

# PE Pipe— Design and Installation

**Second Edition**



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# PE Pipe—Design and Installations

Second Edition



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Manual of Water Supply Practices—M55, First Edition

## PE Pipe—Design and Installation

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Managing Editor/Project Manager: Melissa Valentine  
Technical Editor: Melissa Valentine  
Cover Design/Technical Illustrations: Mike Labruyere  
Manager, Publishing Operations: Gillian Wink  
Production: Innodata  
Senior Specialist - Manuals: Willadee Hitchcock  
Manuals Coordinator 2: Janet Greifinger

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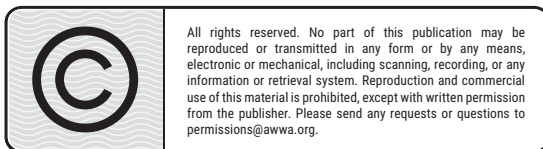
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**American Water Works  
Association**

American Water Works Association  
6666 West Quincy Avenue  
Denver, CO 80235-3098  
[awwa.org](http://awwa.org)

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# Preface



This is the second edition of AWWA M55, *PE Pipe—Design and Installation*. The manual provides the user with both technical and general information to aid in the design, specification, procurement, installation, and understanding of the high-density polyethylene (HDPE) pipe and fittings. It is a discussion of recommended practice, not an American Water Works Association (AWWA) standard calling for compliance with certain specifications. It is intended for use by utilities and municipalities of all sizes, whether as a reference book or textbook for those not fully familiar with HDPE pipe and fittings products. Municipal and consulting engineers may use this manual in preparing plans and specifications for new HDPE pipe projects.

The manual describes HDPE pipe and fittings products and certain appurtenances, and their applications to practical installations, whether of a standard or special nature. For adequate knowledge of these products, the entire manual needs to be studied. Readers will also find the manual a useful source of information for assistance with specific or unusual conditions. The manual contains a list of applicable national standards, which may be purchased from the respective standards organizations (e.g., AWWA, ASTM, etc.). Readers should use the latest editions of the standards that are referenced.

Credit is extended to The Plastics Pipe Institute, Inc. ([www.plasticpipe.org](http://www.plasticpipe.org)) for its contribution to the manual.

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Camille G. Rubeiz, *Chair*

L. Aguiar, Hazen and Sawyer, Coral Gables, Fla.  
J. Allen, Arlington Water Department, Arlington, Tex.  
A. Azimi, Louisiana Technical University, Ruston, La.  
M. Boyce, East Bay Municipal Utilities District, Oakland, Calif.  
J.P. Castronovo, Blue Ridge, Ga.  
A. Dupont, Arlington Water Department, Arlington, Tex.  
J.F. Fishburne, Freese & Nichols Inc., Charlotte, N.C.  
D. Hart, Plastics Pipe Institute, Irving, Tex.  
W. Hitchcock, AWWA Manuals Liaison, AWWA, Denver, Colo.  
A. Howard, Lakewood, Colo.  
T. Iseley, Louisiana Technical University, Ruston, La.  
H. Link, Colorado Springs Utilities, Colorado Springs, Colo.  
R. McKaskle, City of Tulsa – Engineering Services Dept., Tulsa, Okla.  
G. Rocheleau, Makai Ocean Engineering Inc., Kailua, Hawaii  
C.G. Rubeiz, Plastics Pipe Institute, Fairfax, Va.  
A. Schipper, Fort Wayne City Utilities, Fort Wayne, Ind.  
G. Scoby, Cross Bore Consultants, Los Gatos, Calif.  
E. Shaffer, Duluth Public Works & Utilities, Duluth, Minn.  
H. Smith, Duluth Public Works & Utilities, Duluth, Minn.

The following individuals provided support and contributed to the work of the Subcommittee members:

E.A. Ambler, AM Trenchless, Sanford, Fla.  
S. Boros, Pipeline Plastics LLC, Geneva, Ill.  
L.M. Bowles, U.S. Bureau of Reclamation, Denver, Colo.  
R. Brand, East Windsor Municipal Utility Authority, East Windsor, N.J.  
H. Casteel, Performance Pipe, Plano, Tex.  
D. Fink, WL Plastics, Fort Worth, Tex.  
R.P. Fuerst, Denver, Colo.  
L.J. Gill, IPEX, Mississauga, Ont.  
T. Grafenauer, Murphy Pipeline Contractors, Milwaukee, Wis.  
G. Groen, Uponor Infra Limited, Mississauga, Ont.  
W. Heubach, Seattle Public Utilities, Seattle, Wash.  
W. Jee, Sasol Chemicals North America LLC, Houston, Tex.  
D.D. Keller, LyondellBasell Industries, Cincinnati, Ohio  
M.A. Knight, University of Waterloo, Waterloo, Ont.

D. Jensen, Makai Ocean Engineering Inc., Kailua, Hawaii  
J.S. Johnston, McElroy Manufacturing Inc., Tulsa, Okla.  
D. Langston, WL Plastics Corp., Cedar City, Utah  
E. Lever, Gas Technology Institute, Des Plaines, Ill.  
K. Miller, Miller Pipeline, Indianapolis, Ind.  
M. Najafi, University of Texas at Arlington/CUIRE, Arlington, Tex.  
J. Nakano, City Utilities of Springfield, Springfield, Mo.  
M. O'Rourke, Rensselaer Polytechnic Institute, Troy, N.Y.  
D. Pavlovic, Uponor Infra Limited, Mississauga, Ont.  
D.A. Stewart, City of Lago Vista, Lago Vista, Tex.  
D. Stoughton, Charter Plastics Inc., Titusville, Pa.  
H. Svetlik, Georg Fischer Central Plastics LLC, Dallas, Tex.  
M. Whitehouse, ISCO Industries LLC, Louisville, Ky.  
J. Wright, Georg Fischer Central Plastics LLC, Shawnee, Okla.

The AWWA Standards Committee on Polyolefin (PE) Pressure Pipe and Fittings, which reviewed and approved this manual, had the following personnel at the time of approval:

John F. Fishburne, *Chair*  
Camille G. Rubeiz, *Secretary*

*General Interest Members*

L. Aguiar, Hazen and Sawyer, Coral Gables, Fla.  
E.A. Ambler, AM Trenchless, Sanford, Fla.  
J.L. Beaver, Simpson Gumpertz Heger Inc., Waltham, Mass.  
J.P. Castronovo, Blue Ridge, Ga.  
A. Chastain-Howley (*liaison, nonvoting*), Standards Council Liaison, Black & Veatch, Arlington, Tex.  
K.C. Choquette, Des Moines, Iowa.  
A.J. Ciechanowski, NSF International, Ann Arbor, Mich.  
D.E. Duvall, Engineering Systems Inc., Aurora, Ill.  
J.F. Fishburne, Freese & Nichols Inc., Charlotte, N.C.  
D.L. McPherson (*alternate, nonvoting*), HDR, Charlotte, N.C.  
P.J. Olson (*liaison, nonvoting*), Standards Engineer Liaison, AWWA, Denver, Colo.  
J.R. Paschal, Aquatherm, Sandy, Utah  
G. Scoby, Cross Bore Consultants, Los Gatos, Calif.  
S.C. Williams, HDR, Atlanta, Ga.  
S. Ziobro, FM Approvals, Chesham, R.I.

*Producer Members*

S. Boros, Pipeline Plastics LLC, Geneva, Ill.  
G. Garcia (*alternate, nonvoting*), JM Eagle, Los Angeles, Calif.  
L.J. Gill, IPEX, Mississauga, Ont.  
M. Huynh, JM Eagle, Los Angeles, Calif.

R. Houle, Reliance Worldwide Corp., Atlanta, Ga.  
 D. Langston, WL Plastics Corp., Cedar City, Utah  
 L. MacNevin (*alternate, nonvoting*), Plastics Pipe Institute, Ashburn, Va.  
 C.G. Rubeiz, Plastics Pipe Institute, Fairfax, Va.  
 S.D. Sandstrum, ISCO Industries, The Woodlands, Tex.  
 H. Svetlik (*alternate, nonvoting*), Georg Fischer Central Plastics LLC, Dallas, Tex.  
 J. Wright, Georg Fischer Central Plastics LLC, Shawnee, Okla.

*User Members*

J. Allen, Arlington Water Department, Arlington, Tex.  
 M. Boyce, East Bay Municipal Utilities District, Oakland, Calif.  
 J. Cuevas, Los Angeles Department of Water & Power, Los Angeles, Calif.  
 H. Link, Colorado Springs Utilities, Colorado Springs, Colo.  
 A. Marner, U.S. Bureau of Reclamation, Denver, Colo.  
 R. McKaskle, City of Tulsa – Engineering Services Dept., Tulsa, Okla.  
 D.A. Stewart, City of Lago Vista, Lago Vista, Tex.  
 M.A. Wirtz, City of Fort Wayne, Fort Wayne, Ind.

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Chapter **1**

# Engineering Properties of Polyethylene

A fundamental understanding of material characteristics is an inherent part of the design process for any piping system. With such an understanding, the piping designer can use the properties of the material to design for optimum performance. This chapter provides basic information that should assist the reader in understanding how polyethylene's (PE's) material characteristics influence its engineering behavior.

PE is a thermoplastic, which means that it is a polymeric material that can be softened and formed into useful shapes by the application of heat and pressure and which hardens when cooled. PE is a member of the polyolefins family, which also includes polypropylene. As a group of materials, the polyolefins generally possess low water absorption, moderate to low gas permeability, good toughness and flexibility at low temperatures ( $\leq 50^{\circ}\text{F}$ ), and a relatively low heat resistance. PE plastics form flexible but tough products and possess excellent resistance to many chemicals.

## POLYMER CHARACTERISTICS

In general terms, the performance capability of PE in piping applications is determined by three main parameters: density, molecular weight, and molecular weight distribution (MWD). Each of these polymer properties has an effect on the physical performance associated with a specific PE resin. The general effect of variation in these three physical properties as related to polymer performance is shown in Table 1-1.

**Table 1-1 Effects of density, molecular weight, and molecular weight distribution**

| Property                    | As Density Increases | As Molecular Weight Increases | As Molecular Weight Distribution Broadens |
|-----------------------------|----------------------|-------------------------------|-------------------------------------------|
| Tensile stress              | Increases            | Increases                     | —                                         |
| Stiffness                   | Increases            | Increases slightly            | Decreases                                 |
| Impact strength             | Decreases            | Increases                     | Decreases                                 |
| Low temperature brittleness | Increases            | Decreases                     | Decreases                                 |
| Abrasion resistance         | Increases            | Increases                     | —                                         |
| Hardness                    | Increases            | Increases slightly            | —                                         |
| Softening point             | Increases            | —                             | Increases                                 |
| Stress crack resistance     | Decreases            | Increases                     | Increases                                 |
| Permeability                | Decreases            | Increases slightly            | —                                         |
| Chemical resistance         | Increases            | Increases                     | —                                         |
| Melt strength               | —                    | Increases                     | Increases                                 |

## Density

PE is a semicrystalline polymer composed of long, chain-like molecules of varying lengths and numbers of side branches. As the number of side branches increases, polymer crystallinity and hence, density decreases because the molecules cannot pack as closely together. Density affects many of the physical properties associated with the performance of the finished pipe. Properties such as stress crack resistance, tensile strength, and stiffness are all affected by the base resin density of the polymer at a given molecular weight and MWD as shown in Table 1-1.

Base resin density refers to the density of the natural PE that has not been compounded with additives and/or colorants. Within this range, the materials are generically referred to as either medium or high density in nature. PE pipe base resins with density of >0.940 to 0.947 grams per cubic centimeter (g/cc) are high-density polyethylene (HDPE) and are assigned a cell class of 3. HDPE pipe base resins with densities of >0.947 to 0.955 g/cc are assigned a cell class of 4 (see Table 1-3). Industry practice has shown that base resin (unpigmented) densities in the range of 0.940 to 0.955 g/cc offer a highly beneficial combination of performance properties for the majority of piping applications. Density is controlled by the amount of comonomer (typically butene, hexene, or octene) added during polymerization.

The addition of carbon black to the base PE resin does have an impact on the compounded density of the material. Nonblack pigments (e.g., blue or purple) have a negligible effect on density. The addition of 2.0 to 3.0 percent carbon black raises the compounded material density on the order of 0.009–0.013 g/cc. The variability in the actual percentage of carbon black incorporated can have a moderate effect on comparative density values. As a result, industry practice as established by ASTM standard is to provide comparative values on the base resin density as this is a better indicator of the polymer crystallinity.

## Molecular Weight

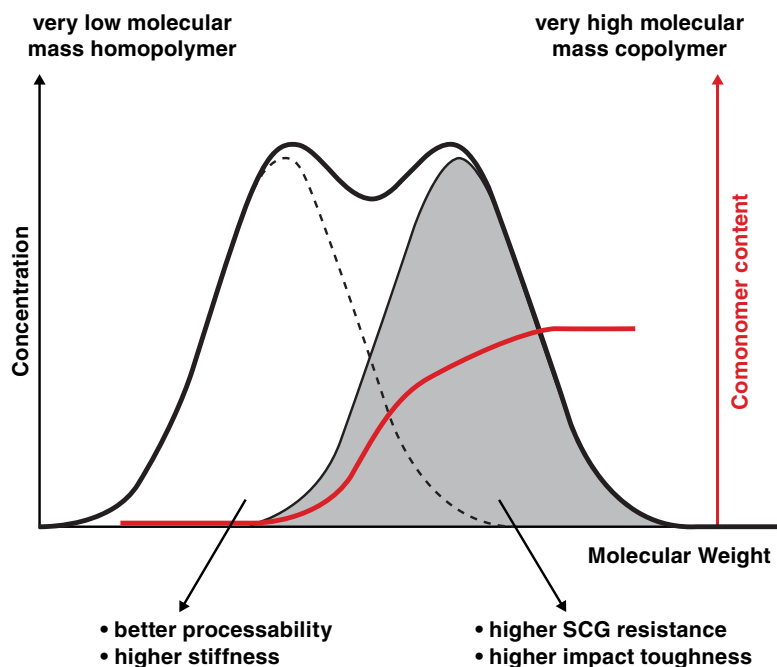
PE resins are composed of a number of molecular chains of varying lengths. As a result, the molecular weight of the resin is the average of the weight of each of these chains. The average weight may be determined using sophisticated scientific techniques, such as gel permeation chromatography (GPC) or size-exclusion chromatography. For PE of a given density and MWD, the effect of increasing molecular weight on physical properties is shown in Table 1-1.

A very rough indicator of the molecular weight of a polymer may be obtained using the melt index technique of analysis as described in ASTM D1238<sup>1</sup>. The melt index technique is an inexpensive means of comparing the molecular weight of PEs having similar structure. Resins with a relatively low average molecular weight will have a comparatively high melt index. Conversely, resins with a relatively high molecular weight will yield a lower melt index. From this relationship, changes in physical properties (as shown in Table 1-1) can be associated with changes in melt index of the material. The melt index should not be used solely as a definitive indicator of molecular weight because variations in polymer structure can affect both molecular weight and melt index.

## Molecular Weight Distribution

Molecular weight distribution refers to the statistical grouping of the individual molecular chains within a PE resin. Resins made up of molecules that vary considerably in molecular weight are considered to have a broad MWD. When most of the molecules are nearly the same length, the MWD is considered narrow. The effect of broadening the MWD of a PE resin having a given density and molecular weight is shown in Table 1-1.

Advances in polymer technology have allowed the production of PE pressure pipe resins with an improved balance of physical properties. The key improvement is to target the comonomer into the higher molecular weight portion of the polymer. Comonomer targeting improves the balance of slow crack growth (SCG) resistance and long-term hydrostatic stress performance. These properties are discussed later in this chapter. One of the ways to target the comonomer is to produce an HDPE with bimodal molecular weight distribution. See Figure 1-1 for a GPC representation of a bimodal resin with comonomer targeting.



Courtesy of HDPE Municipal Advisory Board

Figure 1-1 Example and performance features of the modes of a bimodal PE pressure pipe resin

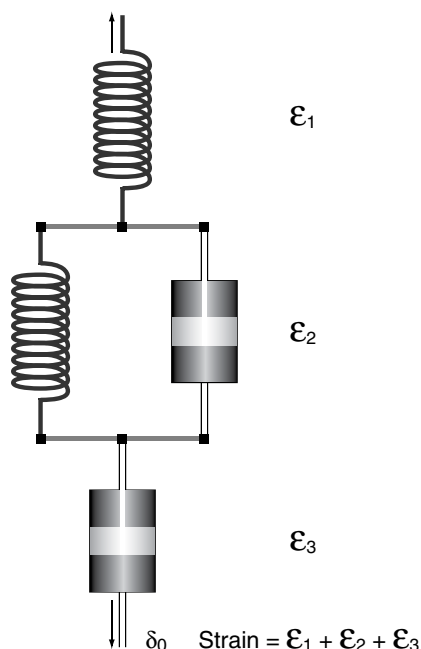


Figure 1-2 Traditional model of HDPE

## MECHANICAL PROPERTIES

### Viscoelasticity

PE is characterized as a viscoelastic construction material. Because of its molecular nature, PE is a complex combination of elastic-like and fluid-like elements. As a result, this material displays properties that are intermediate to crystalline metals and very high viscosity fluids. Figure 1-2 is the traditional diagrammatic representation of PE in which the springs represent those components of the PE matrix that respond to loading in a traditional elastic manner in accordance with Hooke's law. The dashpots represent fluid elements of the polymer that respond to load much as a Newtonian fluid.

As a result of the viscoelastic character of the polymer, the tensile stress-strain curve for PE is divided into three distinct regions. The first of these is an initial linear deformation in response to the load imposed that is generally recoverable when the load is removed. In the second stage of loading, deformation continues but at an ever decreasing rate. Thus, the slope of the stress-strain curve is constantly changing, attesting to its curvilinear nature. Deformation in the second stage may not be fully recoverable. The final stage of the stress-strain curve for PE is characterized by necking down followed by distinct elongation or extension ultimately ending in ductile rupture of the material.

The viscoelastic nature of PE provides for two unique engineering characteristics that are employed in the design of HDPE water piping systems. These are *creep* and *stress relaxation*.

Creep response is a concern for all thermoplastic piping materials including HDPE. Creep refers to the response of PE, over time, to a constant static load. When HDPE is subjected to a constant static load, it deforms immediately to a strain predicted by the stress-strain modulus determined from the tensile stress-strain curve. The material continues to deform indefinitely at an ever decreasing rate. If the load is high enough, the material may yield or rupture. This time-dependent viscous flow component of deformation is called creep. This asserts that the long-term properties of PE are not adequately predicted by

the results of short-term testing, such as tensile stress. As such, PE piping materials are designed in accordance with longer-term tests such as hydrostatic testing and testing for resistance to slow crack growth. When used in accordance with industry recommended practice, the resultant deformation caused by sustained loading, or creep, is not sufficiently large to be an engineering concern.

Stress relaxation is another unique property arising from the viscoelastic nature of PE. When subjected to a constant strain (deformation of a specific degree) that is maintained over time, the load or stress generated by the deformation slowly decreases over time. This is of considerable importance to the design of PE piping systems.

Because of its viscoelastic nature, the response of PE piping systems to loading is time-dependent. The effective modulus of elasticity is significantly reduced by the duration of the loading because of the creep and stress relaxation characteristics of PE. An instantaneous modulus for sudden events, such as water hammer, can be as high as 150,000 psi at 73°F (23°C). For slightly longer duration, but short-term events such as soil settlement and live loadings, the effective modulus for PE is roughly 110,000 to 120,000 psi at 73°F (23°C), and as a long-term property, the effective long-term modulus calculates to be approximately 20,000 to 38,000 psi. This modulus becomes the criteria for the long-term design life of PE piping systems.

This same time-dependent response to loading also gives PE its unique resiliency and resistance to sudden, comparatively short-term loading phenomena. Such is the case with PE's resistance to water hammer, which will be discussed in more detail in chapter 4.

PE is a thermoplastic and, as such, its properties are temperature dependent as well as dependent on the duration of loading. Therefore, the absolute value of the engineering properties of PE will vary in relation to the temperature at which the specific tests are conducted. Industry convention is to design PE piping systems using engineering properties established at the standard temperature of 73°F (23°C) and then employ industry established temperature compensating multipliers to provide for the service condition temperatures.

## Tensile Stress

Tensile stress is a short-term property that provides a basis for classification or comparison when established at specific conditions of temperature and rate of loading but is of limited significance from a design perspective. The tensile stress of PE is typically determined in accordance with ASTM D638<sup>2</sup>. In this test, PE specimens are prepared and pulled in a controlled environment at a constant rate of strain. The response of PE pressure pipe resin in a tensile test is such that the highest value (tensile strength) is reached at the break point (highest strain). From a design perspective, the more important performance property is the tensile stress at yield, which is the value called out in ASTM D3350<sup>3</sup> cell classification (see Table 1-3).

Any material will deform when a force is applied. The amount of deformation per unit length is termed the *strain*, and the force per cross-sectional area is termed the *stress*. As it relates to tensile testing of PE pipe grades, strain is generally approximated by assuming a straight-line relationship to stress at lower stress levels (up to 30 percent of the tensile yield point), and it is reversible. That is, the material deforms but will over time recover its original shape when the stress is removed. The strain in this region is referred to as the elastic strain because it is reversible. The Modulus of Elasticity (or Young's Modulus) is the ratio between the stress and strain in this reversible region. The point at which stress causes a material to deform beyond the elastic region is termed the *tensile stress at yield*. Yield is defined as the point at which an increase in strain occurs without an increase in stress.

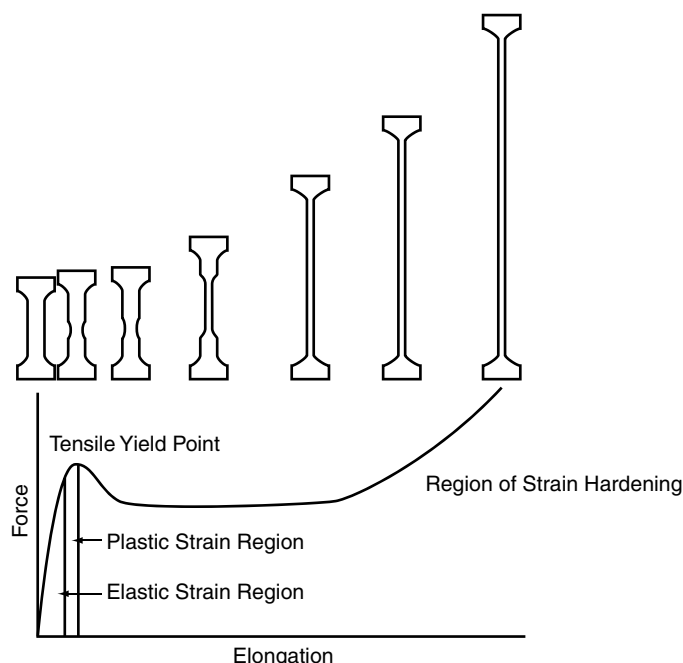


Figure 1-3 Generalized tensile stress-strain curve for PE pipe grades

At stress levels generally greater than 50 percent, strain is no longer proportional to stress and is not reversible, that is, the slope of the stress-strain curve changes at an increasing rate. At these higher stress levels, the materials begin to deform such that the original dimensions are not recoverable. In actual testing of PE pipe grade materials, this stage is characterized by initiation of a distinct “necking” of the tensile specimen. This is called the plastic strain region. The stress required to ultimately break the test specimen is called the *ultimate tensile strength* or the *tensile strength at break* (see Figure 1-3).

Of greater importance is the percent elongation obtained during tensile testing because this information can provide a relative indication of the ductility of the polymer being evaluated. Materials with relatively high levels of elongation are indicative of highly ductile performance as pipe. Modern pipe grade PEs will demonstrate elongations of 400 to 800 percent or more between yield and ultimate tensile rupture.

### Compressive Properties

Compressive forces act in the opposite direction to tensile forces. The effect of compressive force on PE can be measured on a tensile test apparatus using the protocol described in ASTM D695<sup>4</sup>. At small strains (up to 3 percent for most PE pipe resins), the compressive modulus is about equal to the elastic modulus. However, unlike tensile loading, which can result in a failure, compression produces a slow yielding that seldom leads to a failure. For this reason, compressive strength should be reported as the stress required to deform the test specimen to a specific strain. Under conditions of mild compression, the general engineering assumption is that the effective compressive modulus is essentially equivalent to the effective tensile modulus.

## Flexural Properties

The flexural strength of a material is the maximum stress in the outer fiber of a test specimen at 5 percent strain or rupture. Because most PE pipe resins do not break under this test, the true flexural strength of these materials cannot be determined. Per ASTM D3350, the flexural modulus is calculated using the 2 percent secant modulus technique. The standard test method for determining flexural modulus is ASTM D790<sup>5</sup>. Depending on the density of the base resin, the effective flexural modulus of PE can range from 80,000 to 160,000 psi. The flexural modulus of PE is a short-term property that provides a basis for classification but is of limited significance from a design perspective.

## Impact Properties

The amount of energy that a material can absorb without breaking or fracturing is referred to as the impact strength of that material. ASTM D256<sup>6</sup> describes one of the two most commonly used tests for PE pipe compounds, the Izod Impact Test. The other common test, Charpy Impact, can be performed on standard test specimens per ASTM D6110<sup>7</sup> or on thin samples cut from pipe or standard specimens per ASTM F2231<sup>8</sup>. Both tests measure the ability of a PE specimen to absorb energy on failure. Obviously, test information such as this is used to make a relative comparison of the material's resistance to failure on impact under defined circumstances. In this regard, PE is a very tough material demonstrating Izod impact resistance in a "complete" break failure mode with values in the range of 10–12 ft-lbf/in. at standard room temperature. In this range of values, PE pipe grades can also bend or deflect in response to Izod impact testing sometimes resulting in a *hinge* or *no-break* failure mode. These impact values will change to some degree as the temperature at which the test is conducted changes. When Izod impact testing is conducted at very low temperature (<0°F), fracture may occur.

## Abrasion Resistance

PE demonstrates outstanding abrasion resistance under potable water flow conditions. Moreover, the abrasion resistant nature of this material has resulted in the widespread use of PE pipe for liquid slurry handling applications. However, the factors that affect the wear resistance of liquid slurry pipelines are diverse. In addition to flow velocity, one must consider the type of flow regime: laminar (single phase or double phase) or turbulent flow; presence, size, angularity, and concentration of suspended solids; and angle of impingement. While these factors are germane to slurry handling applications, they will have little or no effect on the abrasion resistance of PE pipe used in the transport of clean potable water. At higher flow velocities typical of potable water distribution, there is no erosional effect on PE pipe.

## OTHER PHYSICAL PROPERTIES

### Permeability

The rate of transmission of gases and vapors through polymeric materials varies with the structure of both the permeating molecules and the polymer. Permeability is directly related to the crystallinity of the PE and the size and polarity of the molecule attempting to permeate through the matrix. The higher the crystallinity (the higher the density), the more resistant is the polymer to permeation. PE resins used for the manufacture of water pipe in accordance with ANSI/AWWA C901<sup>9</sup> & ANSI/AWWA C906<sup>10</sup> possess density ranges that make them highly resistant to most types of permeation.

The designer should be aware, however, that all piping systems are susceptible to permeation of light hydrocarbon contaminants that may be present in the soil. With continued exposure over time, these contaminants can permeate from the soil into the pipe itself either through the wall of a plastic pipe or through the elastomeric gasketed joint of a mechanically joined piping system. For this reason, special care should be taken when installing potable water lines through contaminated soils regardless of the type of pipe material (concrete, plastic, ductile iron, etc.).

For more information on permeation, the reader is referred to Appendix B of ANSI/AWWA C901.

## Temperature Effects

PE is a thermoplastic polymer. As such, its physical properties change in response to temperature. These property changes are reversible as the temperature fluctuates. The physical properties of PE are normally determined and published at standard laboratory conditions of 73°F (23°C) with the understanding that the absolute values may change in response to temperature.

For example, the pressure rating of a PE pipe relates directly to the hydrostatic design basis (HDB) of the material from which it is produced. Traditionally, this design property is established at 73°F (23°C). However, as temperature increases, the viscoelastic nature of the polymer yields a lower modulus of elasticity, lower tensile strength, and lower stiffness. As a result, the hydrostatic strength of the material decreases, which yields a lower pressure rating for a specific pipe DR. The effect is reversible in that once the temperature decreases again to standard condition, the pressure capability of the product returns to its normal design basis. However, the elevated temperature pressure rating is always applied for elevated temperature service conditions.

Buried potable water systems typically operate in a range below 73°F (23°C). In these situations, the pressure capability of the pipe may actually exceed the design pressure class ratings listed in ANSI/AWWA C901 and C906. The current industry practice is to set the pressure rating of the pipe at 73°F (23°C) as the standard and consider any added strength at lower service temperatures as an additional margin of safety for design purposes.

The coefficient of linear expansion for unrestrained PE is generally accepted to be  $1.2 \times 10^{-4}$  in./in./°F. This suggests that unrestrained PE will expand or contract considerably in response to thermal fluctuation. However, while the coefficient of expansion for PE is fairly high compared to metal piping products, the modulus of elasticity is comparatively low, approximately 1/300<sup>th</sup> of steel for example. Thermal expansion and contraction effects must be taken into account for surface, above grade, and marine applications where pipe restraint may be limited. But with buried installations, soil friction frequently provides considerable restraint against thermal expansion and contraction movement. In smaller diameter installation, such as those less than 12-in. nominal outside diameter, soil friction restraint can be enhanced by snaking the pipe side to side in the trench prior to backfilling. Additional restraint against movement can be provided with in-line anchors. (See chapter 8.)

In consideration of its thermal properties, PE pipe must be joined using methods that provide longitudinal thrust restraint such as heat fusion, electrofusion, flange connections, and restrained mechanical connections. Additionally, fittings used within the system should possess sufficient pull-out resistance in light of anticipated movement caused by thermal expansion or contraction. Finally, PE pipe should be stabilized or anchored at its termination points to other, more rigid piping or appurtenances to avoid potential stress concentration at the point of transition or to avoid excessive bending moments on system fittings. The reader is referred to chapter 8 for more information regarding control of pull-out forces.

**Table 1-2 Electrical properties of PE**

| Electrical Property | Units     | Test Method | Value                |
|---------------------|-----------|-------------|----------------------|
| Volume Resistivity  | ohms-cm   | ASTM D257   | $>10^{16}$           |
| Surface Resistivity | ohms      | ASTM D257   | $>10^{13}$           |
| Arc Resistance      | seconds   | ASTM D495   | 200 to 250           |
| Dielectric Strength | volts/mil | ASTM D149   | 450 to 1,000         |
| Dielectric Constant | —         | ASTM D150   | 2.25 to 2.35 @ 60 Hz |
| Dissipation Factor  | —         | ASTM D150   | $>0.0005$ @ 60 Hz    |

## Electrical Properties

PE is an excellent insulator and does not conduct electricity. The typical electrical properties of PE are shown in Table 1-2.

## Rapid Crack Propagation

Rapid crack propagation (RCP) is a phenomenon in which a longitudinal crack induced by an external impact propagates rapidly down the pipe and can occur in both plastic and metallic piping materials. The crack is driven by internal pressure and ceases when either the pipe material is able to resist the driving force, or when the piping system has a bell and spigot joint. Air pockets trapped in the line or pressure testing the pipe with air may be contributing factors. Modern HDPE materials (PE4710) have high resistance to RCP due to its ductility and high impact resistance. Piping materials with lower ductility and impact resistance can be more susceptible to an RCP event and additional care should be taken in the design and hydrotesting of the system. The Water Research Foundation has noted that “no known incidents of RCP have occurred in PE water pipe.”<sup>11</sup>

## CHEMICAL PROPERTIES

### Chemical Resistance

An integral part of any piping system design is the assessment of the chemical environment to which the piping will be exposed and the impact it may have on the design life of the pipe. Generally, PE is widely recognized for its unique chemical resistance. As such, this piping material has found extensive utilization in the transport of a variety of aggressive chemicals.

To assist the designer in the selection of PE for piping applications, chemical resistance charts have been published that provide some basic guidelines regarding the suitability of PE as a piping material in the presence of various chemicals. A very comprehensive chemical resistance chart has been published by the Plastics Pipe Institute (PPI) as PPI TR-19<sup>13</sup>.

It is important to note that chemical resistance tables are only a guideline. Data such as this is generally developed on the basis of laboratory tests involving the evaluation of tensile coupons immersed in various concentrations of the reference chemicals. As such, these charts provide a relative indication of the suitability of PE when exposed. They do not assess the impact that continual exposure to these chemicals may have on various aspects of long-term performance nor do they address the effect produced by exposure to various combinations of the chemicals listed. Additionally, these chemical resistance tables do not take into consideration the effect of stress (loading), magnitude of the stress, or duration of application of such stress. In light of this, the designer should use responsible

judgment in the interpretation of this type of data and its utilization for design purposes. Alternatively, the reader is referred to the pipe manufacturer who may have actual field experience under similar specific service conditions.

## Corrosion

PE used in water piping applications is an electrically nonconductive polymer and not adversely affected by naturally occurring soil conditions. As such, it is not subject to galvanic action and does not rust or corrode. This aspect of PE pipe means that cathodic protection is not required to protect the long-term integrity of the pipe even in the most corrosive environments. Proper consideration for corrosion protection should be given to any metal fittings that may be used to join the pipe or system components.

## Tuberculation

The potential for tuberculation of PE pipe is minimal. Tuberculation typically occurs in response to the deposition of soluble encrustants onto the surface of the pipe and subsequent corrosive action with the base material of the pipe. Properly extruded, PE pipe has an extremely smooth inner surface, which provides minimal opportunity for the precipitation of minerals such as calcium carbonate and the like onto the interior surface. PE itself is inert and therefore not prone to galvanic action, which these solubles may initiate in other piping materials.

# ENVIRONMENTAL CONSIDERATIONS

## Weathering

Over time, ultraviolet (UV) radiation and oxygen may induce degradation in plastics that can adversely affect their physical and mechanical properties. To prevent this, various types of stabilizers and additives are compounded into a polymer to give it protection from these phenomena.

The primary UV stabilizer used in the PE pipe industry is carbon black, which is the most effective additive capable of inhibiting UV induced reactions. Carbon black is extremely stable when exposed to the outdoor elements for long periods of time and is relatively inexpensive compared to some of the more exotic colorant systems. The result is a piping system of uniform color that does not chalk, scale, or generate dust in response to extended periods of outdoor exposure.

PE pipe is generally formulated to resist ultraviolet (UV) degradation. Exposure to UV radiation leads to the formation of free radicals within the polymer matrix. These free radicals are then available to react with other molecules within the polymer, and the result can be a significant reduction in physical properties. The carbon black present in PE pipe acts as a primary UV absorber thus precluding the formation of free radicals. In this way, UV degradation is prevented, and the physical properties of the polymer are retained even after substantially long periods of exposure to the elements. Studies conducted by Bell Laboratories on the stability of carbon black containing PE used in wire and cable application have shown that these materials can sustain exposure to the elements over periods of 30 years plus with no appreciable change in the performance characteristics of the polymer<sup>21</sup>.

While carbon black is a very effective UV screen that provides maximum UV protection, the degree of protection it imparts may not be required for buried pipe applications. Generally, UV protection is only required for relatively short periods of time while the pipe is exposed to sunlight such as during storage or while in transit or in the

process of handling during installation. As a result, alternate UV stabilization systems have been developed that have proven very effective and permit the use of colored, nonblack PE pipe. The reader is referred to the pipe manufacturer for information regarding the availability of these nonblack products.

Regardless of type of UV protection (carbon black or UV stabilizers), the damage to the PE pipe from UV exposure is superficial on the ends and external surface of the pipe. Removal of this oxidized surface (by means of facing, scraping, or peeling) is necessary during fusion joining of the PE pipe to ensure joint integrity, see chapter 6 for more information.

## Stabilization

Prolonged exposure to excessive heat can also initiate the generation of free radicals in a polymer. A chemical stabilizer system is typically added to the PE to prevent the generation of these free radicals. Generally, these stabilization systems consist of FDA-approved antioxidants and are designed and selected with the intention of providing long-term protection of the PE polymer from oxidation and thermal degradation. As noted, these additives are generally FDA approved and their suitability of use in potable water applications is determined in accordance with third party standards developed by a consortium that includes NSF International, American Water Works Association, Water Research Foundation, and other groups. The effectiveness of the stabilization system may be evaluated using differential scanning calorimetry (DSC) and/or the carbonyl index test. The DSC test measures the induction time or temperature to the onset of degradation, and the temperature at which degradation begins. The carbonyl index test measures the degree of oxidative degradation by measuring the type and amount of carbonyl functional groups created on the surface of the polymer as a result of excessive exposure to heat, UV radiation, or disinfectant residuals. The presence of carbonyl functional group is an indication that oxidation has occurred but by itself is not a predictor of the mechanical performance of the pipe nor remaining service life.

PE pipe produced in accordance with ANSI/AWWA C901 and C906 must meet the requirements of ASTM D3350. This industry recognized standard requires that the induction temperature by DSC for the onset of degradation must exceed 220°C.

## Biological

Biological attack may be described as the degradation of the piping material caused by the action of organisms such as bacteria, fungi, insects, or rodents. PE has no nutritional value. It is considered inert in that it will neither support nor deter the growth or propagation of micro- or macro-organisms.

Numerous studies have been conducted over the years relative to the biological implications of PE pipe. These studies have revealed that insects or microorganisms pose no threat of damage or degradation to PE pipe. Some indication of rodent damage has been reported but most of this was related to placement of small diameter tubing in rodent infested areas. The resulting damage was attributed to the need for the rodent to maintain their teeth in good condition and the damage associated with gnawing on the profile was felt to be no greater with PE than with any other piping materials installed in these areas. Additional information is available from PPI Technical Report TR-11<sup>12</sup>.

## Disinfectant Residuals

As with any system using mechanical gasketed joints, including HDPE, consideration should be given to the proper selection of gaskets. As shown in ANSI/AWWA C111 (and in others such as C303 and C909), the “selection of materials is critical for water service

and distribution piping in locations where there is a possibility that elastomers will be in contact with chlorine or chloramines. Documented research has shown that elastomers such as gaskets, ... may be degraded when exposed to chlorine or chloramines..." For more details, refer to AWWA C111, Special Issues and to section titled Chlorine and Chloramine Degradation of Elastomers.

In HDPE piping systems, the chlorine classification (i.e., resistance) is determined per section 10.1.11 "Oxidative Resistance Test" of ASTM D3350. Chlorine Classification levels from CC0 (untested/unknown), CC1, CC2 and CC3 (highest performance) are assigned to the PE pipe compound based on the test results and are also added to the material's ANSI/NSF 14<sup>14</sup> listing. Per ANSI/AWWA C901, "PE compounds used in potable water service applications shall be classified as CC2 or CC3 ..." In addition, the AWWA 263 Committee, PPI and the Municipal Advisory Board (MAB) members recommend the use of the highest performing CC3 compounds for ANSI/AWWA C901 and C906 potable water applications.

Secondary disinfectant residuals can lead to the oxidation of HDPE pipe. For a potable water system using chloramine, chlorine, or sodium hypochlorite as the secondary disinfectant, refer to PPI TN-44<sup>15</sup> and PPI TN-49<sup>16</sup> for design guidance. As shown in these PPI documents, there are several factors that need to be considered including water quality (pH, residual level, type of disinfectant), operating conditions (water temperature, system pressure) and piping system (pressure class, diameter, chlorine classification of the HDPE). As was published in the AWWA Journal (Cooper and Gecker 2010)<sup>28</sup>, the design guidance in the PPI documents "shows excellent correlation of the model with observed field performance ..." For a potable water system using ClO<sub>2</sub> as the secondary disinfectant please consult the pipe manufacturer for design guidance.

## LONG-TERM PROPERTIES

### Long-Term Hydrostatic Strength

The pressure capability of PE pipe is based on an extrapolation of stress-rupture data over time. The extrapolation method predominantly used in North America is defined in ASTM D2837<sup>22</sup>. Using this protocol, stress-rupture data at a specific temperature is gathered over a 10,000-hour period. If the data meets certain distribution criteria, the data is extrapolated to 100,000 hours. The stress intercept that is extrapolated at 100,000 hours is referred to as the *long-term hydrostatic strength* (LTHS) of the material being evaluated. The LTHS will fall into one of a series of preferred stress ranges defined in ASTM D2837. The category into which the LTHS falls is referred to as the *hydrostatic design basis* (HDB) of the material. It is this value that is used to determine the pressure capability of a pipe under specified service conditions. The designer is referred to ASTM D2837 for a complete listing of the categories and stress ranges that are used to establish the HDB for thermoplastic materials. The HDB is used to determine the pressure capability of a specific pipe profile or DR under certain conditions of stress. This pressure rating methodology is discussed in detail in chapter 4.

The HDB for a material can be obtained at any of a variety of service temperatures. In fact, it is common practice to evaluate PE at the standard laboratory temperature of 73°F (23°C) and an elevated temperature of 140°F (60°C). Through a statistical analysis of the nature of both of the curves, information regarding the performance of the material under other service temperatures can be determined.

Information such as this is used by the Hydrostatic Stress Board (HSB) of the Plastics Pipe Institute (PPI) to issue recommendations for the HDB of thermoplastics materials that will be used to produce plastic pipe. These recommendations are reviewed and published periodically in PPI's TR-4<sup>23</sup>.

## Resistance to Slow Crack Growth

PE 4710 piping system that is properly designed, installed and manufactured in accordance with the requirements of ANSI/AWWA C901, C906 and AWWA M55 is resistant to slow crack growth.

Slow crack growth is generally referred to as Stage II type failure. In this mode, pipe failure is characterized by very small slit-type failures in the pipe wall that initiate at points of mechanical stress concentration. Mechanical stress concentration can originate from several sources with the most common being improper embedment (e.g., rocks against the pipe wall, improper soil compaction, etc.) Typically, these types of failures are slower in nature and occur as a three-stage process involving: crack initiation, crack propagation, and final ligament yield that results in pipe failure. ANSI/AWWA C901, and C906 include specific requirements to guard against Stage II type failures. ANSI/AWWA C901 and C906 requires that all pipe must be produced from a material for which a PPI hydrostatic design basis (HDB) has been established at 73°F and 140°F per PPI TR-3. This ensures that the PE material meets the stress-rating requirements of both ASTM D2837 as well as the additional requirements in PPI TR-3 to be designated a PE4710. The PE4710 materials are highly resistant to the effects of localized stress concentrations, which can lead to slow crack growth. ANSI/AWWA C901 and C906 also have specific performance requirements for manufactured pipe or fittings, such as thermal stability, an elevated-temperature sustained-pressure test, and a bend back test, which minimizes the potential for SCG failures.

The laboratory test method in ASTM F1473<sup>18</sup> is used to assess resistance to slow crack growth. This standard test method is used within the plastic pipe industry to assess the piping material's resistance to cracking under accelerated conditions of highly concentrated stress and elevated temperature. ASTM F1473, the "PENT" test, applies a constant stress to the PE material and has been particularly well researched as a method to assess the resistance of a PE compound to slow crack growth. The minimum requirement of 500 hours on the PENT test for PE4710 materials has been correlated to more than one hundred years' design life in typical operating conditions. The other slow crack growth tests listed in ASTM D3350, and ASTM D1693, are applied to lower SCG resistant materials such as conduit and corrugated resins and do not adequately assess the performance of pressure pipe materials such as PE4710.

An empirical study of PE pressure piping materials compared ASTM F1473 performance to service life and concluded that a failure time of 12 hours under ASTM F1473 compared to a service history of 50 years<sup>19</sup>. However, an ASTM D3350 SCG cell classification value of 7 (a minimum average failure time of 500 hours per ASTM F1473) is required for PE4710 pipe compounds. This performance level represents at least a 50 times improvement in SCG performance over older PE3408 materials.

In summary, PE pressure piping materials used in AWWA pressure piping are exceptionally resistant to slow crack growth. For further information regarding the evolution of resistance to slow crack growth in PE pipe, see the references at the end of this chapter<sup>20</sup>.

## Fracture Mechanics

Fracture mechanics refers to the study of crack growth originating from flaws that may exist within a material or structure. Flaws may be the result of inhomogeneities within a material, manufacturing inconsistencies, gouges, and scrapes that result from the handling or mishandling of the finished product or any other number of sources.

These flaws, whether microscopic or macroscopic in nature, act to intensify any nominal stress applied within the localized region. At some point, this intensified stress at the flaw will exceed the strength of the material and a small crack may develop. An initiated

crack may subsequently grow and lead to failure of the part or component. Modern PE materials formulated specifically for pressure pipe applications are designed to resist the initiation of this slow crack growth phenomena even when subjected to millions of cycles of pressure transients.

The fracture resistance of a given structure or material will depend on the level of stress applied to it, the presence and size of any flaws in it, and the inherent resistance of the material to crack initiation and growth. Extensive research conducted on gas pipe indicates that modern PE resins designed for pressure piping applications are extremely resistant to slow crack growth<sup>24</sup>. The requirements of ANSI/AWWA C901 and ANSI/AWWA C906 ensure that water pipe produced in accordance with these standards will demonstrate comparable levels of resistance to slow crack growth provided that the pipe system is designed, installed, and operated in accordance with the guidelines stated in subsequent chapters of this manual.

## Fatigue

Each time a PE pipe is pressurized or subjected to hydraulic transients, its circumference expands and unrestrained length decreases in an elastic manner. For applications where the pressure is constant and below the pipe pressure rating, this small amount of expansion (strain) is not important and is not considered a design variable. However, strain does become important when the pipe undergoes higher, cyclic pressurization. There is a maximum critical strain limit, which once exceeded, permanently changes the characteristics of the pipe.

At higher strain levels, microcracks can develop within the PE matrix. Repeated straining that approaches the critical strain limit of the material can cause growth of the microcracks that may eventually propagate into a failure.

For modern PEs used in piping applications, the critical strain limit has been established to be 6 to 7 percent depending on the exact nature of the polymer. The typical PE pressure pipe undergoes a strain of 0.5 to 1.0 percent when placed in service, that is, a safety margin of at least 6 to 1. This is well below the critical strain limit for modern PE pipe resins. Even cyclic pressure surges of up to 100 percent of the operating pressure of the PE water pipe system do not exceed the critical strain limit for these highly ductile materials.

To this end, Bowman and Marshall (1990) have conducted extensive research on the fatigue resistance of modern PE pipe compounds<sup>25, 26</sup>. Based on his research of combined creep and surge regimes at 80°C, Bowman concluded that butt-fused PE piping systems provide years of uncompromised service exceeding millions of surge cycles even under conditions of sustained pressurization. Marshall and his colleagues determined that the current tough PE pipe formulations can withstand sustained periods of high frequency surging (ranging from 1 to 50 cycles per hour) at magnitudes of up to 200 percent of the pipe's static pressure rating with no indication of fatigue and no reduction in long-term serviceability when properly installed. Research results, such as these, serve as the basis for the surge allowances stipulated in ANSI/AWWA C901 and C906. See Appendix A of ANSI/AWWA C901 for more information on surge properties of HDPE pipe.

## INDUSTRY STANDARDS

Industry standards exist to establish the minimum level of performance for polyethylene piping based on the physical properties resulting from the combined effect of the three fundamental molecular properties: density, molecular weight, and MWD. Primary among these standards is ASTM D3350 and the various additional standards included by reference within ASTM D3350.

ASTM D3350 is a comprehensive classification standard that identifies PE compounds by delineating seven key properties associated with piping performance and establishing ranges of performance for each of these. ASTM D3350 is used to classify all PE pipe materials for pressure and nonpressure applications. The result is a matrix of piping related material properties identified by classification cells, which can identify the particular polyethylene compound used to manufacture pipe.

By using ASTM D3350, a specific combination of six numbers, one letter, and the chlorine classification can identify a PE compound in accordance with classified performance properties for the PE compound. Pipe produced in accordance with ANSI/AWWA C901 and ANSI/AWWA C906 must be manufactured from PE material, which meets one of several cell classifications in accordance with ASTM D3350. As noted in ANSI/AWWA C901 and ANSI/AWWA C906, higher cell classes for some of the properties are allowed, but those for density and HDB are not. Considering the case for one of these cell classifications, PE 445574C CC3, Table 1-3 presents an explanation of the physical properties covered by the classification.

The seventh property, color and UV stabilizer, is identified by a letter, which follows the six physical property cell classification numbers. The code letters for color and UV stabilizer are:

- A – for natural
- B – for colored
- C – for black with minimum 2 percent carbon black
- D – for natural with UV stabilizers
- E – for colored with UV stabilizers

PE pipe compounds are typically black with a minimum of two percent carbon black, C, or colored with UV stabilizers, E.

For potable water applications, a suffix to the seven position code is added to indicate the chlorine classification of the pipe compound.

The letter designation in the D3350 method of classification establishes a requirement for color and/or stabilization against the deleterious effects of UV light. In this particular case, the letter C refers to a material that must contain a minimum of 2–3 wt.% carbon black. The carbon black not only acts as a colorant but also as a primary UV stabilizer.

There are also several requirements in addition to cell class properties in ASTM D3350 (elongation at break, low temperature brittleness and DSC induction temperature) with common requirements for all PE pipe materials and can be found in Section 6 of ASTM D3350.

**Table 1-3 Example of D3350 Cell Classification for PE4710\***

| Property                     | ASTM Method | Cell Value | Property Value Range          |
|------------------------------|-------------|------------|-------------------------------|
| Density                      | D1505       | 4          | >0.947–0.955 g/cc             |
| Melt Index                   | D1238       | 4          | 4–20 g/10 min (Cond 190/21.6) |
| Flexural Modulus             | D790        | 5          | 110000–160000 psi             |
| Tensile Strength             | D638        | 5          | 3500–4000 psi                 |
| Slow Crack Growth Resistance | F1473       | 7          | >500 hours                    |
| Hydrostatic Design Basis     | D2837       | 4          | 1600 psi                      |
| Color and UV Stabilizer Code | D3350       | C          | 2–3 wt.% carbon black         |
| Chlorine Classification      | D3350       | CC3        | Highest                       |

\* Because of changes in ASTM D3350 cell classification values with the introduction of PE4710, it is not possible to provide a historical comparison of properties to prior materials such as PE 3408. Instead the reader is referred to the prior edition of M55.

ASTM D3350 is a specification for identifying PE compounds in accordance with a cell classification system. It does not constitute a material specification; that is, ASTM D3350 cell classification properties are not intended for use to specify design or engineering properties for an application. For an ASTM D3350 cell classification, numerous lots of a particular commercially available PE compound are tested, then the average physical property values are classified per ASTM D3350 to determine the cell classification for that particular PE compound. The cell classification values for the PE compounds in ANSI/AWWA C901 and ANSI/AWWA C906 are established such that the PE compounds specified in ANSI/AWWA C901 and C906 can produce PE pipe and fittings that will meet or exceed the product performance requirements established in ANSI/AWWA C901 and C906.

PE is a thermoplastic material and may therefore be manufactured into a product, then ground into particles and remanufactured into another product. Once a product has been reduced to particles of an appropriate size, the material is called *rework* or *regrind*. Rework material for plastic pipe manufacturing is defined in ASTM F412<sup>27</sup>.

ANSI/AWWA C901 and C906 allow for the use of rework material in the production of PE pipe with specific limitations. Clean rework materials are derived from the manufacturer's own pipe or fitting production and are used by the same manufacturer in combination with new PE compound that has the same cell classification or material designation. Rework material shall have met the requirements for new PE compound per ANSI/AWWA C901 or C906, and products containing rework shall meet the requirements of ANSI/AWWA C901 or C906. The specific limitations for rework materials in ANSI/AWWA C901 and C906 assure that using regrind or rework material does not adversely affect pipe or pipe fittings that are produced using a combination of new PE compound and rework material.

The requirement in ANSI/AWWA C901 and C906 for "clean rework materials derived from the manufacturer's own pipe or fitting" prevents the use of PE material that has left the control of the original manufacturer, i.e., pipe products that were in service and were replaced. Materials that have been recovered after leaving the manufacturer's facility or after installation or in-service operation are considered recycled materials. Recycled materials are not allowed in ANSI/AWWA C901 or C906.

Thermoplastic pipe material designation codes (TPMD codes) are technical names for thermoplastic compounds. For PE compounds as defined in ASTM F412, the TPMD code consists of the abbreviation for the thermoplastic material (PE) followed by two numbers for short-term properties (density and SCG resistance classifications), followed by two numbers for the hydrostatic design stress rating in hundreds of psi with tens and units dropped. Per PPI TR-4, the HDS rating of PE4710 is 1,000 psi. See the following example:

- PE4710 = polyethylene (PE); ASTM D3350 density classification 4 (>0.947 to 0.955 g/cc), ASTM D3350 SCG classification 7 (>500 hours per ASTM F1473); 10 = 1,000 psi HDS rating.

## SUMMARY

The information in this chapter is provided to assist the reader in understanding some of the fundamental properties of PE. A basic understanding of these properties will assist the pipe designer in the effective use of these materials and serve to maximize the utility of the service into which they are ultimately placed. For further information concerning the engineering properties of PE piping, the reader is referred to a variety of sources including pipe manufacturer's literature, additional publications of the PPI, and the references at the end of this chapter.

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## Chapter 2

# Manufacturing, Testing, and Inspection

As stated in chapter 1, PE belongs to a group of polymers called thermoplastics. Thermoplastics first soften and then melt with sufficient heating and reharden when cooled. The thermoplastic behavior of PE allows it to be readily shaped by processes such as extrusion, molding, machining, or thermoforming into pipe, fittings, and parts for other applications. Parts processed from PE are essentially isotropic in their properties such that regardless of the orientation of the part or stress applied, properties such as tensile strength and resistance to slow crack growth are essentially the same. This makes it excellent for use in molded parts with complex shapes. In some special molding or production circumstances, PE's isotropy can be reduced, but this reduction can be compensated for and even used to improve material properties for particular applications.

PE is quite viscous in the molten state and can be easily fused to itself. This feature allows PE pipe and fittings to be fabricated by the thermal fusion of separate components. Thermal fusion is also the basis for the butt-, socket-, and electro-fusion processes, which are used for the joining of PE fittings to pipe.

To protect PE against thermal and oxidative degradation during fabrication and ensure a long shelf and service life, PE is always compounded with a small amount of additives. Common additives used in PE pipe compounds include thermal processing stabilizers, long-term antioxidants (e.g., phenolics, phosphites) and ultraviolet inhibitors (e.g. UV absorber, hindered amine light stabilizers (HALS)). Other additives, such as pigments, can also be added to modify the appearance or physical properties of the polymer.

PE pipe resins are generally available to the pipe and fittings manufacturer in the form of natural pellets, whereby all required ingredients except for pigment are premixed and predispersed into the base polymer. These pelletized compounds are commonly

delivered to the piping manufacturer by hopper trucks or tank cars, and off-loaded into silos and transferred to the fabricating equipment by pneumatic conveying systems.

The natural pellets are then mixed with an approved color concentrate at the pipe or fitting production site to result in an appropriately colored finished product.

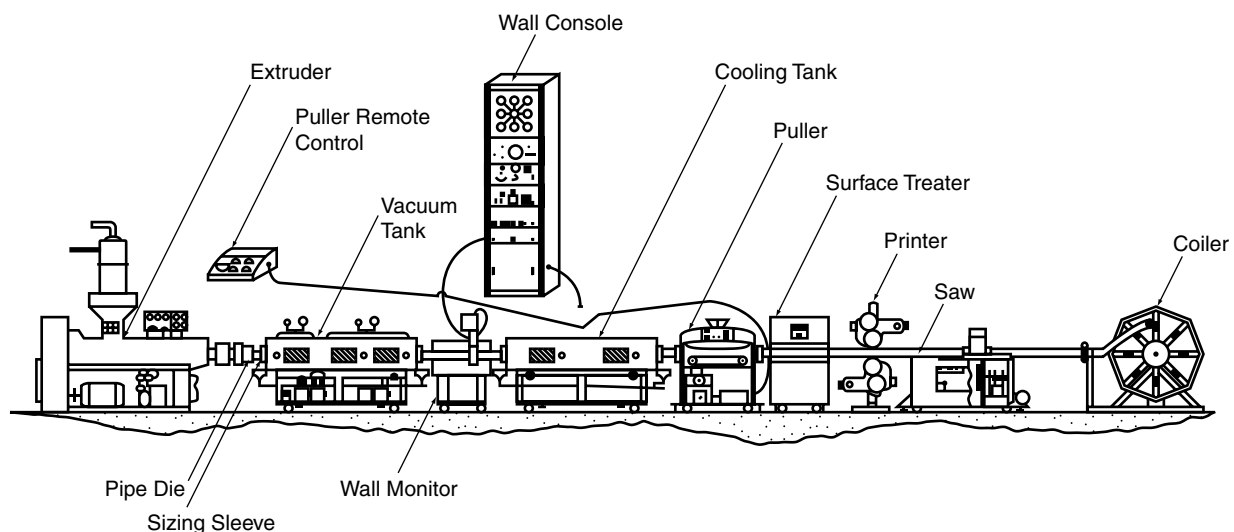
## PIPE MANUFACTURE

In accordance with ANSI/AWWA C901 and ANSI/AWWA C906, PE pressure pipes are manufactured by the extrusion process, whereby molten polymer material is continuously forced through an annular die by a turning screw. As the screw rotates, the flights on the screw continually convey material closer and closer to the die. The pipe is shaped as it exits the die and into the downstream equipment.

Although simple in concept, the extrusion process used in the manufacture of plastic pipe employs a series of fairly sophisticated equipment that reliably and continuously performs the functions of feeding, melting, and mixing the material, delivering it to the die at appropriate and consistent conditions, accurately shaping and sizing the pipe, and cooling and cutting or coiling the product to precise lengths. As illustrated in Figure 2-1, this series of equipment, commonly referred to as an extrusion line, generally consists of the extruder, the pipe die, sizing and cooling tanks, pipe puller, saw, and take-off equipment.

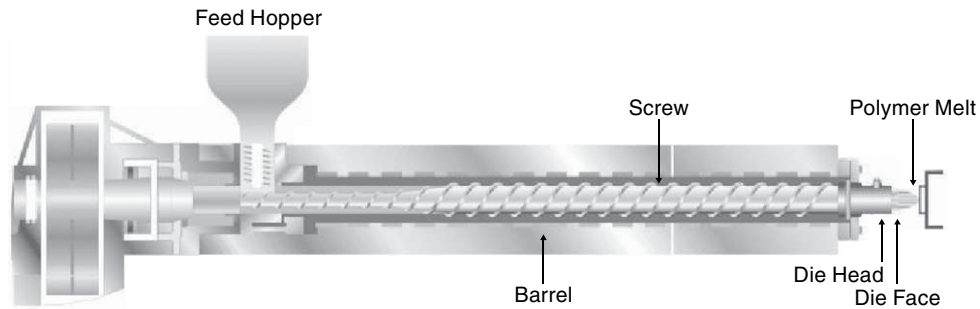
The extruder (Figure 2-2) is used to mix and heat the material to the prescribed temperature and to force the molten polymer through the pipe extrusion die. The source of heat to initially melt the polymer during start-up is usually a series of heater bands wrapped around the extruder barrel. However, once the extruder is operating at steady-state, almost all of the heat needed to melt the PE pellet feed comes from friction caused by the shearing of the PE material by the revolving screw while it is mixing and compressing the plastic. Cooling fans or water hook-ups are also usually attached to the barrel of the extruder in the event cooling is needed.

Throughout the length of the screw, the temperature of the plastic is closely monitored and controlled. The temperature settings depend a great deal on throughput rates, screw and die geometry, and the limits of the material being extruded.



Courtesy of the Plastics Pipe Institute.

**Figure 2-1** Typical extrusion line



Courtesy of HDPE Municipal Advisory Board.

**Figure 2-2 Typical pipe extruder**

The pressure of the molten PE at the end of the extruder barrel before it enters the die can range from 1,000 to 5,000 psi. The melt pressure is dependent on the flow characteristics (molecular weight and molecular weight distribution) of the PE used and the geometry and speed of the extrusion line.

The melt then passes through a screen pack that consists of one or more fine mesh screens before entering the die. The screen pack prevents foreign contaminants from entering the pipe wall, and it also generates some additional back pressure in the polymer melt further enhancing the quality of mixing.

The die shapes the extrusion melt into a cylinder of slightly greater size than the final pipe product. When the PE melt exits the die, it is still molten, but the high viscosity of the material allows it to retain its shape. The final dimensions of the solid pipe are set by the sizing and cooling operation downstream of the die. Sizing is accomplished by pulling the hot PE cylinder through an accurately bored sizing sleeve that fixes the pipe's outside diameter. The pipe's outer surface is tightly held against this sleeve by applying either vacuum on the outside of the pipe or internal pressure on the inside of the pipe. While the pipe is being sized, it is also being cooled with water to set the outside diameter. The pipe must be cooled even after the outside diameter has been set to remove heat stored in the pipe wall. To accomplish this, one or more cooling tanks are set up downstream of the sizing sleeve/tank, and the pipe is pulled through each.

A puller placed after the cooling tanks provides the necessary force to pull the pipe through the entire cooling operation. The pulling rate in relation to the extrusion rate is very carefully set and maintained for accurate control of pipe wall thickness. The pulling rate is usually slightly faster than the extrusion rate to draw down the wall. This practice promotes consistency in wall thickness and some orientation to the polymer melt.

A printer for marking the pipe is usually located either immediately before or after the puller. In accordance with AWWA standards, the marking must be placed at frequent intervals and identify the pipe material, nominal pipe size, pipe class or dimension ratio (DR), the manufacturer, and a manufacturing code that provides specific information such as manufacturing date, location, or other data to assist in the traceability of the product.

Beyond the printer, the pipe is cut to the correct length and dropped into a storage or bundling cart. Small diameter pipe such as 6-in. nominal diameter and smaller is available as coils for handling, shipping, and installation convenience.

## FITTINGS MANUFACTURE

Plastic pipe fittings, because of their complex geometry, are generally manufactured by the injection molding process. This process is similar to extrusion in that the major operational steps are the same: mixing and melting of the material, then shaping and sizing, and finally cooling of the fitting. While these steps are continuous in extrusion, they are performed cyclically in injection molding (Figure 2-3).

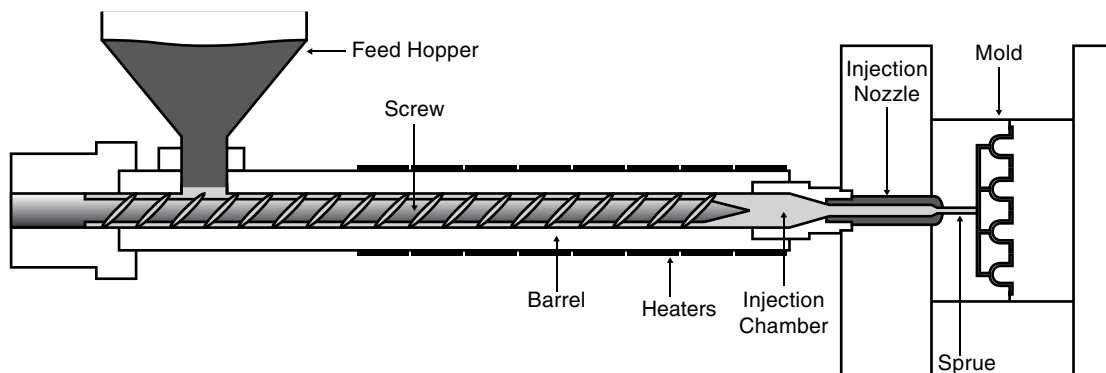
First, incoming resin in the form of pellets is melted by a combination extruder-injection screw. The screw turns to thoroughly melt and mix the pellets while conveying the material to the tip of the screw. The screw plunges forward to force the molten PE through the nozzle and into a closed, heated mold. In the next stage, the full mold is cooled by circulating cold water while the screw maintains pressure on the mold. Once the fitting is thoroughly cooled and solidified, the mold is opened, and the finished fitting is removed.

Injection molded fittings include tees, 45° and 90° elbows, reducers, couplings, caps, flange adapters and stub ends, branch and service saddles, and self-tapping saddle tees, and shall be manufactured in accordance with ASTM D3261 (molded) or ASTM F1055 (electrofusion)<sup>12</sup>. These molded fittings are designed to be applied on the pipe by means of socket-, butt-sidewall or the electro-fusion process (Figure 2-4). The details of the heat fusion process are discussed in chapter 6.

Fittings can also be manually fabricated. Fabricated fittings are constructed by heat fusing sections of pipe, machined blocks, or molded fittings to produce the desired configuration, and shall be manufactured in accordance with ASTM F2206. Because of tests required under AWWA standards, fittings such as elbows cannot be fabricated in the field.

Fabricated fittings intended for full pressure service must be designed with additional material in areas subject to high stress. The common commercial practice is to increase wall thickness in high-stress areas by using heavier wall pipe sections. This is similar to molded fittings that are molded with heavier body wall thickness. Refer to GTI research for further detail on proper design of fabricated fittings<sup>13</sup>. Pressure ratings of fabricated fittings should match the pressure rating of the pipe.

Fittings can also be fabricated using the thermoforming process by heating a section of pipe and using a forming tool to reshape the heated area. Examples are sweep elbows, swaged reducers, and forged stub ends. The area to be shaped is immersed in a hot liquid bath and heated to make it pliable. It is removed from the heating bath and reshaped in the forming tool. The new shape is held until the fitting has cooled.



Courtesy of HDPE Municipal Advisory Board.

**Figure 2-3 Typical injection molding machine**



Courtesy of HDPE Municipal Advisory Board.

**Figure 2-4 Prefabricated 90° elbow being attached in field**

## TESTING AND INSPECTION

The purpose of testing and inspecting raw materials and finished products in the manufacturing of PE piping can be grouped into three categories: 1) to ensure that materials and processes used are qualified for the intended product and service; 2) for quality control of incoming materials and of manufacturing processes; and 3) for assurance that the end product, after manufacture, is in compliance with the requirements of the applicable AWWA Standards such as AWWA C901 and C906 standards.

Qualification testing documents the long-term properties of the PE resin and the process conditions for yielding a product that is suitable for the intended service and is in compliance with the applicable standards. Quality control (QC) testing is conducted during manufacture and provides timely feedback used for maintaining the process and product performance at a high level. Quality assurance (QA) testing, which often takes longer and is more complex to perform than is practical for QC purposes, is conducted to give greater and final assurance of product quality and compliance.

### Qualification Testing

There are qualification requirements imposed on both the material and end product. PE used for the manufacture of pipe and tubing in accordance with AWWA standards must demonstrate the following qualifications:

**Health effects evaluation.** Per ANSI/AWWA C901 and C906, all materials for pipe and fittings must comply with NSF/ANSI/CAN 61<sup>2</sup>. NSF/ANSI/CAN 61, which was developed by a consortium that included the American Water Works Association and the Water Research Foundation, establishes minimum requirements for the control of potentially

adverse human health effects from products that contact drinking water. To qualify under this standard, testing must be conducted to verify that substances cannot be extracted by water in quantities that can reasonably be determined to result in toxic, carcinogenic, teratogenic, or mutagenic effects in humans who may be consuming water that comes in contact with products made from the subject material. NSF/ANSI/CAN 61 certification is included in the NSF/ANSI 14 product listing.

**Long-term hydrostatic strength.** Materials must be tested to establish that their minimum long-term hydrostatic strength is in compliance with the requirements of the applicable AWWA product standard. ANSI/AWWA C901<sup>3</sup> and C906<sup>4</sup> standards allow materials listed in PPI TR-4<sup>5</sup>. To obtain a listing in this document, resin manufacturers are required to submit stress-rupture data developed in accordance with PPI TR-3<sup>6</sup>. Based on such data, PPI assigns the subject material a hydrostatic design basis (HDB) and lists the material's trade name and corresponding HDBs in PPI TR-4.

**Material cell classification.** ANSI/AWWA C901 and C906 also require that PE materials have a cell classification per ASTM D3350<sup>7</sup>. This specification uses a cell format whereby materials are classified according to certain physical properties (i.e., density, flexural modulus, tensile strength, etc.). AWWA standards also require a minimum level of antioxidants and ultraviolet (UV) radiation protection.

Additional qualification requirements for PE pipe and fittings are detailed in ANSI/AWWA C901 and C906 along with their referenced ASTM standards.

## Quality Control Testing

QC testing is conducted both on the incoming plastic piping materials and the manufactured pipe and fittings. The intent of the material QC tests is to determine that the materials comply with AWWA requirements and that the material properties also match the incoming certificate of analysis from the resin manufacturer. The intent of the latter is to ensure that the incoming material type is qualified for pipe and fitting manufacture. Typical material QC tests include density per ASTM D1505<sup>8</sup> or ASTM D792<sup>9</sup> and melt index per ASTM D1238<sup>10</sup>.

PE pipe manufacturing is a continuous process. Therefore, the pipe producer generally monitors those process control variables that are determined as quality critical. Detailed records of these production variables are kept as a means to monitor the pipe production process thereby ensuring the quality of the pipe. Additionally, QC tests are conducted on the pipe during production on a regular basis to further ensure the quality of the finished product. These tests include but are not limited to the following:

- **Dimensions.** Pipe diameter, wall thickness, ovality, and length are periodically measured in accordance with ASTM D2122<sup>11</sup> to ensure compliance. All fittings also are periodically checked for proper dimensions and tolerances.
- **Workmanship.** All pipe, tubing, and fittings are routinely inspected to ensure that they are homogenous throughout—free of visible cracks, holes, foreign inclusions, blisters, dents, or other injurious defects. They are also checked to ensure that they are as uniform as commercially practical in color opacity, density, and physical properties.
- **Tensile tests.** Pipes are subject to one of the following tests per the requirements of ANSI/AWWA C901 or C906:
  - a. Quick-burst test
  - b. Five-second pressure test
  - c. Ring tensile strength test

- **Bend-back test.** The bend-back test evaluates the inside pipe surface for brittleness. The evaluation is made by careful visual inspection of the inside surface of an arc section of the pipe that has been highly strained by bending against the curvature of the outer pipe wall. The presence of visible surface cracking or crazing signals that this surface may have become thermally degraded by excessive extrusion temperatures.
- **Marking.** All pipe and fittings are frequently checked to ensure that they are clearly and appropriately marked in accordance with the applicable AWWA standard.

## Quality Assurance Testing

Quality assurance (QA) testing is performed on a statistical basis at the completion of the manufacturing process for further assurance that the product satisfies all applicable standards. Typical QA testing includes the following:

- **Elevated-temperature sustained-pressure test.** In this test, the average failure time of three pipes and the failure time of two of the three pipes must exceed certain minimum requirements when tested at specified pressures and 80°C. See ANSI/AWWA C901 or C906 for additional information.
- **Thermal stability test.** In this test, a sample cut from extruded pipe is evaluated against the minimum stabilizer protection requirements to ensure that the extrusion process has not used up antioxidants and stabilizers that have been added to the raw materials. This is important for ensuring adequate stabilizer protection for the long-term performance of the piping product.

## SUMMARY

This chapter provides information regarding the qualification, manufacturing, inspection, and testing systems used for the production of PE water pipe and fittings. A fundamental understanding of the production process and the quality assurance and qualification testing inherent to PE pipe should allow the designer or installer of these products to use them with confidence for their intended purpose in potable water applications. For additional information on these systems, please consult the piping or fittings manufacturer or the ASTM and AWWA standards referenced in the text.

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Chapter **3**

# Hydraulics of PE Pipe

This chapter discusses the Darcy-Weisbach and Hazen-Williams flow equations for use with water flow in PE pipe. These equations depend, to some extent, on experimentally determined coefficients. The typical design friction coefficients for PE pipe are presented; however, the engineer may adjust the design friction factors based on experience and actual field conditions.

For the same change in flow velocity and for the same dimension ratio, PE pipes usually experience lower surge pressures than other types of pipe because of the lower elastic modulus of PE. Surge equations are discussed in chapter 4.

## DETERMINING THE FLOW DIAMETER OF A PE PIPE

Most PE pipe is made to controlled standard outside diameters and in either iron pipe sizes (IPS) or ductile iron pipe sizes (DIPS). When the outside pipe diameter is specified, the pipe's inside diameter is determined by the pipe's required wall thickness. The thicker the required wall, the smaller is the pipe's inside diameter.

The minimum wall thickness of a pipe is, in turn, determined by the pipe's specified dimension ratio ( $DR$ ). By definition, the  $DR$  is the ratio of the specified average outside diameter of the pipe ( $D_o$ ) to its minimum required wall thickness ( $t$ ) or,  $DR = D_o/t$ . To ensure compliance with the minimum wall thickness requirements of applicable standards, the average wall thickness of PE pipe is slightly greater than the minimum. The typical tolerance for PE pipe wall thickness is plus 12 percent, so the accepted practice is to assume that the average wall ( $t_a$ ) is 6 percent thicker than the specified minimum ( $t$ ). According to this practice, the average inside pipe diameter ( $D_i$ ) of pipe that is made to a standard outside diameter ( $D_o$ ) is as follows:

$$D_i = D_o - 2t_a = D_o - 2(1.06t) \quad (\text{Eq. 3-1})$$

Because  $t$  is determined by a pipe's  $DR$  (or  $SDR$ ), then:

$$D_i = D_o - \frac{2.12D_o}{DR} \quad (\text{Eq. 3-2})$$

Tables in Appendix E give the dimension ratio, outside diameter, minimum wall thickness, average inside diameter, weight, and static pressure rating for IPS and DIPS pipe.

## FRICTION HEAD LOSS

The frictional head loss that occurs in a moving, essentially incompressible fluid is given by the Darcy-Weisbach equation:

$$h_f = f \frac{v^2 L}{2g D} \quad (\text{Eq. 3-3})$$

where:

- $h_f$  = frictional head loss, ft of liquid head
- $f$  = Darcy-Weisbach Friction Factor, dimensionless
- $v$  = average velocity of flowing fluid, ft/s
- $g$  = acceleration due to gravity, 32.2 ft/s<sup>2</sup>
- $L$  = length of pipe, ft
- $D$  = pipe inside diameter, ft

The velocity of the flowing fluid ( $v$ ) may be calculated from the rate of fluid flow and the pipe's average inside diameter. A commonly used formula is as follows:

$$v = 0.4085 \frac{Q}{d^2} \quad (\text{Eq. 3-4})$$

where:

- $v$  = average velocity of flowing fluid, ft/s
- $Q$  = flow rate, gal/min
- $d$  = pipe inside diameter, in

## DARCY-WEISBACH FRICTION FACTOR

Depending on the characteristics of the pipe surface, the nature and velocity of the flowing fluid, and the operating conditions, flow can occur in one of three regimes: laminar, transitional, or fully turbulent. Each of these three regimes is characterized by a different kind of response of frictional resistance to fluid flow that is presented by the inner pipe surface. These differences are illustrated by the Moody diagram (Figure 3-1) in which the Darcy-Weisbach factor of Eq. 3-3 is plotted against the Reynolds number (Re), a parameter that is defined as follows:

$$\text{Re} = \frac{vD}{\gamma} \quad (\text{Eq. 3-5})$$

where:

- Re = Reynolds number, dimensionless
- $\gamma$  = kinematic viscosity of the flowing fluid, ft<sup>2</sup>/s (the ratio of dynamic viscosity to mass density)
- $D$  = average inside pipe diameter, ft
- $v$  = velocity of the flowing fluid, ft/s

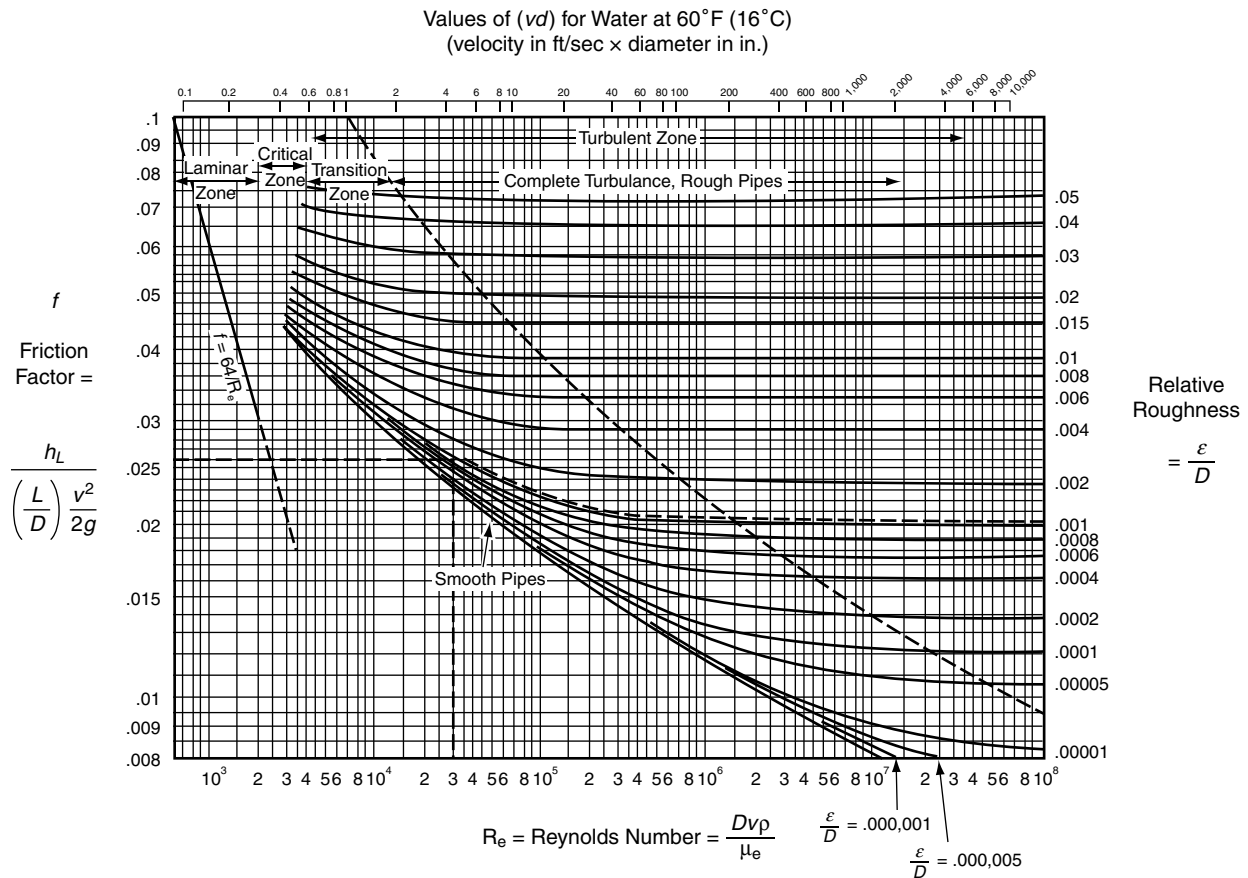


Figure 3-1 Moody diagram

At low Reynolds numbers ( $Re < 2,000$ ), flow is laminar and the friction factor,  $f$ , is not dependent on wall roughness. It is only a function of the Reynolds number.

$$f = \frac{64}{Re} \quad (\text{Eq. 3-6})$$

Eq 3-6 plots as a straight line with a slope of  $-1$  on the Moody diagram.

Between the laminar and transition regions lies a critical zone. In this zone, which lies in the range of Reynolds numbers between approximately 2,000 and 4,000, the flow may be either laminar or turbulent depending on several factors that can include pipe roughness, changes in pipe cross-section and in direction of flow, and obstructions such as valves and fittings. The friction factor in this region is indeterminate and has lower and upper limits based on laminar flow and turbulent flow conditions.

At Reynolds numbers above approximately 4,000, flow conditions become more stable and definite friction factors can be established. The effect of both the Reynolds number and the roughness of the pipe wall on the friction factor in this region has been defined based on extensive experimental data. The results are incorporated into the Moody diagram. Colebrook developed the following empirically derived equation for predicting the friction factor in the transition region between smooth and fully turbulent flow:

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left[ \frac{\epsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}} \right] \quad (\text{Eq. 3-7})$$

where:

$\epsilon$  = absolute roughness of the pipe, ft

As noted on the Moody diagram (Figure 3-1), the quantity  $\epsilon/D$  in the Colebrook equation is referred to as the relative roughness.

Beyond the transition zone is the zone of complete turbulence in which relative pipe roughness ( $\epsilon/D$ ) is essentially independent of the Reynolds number. It should also be noted from inspection of the Moody diagram that for pipes of very low relative roughness, so called *smooth* pipes, flow does not enter the zone of complete turbulence, except at very high Reynolds numbers.

The absolute roughness ( $\epsilon$ ) of PE pipe is 0.000005 ft. The surface characteristic of PE pipe is classified as smooth pipe and as such, it offers minimal resistance to the flow of fluids. Because PE piping is immune to corrosive attack by water and other substances, and because it is less likely to accumulate scaling or tuberculation, its original smooth pipe properties tend to be retained through the pipe's entire service life.

The Moody diagram enables the designer to determine the flow characteristics of any fluid, gas, or liquid flowing in a particular pipe provided the surface roughness of the pipe and the viscosity and weight density of the fluid along its travel in the pipe are known. This diagram is widely accepted for hand calculations. In addition, various software programs based on the Colebrook equation and Moody diagram are available for the conducting of computerized calculations.

### Example 3.1

Find the head loss and pressure drop in 1,000 ft of 10 in. DR17 PE pipe (IPS) carrying water at a velocity of 5 ft/s.

First, estimate the Reynolds number from the Moody diagram. Multiply the velocity times the pipe average,  $D_i$ , to get the ( $vD_i$ ) term, which equals 9.410 in.  $\times$  5 ft/s or 47.1 in.-ft/s. Look across the top of the chart and then directly down to the lower abscissa to find the Reynolds number for water.  $Re = 3.5 \times 10^5$ . The inside diameter is obtained from tables in appendix E (E-1 and E-2).

The relative pipe roughness for 10 in. PE pipe is:

$$\frac{\epsilon}{D} = \frac{0.000005 \text{ ft}}{9.410 \text{ in.}} = 0.00000064$$

This value of relative roughness corresponds with the smooth-pipes line on the diagram. Draw a vertical line from the Reynolds number of  $3.5 \times 10^5$  upward until it intersects the smooth pipes line on the diagram. The friction factor,  $f$ , is given on the left side of the diagram as 0.014. Eq. 3-3 can be solved for the head loss.

$$h_f = f \frac{v^2 L}{2g D} = 0.014 \frac{5^2}{2(32.2)} \frac{1,000}{(9.410 / 12)} = 6.93 \text{ ft of head}$$

The corresponding pressure drop,  $p_f$ , equals 6.93/2.31 or 3.0 psi. Moody diagram calculations are assumed accurate to  $\pm 10$  percent.

## HAZEN-WILLIAMS FORMULA

Over the years, various empirical formulas have been proposed for the more direct and simpler computing of frictional losses incurred in pipes that convey water. First proposed

in 1904 and still very widely used is the Hazen-Williams formula, which is based on water at 60°F:

$$h_f = 0.002083 L \left( \frac{100}{C} \right)^{1.85} \left( \frac{Q}{D_i^{4.87}} \right) \quad (\text{Eq. 3-8})$$

where:

- $h_f$  = friction loss, feet of water
- $L$  = length of pipe, ft
- $C$  = Hazen-Williams pipe flow coefficient, dimensionless
- $Q$  = volumetric flow rate, gpm
- $D_i$  = pipe inside diameter, in.

The flow velocity is given by:

$$v = 0.115 C D_i^{0.63} s^{0.54} \quad (\text{Eq. 3-9})$$

where:

- $v$  = flow velocity, ft/s
- $C$  = Hazen-Williams pipe flow coefficient, dimensionless
- $D_i$  = pipe inside diameter, in.
- $s$  = hydraulic slope (the resultant friction loss in feet of water per foot of pipe), ft/ft

By combining Eq. 3-9 with Eq. 3-4 and when expressing the inside pipe diameter in inches rather than feet, the following commonly used formula is obtained for the flow rate in a pipeline:

$$Q = 0.2815 C D_i^{2.63} s^{0.54} \quad (\text{Eq. 3-10})$$

The appropriate value of  $C$  to be used in the Hazen-Williams equation depends to a large extent on the roughness of the pipe. But, to a lesser extent, it is also affected by pipe diameter, water velocity, and water temperature. Hydraulic studies show that the flow disturbance effect of PE butt-fused joints is minimal and that the Hazen-Williams flow coefficient for butt-fused PE pipes is around 155. The common practice is to assume a  $C$  coefficient of 150 for PE pipelines. No allowance for corrosion and therefore, no subsequent lowering of the flow capacity need be considered when using PE pipe.

## FITTINGS

Friction head losses that develop in piping components such as elbows, tees, and vessel connections are generally expressed as loss of static head in feet of fluid flowing, or as an equivalent length ( $L_{eq}$ ) of straight pipe of the same size that would produce the same static head loss at the flow conditions for which the pipeline is designed. For the various sizes of a line of products such as fittings and valves that are of a consistent design, the test data indicate that the ratio of equivalent pipe length ( $L_{eq}$ ) to inside pipe diameter ( $D_i$ ) tends to be a constant value. Representative values of equivalent pipe length in terms of the number of pipe diameters are listed in Table 3-1 for components frequently used in PE piping systems.