems an extensive load analysis is performed to establish a seal elevation that is adequate for all operating conditions. Refer to the section on hydraulic grade lines. One means of providing this seal is through the use of a seal well, that is, a basin with a water level controlled by an overflow weir. The seal-well water level regulates the height of the siphon recovery, and it is the final elevation to which the system circulating pump delivers the water.

Beyond the seal well, the discharge into the river or other body of water must be done in such a way that the discharge velocity is dissipated without washing away banks, tearing up the bottom, undermining the discharge piping, or permitting uncontrolled recirculation to the intake.

These systems require attention to problems such as air binding and water hammer, as discussed in this chapter.

A concern about maintaining reliability in plants utilizing raw water for cooling is the accumulation of microbiological growth and sediment accumulation (silting). A critical concern in nuclear plants is keeping piping and components free of clogging or bacterial attack. Strong prevention and maintenance programs are the norms for important systems.

The design of high-temperature, high-pressure piping such as boiler feedwater (FW) systems require considerable experience and study. Refer to Chap. B2. Besides those typical hydraulic problems inherent in lower pressure, lower temperature systems, concern for flashing cavitation and the problems associated with handling two-phase flow and large-system transients are encountered. Refer to Chap. B8 and App. E9.

Velocities ranging from 10 to 25 ft/sec (3 to 7.6 m/sec) in high-pressure and high-temperature water systems are normal, as the fluid is usually high-quality, low-solids water. Piping material can range from carbon steel, such as ASTM A106 on the low-temperature end, to carbon, molybdenum and chrome, and molybdenum alloy steels such as ASTM A335 after the high-pressure heater temperature above 750°F (399°C). FW piping is usually seamless and employs welded joints. Flanged connections, where required, must use a temperature-resistant gasket. Refer to Chap. A7.

Network Analysis of Distribution Systems

The complexity of the analysis required for a well-designed water-distribution system is comparable to that of utility electric power networks. There are several procedures that may be used for the analysis of flow in complex piping networks, such as the Hardy-Cross method. All such methods involve the solution of a flow problem considering head losses of a complex distribution network resulting in extremely tedious and time-consuming trial and error calculations. With the development of state-of-the-art computer hardware and software, complex network problems involving hundreds of branches can be solved in a relatively short time. Illustrative Example C1.1 presents a sample problem using the Hardy-Cross method of flow-network solution.

Illustrative Example C1.1

1. Make a skeleton drawing of the network. Indicate by appropriate arrows the points of constant flow input or output, constant head input or output (see Fig. C1.2).
2. Number all loops in the system in arbitrary sequence. Do not include "loops around loops." For example, in Fig. C1.3 there are two loops, not three. The large loop (*abcdefg*) is not numbered. The two basic loops (*abfg* and *bcdef*) are numbered.
3. Number each line. A line has two ends. An end may be a point at which water is drawn from or added to the system, one at which pipe characteristics

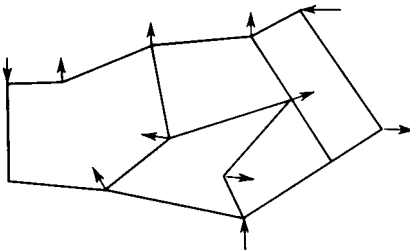


FIGURE C1.2

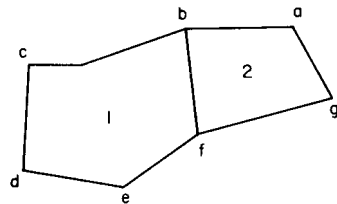


FIGURE C1.3

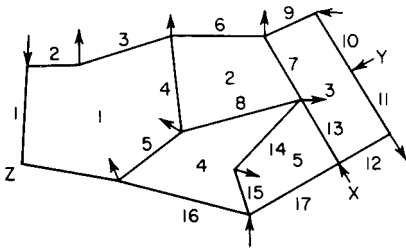


FIGURE C1.4

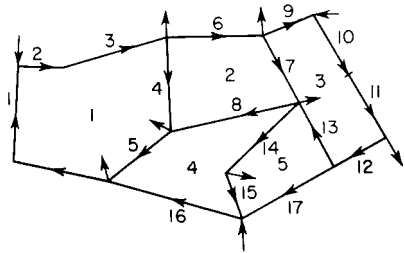


FIGURE C1.5

change, or a tee joint. For example, in Fig. C1.4, the point x is the meeting of three lines, not two; point y is the meeting of two lines where an NPS 8 (DN 200) pipe joins a NPS 10 (DN 250) pipe; point z is simply a bend in the single pipe and is not the end of any line, although it could have been specified as one, if desired. Figure C1.4 shows the complete numbering of the system shown in Fig. C1.2. Note that each line is numbered once and only once, even though it may be in more than one loop. Also note that the numbering is serial; that is, if there are n branches, each of the numbers from 1 to n must be used in the numbering.

4. Assign a base direction. Put an arrow on each line in loop 1, indicating the clockwise direction (as shown in Fig. C1.5). Then put an arrow on each line in loop 2, indicating clockwise direction, except where a line which previously has been assigned a direction is encountered. Then the original assignment is not changed. In Fig. C1.5, line 4 is a member of loop 1 and also of loop 2 but has been given a base direction of loop 1. The line 4 assignment is not changed. This process is continued for every loop in the network, an arrow being assigned in a clockwise direction whenever it has not been assigned previously.

5. In water-distribution systems, the situation often is encountered where system pressure must be raised by the use of booster pumps in series with the supply pipeline. If the higher pressure area is connected to the remainder of the system at one point only, the two pressure-zone networks are hydraulically independent problems. If the pressure zones are connected at two or more points, the booster pumps must be included in the appropriate loops.

For all loops containing booster pumps, an unbalanced or residual head H_0 must be determined. This is done by algebraically summing the assumed constant head changes at the boosters in a clockwise direction.

Note that head *losses* are considered as positive in sign, so proceeding from the suction side of a pump to the discharge side gives a negative head loss.

Following the hydraulic analysis, a check should be made to assure that the pumping head assumptions are sufficiently accurate. The resulting flow-rate values should allow optimum hydraulic design of the booster-station installations.

6. Additional "pseudo-loops" must now be added to the list if there is more than one constant head input (see Fig. C1.6). If the number of such inputs

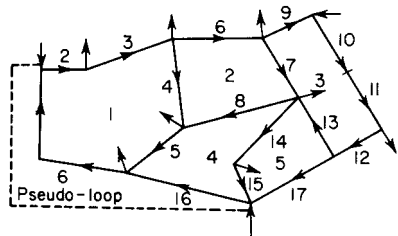


FIGURE C1.6

is m , trace $(m - 1)$ paths between inputs in the same manner in which the loops were traced, making sure that each constant head input is used at the end of at least one of these loops. If the direction of procedure is from the lower to the higher input in each path, H_0 will be the positive difference in the head loss between the two inputs. If booster pumps are encountered, the head change across such pumps must be algebraically added to the head difference between the inputs in order to obtain the H_0 for the pseudo loops.

When the listing of all the loops has been completed (including the consideration of booster pumps), the work should be carefully checked, preferably by a second person, since any errors will completely upset the calculations.

Note that pseudo loops do not introduce any new lines. Note also that each pseudo loop must be assigned its own number.

7. The only remaining task is to supply initial flow values and pipe characteristics which the computer can use as starting values for the calculations. The only restriction on these values is that they satisfy the mass balance condition at each junction. That is, the sum of the flow *into* a junction must equal the sum of the flows *out* of the junction. For example, Fig. C1.7 shows the junction of lines 3, 4, and 6; flows of 50 gpm in line 3 and 100 gpm in line 6 would satisfy the condition.

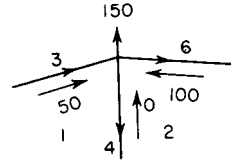


FIGURE C1.7

Proceeding in this manner, balance every junction in the network, working toward the variable-flow (constant-head) inputs which can take up the slack.

When all flows are specified, check the accuracy of the work by summing the inputs and outputs. If these sums are unequal, some computational error has been made and must be corrected. The complete schematic for this system is shown in Fig. C1.8. This schematic includes the assumed starting values of the flows.

Several personal computer (PC)-based and main-frame computer software programs are available that handle steady-state and transient-flow analysis in piping systems. Refer to App. E9 for list of computer programs. Any system configuration, including a variety of components such as storage tanks, pumps, check valves, pressure regulating valves, variable pressure supplies, among others, can be analyzed. These programs can also utilize extended-period simulations of a piping system over a long period of time. These simulations can assess the effect of varying water levels in tanks or reservoirs and can take into account such occurrences as pump operation controlled by water levels or pressure levels. Demand patterns can be varied throughout the simulation to provide a set of solutions for study. These programs can handle any liquid using English and Standard International (SI) units.

In all flow network problems the following conditions must be satisfied:

1. The algebraic sum of the pressure changes around each circuit must be equal to zero.
2. The algebraic flows into and out of each junction must equal zero.
3. The proper relationship between head loss, h , and discharge flow, Q , must be maintained for each pipe.

Parallel and Series Piping. A combination of two or more pipes connected so that the flow is divided among the pipes then joined again, is a *parallel-pipe system*. In *series pipes* the same fluid flows through all the pipes, and the head losses are

Illustrative Example C1.2

$$L_1 = 3000 \text{ ft} \quad D_1 = 1 \text{ ft} \quad \varepsilon_1 = 0.001 \text{ ft}$$

$$L_2 = 2000 \text{ ft} \quad D_2 = 8 \text{ in} \quad \varepsilon_2 = 0.0001 \text{ ft}$$

$$L_3 = 4000 \text{ ft} \quad D_3 = 16 \text{ in} \quad \varepsilon_3 = 0.0008 \text{ ft}$$

$$\rho = 2.00 \text{ slugs/ft}^3 \quad \nu = 0.00003 \text{ ft}^2/\text{s} \quad p_A = 80 \text{ psi} \quad z_A = 100 \text{ ft} \quad z_B = 80 \text{ ft}$$

For a total flow of $12 \text{ ft}^3/\text{s}$, determine flow through each pipe and the pressure at B .

Assume $Q'_1 = 3 \text{ ft}^3/\text{s}$; then $V'_1 = 3.82$, $R'_1 = 3.82 \times 1/0.00003 = 127,000$, $\varepsilon_1/D_1 = 0.001$, $f'_1 = 0.022$, and

$$h'_{f1} = 0.022 \times \frac{3000}{1.0} \frac{(3.82)^2}{64.4} = 14.97 \text{ ft}$$

For pipe 2

$$14.97 = f'_2 \frac{2000}{0.667} \frac{V_2'^2}{2g}$$

Then $\varepsilon_2/D_2 = 0.00015$. Assume $f'_2 = 0.020$; then $V'_2 = 4.01 \text{ ft/s}$, $\mathbf{R}'_2 = 4.01 \times \frac{2}{3} \times 1/0.00003 = 89,000$, $f'_2 = 0.019$, $V'_2 = 4.11 \text{ ft/s}$, $Q'_2 = 1.44 \text{ ft}^3/\text{s}$.

For pipe 3

$$14.97 = f'_3 \frac{4000}{1.333} \frac{V_3'^2}{2g}$$

Then $\varepsilon_3/D_3 = 0.0006$. Assume $f'_3 = 0.020$; then $V'_3 = 4.01 \text{ ft/s}$, $\mathbf{R}'_3 = 4.01 \times 1.333/0.00003 = 178,000$, $f'_3 = 0.020$, $Q'_3 = 5.60 \text{ ft}^3/\text{s}$.

The total discharge for the assumed conditions is

$$\Sigma Q' = 3.00 + 1.44 + 5.60 = 10.04 \text{ ft}^3/\text{s}$$

Hence

$$Q_1 = \frac{3.00}{10.04} \times 12 = 3.58 \text{ ft}^3/\text{s} \quad Q_2 = \frac{1.44}{10.04} \times 12 = 1.72 \text{ ft}^3/\text{s}$$

$$Q_3 = \frac{5.60}{10.04} \times 12 = 6.70 \text{ ft}^3/\text{s}$$

Checking the values of h_1 , h_2 , h_3 ,

$$V_1 = \frac{3.58}{\pi/4} = 4.46 \quad \mathbf{R}_1 = 152,000 \quad f_1 = 0.021 \quad h_{f1} = 20.4 \text{ ft}$$

$$V_2 = \frac{1.72}{\pi/9} = 4.93 \quad \mathbf{R}_2 = 109,200 \quad f_2 = 0.019 \quad h_{f2} = 21.6 \text{ ft}$$

$$V_3 = \frac{6.70}{4\pi/9} = 4.80 \quad \mathbf{R}_3 = 213,000 \quad f_3 = 0.019 \quad h_{f3} = 20.4 \text{ ft}$$

f_2 is about midway between 0.018 and 0.019. If 0.018 had been selected, h_2 would be 20.4 ft.

To find p_B ,

$$\frac{p_A}{\gamma} + z_A = \frac{p_B}{\gamma} + z_B + h_f$$

or

$$\frac{p_B}{\gamma} = \frac{80 \times 144}{62.4} + 100 - 80 - 20.8 = 183.5$$

in which the average head loss was taken. Then

$$p_B = \frac{183.5 \times 2 \times 32.2}{144} = 81.8 \text{ psi}$$

Two types of problems occur (1) with the elevation of the hydraulic grade line at A and B known, to find the discharge Q ; (2) with Q known, to find the distribution of flow and the head loss. Sizes of pipes, fluid properties, and pipe wall roughness are assumed to be known.

The first type is the solution of a traditional pipe discharge problem, as the head loss is the drop in the hydraulic grade line. The individual discharges are then added to determine the total discharge. The second type is more complex, as neither the head loss nor the discharge for any one pipe is known. This type of problem can be solved by

1. Assuming a discharge Q'_1 , through pipe 1
2. Solving for h_f , using the assumed discharge
3. Using h'_{f1} , find Q'_2, Q'_3 ,
4. With the three discharges flowing with a common head loss, now assume that the given Q is split up among the pipe in the same proportion as Q'_1, Q'_2, Q'_3 thus

$$Q_1 = \frac{Q'_1}{Q'} Q \quad (\text{C1.2})$$

$$Q_2 = \frac{Q'_2}{Q'} Q \quad (\text{C1.3})$$

$$Q_3 = \frac{Q'_3}{Q'} Q \quad (\text{C1.4})$$

5. Check the correctness of these discharges by computing h_{f1}, h_{f2}, h_{f3} for the computed Q_1, Q_2 and Q_3 flows.

Some other important relationships to consider in complex flow problems include the following:

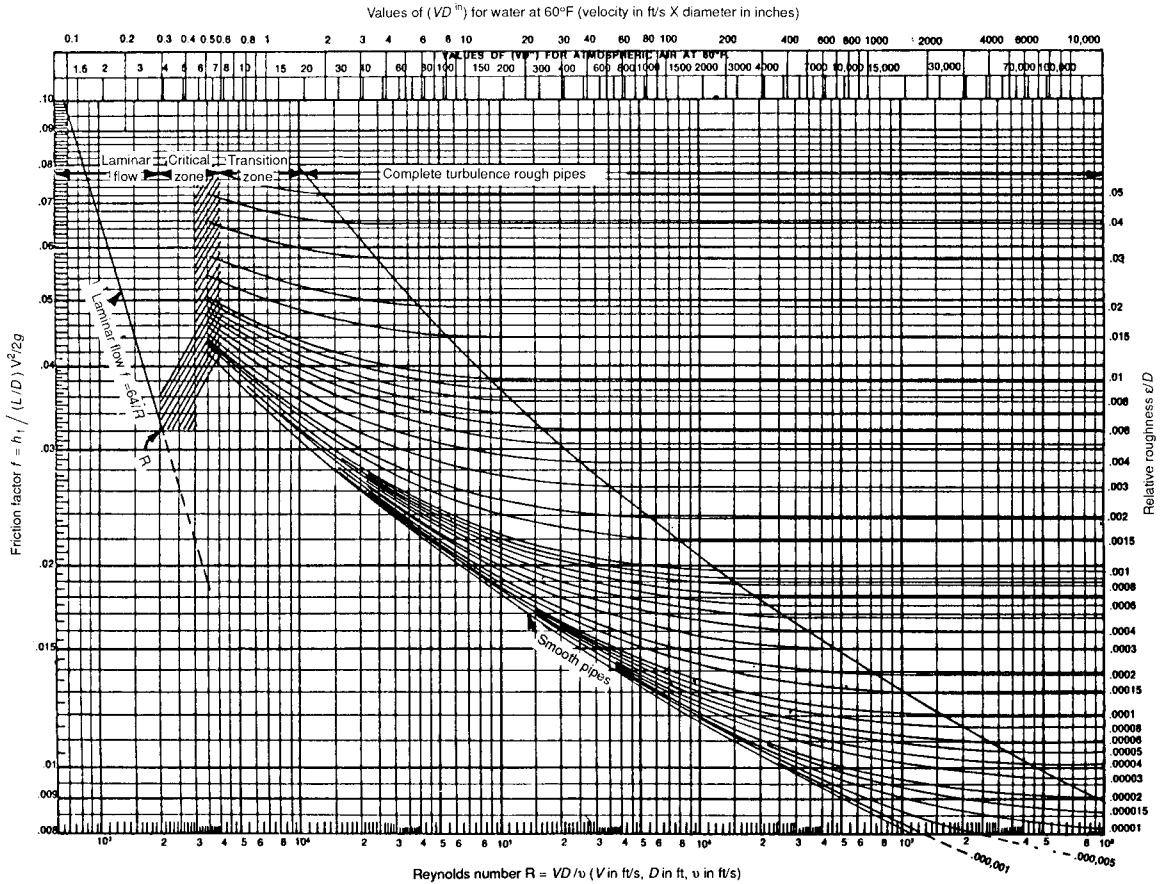


FIGURE C1.10 Moody diagram. Friction factors for any kind and size of pipe. (*Hydraulic Institute.*)

TABLE C1.1 Properties of Water at Various Temperatures from 32 to 720°F

Temp. (°F)	Temp. (°C)	Specific volume (Cu. ft/lb)	Specific gravity			Wt in lb/cu ft	Vapor pressure psi abs
			39.2 F Reference	60 F Reference	68 F Reference		
32	0	.01602	1.000	1.001	1.002	62.42	0.088
35	1.7	.01602	1.000	1.001	1.002	62.42	0.100
40	4.4	.01602	1.000	1.001	1.002	62.42	0.1217
50	10.0	.01603	.999	1.001	1.002	62.38	0.1781
60	15.6	.01604	.999	1.000	1.001	62.34	0.2563
70	21.1	.01606	.998	.999	1.000	62.27	0.3631
80	26.7	.01608	.996	.998	.999	62.19	0.5069
90	32.2	.01610	.995	.996	.997	62.11	0.6982
100	37.8	.01613	.993	.994	.995	62.00	0.9492
120	48.9	.01620	.989	.990	.991	61.73	1.692
140	60.0	.01629	.983	.985	.986	61.39	2.889
160	71.1	.01639	.977	.979	.979	61.01	4.741
180	82.2	.01651	.970	.972	.973	60.57	7.510
200	93.3	.01663	.963	.964	.966	60.13	11.526
212	100.0	.01672	.958	.959	.960	59.81	14.696
220	104.4	.01677	.955	.956	.957	59.63	17.186
240	115.6	.01692	.947	.948	.949	59.10	24.97
260	126.7	.01709	.938	.939	.940	58.51	35.43
280	137.8	.01726	.928	.929	.930	58.00	49.20
300	148.9	.01745	.918	.919	.920	57.31	67.01
320	160.0	.01765	.908	.909	.910	56.66	89.66
340	171.1	.01787	.896	.898	.899	55.96	118.01
360	182.2	.01811	.885	.886	.887	55.22	153.04
380	193.3	.01836	.873	.874	.875	54.47	195.77
400	204.4	.01864	.859	.860	.862	53.65	247.31
420	215.6	.01894	.846	.847	.848	52.80	308.83
440	226.7	.01926	.832	.833	.834	51.92	381.59
460	237.8	.0196	.817	.818	.819	51.02	466.9
480	248.9	.0200	.801	.802	.803	50.00	566.1
500	260.0	.0204	.785	.786	.787	49.02	680.8
520	271.1	.0209	.765	.766	.767	47.85	812.4
540	282.2	.0215	.746	.747	.748	46.51	962.5
560	293.3	.0221	.720	.727	.728	45.8	1133.1
580	304.4	.0228	.703	.704	.704	43.9	1325.8
600	315.6	.0236	.678	.679	.680	42.3	1542.9
620	326.7	.0247	.649	.650	.650	40.5	1786.6
640	337.8	.0260	.617	.618	.618	38.5	2059.7
660	348.9	.0278	.577	.577	.578	36.0	2365.4
680	360.0	.0305	.525	.526	.527	32.8	2708.1
700	371.1	.0369	.434	.435	.435	27.1	3093.7
720	374.1	.0503	.319	.319	.320	19.9	3206.2

Computed from Keenan & Keyes' Steam Table.

In the turbulent region, Reynolds number above 2000 (see Moody diagram, Fig. C1.10, to determine region and establish relationship for head loss), the pressure drop h varies as the 1.85 power of the flow rate Q , that is:

$$\frac{h_1}{h_2} = \left(\frac{Q_1}{Q_2} \right)^{1.85} \tag{C1.5}$$

In the viscous flow region (low flow, Reynolds number below 2000), the pressure drop varies directly as the flow or

$$\frac{h_1}{h_2} = \frac{Q_1}{Q_2} \tag{C1.6}$$

For the same flow, pressure drop varies approximately as the fifth power of the inside diameter D , so that,

$$\frac{h_1}{h_2} = \left(\frac{D^2}{D_1} \right)^5 \tag{C1.7}$$

These relationships have been widely used and have resulted in handy pressure drop tables. Appendix E.4 provides friction-loss data for water and commonly used steel pipe and lined ductile iron pipe (DIP) in some representative sizes. Table C1.1 provides properties of water at various temperatures. Figure C1.10 provides friction factors for any kind and size of pipe, based on pipe relative roughness and Reynolds number.

HYDRAULIC AND ENERGY GRADE LINES

The concepts of hydraulic and energy grade lines are useful in analyzing more complex water flow problems (see Fig. C1.11). If, at each point along a pipe system, the term P/γ is determined and plotted as a vertical distance above the center of

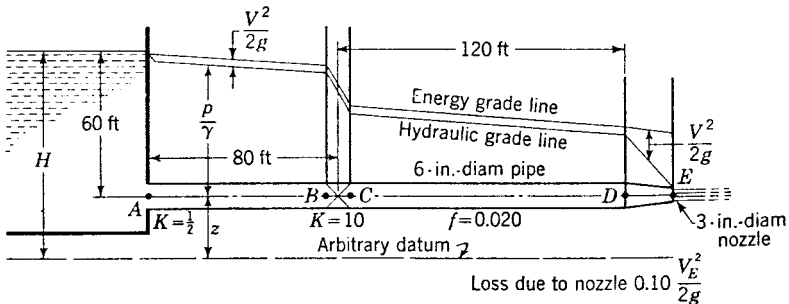


FIGURE C1.11 Hydraulic and energy grade lines.

Series pipes may be solved by the method of equivalent lengths. Two-pipe systems are said to be equivalent when the same head loss produces the same discharge in both systems. This is expressed as

$$\frac{f_1 L_1}{D_1^5} = \frac{f_2 L_2}{D_2^5} \quad (\text{C1.9})$$

Solving for L_2

$$L_2 = L_1 \frac{f_1}{f_2} \left(\frac{D_2}{D_1} \right)^5 \quad (\text{C1.10})$$

which determines the length of a second pipe to be equivalent for use with velocity of the first pipe.

REFERENCE DOCUMENTS

Codes and Standards

Table C1.2 provides a listing of the most commonly used industry codes and standards in water-systems design, fabrication, assembly, and testing.

American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. The ASME code covers design and construction of boilers (Section I) or nuclear power plant components (Section III). Insurance companies and most state and municipal authorities recognize this code and make it a prerequisite for acceptance and installation of such power equipment within their jurisdiction.

The Code involves eleven sections, of which the following are concerned with piping:

Section I Power Boilers

Section II Materials

Section III Nuclear Power Plant Components

Section XI Rules for Inservice Inspection of Nuclear Power Plant Components

ASME Code for Pressure Piping, B31

B31.1 Power Piping

B31.3 Process Piping

B31.9 Building Services Piping

Other Standards

American Petroleum Institute

American Welding Society

American Water Works Association

TABLE C1.2

AWWA designation	ANSI designation	Title
		AWWA standards for ductile-iron pipe and fittings
C-104-95	A21.4	Standard for Cement-Mortar Lining for Ductile-Iron Pipe and Fittings for Water
C-105-93	A21.5	Standard for Polyethylene Encasement for Ductile-Iron Piping for Water and Other Liquids
C-110-93	A21.10	Standard for Ductile-Iron and Gray-Iron Fittings, 3 in. (75 mm) through 48 in. (1200 mm) for Water and Other Liquids
C111-95	A21.11	Standard for Rubber Gasket Joints for Ductile-Iron and Gray-Iron Pressure Pipe and Fittings
C115-94	A21.15	Standard for Flanged Ductile-Iron Pipe with Threaded Flanges
C150-96	A21.50	Standard for Thickness Design of Ductile-Iron Pipe
C151-96	A21.51	Standard for Ductile-Iron Pipe, Centrifugally Cast in Metal Molds or Sand-Lined Molds, for Water or Other Liquids
C153-94	A21.53	Standards for Ductile-Iron Compact Fittings 3 in. through 24 in. (75 mm through 610 mm), and 54 in. through 64 in. (1400 mm through 1600 mm) for water service
		AWWA standards for steel pipe
C200-97	—	Standard for Steel Water Pipe 6 in. (150 mm) and Larger
C203-97	—	Standard for Coal-Tar Protective Coatings and Lining for Steel Water Pipelines Enamel and Tape—Hot Applied
C205-95	—	Standard for Cement-Mortar Protective Lining and Coating for Steel Water Pipe 4 in. and Larger—Shop Applied
C206-97	—	Standard for Field Welding of Steel Water Pipe
C207-94	—	Standard for Steel Pipe Flanges for Waterworks Service Sizes 4 in. through 144 in. (100 mm through 3600 mm)
C208-96	—	Standard for Dimensions for Fabricated Steel Water Pipe Fittings
C209-95	—	Standard for Cold-Applied Tape Coatings for the Exterior of Special Sections, Connections, and Fittings for Steel Water Pipelines
C210-97	—	Standard for Liquid Epoxy Coating Systems for the Interior and Exterior of Steel Water Pipelines
C213-96	—	Standard for Fusion Bonded Epoxy Coating for the Interior and Exterior of Steel Water Pipelines
C214-95	—	Standard for Tape Coating Systems for the Exterior of Steel Water Pipelines
C215-94	—	Standard for Extruded Polyolefin Coatings for the Exterior of Steel Water Pipelines
C216-94	—	Heat-Shrinkable Cross-Linked Polyolefin Coatings for the Exterior of Special Sections, Connections and Fittings for Steel Water Pipelines
C217-95	—	AWWA Standard for Cold-Applied Petrolatum Tape and Petroleum Wax Tape Coatings for the Exterior of Special Sections, Connections, and Fittings for Buried Steel Water Pipelines

TABLE C1.2 (Continued)

AWWA designation	ANSI designation	Title
C218-95	—	AWWA Standard for Coating the Exterior of Aboveground Steel Water Pipelines and Fittings
C219-97	—	AWWA Standard for Bolted, Sleeve-Type Couplings for Plain-End Pipe
C220-92	—	AWWA Standard for Stainless Steel Pipe, 4 in. (100 mm) and Larger
C221-97	—	AWWA Standard for Fabricated Steel Mechanical Slip-Type Expansion Joints
C300-97	—	AWWA standard for concrete pipe
C301-92	—	Standard for Reinforced Concrete Pressure Pipe, Steel Cylinder Type, for Water and Other Liquids
C302-95	—	Standard for Prestressed Concrete Pressure Pipe, Steel Cylinder Type, for Water and Other Liquids
C303-95	—	Standard for Reinforced Concrete Pressure Pipe, Non-cylinder Type
C304-92	—	Standard for Concrete Pressure Pipe, Bar-Wrapped Steel-Cylinder Type
C400-93	—	Standard for Design of Prestressed Concrete Cylinder Pipe Asbestos-Cement Pipe
C401-93	—	AWWA standards for asbestos-cement pipe
C402-95	—	Standard for Asbestos-Cement Distribution Pipe 4 in. through 16 in. (100 mm through 400 mm), for Water Distribution Systems
C403-95	—	Standard for the Selection of Asbestos-Cement Pressure Pipe, 4 in. through 16 in. (100 mm through 400 mm), for Water Distribution Systems
C500-93	—	Standard for Asbestos-Cement Transmission Pipe, 18 in. through 42 in. (450 mm through 1050 mm) for Potable Water and Other Liquids
C501-92	—	Standard for the Selection of Asbestos-Cement Transmission and Feeder Main Pipe, Sizes 18 in. through 42 in. (450 mm through 1050 mm)
C502-94	—	AWWA standards for valves and hydrants
C503-88	—	Standard for Metal-Sealed Gate Valves for Water-Supply Service
C504-94	—	Standard for Cast-Iron Sluice Gates
C507-91	—	Standard for Dry-Barrel Fire Hydrants
C508-93	—	Standard for Wet-Barrel Fire Hydrants
C509-94	—	Standard for Rubber-Seated Butterfly Valves
C510-97	—	Standard for Ball Valves 6 in. through 48 in. (150 mm through 1200 mm)
C511-97	—	Standard for Swing-Check Valves for Waterworks Service, 2 in. (50 mm) through 24 in. (600 mm) NPS
	—	Resilient-Seated Gate Valves for Water Supply Service
	—	AWWA Standard for Double Check Valve Backflow-Prevention Assembly
	—	AWWA Standard for Reduced-Pressure Principle Backflow-Prevention Assembly

TABLE C1.2 (Continued)

AWWA designation	ANSI designation	Title
C512-92	—	AWWA Standard for Air-Release, Air/Vacuum, and Combination Air Valves for Waterworks Service
C513-97	—	AWWA Standard for Open-Channel, Fabricated Metal Slide Gates
C540-93	—	Standard for Power-Actuating Devices for Valves and Sluice Gates
C550-90	—	Standard for Protective Epoxy Interior Coatings for Valves and Hydrants
C600-93	—	AWWA standards for pipe installation Standard for Installation of Ductile-Iron Water Mains and Their Appurtenances
C602-95	—	Standard for Cement-Mortar Lining of Water Pipelines—4 in. (100 mm) and Larger in Place
C603-96	—	Standard for Installation of Asbestos-Cement Pressure Pipe
C605-94	—	AWWA Standard for Underground Installation of Polyvinyl Chloride (PVC) Pressure Pipe Fittings for Water
C606-97	—	Standard for Grooved and Shouldered Joints
C651-92	—	Standard for Disinfecting Water Mains
C652-92	—	Standard for Disinfection of Water Storage Facilities
C653-97	—	Standard for Disinfection for Water Treatment Plants
C654-97	—	Standard for Disinfection of Wells
C700-95	—	AWWA standards for meters Cold Water Meters—Displacement Type, Bronze Main Case
C701-88	—	Cold Water Meters—Turbine Type, for Customer Service
C702-92	—	Cold Water Meters—Compound Type
C703-96	—	Cold Water Meters—Fire-Service Type
C704-92	—	Cold Water Meters—Propeller Type for Waterworks Applications (R 1984)
C706-96	—	Standard for Direct Reading Remote-Registration Systems for Cold Water Meters
C707-82(R 92)	—	Standard for Encoder-Type Remote-Registration Systems for Cold Water Meters
C708-96	—	Standard for Cold Water Meters—Multi-Jet Types
C710-95	—	AWWA Standard for Cold-Water Meters—Displacement Type, Plastic Main Case (Includes addendum C710a-91.) AWWA standard for service lines
C800-89	—	Standard for Underground Service Line Valves and Fittings AWWA standard for plastic pipe
C900-97	—	Standard for Polyvinyl Chloride (PVC) Pressure Pipe, 4 in. through 12 in. (100 mm 300 mm) for Water Distribution
C901-96	—	Standard for Polyethylene (PE) Pressure Pipe and Tubing, ½ in. (13 mm) through 3 in. (76 mm) for Water Service
C905-97	—	Standard for Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 14 in. through 48 in. (350 mm through 1,200 mm), for Water Transmission and Distribution

TABLE C1.2 (Continued)

AWWA designation	ANSI designation	Title
C906-90	—	Standard for Polyethylene (PE) Pressure Pipe and Fittings, 4 in. through 63 in., for Water Distribution
C907-91	—	Standard for Polyvinyl Chloride (PVC) Pressure Fittings for Water—4 in. through 8 in. (100 mm through 200 mm)
C908-97	—	Standard for PVC Self-Tapping Saddle Tees for Use on PVC Pipe
C950-95	—	Standard for Fiberglass Pressure Pipe AWWA standards for storage
D100-96	—	Standard for Welded Steel Tanks for Water Storage
D101-53(R86)	—	Standard for Inspecting and Repairing Steel Water Tanks, Standpipes, Reservoirs and Elevated Tanks for Water Storage (R 1986)
D102-97	—	Standard for Painting Steel Water-Storage Tanks
D103-97	—	Standard for Factory-Coated Bolted Steel Tanks for Water Storage
D104-97	—	Standard for Automatically Controlled, Impressed-Current Cathodic Protection for the Interior of Steel Water Tanks
D110-95	—	Standard for Wire- and Strand-Wound Circular Prestressed-Concrete Water Tanks
D115-95	—	AWWA Standard for Circular Prestressed Concrete Water Tanks with Circumferential Tendons
D120-84(R89)	—	Standard for Thermosetting Fiberglass-Reinforced Plastic Tanks
D130-96	—	Standard for Flexible Membrane-lining and Floating Cover Materials for Potable-Water Storage AWWA standard for vertical turbine pumps
E101-88	—	Standard for Vertical Turbine Pumps—Line Shaft and Submersible Types

Pipe Fabrication Institute

National Fire Protection Association (NFPA)

DESIGN BASIS CONSIDERATIONS

Design Criteria

Design Pressure. In the design of water piping systems the following guidance is provided in determining and specifying system-design pressure requirements.

The design pressure shall be based on the maximum expected operating pressure of a particular system which is determined from the maximum operating pressure

of the connected pump, pressure vessels, relief valve settings, et cetera, depending on the type of system and equipment used. Reasonable margin shall be added to cover variations in expected maximum performance, transients, and control tolerances.

The internal design pressure, including the effect of the static head and allowance for pressure surges, shall not be less than the maximum sustained fluid operating pressure. Consideration shall also be given to pump shut-off pressure.

Piping subject to external pressure shall be designed for the maximum differential pressure anticipated during operating, shutdown, or test conditions, excluding pressure tests. Refer to Chap. B2. For buried piping this includes loading due to earth cover and traffic.

In accordance with ASME B31.1, Paragraph 102.2.4, the piping system shall be considered safe for occasional short operating periods at higher than design pressure or temperature, if the calculated stress value is not exceeded by more than 15 percent during less than 10 percent of any 24-hour operating period or by more than 20 percent during less than 1 percent of any 24-hour operating period.

A piping system is considered safe for operation if the maximum sustained pressure and temperature which may act at any part or component of the system does not exceed the maximum pressure and temperature determined in accordance with Code rules by the Power Piping Code ASME B31.1. Allowable stress values and pressure-temperature ratings are provided by the piping codes and the standards referenced therein.

Design Temperature. In the design of water distribution systems, the following guidance is provided in determining and specifying system-design temperature requirements.

The design temperature shall be determined on the basis of the maximum expected operating temperature. The effects of pumping, throttling, heating, cooling, et cetera, must be considered in the determination of the design temperature of the piping system.

Pipe Sizing Criteria. Typically, total piping system cost is approximately 7 to 8 percent of the total plant investment. These values range upward to 30 percent for municipal water systems and some ships. Selection of pipe sizes, beside affecting initial cost, will also affect operating costs due to their sensitivity to changes in pressure drop, heat losses, and maintenance requirements.

Selection of a pipe-line size involves determination of an optimum size. For instance, if extra pumping is needed to boost the fluid pressure or if the heat rate will be affected adversely, then the cost of the extra energy required becomes a significant factor in the evaluations. The optimum pipe size is obtained when the sum of installed and operating costs is at the minimum.

Piping optimization is not widely used in preliminary calculations. Where the pressure drop is defined by other considerations, the minimum pipe size compatible with good engineering practice will be selected.

Other related considerations which have an important impact on pipe size selection, include:

1. Noise—which can result from high velocity flow, cavitation or two-phase flow.
2. Vibration—which can result from noise, excessive velocities at changes in the direction of the fluid flow, or the causes of cavitation.
3. Erosion or corrosion—due to chemical action of the fluid, excessive velocities, cavitation, and excessive turbulence at fittings, valves, branch connections, etc.

4. Flow distribution—the more uniform the cross-sectional velocity profile, the more likely that the above factors will be reduced. This can be achieved by using reasonable velocities along with a piping layout that will produce a smooth flow pattern.
5. Cavitation—which can result from the collapse of bubbles close to a metallic surface at a high enough velocity to cause erosion, and two-phase flow fluids.

Effects of Velocity. Higher allowable velocities will lead to smaller pipe sizes and higher pressure drops. Excessively high velocities can cause noise, vibration, and erosion. Velocities in pump-suction lines shall be kept sufficiently low in order to maintain the pump's required net positive suction head (NPSH).

The pressure drop in a system can be decreased by selecting a larger pipe size or sometimes by using more than one pipe for the total flow.

For water piping systems a velocity in the range of 4 to 15 ft/sec (1.2 to 4.6 m/sec) is acceptable. Depending upon the material selected, piping design and size is either in the low or high side of this range, considering the economics of system installation and operation. For example, for brass pipe a velocity between 4 to 15 ft/sec (1.2 to 4.6 m/sec) would be recommended, while for steel pipe, a velocity of 7 to 10 ft/sec (2.1 to 3 m/sec) is the recommended range, while velocities to 30 ft/sec (9.1 m/sec) may be acceptable. Higher velocities are acceptable if materials less susceptible to erosion (e.g., stainless steel) are selected. Concurrently reducing vibration and meeting system hydraulic requirements will reduce the piping's susceptibility to erosion. In all cases, it should be recognized that these ranges are recommended only if system operating requirements are also satisfied. High velocities are often conducive to water hammer problems.

Pipe-Wall Thickness Selection. After determining the internal diameter of the pipe, the designer must select materials, consider their strength, and select a pipe-wall thickness or schedule, as a function of temperature, pressure, corrosion, erosion, vibration, and external loads, as required.

Pipe-wall thickness determination begins with the basic hoop stress in the pipe wall. This stress calculation ignores longitudinal wall stress that exists if the pipe has closed ends. An example of this is a flask or short header.

Advanced analysis shows that for thin-wall pipe, the outside diameter should be used in the hoop stress equation:

$$S = \frac{PD_o}{2t_{\min}} \quad (\text{C1.11})$$

where P = internal design pressure, psig (kPa) [gauge]
 D_o = outside diameter of pipe, in (mm)
 t_{\min} = minimum required pipe wall thickness, in (mm)
 S = allowable stress, psi (kPa)

This equation, called the Barlow formula, is the basis for most code stress-pipewall-thickness calculations such as those provided in ASME B31.1 and B31.3. The formula also applies to thick-walled pipe.

The Barlow formula allows determination of wall thickness for flexible pipe required to handle internal pressure. Pipe-wall thickness must also be adequate to handle external loads such as soil cover and vehicle loads, vacuum, and buckling. For flexible pipe such as steel, ductile iron, PVC, and HDPE, determination of thickness for internal pressure and determination of thickness to handle external

loads are calculated separately, and the greater of the two thicknesses is used. For flexible pipe, thickness required to handle deflection from external soil and vehicle loads is calculated using the Modified Iowa formula:

$$\Delta X = (D_L \times K \times W \times r^3) / \{(E \times I) + (.061 \times E' \times r^3)\} \quad (C1.12)$$

where D_L = deflection lag factor

K = bedding constant

W = load per unit length of pipe

r = pipe radius

E = modulus of elasticity of pipe material

I = moment of inertia of pipe

E' = modulus of soil reaction

ΔX = deflection

The minimum thickness is determined based on maximum allowable deflection. Maximum allowable deflection varies for different materials, e.g., steel, ductile iron, PVC, HDPE, et cetera. For steel and ductile iron, the limiting factor in maximum allowable deflection is the nature of lining and coating of the pipe, with concrete lining or coating limiting deflection to less than that for a more flexible lining or coating such as epoxy. For PVC and HDPE, the allowable stress and strain in the pipe wall determines the maximum allowable deflection. In the municipal water works industry, guidance for calculating pipe wall thickness for steel pipe is provided in AWWA Manual M11, in AWWA C900 and C905 and Manual M23 for PVC, in AWWA C906 and manufacturers' literature for HDPE, and in AWWA C150 for ductile iron.

For certain types of rigid-pressure pipe, for example, prestressed concrete-cylinder pipe and cast-iron pipe (no longer used), design is based on combined loading, wherein internal pressure and external load are considered simultaneously—as internal pressure increases, allowable external loading decreases, and vice-versa. Design guidelines for prestressed concrete-cylinder pipe are found in AWWA Manual M9.

In the design of pipe, various configurations of bedding, backfill, and trench preparation can contribute to the pipe's adequacy to handle external load. These factors are addressed in the aforementioned manuals and specifications.

The allowable stress in a pipe wall is not determined solely by the material's strength at the service temperature. In pipe with a longitudinal welded seam, the efficiency of the welded joint must also be considered.

ASME Power Piping Code, Section B31.1, provides efficiency factors of 0.60 for a furnace butt weld, 0.85 for an electric-resistance weld, and 1.00 for single or double butt weld with 100 percent radiography. Allowable stress for welded pipe is determined by multiplying the allowable stress value for seamless pipe at the given temperature by the efficiency factor. Tables of allowable stress in Codes, such as B31.1, include the joint efficiency. The B31.1 Code further specifies the following formula for determining the minimum thickness of pipe wall at design temperatures,

$$t_m = \frac{PD_o}{2(SE + Py)} + A \quad (C1.13)$$

or,

$$t_m = \frac{Pd + 2SEA + 2yPA}{2(SE + Py - P)} \quad (C1.14)$$

and the design pressure shall not exceed

$$P = \frac{2SE(t_m - A)}{D_o - 2y(t_m - A)} \quad (C1.15)$$

$$P = \frac{2SE(t_m - A)}{d - 2y(t_m - A) + 2t_m} \quad (C1.16)$$

where t_m = minimum pipe wall thickness, in (mm)

P = internal design pressure, psig (kPa [gage])

D_o = outside diameter of pipe, in (mm). For design calculations, the outside diameter of pipe, as given in tables of standards and specifications, is used in obtaining the value of t_m . When calculating the allowable working pressure of pipe on hand or in stock, the actual measured outside diameter and actual measured minimum wall thickness at the thinner end of the pipe may be used to calculate this pressure.

d = inside diameter of pipe, in (mm). For design calculations, the inside diameter of pipe is the maximum possible value allowable under the purchase specification. When calculating the allowable working pressure of pipe on hand or in stock, the actual measured inside diameter and actual measured minimum wall thickness at the thinner end of the pipe may be used to calculate this pressure.

SE = allowable stress for the material due to internal pressure and joint efficiency, at the design temperature, psi (kPa)

A = allowance for threading, grooving, mechanical strength, and the effects of erosion and corrosion, in (mm)

y = 0.4 for ferritic steels and austenitic steels for temperatures up to 900°F (480°C). For pipe with a D_o/t_m ratio less than 6, the value of y for ferritic and austenitic steels designed for temperature of 900 F (480°C) and below shall be taken as:

$$y = \frac{d}{d + D_o} \quad (C1.17)$$

If pipe is ordered by its nominal wall thickness, the manufacturing tolerance on wall thickness must be taken into account. After the minimum pipe wall thickness t_m is determined by equation C1.13 or C1.14, this minimum thickness shall be increased by an amount sufficient to provide the manufacturing tolerance allowed in the applicable pipe specification or required by the process. The next heavier commercial wall thickness shall then be selected from thickness schedules such as contained in ASME B36.10M, ASME B36.19, or from manufacturers' schedules for other than standard thickness. Refer to Chap. B2 for details on calculating the pipe-wall thickness. For cast piping components, or to compensate for thinning in bends, refer to the applicable Code.

Where ends are subject to forming or machining for jointing, the wall thickness of the pipe, tube, or component shall not be less than t_m , after such forming and machining.

The thickness of gray and ductile-iron pipe conveying liquids may be determined by selection from AWWA/ANSI C110/A21.10, AWWA/ANSI C115/A21.15, AWWA/ANSI C150/A21.50, AWWA/ANSI C151/A21.51, and Federal Specification WW-P-421.

While the thickness of steel pipe determined from Eq. C1.13 or C1.14 is theoretic-

cally ample for both bursting pressure and material removed in threading, the following minimum requirements are mandatory to provide added mechanical strength:

1. Where steel pipe is threaded and used for water service above 100 psi (700 kPa) with water temperature above 220°F (105°C), the pipe shall be seamless, having the minimum ultimate tensile strength of 48,000 psi (330 MPa) and a weight at least equal to Schedule 80 of ASME B36.10M.
2. Where threaded brass or copper pipe is used for the services described previously, it shall comply with pressure and temperature classifications permitted for these materials by other paragraphs of the applicable Code and shall have a wall thickness at least equal to that specified for steel pipe of corresponding size.
3. Plain-end nonferrous pipe or tube shall have minimum thickness as follows:
 - a. For nominal sizes smaller than NPS $\frac{3}{4}$ (DN20), the thickness shall not be less than that specified for Type K of ASTM B 88 for copper tubing.
 - b. For nominal sizes NPS $\frac{3}{4}$ (DN20) and larger, the wall thickness shall not be less than 0.049 in (1.25 mm). The wall thickness shall be further increased as required by determining the minimum wall.
4. After calculating the required minimum wall thickness, choice is usually made from standard thickness or schedules. Tables of pipe sizes and wall thickness (schedules) are presented in App. E2 and E2M. For tubing, refer to App. E3 and E3M.
5. For piping systems other than steel or cast iron, the reader is referred to the applicable code.

Design Features

Materials. This section discusses the most commonly used materials for water-distribution-system piping and piping components. Pipe description, material-specifications characteristics, available sizes, normal use, and advantages or disadvantages of different materials are briefly noted in Table C1.3. It should also be noted that state and local regulations may govern the preferred types of pipe to be used for water distribution systems.

The selection of water-distribution-system piping is based upon the following considerations: strength, ductility, modulus of elasticity, toughness, corrosion, erosion and abrasion resistance, weldability, workability, and surface smoothness. The most common piping materials are steel, either low-carbon, low-alloy, or stainless; plastic, either thermoplastic or thermosetting with fiberglass reinforcement; or concrete, lined and unlined. Aluminum, copper, brass, titanium, and high-nickel alloys are also used for some specific applications.

The metallurgy of the various types of metallic pipe material is somewhat complicated; however, an understanding of the basic physical properties and their effects is necessary for design engineers concerned with selecting pipe material, pipe fabrication process, welding process, and corrosion resistance properties. The most commonly accepted piping standards are those of the American Society for Testing and Materials (ASTM), American Water Works Association (AWWA), American National Standards Institute (ANSI), the American Society of Mechanical Engineers (ASME), and the American Petroleum Institute (API).

These standards have been developed by experimentation, testing, and experience. Most regulatory agencies use these guidelines to set their own requirements. Pipe manufacturers also publish product literature that is useful in pipe selection and installation. Table C1.4 summarizes the advantages and disadvantages of piping materials and related data of pipe joints and their applications.

TABLE C1.3 Piping Material Specifications, Standards, and Applications Material

Material	Industry standards	Common sizes diam in (mm)	Normal maximum working pressure psi (kPa)	Advantages	Disadvantages
Cast-iron pipe Ductile iron Centrifugally cast in metal Molds or sand-lined molds for water and other liquids	ANSI/AWWA/C151/A21.51 ASTM A377	4–30 (100–760)	350 (2414)	Durable, strong, flexural-strength, lighter weight than cast iron, greater carrying capacity, same external diameter, fracture resistant, easily tapped.	Subject to electrolysis and attack from acid and alkali soil, heavy to handle; may require thrust blocks at changes in direction or restraint of joints to counteract unbalanced forces.
Concrete Reinforced concrete pressure Pipe noncylinder type for water and other liquids	AWWA C302	12–168 (300–4300)	50 (345)	Durable with low maintenance, good corrosion resistance, good flow characteristics, generally suited for gravity systems with low gradient.	May deteriorate in alkaline soil if cement type is improper or in acid soil if not protected; may require thrust blocks at changes in direction or restraint of joints to counteract unbalanced forces.
Prestressed concrete Pressure-pipe steel cylinder Type for water and other liquids	ANSI/AWWA C301 and C304	16–144 (410 mm– 3660 mm)	250 (1724)	Durable, low maintenance, good corrosion resistance, good flow characteristics, resists backfill and external loads.	Same as above.
Steel Seamless pipe for high temperature service Seamless and seam-welded pipe Forged and bored pipe for high-temperature service	ASTM A106, A335, A376 ASTM A53, A312, A333, A714 ASTM A426, A451, A452	4–120 (100–3000)	High	Easy to install, tensile strength, low cost, good hydraulically when lined, adapted to locations where some movement may occur.	Subject to electrolysis external corrosion in acid or alkali soil, poor corrosion-resistance welded unless properly lined, coated, and wrapped; low resistance to external pressure in large sizes; air-vacuum valves imperative in large sizes; subject to tuberculation when unlined.
Polyvinyl chloride (PVC) PVC plastic pipe Schedule 40, 80 pressure rated (SDR) series PVC pressure pipe	ASTM D1785 ASTM D2241 ANSI/AWWA C900 and C905	4–36 (100–900)	200 (1380)	Light weight, easy to install, excellent resistance to corrosion, good flow characteristics, high tensile and impact strength	Difficult to locate underground; requires special care when tapping; susceptible to damage during handling; aboveground use may require more supports. PVC pipe also requires thrust restraint at change in direction or velocity.

TABLE C1.3 Piping Material Specifications, Standards, and Applications Material (Continued)

Material	Industry standards	Common sizes diam in (mm)	Normal maximum working pressure psi (kPa)	Advantages	Disadvantages
Copper Seamless copper Standard sizes Seamless copper Water tube for general plumbing Purposes	ASTM B42 ASTM B88	½–12 (3–300)	<700 (4828)	Excellent resistance to corrosion; ideal for use in water supply and plumbing, including DWV, compressed-air-instrumentation lines, and heat transfer equipment.	Copper deteriorates rapidly under high temperature and repeated stresses.
Seamless, threadless copper pipe Seamless copper tube Copper nickel, seamless copper, nickel pipe and tube Welded copper nickel pipe Welded copper and copper alloy Heat-exchange tube, 90-10 and 70-30	ASTM B302 ASTM B75 ASTM B466 ASTM B467			High level of corrosion resistance of copper nickel; 10% to corrosion and bifouling make ideal for use in piping systems for brackish or sea water. Copper nickel, 30% provides the best service under the most adverse condition. It offers excellent corrosion resistance to high-velocity seawater, immune to stress-corrosion cracking and resistant to the action of ammonia.	May undergo a general attack or uniform thinning in aggressive environment containing high concentration of oxygen and carbon-dioxide.
Aluminum Aluminum and aluminum alloy Seamless-pipe extruded tube Drawn seamless tube for condensers and heat exchangers Aluminum-alloy drawn seamless tube	ASTM B241 ASTM B234 ASTM B210	½–12 (3–300)	<300 (2069)	Light weight, durable, strong, ideal for use in cryogenic systems, heat-transpressure lines, process systems where performance requirements outweigh cost.	Requires special techniques and skills for brazing or welding joints depending on type of alloy.
Titanium Seamless and welded titanium Alloy pipe Seamless and welded titanium Alloy tube for condensers and heat exchangers	ASTM B337 ASTM B338	½–12 (3–300)	High	Excellent for general corrosion resisting and elevated temperature service. Lighter than steel while having strength comparable with alloy steel. Excellent for use with cooling water, fresh brackish or salt, polluted, etc., essentially immune to all forms of corrosion in condenser environments.	Resistance to bifouling is relatively poor when compared to copper alloy for similar application; coupling of titanium tubes with copper-alloy tube sheets in condensers may result in galvanic attack on the tube sheet in all types and make it essential to provide some form of cathodic protection.

Note: Materials used for piping within the jurisdiction of ASME I and ASME III, and boiler external piping are designated by SA/SB numbers and are derived from ASTM "A" specifications for ASME Boiler and Pressure Vessel Code applications, see related specifications SA/SB in Section II of the ASME Boiler and Pressure Vessel Code.

TABLE C1.4 Pipe Joints and Their Applications

Pipe material	Type of joints	Applications
Steel	Mechanical-type couplings	Pipes are less than 24 in od, especially linings.
Steel	Welded joints	Pipes 24 in od and larger with inside coatings ideal for soft soils where settlement may be excessive.
Steel	Flanged joints	Where flanged valves, fittings or nozzles of equipment are to be attached. Offer ease of assembly and disassembly.
Copper	Welded, flanged, threaded, screwed, or brazed, flared fittings	Generally used in underground water service, interior water, steam, gas, fuel, oil and for some underground drainage.
Copper-nickel	Flanged, soldered, or brazed fittings used with hard drain temperatures; flared compression fittings used with annealed temper tubes	Used in condenser tubing, systems for sea or brackish water.
Aluminum	Brazed, welded	Used in cryogenic systems, heat transfer, process systems and pressure lines.
Titanium	Welded	Used with any kind of cooling water in large power plant condenser tubing.

Pipe Toughness. Pipe toughness is the ability of piping to absorb impact without brittle rupture. Service metal temperature is important in design, as most pipe metals have a transition range over which ductile behavior changes to brittle behavior on impact as the temperature drops.

Gray and Ductile-Iron Pipe. Cast-iron pipe has been the standard for water distribution systems worldwide for many years. There are more miles of this pipe in use today than any other pipe. Two types of cast iron commonly found in distribution systems are gray cast-iron pipe (CIP) and ductile-iron pipe (DIP). (In this text, CIP is used as the abbreviation for gray cast-iron pipe; it does not stand for cast-iron pipe in general.)

Gray cast-iron pipe is strong but brittle, usually offers a long service life, and is reasonably maintenance free. Ductile-iron pipe resembles CIP in appearance and has many of the same characteristics. It differs from CIP in that the graphite is distributed in the metal in spheroidal or nodular form, that is, in ball-shape form rather than in flake form. This is achieved by adding a material called an inoculant, usually magnesium, to the molten iron. Ductile-iron pipe is much stronger, tougher, and more ductile than CIP. Gray cast-iron pipe has not been produced since 1980, due to the increased reliability of DIP, but is still used in the manufacture of valves and fittings.

Although unlined cast iron has a certain resistance to corrosion, aggressive waters can cause the pipe to lose carrying capacity through corrosion and tuberculation. The process for lining pipe with a thin coating of cement mortar made it possible

to minimize tuberculation and maintain the carrying capacity of the pipe. The cement-mortar lining is approximately $\frac{1}{8}$ in (3 mm) thick and adheres to the pipe. The lined pipe may be cut or tapped without damage to the lining. Ductile-iron pipe internal lining can be cement mortar. Various thermoplastic and other epoxy-lined pipe are also available but are expensive. Generally these would be used to handle fluids considerably more corrosive than water. Bituminous external coating and polyethylene wraps are methods commonly used to reduce external corrosion.

Ductile-iron pipe is available with standard wall thickness (referred to as TC) in diameters of 4 in (100 mm) and larger. The standard lengths are 18 and 20 ft (5.5 and 6.1 m). Ductile-iron pipe is strong and can withstand the working pressures found in distribution systems. It is also durable and can be cut and tapped in the field.

CIP and DIP Joints. Gray cast-iron and ductile-iron joints of the following types have been used to join pipe lengths together (listed in order of development):

- Flanged joints
- Bell-and-spigot joints
- Mechanical joints
- Ball-and-socket or submarine joints
- Push-on joints
- Bolted retainer-gland joints, to prevent pullout
- Push-on joints with restrained gaskets to prevent pullout

Flanged joints are easy to make and require no special tools. They are used aboveground in water plants, pump houses, and other places where rigidity, self-restraint, and tightness are required. Flanged joints will not flex and are not normally used underground.

Mechanical joints are made by bolting a moveable follower ring on the spigot to a flange on the bell and compressing a rubber gasket to form a tight seal. The mechanical joint is less economical than previously mentioned joints but is easily made and requires no special skill. Since the bell-and-spigot ends need not fit tightly, each joint can be made to deflect slightly.

Bell-and-socket joints are special-purpose joints most commonly used for submerged installations. Their great advantage is that they can accommodate large deflections (up to 15°). This makes them very useful for pipe lines laid across mountainous terrain or under rivers. Boltless flexible-pipe joints, designed on the brass-and-socket principle, are also available.

Push-on joints are the most popular joints in water-distribution-system installation today. The joint consists of a bell with a specially designed recess to accept a rubber ring gasket and a beveled-end spigot. The joint offers ease of installation, and when made up, the rubber ring gasket is compressed to produce water tightness and locked in place against further displacement. Push-on joints are available in several designs. In addition to ease of installation and water tightness, the joint permits deflections of 3° to 5° , depending on the design, for installation on a curve or irregular terrain. Small diameters may be assembled by hand; larger sizes usually require mechanical aids. For detailed discussion on the above joints, refer to Chap. A2.

Steel Pipe and Reinforced Concrete Pipe. Steel pipe and reinforced concrete pipe are sometimes used as large feeder mains in water-distribution systems.

Plastic Pipe. Plastic pipe is also used in water-distribution applications. Plastic pipe was first introduced in the United States around 1940.

Plastic pipe materials include polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC), polyethylene (PE), and a crylonitrile-butadiene-styrene (ABS). ASTM and AWWA standards cover PVC pipe in sizes from NPS 4 to 12 (DN100 to 300) in diameter. Polyvinyl chloride pipe is a rigid pipe manufactured by an extrusion process. Fittings are made by a mold process. It is available in diameters up to NPS 36 (DN900); lengths of 20–40 ft (6–12 m); and various types, grades, and pressure ratings. Within a given nominal pipe diameter, there are several equivalent systems for specifying internal and external diameters. Larger than NPS 12 (DN300) plastic pipe is normally specified by a sizing system other than the iron-pipe size (IPS) system.

The AWWA standard is based on outside diameter, the same as DIP. A new sizing system, termed the standard dimension ratio-pressure rated (SDR-PR) system, is a ratio of the outside pipe diameter to wall thickness. See Table C1.5. For more detailed discussion of thermoplastic pipe, refer to Chap. D1.

The SDR-PR system recognizes the strength properties of plastic and allows pipe of one pressure rating to be available in various sizes. State and local regulations should be checked to determine what types and sizes of plastic pipe are approved for a particular application.

Manufacturers' recommendations should be consulted when tap diameters exceed NPS 2 (DN50).

PVC pipe may be joined by a bell-and-spigot push-on joint or by a solvent-weld joint. Refer to Chap. D1 of this handbook.

Steel Pipe. Application may dictate the need for steel piping to be lined or coated with a plastic, tar, plastic-encapsulated cement, or rubber. ASME B31.1 App. IV, Corrosion Control for ASME B31.1—Power Piping Systems provides guidelines for the control of corrosion of steel piping.

The American Water Works Association likewise provides guidelines and standards for coating and lining potable water lines for corrosion protection. Also, refer to Chaps. B9, B10, B11, and B12.

Special applications might require the use of stainless steel, ductile iron, copper, copper alloys, plastic, fiberglass, and aluminum-alloy pipe. Utilization of these materials is generally based on their corrosion-resistance properties and ease of installation.

Copper is widely used in service connections for potable water. Heat-exchanger tubing is a common use for nonferrous metals, including copper, copper-nickel alloys, titanium, and aluminum.

Copper and its alloys, e.g., brass, are useful in this application because of their good thermal conductivity and favorable cold or hot working properties and corrosion resistance.

Aluminum's low density and relatively high strength of its alloys give it good corrosion resistance and good working properties.

Titanium and its alloys have strength comparable to alloy steels at 60 percent of its weight. Corrosion resistance is superior to that of aluminum and even stainless steel.

Expansion, Flexibility, and Support

Expansion and Flexibility. Water systems piping shall have adequate flexibility to account for thermal expansion. Water systems operating under low temperature (less than 250°F [121°C]) and low pressure (less than 300 psig [2070 kPa(gage)])

TABLE C1.5 PVC Type I Pressure Rated Pipe

Nominal pipe size (DN)	od	Min wall	Average id	Nominal weight per ft
SDR 26 NSF—W.P. 160 PSI (Water @ 73.4°F)				
½ (15)		See SDR 13.5		
¾ (20)		See SDR 21		
1 (25)	1.315	0.060	1.175	0.164
1¼ (32)	1.660	0.064	1.512	0.221
1½ (40)	1.900	0.073	1.734	0.284
2* (50)	2.375	0.091	2.173	0.432
2½* (65)	2.875	0.110	2.635	0.622
3* (80)	3.500	0.135	3.210	0.915
3½ (90)	4.000	0.154	3.672	1.183
4* (100)	4.500	0.173	4.134	1.494
5 (125)	5.563	0.214	5.109	2.288
6* (150)	6.625	0.255	6.085	3.228
8* (200)	8.625	0.332	7.921	5.468
10* (250)	10.750	0.413	9.874	8.492
12* (300)	12.750	0.490	11.710	11.956
14 (350)	14.000	0.538	12.860	14.430
16 (400)	16.000	0.615	14.696	18.810
18 (450)	18.000	0.692	16.534	23.860
20 (500)	20.000	0.769	18.370	29.470
24 (600)	24.000	0.923	22.043	42.520
SDR 41—W.P. 100 PSI (Water @ 73.4°F)				
18 (450)	18.000	0.439	17.070	15.370
20 (500)	20.000	0.488	18.970	18.920
24 (600)	24.000	0.585	22.748	27.320
SDR 21 NSF—W.P. 200 PSI (Water @ 73.4°F)				
½ (15)		See SDR 13.5		
¾ (20)	1.050	0.060	0.910	0.129
1 (25)	1.315	0.063	1.169	0.170
1¼ (32)	1.660	0.079	1.482	0.263
1½ (40)	1.900	0.090	1.700	0.339
2 (50)	2.375	0.113	2.129	0.521
2½ (65)	2.875	0.137	2.581	0.754
3 (80)	3.500	0.167	3.146	1.106
3½ (90)	4.000	0.190	3.596	1.443
4 (100)	4.500	0.214	4.046	1.825
5 (125)	5.563	0.265	5.001	2.792
6 (150)	6.625	0.316	5.955	3.964
8 (200)	8.625	0.410	7.755	6.679
SDR 13.5 NSF—W.P. 315 PSI (Water @ 73.4°F)				
½ (15)	0.840	0.062	0.696	0.104

Source: Harvel Plastics Inc. Product Bulletin 112/401, Effective 7.1.87, Revised 1/1/89, Harvel Plastics, Inc.

conditions are considered to have adequate flexibility if the following conditions are satisfied:

$$\frac{Dy}{(L - U)^2} \leq 0.03 \quad (\text{C1.18})$$

where D = Nominal pipe diameter, in (mm)
 y = Thermal growth of the pipe, in (mm)
 L = Length of pipe in the system, ft (m)
 U = Distance between rigid supports, ft (m)

If the conditions above are not met, a detailed analysis of the piping system may be needed. The reader is referred to Chap. B4, Stress Analysis of Piping Systems, for more information.

In piping systems without adequate flexibility, thermal expansion may lead to failure of piping or anchors. It may also lead to joint leakage and excessive loads on nozzles. The thermal expansion of piping can be controlled by use of proper locations of anchors, guides, and snubbers. Where expansion cannot be controlled, flexibility is provided by use of bends, loops, or expansion joints (bellows or slip-joints).

Detailed calculations for underground water-piping systems are not needed unless significant settlement, seismic, or temperature changes are expected. Buried piping, although supported throughout by proper bedding and backfilling procedures, also requires thrust restraint for unrestrained joints at changes of direction.

Pipe Support Systems. Standard component supports are normally used to carry dead weight and thermal expansion loads. The dead weight and thermal supports typically used are defined in MSS-SP-58. Part B, Chap. B5 of this handbook discusses pipe-support design and selection in detail.

Valve Selection. In water-piping systems, valves are generally used for isolating a section of a water main, draining the water line, throttling fluid flow, regulating water-storage levels, controlling water hammer, bleed off of air, or preventing backflow. Refer to Chap. A10.

Isolation. Gate valves are used to isolate specific areas of the system during repair work or to reroute water flow throughout the distribution system. An open gate valve allows water to flow through in a straight line. The valve may be closed during an emergency, such as a water-main break, or during routine maintenance.

Gate valves commonly used in water distribution systems are the iron-body bronze-mounted (IBBM) nonrising-stem (NRS) gate valves. Buried gate valves are usually nonrising-stem valves. In situations where an operator will need to know by observation whether a valve is open or closed, a rising-stem valve with an outside screw and yoke (OS&Y) is often used.

Service stops valves are used to shut off service lines to individual homes or businesses. Specific types of service stops include the corporation stop, which is tapped into the main, and the curb stop, which is located near the property line. Access to the curb stop is through a curb box. Small plug valves are used as curb stops and corporation stops.

Butterfly valves are also used for isolation purposes. Because the disk remains in the water path in all positions, the butterfly valve may create a slightly higher head loss than the gate valve. The position of the disk also makes it difficult to clean scale from a pipeline because the pig or swab is blocked by the valve disk. However, butterfly valves open easily, as the water pressures acting on one-half of the upstream side of the disk tends to force it open, balancing the pressure on the

other half, which tends to force it closed. The cost of NPS 16 (DN400) and larger butterfly valves is less than the cost of large gate valves, as large gate valves normally require reduction gears, a bypass valve, rollers, tracks, and scrapers. Butterfly valves should be located away from sources of turbulence to preclude damaging effects of turbulence to the disk.

Draining the Water Line. Drain or blow-off valves may be installed at low points to flush sediment from the main or to drain the entire main. Gate valves are commonly used as drain valves. Where rapid draining is not important, globe valves may be used to drain lines where sediment accumulation is not a problem. Though quicker to operate and less costly to repair than gate valves, NPS 3 (DN80) and larger globe valves are less economical.

Throttling Flow and Regulating Water-Storage Levels. In addition to on-off control of flow, globe valves may be used to regulate or throttle flow. This can be done manually, although it is usually done automatically. For throttling under low-flow and low-pressure conditions, butterfly valves are also used. Large-plug valves may be used for throttling.

An altitude valve is a type of control valve, diaphragm or piston type, used to control the level of water in a tank supplied from a pressure system. There are two general types of altitude valves: single acting and double acting.

A single-acting altitude valve is used for filling the tank. A bypass line with check valves around the altitude valve is needed to permit backflow out of the tank and into the distribution system when the inlet pressure is lower than the tank. The tank discharges through a separate line or through a check valve in a bypass line around the altitude valve.

A double-acting altitude valve allows to flow both to and from the tank. When the tank becomes full, the valve closes to prevent overflow. When the distribution pressure drops below the pressure exerted by the full tank, the valve opens to discharge water into the distribution system.

Controlling Water Hammer. In a water distribution system, opening or closing a valve too fast can cause water hammer. This phenomena is discussed in Chap. B8. Pressure-relief valves are used to help control water hammer by releasing some of the energy that is created by a sudden stop in flow. They are fitted with an adjustable spring to set the maximum pressure of the line. When line pressure becomes greater than the set pressure, the valve opens until the pressure is equalized. Other choices include standpipes open to atmosphere and various kinds of surge tanks.

Bleed Off of Air and Breaking Vacuum. Air tends to collect in water lines. Under the pressure of the distribution system, air dissolves and can reappear as microscopic air bubbles, which gives water a cloudy appearance. A more common operating problem occurs when air collects in high places in the distribution system producing air pockets. Air pockets effectively reduce the area of pipe through which water flows, causing an affect known as *air binding*. The result is pressure loss and increased pumping costs.

Air vacuum and air release valves can be installed to eliminate these problems in pumping stations where air can enter the system and at high points where it can collect. Air-relief/release valves solve the problem by automatically venting any air that accumulates. Conversely, vacuum caused by column separation can be broken with vacuum-relief valves. Combination air and vacuum relief valves are used for this application.

Figure C1.13 shows a spring-loaded check valve that opens during forward flow and is closed by the spring when flow stops. When pressure drops to a low value, a second valve opens and allows air to enter this breaker. With this arrangement,

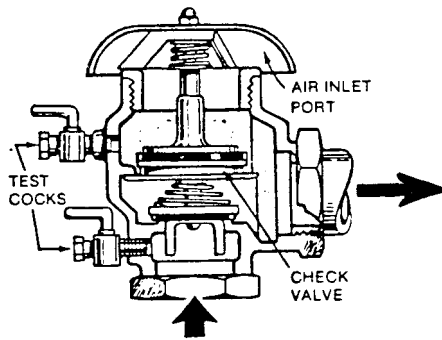


FIGURE C1.13 Pressure and vacuum breaker.

the breaker can remain under supply pressure for long periods without sticking and can be installed upstream from the last shut-off valve.

Figure C1.14 shows an atmospheric vacuum breaker, consisting of a check valve operated by water flow and a vent to the atmosphere. When flow is in the forward direction, the valve lifts and shuts off the air vent; when flow stops or reverses, the valve drops to close the water-supply entry and open an air vent.

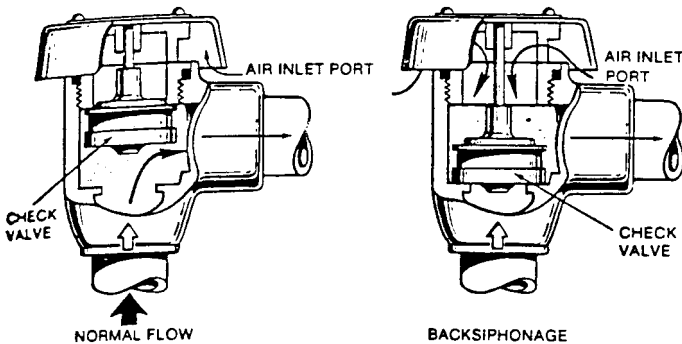


FIGURE C1.14 Atmospheric vacuum breaker.

Preventing Backflow. Backflow in a pump discharge line can be prevented by installing a check valve to allow flow in one direction only—away from the pump. However, check valves can contribute to water hammer problems, especially in the case of pump failure. Proper precautions to avoid or relieve these surges must be taken.

Backflow, or reversed flow, could result in contaminated or polluted water entering the water system. Backflow can occur through a cross-connection under two conditions: back pressure and back-siphonage (see Fig. C1.15). If a pressurized nontreated system is cross connected with a lower-pressure treated water system, then the pressure in the nontreated system can force nontreated fluid into the treated supply. This situation is referred to as backflow due to back pressure.

Valves are used as backflow-prevention devices. A device that can be used in every cross-connection situation and with every degree of risk is the reduced-

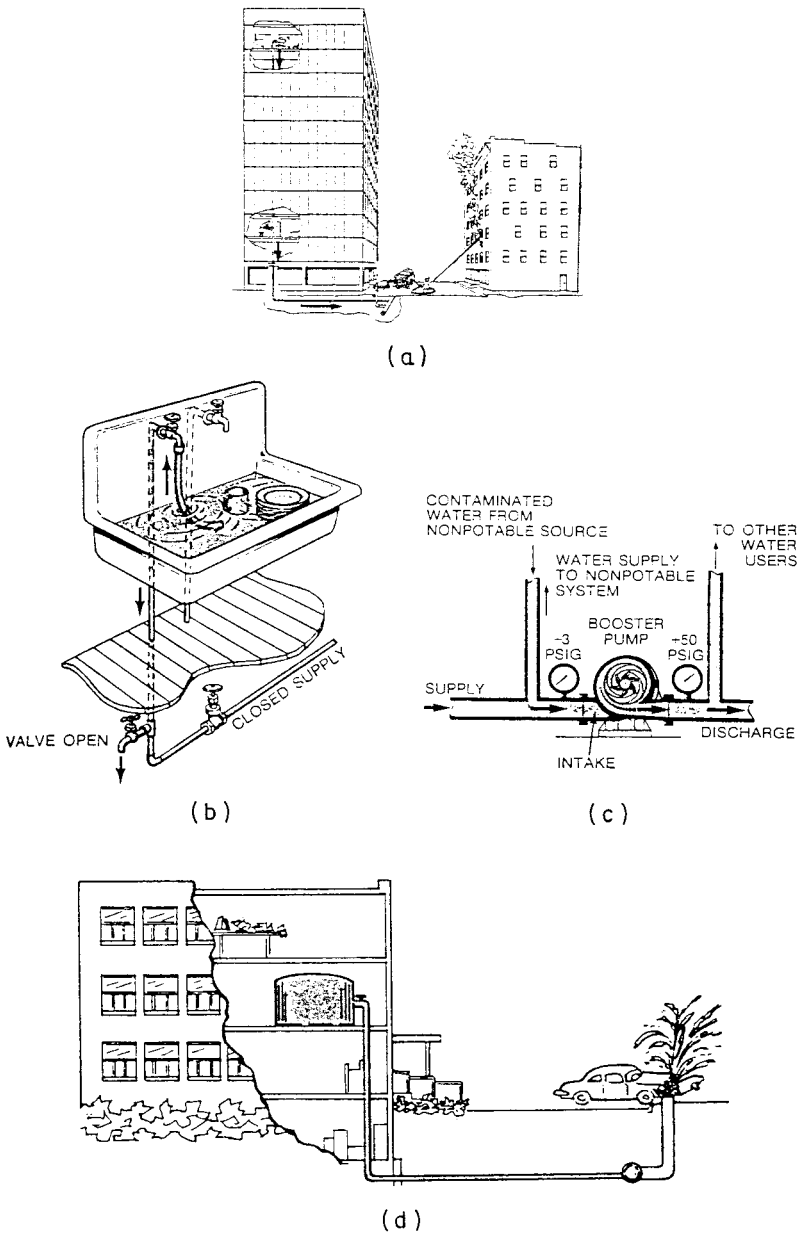


FIGURE C1.15 Examples of backflow due to back siphonage. (a) Backsiphonage due to pressure loss; (b) backsiphonage—hose forms cross connection; (c) backsiphonage from a booster pump; (d) backsiphonage due to a broken main. (*Introduction to Water Distribution Principles and Practices of Water Supply Operations*, American Water Works Association, 1986.)

pressure-zone backflow. This device consists of two spring-loaded check valves with a pressure-regulated relief valve located between them. Two check valves, even though well designed and constructed, are not considered sufficient protection, because all valves leak from wear or obstruction. For this reason, a relief valve is positioned between the two checks. Typical backflow conditions are illustrated in Fig. C1.16.

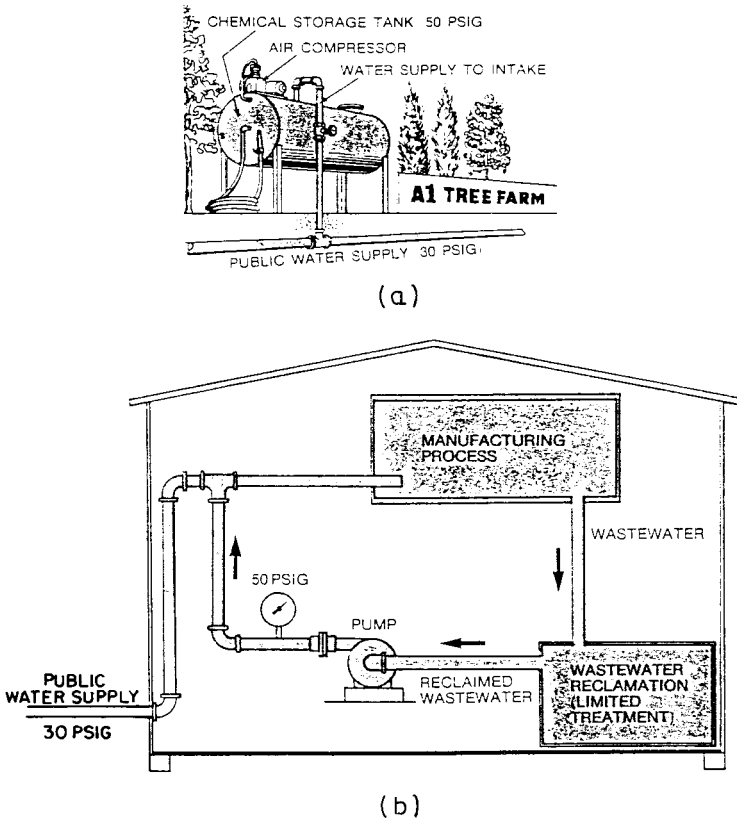


FIGURE C1.16 Examples of backflow due to back pressure. (a) Cross connection between pressurized nonpotable system and lower pressure potable system; (b) backflow from recirculated system. (*Introduction to Water Distribution Principles and Practices of Water Supply Operations*, American Water Works Association, 1986.)

If a treated water-distribution system is cross connected to a nontreated source that is open to the atmosphere, and if the pressure in the treated system falls below atmospheric pressure, then the pressure of the atmosphere can force the nontreated fluid into the treated supply. This situation is called backflow due to *backsiphonage*. Examples of backsiphonage conditions include overpumping by fire or booster pumps, undersized distribution piping, and a broken main. When backsiphonage occurs, the partial vacuum pulls liquid back into the supply line. If air enters the line between a cross-connection and the source of the vacuum, then the vacuum will be broken and backsiphonage will be prevented.

Water Hammer and Surge Control. The problem of water hammer in water piping systems consists of containing the pressure and dissipating the water-flow energy. For example, the energy necessary to move the water through the piping is supplied by the pump. If a valve is suddenly closed at the end of the discharge line, the moving column of water is brought to a stop at the valve. The kinetic energy contained in the column of water, originally given to the water by the pump, is still present and must be dissipated. The column of water compresses, the pressure rises, and some of the kinetic energy is transformed to internal energy. The higher water pressure acts upon the pipe wall and does work in stretching it, but only a small percentage of energy will be lost in this. The pipe will obey the laws of vibration and return most of the energy to the water.

The water-hammer effects are obtained from equations that define relations between head and flow in the discharge line during the transient flow condition which results from water-hammer wave action.

Water-column separation might occur at high points near the hydraulic gradient on long discharge lines. This condition can create high-pressure conditions at the moment of rejoining of the separated water columns.

TABLE C1.6 Waterhammer Velocity in Piping Systems (a , wave velocity in feet per second)

D/t	Steel ($E = 28 \times 10^6$ psi)	Cast iron ($E = 16 \times 10^6$ psi)	Transite ($E = 3.4 \times 10^4$ psi)
20	4300	4100	3000
40	4000	3600	2300
60	3800	3350	2000
80	3600	3100	1750
100	3400	2900	1600
150	3100	2500	1300
200	2800	2250	1150
250	2600	2050	
300	2400		

Table C1.6 gives the water-hammer wave velocity as a function of diameter-to-thickness ratios for three different piping materials encountered frequently in water-supply or distribution systems. In this tabulation, a is the wave velocity in ft/sec (m/sec), D/t is the dimensionless ratio of diameter to thickness, and E is the modulus of elasticity.

If a valve is closed in the time of one wave cycle (in the time a pressure wave travels to the other end of the pipeline and returns to the closing valve) or less, then the water hammer should be calculated on the basis of instant valve closure.

To determine time for the wave cycle, use

$$T = \frac{2L}{a} \quad (\text{C1.19})$$

To determine water hammer for instantaneous valve closing, use

$$h = \frac{aV}{g} \quad (\text{C1.20})$$

where T = time for one wave cycle, sec

L = pipeline length, ft (m)

h = water-hammer head above static head, ft (m)

a = velocity of pressure wave, ft/sec (m/s)

V = water velocity at instant before valve closure, ft/sec (m/s)

$g = 32.2 \text{ ft/sec}^2 \text{ (} 9.81 \text{ m/sec}^2 \text{)}$

To determine water hammer for slower valve closing, use

$$h_2 - h_1 = \frac{a(V_1 - V_2)}{g} \quad (\text{C1.21})$$

where h_2 = pressure after partial closing of valve, ft (m)

h_1 = pressure before start of valve closing, ft (m)

$h_2 - h_1$ = pressure rise due to water hammer, ft (m)

V_1 = water velocity before start of valve closing, ft/sec (m/s)

V_2 = water velocity after partial closing of valve, ft/sec (m/s)

The phenomenon and damaging effects of water hammer is discussed in detail in Part B, Chap. B8 of this handbook.

A means of eliminating water hammer is to permit the liquid to surge into a tank or discharge to atmosphere. To quickly suppress all the momentum in a long pipe system would require high-pressure piping, which is very costly. With a surge tank or relief valve as near the valve as feasible, the development of excessive pressure in this region is prevented.

Surge tanks may be classified as simple, orifice, and differential. The simple surge tank has an unrestricted opening into it and must be of adequate size so that it will not overflow and so it will not be emptied to permit air to enter the pipeline. An orifice surge tank has a restricted opening between pipeline and tank and allows more rapid pressure changes in the pipeline. A more rapid pressure change causes a more rapid adjustment of flow. A differential surge tank is a combination of an orifice surge tank and a simple surge tank of small cross-sectional area.

Surge tanks under air pressure are utilized in certain circumstances, such as after a reciprocating pump. They are generally uneconomical for large pipelines.

Relief valves are available in various types from spring loaded to control blow-down diaphragm types.

Air Binding. Air which accumulates in water piping will reduce the effective cross-sectional area for water flow and thus increase pumping costs through the resulting extra head loss. Air enters the piping system from several sources, such as the release of air from the water, air carried in through vortices into the pump suction, air leaking in through joints that may be under negative pressure, and having air present in the piping system before filling.

The water from the water source may be nearly saturated with air. If the temperature of this water is raised and the pressure is lowered by the siphon action, the water will release most of its air. However, this air release is not instantaneous but proceeds on a time-rate release and is therefore dependent upon the length of time the water remains in the piping. Experience indicates that the actual air release in a circulating water system of a conventional power-generating plant is probably on the order of 10 percent of calculated theoretical release.

On gentle downward slopes, a continuous air pocket may form along the top of the pipe for the entire slope. In a sharper downward slope, several air pockets may form, each air pocket terminating in a hydraulic jump. Slopes may require a

water velocity in excess of 10 fps (3 m/s) to assure that the piping remains free of air. In a 90° drop, an air pocket may form in the upper portion of the bend and a velocity in excess of 7 fps (2 m/s) may be required for air elimination. Connections for air vents should be provided at all high points in the piping system and along sloping piping of considerable length. Air-release valves at the high points of these systems' mains eliminate air pockets.

Pipeline Alignment. Alignment, both horizontal and vertical, is one of the most important considerations in the design of a pipeline system. The pipeline must be buried deep enough to prevent freezing of pipe contents as well as to prevent flotation where the pipe is in a high-groundwater environment and may be empty on occasion. The designer must provide an alignment that provides sufficient clearance from other existing and proposed pipelines and structures, minimizes need for fittings, and avoids highways or other paving when possible. Under important roadways, the highway authorities may require the pipe to be placed in a casing. Additionally, the alignment should be such that it minimizes damage to life and property in case of pipeline failure.

Finally, changes in pipeline direction or change in fluid velocity cause unbalanced forces in the pipeline. To provide pipeline stability, these forces must be restrained, using either thrust blocking or harnessing joints of enough pipe lengths to mobilize sufficient friction to counteract unbalanced forces.

Corrosion and Erosion Effects

Corrosion. All raw water coming from wells, rivers, lakes, or ocean is an extremely dilute water solution of mineral salts and gases. The salts are mineral matter dissolved by water flowing over and through the earth layers. The salts are mainly sulfates, bicarbonates, chlorides of calcium, sodium, and magnesium. These minerals give water its hardness (destroying soap and preventing lather) and precipitate as a white lime-type scale. The dissolved gases are atmospheric oxygen and carbon dioxide, picked up by water-atmosphere contact (e.g., spray, raindrops, and ammonia from decaying vegetable matter).

The dissolved gases are the prime agents of chemical corrosion that act on the metals of piping systems. The oxygen attacks the iron or steel, and the process is accelerated by the carbon dioxide. The rate and extent of the chemical corrosion are influenced by the amounts of mineral salts dissolved in the water.

The calcium content of water is used to measure the tendency of water to corrode or form scale. For this purpose, values are assigned to the calcium content and the alkalinity of the water. Adjustments are made for temperature and the effect of totally dissolved solids. The resultant value is compared with the observed pH of the water to determine whether it is corrosive or scaling. This is basically the Langelier saturation index as reported by Larson-Buswell in the *Journal of the American Water Works Association*, Vol. 28.

The water is corrosive when the Langelier index (calcium carbonate saturation index) is minus (-). The water analysis will generally, but not always, show a pH value below 7 (acidic).

The scaling in water lines occurs when the Langelier index is plus (+). The water analysis will generally show a pH value above 7 (basic).

The precipitation of calcium carbonate as a scale or film thickness may be desirable as a means of protection against corrosion if the rate of buildup is sufficiently low. Calcium carbonate is undesirable on heat-transfer surfaces. Since temperature lowers the solubility of calcium carbonate and calcium sulfate, the Langelier index will vary for colder water and for warm water.

The exterior of unprotected buried metallic pipe is subject to similar chemical

action due to exposure to water. In addition, the pipe exterior is susceptible to attack by aerobic and anaerobic bacteria, galvanic action, and stray electric currents. The chemical action on the pipe exterior may be more intense because of concentration of oxygen, salts, and other chemicals leached out of the surrounding earth by ground water.

Some forms of anaerobic bacteria that thrive only in the absence of free oxygen obtain their oxygen by the chemical breakdown of oxygen compounds in the earth, with the resultant production of substances such as hydrogen sulfide that will corrode the base-metallic buried pipeline. There are also many types of aerobic bacteria that produce sulfuric acid, sulfate, and ferric hydroxide, compounds that are all corrosive to steel or iron. Organic soil should be kept away from the vicinity of the pipeline to minimize possibility of this corrosive action.

Also, when iron or steel is in contact with a more cathodic material, for example, copper or brass, a galvanic cell is formed, electrolysis results, and the corrosion rate of steel or iron increases. If iron or steel is in contact with a more anodic material, for example, zinc, the zinc will be the affected material and the corrosion rate of the steel or iron will decrease.

There is some natural resistance to chemical corrosion of the base-metallic pipe materials. The chemical-corrosion product, an oxide film, may build up sufficiently to slow down or prevent further corrosion.

The natural coating characteristics of the most commonly used piping materials are mentioned briefly below.

On cast iron, the rust (iron oxide) builds up into a strong adhesive coating that finally forms a barrier sufficient to stop or slow down further corrosion. The higher silicon cast iron has the best characteristics in this respect.

On steel, the rust powders and flakes off easily and does not build up into an adhesive, providing sufficient protective coating.

For concrete and cement piping, the corrosion is of a different form. These materials are subject to leaching of the free lime from the cement, deterioration in alkali soils, and attack by organic growth.

Cathodic Protection. If no protective coating is used, or if a low-cost, limited-life coating has been selected, cathodic protection may be considered as a means of limiting the main agent of corrosion, which is the electro-chemical process. In this process, the moist earth is the electrolyte, two dissimilar materials are the anode and the cathode, and the pipe wall between them completes the electric circuit. This process may be set in motion in a number of different ways, among which are dissimilar metals, galvanic action of a single metal due to dissimilar soils, variation in moisture and chemical content of soil, nonuniformity of metal caused by mill scale, surface scarring, welding, and even temperature differentials.

The current flows from the anode to the cathode and causes corrosion at a rate greater than that which would occur by normal chemical means. Corrosion rate is increased at the anode end and decreases at the cathode end. The anode is the point or area at which the current leaves the metal, and the cathode is the point at which the current enters the metal.

The electro-chemical galvanic series (Table C1.7) gives the relation between metals. The metal listed nearer the top of the table is the anode that will waste away. The metal nearer the bottom of the table is the cathode and will be protected. The farther from each other the metals are located in the table, the greater the potential difference will be between them and the greater the corrosion rate of the anode end.

A typical example of the galvanic action of dissimilar metals is represented by a steam condenser having a steel shell, steel-tube sheets, and copper-alloy tubes.

TABLE C1.7 Galvanic Series

Anode end (least noble, the wasting end)
Magnesium
Magnesium alloys
Zinc
Aluminum
Aluminum alloys
Cadmium
Carbon steel
Cast iron
Stainless steel (active)
Soft solder
Tin
Lead
Nickel (active)
Brasses
Copper
Bronzes
Nickel-copper alloys
Nickel (passive)
Stainless steel (passive)
Titanium
Silver solder
Silver
Graphite
Gold
Platinum
Cathode end (most noble, the protected end)

The steel is nearer the anode end than is the copper alloy and, as a consequence, the corrosion of the steel tube sheets and shell is accelerated. Always, that metal which is higher in the galvanic series will waste away.

Cathodic protection is a means of diverting the electro-chemical corrosion from the pipeline to wasting anodes.

There are two methods of providing cathodic protection. The less costly installation is the galvanic method based on a natural battery action between the position of metals in the electro-chemical table. An anode or wasting piece is deliberately used. This approach requires very careful analysis of all the varying conditions involved.

The second and more costly cathodic protection is the impressed-current method that requires an external source of electricity. The impressed-current renders the piping cathodic to the surrounding soil by a controlled difference of potential.

In locations where there may be stray currents, the installation of removal wires at designated points so that the current may leave the pipeline should be considered. In other words, stray currents are utilized to provide cathodic protection for the pipeline.

Protective Coatings. Since corrosion of metal is a surface reaction, it is obvious that, if a protective coating which is continuous, impervious, chemically inert, and electrically insulating can be bonded to the interior or exterior of the piping, corrosion cannot take place on the pipe surface as long as the protective coating remains in place undamaged and without cracks or pinholes.

The basis of selection for the best coating differs for the interior and exterior of the pipe.

The coating on the interior of the pipe, to perform its function properly, would be selected for its chemical inertness, imperviousness, adhesiveness, adjustment to pipe deformation, and resistance to erosion caused by the flowing water.

The coating on the exterior of the pipe would be selected for its chemical inertness, electrical resistance, imperviousness, adhesiveness, adjustment to pipe deformation, and resistance to shear and compression due to varying earth conditions.

Galvanizing. The zinc used for galvanizing pipe is on the anodic (wasting) or electro-chemical protective side of the steel, and it is wasted or changed to zinc compounds before the steel pipe will be attacked.

Coal-Tar Enamel. Specification AWWA C203 covers the coal-tar enamel protective coatings for steel water pipe. This standard delineates the specifications for the materials involved, method of application to the inside and outside of the piping, the thickness required, protection of the coatings, testing, and other specifications.

The type of enamel is specified as AWWA coal-tar enamel and is described in this standard with full characteristics and the ASTM tests required.

Erosion. Erosion effects in water piping systems is fundamentally an accelerated form of corrosion and as such is distinguishable from mechanical processes such as erosion abrasion and cavitation. Single-phase and two-phase erosion-corrosion differ in that a second damage process (droplet impingement) is available under two-phase conditions, and this can accelerate the overall rate of attack. In the most severe cases of two-phase erosion-corrosion, rapid rates of metal loss (approximately 40 mils/year) have been reported.

Erosion is observed only when specific combinations of material, water chemistry, and hydrodynamic conditions coexist. Most problems have been associated with plain carbon or very highly alloyed steels having a low content of dissolved oxygen and a pH less than about 9.3. Detrimental erosion occurs at temperatures within the range of 212°F to 525°F ([100°C to 274°C] but most rapidly between 260°F and 400°F [127°C and 204°C]) and is restricted to locations where the mass-transfer coefficient is high. This can be either as a result of a high-fluid flow rate or because of the presence of a geometric flow discontinuity such as an impingement orifice, bend, tee, et cetera.

Erosion under both single-phase and two-phase conditions can lead to a characteristic *scalloped* surface appearance, and in carbon steels the pearlite is preferentially attacked. Corrosion films are typically very thin and the surface sometimes appears polished, in marked contrast to adjacent regions which generally are more heavily oxidized.

A number of laboratory investigations of erosion have been conducted (almost exclusively in single-phase water flow only), and major variables affecting the process have been identified and their effects documented. Quantitative mechanistic understanding is not yet complete, but empirical predictive models are available. Laboratory studies have shown the feasibility of a variety of mitigating actions and remedies, and several of these have been applied successfully. The physical picture of the erosion process that has emerged from this work is illustrated in Fig. C1.17. As can be seen, erosion can be viewed as a flow-accelerated corrosion process characterized by the presence of a poorly adherent magnetite film.

The rate of metal removal depends on interactions between the rates of a number of subprocesses.

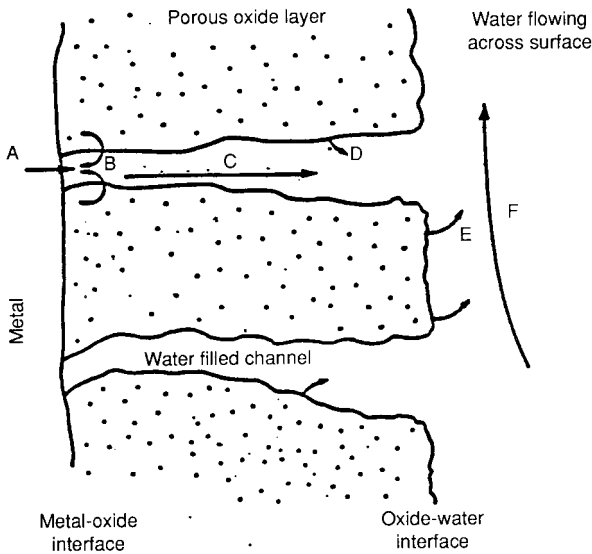


FIGURE C1.17 Phenomena occurring during erosion-corrosion.

The laboratory work shows that three main groups of variables affect the rate of metal loss by erosion under single-phase conditions:

- Material variables (chiefly the chemical composition)
- Water-chemistry variables (temperature, pH, oxygen concentration, impurity content)
- Hydrodynamic variables (flow rate, geometry)

Some largely empirical models have been developed (Ref. 5) and are capable of metal-loss predictions within the range of the data on which they are based.

Erosion occurs most readily in plain carbon steel. Austenitic stainless steels essentially are immune to erosion-corrosion. In ferritic steels, alloying elements such as molybdenum, copper and particularly chromium (even when present at levels of 1 percent or less) can greatly improve the erosion-corrosion resistance.

The effect of steel composition depends on the severity of hydrodynamic conditions; as conditions become more demanding, higher alloy contents are required to confer the same resistance to erosion-corrosion. However, in the relatively mild situation typical of feedwater piping, significant effects of small changes in material composition would be anticipated based on the laboratory data.

The effects on the erosion rates of water temperature, pH, and dissolved oxygen content have been studied by a number of investigators. For the orifice configuration tested, the temperature dependence at pH 9.05 has a flow-rate-dependent peak at about 284°F (140°C), suggesting that the erosion-corrosion rate is controlled by oxide dissolution kinetics at low temperatures and by mass-transfer limitations at higher temperatures. A marked decrease in erosion rate accompanies increases of pH.

Dissolved oxygen also has a marked effect in neutral water. Iron-release rates from carbon steel in 100°F to 400°F (38°C to 204°C) water at a flow rate of 6 ft/sec (1.8 m/s) have been shown to decrease by up to two orders of magnitude as oxygen concentration was increased over the range 1 to 200 ppb. Tests indicated that it is important to keep oxygen levels above 15 to 20 ppb, and oxygen dosing is a fairly common practice.

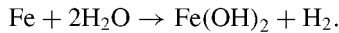
The effects on erosion of ionic impurities such as chlorides and sulfates have not been widely studied. In particular, there is little information which bears upon the question of whether a long prior period of adverse chemistry could have any irreversible effects.

Plant experience indicates that geometry and flow rate are important factors in erosion. The physical picture of the process shown in Fig. C1.17 suggests that the importance of geometry and flow rate rises through their influence on the rate of mass transfer of oxide dissolution products away from the oxide-water interface. Laboratory studies have confirmed that the mass-transfer coefficient is the controlling parameter; however, the exponent of the power function relating the erosion-corrosion rate and the mass-transfer coefficient is dependent on temperature. Since the mass-transfer coefficients for simple flow geometries can be calculated, the existence of these empirical relationships allows the erosion rate to be estimated for a variety of situations. However, local mass-transfer coefficients are sensitive to local geometrical discontinuities and at present can only be derived empirically.

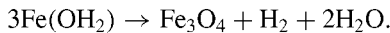
Component redesign or flow-path geometry improvements, aimed at reducing the mass-transfer coefficient, can sometimes be used to remedy erosion-corrosion problems.

Referring to Fig. C1.17, the phenomena occurring during erosion is

A. Iron hydroxides are generated:



B. Magnetite is formed according to the Schikorr reaction:



C. A fraction of the hydroxides formed in step B and hydrogen generated in steps A and B diffuse along pores in the oxide.

D. Magnetite can dissolve in the pore.

E. Magnetite dissolves at the oxide-water interface.

F. Water flow removes the dissolved species by a convection mass transfer mechanism.

Example C1.3. The following presents a sample calculation of the rate of erosion-corrosion under single-phase flow conditions. The methodology used is based upon the work performed by Coney (Refs. 6 and 7).

Physical and flow conditions for this example are

Pipe outside diameter = 18.00 in (0.46 m)

Pipe inside diameter = 17.00 in (0.43 m)

Wall thickness (nom.)	= 0.50 in (.013 m)
pH	= 9
Pressure	= 367 psig (2531 KPa) [gauge]
Temperature	= 380°F (193°C)
Flow Rate	= 5,000,000 lbm/hr (630 kg/s)

For these conditions the Reynolds number, \overline{Re} , is

$$\overline{Re} = VD_H \rho / \mu \quad (C1.22)$$

where V = velocity, ft/sec (m/sec)

D_H = inside diameter, ft (m)

μ = dynamic viscosity, lbm/sec·ft (N·s/m²)

ρ = density, lbm/ft³ (kg/m³)

Since the flow rate is known, the velocity can be calculated:

$$W = \rho AV \quad (C1.23)$$

or

$$V = \frac{W}{A\rho} \quad (C1.24)$$

where W = flow rate, lbm/hr (kg/sec)

A = flow area, ft² (m²)

and

$$\overline{Re} = \frac{(55) \frac{\text{lbm}}{\text{ft}^3} \left(\frac{\text{kg}}{\text{m}^3} \right) \times (17) \frac{\text{ft}}{\text{sec}} \left(\frac{\text{m}}{\text{sec}} \right) \frac{17}{(12) \text{ft}} \left(\frac{1}{\text{m}} \right)}{9.66 \times 10^{-5} \frac{\text{lbm}}{\text{sec}\cdot\text{ft}} \left(\frac{\text{N}\cdot\text{s}}{\text{m}^2} \right)} = 1.29 \times 10^7$$

$$V = \frac{(5 \times 10^6) \frac{\text{lbm}}{\text{hr}} \left(\frac{\text{kg}}{\text{sec}} \right) \times \frac{1 \text{hr}}{3600} \text{sec}}{\frac{\pi}{4} \left(\frac{17}{12} \right)^2 \text{ft}^2 (\text{m}^2) \times 55 \frac{\text{lbm}}{\text{ft}^3} \left(\frac{\text{kg}}{\text{m}^3} \right)} = 17 \text{ ft/sec, (m)/sec}$$

The mass-transfer rate is now calculated.

In order to calculate the mass-transfer coefficient, an empirical correlation must be used. The Berger and Hau correlation is used predicting this coefficient. The recommended range of this correlation is $10^4 < \overline{Re} < 10^6$. This correlation will be used for two reasons:

1. The turbulent-flow mass-transfer correlations are based, by analogy, on heat-transfer correlations. And heat-transfer correlations of the same form as Berger and Hau typically are valid up to $\overline{Re} = 10^7$.

2. In view of the limited mass-transfer data at very high Reynolds number, this was judged to be the most suitable correlation for this application.

The Berger and Hau (Ref. 8) correlation is

$$\text{Sh} = 0.0165 \text{Re}^{0.86} \text{Sc}^{0.33} \quad (\text{C1.25})$$

where the Sherwood number and the Schmidt number are dimensionless numbers defined as

$$\text{Sh} = \frac{KD_H}{d} \quad (\text{C1.26})$$

$$\text{Sc} = \frac{\mu}{\rho d} \quad (\text{C1.27})$$

where K = mass-transfer coefficient, ft/sec (m/sec)
 d = diffusivity, ft²/sec (m²/sec)

The diffusivity of dissolved species in water, d , is equal to about 135×10^{-9} ft²/sec (m²/sec) for the temperature of interest.

Thus,

$$\text{Sc} = \frac{\mu}{\rho d} = \frac{9.66 \times 10^{-5} \left(\frac{\text{lbm}}{\text{sec-ft}} \right) \left(\frac{\text{N} \cdot \text{s}}{\text{m}^2} \right)}{55 \left(\frac{\text{lbm}}{\text{ft}^3} \right) \left(\frac{\text{kg}}{\text{m}^3} \right) \times 135 \times 10^{-9} \left(\frac{\text{ft}^2}{\text{sec}} \right) \left(\frac{\text{m}^2}{\text{sec}} \right)} = 13$$

Using the Berger and Hau correlation and rewriting to solve for K ,

$$K = \left(\frac{d}{D_H} \right) (0.0165)(\text{Re})^{0.86} (\text{Sc})^{0.33} \quad (\text{C1.28})$$

Since everything is now known, K is calculated

$$K = \frac{(135 \times 10^{-9} \frac{\text{ft}^2}{\text{sec}}) (\frac{\text{m}^2}{\text{sec}})}{(\frac{17}{12} \text{ft}) (\frac{1}{\text{m}})} (0.0165)(1.37 \times 10^7)^{0.86} (13)^{0.33}$$

$$K = 0.005 \text{ ft/sec or } 1.53 \text{ mm/sec}$$

This mass-transfer coefficient is for a straight pipe. For a rupture occurring near a change in flow direction, the straight pipe value should be increased. Figure C1.18 presents a wide range of data showing the increase of heat and mass transfer with bends of various geometries. At the value corresponding to the elbow (0.5), the data range from about 0.4 to almost 2.0, with most of the data less than 0.7. To bound the problem, three calculations have been made. A low case at a value of 0.4, a midcase at a value of 0.55, and a high case at a value of 0.7. For a straight-pipe mass-transfer coefficient of 1.53 mm/sec, the low-, mid-, and high-mass transfer coefficients in the elbow are: 2.14, 2.35, and 2.60 mm/sec, respectively.

There is a large amount of experimental data correlating mass-transfer coefficient and erosion rate. The data are presented in Fig. C1.19. Using this figure, at the above values, and a pH of 9.0, the predicted erosion-corrosion rates are about 0.4,

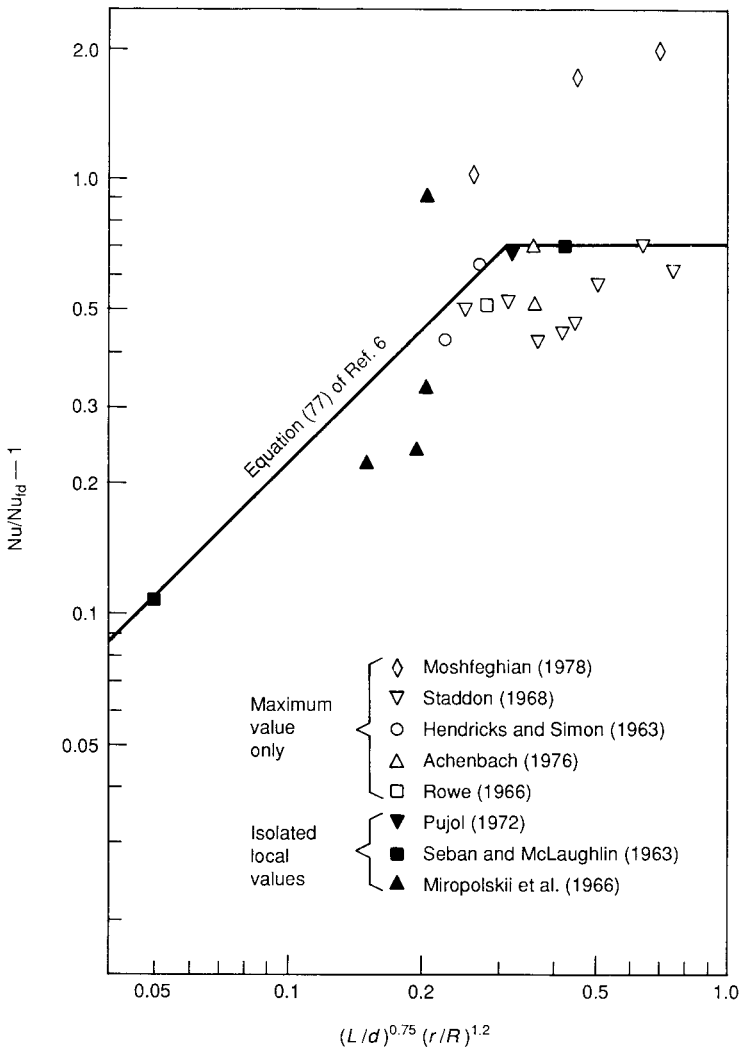


FIGURE C1.18 Comparison of Eq. (77) of Ref. 6 with the data of various authors on heat and mass transfer in bends.

0.5, 0.8 mm/year, respectively. How long would it take at the nd erosion rate to erode the pipe to one-half its original thickness?

$$\text{time} = \frac{\text{thickness}}{\text{erosion rate}} \tag{C1.29}$$

$$\text{time} = \frac{0.25 \text{ inches} \times 25.4 \frac{\text{mm}}{\text{inches}}}{0.5 \text{ mm/year}} = 12.7 \text{ years}$$

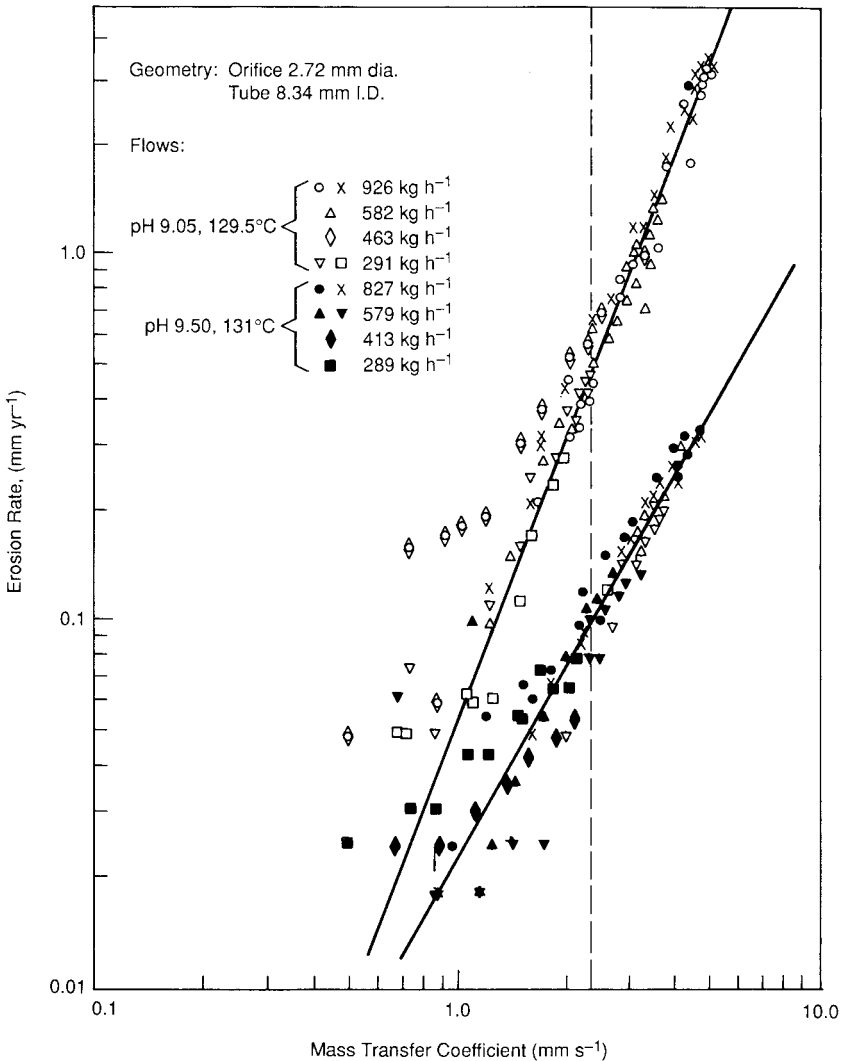


FIGURE C1.19 Mass transfer coefficient dependencies at different pHs. Correlations from loss profiles of specimens at four flow velocities.

At the low rate, the time to thin the wall to half the original thickness is about 15.9 years. At the high erosion rate it is about 7.9 years.

Start-Up, Operation, and Maintenance Considerations

Start-Up and Operation. Prior to start-up of water systems, the piping system should be cleaned as required. In some cases, chemical solvents are utilized, followed by flushing. Care should be taken that components not compatible with the chemical being used are removed during the cleaning and flushing process. Temporary strain-

ers are sometimes included in the system for preoperational purposes. This practice protects pumps and valve-seating surfaces from large particles left in the pipe from the installation and testing periods. Temporary strainers are replaced by spool pieces when the system is ready for start-up. The strainers should be kept on hand and installed in the system during major work or repair to the system and replaced by the spool pieces after the system is certified to be clean. Potable water lines are disinfected prior to being put in service.

Prior to starting any system, the following precautions should be taken and included in plant procedures:

1. Verify that the system is free of debris, has been cleaned and flushed thoroughly, and that all testing and inspections are complete.
2. Verify that all components function as required. Rotate pumps by hand to ensure that impellers rotate freely, exercise valves several times, and if necessary, adjust packing.
3. Verify that all instrumentation is in place and root valves open.
4. Verify that the system piping and components are properly vented and drained. For high-pressure or high-temperature systems, ensure that vents and drains are routed away from personnel or sensitive equipment. Close the valves as evidence of complete venting and drainage occur.
5. Verify valve line up intended for start-up, especially the required positions of pump discharge valves and minimum-flow recirculation valves.
6. Monitor system initial operation for anomalies, such as surges, spikes, leaks, and control failures, and make necessary adjustments or shutdown the system and correct any problems.
7. Monitor system pressures, flow rates, and component response as a regular planned routine. Logs should be maintained to develop a baseline condition for comparison for all modes of operation.
8. System shutdown should generally be performed in reverse of the startup procedure. It is important, however, that specific instructions for the shutdown and securing of a system be included in operational procedures. In most cases drains should be left opened.
9. High-energy systems require extra precautionary measures such as tagging or locking valve positions and the active overrides to controls and interlocks.

Flow Balancing. The system through which water flows offers resistance to flow (as discussed) such as friction, static head, and back pressure. Flow rates in a system vary, depending on several factors, such as

1. Variations in static head
2. Valve alignment
3. System demands or loads
4. Flow control valve operation

All affect system resistance.

To design and operate a system, it would be ideal to assume steady-state operation. If steady-state operation is assumed and the system contains branch lines of flow, it is important for economy and system stability to proportion flow in accordance with the specific demands of each branch or service. This is achieved by flow

balancing. On a theoretical basis this is done by plotting the system resistance curves for each branch for a given system flow. Since the total flow must equal the sum of all branch flows and the total pressure drop across each branch between junction points must be identical, the flow divides to produce these identical losses. The sum of the flow rates through each branch at a particular head provides the total flow rate for the system at that head. The total system flow required can be determined from load data, and resistance can be added to the branch lines by adjusting throttle-valve positions. In some cases orifices may be warranted.

This practice in the field can be tedious but may be made easier with the proper flow- and pressure-measuring instrumentation and favorable throttle-valve characteristics.

Maintenance. A major factor in developing a maintenance program is the accessibility of piping and components. Although accessibility should be designed into a system, it is not always practical; for example, in intake or municipal water systems, where most of the piping is buried. In cases such as this, it is cost effective to maintain piping upon failure. The designer should therefore be attentive about the design for buried pipe, including wall design to handle internal pressure and external loading, coating and linings to protect from corrosion, and other design elements. In considering accessibility of buried piping, the designer considers an alignment that will provide sufficient clearances from adjacent pipelines and structures to allow for possible future excavation and repair. Likewise, the designer may choose an alignment that avoids existing or future paved areas in order to minimize the expense of demolition or repair of the pavement and to minimize traffic disruption during initial construction as well as subsequently if pipeline maintenance is required. Generally, the buried portion of a system is limited to passive components. Piping and normally opened or closed valves not usually requiring normal maintenance fall in this category. Other active components such as pressure regulators, relief valves, pumps, large valves, and metering devices should be located in buildings, modules, or manholes and be readily accessible. For this latter category of components, a rigorous maintenance schedule should be developed.

Depending on the degree of importance for safety and operation of a system, an inspection program should be instituted. Inspection during operation is mostly visual; however, some systems may be fitted with taps or probes for on-line inspection.

Beyond inspection, there are components which must be maintained on a regular basis regardless of need. The components' manufacturer provides instruction manuals which recommend maintenance and spare parts for replacement. The station operator must also use judgment and operating experience in the development and implementation of maintenance procedures. Generally speaking, bolt tensions, gasket condition, and packing leakage can be monitored daily. Pressure and temperature monitoring can show evidence of component deterioration or malfunction. Problems such as clogged strainers, hung-up valves, and leaks or breaks can be determined by instrumentation readings when the problem is not normally visible. Instrument calibration for both system components and testing instruments should be more tightly controlled, although frequency varies. Inspection of coatings and painting on a scheduled basis will help to eliminate corrosion problems for exposed components.

Accordingly, a sufficient supply of spare parts should be on hand. The system can be surveyed to determine which parts should be ordered. Operating experience can also help predict the expected life of parts that wear.

Water sampling should be performed routinely. Depending on the service, it can determine the safety of the supply (if it is for human consumption) or prevent

corrosive or abrasive attack on internal components of the system. Sampling procedures should be developed to locate sampling points and to facilitate storage or transportation to the testing laboratory. Procedures should also contain acceptance criteria for each system application and associated water-treatment solutions for unacceptable water quality.

Occasionally, water systems require flushing or mechanical cleaning. These operations remove bacteriological growth, silt deposits, and scale buildup on pipe walls. Again, strict procedures must be developed and adhered to in order to control work.

Installation and Testing. Designer's piping-arrangement drawings and isometrics, if provided, are the governing documents for installation of piping. Unless existing site conditions warrant otherwise, piping shall be installed in accordance with the piping-arrangement drawings.

Buried Piping. The trench for installation of buried piping shall be of sufficient width and depth to provide necessary bedding and cover, depending on traffic volume and depth of frost line, and to facilitate joining, tapping, and future maintenance considerations. Pipe should be laid flat on the bedding and not supported on the end by the bell.

The trench should be filled in accordance with the specified requirements for fill material, rock size, and compaction. When specified, an insulating type of initial fill may be used. As indicated previously, configuration of trench and type and compaction of bedding and backfill can have a large impact on pipe adequacy to handle external loads. Generally, in the municipal waterworks industry, ductile-iron pipe is installed in accordance with AWWA C600, PVC in accordance with AWWA C905, prestressed concrete pipe in accordance with AWWA Manual M9, and steel pipe with AWWA Manual M11.

Aboveground Piping. For support of aboveground piping, there are two generally accepted procedures. One is to temporarily support the piping during fit-up and then to install the supports. The second procedure is to install the pipe support, then the piping. In either case, location tolerances should be provided and adhered to during design so as not to invalidate stress-analysis calculations. Cold springing of pipe should also be avoided but, if required, kept within tolerances.

Prior to being placed in service, pipelines are generally tested for a specified time period at pressures that include operating and possibly surge-allowance pressures.

REFERENCES

1. *AWWA Principles and Practices of Water Supply Operations*, Vol. 3—"Introduction to Water Distribution."
2. *Hydraulic Institute Engineering Data Book*, 2d ed., 1990, Hydraulic Institute.
3. Harvel Plastics, Inc. Products Bulletin 112/401, Effective 7/1/87, Revised 1/1/89, Havel Plastics, Inc.
4. Larson and Buswell, *Journal of the American Water Works Association*, Vol. 28, 1931, pp. 1500.
5. *EPRI Final Report—Single Phase Erosion-Corrosion of Carbon Steel Piping*, Feb. 19, 1987.
6. M.W.E. Coney, "Erosion-Corrosion: The Calculation of Mass-transfer Coefficients," Central Electricity Generating Board, May 1981, RD/L/N 197/80, Job No. VE 280.
7. M.W.E. Coney, S.J. Wilkin, and H.S. Oates, "Thermal-hydraulic Effects on Mass-transfer Behaviour and on Erosion-Corrosion Metal Loss Rates," Jan. 1983, Central Electricity Generating Board, TPRD/L/2349/N82.

8. F.P. Berger and K.-F F-L Hau, "Mass Transfer in Turbulent Pipe Flow Measured by the Electrochemical Method," 1977, *Int. J. Heat Mass-Transfer*, 20:1185–1194.
9. Ductile Iron Pipe Research Association, TL/8-96/2M, Truck Loads on Pipe Buried at Shallow Depths.
10. Ductile Iron Pipe Research Association, DIPRA/8–96/5M, Design of Ductile Iron Pipe.
11. Ductile Iron Pipe Research Association, Thrust Restraint Design for Ductile Iron Pipe, 3d ed., 1992.