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NONMETALLIC PIPING

CHAPTER D1
THERMOPLASTICS PIPING

Dr. Timothy J. McGrath
Principal
Simpson Gumpertz & Heger Inc.
Arlington, Massachusetts

Stanley A. Mruk
Plastics Pipe Consultant
New Providence, New Jersey

SCOPE

This chapter reviews the principal properties and uses of thermoplastics piping, discusses its advantages and limitations, and presents general and basic information on materials, properties, standardization, design, and installation. This information is intended to guide the reader in evaluating the applicability of thermoplastics piping for an intended application; in choosing the appropriate material and product; and in its proper design and installation. References are provided for more detailed information and for further guidance on these and related subjects.

INTRODUCTION

Plastics piping is made from either of two basic groups of synthetic materials, *thermoplastic* and *thermosetting.* Thermoplastics can be softened and reshaped repeatedly by the application of heat. In contrast thermosetting materials are irreversibly *set,* or *cured,* or *hardened* into a permanent shape during factory manufacture. Once *hardened* into their final shape, thermosetting products cannot be softened and therefore may not be reshaped by heating.

Thermoplastic materials include minimal reinforcements, whereas thermosetting resins are almost always combined with reinforcements (such as glass fibers) and sometimes fillers (such as sand) to produce structurally integrated composite constructions. Chapter D2 in this handbook presents information on fiberglass reinforced thermosetting resin piping.

Principal Materials

Thermoplastics account for the lion's share of plastics used for piping. During 1989, over 95 percent of the approximately 7.5 billion pounds (3.75 million metric tons) of plastics that went into pipe, conduit, and fittings consisted of thermoplastics.[1] *Polyvinyl chloride* (PVC) accounted for about three-quarters of all thermoplastic pipe. The second most widely used thermoplastic is *polyethylene* (PE), accounting for about a 15 percent share, followed by *acrylonitrile-butadiene-styrene* (ABS), representing about a 4 percent share. The balance about 6 percent, consists of special-purpose materials, such as chlorinated polyvinyl chloride (CPVC), cross-linked polyethylene (PEX), polybutylene (PB), polypropylene (PP), and various fluorinated polymers, principally polyvinylidene fluoride (PVDF). In 1955, total U.S. shipments of thermoplastic pipe were under 40 million pounds (18,000 metric tons). By 1998, the rate of shipments had increased almost 200 fold, and it is still growing.

More footage of thermoplastic pipe is now being installed than that of all other types of piping materials combined.[2] However, the total dollar value of installed thermoplastic pipe is second to and only about one-quarter of that of the leading material, steel.[3] This is because the principal use of thermoplastics piping is in the smaller sizes. But the very successful track record in these sizes has been leading to increasing acceptance and use of the larger diameters, which currently comprise the fastest growing segment. As of this writing, thermoplastic pipe is available through NPS 60* (DN1500) for pressure uses and NPS 108 (DN 2700) for sewer and drain applications.

The first thermoplastic tubes were made in Germany during the 1930s from a PVC copolymer. Thermoplastics pipe was first manufactured commercially in the United States in 1940 from cellulose acetate butyrate (CAB) and was used by The Southern California Gas Company for distributing natural gas. Volume production commenced in 1948 when PE pipe was first offered for non-code-regulated water service applications. ABS and PVC pipe were first commercially made in the United States in 1949 and 1950, respectively. During the 1940s and 1950s many fundamental advances were introduced in polymer chemistry, materials formulation, and product fabrication technology, which laid the foundation for the thermoplastics pipe industry. Improvements in these areas are still continuing.

However, the start of the evolution of thermoplastics piping as engineering materials is considered to have taken place in 1950 when an American Society for Testing and Materials (ASTM) group for plastics pipe standardization was organized. Soon thereafter the first ASTM standards covering materials, test methods, and piping products began to be issued. At present over 180 ASTM standards define plastic piping, plastic piping materials, test methods, and recommended practices for joining and installation. Numerous plastics piping standards have also been issued by other organizations. A listing of the principal U.S. and Canadian plastic piping product standards is presented in Table D1.1.

Available Products

Plastics pipe and fittings are available in a vast array of materials, diameters, wall thicknesses, and designs. For nonpressure applications special wall constructions are offered—such as double wall, ribbed, and foamed core—which are designed

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* NPS 60 is size designator for 60-inch pipe. Refer to Chapter A1.

to more economically achieve a desired longitudinal and diametrical pipe stiffness. Most of these products are covered by national standards. Table D1.1, which lists standards that cover principal commercial products, also identifies each product's primary application and gives the range of nominal sizes covered by the standard. As the updating of existing and the writing of new product standards is a dynamic ongoing process, the reader is advised to contact standards-issuing organizations for the latest status. The American Society for Testing and Materials (ASTM),* for example, each year updates a volume of its ''Annual Book of ASTM Standards'' which includes all of its current standards covering plastics piping. The Plastics Pipe Institute (PPI) publishes a periodically updated report, PPI TR-5, which includes a comprehensive listing of North American and International Standards Organization (ISO) standards on thermoplastics piping. There are also many commercially available piping appurtenances, such as identified in Table D1.2, that are fabricated from plastics but which are not covered by any national standard. In addition, some pipe and fitting manufacturers and their distributors can custom-fabricate components that may or may not be shown in product catalogs. These specials include manholes for both infrastructure and industrial applications. Fabricated fittings intended for pressure service are often reinforced by an overwrap with a glass-fiber thermosetting resin composite.

Principal Uses

Thermoplastics piping is routinely used for many common pressure and nonpressure applications. Approximately 80 percent of the newly installed mains and 90 percent of the services for gas distribution are made of PE. Over 90 percent of rural water distribution mains and over 40 percent of municipal mains are made of PVC. Most of the smaller-diameter piping installed for agricultural and turf irrigation is made primarily from PE and PVC. CPVC and PEX piping are increasingly used for hot/cold water distributing piping for residential and other construction. In oil and gas production, significant quantities of PE pipe are used to convey water and well gases. Thermoplastics piping is also frequently used for commercial and industrial applications such as for conveying chilled and process waters, aqueous solutions of corrosive chemicals, slurries, foods, and substances that must remain uncontaminated by metallic ions.

More than half the tonnage of all thermoplastic pipe goes into nonpressure uses. Over 85 percent of the newly installed underground building sewer connections are made of PVC. PVC also accounts for a similar share of the sewer collection mains in sizes NPS 4 through 18 (DN 100 through 450). About 80 percent of new single-family dwellings utilize either PVC or ABS drain, waste, and vent (DWV) piping. Most drainage systems, including those for building foundations, leaching fields, agriculture, and road construction now consist of thermoplastics piping, mostly PE and PVC. And both PVC and PE are increasingly used for larger-diameter sewers, drains and culverts. One of the faster growing applications is the use of PE and PVC pipes of profile wall constructions for drainage, particulalry alongside and under roadways (see Fig. D1.1). Another is the rehabilitation of older sewers, drains, and pressure pipelines by the insertion of new PE or PVC pipes.† In one rehabilitation technology a PE or PVC pipe is deformed when

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* Societies and associations that write standards or that offer information relating to plastics piping are listed at the end of this chapter.

† Information on the rehabilitation of existing pipelines by the insertion of new themoplastics pipes may be obtained by contacting the North American Society for Trenchless Technology. See previous footnote.

TABLE D1.1 Principal Thermoplastic Piping Standards

Piping material* and product standard†	Subject product, or abbreviated title of standard	Nominal sizes range (in)	Principal applications
ABS, PP and PVC			
ASTM D3311	DWV fittings patterns	1¼–8	Drain, waste & vent
ABS and PVC			
ASTM D2680	ABS and PVC sewer pipe of composite wall construction	4–15	Sewer & drain
ASTM F409	Accessible and replaceable tube and fittings	1¼–1½	Drain, waste & vent
ASTM F480	Thermoplastic water well casing	2–16	Water-well casing
ASTM F1499	Coextruded, composite DWV pipe	1¼–8	Drain, waste & vent
CSA B181.5	Coextruded ABS/PVC DWV pipe	1¼–6	Drain, waste & vent
ABS, PVC & CPVC			
ASTM F1488	Coextruded composite pipe	2–12	Drain, waste & vent; sewer & drain; electrical & communications conduit
ABS			
ASTM D1527	ABS Pipe, Schedules 40 and 80	⅛–12	Cold water; industrial
ASTM D2282	ABS Pipe, dimension ratio series	⅛–12	Cold water; industrial
ASTM D2468	ABS Socket fittings, Schedule 40	⅛–8	Cold water; industrial
ASTM D2661	ABS DWV pipe and fittings	1¼–6	Drain, waste & vent
ASTM D2750	ABS Utility conduit and fittings	1–6	Electrical duct
ASTM D 2751	ABS Sewer pipe and fittings	3–12	Sewer & drain
ASTM F 628	ABS Foam core DWV	1¼–6	Drain, waste & vent
CSA B181.1	ABS DWV pipe and fittings	1¼–6	Drain, waste & vent
PA			
ASTM F1733	Butt heat fusion fittings for polyamid pipe and tubing	½–48	Gas distribution
CSA B137.12	Polyamid piping systems for gas service	½–8	Gas distribution

TABLE D1.1 Principal Thermoplastic Piping Standards (*Continued*)

Piping material* and product standard†	Subject product, or abbreviated title of standard	Nominal sizes range (in)	Principal applications
PB			
ASTM D2662	PB pipe, dimension ratio series, ID base	½–6	Hot & cold water, industrial
ASTM D2666	PB tubing	½–2	Hot & cold water; industrial
ASTM D3000	PB pipe, dimension ratio series	½–6	Hot & cold water; industrial
ASTM D3309	PB tubing for hot & cold water distribution	⅛–2	Hot & cold water
ASTM F809	Larger diameter PB pipe	3–42	Hot & cold water; industrial
ASTM F845	Plastic insert fittings for PB pipe & tubing	⅜–¼	Hot & cold water; water service
ASTM F878	PB Drip irrigation tubing	½	Drip irrigation
ASTM F1380	Metal insert fittings for PB tubing	⅜–1	Hot & cold water
CSA B137.7	Pipe for cold water distribution systems	½–2½	Hot & cold water; water service
CSA B137.8	PB Piping for pressure applications	¼–2	Hot & cold water; industrial
PE, PVC & PA			
ASTM D2513	Thermoplastic gas pressure pipe and fittings	¼–24	Natural gas & LPG distribution
PE & PP			
CSA B181.3	Polyolefin drainage systems	1¼–6	Industrial
PE			
AASHTO M252	Corrugated PE drainage tubing	3–15	Subsurface drainage
AASHTO M294	Corrugated PE pipe	12–24	Subsurface drainage
API 15LE	PE line pipe	½–12	Oil and gas production; cold water
ASTM D2104	PE pipe, Schedule 40, ID based	½–6	Cold water, industrial
ASTM D2239	PE pipe, dimension ratio series, ID based	½–6	Cold water; industrial
ASTM D2447	PE Pipe, Schedules 40 & 80	½–12	Cold water; industrial
ASTM D2609	Plastic insert fittings for PE pipe	½–6	Cold water
ASTM D2683	PE fittings, socket fusion type	½–4	Cold water; natural gas; industrial
ASTM D2737	PE tubing	½–2	Cold water
ASTM D3035	PE pipe, dimension ratio series	½–6	Cold water; industrial
ASTM D3261	PE fittings, butt fusion type	½–48	Cold water; natural gas; industrial

TABLE D1.1 Principal Thermoplastic Piping Standards (*Continued*)

Piping material⁺ and product standard*	Subject product, or abbreviated title of standard	Nominal sizes range (in)	Principal applications
PE (*Continued*)			
ASTM F405	PE corrugated tubing & fittings	3–6	Drainage; leaching fields
ASTM F667	PE corrugated tubing, larger diameter	8–24	Drainage; leaching fields
ASTM F714	PE pipe, larger diameter	3–48	Cold water; sewer & drain; industrial
ASTM F771	PE pipe for irrigation	½–6	Irrigation
ASTM F810	PE pipe for drainage & waste disposal	3–6	Drainage; leaching fields
ASTM F892	PE corrugated pipe with smooth interior	4	Sewer; drain; conduit
ASTM F894	PE profile wall pipe, large diameter	18–120	Sewer; drain; industrial
ASTM F1055	PE electrofusion fittings	½–12	Water; natural gas; industrial
ASTM F1533	Deformed PE liner for pipeline rehabilitation	3–18	Rehabilitation of existing pressure & non-pressure pipelines
ASTM F1759	PE manholes for subsurface applications	—	Sewer & drain; industrial
AWWA C901	PE pipe and tubing for water service	½–3	Cold water service
AWWA C906	PE pipe for water distribution & transmission	4–63	Water distribution & transmission
CSA B137.1	PE pipe, tubing and fittings for cold water	½–6	Cold water, industrial
CSA B137.4	PE piping (pipe & tubing) for gas service	½–8	Natural gas distribution
CSA B137.4.1	Electrofusion-type PE fittings for gas service	½–8	Natural gas distribution
CSA B182.6	Profile PE pipe and fittings	4–48	Drainage; leaching fields
PE/AL/PE			
ASTM F1282	Polyethylene/Aluminum/Polyethylene composite pressure pipe	¼–1	Cold water service; industrial
CSA B137.9	Polyethylene/Aluminum/Polyethylene composite pressure piping	¼–1	Cold water service; industrial

TABLE D1.1 Principal Thermoplastic Piping Standards (*Continued*)

Piping material⁺ and product standard*	Subject product, or abbreviated title of standard	Nominal sizes range (in)	Principal applications
PEX			
ASTM F876	Cross-linked PE tubing	¼–2	Hydronic heating
ASTM F877	Cross-linked PE tubing	¼–2	Hot & cold water distributing
ASTM F1807	Metal insert fittings utilizing a copper crimp ring for cross-linked PE tubing	⅜–1	Hot & cold water
CSA B137.5	Cross-linked PE tubing systems	¼–2	Hot & cold water
PEX/AL/PEX			
ASTM F1281	Cross-linked PE/Aluminum/Cross-linked PE composite pressure pipe	¼–1	Hot & cold, hydronic heating
CSA B 137.10	Cross-linked PE/Aluminum/Cross-linked PE composite pressure piping	¼–1	Hot & cold water; hydronic heating
PP			
CSA B137.11	Polypropylene pipe and fittings for pressure applications	⅜–3	Industrial
PVC			
AASHTO M278	PVC Drainage pipe	—	Drainage
ASTM D1785	PVC Pipe, Schedules 40, 80 & 120	½–12	Cold water; industrial
ASTM D2241	PVC Pipe, Dimension Ratio Series	⅛–38	Cold water; industrial
ASTM D2466	PVC Socket fittings, Schedule 40	⅛–8	Cold water; industrial
ASTM D2467	PVC Socket fittings, Schedule 80	⅛–8	Cold water; industrial
ASTM D2665	PVC DWV Pipe & fittings	1¼–12	Drain, waste & vent
ASTM D2672	Specification for solvent cement type PVC pipe joints	⅛–12	Cold water; industrial
ASTM D2729	PVC drain pipe & fittings	2–6	Drain; leaching fields
ASTM D2949	PVC thin walled DWV pipe	3	Drain, waste & vent
ASTM D3034	PVC sewer pipe & fittings	4–15	Sewer & drain
ASTM F512	PVC conduit for buried applications	1–6	Electrical duct
ASTM F679	PVC sewer pipe & fittings, larger diameter	18–36	Sewer & drain
ASTM F758	PVC underdrain piping	4–8	Drain
ASTM F789	PVC sewer pipe, 46 psi stiffness	4–15	Sewer & drain
ASTM F794	PVC sewer pipe, ribbed wall	4–48	Sewer & drain
ASTM F891	Coextruded PVC pipe with a cellular core	2–18	Drain, waste & vent; sewer & drain

TABLE D1.1 Principal Thermoplastic Piping Standards (*Continued*)

Piping material⁺ and product standard*	Subject product, or abbreviated title of standard	Nominal sizes range (in)	Principal applications
PVC (*Continued*)			
ASTM F949	PVC sewer pipe, corrugated wall, smooth interior surface	4–10	Sewer & drain
ASTM F1336	PVC gasketed sewer fittings	4–27	Sewer & drain
ASTM F1483	Oriented PVC pipe	4–16	Water distribution & transmission
ASTM F1504	Folded PVC pipe for pipeline rehabilitation	4–15	Rehabilitation of existing sewers and conduits
ASTM F1732	PVC sewer & drain pipe containing recycled material	2–6	Sewer & drain
ASTM F1760	Coextruded PVC non-pressure pipe containing recycled material	4–15	Drain, waste & vent; sewer & drain; electrical & communications duct
ASTM F1803	PVC closed profile gravity pipe made to controlled inside diameters	18–60	Sewer & drain
AWWA C900	PVC pipe for water distribution	4–12	Water distribution
AWWA C905	PVC pipe for water distribution & transmission	14–36	Water distribution & transmission
AWWA C907	PVC gasketed fittings for water	4–8	Water distribution
CSA B137.2	PVC gasketed fittings for water	4–12	Water distribution
CSA B 137.3	PVC pipe for pressure applications	⅛–48	Cold water, industrial
CSA B181.2	PVC DWV pipe and fittings	1¼–24	Drain, waste & vent
CSA B182.1	Drain and sewer pipe and fittings	2–6	Drain & sewer piping
CSA B182.2	PVC sewer pipe and fittings	3–48	Sewer collection
CSA B182.4	Profile wall PVC sewer pipe and fittings	4–48	Sewer collection
CSA B182.7	Multilayer PVC sewer pipe having reprocessed-recycled content	4–48	Sewer collection
CSA B196.3	PVC underground telecommunications cable ducting and fittings	2½–4	Communications ducting

TABLE D1.1 Principal Thermoplastic Piping Standards (*Continued*)

Piping material[†] and product standard*	Subject product, or abbreviated title of standard	Nominal sizes range (in)	Principal applications
NEMA TC-2	PVC electrical conduit	½–6	Electrical conduit
NEMA TC-3	PVC conduit fittings	½–6	Electrical conduit
UL 514	PVC electrical outlet boxes and fittings	½–6	Electrical conduit
UL 651	PVC rigid non-metallic conduit	½–6	Electrical conduit
CPVC			
ASTM D2846	CPVC hot & cold water piping	⅜–2	Hot & cold water
ASTM F437	CPVC fittings, threaded, Schedule 80	¼–6	Hot & cold water, industrial
ASTM F438	CPVC fittings, socket, Schedule 40	¼–6	Hot & cold water, industrial
ASTM F439	CPVC fittings, socket, Schedule 80	¼–6	Hot & cold water, industrial
ASTM F441	CPVC pipe, Schedules 40 and 80	¼–12	Hot & cold water, industrial
ASTM F442	CPVC pipe, dimension ratio series	¼–12	Hot & cold water, industrial
CSA B137.6	CPVC pipe, tubing and fittings for hot & cold water distributing systems	⅜–2	Hot & cold water, plumbing
PVDF			
ASTM F1673	PVDF corrosive waste drainage piping	1¼–12	Industrial

* Materials: ABS—Acrylonitrile-butadiene-styrene, CPVC—Chlorinated polyvinyl chloride, PA—Polyamide (Nylon), PB—Polybutylene, PE—Polyethylene, PEX—Cross-linked polyethylene, PE/AL/PE—Polyethylene/aluminum/polyethylene composite, PEX/AL/PEX—Cross-linked polyethylene/aluminum/cross-linked polyethylene composite, PP—Polypropylene, PVC—Polyvinyl Chloride, PVDF—Polyvinylidene Fluoride.

† Issuing organizations:

AASHTO (American Association of State Highway and Transportation Officials, Room 341, National Press Building, Washington, DC 20045.

API (American Petroleum Institute), Publications and Distribution Section, 1200 L Street, N.W., Washington, DC 20005.

ASTM (American Society for Testing and Materials), 100 Barr Harbor Drive, West Conshohocken, PA 19428.

CSA (Canadian Standards Association), 178 Resdale, Blvd., Etobicoke, Toronto, Ontario, Canada M9W 1R3.

NEMA (National Electrical Manufacturer's Association), 2101 L Street, N.W., Suite 300 Washington, DC 20038.

UL (Underwriter's Laboratories, Inc.), 333 Pfingsten Road, Northbrook, IL 60062.

A current listing of North American plastic piping standards is available in PPI Technical Report TR-5, *Standards for Plastics Piping*, Plastics Pipe Institute, 1801 K Street, N.W., Suite 600K, Washington, DC 20006.

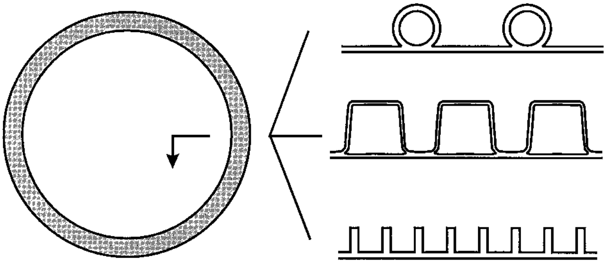
TABLE D1.2 Size Range of Readily Available Thermoplastic Valves and Other Appurtenances (nominal pipe sizes expressed in inches)

Item	PVC	CPVC	PE	PP	PVDF
Valves					
Needle	¼–½	¼–½	—	—	—
Ball	¼–6	¼—4	—	¼–4	¼–6
Gate	½–6	½–6	—	—	—
Butterfly	4–24	—	—	—	—
Check	¼–16	½–4	—	½–4	½–4
Globe	⅛–4	—	—	—	—
Diaphragm	½–10	½–10	—	—	½–6
Foot	½–4	½–4	—	½	—
Solenoid	⅛–3	⅛–3	—	—	—
Gas service	—	—	¼–6	—	—
Strainers	⅛–3	⅛–3	—	—	—
Saddles, tapping	2–8	2–12	—	—	—
Expansion joints	½–12	½–6	—	½–4	½–4
Flange adapters	2–12	2–12	2–42	2–6	2–6

manufactured into a "U" shape approximately one-half the diameter of the host pipe. At the installation site, the "U" deformed pipe is pulled through the damaged host pipe and then reformed by a combination of heat and pressure to tightly fit the shape of the host pipe (see Fig. D1.2).

Advantages and Limitations

A number of important performance advantages have sparked the widespread adoption of thermoplastics piping for so many pressure and nonpressure uses. The most universally recognized advantage is the piping's virtual freedom from attack by ambient water and moisture. Thermoplastics piping is not subject to surface attacks in any way comparable to the rusting or environmental corrosion of metals. Thermoplastics, being nonconductors, are immune to the electrochemical-based



Note - Other corrugation profiles are available

FIGURE D1.1 Examples of plastic pipe wall cross sections.

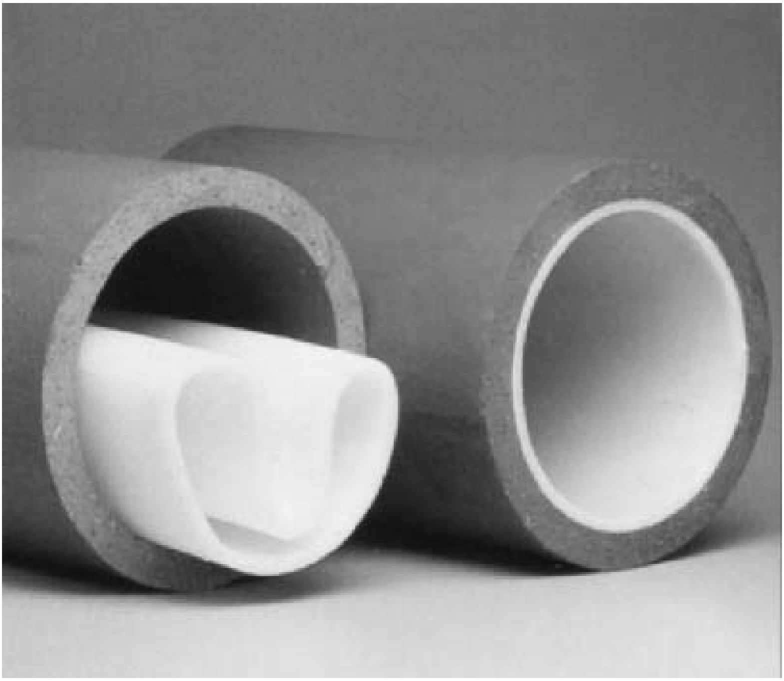


FIGURE D1.2 Deformed and reformed polyethylene liner pipe.

corrosion process induced by electrolytes such as acids, bases, and salts. In addition, plastics pipe materials are not vulnerable to biological attack. In sum, thermoplastics are not subject to corrosion in most environments in both aboveground and underground service. This has resulted in negligible costs for maintenance and external protection such as painting, plastic coating, galvanizing, electroplating, wrapping, and cathodic protection.

Another principal advantage offered by thermoplastics is their lower specific gravity, which results in ease of handling, storage, and installation, as well as in lower transportation costs. The smooth pipe surfaces yield low friction factors and very low tendency to fouling. They also offer very good abrasion resistance, even when conveying slurries that can rapidly abrade harder materials.

High deformation capacity without fracture—or *strainability* (Janson[4])—is another important performance feature, particularly for underground service. In response to earth loading, buried flexible pipes deform (deflect) and thereby activate additional and substantial support from the surrounding soil. This capability to activate additional support by deformation results in a pipe-soil structure that is capable of supporting earth fills and surface live loads of a magnitude that could fracture stronger but less strainable materials.

Thermoplastics piping, particularly in the sizes under around NPS 18 (DN 450), can be competitive in cost to piping of other materials. In the larger sizes, thermoplastics will oftentimes overcome a first-cost disadvantage when consideration is given to their lower operating and maintenance costs and longer life.

The principal limitations of thermoplastics arise from their relatively low strength and stiffness and greater sensitivity of mechanical properties to temperature. As a result, their primary use is for gravity and lower-pressure applications at near-ambient temperatures. Some plastics qualify for hot water service, and there are some specialty materials that can be used to close to 300°F (149°C). Notwithstanding these restrictions, thermoplastics piping satisfies the performance requirements for a very broad range of applications.

Successful design with thermoplastics requires recognition of their viscoelastic nature. These materials do not exhibit the relatively simple stress/strain relationship that is characteristic of metals. Duration of loading, as well as temperature and environment, can have a profound effect on their stress-strain response, rupture strength, ultimate strain capacity, and other engineering properties. The extent to which duration of loading, temperature, and environment influence ultimate mechanical properties varies not only from one class of thermoplastic material to another (for example, between PVC and PE) but can also significantly differ within the same generic material, depending on the specific nature of the polymer (e.g., molecular weight, molecular weight distribution, degree of branching, and extent of copolymerization with other monomers), the type and quantity of polymer additives and modifiers, and the processing conditions. These factors must be recognized when characterizing the engineering properties of thermoplastic piping, particularly when defining allowable stress, strain, and upper temperature limits; and it goes without saying that for effective design and installation, they must be given consideration by the piping specifier, designer, and user.

Compared to traditional piping materials, thermoplastics have high coefficients of thermal expansion and contraction. For example, the thermal expansion rate can be from 6 to 10 times greater than that of metal pipe. This must be recognized both in design and installation, particularly for aboveground applications where resultant piping reaction may require frequent use of expansion loops or pipe supports. For aboveground piping more attention may also need to be given to proper pipe restraint because the low mass of thermoplastics provides less inertia against piping movements that may be induced by sudden changes in the fluid flow velocity. Additionally, aboveground thermoplastics should be positioned or protected against possible accidental mechanical damage.

Since thermoplastics are combustible, their use in certain locations may be limited by fire safety concerns and regulations. Construction and building codes address these concerns through various requirements, including the placing of thermoplastics piping inside suitable fire-resistant walls and chases and the use of fire stops when pipe penetrates through such structures.

THERMOPLASTIC PIPING MATERIALS

The term *polymer* (from the Greek *poly,* meaning ''many,'' and *mer* meaning ''unit'') is used to denote the long-chain or network structure of macromolecules that are produced either naturally or that are made by man. The latter are referred to as *synthetic polymers.* Polymers which are the base material for plastics are oftentimes termed *resins.* Plastics are compounds of *resins* and *additives.* As previously explained, plastics are divided into two broad categories, *thermoplastics* and *thermosets.* Since thermoplastics are capable of being softened by heating and hardened by cooling, they can be shaped into articles by operations such as molding or extrusion, which take advantage of this capability.

Additives are incorporated into a thermoplastics composition to achieve specific purposes during fabrication or service. The precise nature and amounts of these additives depends on the plastic and its inherent properties; the processing method used to convert it to a finished article; and any desired modification of properties to achieve certain aesthetic, performance, or economic objectives. The main kinds of additives that may be used in thermoplastic piping compositions include the following:

Heat stabilizers. To protect the plastic against thermal degradation, particularly during processing

Antioxidants. To protect against oxidation during processing and when in service

Ultraviolet screens, or stabilizers. To protect against ultraviolet radiation in sunlight during outdoor storage and weather-exposed service

Lubricants. To facilitate and improve fabrication by reducing viscosity and lessening frictional drag through dies and other surfaces

Pigments. To give the product a distinctive color

Processing aids. To facilitate material mixing and fusion during processing and thereby optimize the homogenization of material and its properties

Property modifiers. To enhance a particular property such as impact strength or flexibility

Fillers. Most often used to reduce volume cost; however, fillers may also be used to increase stiffness or to modify processing characteristics

Additives are essential components of most thermoplastic piping compositions. They facilitate processing, enhance certain properties, give a product a distinctive appearance and color, and provide required protection during fabrication and service. There are only a few thermoplastics [e.g., certain fluorinated polymers such as polyvinylidene fluoride (PVDF)] that do not require the incorporation of some type of additive because they already have sufficient natural thermal stability and aging and weathering resistance.

The precise nature and quantities of additives that can be used for piping compositions are delimited by their effect on engineering properties, such as rigidity, impact strength, chemical resistance, creep resistance, rupture strength under long-term loading, and fatigue endurance. For example, the use of an inorganic filler can compromise the natural resistance of polymers to very strong acids or bases. Also, too much filler, or use of a filler of a coarser grade, or its inadeqate dispersion can introduce physical discontinuities, or internal faults, that can compromise long-term strength, ductility, toughness, and fatigue endurance. Another example is the excessive use of liquid stabilizers or lubricants, which tends to plasticize the plastic and thereby make it less creep-resistant and more sensitive to temperature.

Additionally, the properties of the base polymer used in a plastics piping composition are not only determined by the chemical elements, or atoms, from which the polymer is made, but are also profoundly influenced by the specific geometrical arrangement by which the polymer's atoms are combined to form a macromolecule. A most important molecular structural parameter is the length of the molecular chain. The longer the chain, the larger and heavier the molecule. Polymers used for engineering applications consist of relatively long molecules in order to yield satisfactory levels of longer-term strength, ductility, and toughness.

Molecule size is denoted by *molecular weight,* which is the sum of the atomic masses of all the elements in the molecule. Since all the molecules in a polymer are not of the same size, the degree of polymerization is usually expressed by the polymer's *average* molecular weight. The nature of the distribution of molecular sizes also bears a significant influence on a number of physical and mechanical properties. Thermoplastics used for piping applications tend to be of relatively high molecular weight (generally over 100,000) and of relatively narrow molecular weight distribution. However, the molecular weight cannot be so large as to result in a melt viscosity so high as to hinder proper fabrication of the end product.

Another molecular structural parameter is the *length and frequency of shorter molecular chains* that occasionally branch out from the main polymer chain. These branches help determine how closely the polymer molecules can lie next to each other, which has an influence on the polymer's physical and mechanical properties. The length and frequency of polymer branches may be controlled by conditions of chemical reaction, catalysts used, and by the copolymerization with other than the principal monomer. For example, polyethylene pipe polymers are in fact copolymers of ethylene with small amounts of other olefin monomers such as propylene, butene, pentene, and hexene. Although the amount of other monomers used is low, and thereby the polymer still falls under the classification of polyethylene, it is enough to modify the polymer's molecular structure—principally the number of short branches along the linear molecular chains—and thereby exert significant influence on engineering prperties. Many commercial polymers, including polypropylene (PP) and polybutylene (PB), are also partial copolymers.

Chemical geometry, sometimes referred to as *polymer architecture,* also helps determine the relative physical arrangement of molecules to one another and, thereby, the polymer's physical properties. Generally, the long molecules in polymers tend to align themselves near each other in a random symmetry analogous to spaghetti in a bowl. This random arrangement is referred to as the *amorphous state.* The proximity of polymer molecules to one another and their physical entanglement gives rise to mechanical forces that greatly account for a polymer's mechanical properties. PVC and ABS are polymers that are essentially amorphous materials.

Certain other polymers, such as PE, PP, PB, and PVDF, are partly crystalline materials. Portions of their polymer chains organize themselves in close and very well ordered arrangements called *crystallites;* other portions lie in the amorphous regions. The stronger physical bonds in the well-ordered, closely packed crystalline regions have significant influence over mechanical properties such as strength, stiffness, and toughness. The extent of crystallization and the size and nature of the crystalline regions, as well as the nature of the interconnective network of molecules running from one crystalline region to another can all be somewhat controlled by tailoring molecular architecture.

The many possible variations in polymer structure, combined with the different types and amounts of additives that can be used, result in a great diversity of plastic compositions, even within a particular polymer group such as polyvinyl chloride (PVC) or polyethylene (PE). The defining and classifying of such compositions is, understandably, not a simple task. The primary standard plastic material specifications are issued by the American Society for Testing and Materials (ASTM). The first ASTM standards classified plastic materials by a "Type, Grade, and Class" system in accordance with three key properties. However, with the growing need to better define plastic materials by more than just three properties, a number of ASTM standards have adopted a cell classification system whereby each of a number of primary properties is given a property cell number depending on the property value. All the resultant property cell numbers (there can be as many as needed) are then listed in a specified order. For example, referring to Table D1.3, in accor-

TABLE D1.3 Primary Properties: Cell classification Limits for PE Piping Materials in Accordance with ASTM D 3350

	Property cell limits									
Property and test method (Note 1)	Cell 0	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8	Cell 9
1. Density ASTM D1505 (g/cc)	Not specified	0.910 to 0.925	0.926 to 0.940	0.941 to 0.955	> 0.955					Specify value
2. Melt index ASTM D1238 (g/10 min)	Not specified	>1.0	0.4 to 1.0	.015 to 0.4	<0.15	(Note 2)	(Note 3)			Specify value
3. Flexural modulus ASTM D790 (psi)	Not specified	< 20.000	20,000 to 40,000	40,000 to 80,000	80,000 to 110,000	110,000 to 160,000	> 160,000			Specify value
4. Yield strength ASTM D638 (psi)	Not specified	< 2,200	2,200 to 2,600	2,600 to 3,000	3,000 to 3,500	3,500 to 4,000	>4,000			Specify value
5. Environmental stress crack resistance	Not specified									Specify value
—Method A ASTM F1473 (min. hrs) (Note 4)						0.15	3	10	30	
—Method B ASTM D1693										
Test condition		A	B	C	C					
Test duration (hrs)		48	24	192	600					
Failure, max (%)		50	50	20	20					
6. Hydrostatic design basis, ASTM D2837 (hrs)	Not specified (Note 5)	800	1,000	1,250	1,600					Specify value

Notes:

(1) To convert psi to Mpa, multiply by 6.90 × 10^{-3}.

(2) Materials with MI less than Cell 4 but which have a flow rate of <4.0 g/10 min when tested in accordance with D1238, Condition F.

(3) Materials with MI less than Cell 4 but which have flow rate of <0.30 g/10 min when tested in accordance with ASTM D 1238, but at a temperature of 590°F (310°C) and under a total load of 12,480 g).

(4) Test is conducted on compression molded samples, notched to a depth in accordance with Table 1 of F1473, at a load of 350 psi (2.4 Mpa) and at a temperature of 176°F (80°C).

(5) Compositions for which an HDB has not been established are designated as NPR (non-pressure rated).

dance with the cell classification system of ASTM D3350, ''Standard Specification for Polyethylene Plastics Pipe and Fitting Materials,'' Class 234424 polyethylene designates a material with properties that fall within the following range of values:

Property	*Requirement*
Density:	Cell 2 of property 1 [0.926 to 0.940 g/cm^3]
Melt index:	Cell 3 of property 2 [<0.4 to 0.15 g/10 min]
Flexural modulus:	Cell 4 of property 3 [80,000 to <110,000 psi, 550 to 760 MPa]
Tensile strength at yield:	Cell 4 of property 4 [3000 to <3500 psi, 21 to <24 MPa]
Resistance to slow crack growth:	Cell 2 of property 5 [50 percent max failure after 24 hrs, when using test method B, Condition C]
Hydrostatic design basis at 23°C:	Cell 4 of property 6 [1600 psi or 11 MPa]

Although this newer cell-type format is a major improvement in classifying and specifying piping materials by a broader array of significant property and performance characteristics, it may not always be a sufficiently definitive predictor of longer-term performance properties. The manufacturer may have to be consulted for further information. For example, two PE materials with the same ASTM material cell classification may have a strength under long-term loading that responds somewhat differently to increasing temperature, or to fatigue loading, or to chemical environments.

A brief description of the major materials used for thermoplastics piping follows. The principal standard piping products made from these materials, and their applications, are identified in Table D1.1. Nonstandard or specialty piping products are also offered from these materials.

Polyvinyl Chloride (PVC)

In its virgin state PVC is a translucent, colorless, rigid polymer. When PVC was first commercialized it was softened by the addition of plasticizers, and the resultant compositions were primarily used in the manufacture of such items as luggage, upholstery, garden hose, wire coating, floor tiles, and laboratory tubing. Subsequent advances in extrusion and molding equipment, and in the availability of more effective stabilizer and lubrication additives, allowed for the extrusion of the much more viscous, rigid compositions which are the only ones suitable for piping. To differentiate these newer unplasticized compositions from the early plasticized versions they were identified as *uPVC,* or *rigid PVC.* These designations are still often used.

Of the commonly available thermoplastics, rigid PVC offers the highest strength and stiffness at the least volume cost, which accounts for its having become the leading plastic material for both pressure and nonpressure piping. Major uses include water mains; irrigation; drain, waste, and vent (DWV); sewage and drainage; well casing; electric conduit; and power and communications ducting. PVC is available in a much broader range of pipe sizes and wall thicknesses, fittings, valves, and appurtenances than in any other plastic.

PVC piping is joined primarily by two techniques, *solvent cementing* and *elastomeric seals.* Although it can be joined by thermal fusion, its melt viscosity is too high for making reliably strong joints under field conditions.

PVC piping is made only from rigid compounds containing no plasticizers and relatively small quantities of other ingredients. To minimize adverse effects on long-term strength and chemical resistance, minimal quantities of additives are used in pressure pipe compounds. To improve impact strength for conduit and other applications that may be subject to mechanical abuse, small quantities of solid polymeric impact modifiers (but not plasticizers, which are generally liquids) are sometimes incorporated into the composition. When improved stiffness is desired, filler—generally very finely divided calcium carbonate—is added. Combinations of these and other additives can be used to optimize a rigid PVC composition for its intended application. The enhancement of a particular property by the use of additives may often require a trade-off with some other property.

For the defining of rigid PVC compositions based on resultant properties, ASTM has established two material specifications based on the property cell classification system. One of these is ASTM D1784, ''Standard Specification for Rigid Poly(Vinyl Chloride) and Chlorinated Poly(Vinyl Chloride) Compounds,'' which classifies PVC materials in accordance with the nature of the polymer and four primary properties.

TABLE D1.4 Primary Properties: Cell Classification Limits for PVC Materials in Accordance with ASTM D 1784

Property and test method(2)	Property cell limits(1)								
	Cell 0	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8
1. Base resin	Unspecified	Poly (vinyl) homopolymer	Chlorinated poly(vinyl) chloride	Vinyl copolymer					
2. Min. impact strength (Izod) (ft-lb/in of notch) ASTM D256	Unspecified	<0.65	0.65	1.5	5.0	10.0	15.0		
3. Tensile strength, min. (psi) ASTM D638	Unspecified	<5,000	5,000	6,000	7,000	8,000			
4. Modulus of elasticity, min. (psi) ASTM D638	Unspecified	<280,000	280,000	320,000	360,000 0	400,000 0	440,000 0		
5. Deflection temperature under load (264 psi), min. (°F) [°C]	Unspecified	<131 [55]	131 [55]	140 [60]	158 [70]	176 [80]	194 [90]	212 [100]	230 [110]
Flamability	(3)	(3)	(3)	(3)	(3)	(3)	(3)	(3)	(3)

Notes:

(1) The minimum property value determines the cell number, even though the maximum measured value may fall within a higher cell

(2) Conversion factors to common metric units are as follows:

- psi to Mpa—multiply by 6.90×10^{-3}
- ft-lb/in of notch to J/m of notch—multiply by 53.4

(3) All compounds covered by this specification when tested in accordance with ASTM method D635 shall yield not less than the following result: average extent of burning <25 mm; average time of burning <10 s.

These four primary properties and the cell class ranges established for each are presented in Table D1.4 The requirements for a fifth property, chemical resistance, are presented in Table D1.5 The manner in which a rigid PVC material is identified by this classification system is illustrated by a Class 12454-B PVC material which, according to Tables D1.4 and D1.5, would have to meet the following property requirements:

Property	*Requirement*
Base resin:	Cell 1 of property 1 [poly(vinylchloride) homopolymer]
Impact strength (Izod):	Cell 2 of property 2 [0.65 ft-lbf/in, minimum, 0.035 N-m/mm]
Tensile strength:	Cell 4 of property 3 [7,000 psi, minimum or 48 MPa]
Modulus of elasticity in tension:	Cell 5 of property 4 [400,000 psi, or 2.8 GPa minimum]
Deflection temperature under load:	Cell 4 of property 5 [158°F (70°C), minimum]
Chemical resistance:	Must meet the minimum requirements listed under Suffix B of Table D1.5

Most PVC pressure pipe is made from materials that meet the minimum requirements of cell 12454-C, which, to maximize long-term strength, generally is formu-

TABLE D1.5 PVC Compositions, Suffix Designation for Chemical Resistance

Test solution	Suffix A	Suffix B	Suffix C	Suffix D
H_2SO_4 (93%)—14 days immersion at 55 ± 2°C				
Change in weight:				
Increase, max., %	1.0*	5.0*	25.0	NA⁺
Decrease, max., %	0.1*	0.1*	0.1	NA
Change in flexural yield strength:				
Increase, max., %	5.0*	5.0*	5.0	NA
Decrease, max., %	5.0*	25.0*	50.0	NA
H_2SO_4 (80%)—30 days immersion at 60 ± 2°C				
Change in weight:				
Increase, max., %	NA	NA	5.0	15.0
Decrease, max., %	NA	NA	5.0	0.1
Change in flexural yield strength				
Increase, max., %	NA	NA	15.0	25.0
Decrease, max., %	NA	NA	15.0	25.0
ASTM Oil No. 3—30 days immersion at 23°C				
Change in weight:				
Increase, max., %	0.5	1.0	1.0	10.0
Decrease, max., %	0.5	1.0	1.0	0.1

* Specimens washed in running water and dried by air blast or other mechanical means shall show no sweating within 2 hours after removal from the acid bath.

⁺ NA—Not applicable

lated with minimal quantities of processing additives and property modifiers. An older "Type and Grade" system found in earlier versions of D1784, although technically obsolete, continues to be referenced by a number of piping standards. The newer issues of D1784 include a table (see Table D1.6) that cross-references the former with the new designations.

For pressure pipe applications, the cell classification system of ASTM D1784 is often complemented by one additional material requirement. All PVC pressure

TABLE D1.6 Classification of commercial Types and Grades of Rigid Polyvinyl Chloride Piping Materials: Comparison of former to Newer Designations

Type and grade designation based on older edition of ASTM D 1784	Corresponding cell classification based on current edition of ASTM D1784 (See Tables D 1.4 & D 1.5)
Rigid PVC materials	
Type I, Grade 1	12454-B
Type I, Grade 2	12454-C
Type I, Grade 3	11443-B
Type II, Grade 1	14333-D
Type III, Grade 1	13233
CPVC materials	
Type IV, Grade 1	23447-B

pipe standards require that the pipe be made from a formulation with a specified minimum long-term strength that has been established in accordance with ASTM D2837, ‘‘Standard Method for Obtaining the Hydrostatic Design Basis for Thermoplastic Pipe Materials.’’ Standards for products intended for the transport of potable water also require that the material meet certain minimum chemical extraction requirements designed to protect water quality. (See discussion in ‘‘Effects of Fluids Being Conveyed.’’)

Most ASTM and a number of other PVC pressure pipe standards identify PVC stress-rated materials by a four-digit number, of which the first two digits designate its type and grade in accordance with the older editions of ASTM D1784 (see Table D1.6) and the last two identify, in hundreds of pounds per square inch, the material’s maximum recommended hydrostatic design stress (HDS) for water at 73.4°F (23°C). In accordance with ASTM convention, the maximum HDS is one-half the material’s hydrostatic design basis (HDB), which refers to the material’s long-term hydrostatic strength (LTHS) category when established in accordance with ASTM D2837. The following list describes the most common PVC stress-rated materials covered by this designation system:

- PVC 1120 is a Type 1, Grade 1 PVC material (minimum cell class 12454-B) with a maximum recommended HDS of 2,000 psi (13.8 MPa) for water at 73.4°F (23°C).
- PVC 2110 is a Type 2, Grade 1 PVC material (minimum cell class 14333-D) with a maximum recommended HDS of 1,000 psi (6.9 MPa).
- PVC 2116 is a Type 2, Grade 1 PVC material (same minimum cell class as above) with a maximum recommended HDS of 1,600 psi (11 MPa).

Since by the ASTM convention the maximum recommended HDS is one-half the material’s HDB, it follows that the HDBs for these materials are 4,000 psi (27.6 MPa), 2,000 psi (13.8 MPa), and 3,200 psi (22.1 MPa), respectively.

The Plastics Pipe Institute (PPI) lists a generic PVC 1120 formulation that provides for certain specified alternative choices of ingredients and formulation quantities that have been determined to allow the formulated compounds to satisfy both the short- and long-term requirements established for this material classification. This formulation, which is listed in PPI TR-3, ‘‘Policies and Procedures for Developing Recommended Hydrostatic Strengths and Design Stresses for Thermoplastic Pipe Materials,’’ is periodically updated to include any new alternate choices of ingredients that have been validated by means of both short-term and long-term tests.

The other PVC material specification is ASTM D4396, ‘‘Standard Specification for Rigid Polyvinyl Chloride (PVC) and Related Plastic Compounds for Non-Pressure Piping Products’’ As indicated by its title, this specification covers compounds only intended for nonpressure uses. It is similar to D1784 in that it is also based on the cell format and most of the same primary classification properties.

Chlorinated Polyvinyl Chloride (CPVC)

As implied by its name, CPVC is a chemical modification of PVC. It is very similar to PVC in many properties, including strength and stiffness at ambient temperature. But the extra chlorine in CPVC’s chemical structure increases this material’s maximum operating temperature limit by about 50°F (28°C) above that for PVC. Thus, CPVC can be used up to nearly 200°F (93°C) for pressure uses and up to about

210°F (100°C) for nonpressure applications. Principal uses for CPVC are domestic hot water and cold water piping, residential fire-sprinkling piping, and many industrial applications which can take advantage of its elevated-temperature capabilities and superior chemical resistance.

CPVC materials are also classified by the previously discussed ASTM D1784. Similar to PVC, most CPVC standards that cover pressure-rated products identify stress-rated materials by a four-digit number that combines the older type and grade designation with the material's maximum recommended HDS for water at 73.4°F (23°C). Currently, the only recognized stress-rated CPVC designation is CPVC 4120, signifying a Type IV, Grade 1 material in accordance with D1784 (see Table D1.6), with a maximum recommended hydrostatic design stress of 2,000 psi (13.8 MPa) for water at 73.4°F (23°C) in accordance with ASTM D2837. In addition, most CPVC pipe standards that cover products intended for elevated-temperature service, such as for hot water piping, require that the CPVC material have no less than a recommended HDS of 500 psi (3.5 MPa) (equivalent to an HDB of 1,000 psi or 6.9 MPa) for water at 180°F (82°C).

Polyethylene (PE)

Polyethylene (PE) is possibly the best-known member of the polyolefin family (materials derived from the polymerization of olefin gases including ethylene, propylene, and butylene) because it has penetrated so widely into everyday household uses. PE in its virgin form is a translucent and tough substance with a waxlike feel and appearance. As is the case of the other polyolefins, PE is a partly crystalline and partly amorphous material. The extent to which it crystallizes (which determines many of its resultant properties) is a function of its molecular structure. PE's backbone consists of a long molecular chain, from which short-chain branches occasionally project. The length, type, and frequency of distribution of these branches, as well as other parameters such as molecular weight and molecular weight distribution, determine the degree of crystallinity and the network of molecules that anchor the crystal-like regions to one another. These structural characteristics greatly influence the short- and long-term mechanical properties of PE. The extent to which crystalline regions can form in a PE polymer is reflected by its density—the higher-density materials have more crystalline regions, which results in greater stiffness and tensile strength. However, as the crystallinity increases, there is some accompanying loss in ductility and toughness.

Polyethylene polymers used for piping are classified into three types: a low-density, relatively flexible form; a medium-density, somewhat stiffer and less-flexible form; and a high-density form, which is more rigid and stronger. Most pressure pipe is made of materials of densities lying around the high end of the medium-density PEs and the lower end of the high-density materials. This range has established itself as offering the best balance of toughness, flexibility, and long-term strength. Nonpressure pipe is primarily made from the more rigid, higher-density materials.

PE, which is somewhat less strong and less rigid than PVC at ambient temperature, is the second most used plastic pipe material, primarily because of its toughness, ductility, and flexibility, even at low temperatures. PE pipes do not fracture under the expansive action of freezing water. In an emergency, smaller-diameter PE pipes can be safely "squeezed-off" (clamped tightly) by suitable procedures, to shut down the flow of fluids. Also, PE pipe is much less prone to failure by a rapidly running crack. These two last-named characteristics are important reasons why PE pipe is now used in over 85 percent of all current new installations of piping for gas distribution.

PE pipes also have superior fatigue endurance. This feature, plus their ability to dampen water hammer shock, has led to their use for applications such as in sewer force mains, where repeated cyclic pressure changes tend to occur.

The high strainability and fracture resistance of PE have led to its selection for use in unstable soils and situations where axial bending and diametrical deflection are anticipated. Example installations that utilize this feature are methane collection systems for solid-waste sites, pipes installed by directional trenchless boring techniques, lake and river crossings, and outfall pipes discharging treated effluent into seas and oceans.

PE pipe is also used for the rehabilitation of old pipelines. Lengths of PE pipe which have been joined to the required length by the butt-fusion method are pulled, or sometimes pushed, inside the old line. New rehabilitation procedures have evolved by which, for ease of insertion, the diameter of the liner PE pipe is reduced by a squeeze-down procedure, or by folding the pipe into a U-shape. Once inside the old pipe, the strain memory in the material is relieved by a combination of heating and internal pressure, allowing the PE pipe to reround so that it fits snugly inside the existing pipe (see Fig. D1.2).

The low stiffness of PE permits the coiling of smaller-diameter pipe [generally up to about 4 in (100 mm) although pipe up to NPS 6 (DN 150) diameter has been coiled for special jobs]. The coiled length can be hundreds of feet and sometimes over a thousand feet (300 meters) long, depending on material, wall thickness, and diameter. PE pipe is readily heat-fusible and can be joined to itself or to fittings by the butt-fusion process. PE fittings are also available for joining pipe by the socket fusion and electrofusion processes.

For nonpressure buried pipe applications, such as for stormwater, roadway, and land drainage, various designs of profile wall constructions have been developed which enhance pipe wall stiffness while minimizing material usage (see Figure D1.1). Because of their corrosion resistance, these pipes are displacing metallic drainage piping.

To protect the PE polymer during processing, storage, and service, PE piping compounds contain small quantities of heat stabilizers, antioxidants, and ultraviolet (UV) screens or UV chemical stabilizers. Black PE pipe materials incorporate very finely divided carbon black as both a coloring pigment and to screen the polymer against the potentially damaging UV radiation in sunlight. Nonblack piping compositions include a UV chemical stabilizer in addition to a coloring pigment (usually tan or yellow for gas, blue for water, and orange for communications ducting).

The primary specification for identifying and classifying PE piping materials is ASTM D3350, ‘‘Standard Specification for Polyethylene Pipe and Fittings Materials.’’ Standard D3350 employs the cell class format to cover the diversity of materials used for piping. As shown by Table D1.3, this specification classifies PE materials by a matrix of six primary properties and a specified range of cell values for each of these properties. In addition, an ending code letter is used to designate the incorporation of a colorant and UV stabilizer. An example of how PE materials are identified by this system was illustrated under the discussion ‘‘Thermoplastics Piping Materials.’’

A recent addition to ASTM D3350 is a new test for the classifying of PE’s resistance to crack growth under sustained tensile loading. The test method used for this purpose is ASTM F1473, ‘‘Notch Tensile Test to Measure the Resistance to Slow Crack Growth of Polyethylene Pipe and Resins.’’ Results obtained under this method have been determined to give a more reliable index than the traditional

TABLE D1.7 Classification of Commercial Polyethylene Piping Materials: Comparison of Former to Newer Designations

PE material designation based on type and grade in accordance with former ASTM D1248, plus a code for material's maximum recommended hydrostatic design stress for water, for 73°F	Corresponding minimum cell classification in accordance with cell classification system of ASTM D3350*
PE 2406	PE 213333
PE 3406	PE 324433
PE 3408	PE 334434

* For cells 1 and 6 the resultant values must fall within the limits shown for the particular property cell. For the other properties, material values may fall within or be above the designated cell limits. Refer to Table D 1.3 for the listing of range of property values for each property cell.

stress-crack method (ASTM D 1693) of a PE material's resistance to crack formation and growth when subject to sustained localized intensified stressing, such as can occur in piping applications. A similar method, as follows, which was developed for geomembranes, is also being used to rank the slow-crack growth resistance of PE materials that are intended for nonpressure applications: ASTM D5397, ''Standard Test Method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test.''

Prior to the issuance of ASTM D 3350, most PE piping standards referred to ASTM D1248, ''Standard Specification for Polyethylene Plastics Molding and Extrusion Materials,'' for the defining of material requirements. ASTM D1248 classified PE by type, representing the material's density category, and grade, reflecting a combination of properties, primarily the melt flow or processing characteristics. Similar to PVC, PE piping standards classify PE stress-rated materials by means of a four-digit number, of which the first two digits refer to the older type and grade designation and the last two represent, in hundreds of pounds per square inch, the material's maximum recommended hydrostatic design stress (HDS) for water at 73.4°F (23°C). The following list describes the commonly used PE piping materials in accordance with this traditional designation system:

- PE 2406 is a Type 2 (i.e., medium-density), Grade 4 PE material, in accordance with ASTM D1248, which carries a recommended maximum hydrostatic design stress of 630 psi (4.3 MPa), for water at 73.4°F (23°C). [The ''06'' in the 2406 designates the 630 psi (4.3 MPa) design stress.]
- PE 3408 is a Type 3 (i.e., high-density), Grade 4 PE material, in accordance with ASTM D1248, which carries a recommended maximum hydrostatic design stress of 800 psi (5.5 MPa) for water at 73.4°F (23°C).

To relate this older designation system to the newer cell system of D 3350, the latter standard includes a cross-reference. The crossovers recognized by the 1993 edition of D 3350 are presented in Table D1.7.

Polybutylene (PB)

Polybutylene is a polyolefin with a stiffness resembling that of low-density polyethylene, but with a long-term strength that is greater than that of high-density polyethylene (PE). Its most distinctive feature, however, is that the long-term strength is less affected by increasing temperature than that of PE. While most PEs have an upper temperature limit of around 140°F (60°C), the limit for PB is nearly 200°F (93°C).

Major applications for PB pipe and tubing are for water service lines and for uses that take advantage of its improved elevated-temperature strength. They include piping for residential hot and cold water distribution, residential fire sprinklers, and industrial uses such as hot effluent lines.

PB is similar to PE in its chemical resistance and heat fusibility. PB piping materials are covered by ASTM D2581, ''Standard Specification for Polybutylene (PB) Plastics Molding and Extrusion Materials.'' Materials for pressure applications are designated as PB 2110, signifying a Type 2, Grade 1 material in accordance with D2581, and with a recommended maximum HDS of 1,000 psi (6.9 MPa) for water, at 73.4°F (23°C). Hot water piping standards generally require that the PB material also have an established recommended maximum HDS of 500 psi (3.5 MPa) for water at 180°F (82°C).

Cross-Linked Polyethylene (PEX)

Cross-linked polyethylene, as its name implies, is actually a thermoset. It is covered in this chapter because PEX pipe and tubing are made from PE, a thermoplastic, by essentially the same extrusion process used to manufacture all thermoplastic pipes. The only difference is that in the case of PEX a cross-linking of the polymer chains occurs during or soon after pipe extrusion. Cross-linking of PE improves elevated temperature performance, chemical and stress-crack resistance, creep resistance, and abrasion resistance. While most PEs have an upper temperature limit of about 140°F (60°C), PEX piping may be used up to around 200°F (93°C).

Three methods, as follows, are used commercially to cross-link PE piping materials: *silane curing; peroxide curing;* and *radiation.* Silene PEX materials are often referred as *moisture-cured* because they cross-link on exposure of the pipe to water. The pipe is produced by a two-stage process. First, a silene-grafted PE is combined with a catalyst PE concentrate and extruded into pipe using standard extrusion equipment. Then, after the pipe has been extruded, cross-linking is effected by exposing the pipe to moisture.

Peroxide PEX derives its name from the class of chemicals, *peroxides,* that is used to achieve cross-linking. These cross-linking agents are incorporated into the base PE either during or after extrusion. Cross-linking is initiated when the temperature reaches that at which the peroxide decomposes, thereby yielding free-radicals that cross-link the PE.

Radiation PEX pipe is produced by subjecting PE pipe to electromagnetic radiation (gamma radiation) or high-energy electrons (beta radiation).

All three methods are capable of producing equivalent products. PEX pipe is tested to the same performance standards regardless of the manufacturing method. Properties of a PEX material are determined by the properties of the base PE, the stabilizer and additive package, and the degree of cross-linking as determined using method ASTM D2765, ''Standard Test Method for Determination of Gel Content and Swell Ratio of Cross-linked Ethylene Plastics.'' To comply with existing standards PEX piping must be cross-linked to within a range of 65 to 89 percent.

Current PEX piping materials carry a recommended maximum HDS for water of 630 psi (4.3 MPa) at 73.4°F (23°C), and 400 psi (2.8 MPa) at 180°F (82°C). Some materials are also listed with a recommended maximum HDS of 315 psi (2.2 MPa) at 200°F (93°C).

PEX is also commonly used in PEX-Aluminum-PEX (PEX-Al-PEX) composite pipe. In this pipe PEX inner and outer layers sandwich a thin tubular aluminum reinforcement which significantly enhances the pipe pressure rating.

PEX and PEX-Al-PEX pipes are manufactured in North America in diameters through NPS 2 (DN 50). Their primary applications take advantage of improved elevated temperature performance. These include hot and cold water piping systems, hydronic heating, under-floor or radiant-heating systems, snow-melting systems, and residential fire sprinkler piping.

Polypropylene (PP)

Polypropylene is a polyolefin similar in properties to high-density PE but somewhat harder, more temperature-resistant, and lighter in weight, but less tough. It is also similar to PE in its chemical resistance and heat fusibility. As in the case of PE, PP can be joined to itself by socket fusion, butt fusion, and electrofusion.

Because of its greater stiffness and better tolerance to elevated temperates, PP is sometimes chosen over PE where these qualities are advantageous (e.g., for aboveground piping and for the conveying of hot fluids). A principal application is for corrosive drainage piping, for which PP offers better solvent resistance than either ABS or PVC. A product line of PP corrosive drainage piping made from a flame-retardant grade of material is offered for use in laboratories and hospitals, and for chemical manufacturing.

Another principal application for PP is for conveying corrosive chemicals under pressure. For this application, socket fusion systems of pressure-rated PP pipe and fittings are available through NPS 6 (DN 150). At present there are no consensus standards covering PP pressure pipe; all available products are proprietary.

Polypropylene materials are classified by ASTM D4101, ‘‘Standard Specification for Polypropylene Molding and Extrusion Materials,’’ into two types. Type I covers materials that have the highest rigidity and strength but that offer only moderate toughness. Type II covers materials (copolymers of propylene with ethylene or other olefins) which tend to be less rigid and strong but have improved toughness, particularly at lower temperatures. Both types are used for pipe.

Acrylonitrile-Butadiene-Styrene (ABS)

ABS plastics are made by combining styrene-acrylonitrile copolymers with copolymers formed by reacting styrene-acrylonitrile with butadiene. The butadiene copolymers impart toughness, while the acrylonitrile copolymers contribute strength, rigidity, and hardness. The result is a tough, relatively strong plastic that is easy to mold and extrude.

The ABS family covers a wide range of materials. The proportions of the basic components and the way in which they are combined can be varied to produce a wide range of end properties. A major use of ABS for pipe is in the manufacture of drain-waste-vent (DWV) piping, for which it offers good rigidity, temperature resistance, low-temperature toughness, and the ability to make fast-setting solvent cemented joints. ABS has been used for pressure piping, primarily for water service applications, but it has been largely displaced by the stronger, more chemically resistant, and more economical PVC. However, compressed-air piping made from a proprietary extra-tough, shatter-resistant composition is currently marketed in Europe and the United States.

ABS materials are classified by ASTM D1788, ‘‘Standard Specification for Rigid Acrylonitrile-Butadiene-Styrene (ABS) Plastics,’’ in accordance with the cell class format by which each of three properties—impact strength (toughness), tensile stress at yield (short-term strength), and deflection temperature under load (temperature resistance)—is accorded a cell number depending on the property value. The ASTM specification for ABS DWV pipe requires that the material have a minimum cell classification of ABS 2–2–2, which signifies the following minimum properties: notch impact strength of 2 ft-lb/in (0.1 N-m/mm) of notch, 180°F (82°C) deflection temperature, and 4,000 psi (2.8 MPa) tensile strength.

Fluoroplastics

Fluoroplastics designate a broad family of paraffinic polymers that have some or all of the hydrogen replaced by fluorine. The fully fluorinated fluorocarbons include perfluoroalkoxy (PFA), polytrafluoroethylene (PTFE), and fluorinated ethylene propylene (FEP). The partially fluorinated fluoroplastics include ethylene tetrafluoroethylene (ETFE), polychlorotrifluoroethylene (CTFE), ethylenechlorotrifluoroethylene (ECTFE), and polyvinylidene fluoride (PVDF).

Fluorinated polymers have outstanding resistance to chemicals and excellent resistance to solvents. They also offer improved elevated-temperature properties and are very stable and durable. Most members of this family require little or no addition of processing or thermal stabilizers. For this reason they are often specified when exceptional purity of water or other liquids must be maintained. These materials are also very fire resistant.

The various kinds of fluorinated polymers just listed have been used as liners for metal piping to enhance its chemical resistance. Pipe, tubing, and fittings totally made of fluorinated plastics are commercially available, principally from PVDF and PFA, in sizes up to about NPS 6 (DN 150). The pipe is generally joined by means of heat-fused socket fittings. PVDF has good strength, wear resistance, and creep resistance, and can be used over a temperature range from about −100 to 300°F (−70° to 150°C). PFA has somewhat less strength and creep resistance but offers greater toughness and can be used up to over 400°F (200°C).

Fluorinated plastics also have outstanding resistance to weathering and electromagnetic radiation. These materials do not require the use of additives to achieve weathering and ultraviolet resistance. Because of their immunity to radiation, they are used in the reprocessing of nuclear wastes and similar radiation-intensive exposures. And because they are additive-free, these pipes are also used to convey fluids that must remain ultrapure and totally free of metallic ion contamination.

JOINING METHODS

Plastics piping can be joined by different methods (see Table D1.8) depending on the characteristics of the material. For example, ABS, PVC, and CPVC can be solvent cemented. However, polyolefins (PE, PB, and PP) and fluoropolymers cannot be joined by this method because of their high solvent resistance; but they can be readily heat-fused. Both heat fusion and solvent cementing yield monolithic

TABLE D1.8 Common Methods for Joining Thermoplastics Piping

Joining Method	ABS	PVC	CPVC	PE	PEX	PB	PP	PVDF
Solvent cementing	X	X	X	—	—	—	—	—
Heat fusion	—	—	—	X	—	X	X	X
Threading(1)	X	X	X	X	—	—	X	X
Flanged connectors(2)	X	X	X	X	—	X	X	X
Grooved joints(3)	X	X	X	X	—	—	X	X
Mechanical compression(4)	X	X	X	X	X	X	X	X
Elastomeric seal	X	X	X	X	X	X	X	X
Flaring(5)	—	—	—	X	—	X	—	—

Notes:

1. Generally limited to pipes of wall thickness not less than that of Schedule 80.
2. Flanged adapters can be fastened to plastic pipe by means of heat fusion, solvent cementing, or threading.
3. Grooving requires a minimum pipe wall thickness which depends on the material. The pipe manufacturer should be consulted.
4. In most cases internal stiffeners are required to permanently support the pipe against compressive forces generated by these fittings.
5. Not all commercial grades may be flared. Consult the pipe manufacturer for specific recommendations.

joints of maximum strength and of chemical resistance that is not compromised by the introduction of other materials.

In *solvent cementing,* often referred to as *solvent welding,* the mating spigot-socket or saddle-pipe surfaces are readily fused to each other by the softening action of the solvent cement that is placed between the contacting surfaces. Solvent cements achieve bonding by a fusion process, and not by adhesion. Thorough contact of these surfaces with no gaps is essential to the development of good fusion. After initial bonding of the two mating surfaces is achieved, the solvent in the solvent cement gradually migrates and evaporates away. When the solvent is gone the joint is said to have been “cured”, at which point it achieves its maximum strength. Handling strength is usually achieved in a few minutes. Complete curing may take from hours to longer than a day, depending on the temperature and other conditions. A description of the proper procedure for solvent cementing PVC pipe and fittings is the subject of ASTM Standard Practice D2855.

In *heat fusion* softening of the mating surfaces is achieved by melting. There are two techniques used for achieving the required degree of surface melting. One is to heat with a specially designed heating iron just prior to joining. In the other, the surfaces are first mated and then brought to the proper melt temperature by means of heating wires embedded in the socket. This latter technique, called *electrofusion,* is used with PE piping and also for PP industrial drainage piping.

There are two kinds of heat fusion jointing systems. One of them is the *socket-spigot system,* similar to that used for solvent cementing. In the other the butt ends of pipe and/or fittings are squared off precisely, heated, and then quickly brought together and kept under sufficient pressure until enough cooling has occurred for the development of adequate working strength. Socket fusion is limited to the smaller piping sizes, generally not above 4 in (100 mm). Larger-diameter pipe is heat-fused by the butt-fusion process. Automatic, portable equipment for field joining by butt fusion is available to join all available pressure pipe sizes. ASTM Recommended Practice D2657 covers socket, butt, and saddle heat fusion. The standard recommended practice for electrofusion joining is given by ASTM F1290.

Flanged connections are often used for industrial applications, particularly when making transitions to nonplastic components such as to a metal valve or to a tank outlet, or when it is advantageous to provide for easy removal of a pipe section or other component from a pipeline for cleaning, maintenance, or other purpose. Flange connectors can be applied on the pipe by heat fusion (socket or butt), or solvent cementing, depending on the material. Oftentimes, particularly in the cases of larger-diameter pipes, the use of plastic flanges requires the use of a backup metal flange to ensure even distribution of compressive stresses and optimum fluid tightness. Recommendations regarding proper use of flanges, including bolt tightening limits, are covered by industry manuals and are also available from piping manufacturers.

Much of the pipe used for buried water and sewer lines and drains is joined with *bell-and-spigot connections* that include an elastomeric gasket to seal the joint. The bell, including the gasket cavity, is usually formed during manufacture of the pipe or fitting and is an integral part of the product. Rubber-gasketed connectors facilitate construction and produce tight joints, even when made under foul-weather and poor field conditions, when solvent cementing and heat fusion joining may be adversely affected. ASTM D3112 prescribes requirements for elastomeric joints for nonpressure applications, and D3139 presents requirements for elastomeric joints intended for pressure uses.

Threading is also sometimes used with certain of the more rigid plastics like PVC or CPVC. Molded threads with reduced roots are preferred because cut threads are more notch-sensitive. Molded threaded adapters are available for solvent cementing to PVC and CPVC pipe. If pipe is to be threaded, it is generally recommended that its wall thickness be not less than that corresponding to Schedule 80. Threaded connections of any type are prohibited for gas distribution.

Mechanical compression fittings are also used, particularly when making transition connections to dissimilar materials. Mechanical connectors are the only option for connecting PEX since it cannot be solvent-cemented or heat-fused. ASTM F1807 covers the commonly used metal insert fittings for PEX pipe. In one design, the fitting is inserted inside the PEX pipe, and a copper ring on the outside of the pipe is crimped by means of a tool to achieve the holding strength and to provide the seal.

Many styles of mechanical fittings designed for plastics use *compressed elastomeric gaskets* for sealing. To ensure this seal is not lost through pipe deformation, the design incorporates a metal sleeve that fits inside the plastic pipe to stiffen it against the compression forces. When selecting compression fittings consideration should be given to the fitting's capacity to hold the pipe in place against pull-out forces such as can be generated by thermal contraction or earth settlement. A number of compression fittings, especially for the smaller pipe sizes, are designed to hold the pipe against pull-out forces large enough to cause the pipe to either fail or to permanently stretch by yielding.

DIMENSIONING SYSTEMS

Thermoplastic pipe is made to a number of dimensioning systems based on controlled *outside* diameters. Pipe from all thermoplastic materials is manufactured to the standard outside diameters of iron pipe sizes (IPS) of commercial wrought steel pipe (ASME B36.10). In this diameter system some plastic pipes are offered with wall thicknesses that are the same as those of Schedule 40 and Schedule 80 iron pipes.

Much more common, however, is plastic pipe with outside diameters conforming to IPS standards but with wall thicknesses sized in accordance with the standard dimension ratio (SDR) principle, whereby all pipe sizes in a given SDR series have a uniform ratio of outside diameter to minimum wall thickness. The SDRs adopted by ASTM and other organizations follow the following series: 9; 11; 13.5; 17; 21; 26; and so on. However, nonstandard dimension ratios are also sometimes used, in which case they are identified by the prefix DR. The broad acceptance of the SDR dimension system arises from the fact that certain pipe performance ratings are directly proportional to the ratio of pipe diameter to wall thickness. For example, pipes made from the same material and to the same ratio of diameter to wall thickness have the same pressure rating, and also the same pipe stiffness, irrespective of pipe size.

Other diameter systems to which plastic pipe is made include:

- *Cast-iron (Cl), or ductile-iron (Dl) pipe sizes.* PVC and PE pipes are available in this diameter sizing system to facilitate connections to fittings, valves, and hydrants in water works systems, which generally are made to cast-iron (now ductile-iron) sizes.
- *Copper tubing sizes (CTS).* CTS-sized pipe is made because it can be joined using various compression and flare fittings originally designed for copper tubing. Plastics pipe in CTS sizes is generally used for gas and water services and for hot and cold water piping.
- *Plastic pipe sizes.* Certain products, particularly nonpressure pipes made for sewer and drain applications are available in outside diameter systems that are not a copy of that used by any traditional material.
- *International Standards Organization (ISO) sizes.* Some of the larger-diameter PE pipes are made to an internationally established outside diameter dimensioning system specifically designed for plastics piping.

There is one plastic pipe that is also made to a standard *inside* diameter dimensioning system. PE pressure-rated pipes, up to NPS 6 (DN 150), are made to controlled inside diameters that are the same as the inside diameters of Schedule 40 iron pipe size (IPS). The inside diameter is controlled because this pipe series is designed to be used with insert fittings which must fit snugly inside the pipe, notwithstanding the pipe's wall thickness. The outside diameter of such pipe depends on the thickness of the pipe wall, which is determined by the pipe's pressure rating.

Many manufacturers also make non-standard-sized pipes on special order. Such pipes may be required for a particular situation, such as the sliplining of an existing corroded line with the largest possible plastics pipe that can be pulled into place.

PHYSICAL AND MECHANICAL PROPERTIES

Approximate values of some of the physical and mechanical properties for the more common generic thermoplastic piping materials are given in Table D1.9. The actual property values for a particular commercial grade of material are not accurately predictable from its ASTM classification; they can be significantly affected by the specific nature of the base polymer (e.g., its molecular weight, molecular weight distribution, kind and frequency of branches), the plastic composition (type and amount of additives), and effects of processing (e.g., some anisotropy of proper-

TABLE D1.9 Approximate Values of Physical Properties of Thermoplastic Piping Materials

Property(1)	ASTM Test Method	Approximate value at 75°F						
		ABS	PVC	CPVC	PE	PEX	PB	PVDF
Specific gravity	D792	1.08	1.4	1.54	0.95	0.94	0.92	1.76
Tensile strength $(\times 10^{-3})$ psi	D638	7.0	8.0	8.0	3.2	2.8	4.2	7.0
Tensile modulus $(\times 10^{-3})$ psi	D638	340	410	420	120	9–	55	220
Impact strength, Izod ft-lb/in of notch	D256	4	1	1.5	>10	>10	>10	3.8
Coeff. of linear expansion $(\times 10^{6})$ in/in · °F	D696	60	30	35	90	90	72	70
Thermal conductivity Btu · in/h · ft^2 · °F	C177	1.35	1.1	1.0	3.2	3.2	1.5	1.5
Specific heat Btu/lb · °F	—	0.34	0.25	0.20	0.55	0.55	0.45	0.29
Approx. operating temp. limits	—							
nonpressure, °F		180	150	210	160	210	210	300
(°C)		(80)	(65)	(100)	(70)	(100)	(100)	(150)
pressure, °F		160	130	180	140	200	180	280
(°C)		(70)	(55)	(80)	(60)	(95)	(80)	(140)

(1) Conversion factors to commonly used metric equivalents are as follows:

- psi (pounds-force per square inch) to Mpa (megapascals)—multiple by 6.9×10^3
- ft-lb/in of notch (foot · pounds-force/inch of notch) to J/m of notch (Joules/meter)—multiply by 53.4
- in/in · °F to m/m · °C—multiply by 1.8
- Btu · in/h · ft^2 · °F to cal · cm/s · °C—multiply by 344×10^6
- Btu/lb · °F to cal/g · °C—multiply by 1.0

ties and residual stresses may result because of processing conditions). Furthermore, the ultimate properties may also be somewhat influenced by the degree of stress triaxiality and the history of previously applied stresses and strains.

Compared to traditional piping materials, thermoplastics are lighter in weight, have lower heat capacities, are poorer conductors of heat, and have significantly larger coefficients of expansion and contraction. They are also less strong and rigid. However, they offer sufficient rigidity and strength to satisfy the performance requirements of a great many applications, and they are not subject to gradual degradation by rusting and other corrosive processes that commonly afflict most traditional pipe materials. When establishing appropriate values of mechanical design properties such as strength, stiffness, and strain capacity, the special consideration with plastics is over their unique time- and temperature-dependent load-deformation response.

Plastics are viscoelastic materials. Their deformation and strength properties are very significantly affected by temperature and duration of loading. Some of their properties can also be profoundly influenced by service environment. Tensile strength and stiffness values, such as given in Table D1.9 and which have been obtained by means of short-term mechanical tests adapted from metal testing, are not appropriate for design of piping systems that are subjected to longer-term sustained loading. In the case of metals the conventional tensile test is used to define basic properties such as elastic modulus, proportional limit, and yield strength. These are important not only for defining and specifying a metal but they are also basic constants for use in design equations based on elastic theory where strain is assumed to be proportional to stress. Although very few materials are perfectly elastic, the assumption of such behavior in metals is usually sufficiently close for purposes of engineering design.

The stress-strain response for plastics is curvilinear and can depart greatly from an assumption of proportionality. Furthermore, the viscoelastic nature of plastics results in a relationship between stress and strain that is greatly influenced by elapsed time under load (or by the rate of straining in the case of a tensile test), temperature, and environment. As depicted schematically by Fig. D1.3, the stress-strain response and fracture strength depend on the test conditions. For example, with some thermoplastics a reduction of about two decades in tensile strain rate, or an increase in temperature of around 50°F (28°C) can result in nearly a doubling of the strain response at failure. However, at very low strain rates total strain prior to failure tends to decrease with strain rate. Thus, the strain at failure as measured under the relatively high strain rates in a tensile test is not an accurate index of the elongation at failure, or ductility, under conditions of very low strain rates.

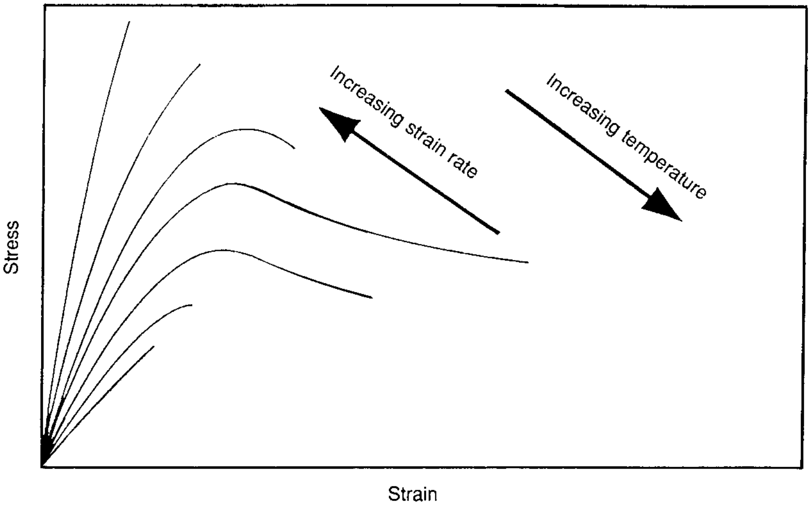


FIGURE D1.3 Tensile stress-strain response of a thermoplastic exhibiting ductile behavior at intermediate strain rates. Possible effects of strain rate and temperature are shown.

Also, as depicted by Fig. D1.3, the stress-strain response is nonlinear (although near the origin the behavior is fairly linear). Accordingly, plastics have no true elastic constants—such as the elastic modulus or the proportional limit of metals—nor do they have sharply defined yield points. The reported tensile elastic modulus for plastics represents a tangent modulus that is calculated by extending the initial portion of the load-extension curve, as obtained under a specified set of test conditions. Since plastics have no true elastic properties, the propriety of applying the term "elastic modulus," or even "modulus," in describing the stiffness or rigidity of a plastic has been questioned. However, such a "constant" has proven useful both for specification and design when its arbitrary nature and its dependence on duration of loading, temperature, and similar factors is recognized.

Even though plastic's behavior is inelastic, most of the equations for stress analysis (such as for pipe, beams, and pressure vessels) which have been derived on the assumption of elastic behavior can still be used, provided values for strength and stiffness are appropriately established. Thus, property values obtained by means of short-term tests should only be used for predicting response under loads of short duration. Short-term tests, of course, also have important value for the defining and classifying of plastic materials.

To be able to use elastic equations to forecast response under sustained, longer-term loading requires the use of "effective" values of strength and modulus that reflect mechanical behavior under such conditions. The development of longer-term property values usually involves some form of extrapolation protocol. The extrapolating procedures that are used have been borrowed from and are similar to those used with other inelastic engineering materials, such as metals at very high temperatures, which also exhibit a viscoelastic behavior. As will be discussed later, the protocols for plastics for the defining of the effects of duration of loading and temperature on engineering properties generally rely on analysis of information obtained from longer-duration testing, in some cases lasting many thousands of hours.

Viscoelasticity

As the name implies, viscoelastic materials respond to stress as complex aggregates of many different elastic and viscous (fluid) elements. The springs in the highly simplified model of Fig. D1.4 represent the elastic elements of a polymer (e.g., chain rigidity, chemical bonds, and crystallinity), each spring having a different constant that represents a *time-independent* modulus of elasticity. The dashpots represent the fluid elements (e.g., molecules slipping past each other), each one having a different viscosity or *time-dependent* stress-strain response.

When a load is first applied on this model, it results in an initial, essentially

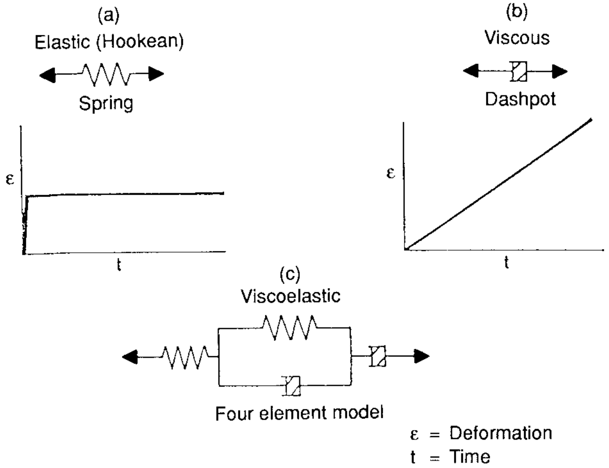
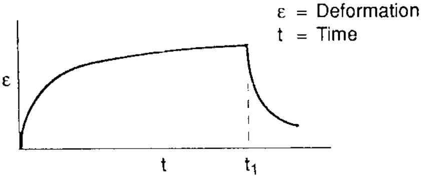


FIGURE D1.4 Model of viscoelastic behavior.

Creep (constant load)



Stress relaxation (constant deformation)

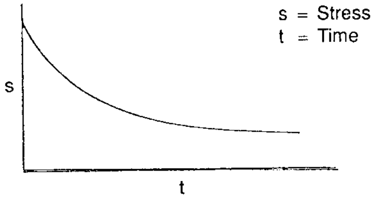


FIGURE D1.5 Viscoelastic responses.

elastic deformation. As time under load increases, the deformation increases indefinitely but at a gradually diminishing rate (Fig. D1.5). After sufficient time the rate becomes so low that for most engineering purposes one can consider that it is zero. This phenomenon of continuing deformation, which also occurs in concrete, soft metals, wood, and structural metals at very high temperatures, is called *creep.* If the load is removed after a certain time (say, at point t_1 in Fig. D1.5), a rapid initial recovery of the creep strain occurs, followed by a continuing recovery but at a steadily decreasing rate. In this model complete recovery has not been achieved. However, if the creep strain did not cause irreversible structural changes and sufficient time is allowed, the strain recovery will in time be almost complete. The rate and extent of creep strain and its recovery are sensitive to temperature and can also be influenced by environmental effects such as the absorption of solvents or other materials with which the plastic may have come in contact while under stress.

An analogous response of viscoelastic materials is stress relaxation. The load required to maintain a certain initial deformation will tend to gradually relax when that deformation is kept constant (see Fig. D1.5). Initially, stress relaxation occurs rapidly, and then with increasing time it decreases at a decreasing rate toward some ultimate value.

Tensile Creep

Each material has a characteristic stress-strain-time-temperature function. The primary form for characterizing this function is with a family of *tensile creep curves.* Creep curves plotted on Cartesian coordinates (Fig. D1.6) generally show three continuous stages: a first stage marked by large and initial deformation; a second

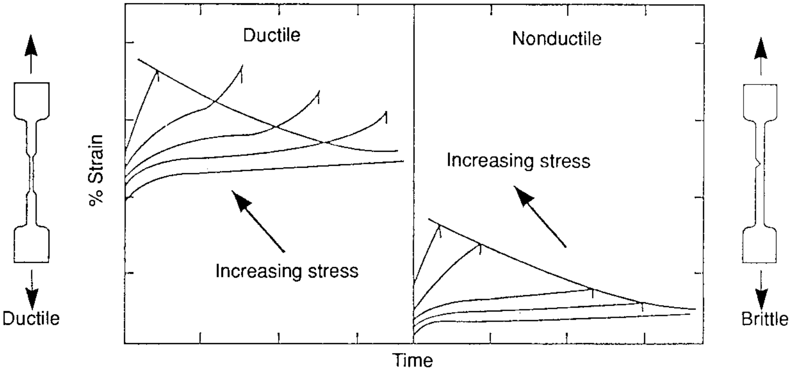


FIGURE D1.6 Schematic of creep rupture strength of thermoplastics in tension.

stage where deformation continues at a relatively slow and constant rate; and a third stage during which rupture occurs. In ductile plastics third-stage creep usually includes a distinct elongation or yielding just prior to rupture. In nonductile plastics, rupture occurs abruptly during second-stage creep. As illustrated by Fig. D1.7, which has been obtained on a certain pipe grade PE material, tensile creep curves are frequently plotted with log time as the abscissa. Such logarithmic plots allow for a more practical way of representing the information over the time range of engineering interest, and they also facilitate extrapolation of data to longer times. Many mathematical methods have been proposed to describe the creep behavior

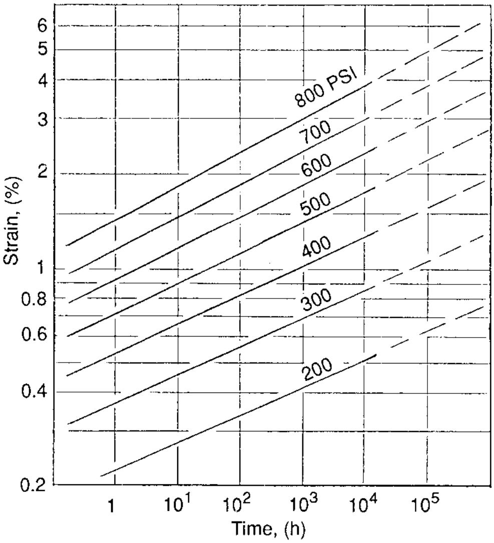


FIGURE D1.7 Tensile creep response for high-density polyethylene pipe material.

of plastic materials in terms of stress, strain, and time. One such method, which is contained in an American Society of Civil Engineers standard design practice, presents constants for PVC and PE that have been verified by tests lasting nearly 20 years.[5]

Any point on any creep curve gives a stress-strain ratio. This ratio is usually designated as the *creep modulus, apparent modulus* or, *effective modulus,* and is used for design calculations where the stress is prescribed but the strain is free to vary. Creep modulus curves derived from the creep data in Fig. D1.7 are presented in Fig. D1.8.

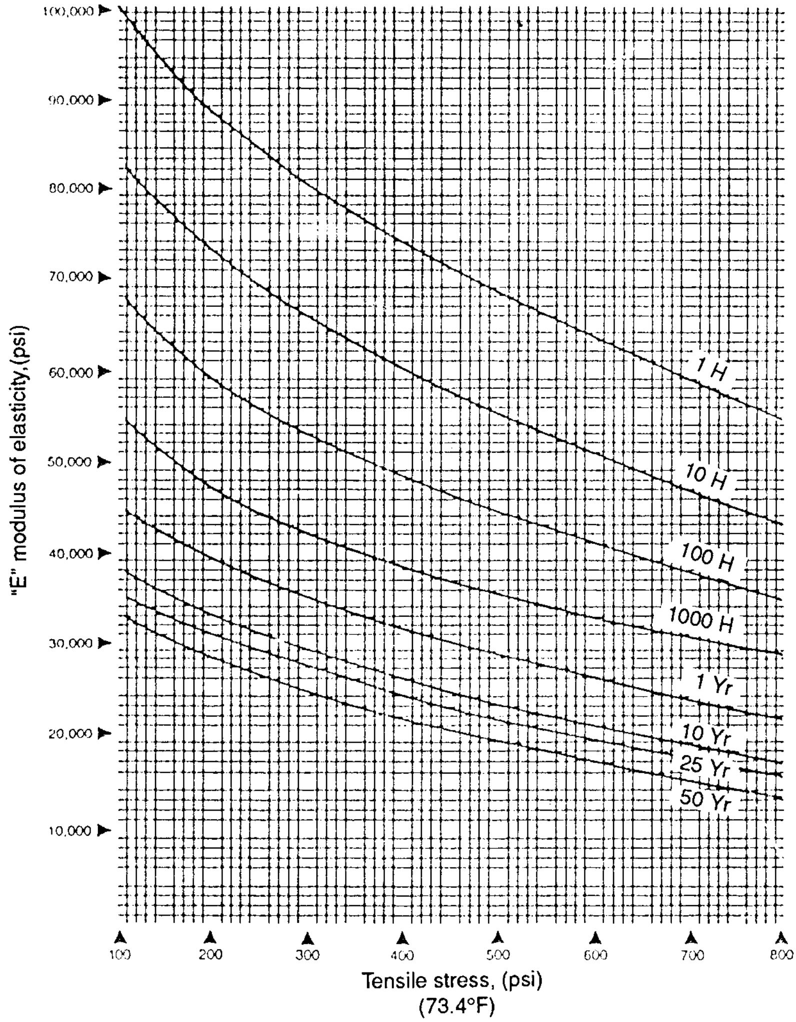


FIGURE D1.8 Creep modulus of elasticity versus stress intensity for a high-density polyethylene.

Analogous ''stress-relaxation moduli'' can be derived from stress-relaxation data. The *stress-relaxation modulus* is the property required for design calculations when the strain is prescribed and the stress is free to vary. However, the numerical difference between the relaxation modulus and the creep modulus is often small when the strain is small and elapsed times under continuous loading or straining are matched. Accordingly, the two can often be used interchangeably for engineering design. A procedure has been proposed to define the range over which the above assumption provides a reasonable approximation.[5] This reference includes a detailed discussion on how viscoelastic properties can be used to model stress-strain response under a variety of time-dependent loading conditions.

The creep modulus for a certain duration of loading is often expressed as a fraction of the modulus of elasticity that has been measured by a particular short-term tensile test. Such a simplified representation (see Table D1.10) assumes that over the range of engineering stresses for which the approximation will be used, creep modulus is independent of stress intensity. The consequence of this simplification is usually small and acceptable for most pipe design. The reciprocal of this fraction, called the *creep factor,* was introduced by Ref. 5 and is used by certain design practices, for example, those of the American Association of State Highway and Transportation Officials (AASHTO) culvert design specifications.[6]

TABLE D1.10 Approximate Ratio of Creep Modulus to Short-Term Modulus as a Function of Duration of Continuous Loading, for 73°F (23°C)

Duration of uninterrupted loading, h	Approximate ratio of creep to short-term modulus*	
	High-density PE	Type I PVC
1	0.80	0.84
100	0.52	0.60
10,000	0.28	0.40
438,000 (50 yrs)	0.22	0.34

* Exact ratio depends on the specific commercial grade of material, stress field, fabrication residual stresses and other factors.

Even though the deformation behavior of plastics is rather complicated, successful design can be simplified by using a creep or an apparent modulus that reasonably reflects response under the anticipated loads. For example, a buried pipe may be subjected to relatively short periods of externally induced high loads, followed by longer periods at lower loading. For such conditions, Boltzman superposition theory can be used to estimate an appropriate creep modulus.[5] More often though, a simpler design check assuming a worse-case condition is all that is required. For example, the wall thickness of a buried pipe is first selected based on pressure rating considerations and then a check is made to ensure that this wall is sufficient to withstand a given combination of traffic (short-term) and soil (long-term) loads. To conduct the design check, it can be assumed that the two loads are simultaneously and continuously present; if the pipe is adequate to this task then no further calculation need be made. While procedures such as this are often used to simplify design, care must be exercised not to make unduly conservative assumptions which could rule out a fully acceptable construction that would be justified by a more refined evaluation.

Allowable Strength When Load is Constant

The relationship between tensile load and time-to-fracture is described by the creep-rupture strength envelope of tensile creep curves (see Fig. D1.6). Each material has a specific envelope depending on the nature of the base polymer and the amount and kinds of additives used in its formulation. To simplify the task of obtaining data from which estimates of a material's long-term strength may be projected, the general practice is to ignore the creep response as a function of stress and time and only track the time-to-fail as a function of the test tensile stress. As is discussed later, excessive deformation under load is seldom, if ever, a factor in delimiting long-term strength.

Stress-rupture data are obtained by means of long-term pressure tests that are conducted on pipe specimens made from the material under evaluation. The use of pipe specimens replicates the combined hoop and axial stresses that are seen by plastic pipe in actual service. Pipe stress-rupture testing is performed in accordance with ASTM D 1598, ''Time to Failure of Plastic Pipe Under Constant Internal Pressure.'' Sufficient pressure versus time-to-fail points are obtained for a set of temperature and test environment conditions to define a hoop stress-rupture envelope through at least 10,000 h. The following relationship, commonly known as the ISO equation (denoting its adoption by the International Standards Organization), is used to calculate the pipe hoop stress generated by the internal test pressure:

$$S = [P/2] \times [D_m/t] \tag{D1.1}$$

where S = hoop stress, psi (MPa)
P = internal pressure, psi (MPa)
D_m = mean pipe diameter, in (mm)
t = minimum pipe wall thickness, in (mm)

The stress-rupture data obtained by testing in accordance with ASTM D1598 are plotted on log stress versus log time-to-fail coordinates. If, as is generally the case for materials that qualify for pressure piping, the data plot along a straight line, the best least-squares line is determined mathematically and then extrapolated to 100,000 h to determine that material's estimated average *long-term hydrostatic strength* (LTHS). The extrapolation procedure used is that of ASTM D 2837, ''Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials.'' A material's *hydrostatic design basis* (HDB) is then established by categorizing its estimated average LTHS into one of a series of standard long-term strength values in which the numbers ascend in increments of 25 percent, as follows: 1,000 psi, 1,250 psi, 1,600 psi, 2,000 psi (6.9 MPa 8.6 MPa, 11.0 MPa, 13.8 MPa), and so on. The purpose of categorizing LTHSs into a limited number of standard HDB values is to simplify material standardization and product design. Figure D1.9 illustrates the application of the ASTM D2837 procedure to establish the HDB of a PVC 1120 material.

Every major standard specification for thermoplastic pressure pipe requires that the material from which the pipe is made have an established HDB for the standard condition of water at 73°F (23°C). Piping materials intended for hot water applications are generally required to also have an established HDB for water for 180°F (82°C). Standards covering natural gas piping require evaluation of the HDB with natural gas—which consists of methane, with minor quantities of other gases—as the test medium. However, water may be used in the case of plastics for which it has been shown that the results are essentially equivalent. For most thermoplastics, testing with water or natural gas result in little difference. However, other gaseous

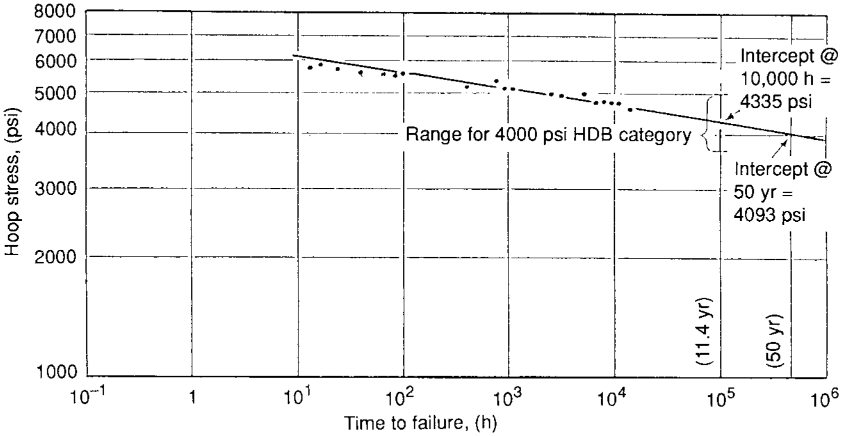


FIGURE D1.9 Application of method ASTM D 2837 to establish the hydrostatic design basis (HDB) for 73°F for a typical PVC 1120 material.

fuels such as propane and butane can make a difference, depending on the degree to which they may be absorbed by the plastic.

For some plastics, particularly those used for industrial applications, there exist stress-rupture data that have been obtained using chemical reagents of special interest.

The Plastics Pipe Institute (PPI) publishes a periodically updated list of thermoplastic pipe materials with HDBs for water which have been established in accordance with ASTM D 2837 and the additional requirements included in PPI TR-3, “Policies and Procedures for Developing Hydrostatic Design bases and Maximum Recommended Hydrostatic Design Stresses for Thermoplastic Piping Materials.” Compositions that carry a PPI recommended HDB are listed in PPI TR-4, “HDB Listed Materials.” A number of pressure pipe standards require that the material have a PPI listed HDB.

The HDB that is forecast by method ASTM D2837 is predicated on a fundamental assumption: that the straight-line log stress versus log time-to-fail behavior that is defined by the data obtained through at least 10,000 test hours (1.14 years) will continue its straight course through at least the 100,000-h (11.4-year) intercept. To lend confidence to this assumption, certain requirements and procedures, as follows, have been included in method D2837:

- Experimental data must include not less than 18 data points, 4 of which must span not less than 6,000 testing hours.
- At least one data point must span a test time of not less than 10,000 h.
- Statistical analysis of the data must yield a 95 percent lower confidence value for the projected 100,000-h intercept that is not less than 85 percent of the projected mean strength at 100,000 h.

Additional data requirements, particularly when establishing HDBs for elevated temperatures, have been adopted by PPI and are included in the aforementioned PPI TR-3 report.

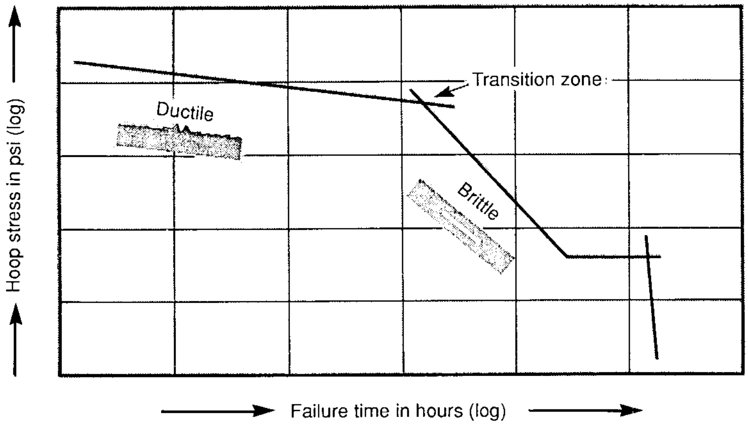


FIGURE D1.10 Schematic of the stress-rupture behavior of a polyethylene material subject to slow crack growth (first downturn) and chemical degradation (second downturn). Such materials are excluded from pressure service.

In the case of PE pipe compositions there is a further requirement in ASTM D2837 which is designed to validate the assumption that the 73.4°F stress-rupture data obtained through 10,000 h will continue its straight-line course through at least 100,000 h. PE piping materials can only qualify for pressure pipe service when they demonstrate compliance to this validation requirement. The reason for this additional requirement is the finding that PE pipe under long-term load can fail by one of three distinct failure modes, as follows[7] (see Fig. D1.10):

- The first is a ductile failure whereby the specimen ruptures as a consequence of gross yielding at a location subjected to maximum *average tensile stress.* The lower the stress, the longer it takes for yielding to occur. No, or little, irreversible structural damage occurs in the material prior to yielding. When this failure mode controls, the slope of the stress-rupture line is relatively flat.
- The second is a slit failure which is the end result of a slow crack growth mechanism, whereby *localized stress concentrations,* created by minute defects or inclusions in the material, spawn small cracks which then grow, so long as sufficient stress intensity is present. As shown by Fig. D1.10, the strength of PE regresses faster in the brittlelike slow crack zone than is projected by the ductile failure trend. If the transition from ductile to brittlelike failure occurs within the intended design life of a pipe, a forecast of its long-term strength based solely on the earlier ductile behavior can result in an overestimate of a material's actual long-term strength. Accordingly, PE materials used for pressure piping have to have high resistance to this failure mechanism to ensure continuance of the ductile stress-rupture line, and thereby optimum long-term strength.
- The third is the result of a breakdown of the polymer molecule through *oxidative or other degradation.* When this occurs, the polymer's longer-term strength can be severely compromised. For ordinary applications this possibility is precluded by the addition into the pipe composition of appropriate kinds and amounts of stabilizers and antioxidants (see discussion on chemical resistance).

The ASTM D2837 procedure for validating the HDB of PE piping materials is designed to ensure that the material's long-term strength will not be compromised by inadequate resistance to slow crack growth. The procedure used is based on the observation that the time for the onset of the slow crack growth mechanism that leads to brittlelike failure (the first downturn in Fig. D1.10) is greatly accelerated by increasing temperature, and that the rate of acceleration follows basic rate process principles. The extent by which increasing test temperature accelerates the onset of brittlelike failure is illustrated by Fig. D1.11 By relating the effect of the increased test temperatures on the shortening of the test time required to reach the brittlelike failure zone at a given stress level, one may validate the assumption that the straight-line behavior described by the ambient temperature data will continue its straight-line course through at least 100,000 h. In accordance with current standards, PE materials that do not meet the validation requirement of ASTM D2837 are excluded from pressure pipe applications.

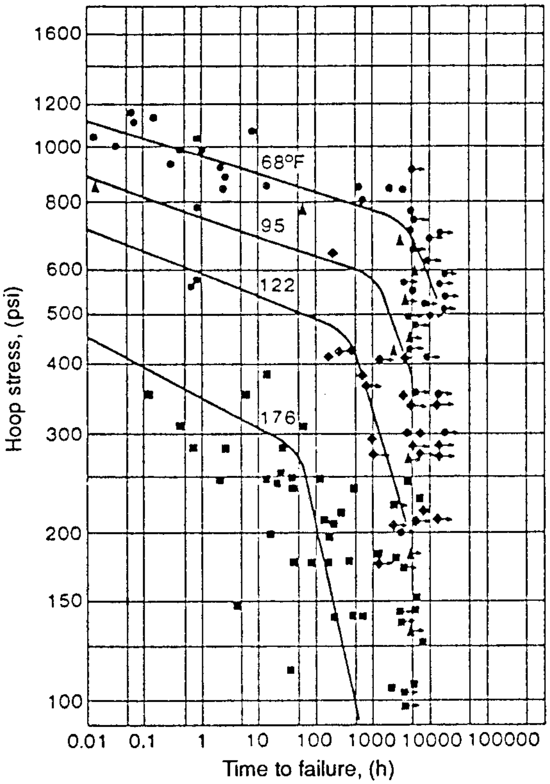


FIGURE D1.11 Effect of temperature on the time required to reach downturns caused by slow crack growth. This material does not qualify for pressure service.

The fracture mechanics process by which slowly growing cracks are incubated and then propagated has been the subject of much investigation in the recent past.[8,9] One result of this work is the development of two new test methods—both based on measuring the time-to-fail of a notched tensile specimen that is subjected to a constant tensile load at an elevated temperature—that give in relatively short time a good index of a PE's very-long-term resistance to failure by the slow crack growth process. As reported under the discussion of PE piping materials, ASTM D3350, the PE piping material specification, has been recently revised to include this test method as a material performance criterion.

To protect against oxidative degradation, the cause of the second downturn in Figure D1.10, current PE piping formulations include appropriate amounts and types of stabilizer packages. Accelerated aging studies, as well as those conducted on pipe that has been in actual service for many years, indicate that PE can be suitably protected against oxidative degradation over its intended service life when conveying water, gas, and similar fluids.[7]

Other Materials. Downturns in stress-rupture behavior have also been observed in other thermoplastics. A material's susceptibility to ''aging'' by gradual physical and chemical changes created by the stress and environmental conditions to which it is continuously subjected can result, after sufficient time, in a transition in failure mechanism that sometimes—but not always—results in a significant downward shift in its longer-term stress-rupture behavior. In cases where a significant downturn occurs after longer times than the longest test period, a forecast of long-term strength that is based on the earlier observed stress-rupture behavior could result in a significant overestimation of a material's actual long-term strength. While the primary objective of long-term stress-rupture characterization is to establish a reliable estimate of a material's long-term strength, another function of this test is to exclude from pressure piping those materials and formulations that are inadequate for very long-term service when subjected to sustained loading. Longer-term stress rupture testing is a fairly effective test procedure for screening out from pressure applications those materials that are prone to downturning in their stress rupture properties. However, as will be discussed, for more effective screening other information should also be considered.

A plastic material's susceptibility to detrimental ''aging'' that could cause downturns in its very-long-term stress-rupture properties depends on a number of factors, including the nature of the service environments; the polymer's chemical nature (e.g., PVC, PE, PB, and so on); its molecular structure (molecular weight, molecular weight distribution, branching, and so on); the formulation of the plastics composition (kind and amounts of additives, including stabilizers); and quality of manufacture. As an example, significant downturning in stress-rupture properties has been reported in PVC materials of lower molecular weights.[10] The same trend has been observed with PVC formulations that include more than relatively low quantities of finely divided fillers, such as calcium carbonates. For these reasons the policies in PPI TR-3 limit the minimum molecular weight of PVC resins, and the kind and amounts of calcium carbonate that can be used in PVC formulations intended for pressure pipe applications.

Excepting for the special requirement for PE materials that is discussed above, there is no formal general protocol in ASTM D2837 for ensuring for the particular material being analyzed that a significant downturn in stress-rupture properties will not occur sometime beyond the maximum time over which the experimental data were gathered. Therefore, the applicability of this extrapolation method to a plastic material has to be judged in consideration of other information that can give an indication about the possible occurrence of a future downturn. A positive source of confidence is, of course, successful long-term service experience with the kind of plastics for which a long-term forecast is being made. A second one is the demonstrated continuance of straight line stress-rupture behavior for much beyond the minimum 10,000 h required by ASTM D2837. Certain materials have been on test for well over 10 years. A third one is information gathered from other tests and from actual field experience about the ‘‘aging’’ effects on the material by the physical and chemical environments to which it may be subjected while in service. And a further source is the absence of a downturn during at least the first 10,000 test hours when testing the plastic at a higher temperature, say, about 40°F (22°C) above that for which the HDB is being established. As discussed previously, increasing the test temperature has a profound effect in shifting downturns to much earlier times. Therefore, the absence of a downturn in such an elevated temperature test during the first 10,000 h of testing is taken as a very good indicator that a downturn will not occur for very much longer times at the lower end-use temperature. The listings of HDBs that are issued by PPI have been established with consideration of these various means for enhancing confidence in the forecasts of longer-term strength of thermoplastics piping materials. In many cases manufacturers of plastics piping and of plastics piping materials issue reports that details other information they have accumulated in support of the appropriateness of the long-term strength predicted by method ASTM D2837.

The International Standards Organization (ISO) has recently issued report ISO/TR 9080, ‘‘Methods of Extrapolation of Hydrostatic Stress-Rupture Data to Determine the Long-Term Strength of Thermoplastics Pipe Materials.’’* This ISO method includes mathematically based procedures for the analysis of elevated multitemperature data to give assurance that the projected long-term strength for a lower maximum service temperature will not be compromised by an unanticipated downturn during the pipe’s intended service life.

Deformation under Load and Ultimate Strain Capacity

As mentioned earlier, the property of ductility—sometimes referred to as *strainability*—of thermoplastics piping materials is a generally recognized beneficial characteristic of these materials. Their capacity to deform significantly prior to rupturing allows them to shed-off, through localized deformation, stress concentrations that could initiate cracking in less ductile materials. Another benefit of ductility is the soil-pipe interaction that is generated by the flexibility of buried plastics piping.

However, too much creep while under load can lead to performance limitations such as excessive diametrical deformation of pipe under pressure. To ensure that this is not a problem, ASTM D2837 imposes the following limitation: The HDB that is projected by the extrapolation of the stress-rupture data cannot be greater than the sustained stress which would produce a 5 percent diametrical expansion at 100,000 h. For all the presently used stress-rated thermoplastic pipe materials in North America, the 5 percent expansion strength has been determined not to be a limiting factor. Therefore, expansion measurements are not required for these materials.

Although the diametrical expansion at failure of a thermoplastic pipe subjected to a stress equal to its HDB is under 5 percent, it is generally above 3 percent and usually closer to 4 percent. Engineering materials are considered to be ductile when

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* Copies of ISO standards may be obtained from the American National Standards Institute. See listing of standards writing associations for address.

they are able to deform prior to failure by at least 3 percent. When a material is ductile a localized stress concentration only leads to localized plastic deformations which modify the local geometry and thereby both reduce and redistribute localized stress. If the material is brittle—that is, if it fails after but minimal deformation—localized stress concentrations remain high and can initiate a crack, which once started, is then propagated by the greatly magnified stresses that develop at the bottom of a crack under tension. Therefore, design with ductile materials can be based on *average* or nominal stress due to tension, shear, or bending. All the common design protocols for thermoplastics piping assume ductile behavior. In contrast, design with brittle materials must be based on a combined stress analysis the objective of which is to identify the *maximum* stress, or strain, in consequence of any and all possible loads, that can occur at any point in the piping, but particularly at points that invite the development of multiaxial stress intensification.

Experience has shown that thermoplastic piping materials which exhibit low strain capacity under sustained loading tend to fail in time by cracks that initiate and then slowly grow at points of localized stress concentration. In the case of buried pipes, conditions that can produce localized stress concentrations include stone impingement, shear loading due to differential settlement, excessive bending, and nonrounded corners in fittings. While the occurrence of localized stress intensifications should always be mitigated by proper product design and installation, if the pipe material is too strain-sensitive it can be subject to premature failure even under the best of conditions. Consider the experience with early vintage high-density PE pipe materials such as the one that exhibits the stress-rupture properties depicted by Fig. D1.11 After some time in service, even as long as after 25 years, buried pipes made from such materials have failed by small cracks that were initiated at points of localized stress intensification. As shown by Fig. D1.11, sustained pressure testing of pipes made from such materials revealed that their longer-term strength was compromised by a subsequent downturn in stress-rupture properties. However, the downturn had another important negative consequence: It resulted in a loss of ductility.

In a short-term tensile test, which is conducted at a strain rate of around 20 in/min (500 mm/min), PE piping materials exhibit a total elongation at failure of well over 100 percent, in some cases over 500 percent. As is the case with all plastics, under sustained loading the elongation at failure of PE steadily decreases with increased time-to-failure. But as already mentioned, PEs now considered suitable for pressure applications always fail at deformations not less than about 3 percent, even after the longest time under sustained loading. However, the material for which the data in Figure D1.11 were obtained fails in time at diametrical expansions of under 3 percent, and the longer the time under load, the lower the value. This is shown by Figure D1.12, which compares 68°F (20°C) isometric (constant strain) diametrical expansion curves to the 68°F (20°C) stress-rupture data obtained on this PE material. In the region where the stress-rupture line (band in this case) is parallel to the isometric curves, ductile failure dominates and the diametrical expansion is fairly large. But in the region where the stress-rupture line downturns, brittlelike failures dominate and the diametrical expansion at failure can be as low as 1 percent. So, the effect of a downturn for this PE is not only a reduction in its long-term strength but its transformation from a ductile to a brittlelike-behaving material. As already mentioned, the validation requirement of ASTM D2937 excludes such PEs from pressure pipe service.

All commercial grade thermoplastic piping materials that have demonstrated permanent ductility under conditions of service exhibit stress-rupture characteristics that are free of significant downturns.

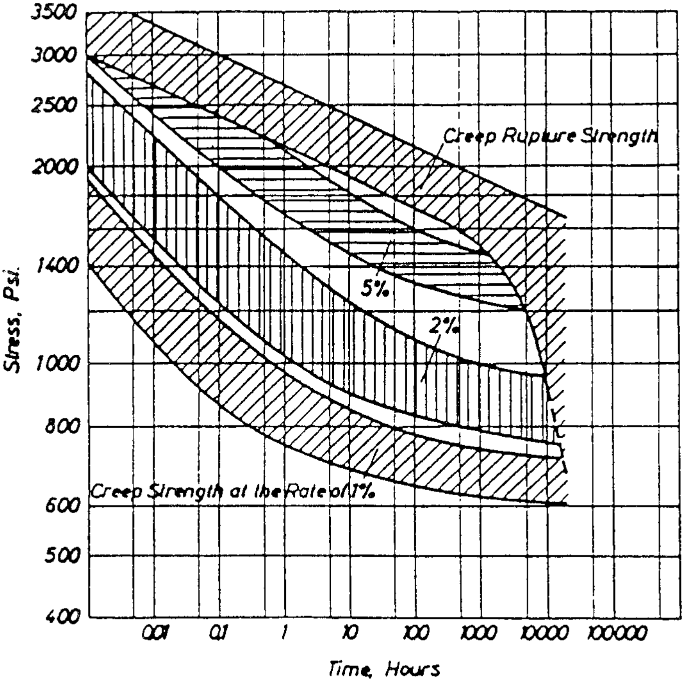


FIGURE D1.12 Comparison of the creep-rupture (also referred as stress-rupture) strength to isometric curves (constant strain) for 68°F (20°C) that have been experimentally determined on pipe made from a PE material that exhibits an early downturn in its stress versus time-to-fail characteristics.

Allowable Strain

As explained earlier, when deformation is kept constant during loading time, the load gradually relaxes, reducing—but never completely eliminating—any stress intensity which could generate and propagate cracks. As a result, the long-term strain capacity of a material maintained at constant deformation is somewhat greater than if deformation had been achieved over the same time of loading by free creeping, with no relaxation of loading. However, even though stress relaxation gives somewhat more leeway, materials intended for nonpressure pipe applications must still have a good measure of long-term strain capacity (i.e., ductility); otherwise they will behave over the long-term as brittle materials for which design and installation must anticipate and avoid any and all localized stress intensifications. This is particularly the case for materials used in profile wall construction, the geometry of which tends to produce localized stress risers.

Unlike what has become the generally accepted practice for the qualifying of pressure piping materials, for which evaluation by ASTM D 2837—or, by another suitable procedure that relies on longer-term data—is a controlling requirement, there is no common longer-term test protocol by which to judge the suitability of a plastic for nonpressure service. Recognizing the value of longer-term data some standards for nonpressure piping do require that the pipe material have an established HDB. However, because the HDB test is time consuming and expensive to run, and because some believe it is excessively demanding for nonpressure piping, the material requirements for many nonpressure pipe standards are based only on the results of shorter-term tests. The particular minimum property requirements for these materials have been established by relating their shorter-term properties to observed quality of longer-term field performance.[13,14] While this approach has generally worked quite well, experience has shown that in some cases it is not as reliable a predictor of adequacy of longer-term strain capacity as is needed. The recent emergence of new testing procedures based on fracture mechanics for the evaluating of the resistance to failure mechanisms that can compromise a materials longer-term strength and ductility promises improved discrimination for the specifying of nonpressure piping materials.[11] As of this writing, the new ASTM notched constant tensile tests that were referenced earlier are also being evaluated for use as an index of the longer-term stress crack resistance of PE materials intended for nonpressure piping.[12]

Resistance to Short-Term Loading

By virtue of the relationship of duration of loading on ultimate strain and ultimate strength, plastics have a certain ability to withstand a higher temporary loading than that indicated by their long-term strength. In short-term loading—such as represented by the higher momentary pressure created by internal pressure waves, or by the temporary added external soil pressure caused by rolling traffic—the limiting stress for long periods of sustained loading can be considerably exceeded, provided the temporary overloading is kept within reasonable limits and its occurrence is sufficiently infrequent so as not cause damage to the plastic by fatigue. Some standards (such as those of AWWA) and a number of design practices give information on the magnitude of infrequent overloading that can be safely tolerated by certain plastic pipes. In cases where the overloading is likely to occur relatively frequently, a pipe's fatigue resistance capabilities need to be considered.

Fatigue Resistance

As with any other engineering material, repeated cyclic stressing of plastics can cause a reduction in their strength through fatigue. Also, brittlelike fracture at points of stress intensification is more likely under cyclic loads than under a simple static load. There is a similarity between the shape of fatigue or *S-N* (stress amplitude versus number of cycles to failure) curves for plastics and those obtained for metals. *S-N* data[15,16] for PVC and PE pipes indicate that fatigue sensitivity varies not only from one plastic to another but can be different within the same plastic family depending on molecular structure, formulation, and fabrication quality. Also, stress risers caused by fitting or joint geometry can magnify the effects of fatigue. By limiting the magnitude of the maximum stress caused by cyclic plus static stresses, or by suppressing the amplitude of the stress change to the “safe” value indicated by *S-N* curves, long service life can be achieved. A number of design practices prescribe such limits.[17,18,20]

Potential Consequence of Failure Mode

The potential failure mode of a plastic pipe may determine the choice of material and/or the limiting service conditions. Some thermoplastics are subject to failure by shattering, which could present a hazard to personnel when the pipe is either used for the aboveground conveying of pressurized gases or when it is pressure tested with compressed air. For this reason, the Plastics Pipe Institute recommends that no thermoplastic pipe be tested with compressed air or used for aboveground compressed gas service unless it has been evaluated and is specifically recommended by the manufacturer for that service.

Thermoplastic pipe failure can also occur by a rapid crack propagation (RCP) process, whereby axial cracks may travel long distances and at high speeds in a pressurized pipeline. Resistance to RCP has been linked to the absorbed energy in the Charpy impact test, a property highly influenced by temperature. The possibility for the occurrence of RCP increases with increasing pressure and pipe diameter, as well as with decreasing temperature. For certain applications, such as gas distribution, a design objective is to ensure that the selected pipe material in the largest pipe diameter when operating at maximum pressure and minimum temperature will not lead to RCP should the pipe be accidentally damaged. Calculation procedures for evaluating compliance with this objective have been proposed.[19]

CHEMICAL RESISTANCE

A major reason for the broad acceptance of thermoplastics piping is its virtual freedom from attack by ambient moisture and other common corrosives. This applies not only to external surroundings, both below as well as aboveground, but also to the materials being conveyed. Being nonconductors, plastics are immune to galvanic or electrochemical corrosion. The electrical activity of electrolytes such as acids, bases, and salts is of no consequence. Plastics piping is generally durable and not subject to a gradual degradation of material and properties comparable to the rusting of steel, or atmospheric corrosion of copper, or pitting of concrete. Painting, wrapping, lining, and cathodic and other forms of corrosion protection are not required. Maintenance costs are therefore, minimal.

However, as indicated by the abbreviated chemical-resistance guide shown in Table D1.11, for each plastic there are certain substances that can be hostile. Identifying the suitability of a plastic to a specific chemical is inherently more complex than for metals for several reasons. One of these, as previously elaborated, is that even within the same family of plastics the individual members may differ in molecular composition and in the nature and quantity of compounding additives. All of these can affect chemical resistance. Chemical-resistance charts, such as the abbreviated Table D1.11, are not to be considered more than a preliminary guide.

Another reason is that plastics can interact with chemical environments by a number of different mechanisms that can vary in rate, and in degree of impairment of performance properties, depending on concentration, temperature, and stress level. The primary mechanisms are as follows:

- *Chemical attack.* A chemical environment can attack certain active sites on the polymer chain, leading to chain scission and, ultimately, to significant ‘‘aging’’ or degradation of the polymer. The rate of attack can determine suitability of the plastic—if very slow, or if arrested by the addition of an appropriate stabilizer, long service life can be realized. Strong oxidizers will attack many plastics. This is why antioxidants are generally included in the stabilization package of many thermoplastic compounds.
- *Solvation.* The absorption by a plastic of an organic solvent is called *solvation.* Its effect may range from a slight swelling and softening, with minor effect on properties, to a complete solution. For example, the solvent cementing of ABS and PVC is based on solvation.

TABLE D1.11 Thermoplastic Piping Materials: Chemical Resistance Guide for Ambient Temperatures (See Note 1)

		PVC							
Chemical	ABS	Type I	Type II	CPVC	PE	PEX	PB	PP	PVDF
Inorganic materials									
Acids, dilute	G	G	L	G	G	G	G	G	G
Acids, concentrated (<80%)	L	L	L	G	L	L	L	L	G
Acids, oxidizing	L	P	P	L	P	L	P	P	G
Alkalies, dilute	G	G	G	G	G	G	G	G	G
Alkalies, concentrated (<80%)	L	G	L	G	G	G	G	G	G
Gases, HCl & HF, dry	L	L	L	L	L	L	L	L	G
Gases, HCl & HF, wet	L	G	L	G	L	L	L	L	G
Gases, ammonia, dry	L	G	L	G	G	G	G	G	G
Gases, halogen, dry	L	L	L	L	L	L	L	P	G
Gases, sulfur containing, dry	P	G	L	G	G	G	L	P	G
Salts, acidic	G	G	G	G	G	G	G	G	G
Salts, basic	G	G	G	G	G	G	G	G	G
Salts, neutral	G	G	G	G	G	G	G	G	G
Salts, oxidizing	L	L	L	L	G	G	G	G	G
Organic chemicals									
Acids	G	G	G	L	G	G	G	G	G
Acid anhydrides	L	L	L	P	L	L	L	L	L
Alcohols, glycols	L	G	L	G	L(2)	G	G	G	G
Esters, ethers, ketones	P	P	P	P	L	L	L	L	L
Hydrocarbons, aliphatic	L	L	L	G	L	L	L	L	G
Hydrocarbons, aromatic	P	P	P	L	P	L	P	P	G
Hydrocarbons, halogenated	L	L	L	L	P	L	P	P	L
Natural gas (fuel)	G	G	G	G	G	G	G	G	G
Mineral oil	G(2)	G	G	G	L(2)	G	G	G	G
Oils, animal & vegetable	G(2)	G	G	G	L(2)	G	G	G	G
Synthetic gas (fuel)	L	L	L	L	L	L	L	L	G

Notes:

1. G denotes good; L limited resistance; and P poor. These ratings are only for general guidance. For determination of suitability of chemical resistance under the actual anticipated end use conditions more detailed information should be consulted.
2. Stress crack resistant grade of plastic material should be used.

- *Plasticization.* When a liquid hydrocarbon is an imperfect solvent; that is, when it is miscible with a polymer but unable to dissolve it, *plasticization* may result. The plasticizing effect can vary over a wide range, depending on relative miscibilities. Plasticization can significantly compromise mechanical properties, including creep-rupture behavior.
- *Environmental stress-cracking.* Under this mechanism, fracture of the plastic can occur after some time in response to a synergistic action of stress and environment. Stress-cracking agents tend to be strong surface-wetting liquids, such as detergents, surfactants, glycols, and alcohols, which by some mechanism not yet fully identified facilitate the development and growth of microcracks when under stress. Susceptibility to stress-cracking can be mitigated by selecting stress-crack-resistant grades of material.

In all these mechanisms, stress, reagent concentration, and time are important variables. In addition, temperature has a profound effect on the results. Raising the temperature significantly increases the reaction rates. It also causes a polymer to expand and become more penetrable, more permeable, and more soluble. Forecasting performance at higher temperatures based on lower-temperature results can, therefore, be risky.

Because chemical resistance can be limited by any of the just-noted mechanisms and be affected by many variables, shorter-time ‘‘soak’’ tests cannot reliably predict actual performance. Most chemical-resistance charts are, however, based on such information. They should only be considered as an initial guide. A more effective method of evaluating the effects of chemicals, particularly for pressure piping, is creep rupture with the specimen immersed in or in contact with the test environment.

A creep-rupture test method specifically designed for evaluating the chemical resistance of plastics pipe is the subject of ISO Standard ISO 8584. ‘‘Thermoplastic Pipes for Industrial Applications Under Pressure-Determination of the Chemical Resistance Factor and of the Basic Stress.’’ Chemical resistance evaluated under this or similar methods is reported by some manufacturers. Successful previews in the same or similar service are also reliable indicators. Lacking this, chemical resistance will be best established by actual service testing. Manufacturers and trade associations can assist in obtaining this information. An advantage of service testing is that it is sure to include some minor chemical component, such as a surfactant, which could influence the final result.

When selecting plastic pipe for a given application, consideration should also be given to the possibility that the quality of the fluid being transported could be affected by permeation of organic pollutants with which the outside of a pipe may be exposed. Thermoplastics, as well as elastomers (such as used in rubber gaskets) and porous materials such as asbestos cement and concrete, may be subject to permeation through the pipe wall by lower molecular weight solvents and other liquid organics, such as petroleum products. Prior to selecting materials for installation in soil or other material that is or can be contaminated by organic solvents, the piping manufacturer should be consulted regarding permeation properties of the pipe walls, fittings, and jointing materials.

Effect on Fluids Being Conveyed

Plastic pipe materials are generally inert to the materials being transported. Because their composition includes minimal or no quantities of materials which can produce dissolved ions, plastics pipes are often used for the transport of pure materials, including deionized water. For food service there are pipes available that have been made from materials approved by the Federal Food and Drug Administration.

Plastic pipe resins are also neutral to potable water. However, because it is possible to formulate pipe with certain ingredients (such as stabilizers, catalysts, or modifiers) that could leach out and adversely impact water quality, most standards and codes require that pipe intended for this service meet the requirements of National Sanitation Foundation Standard 61, ‘‘Drinking Water System Components-Health Effects (November, 1996).’’

DESIGN AND INSTALLATION

As discussed earlier, thermoplastics are viscoelastic materials; thus they exhibit a profoundly different stress-strain and stress-rupture response than do elastic materials. Nonetheless, elastic equations used for other types of piping are frequently applicable to thermoplastics piping, provided that their engineering behavior is represented through appropriately derived values of apparent modulus and strength. Since these properties are greatly influenced by the history of the material's exposure to stress as well as by temperature and environment, proper use of traditional elastic equations requires appropriately established or estimated property values. Long-term strength values for certain conditions [such as for water at 73°F (23°C)] are available, and in some cases (i.e., maximum recommended hydrostatic design stress) they may even be part of the product standard. In addition, some codes and suggested design protocols either list or give procedures for arriving at appropriate values of strength, stiffness, and allowable strain. As this is a still developing technology, not all properties for all materials are yet available in a standardized basis. However, for the more frequently used materials, sufficient information for the majority of applications is either available or may be adequately estimated.

While the viscoelasticity of thermoplastics somewhat complicates the process of selecting appropriate material constants, materials with high strain capacity help to facilitate design. Under a great many conditions thermoplastics display a ductilelike behavior: They are able to deform significantly before fracture. This behavior helps to redistribute stresses and preclude failure by localized stress intensification which could initiate cracking in brittlelike materials. Within certain limits, design of thermoplastics piping is based on average stress; localized stress concentrations are generally ignored.

Also, as previously pointed out, the strain capacity of thermoplastics under constant strain (where stresses can gradually decrease through stress relaxation) is often significantly greater than that under constant load (where stresses intensify as the material deforms). Allowable strain limits under constant strain can therefore often be greater than the fracture strains observed under sustained loading. For example, several investigations of PVC and PE pipes subjected to constant deflections over long periods of time show that the materials did not fail at sustained strains of as high as from 5 to 10 percent.[13,14] These same strains corresponded to relatively short lifetimes when the materials were subject to constant load.

One simplification commonly employed in the North American design of flexible buried plastic pipes (the word *flexible* in this instance signifies that the pipe can undergo significant permanent deformation without cracking) assumes that internal pressure (constant load) and external loading (resulting largely in pipe bending stresses relieved by both pipe deformation and stress relaxation) are acting independently. That is, the pipe wall thickness is chosen on the basis of internal fluid pressure, and then a separate analysis is made to ensure that the pipe is sufficiently strong and structurally stable under the external loads acting alone.[17,18] In effect, localized fiber stresses due to bending and other external loadings are neglected. Standard installation practices include recommendations for avoiding localized stress concentrations. For cases where localized strain cannot be avoided and where it may thus limit design, more rigorous design protocols based on a combined loading analysis are available.[5]

There are many potential factors that could cause a material with apparent high strain capacity to shift from the ductilelike to the brittlelike state and as a result, fail at lower-than-expected strains. These can include temperature, environment, duration of loading, nature of loading (unrelieved or relieved by stress relaxation), stress triaxiality, fatigue, scale factors (such as wall thickness), damage (cuts, gouges), stored energy in system (such as residual stresses from manufacture), material imperfections (voids, contaminants), polymer aging, and chemical attack. Judging from the good track record that exists, these influences, although difficult to quantify, appear to have been adequately considered for typical uses by standards, design protocols, and installation practices. In addition, material requirements and improvements have been evolving that ensure greater durability in pipe products. Furthermore, design practices give recognition to the effects on strength and stiffness and other long-term engineering properties by time, temperature, and environment. Finally, installation recommendations address many of the unique characteristics of plastics that can affect structural integrity and durability. To be sure, the state of the art of thermoplastics piping is still evolving, and considerable work yet remains to be accomplished to further define materials properties and performance limits. Such work is ongoing, and for the latest information the reader is encouraged to refer to the growing literature, particularly to the papers presented at the various conferences that address plastics piping technology.

As demonstrated by the successful record of experience, sufficient information is available to successfully support proper application of thermoplastics over a very broad range of engineering uses. To best realize the performance potential of thermoplastics piping, the user should base materials selection and utilize design and installation practices on information, such as standards and recommended practices, which has been developed under the technical scrutiny of the consensus process of an established professional society or technical association, as well as upon the recommendations and reports issued by industry and independent sources. A number of such references are provided at the end of this chapter.

The following material is an introduction to some of the more basic aspects of the design and installation of thermoplastics piping. More detailed recommendations suitable to a particular product and situation should be sought and followed.

COMMON DESIGN AND INSTALLATION CONSIDERATIONS

Internal Hydraulic Pressure

Thermoplastic pipe is pressure rated by means of the ISO Eq. (D1.1). When rewritten to solve for pressure, this equation takes the form:

$$\mathrm{PR} = 2(\mathrm{HDS}) \times t/D_m \tag{D1.2}$$

where PR = pipe pressure rating, psi (MPa)
t = minimum wall thickness, in (mm)
D_m = mean diameter, in (mm)
HDS = HDB × DF, where HDB is in psi (MPa) units and DF is the pipe design factor

Values of HDS for water at 73°F (23°C) are specified by most ASTM and other standards that cover water and gas applications. The maximum HDS for water is generally determined by multiplying the material's HDB by a design factor (DF) of 0.5. In selecting the appropriate design factor, consideration is given to two general groups of conditions. The first group considers the manufacturing and testing variables, specifically normal variations in the material, manufacture, dimensions, quality of handling techniques, and the accuracy of the long-term strength prediction. The second group considers the application or use, specifically installation, environment, temperature, hazard involved, life expectancy desired, and the degree of reliability selected.

For gas pipe, a DF of 0.32 is prescribed by the federal code. Certain other codes and standards (e.g., those of AWWA) may prescribe specific design factors. A DF smaller than 0.5 is used in applications where greater compensation is advisable for certain anticipated conditions (e.g., surges or temperature), or where the fluid conveyed may have some effect on the pipe material properties. The final determination of the appropriate DF for any given application is up to the discretion of the design engineer.

By assuming that a pipe's outside diameter is equal to $D_m + t$, the previous equation takes the following form:

$$\mathrm{PR} = 2(\mathrm{HDS})/(\mathrm{DR} - 1) \tag{D1.3}$$

where DR = ratio of average outside pipe diameter to minimum wall thickness

Equation D1.3 is used to compute the pressure rating of DR dimensioned pipe.

There is no equivalent design system for establishing the pressure rating of fittings. Some fitting standards require that fittings have a short-term burst strength, and in some cases a 1000 h strength, that is not less than that of the pipe for which the fitting is intended. This is not always sufficient to ensure that fittings will have long-term strengths that are comparable to that of the pipe. Because of their geometry, the stresses generated by pressure on a fitting body are more complex and not amenable to easy calculations. Furthermore, such complex stress fields tend to result in a faster regression of strength with duration of loading than occurs in the simple cylindrical pipe shape. For these reasons, even if a fitting matches the short-term strength of a pipe, it may become the weak link over the long term. This is more likely the case where there are cyclic pressures that can weaken the material by fatigue, usually at fitting stress risers.

Fittings are also sometimes made from a lower molecular weight or better lubricated compound in order to facilitate molding. Such compounds may have somewhat weaker creep-rupture and fatigue characteristics, which may need to be compensated by thicker walls or by limiting the maximum service conditions of pressure and temperature. For these reasons the designer should not presume that a fitting labeled with a certain schedule (say, Schedule 40 or 80) will have the same pressure rating as the pipe of the same designation. Suggested maximum pressure ratings for PVC fittings Schedule 40 and 80 have been published[20] (see Table D1.12), and these are significantly lower than for pipe. Because of differences in mold design and other factors, it is best for the designer to consult with the fitting manufacturer for fitting pressure-rating recommendations.

AWWA C 907, "AWWA Standard for Polyvinyl Chloride (PVC) Pressure Fittings for Water—4 Inch Through 8 Inch," is distinctive from most other fitting standards in that it requires each molded fitting configuration to be qualified by an accelerated regression pressure testing intended to ensure a minimum long-term pressure strength sufficient for a 150 psi (1.0 MPa) fitting Pressure Class.

Surge Pressure

Transient and regularly recurring surge pressures may cause damage to pipe and fittings by either of two possible effects: The surge exceeds the short-term fracture strength of the pipe or one of the components; or (and this is the more likely possibility) the repetitive changes in pressure exceed the fatigue endurance limit of the pipe or some piping component. Transient or water hammer surges result from sudden changes in velocity. The pressure rise caused by the velocity change

TABLE D1.12 Suggested Maximum Sustained Working Pressures for Water for 73°F (23°C) for Schedule 40 and Schedule 80 PVC Fittings*

	Schedule 40		Schedule 80	
Nominal size, in	Required minimum burst pressure by ASTM D2466 psig	Maximum suggested working pressure psig	Required minimum burst pressure by ASTM D2467 psig	Maximum suggested working pressure psig
½	1910	358	2720	509
¾	1540	289	2200	413
1	1440	270	2020	378
1¼	1180	221	1660	312
1½	1060	198	1510	282
2	890	166	1290	243
2½	970	182	1360	255
3	840	158	1200	225
3½	770	144	1110	207
4	710	133	1040	194
5	620	117	930	173
6	560	106	890	167
8	500	93	790	148
10	450	84	600	140
12	420	79	580	137

* This table is only intended as a general guide. Appropriate maximum working pressures may vary widely depending on specific fitting design and field conditions, particularly when repetitive surge pressures are present as these may lower the long-term strength because of fatigue effects. The fitting manufacturer should be consulted for recommendations. Source of these suggested values is Ref. 20.

can be estimated by means of the same equations used for calculating the effects of water hammer in other pipes. The only difference is that with plastics the appropriate material modulus is that for the condition of dynamic, instantaneous response (about 150,000 psi (1.0 GPa) and 460,000 psi (3.2 GPa) for high-density PE and PVC, respectively, at 73°F (23°C)). In cases of network piping it is suggested that a complete network analysis be performed for more accurate estimates of possible surge pressures.

Because of the lower stiffness of plastics, the surge pressure rise that occurs from water hammer is significantly lower than for metallic piping. For example, the surge pressure rise for each foot-per-second change in flow velocity is from about 16 to 20 psi (110 to 140 kPa) and 8 to 12 psi (55 to 83 kPa) for PVC and PE, respectively, at 73°F (23°C). The exact value depends on pipe wall thickness—the thicker the wall, the larger the pressure rise. As noted previously, if there is no damage accrued by excessive fatigue, thermoplastic pipes have the capability to withstand momentary pressures that are significantly greater than the pipe's pressure rating. This is due to the stress versus time-to-failure characteristics of thermoplastic pipe materials. However, if the sum of short-term pressure rise plus the sustained working pressure exceed the pipe's short-term burst strength, failure will result.

Entrapped air in a pipeline can produce sudden accelerations of air-separated water columns. The kinetic energy of these fast-moving columns can sometimes be high enough to fracture the pipe. For this reason, when plastic piping systems are first filled with water, either for operation or testing, they should be filled carefully and relatively slowly to minimize air entrapment. Air should be vented from the high points before the system is pressurized. Other precautions should also be taken, such as carefully laying pipe to grade or using air vent-vacuum relief lines, to minimize the entrapment of air in operating pipelines.

When there exists a frequently recurring pressure surge of significant amplitude—say, over 25 percent of the operating pressure—the designer should evaluate the piping for adequacy of fatigue endurance. The resistance to fatigue varies from material to material. For example, PE pipe is quite tolerant; modern materials can withstand frequent surging up to one-half of the pipe pressure rating even when the pipe is operating at its full rating based on only static pressure considerations. In the case of PVC pipe, which is somewhat more sensitive to effects of fatigue, the following equation has been proposed[15] for estimating the maximum total hoop stress, due to both static and cyclic pressure, that PVC pipe can safely tolerate as a function of the total number of anticipated surge pressure events:

$$S' = \left(\frac{5.05 \times 10^{21}}{C'} \right) \tag{D1.4}$$

where S' = maximum allowable total hoop stress, psi (no safety factor) (for S' in MPa, multiply by 0.0069)
C' = total number of cycles

Resistance to Vacuum and External Pressure

The performance of flexible pipe with thin walls that is made from materials with low modulus of elasticity can sometimes be limited by buckling under vacuum or external pressure. A net external pressure can result from external hydrostatic loading, from internal negative pressure, from the temporary vacuum that may accompany pressure surging, or from a combination of these elements. The buckling resistance of plastic pipes may be estimated using the following adaptation of the elastic buckling equation for thin tubes:

$$P_c = \left(\frac{24EI}{1 - \nu^2} \right) \times \frac{1}{D_m^3} C \tag{D1.5}$$

where P_c = critical buckling pressure, psi (MPa)
E = apparent modulus of elasticity, psi (MPa) (For short-term loading conditions, use the values of E and ν as obtained from short-term tensile tests; for long-term loading, appropriate values as determined from long-term loading tests should be employed)
I = pipe wall moment of inertia, in^4/in (mm^4/mm)
ν = Poisson's ratio (approximately 0.35 to 0.45 for long-term loading)
D_m = mean diameter, in (mm) = diameter to centroid of pipe wall for profile wall pipe
C = ovality correction factor, $(r_0/r_1)^3$, where r_1 is the major radius of curvature of the ovalized pipe, and r_0 is the radius assuming no ovalization

For pipe of solid wall construction, for which $I = t^3/12$, the previous equation is usually expressed as follows:

$$P_c = \left(\frac{2E}{1 - \nu^2}\right) \times \left(\frac{t}{D_m}\right)^3 \times C \tag{D1.6}$$

where t = pipe wall thickness, in (mm)

According to this equation, pipe made to a constant ratio of diameter to wall thickness has the same resistance to hydraulic collapse, independent of pipe diameter.

For buried pipe, the stiffening effect of embedment can substantially increase the buckling capacity. This is discussed in a later section.

Temperature Effects

As the system temperature increases, thermoplastics piping becomes less rigid, exhibits higher impact strength, and offers lower short- and long-term strength. The opposite effects take place as temperature decreases. The exact effect depends not only on material class but its specific composition. For example, there are PEs suitable for service at temperatures as high as around 160°F (71°C); whereas other PEs might only have sufficient strength through about 120°F (49°C). In the case of fittings, wall thickness and product design also influence the effects of temperature on strength.

The best way to determine the effect of temperature on long-term strength is through stress-rupture testing. PPI TR-4, ‘‘Recommended Hydrostatic Strengths and Design Stresses for Thermoplastic Pipe and Fittings Compounds,’’ lists recommended HDBs for various commercial grade thermoplastics for temperatures up to 200°F (93°C). Table D1.13 lists approximate temperature derating factors for some of the more commonly used materials.

Because of its effect on stiffness, increasing temperature also decreases the collapse resistance of plastics pipe. As evident from inspection of Eq. (D1.5), this effect is in direct proportion to the change in the material's apparent modulus of elasticity. This modulus changes with temperature at a rate roughly parallel with the strength derating factors given in Table D1.13.

Other principal effects to be considered in piping design and installation are those resulting from thermoplastics' high coefficient of expansion and contraction. Some potential consequences to be considered include:

1. Piping that is installed hot may cool sufficiently after installation to generate substantial tensile forces. The final connection should be made after the pipe has equilibrated to ambient, or to the desired temperature.
2. Unrestrained pipe may shrink enough to pull out from elastomeric gasket or compression joints. The pipe should be adequately restrained by the use of anchors, or the fitting should be designed to either resist pull-out forces or to tolerate the maximum anticipated pipe movement.
3. Piping exposed to cyclic temperature changes may be susceptible to fatigue damage at points subject to repetitive bending.
4. Pipe installed when ambient temperatures are low may buckle if the compression forces developed on subsequent pipe expansion are not adequately relieved.

TABLE D1.13 Effect of Temperature on Strength and Stiffness of Thermoplastics Pipe: Approximate Temperature Derating Factors(1)

Temperature (°F)	PE	PEX	PB	PVC Type 1	CPVC	PVDF
70	1.0	1.0	1.0	1.0	1.0	1.0
80	0.95	0.95	0.97	0.88	—	0.93
90	0.90	0.91	0.92	0.75	—	0.87
100	0.80	0.87	0.86	0.62	0.78	0.82
110	0.75	0.83	0.82	0.50	—	0.76
120	0.70	0.79	0.77	0.40	0.65	0.71
130	0.50	0.76	0.72	0.30	—	0.65
140	0.40	0.73	0.68	0.22	0.50	0.61
150	0.20	0.69	0.69	NR(2)	—	0.57
160	NR	0.66	0.58	NR	0.40	0.54
180	NR	0.63	0.48	NR	0.25	0.47
200	NR	0.50	0.40	NR	0.20	0.41
220	NR	NR	NR	NR	NR	0.38
250	NR	NR	NR	NR	NR	0.35
280	NR	NR	NR	NR	NR	0.28

(1) Check with pipe manufacturer for his recommendations for derating factors for the specific composition under consideration.

(2) NR—Not resistant for continuous service at indicated temperature.

CONSIDERATIONS FOR ABOVEGROUND USES

Thermoplastic piping systems in aboveground service must be properly supported to avoid excessive stresses and sagging. Valves and other heavy piping components should be individually supported. Piping should be located, or protected, to avoid mechanical damage. The piping layout should have sufficient flexibility or other means of mitigating excessive bending and axial stresses and fatigue effects induced by repetitive expansion-contraction.

Supports and Anchors

Horizontal runs require the use of hangers that are carefully aligned and are free of rough and sharp edges. Many hangers designed for metal pipe are suitable for thermoplastic pipe as well. These include the shoe, clamp clevis, sling, and roller types. To preclude high localized support pressures, it is generally advisable to modify the hangers by increasing the bearing area by inserting a protective sleeve of plastic between the pipe and the hanger.

Vertical lines must also be supported at intervals to reduce loads on the lower fittings. This can be accomplished by using riser clamps or double bolt clamps located just below a coupling or other fitting to support the pipe. When so located, these provide the necessary support without excessive compression of the pipe.

Anchors are used in thermoplastic piping systems as fixed points from which to direct expansion-contraction and other movements in a defined direction. Their placement is selected to prevent overloading of the piping, particularly at changes of direction where pipe movement could generate excessive bending and axial stresses. Anchors should be placed as close to elbows and tees as possible. Guides are used to allow axial motion while preventing transverse movement. Both anchors and guides may be used in the control of expansion and contraction of pipelines. They should be of a style and be so located as to prevent overstressing of the pipe. A flexibility analysis can be used to determine suitable arrangements for anchors and guides.

Support Spacing

Support spacing requirements are computed using the same beam deflection equations used for metal piping. The minimum spacing requirement can result from either maximum allowable stress, or maximum allowable pipe deflection considerations for the maximum anticipated service temperature. Maximum beam deflection, or sag, is frequently the controlling factor. Typical support spacing recommendations are presented in Table D1.14.

Expansion-Contraction

There are several methods used for controlling or compensating for axial and bending stresses caused by thermal expansion. Piping runs may include changes in direction which will allow the thermally induced length changes to be taken up safely. Where this method is employed, the pipe must be able to float except at anchor points.

When the piping layout does not include sufficient changes in direction, appropriate expansion loops or offsets have to be provided. The size of the loops and offsets depend on the design (see Fig. D1.13), and the change in length of pipe that has to be accommodated. The dimensions of loops and offsets are calculated using the following equation for cantilevered beams loaded at one end[21]:

$$L = \left[\frac{3}{2} \cdot \frac{E}{S}\right]^{0.5} [D_o(\Delta L)]^{0.5} \tag{D1.7}$$

where L = loop length, in (mm)
E = modulus of elasticity at the working temperature, psi (MPa)
S = maximum allowable stress at the working temperature, psi (MPa)
D_o = outside pipe diameter, in (mm)
ΔL = change in length due to temperature change, in (mm)

Assuming a maximum allowable strain of 0.01, as suggested by a plastics industry publication,[22] the above equation reduces to:

$$L = 12.2[D_o(\Delta L)]^{0.5} \tag{D1.8}$$

For Eq. (D1.7), the convention is to use the short-term apparent modulus in combination with the maximum allowable long-term working stress (often the same value is used as the material's hydrostatic design stress). Since expansion/contraction does not occur instantaneously and since the working stress applies to a condition of constant load where, unlike this situation, there is no stress reduction due to stress relaxation, this combination is conservative. This helps to compensate for other factors, such as fatigue effects caused by repetitive expansion-contraction. Since for most plastics E and S vary with temperature at approximately the same rate,

TABLE D1.14 Typical Recommended Maximum Support Spacing, in Feet, for Thermoplastic Pipe for Continuous Spans and for Uninsulated Lines Conveying Fluids of Specific Gravity up to 1.35

Pipe dimension	PVC			CPVC				PVDF				PP			
Nominal diam., in	60°F	100°F	140°F	60°F	100°F	140°F	180°F	80°F	100°F	140°F	160°F*	60°F	100°F	140°F	180°F
Wall Schedule 40															
½	4½	4	2½	5	4½	4	2½	3¾	3½	2		1¾	1¾	1½	1¼
¾	5	4	2½	5½	5	4	2½	4	3¾	2½		2	2	1¾	1¾
1	5½	4½	2½	6	5½	4½	2½	4¼	4	2½		2	2	2	1¾
1¼	5½	5	3	6	5½	5	3	—	—	—		2½	2¼	2	2
1½	6	5	3	6½	6	5	3	4½	4½	2½		2½	2½	2¼	2
2	6	5	3	6½	6	5	3	4½	4½	2¼		3	2¼	2½	2¼
3	7	6	3½	8	7	6	3½					3½	2¼	3	2¾
4	7½	6½	4	8½	7½	6½	4					4	3¼	3½	3
6	8½	7½	4½	9½	8½	7½	4½								
8	9	8	4½												
Wall Schedule 80															
½	5	4½	2½	5½	5	4½	2½	4½	4½	2½		2	2	2	1½
¼	5½	4½	2½	6	5½	4½	2½	4½	4½	3		2½	2½	2¼	2
1	6	5	3	6½	6	5	3	5	4¾	3		2½	2½	2¼	2
1¼	—	—	—	—	—	—	—	—	—	—		3	2¾	2½	2½
1½	6½	5½	3½	7	6½	5½	3½	5½	5	3		3	3	2¾	2½
2	7	6	3½	7½	7	6	3½	5½	5¼	3		3½	3¼	3	2¾
3	8	7	4	9	8	7	4					4	4	3½	3½
4	9	7½	4½	10	9	7½	4½					4½	4½	4	3½
6	10	9	5	11	10	9	5								
8	11	9½	5½												

* Continuous support recommended.

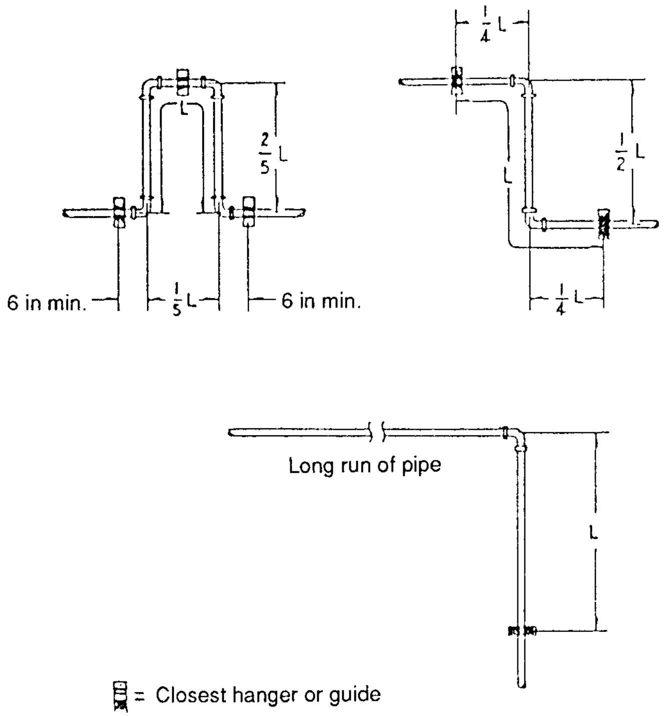


FIGURE D1.13 Expansion loops relieve thermal stresses by transforming them to bending stresses. The minimum loop strength *L* is generally determined by the maximum allowable bending stress or strain.

calculations based on ambient temperature values are generally also appropriate for a fairly wide operating temperature range.

Because the fitting restrains the pipe, a separate check should be made with the manufacturer regarding the fitting's capacity to absorb expansion-contraction stresses and bending moments.

Expansion joints of bellows and piston designs are available and sometimes used. However, piston expansion joints for pressure applications are generally expensive. Proper alignment of piston joints is critical to prevent binding. Bellows-type joints can accept some lateral movement.

CONSIDERATIONS FOR BELOWGROUND USES

Design and installation of thermoplastic pipe for belowground uses recognizes its "flexible" conduit behavior. As noted earlier, the word *flexible* primarily signifies that the pipe has the capacity to sustain significant deflection without failure. Although this value is somewhat arbitrary, a pipe is often considered flexible if it can sustain 2 percent deflection. Conduits that are strong and stiff and that fail at low deformations are classified as *rigid.* Both rigid and flexible piping systems take advantage of soil support to minimize internal stresses and must be designed and installed to avoid stress concentrations and deformations that could result in excessive localized stresses. Thus, the installed buried pipe is actually a pipe-soil system, with both the pipe and the soil contributing to the structural performance. This is an important concept for all types of buried piping systems.

Designing pipe for buried conditions may be different for pressure pipe and nonpressure pipe. The stresses induced by internal pressure are often high relative to those in nonpressure pipe, and the stresses in pressure pipe are constant (subject to creep), while the strains in nonpressure pipe are constant (subject to relaxation, i.e., stresses relax with time). In addition, when subjected to internal pressure, a pipe rerounds, reducing the deflection and bending stresses that result from earth loading.[5]

Thus, for many pressure pipes, a design that meets the requirements of the internal pressure condition can be considered adequate for buried applications, provided the pipe is properly installed in good-quality backfill materials. Although all designers should satisfy themselves to this through calculation checks, in general, if the following conditions are met, a pressure pipe design may be considered adequate for burial without checking the capacity for earth and live loads:

1. Minimum depth of cover of 3 ft (1 m) for live loads up to the magnitude of an AASHTO H20 truck.
2. Maximum depth of burial of 20 ft (6 m).
3. No unusual concentrated or surcharge loads exist.
4. Embedment materials are granular, stable, and compacted to at least 85 percent of maximum standard Proctor density.
5. The pipe is uniformly supported on bedding that is firm but not hard.
6. The pipe is protected from concentrated loads at transitions from soil support to structural support, such as fittings, foundation penetrations, and other connections.

For nonpressure pipe, and for pressure pipe not meeting the just-noted criteria, the following conditions must be met in designing for earth loads:

1. The pipe should not deflect excessively under earth or live loads.
2. The pipe should safely resist maximum wall compressive thrust forces due to external loads.
3. The pipe should not buckle in response to anticipated external soil and hydrostatic loads.
4. The pipe should safely resist bending stresses that result from deflection.

Because of the wide variety of pipe wall profiles and material types, not all of these criteria will be significant for every type of pipe; for instance, resistance to wall compressive thrust forces is important for profile wall pipe, but rarely is significant for solid-wall pipe.

Pipe-Soil System Parameters

The behavior of pipe-soil systems is controlled by two parameters: the *hoop stiffness parameter* S_H; and the *bending stiffness parameter* S_B. These are both ratios of the soil stiffness to the pipe stiffness. An elasticity solution for pipe embedded in an infinite elastic media was developed by Burns and Richard[23] and utilizes these two parameters to describe buried pipe behavior.

The hoop stiffness parameter is defined as:

$$S_H = M_s/\mathrm{PS}_H \tag{D1.9}$$

where S_H = hoop stiffness parameter
M_s = constrained modulus of soil, psi (MPa)
PS_H = pipe hoop stiffness parameter, psi (MPa)

The pipe hoop stiffness parameter is defined as

$$\mathrm{PS}_H = EA/R \tag{D1.10}$$

where E = pipe material modulus of elasticity, psi (MPa)
A = pipe wall area per unit length of pipe, $\mathrm{in}^2/\mathrm{in}$ ($\mathrm{mm}^2/\mathrm{mm}$)
R = radius to centroid of pipe wall, in (mm)

The bending stiffness parameter is defined as:

$$S_B = M_s/PS_B \tag{D1.11}$$

where S_B = bending stiffness parameter
M_s = constrained modulus of soil, psi (MPa)
PS_B = pipe bending stiffness parameter, psi (MPa)

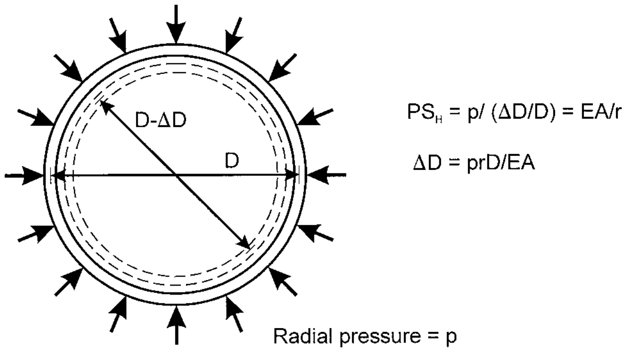
The pipe bending stiffness parameter is defined as

$$\mathrm{PS}_B = EI/R^3 \tag{D1.12}$$

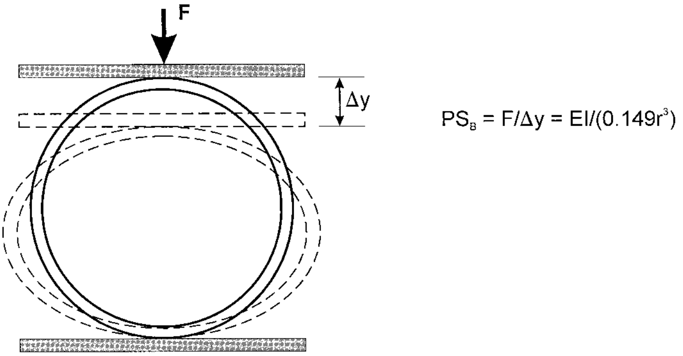
where I = pipe wall moment of inertia per unit length, $\mathrm{in}^4/\mathrm{in}$ ($\mathrm{mm}^4/\mathrm{mm}$)

The hoop stiffness parameter represents a ratio of the soil stiffness to the pipe extensional stiffness, and the bending stiffness parameter represents the ratio of the soil stiffness to the pipe flexural stiffness. In a detailed analysis the Poisson's ratio of the soil and the pipe material are also important; however, since most design methods are based on simplified models of behavior, and most pipe installation is completed by relatively crude methods, very little accuracy is lost by ignoring this parameter. The contribution of each of the hoop and bending stiffness parameters to the overall pipe soil system is important and bears discussion.

The pipe hoop stiffness parameter represents the change in pipe diameter that results from a radial pressure applied to the perimeter as shown in Fig. D1.14*a*. This change in diameter results from a reduction in the pipe circumference due to the axial compressive stress produced by the loading. The pipe bending stiffness parameter represents the change in diameter that results from a concentrated load as demonstrated in Fig. D1.14*b*. This deformation results from flexural stresses produced by the concentrated loading.



a. Pipe Hoop Stiffness



b. Pipe Bending Stiffness (Determined in Parallel Plate Test)

FIGURE D1.14 Pipe stiffness parameters.

Soil Stiffness. While many geotechnical design problems are solved based on the soil strength, represented by the soil friction angle N, buried pipe problems are often addressed using soil stiffness as the governing property. The constrained modulus M_s represents the stiffness of an elastic material in a one-dimensional compression test where no lateral strain is allowed. Thus it is often called the *one-dimensional modulus.* In the one-dimensional compression test, the soil stiffness increases with increasing load, as demonstrated in Fig. D1.15 For simplified design methods the slope of the secant from the origin of the curve to the stress that represents the free field soil stress at the level of the pipe springline is used to represent the average soil behavior during backfilling, represented by M_{s1} in Fig. D1.15. For short-term loads, such as live loading, the instantaneous or tangent modulus, represented by M_{s2} in Fig. D1.15, would be appropriate. Table D1.15 presents suggested design values of the constrained modulus[24] based on triaxial compression tests.[25] The testing was conducted on only three types of soils; however Table D1.16 suggests reasonable extensions of the tested soil types to other types based on AASHTO and ASTM soil classification systems. The soil stiffness values

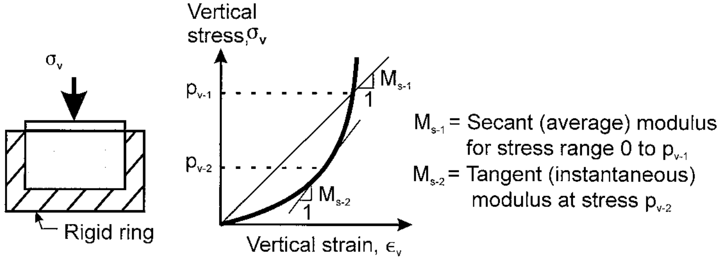


FIGURE D1.15 Constrained modulus, M_s.

proposed in Table D1.15 show an increase in stiffness with increasing depth of fill, which is consistent with known soil behavior. The values also compare well with the more traditional but empirical soil stiffness parameter, the modulus of soil reaction E,[26,27] which is discussed in the section on predicting deflections.

Pipe Flexural Stiffness. Flexible conduits need sufficient flexural stiffness to resist excessive deformation during handling and installation, as well as to maintain shape and structural stability in the final pipe-soil system when subjected to all the loads that can occur during pipe installation and over the intended design life. The parameter most often used to distinguish between rigid and flexible pipe, and the parameter used in many design methods for flexible pipe is *flexural stiffness.* In common practice, the pipe flexural stiffness is expressed in a form which represents the pipe resistance to deflection in a parallel plate test. The parallel plate test is a common quality control test where a pipe is compressed between two parallel plates (Fig. D1.14b). The resistance to deflection is called simply the pipe stiffness:

$$\mathrm{PS} = F/\Delta y = \mathrm{PS}_B/0.149 = EI/(0.149\ R^3) \qquad \text{(D1.13)}$$

where PS = pipe stiffness, lb/in/in (kN/m/m)
F = load on the pipe in the parallel plate test, lb/in (kN/m)
Δy = change in vertical diameter under load, F, in (m)

The parallel plate test is defined in ASTM D2412, “External Loading Properties of Plastic Pipe by Parallel Plate Loading.” It is most common to determine the pipe stiffness at a deflection representing a 5 percent decrease in the vertical diameter from the undeformed pipe, but other reference deflection levels are sometimes used. Because of the nonlinear material behavior, and the nonlinear geometric behavior in the test, the reference deflection level will affect the pipe stiffness reported from the test. Minimum short-term pipe stiffness requirements are included in most standards for thermoplastic pipe intended for buried applications. Many such documents offer more than one series of different standard pipe stiffness categories. Categorizing pipes in accordance with pipe stiffness has proven useful to designers and installers. This parameter is an important indicator of a flexible conduit’s deformation response, particularly under service loads. However, anticipated performance comparisons based on the pipe stiffness alone cannot always be made for a variety of reasons, including the following:

- Pipe stiffness is a short-term property, which, because of differences in viscoelastic behavior from one material to the next, does not always bear the same relationship to a pipe’s long-term stiffness.

TABLE D1.15 Design Values for Constrained Soil Modulus M_S

Stress level (psi)	Soil type and compaction condition (See notes 1 and 2)			
Stress level (psi)	Sn-100 (psi)	Sn-95 (psi)	Sn-90 (psi)	Sn-85 (psi)
1	2,350	2,000	1,275	470
5	3,450	2,600	1,500	520
10	4,200	3,000	1,625	570
20	5,500	3,450	1,800	650
40	7,500	4,251	2,100	825
60	9,300	5,000	2,500	1,000
Stress level (psi)		Si-95 (psi)	Si-90 (psi)	Si-85 (psi)
1		1,415	670	360
5		1,670	740	390
10		1,770	750	400
20		1,880	790	430
40		2,090	900	510
60		2,300	1,025	600
Stress level (psi)		Cl-95 (psi)	Cl-90 (psi)	Cl-85 (psi)
1		533	255	130
5		625	320	175
10		690	355	200
20		740	395	230
40		815	460	285
60		895	525	345

Notes:

1. The soil types are defined by a two-letter designation that indicates general soil classification, Sn for sands and gravels, Si for silts, and Cl for clays. Specific soil groups that fall into these categories, based on ASTM D 2487 and AASHTO M 145, are listed in Table D1.16.
2. The numerical suffix to the soil type indicates the compaction level of the soil as a percentage of maximum dry density determined in accordance with AASHTO T-99 (ASTM D698).
3. 1 MPa = 145 psi.

TABLE D1.16 Equivalent ASTM and AASHTO Soil Classifications

Basic Soil Type	ASTM D 2487	AASHTO M 145
Sn (Gravelly sand, SW)	SW, SP GW, GP	A1, A3
Si (Sandy silt, ML)	GM, SM, ML also GC and SC with less than 20% passing #200 sieve	A-2-4, A-2-5, A4
Cl (Silty clay, CL)	CL, MH, GC, SC also GC and SC with more than 20% passing #200 sieve	A-2-6, A-2-7, A5, A6

Note: The soil classification listed in parentheses is the type that was tested to develop the constrained soil modulus values in Table D1.15. The correlations to other soil types are approximate.

- Service deflections are controlled more by soil stiffness than by pipe flexural stiffness, which, among other things, means that quality of installation and nature of soil are often more important for controlling ultimate deflection than is pipe stiffness.
- The same pipe stiffness for two pipes does not mean that the pipes have an equivalent resistance to deformation by point loading such as can result from handling and installation (including compaction). Profile-wall pipe will respond differently to point loading than smooth-wall pipe, and even for a solid-wall pipe with the same DR, as pipe diameter increases the pipe's relative resistance to deformation under point loading also increases. This is because resistance to point loading is a result of longitudinal pipe stiffness as well as circumferential pipe stiffness.

To illustrate the last point, consider the example of two pipes, one NPS 6 (DN 150) and the other NPS 60 (DN 1500), each with a pipe stiffness of 60 lb/in/in (410 kN/m/m). A 60-lb load per in (10.5 kN/m) of pipe length applied to either of these two pipes produces the same decrease in vertical diameter, namely NPS 1 (DN 25). Clearly, this NPS 1 (DN 25) deformation is much more significant to the NPS 6 (DN 150) diameter pipe than to the NPS 60 (DN 1500) pipe. In recognition of this, certain larger-diameter standards categorize pipe in accordance with a *ring stiffness constant* (RSC). The RSC is defined as the parallel plate load in pounds per foot of pipe length, which causes a 1 percent reduction in diameter, when measured at 3 percent deflection. Essentially the same test, ASTM D 2412, as used to measure pipe stiffness, is used to measure RSC. The main difference is the form in which the results are expressed. Pipes with equal RSC values will undergo equal percent deflection under equal load. RSC is related to pipe properties by the following relationship:

$$\mathrm{RSC} = 6.44 E I_{\mathrm{ft}} / D^2 \tag{D1.14}$$

where RSC = ring stiffness constant, lb/ft/percent (kN/m/percent)
D = diameter to centroid of pipe wall, in (m)
I_{ft} = pipe wall moment of inertia per unit length, in^4/ft (m^4/m)

The RSC concept is an adaptation of the *flexibility factor* (FF) which is used by the American Association of State Highway and Transportation Officials (AASHTO)[6] to classify the handling and installation flexibility of flexible conduits, including both thermoplastic and corrugated metal pipe and culvert:

$$\mathrm{FF} = D_m^2/EI \tag{D1.15}$$

where FF = flexibility factor, in/lb (m/kN)
D_m = mean diameter of pipe, in (mm)

The classification of larger-diameter thermoplastic pipe based on the handling and installation flexibility concept recognizes that the ultimate deformation of installed conduit is greatly influenced by the conduit's response to all the short-term loads experienced during handling, placement of bedding, compaction of backfill, and other installation operations. This generally means that as pipe diameter increases, less pipe stiffness (as measured by ASTM D 2412) is required for satisfactory handling and installation. However, after selecting a conduit of adequate wall stiffness based on handling and installation concerns, the designer still has to check for structural adequacy under the anticipated lifetime service loads.

Thermoplastic pipes and conduit for nonpressure buried applications are available in a broad range of wall stiffnesses. As discussed previously, the larger the pipe size, generally the lower the pipe stiffness. Up to about NPS 4 (DN 100) pipe, stiffness is generally above 50 lb/in/in (350 kN/m/m) and can be over 200 lb/in/in (1.4 kN/m/m). In the mid sizes, through about NPS 18 (DN 450), pipe stiffness ranges from about 30 to 60 lb/in/in (210 to 410 kN/m/m). Above this size, values tend to decrease, down to 8 lb/in/in (55 kN/m/m) for the largest sizes.

AASHTO recommends a maximum flexibility factor (FF) of 9.5×10^{-2} in/lb (0.054 m/kN) for both PVC and PE. This value was originally established for corrugated aluminum conduit. This is equivalent to an RSC of about 65 lb/ft/percent (0.95 kN/m/percent) deflection. RSC's of commercially available larger sizes (NPS 18 through 96) (DN 450 through 2500) PE pipes range from 40 to 120 lb/ft/percent (0.6 to 1.8 kN/m/percent).

Pipe Hoop Stiffness. The pipe hoop stiffness has not been given significant consideration in buried pipe design. Pipes manufactured from more traditional materials have very high values for the pipe hoop stiffness and thus, for these materials, the parameter does not have a substantial effect on overall pipe behavior. More recently it has been demonstrated that some thermoplastic pipes with low cross-sectional area and low elastic modulus have much lower values for the pipe hoop stiffness, and this can have a significant effect on the pipe performance.

A high value of the hoop stiffness parameter S_H indicates that the hoop compression strain in the pipe can result in significant (1 to 2 percent) shortening of the circumference of the pipe.

Design for Earth Loads

Under vertical earth loads, buried flexible conduits deflect downward vertically and outward horizontally, thereby mobilizing passive lateral soil support for the pipe, which in turn precludes significant further downward deflection. Thus the pipe and surrounding soil interact and behave as a structural system. In this system, pipe deflection is controlled more by soil stiffness than by pipe flexural stiffness, and the soil arching characteristics bear great influence on the system's load-carrying capacity. Flexible pipe properly installed in stable soils can resist very substantial loads.

Since the pipe and the soil interact, design and installation of buried flexible pipe must always consider both the pipe and the soil around it. If a designer allows different pipes in a specification, the suitability of the backfill and installation specifications should be evaluated for each type of pipe.

One of the advantages of flexible pipe is that the quality of installation can readily be checked via a deflection test after installation is complete. A particular benefit of most thermoplastic pipe is its high strain capacity, which allows it to deform considerably and thereby generate further soil support. To take economic advantage of this benefit, many of the newer larger-diameter thermoplastic pipes are offered with relatively low wall stiffness, which requires that careful attention be given to proper design and installation in order to ensure durable and stable performance. Since the soil and the pipe must always work together to constitute a pipe-soil system, the designer has to consider both when evaluating alternate pipe materials.

Earth Loads on Buried Flexible Pipes. The load acting on a buried pipe consists of *dead load* and *surcharge load.* The dead load is the permanent load from the weight of soil and pavement above the pipe and sometimes, from any surcharge loads applied at the ground surface. Surcharge loads may, or may not, be permanent. Surface-applied wheel loads are called *live loads.*

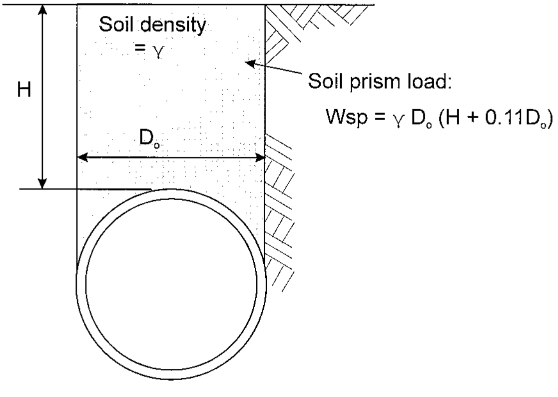


FIGURE D1.16 Soil prism load.

Earth load is measured as the hoop thrust at the springline of the pipe, and is often characterized as a function of the *soil prism load,* which is the weight of earth directly over the pipe (Fig. D1.16). The weight of the soil prism is modified by the *vertical arching factor* (VAF) to represent the effects of pipe-soil interaction. This is expressed as:

$$W_{sp} = \gamma D_o(H + 0.11 D_O) \tag{D1.16}$$

where W_{sp} = soil prism load, lb/ft (kN/m)
γ = soil unit weight, lb/ft^3 (kN/m^3)
D_o = outside diameter of pipe, ft(m)
H = depth of fill over top of pipe, ft(m)

and

$$W_p = \mathrm{VAF}(W_{sp}) \qquad \text{(D1.17)}$$

where VAF = vertical arching factor
W_p = effective soil load, lb/ft (kN/m)

Flexible pipe are often designed with a vertical arching factor of 1.0 (for reference purposes, rigid pipe installed in embankment conditions are often designed for an arching factor of about 1.4). While VAF = 1.0 is considered conservative for flexible pipe, recent research[28,29] has shown that the VAF can be much lower for some thermoplastic pipe with low moduli of elasticity and low cross-sectional area.

Analysis of the Burns and Richard elasticity solution for buried pipe[30] indicates that the hoop stiffness parameter introduced in the previous subsection, is in fact the most important parameter in controlling the load on buried pipe. The Burns and Richard solution solves for two conditions at the interface between the buried pipe and the soil: (1) full slip—a condition where the interface is frictionless; and (2) no slip—a condition where the interface is fully bonded and shear stresses develop. The Burns and Richard equations for the buried pipe problem can be simplified and expressed in the form of the VAF without significant error as:

$$\mathrm{VAF}_{FS} = 0.76 - 0.71(S_H - 0.7)/(S_H + 1.75) \qquad \text{(D1.18)}$$

where VAF_{FS} = vertical arching factor for the full slip solution

and

$$\mathrm{VAF}_{NS} = 1.06 - 0.96(S_H - 0.7)/(S_H + 1.75) \qquad \text{(D1.19)}$$

where VAF_{NS} = vertical arching factor for the no-slip solution

The expressions for the VAFs are shown graphically in Fig. D1.17 When computing the VAFs for actual installations, the long-term modulus of elasticity can be used to compute S_H for long-term loads such as earth load, and the short-term modulus of elasticity can be used to compute S_H for short-term loads such as vehicle loads.

If the value of S_H is low, which is the case for most traditional pipe designs, then the no-slip VAF is a constant value of about 1.4, which is the traditional design value for rigid pipe, and the full-slip VAF is a constant value of about 1.0, which

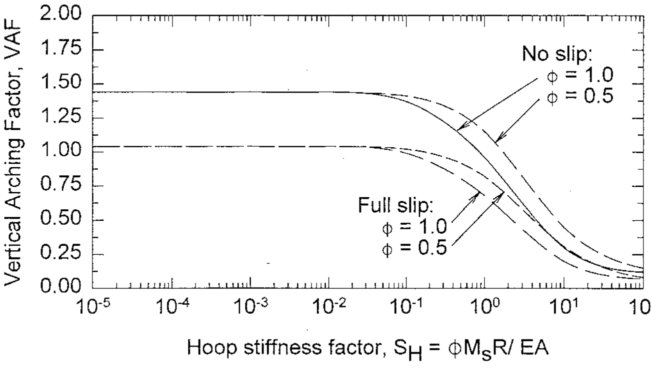


FIGURE D1.17 Burns and Richard VAF and sensitivity to soil stiffness.

is the traditional design value for flexible pipe. No research has been completed to investigate the actual condition of interface shear for flexible and rigid pipe.

Also demonstrated in Fig. D1.17 is the sensitivity of the VAF to the soil stiffness. The lines labeled "$\phi = 0.5$" represent a reduction of soil stiffness of 50%, relative to the line labeled "$\phi = 1.0$". This indicates that on the steep portion of the curve a loss of 50% of the soil stiffness causes a reduction of about 0.2 in the VAF. A reduction of soil stiffness of 50% is often associated with a reduction in density of about 5% standard Proctor density.

While the described analysis has not yet been adopted into any standards, the theory of elasticity solution of Burns and Richard[23] and field research[28,29] are consistent and suggest that the approach could be used for special installations, such as unusually deep fills. Alternatively, in 1930 Marston published a solution for determining the loads on a buried flexible pipe that is still in use today (ASCE Manual of Practice No. 60[31]). This solution assumes some of the backfill load is carried by the flexible pipe; some is carried by the trench walls; and some by the backfill at the sides of the pipe. Thus in narrow trench installations, the load is substantially less than the soil prism load. This is consistent with trench load theory for rigid pipe.

Surcharge, as well as traffic, railway, aircraft, and other live loads are generally estimated using the same methods and equations employed for other conduits, such as presented in ASCE Manual No. 60[31] and in AASHTO Specifications.[6]

When subjected to the calculated hoop compression forces, a pipe must meet the following criteria:

- *Wall Thrust.* The wall stress due to the hoop compression forces must be less than the limiting strength of the material. Little research has been done on the limiting strength of the plastics materials that are used for buried pipe, and the tension strength is often used as a limiting criteria. AASHTO[6] provides suggested limiting stresses for this purpose. Short-term strength should be used for evaluating short-term load conditions, and long-term strength should be used for evaluating long-term load conditions.
- *General Buckling.* If the hoop compression forces are sufficiently high, the pipe can buckle. This is a function of the pipe flexural stiffness and the soil stiffness. The expression most often used to evaluate this condition[5,6,32] is:

$$N = (1/\mathrm{FS})D_o[32R_w B' E'(EI/D_m^3)]^{0.5} \tag{D1.20}$$

where N = allowable wall thrust, lb/in (kN/m)
FS = factor of safety, often taken as 2.5 to 3.0
D_m = mean diameter of pipe, in (m)
R_w = coefficient for depth of groundwater above top of pipe

$$= 1 - 0.33(H_w/H) \tag{D1.21}$$

H_w = depth of groundwater above top of pipe ($<H$), ft(m)
H = depth of earth cover over top of pipe, ft (m)
B' = coefficient for uniformity of pipe support

$$= 1/(1 + e^{-0.065H})\ [H \text{ in ft}] \tag{D1.22}$$

E' = modulus of soil reaction, psi (MPa)
E and I are as previously defined.

Note that the constrained soil modulus M_s may be used as a direct substitute for the modulus of soil reaction, E'. For trench installations, a method of computing a "composite" value of E' that considers the stiffness of both the backfill soil and the native soil in the trench wall is presented in AWWA Manual of Practice M45.[32] This is based on the work of Leonhardt.[33,34] This buckling theory was developed based on buckling of a tube supported at discreet locations by a tube. More recently a buckling theory has been proposed based on a continuously supported ring, which more accurately reflects the condition of a buried pipe.[35] This theory is now being reviewed in the scientific community.

- *Local Buckling of Profile Pipe Wall Cross Sections.* Pipe with corrugated cross sections or other profile configurations must be able to carry the hoop compression stresses without local buckling of the thin elements. There are no currently available criteria for evaluating this condition that have consensus support at this time. Successful experience is the best current guide.

Deflection of Flexible Pipe Under Earth Load. As noted, buried flexible pipes deflect (decrease vertical diameter and increase the horizontal diameter) when subjected to earth, live, and surcharge loads. The installation conditions must be designed to assure that the ultimately achieved deflections are within acceptable limits. This will preserve the serviceability of the pipeline and assure that material stress or strain limits are not exceeded. Generally, deflection limits for flexible pipe are limited to between 7.5 and 10 percent decrease in the vertical diameter.

One of the better-known relationships, sometimes called the *Iowa formula,* was developed for flexible metal conduits at Iowa State University.[36,37] A modification of this equation is as follows:

$$\Delta v = D_l K W_{SP}/(EI/R^3 + 0.061E') \tag{D1.23}$$

where Δv = change in vertical diameter, in (m)
D_l = deflection lag factor to account for time effects (typically taken between 1 and 1.5)
K = bedding factor (0.083 to 0.110)
W_{SP} = soil prism load, lb/in (MN/m)
EI/R^3 = pipe flexural stiffness, psi (MPa)
E' = modulus of soil reaction, psi (MPa)

The deflection lag factor accounts for change in load with time and is typically taken at a value of 1 to 1.5. The bedding factor accounts for the width of the bedding support and can vary from 0.083 to 0.110.

The modulus of soil reaction E' is an empirical measure of the stiffness of the soil in resisting pipe deflection and must be obtained empirically by back-calculating it from measured pipe deflections. The most extensive field study to determine E' was conducted by A. Howard of the U.S. Bureau of Reclamation.[26] In this study, data were collected from 113 field installations on different types of flexible pipe buried up to 50 ft (15 m) deep. For this work Howard assumed a prism load, $K = 0.1$, and $D_l = 1.0$; and, in the case of plastic pipes he computed the term EI/R^3 based on the material's short-term apparent modulus. The resultant back-calculated values of E' are tabulated in Table D1.17 in accordance with soil type. This table also identifies soils by the classification system of ASTM D 2321, "Standard Practice for Underground Installation of Thermoplastic Pipe for Sewers and Other Gravity-Flow Applications."

While E' is not a true soil property that can be evaluated by laboratory tests, recent work suggests that the constrained modulus of elasticity, M_s (see earlier discussion) may be directly substituted for E' in the Iowa formula.[23] Making this substitution and rearranging terms shows that the Iowa formula can also be written in terms of the bending stiffness parameter, S_B:

$$\Delta v = D_l K (W_{SP}/M_s)/(S_B + 0.061) \tag{D1.24}$$

TABLE D1.17 Bureau of Reclamation Recommendations for E'(26)

Backfill type (ASTM D2487)	E' for degree of compaction of bedding, psi[3]			
	Dumped	Slight <85% Proctor <40% relative density	Moderate 85–95% Proctor 40–70% relative density	High >95% Proctor >70% relative density
Fine-grained soils (liquid limit > 50) CH, MH, CH-MH	No data available; consult a competent soils engineer; otherwise, use $E' = 0$			
Fine-grained soils (liquid limit < 50) CL, ML, ML-CL, with less than 25% coarse-grained particles	50	200	400	1,000
Fine-grained soils (liquid limit < 50) CL, ML, ML-CL, with more than 25% coarse-grained particles *Coarse-grained soils with fines*, GM, GC, SM, SC[1] with more than 12% fines	100	400	1,000	2,000
Coarse-grained soils with little or no fines GW, GP, SW, SP with less than 12% fines	200	1,000	2,000	3,000
Crushed Rock	1,000	3,000		
Accuracy in terms of percent deflection[2]	±2%	±2%	+1%	±0.5%

[1] Or any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC).

[2] For ±1% accuracy and predicted deflection of 3%, actual deflection would be between 2% and 4%.

[3] 1 MPa = 145 psi

Notes:

A. Values applicable only for fills less than 50 ft (15 m).

B. Table does not include any safety factor.

C. For use in predicting initial deflections only; appropriate deflection lag factor must be applied for long-term deflections.

D. If bedding falls on the borderline between two compaction categories, select lower E' value or average the two values.

E. Percent Proctor based on laboratory maximum dry density from ASTM D-698.

This expression of the Iowa formula clearly shows that deflection is controlled by the soil stiffness far more than by the pipe stiffness. Designers should understand that design of buried pipe installations is actually more a design of the backfill and installation procedures than of the pipe. The significance of this is that the installation process is critical to proper performance.

Another significant aspect of Eq. (D1.24) is that the deflection will not go to infinity even if the pipe stiffness goes to zero. The apparent implication that pipe stiffness is insignificant to controlling deflection and overall pipe performance is not correct for two reasons:

- The pipe stiffness not only contributes to deflection control as predicted in the Iowa formula; it also controls the variability of deflection (i.e., the standard deviation) which is relatively independent of the average deflection predicted by the Iowa formula. NCHRP Report 225[38] demonstrated this for a wide range of pipe stiffnesses. Deflection variability is also a function of the compaction effort required to densify a soil. Variability will be reduced with backfill materials that densify easily, such as crushed stone and coarse gravel, and increased for soils that are moisture sensitive and require increased compaction effort to reach adequate density, such as silts and fine sands.
- If the pipe stiffness is too low, the buckling criterion noted above will control the design.

Various other methods have been proposed for estimating deflection, for example by Watkins,[39] Gaube,[40] and Brown and Lytton.[41] Recently, more precise approaches to forecasting deflection have been made possible by the application of computer-run finite element analysis programs that utilize soil models that incorporate true nonlinear soil behavior.[42]

Longitudinal Effects. In pressure pipe, changes in direction such as elbows and tees-result in longitudinal forces in the pipeline. These can be controlled by the use of thrust blocks, which result in minimal longitudinal stresses, or with restrained joints, which can develop significant longitudinal forces in the pipe. Most pressure pipe has adequate longitudinal capacity for this loading. Buried pipe is not specifically designed for longitudinal stresses due to uneven bedding. Uniform support due to proper installation is relied upon to avoid this condition.

INSTALLATION

Concurrent with the development of structural design methods for thermoplastics, installation practices dedicated to these materials have also been developed. Noteworthy among these are ASTM D 2774, ‘‘Underground Installation of Thermoplastic Pressure Piping,’’ ASTM D 2321, ‘‘Underground Installation of Thermoplastic Pipe for Sewers and Other Gravity-Flow Applications,’’ and ASTM F 1668 ‘‘Construction Procedures for Buried Plastic Pipe.’’

A commentary on the installation issues that are critical to the long-term performance of flexible nonpressure plastics pipe has been offered by T. J. McGrath.[31] Howard has published a book devoted to pipe installation issues.[27] Installation as well as design recommendations are also issued by various professional and trade associations. A number of these references are identified in the following section.

A significant development in pipe installation practice is the use of *controlled* *low-strength materials* (CLSM, also known as *flowable fill*) for pipe backfill. CLSM is a mixture of sand, cement, fly ash, and water with excellent flow characteristics such that vibration is not required to place it around and under a pipe or other obstructions in a trench. Strengths are low, sometimes as low as 35 psi (240 kPa) at 28 days, in order to assure that the material can be excavated in the event that an encased utility requires a repair. In 1997 ASTM held a three-day symposium on the subject of CLSM, with many papers devoted to its use around pipes.[43] One benefit of CLSM is that shrinkage is minimal after placement; thus, if used to backfill an entire trench the settlement and pavement damage that often occurs with soil backfill can be avoided.

Pipe installation can be difficult if ground conditions are poor, and it is also expensive to provide full-time inspection of pipe-laying crews. Therefore, a key step in quality control of pipe installations is to check the pipe deflection levels after the installation is complete. This should be a standard part of all pipe installation specifications.

SOURCES OF ADDITIONAL INFORMATION

On New Developments

The inroads that thermoplastics piping has made in fuel gas distribution, sewer, water, agricultural, and highway drainage, and in various industrial uses has generated many studies regarding the durability and engineering performance of these materials. Topics of particular recent interest relate to the use of these materials for larger-diameter applications for which certain limits of performance, such as maximum depth of burial, buckling resistance, and compressive wall strength are often design limiting. A reader interested in these topics, as well as in the general state of the art, should consult the proceedings of the following periodically held symposia and conferences:

Proceedings of International Conferences on Pipeline Design and Installation, American Society of Civil Engineers, 345 East 47th Street, New York, NY 10017.

Proceedings of the Symposium on Buried Plastic Pipe Technology, American Society for Testing & Materials, 100 Bar Harbor Drive, West Conshohocken, PA 19428.

Proceedings of the Fuel Gas Plastic Pipe Symposium, American Gas Association, 1515 Wilson Boulevard, Arlington, VA 22209.

Proceedings of the National Conference on Flexible Pipes, Center for Geotechnical and Groundwater Research, Ohio University, Athens, OH 45701.

Proceedings of the International Conferences on Plastics Pipe, Plastics and Rubber Institute, 11 Hobart Place, London, England SW1W OHL.

Publications Related to Standards

The following publications contain much information that is useful for all applications of plastics piping, particularly with respect to design and installation:

ASME Guide for Gas Transmission and Distribution Piping Systems. Available from American Society of Mechanical Engineers, United Engineering Center, 345 East 47th Street, New York, NY 10017, (212) 705-7722.

AGA Plastic Pipe Manual for Gas Service. Available from American Gas Association, 1515 Wilson Boulevard, Arlington, VA 22209, (703) 841-8454.

Maintenance of Operation of Gas Systems, November, 1970, Army TM5–654; NAVFAC-MO–220; Air Force AFM 91–6. Available from Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

Associations

Various trade and technical associations issue reports, manuals, and lists of references on properties, design, and installation of plastics piping. A listing of current literature offerings may be obtained by contacting these organizations at the following addresses:

Thermoplastic pipe (industrial gas distribution, sewerage, water, and general uses): The Plastics Pipe Institute, 1825 Connecticut Ave., N.W., Suite 680, Washington, DC 20009.

Thermoplastics pipe (plumbing applications): Plastics Pipe & Fittings Association, 800 Roosevelt Road, Building C, Suite 20, Glen Ellyn, IL 60137.

PVC piping (water distribution, sewerage, and irrigation): Uni-Bell PVC Pipe Association, 2655 Villa Creek Drive, Suite 155, Dallas, TX 75234.

''No-Dig'' methods for the rehabilitation of existing buried pipelines: North American Society for Trenchless Technology, 435 North Michigan Avenue, Suite 1717 Chicago, IL 60611.

Codes

Thermoplastics piping for plumbing, heating, cooling and ventilating, sewer, water, fire protection, gas distribution, and other hazardous materials may be subject to the provisions of a code or other regulation. Nearly all plumbing codes allow plastics piping for certain applications. The major model building and plumbing codes from which most such codes are derived are issued by the following organizations:

BOCA: National Building Code, BOCA National Mechanical Code, and BOCA National Plumbing Code. Building Officials and Code Administrators, International, Inc., 4051 West Flossmoor Road, Country Club Hills, IL 60478.

CABO: One and Two Family Dwelling Code. Council of American Building Officials, 5203 Leesburg Pike, Falls Church, VA 22041.

IAPMO: Uniform Plumbing Code. International Association of Building and Mechanical Officials, 20001 Walnut Drive South, Walnut, CA 91789–2855.

ICBO: Uniform Building Code and Uniform Mechanical Code. International Conference of Building Officials, 5360 South Workman Mill Road, Whittier, CA 90601.

PHCC: National Standard Plumbing Code. National Association of PlumbingHeating-Cooling Contractors, P.O. Box 6808, Falls Church, VA 22040.

SBCI: SBCCI Southern Building Code, SBCCI Southern Standard Plumbing Code, and SBCCI Southern Standard Mechanical Code. Southern Building Code Congress International, 900 Montclair Road, Birmingham, AL 35213.

Plastics piping for other applications may also be covered by other codes, such as the following:

American National Standards Institute

ANSI B31.3 Chemical Plant and Petroleum Refinery Piping. Thermoplastic Piping

ANSI B31.8 Gas Transmission and Distribution Piping Systems. ANSI Z223, National Fuel Gas Code.

Department of Transportation, Hazardous Materials Board, Office of Pipeline Safety Operations

Code of Federal Regulations (CFR), Title 49, Part 192. Transportation of Natural Gas and Other Gas by Pipeline: Minimum Federal Safety Standards.

Code of Federal Regulations (CFR), Title 49, Part 195. Transportation of Liquids by Pipeline, Minimum Federal Safety Standards.

The National Fire Protection Association (Quincy, MA) Model Codes

NFPA 30 Flammable and Combustible Liquids Codes.

NFPA 54 National Fuel Gas Code.

*NFPA 70 National Electrical Code.**

NFPA 70A Electrical Code for One and Two Family Dwellings.

NFPA 34 Outdoor Piping.

NFPA 13D, Standard for the Installation of Sprinkler Systems in One and Two Family Dwellings and Manufactured Homes.

Some standards and various jurisdictions and authorities require that before a pipe may be used for certain applications, it first must be approved for that use by a recognized, or specifically designated, organization. Organizations and approval programs for plastic pipe include the following:

For potable water:

NSF International, NSF Building, Post Office Box 1468, Ann Arbor, MI 48106.

Canadian Standards Association, 178 Rexdale Boulevard, Rexdale, Ontario, Canada, M9W 1R3

For drain, waste, and vent:

NSF International and Canadian Standards Association (see above).

For meat- and food-processing plants:

U.S. Department of Agriculture, 14th and Independence S.W., Room 0717 South, Washington, DC 20250.

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* National Electrical Code is a registered trademark of the National Fire Protection Association, Quincy, MA 02269.

For fire protection systems, including fire sprinklers:

Underwriters Laboratories Inc., 333 Pfingsten Road, Northbrook, IL 60062.

Factory Mutual Research Corporation, 1151 Boston-Providence Turnpike, Post Office Box 688, Norwood, MA 02062.

For underground gasoline and petroleum lines:

Underwriters Laboratories Inc. (see above).

For water pipe:

American Water Works Association, Denver, CO.

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