Chapter 3

Engineering Properties

Scope

This chapter reviews the history, structure and the fundamental properties of polyethylene (PE) pipe. A basic understanding of the physical and chemical nature of polyethylene and of its engineering behavior is very important for the proper design and installation of this material.

Polyethylene Plastics

Plastics are solid materials that contain one or more polymeric substances which can be shaped by flow. Polymers, the basic ingredient of plastics, compose a broad class of materials that include natural and synthetic polymers. Nearly all plastics are made from the latter. In commercial practice, polymers are frequently designated as resins. For example, a polyethylene pipe compound consists of polyethylene resin combined with colorants, stabilizers, anti-oxidants or other ingredients required to protect and enhance properties during fabrication and service.

Plastics are divided into two basic groups, thermoplastics and thermosets, both of which are used to produce plastic pipe.

Thermoplastics include compositions of polyethylene, polypropylene, polybutylene and polyvinyl chloride (PVC). These can be re-melted upon the application of heat. The solid state of thermoplastics is the result of physical forces that immobilize polymer chains and prevent them from slipping past each other. When heat is applied, these forces weaken and allow the material to soften or melt. Upon cooling, the molecular chains stop slipping and are held firmly against each other in the solid state. Thermoplastics can be shaped during the molten phase of the resin and therefore can be extruded or molded into a variety of shapes, such as pipe flanges or valves.

Thermoset plastics are similar to thermoplastics prior to “curing,” a chemical reaction by which polymer chains are chemically bonded to each other by new cross-links. The curing is usually done during or right after the shaping of the final product. Cross-linking is the random bonding of molecules to each other to form a giant three-dimensional network. Thermoset resins form a permanent insoluble and infusible shape after the application of heat or a curing agent. They cannot be re-melted after they have been shaped and cured. This is the main difference between thermosets and thermoplastics. As heat is applied to a thermoset part, degradation occurs at a temperature lower than the melting point. The properties of thermosetting resins make it possible to combine these materials with reinforcements to form strong composites. Fiberglass is the most popular reinforcement, and fiberglass-reinforced pipe (FRP) is the most common form of thermoset-type pipe.

History of Polyethylene

The Imperial Chemical Company (ICI) in England first invented polyethylene in 1933.(24) ICI did not commercialize the production of polyethylene until 1939 when the product was used to insulate telephone cables and coaxial cables, the latter being a very important element in the development of radar during World War II. The early polymerization processes used high-pressure (14,000 to 44,000 psi) autoclave reactors and temperatures of 200° to 600° F (93° to 316° C). The polyethylene that came from these reactors was called "high pressure polyethylene." It was produced in a free radical chain reaction by combining ethylene gas under high pressure with peroxide or a trace amount of oxygen.

The original process was dangerous and expensive, so other safer and less expensive processes were developed. Polyethylene produced at low pressure was introduced in the 1950's. These methods also afforded greater versatility in tailoring molecular structures through variations in catalysts, temperatures, and pressures.

Manufacture of Polyethylene

Polymers are large molecules formed by the polymerization (i.e. the chemical linking) of repeating small molecular units. To produce polyethylene, the starting unit is ethylene, a colorless gas composed of two double-bonded carbon atoms and four hydrogen atoms (see Figure 1).

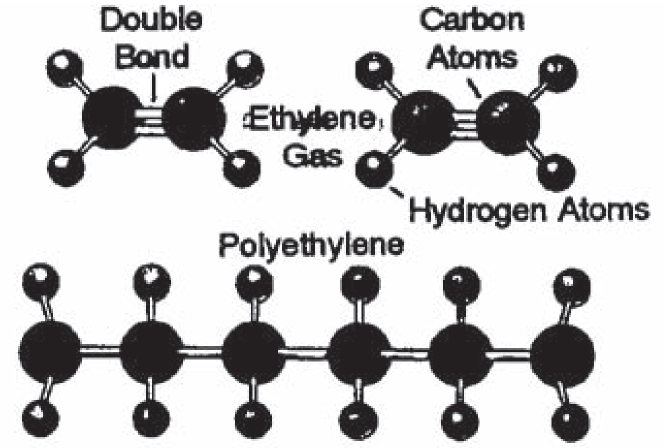


Figure 1 Manufacture of Polyethylene

There are currently three primary low-pressure methods for producing polyethylene: gas-phase, solution and slurry (liquid phase). The polymerization of ethylene may take place with various types of catalysts, under varying conditions of pressure and temperature and in reactor systems of radically different design. Ethylene can also be copolymerized with small amounts of other monomers such as butene, propylene, hexene, and octene. This type of copolymerization results in small modifications in chemical structure, which are reflected in certain differences in properties, such as density, ductility, hardness, etc. Resins that are produced without comonomer are called homopolymers.

Regardless of process type, the chemical process is the same. Under reaction conditions, the double bond between the carbon atoms is broken, allowing a bond to form with another carbon atom as shown in Figure 1. Thus, a single chain of polyethylene is formed. This process is repeated until the reaction is terminated and the chain length is fixed. Polyethylene is made by the linking of thousands of monomeric units of ethylene.

Polymer Characteristics

Polyethylene resins can be described by three basic characteristics that greatly influence the processing and end-use properties: density, molecular weight and molecular weight distribution. The physical properties and processing characteristics of any polyethylene resin require an understanding of the roles played by these three major parameters.

Density

The earliest production of polyethylene was done using the high-pressure process which resulted in a product that contained considerable "side branching." Side branching is the random bonding of short polymer chains to the main polymer chain. Since branched chains are unable to pack together very tightly, the resulting material had a relatively low density, which led to it being named low-density polyethylene (LDPE).

As time passed and polyethylenes of different degrees of branching were produced, there was a need for an industry standard that would classify the resin according to density. The American Society for Testing of Materials (ASTM) established the following classification system, still in use today. It is a part of ASTM D1248, *Standard Specification for Polyethylene Plastics Molding and Extrusion Materials*(2,5).

Type	Density
I	0.910 - 0.925 (low)
II	0.926 - 0.940 (medium)
III	0.941 - 0.959 (high)
IV	0.960 and above (high, homopolymer)

Type I is a low-density resin produced mainly in high-pressure processes. Also contained within this range are the linear-low-density polyethylenes (LLDPE), which represent a recent development in the polyethylene area using low-pressure processes.

Type II is a medium density resin produced either by low- or high-pressure processes.

Types III and IV are high-density polyethylenes. Type III materials are usually produced with a small amount of a comonomer (typically butene or hexene) that is used to control chain branching. Controlled branching results in improved performance in applications where certain types of stresses are involved. Type IV resins are referred to as homopolymers since only ethylene is used in the polymerization process, which results in least-branched and highest-possible-density material. Figure 2 depicts the various molecular structures associated with each type of polyethylene.

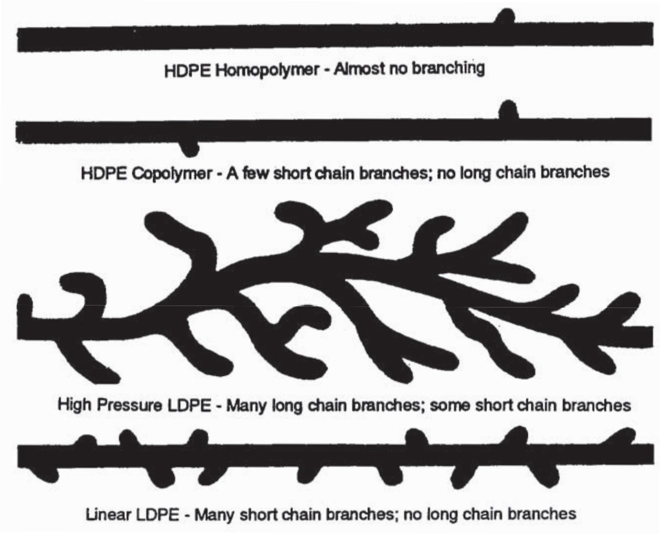


Figure 2 Chain Structure of Polyethylene

Crystallinity

The amount of side branching determines the density of the polyethylene molecule. The more side branches, the lower the density. The packing phenomenon that occurs in polyethylene can also be explained in terms of crystalline versus non-crystalline or amorphous regions as illustrated in Figure 3. When molecules pack together in tight formation, the intermolecular spacing is reduced.

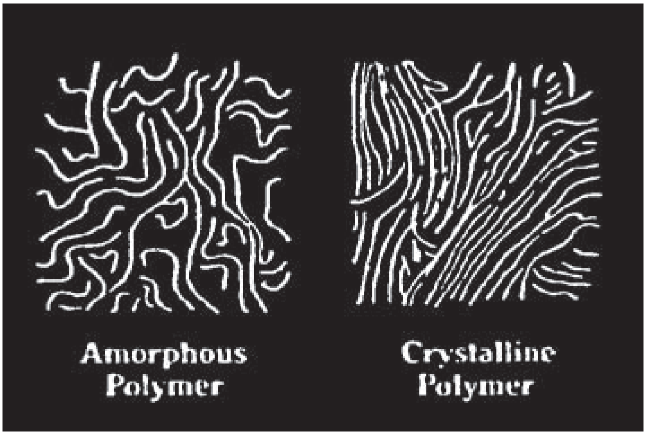
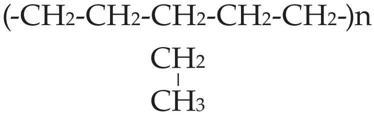


Figure 3 Crystallinity in Polyethylene

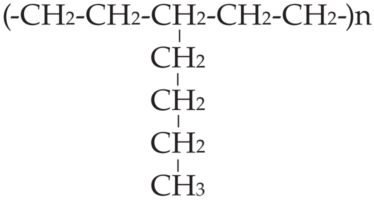
Polyethylene is one of a number of polymers in which portions of the polymer chain in certain regions align themselves in closely packed and very well ordered arrangements of polyhedral-shaped, microscopic crystals called spherulites. Other portions of the polymer chain lie in amorphous regions having no definite molecular arrangement. Since polyethylene contains both crystalline and amorphous regions, it is called a semicrystalline material. Certain grades of HDPE can consist of up to 90% crystalline regions compared to 40% for LDPE. Because of their closer packing, crystalline regions are denser than amorphous regions. Polymer density, therefore, reflects the degree of crystallinity.

As chain branches are added to a polyethylene backbone through co-polymerization, the site and frequency of chain branches affect other aspects of the crystalline/amorphous network. This includes the site and distribution of spherulites, as well as the nature of the intermediate network of molecules that are between spherulites. For example, using butene as co-monomer results in the following "ethyl" side chain structure(8):



$$(\text{-}CH_2\text{-}CH_2\text{-}\underset{\substack{CH_2\\|\\CH_3}}{CH_2}\text{-}CH_2\text{-}CH_2\text{-})n$$

or using hexene results in this "butyl" side chain:



$$(\text{-}CH_2\text{-}CH_2\text{-}\underset{\substack{|\\CH_2\\|\\CH_2\\|\\CH_2\\|\\CH_3}}{CH_2}\text{-}CH_2\text{-}CH_2\text{-})n$$

If two polymers were produced, one using ethyl and the other butyl, the polymer that contained the butyl branches would have a lower density. Longer side branching reduces crystallinity and therefore lowers density. For high-density polyethylene, the number of short chain branches is on the order of 3 to 4 side chains per 1,000 carbon atoms. It only takes a small amount of branching to affect the density.

Resin density influences a number of physical properties. Characteristics such as tensile yield strength and stiffness (flexural or tensile modulus) are increased as density is increased.

Molecular Weight

The size of a polymer molecule is represented by its molecular weight, which is the total of the atomic weights of all the atoms that make up the molecule. Molecular weight exerts a great influence on the processability and the final physical and mechanical properties of the polymer. Thermoplastics for piping systems are of high molecular weight (over 100,000) but not so high as to hamper shaping during manufacture or subsequent operations such as heat fusion.

Molecular weight is controlled during the manufacturing process. The amount of length variation is usually determined by catalyst, conditions of polymerization, and type of process used. During the production of polyethylene, not all molecules grow to the same length. Since the polymer contains molecules of different lengths, the molecular weight is usually expressed as an average value.

There are various ways to express average molecular weight, but the most common is the number average (Mn) and weight average (Mw). The definitions of these terms are as follows:

Mn = Total weight of all molecules ÷ Total number of molecules

Mw = (Total weight of each size) (respective weights) ÷
Total weight of all molecules

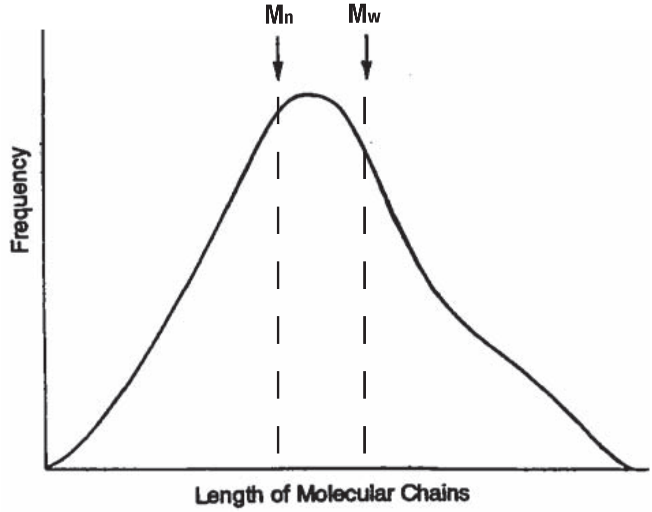


Figure 4 Typical Molecular Weight Distribution

Figure 4 illustrates the significance of these terms and includes other less frequently used terms for describing molecular weight.

Molecular weight is the main factor that determines the durability-related properties of a polymer. Long-term strength, toughness, ductility, and fatigue-endurance improve as the molecular weight increases. The current grades of highly durable materials result from the high molecular weight of the polymer.

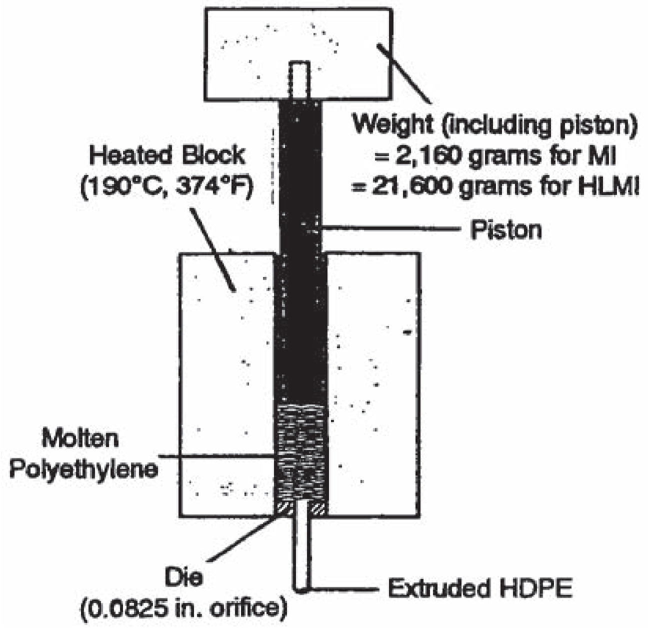


Figure 5 The Melt Index Test (per ASTM D1238)

Molecular weight affects a polymer's melt viscosity or its ability to flow in the molten state. The standard method used to determine this "flowability" is the melt flow rate apparatus, which is shown in Figure 5. ASTM D1238, *Standard Test Method for Flow Rates of Thermoplastics by Extrusion Plastometer*(2), is the industry standard for measuring the melt flow rate. The test apparatus measures the amount of material that passes through a certain size orifice in a given period of time when extruded at a predetermined temperature and under a specified weight The melt flow rate is the calculated amount of material that passes through the orifice in ten minutes.
The standard nomenclature for melt flow rate, as described in ASTM D1238, lists the test temperature and weight used. A typical designation is condition 190/2.16 that indicates the test was conducted at a temperature of 190°C while using a 2.16-kg weight on top of the piston. Other common weights include: 5 kg, 10 kg, 15 kg and 21.6 kg.

The term "melt index"(MI) is the melt flow rate when measured under a particular set of standard conditions – 190°C/2.16 kg. This term is commonly used throughout the polyethylene industry.

Melt flow rate is a rough guide to the molecular weight and processability of the polymer. This number is inversely related to molecular weight. Resins that have a low molecular weight flow through the orifice easily and are said to have a high melt flow rate. Longer chain length resins resist flow and have a low melt flow rate. The melt flow rates of these very viscous (stiff) resins are very difficult to measure under the common conditions specified by this test. Therefore, another procedure is used where the weight is increased to 21.6 kg from the 2.16 kg weight used in the normal test procedure. This measurement is commonly referred to as the High Load Melt Index (HLMI) or 10X scale. There are other melt flow rate scales that use 5 kg, 10 kg or 15 kg weights.

There are various elaborate analytical techniques for determining molecular weight of a polymer. The melt flow rate gives a very quick, simple indication of the molecular weight. The more sophisticated methods include Gel Permeation Chromatography (GPC). The essence of GPC is to dissolve the polymer in a solvent and then inject the solution into a column (tubing). The column contains a porous packing material that retards the movements of the various polymer chains as they flow through the column under pressure. The time for the polymer to pass through the column depends upon the length of the particular polymer chain. Shorter chains take the longest time due to a greater number of possible pathways. Longer chain molecules will pass more quickly since they are retained in fewer pores. This method measures the distribution of the lengths of polymer chains along with the average molecular weight.

Effect of Molecular Weight Distribution on Properties

The distribution of different sized molecules in a polyethylene polymer typically follows the bell shaped normal distribution curve described by Gaussian probability theory. As with other populations, the bell shaped curve can reflect distributions ranging from narrow to broad. A polymer with a narrow molecular weight distribution (MWD) contains molecules that are nearly the same in molecular weight. It will crystallize at a faster, more uniform rate. This results in a part that will have less warpage.

A polymer that contains a broader range of chain lengths, from *short* to *long* is said to have a broad MWD. Resins with this type of distribution have good Environmental Stress Crack Resistance (ESCR), good impact resistance and good processability.

Polymers can also have a bimodal shaped distribution curve which, as the name suggests, seem to depict a blend of two different polymer populations, each with its particular average and distribution. Resins having a bimodal MWD contain both very short and very long polyethylene molecules, giving the resin excellent physical properties while maintaining good processability. Figure 6 shows the difference in these various distributions.

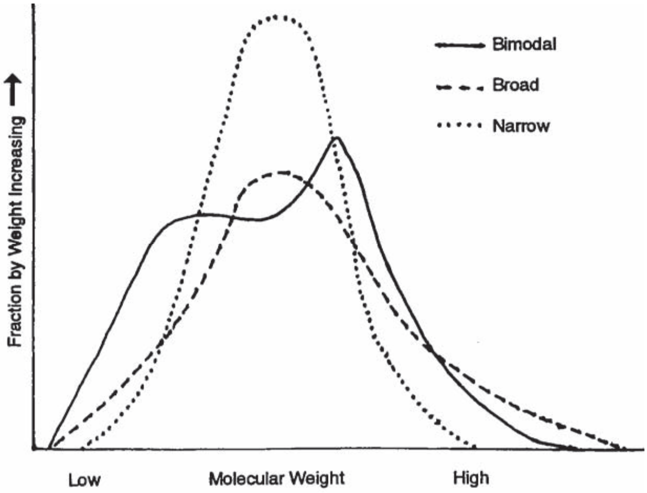


Figure 6 Molecular Weight Distribution

MWD is very dependent upon the type of process used to manufacture the particular polyethylene resin. For polymers of the same density and average molecular weight, their melt flow rates are relatively independent of MWD. Therefore, resins that have the same density and MI can have very different molecular weight distributions. The effects of density, molecular weight, and molecular weight distribution on physical properties are summarized in Table 1.

TABLE 1
Effects of Changes in Density, Melt Index, and Molecular Weight Distribution

Property	**As Density Increases, Property**	**As Melt Index Increases, Property**	**As Molecular Wt. Distribution Broadens, Property**
Tensile Strength (@ Yield)	Increases	Decreases	—
Stiffness	Increases	Decreases Slightly	Decreases Slightly
Impact Strength	Decreases	Decreases	Decreases
Low Temperature Brittleness	Increases	Increases	Decreases
Abrasion Resistance	Increases	Decreases	—
Hardness	Increases	Decreases Slightly	—
Softening Point	Increases	—	Increases
Stress Crack Resistance	Decreases	Decreases	Increases
Permeability	Decreases	Increases Slightly	—
Chemical Resistance	Increases	Decreases	—
Melt Strength	—	Decreases	Increases
Gloss	Increases	Increases	Decreases
Haze	Decreases	Decreases	—
Shrinkage	Increases	Decreases	Increases

Mechanical Properties

Establishing Long-Term Design Properties

In the case of metal piping, the conventional tensile test is relied upon to define basic mechanical properties such as elastic strength, proportional limit and yield strength. These are important for defining and specifying the pipe material. They are also basic constants for use in the many design equations that have been developed based upon elastic theory, where strain is always assumed to be proportional to stress. With plastics there is no such proportionality. The relationship between stress and strain is greatly influenced by duration of loading (e.g., rate of straining in a tensile test), temperature and environment. As depicted in Figure 3.7, the stress/strain response for polyethylene is profoundly dependent on the tensile test conditions. In addition, the stress-strain response is curvilinear. Even though near the origin there might appear to be an essentially linear response, in reality there is never a zone of true proportionality between stress and strain.

Accordingly, plastics have no true elastic constants, such as elastic modulus or proportional limit, nor do they have sharply defined yield points.

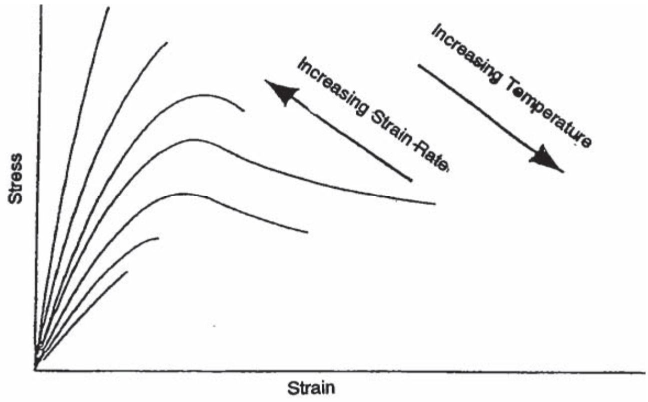


Figure 7 Schematic of Tensile Stress - Strain Response of a Thermoplastic Exhibiting Ductility at Intermediate Strain Rates

The values of moduli derived from tensile tests only represent the initial portion, either the secant or the tangent, of the stress-strain curve and only for the particular conditions of the test (see *Tensile Properties*). The primary value of the modulus, yield strength and other short-term properties of plastics is for defining and classifying materials. Strength and stiffness values that have been determined by means of short-term tests are not suitable constants for use in the large body of equations that have been derived on the assumption of elastic behavior. However, most of these equations can be, and are, used with plastics provided their strength and rigidity are defined by property values that give consideration to their non-elastic behavior. Test methods and systems for developing and applying such information are described in ensuing paragraphs.

Since polyethylene is composed of both crystalline and amorphous areas, its mechanical behavior is complex. The crystalline regions primarily account for the elastic response to forces, whereas the amorphous regions account for the viscous fluid-like response. The overall mechanical response to applied forces is called "viscoelastic" since it lies between these two types of behavior.

Models have been developed to understand, quantify, and characterize viscoelastic behavior(19,21). The spring is used to demonstrate ideal elastic behavior. The deformation of the spring is directly proportional to the force needed to pull the spring. The relationship between force and deformation is $F = Kx$, where x represents the distance pulled, commonly called strain, and K is the spring stiffness. This relationship is known as Hooke's Law. An elastic material returns to its original length when the load (force) is removed. This is true because the spring has stored the applied force (energy) and has returned practically all of it back to the material.

A dashpot can be used to represent an ideal viscous material. When a force is applied to pull the dashpot, the amount of deformation (strain) is independent of the force but proportional to the velocity (v) at which the force is applied. This is shown mathematically as $F \cong v$. The dashpot will not return to its original position once the force is released. This is true because the energy is not stored in the dashpot but is fully spent in deforming the purely viscous material.

Since polyethylene behaves as both an elastic and viscous material, its behavior can be modeled by combining springs and dashpots together into a very simple configuration known as the Maxwell Model(40) as shown in Figure 8. The springs represent the elastic behavior, each one having a different spring constant. The dashpots, each containing a different viscosity fluid, represent the viscous behavior. By combining various numbers of springs and dashpots, the stress-strain relationships for different plastics can be approximated.

These models may be used to characterize the stress-strain relationship of plastics as a function of duration of loading, temperature, and environment. However, there are other methods that express the stress-strain and fracture strength which are more commonly used for engineering design. These are based on tensile creep, stress-relaxation, and stress-rupture data that have been obtained on the subject material.

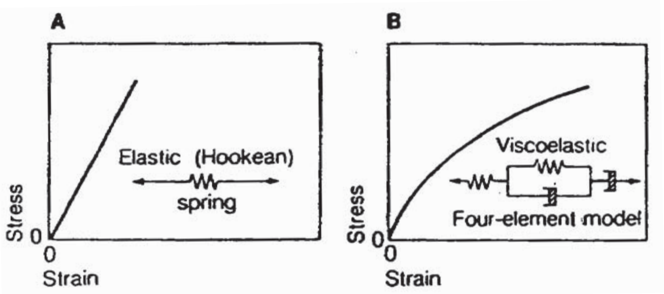


Figure 8 The Maxwell Model

Tensile Creep Curves

When a constant load is applied to a plastic part, it deforms quickly to an initial strain (deformation). It then continues to deform at a slower rate for an indefinite amount of time or until rupture occurs. This secondary deformation is termed creep. In ductile plastics, rupture is usually preceded by a stage of accelerated creep or yielding. In nonductile plastics, rupture occurs during creep. These typical responses are illustrated in Figure 9, which has been drawn on cartesian coordinate. As the stress level increases, so does the strain; however, it is not a linear relationship. A doubling of stress will not double the strain except at small strains or short times.

Temperature will also affect the strain. For a given stress level and time, a higher temperature will increase the strain.

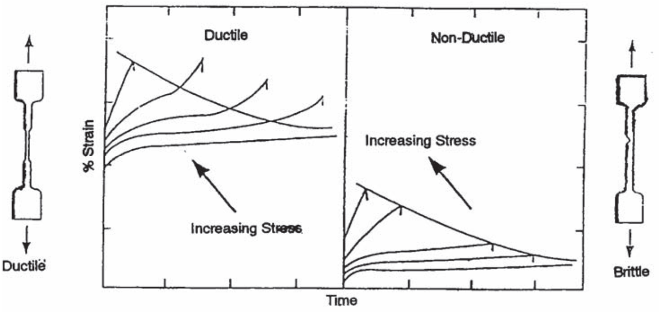


Figure 9 Schematic of Creep Rupture of Thermoplastics in Tension

A more practical way of representing tensile creep and creep-rupture information over the longer times of engineering interest is to plot the data on log-log coordinates. This method, which also facilitates graphical interpolation of data, is illustrated by Figure 10, which was developed for a high density polyethylene resin.

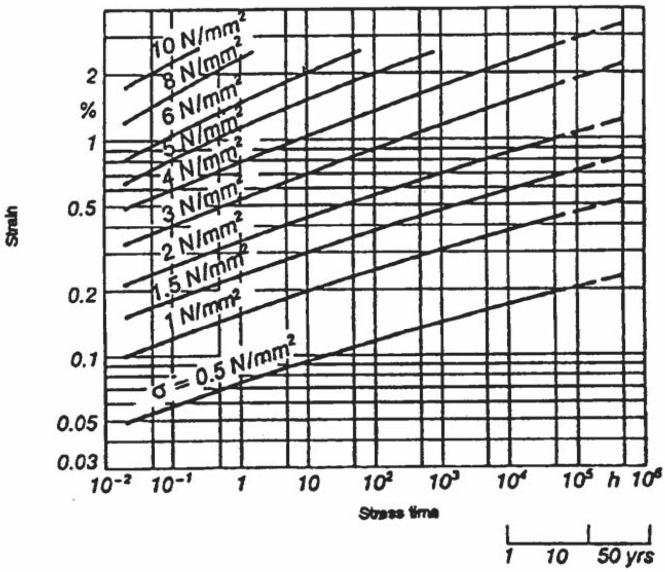


Figure 10 Strain-Time Curves at Constant Stress
Note: 1N/mm2 = 145 psi, Temperature = 73°4F (23°C)

Tensile Creep or Apparent Modulus

Any point on any creep curve gives a stress/strain ratio. The value of this ratio, Ec, is termed the creep modulus or apparent modulus. It is specific for the conditions where the stress is prescribed and the strain is free to vary. It is used in design equations in place of the tensile modulus.

The creep or apparent modulus is defined as the initial applied stress divided by the creep-strain at a given time and temperature, in units of lbs/in^2 (N/mm^2). The modulus decreases as the duration of loading increases.

When designing a pipeline for a 50-year life, the long-term tensile creep modulus of polyethylene should be used. This value will range from 20,000 psi to 30,000 psi depending on the type of polyethylene pipe material. As a comparison, the short-term modulus, derived from short-term tensile tests, is between 100,000 to 130,000 psi. Figure 11 represents typical tensile creep moduli data for polyethylene.

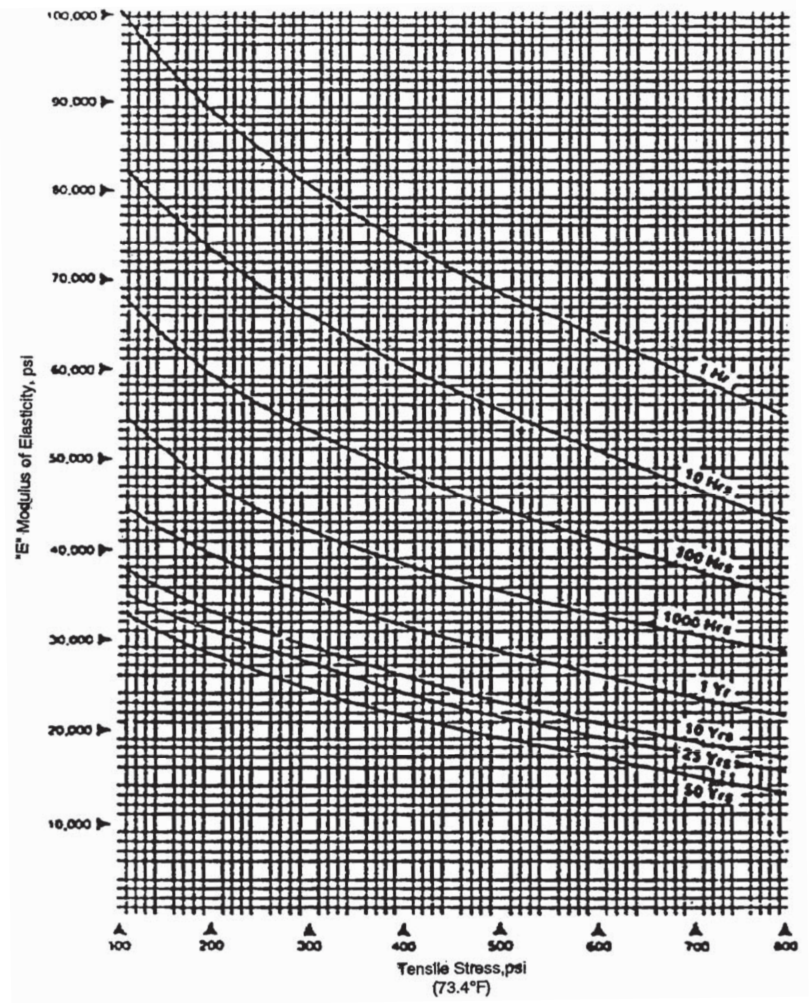


Figure 11 Tensile Creep Modulus versus Stress Intensity for a High-Density Polyethylene for Uniaxial Stress Conditions

Stress Relaxation

When a plastic part is deformed and maintained in that condition, the stress developed in the material decays gradually with time. The decrease in stress that occurs under constant strain is called stress relaxation. Initially, stress relaxation occurs at the fastest rate and then steadily decreases. Given enough time, the stress level approaches an equilibrium value.

An increase in temperature will decrease the time required for a given amount of stress relaxation to occur.

An example of stress relaxation is the reduction in stress that occurs when a polyethylene pipe bends around a curve or conforms to a contour.

Stress-relaxation apparent moduli can also be derived from stress-relaxation data. The stress-relaxation modulus is required for design calculations in which the strain is prescribed and the stress is free to vary. However, for the purpose of engineering design, the numerical difference between the relaxation and the creep modulus is often small when the strain and elapsed times are matched. The two can therefore be used interchangeably for most engineering design.

Simplified Representation of Creep & Stress-Relaxation Modulus

To simplify calculations, the creep and stress relaxation modulus for a certain time duration of loading is often represented as a fraction. The fraction is the long-term creep modulus divided by the short-term modulus (obtained by the tensile test). For such a simple representation, which is shown in Figure 12, it is assumed that the modulus is independent of stress intensity over the range of engineering stress for which this approximation applies. The consequence of this simplification is usually small and acceptable for most design.

Creep Recovery

Once the stress is removed at the end of a deformation test, the plastic will gradually return to its original dimension, but sometimes not completely. Incomplete recovery can occur even if the applied stress was below the yield point, established from the short-term tensile tests. The extent of recovery will depend upon the magnitude of the applied stress, the length of time over which the initial stress was applied and the properties of the material. At short-term creep or low-stress conditions, the recovery period can be rapid, but at long-term creep or high-stress conditions, the recovery can be quite slow. Figure 13 shows this phenomenon.

Duration of Uninterrupted Loading (Hours)	Approximate Ratio of Creep to Short-Term Modulus
1	0.80
100	0.52
10,000	0.28
438,000 (50 years)	0.22

Approximate Ratio of Creep Modulus to Short-Term Modulus as a Function of Loading Duration, for 73.4°F (23°C)

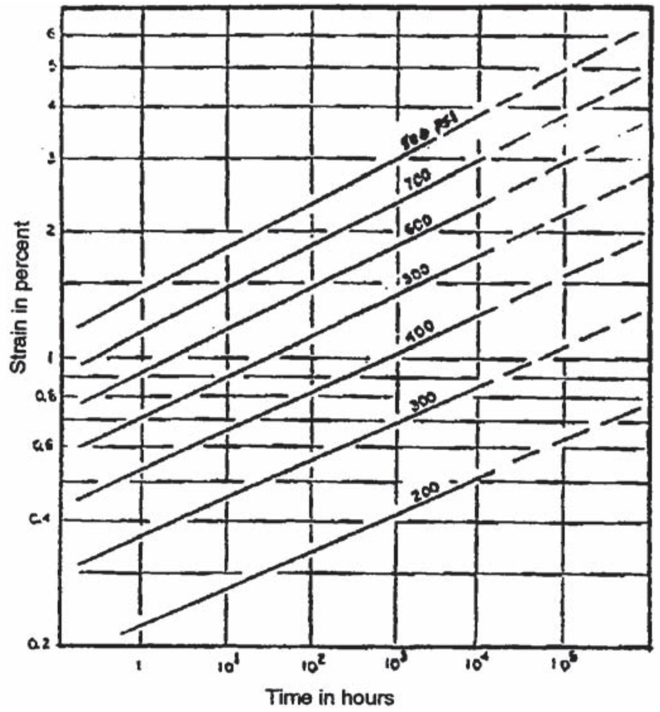


Figure 12 Tensile Creep Response for High-Density Polyethylene Pipe Material

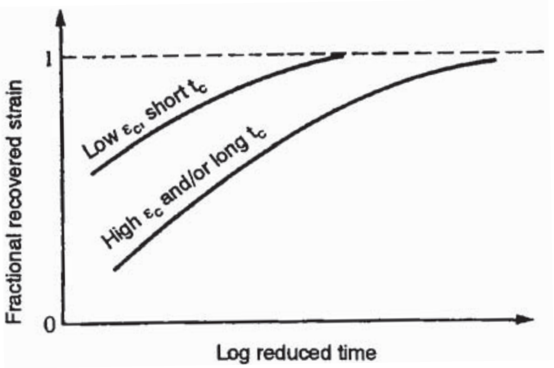


Figure 13 Creep Recovery as a Function of Time

Creep Rupture

Creep Rupture Characteristics

The relationship between tensile load and lifetime is described by the creep-rupture envelope of tensile creep curves. Each composition has a characteristic envelope for a given set of conditions of temperature and environment.

The stress versus lifetime characteristics of thermoplastic materials intended for pressure piping are determined by means of long-term pressure tests conducted on pipe specimens. Such characterization is generally referred to as stress-rupture testing.

The pipe samples are pressurized, usually with water, and immersed in a water bath at a certain temperature. The time required for each pipe to fail is recorded. By testing pipe at various temperatures and hoop stresses, creep rupture curves are generated, as shown in Figure 14. Note that the time for pipe failure to occur increases as applied stress decreases. The applied stresses are below the yield stress of polyethylene (measured by the short-term tensile test). This is typical of all materials that exhibit creep behavior, including metals and ceramics at very high temperatures(15,22).

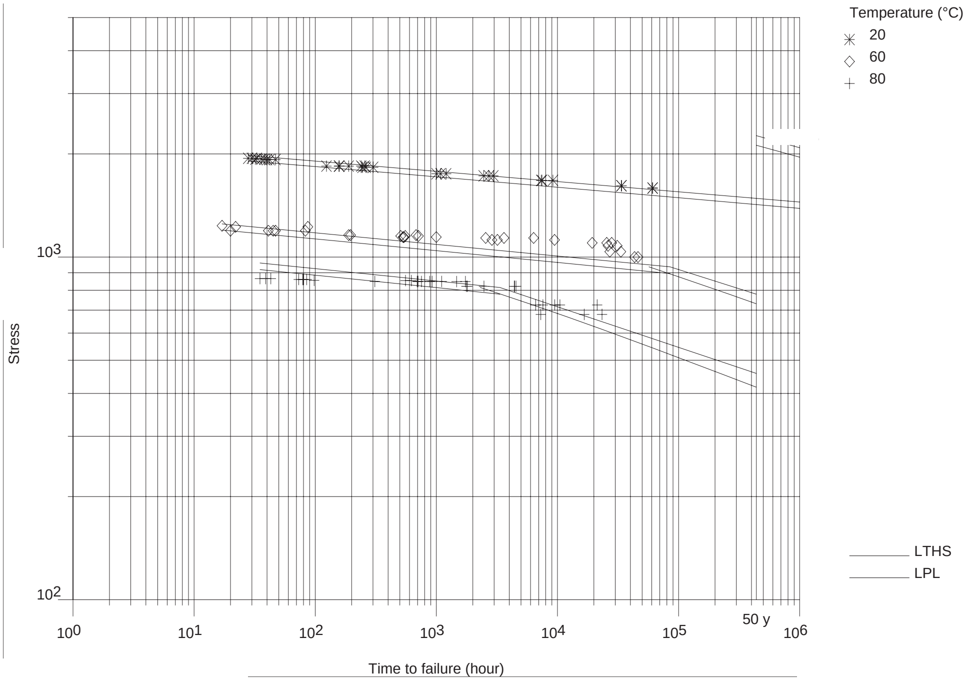


Figure 14 Typical Creep Rupture Curve for HDPE Pipe

When a pipe is pressurized, principal stresses are developed in both the axial and hoop (circumferential) directions. For a thick wall pipe, the fiber hoop stress is a function of the distance of the fiber from the inside pipe surface. The fiber at the inner surface is subject to a higher hoop stress than the outer wall. The axial stress is one-half the level of the average fiber hoop stress.

Long-Term Hydrostatic Strength

To correlate hoop stress with time-to-failure, the general practice is to calculate hoop stress by means of the relationship known as the ISO equation (denoting its adoption by the International Standards Organization):

$$S = p\,(OD-t)/2t$$

WHERE

S = hoop stress, psi

p = internal pressure, psi

t = minimum pipe wall thickness, inches

OD = outside pipe diameter, inches

This ISO equation is a form of a thin-wall vessel equation, which assumes that the fiber stress is constant between the inner and outer diameters. This assumption has been found to be a satisfactory representation for all plastic pipes. Stress-rupture testing is performed in accordance with the ASTM D1598(2) specification, *Time to Failure of Plastic Pipe Under Constant Internal Pressure.* Data obtained by D1598 testing is plotted on a log-log plot of stress versus time-to-failure. If the data falls along a straight line, then the *best least-squares straight line* is determined mathematically and extrapolated to the 100,000 hour intercept to forecast the long-term hydrostatic strength (LTHS). The extrapolation procedure used is that of ASTM D2837(3), *Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials.* Each hydrostatic design basis (HDB) includes a range of the material's LTHS in a preferred stress category. These stress categories and the ranges of calculated LTHS are listed in Table 2.

The Hydrostatic Stress Board of the Plastics Pipe Institute issues recommendations of HDB for thermoplastic piping materials based upon ASTM D2837 and the additional requirements given in PPI Technical Report, TR-3(35), *Policies and Procedures for Developing Recommended Hydrostatic Design Stresses for Thermoplastic Pipe Materials.* Pipe compounds that are awarded an HDB are listed in the periodically update PPI Technical Report, TR-4(36), *Recommended Hydrostatic Strengths and Design Stresses for Thermoplastic Pipe and Fittings Compounds.*

TABLE 2
Hydrostatic Design Basis Categories

Range of Calculated LTHS Values		Hydrostatic Design Basis	
psi	Mpa	psi	MPa
190 to < 240	1.31 to < 1.65	200	1.36
240 to < 300	1.65 to < 2.07	250	1.72
300 to < 380	2.07 to < 2.62	315	2.17
380 to < 480	2.62 to < 3.31	400	2.76
480 to < 600	3.31 to < 4.14	500	3.45
600 to < 760	4.14 to < 5.24	630	4.34
760 to < 960	5.24 to < 6.62	800	5.52
960 to < 1200	6.62 to < 8.27	1000	6.89
1200 to < 1530	8.27 to < 10.55	1250	8.62
1530 to < 1920	10.55 to < 13.24	1600	11.03
1920 to < 2400	13.24 to < 16.55	2000	13.79
2400 to < 3020	16.55 to < 20.82	2500	17.24
3020 to < 3830	20.82 to < 26.41	3150	21.72
3830 to < 4800	26.41 to < 33.09	4000	27.58
4800 to < 6040	33.09 to < 41.62	5000	34.47

The ASTM D2837 extrapolation method has been used since the 1960's as the primary requirement for qualifying thermoplastic pressure piping materials. The excellent field performance achieved by adopting this test has proven its value for pipe design. Because a few exceptions to this performance have been noted with some polyethylene materials, the industry has investigated improved methods for predicting the long-term behavior of polyethylene pipe.

The stress-rupture line for polyethylene can have a downturn or "knee" where the failure mode changes from ductile to brittle. Figure 14 shows these "knees." Ductile failure mode is characterized by areas in the material that have undergone substantial cold-drawing with a significant elongation in the immediate area of the rupture. The failure looks like a "parrot's beak." Brittle failures are characterized by little or no deformation in the rupture. They are typically referred to as brittle or slit failures due to the formation of cracks or small pin holes within the pipe wall. These types of failures are the result of the manifestation of a fracture mechanics mechanism, which involves crack formation, propagation and ultimate failure. This is the type of failure generally seen in the field.

The assumption of the ASTM D2837 test method is that a straight line described by at least 10,000-hour test data will continue as a straight line through at least 100,000 hours. However, it is now known that certain polyethylene compounds that have met this requirement still can show a downturn prior to 100,000 hours. Therefore, another test method was needed that would confirm or "validate" that the 73°F (23°C) extrapolated line is straight at least through 100,000 hours.

Rate Process Method Validation

Many naturally occurring rate processes follow the law discovered by Arrhenius and represented by(28):

$$k= koe^{-ER/T}$$

This expression states that the reaction rate is a function of the absolute temperature. This law applies to experimental data from many types of processes, including estimating the slit mode failure time of plastic pipe as a function of temperature.

The new test method selected is based upon an activated rate process theory for the rupture of materials and is commonly referred to as the Rate Process Method (RPM) Validation(1,29,32,33). A three-coefficient mathematical formula is utilized to fit brittle failure data obtained at different elevated temperatures. The equation used is:

$$\log t = A + B/T + C/T \log S$$

WHERE

t = time to failure, hours

T = absolute temperature, °K

S = hoop stress, psi

A, B, C = coefficients

This equation is then used to predict the onset of the 73°F (23°C) brittle-type failures from brittle-type data obtained at elevated temperatures. It has been applied to six different polyethylenes of known long-term field performance and has accurately differentiated between good- and poor-performance pipes. It is mandatory that all pressure pipe compounds have to pass the validation test before a PPI listing is granted.

An example of the RPM validation procedure is explained in the following steps with the help of Figure 15.

1. Plot the log-stress versus log time for the ductile failures at 73°F (23°C) according to ASTM D2837, using data up to 10,000 hours. Extrapolate the data out to 100,000 hours (line aa’) and obtain the LTHS intercept (Point 1).

At least six pieces of pipe are tested at each of the following conditions.

2. Select an elevated temperature (90°C or lower) and hoop stress where brittle failures will occur in 100 to 500 hours as shown by Point II. This is known as Condition 1.

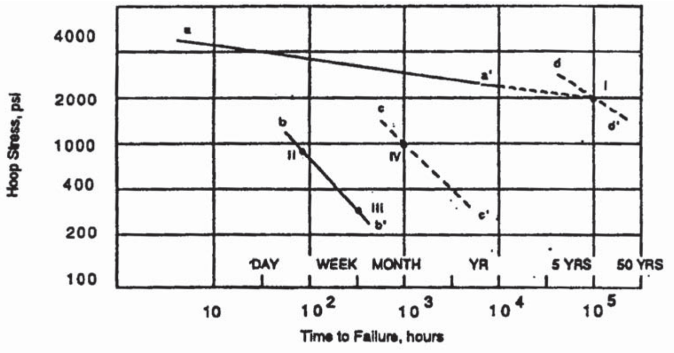


Figure 15 Hoop Stress vs Time to Failure

3. Using the same temperature, select a stress at least 75 psi lower than in Condition I. Failure times should range from 1,000 to 2,000 hours as shown by Point III. This is Condition II. The line (bb′) determined by points II & III will be used to determine the minimum failure time of the next test condition.
4. The underlying theory in ASTM D2837 assumes that the downturn or 'knee' will occur after 100,000 hours. Therefore, the worst case assumes that the 73°F knee will occur at 100,000 hours, which is indicated by line dd′. To confirm that the 73°F knee is at or beyond this worst case situation, select a temperature at least 15°C lower than Condition I but use the same stress as Condition I. This is known as Condition III and is indicated as Point IV and line cc′. The experimentally determined average log-failure time at Condition III is then compared to the time predicted by the RPM equation $\log t = A + B/T + (C/T)\log S$, where the coefficients A, B, and C are calculated using the Points I, II, and III.
5. If the experiment results in a test failure time that meets or exceeds this predicted RPM failure time for point IV, the hypothesis that the knee occurs at or beyond 100,000 hours has been confirmed independently and the ASTM D2837 procedure has been validated. If the actual failure time is less than the RPM predicted time, the pipe is disqualified and cannot be considered adequate for pressure pipe.

The RPM process can be used to study the effects of resin formulation or pipe processing changes in a shorter time period than having to retest under ASTM D2837. Another advantage to this method is that the long-term strength forecast is based on brittle-like failures that simulate long-term field failures. It can also be used as a Quality Control test for subsequent monitoring of pipe after the initial RPM rating is established.

Fracture Mechanics

The fundamental premise of fracture mechanics is that an object fractures under an applied stress due to the growth of cracks from flaws inherent in the object. These flaws may be material defects (contamination or an undesired multi-phase structure), manufacturing defects (voids or surface embrittlement), or post production damage (scratches, gouges, improper joining). They may be microscopic or macroscopic in size. Whatever the source or size, such flaws serve to intensify the nominal applied stress within their vicinity. At some point this intensified stress at the flaw will exceed the strength of the material and a crack will begin to grow. Ultimately, such growing cracks will lead to failure of the entire object.

Thus, the fracture resistance of a given structure or material will depend upon the level of stress applied to it, the presence and size of flaws, and the resistance of the material to crack initiation and growth. The objective of fracture mechanics is to provide quantitative relationships between some of these factors. There are two basic approaches to this problem, one method, originally proposed by Griffith(18), is concerned with the balance between strain energy stored within a stressed body and that released when a crack within that body extends by some amount. The second method, which will be presented here, deals with the mechanical environment near the tip of a flaw which will initiate a growing crack.

This latter method states that the amount of stress concentration at the tip of a crack (flaw) contained within a stress body can be characterized by a Stress Intensity Factor, K. For crack growth in the plane ahead of the flaw caused by some applied tensile stress, the value is denoted as K1 and is given by the equation:

$$K1 = (Y)(s)(\pi a)½$$

WHERE

s = nominal applied stress, psi^{p}

π = length of the crack, inch

Y = a factor that accounts for the geometry of the specimen

Values of Y have been tabulated for a wide range of geometries(43,44). Crack growth is assumed to occur when the value of $K1_i$, that exists in the stressed specimen exceeds some critical value, $K1_c$, that is characteristic of the material from which the specimen is made.

In its simplest form, this treatment assumes that the material behaves as a linear elastic solid up to the point where fracture occurs. However, it soon becomes apparent that, except for cases where fracture occurs at very low stress levels in comparison to the material yield stress, the fracture process does result in some plastic deformation. Due to the stress concentration effect, a volume of material near to the crack tip and at free surfaces of a specimen (if the crack extends to such surfaces) will yield, even if the bulk of the specimen is still at a stress below the yield stress. However, as long as this plastic deformation is constrained to a relatively small percentage of the total area ahead of the growing crack, linear elastic fracture mechanics can still be utilized.

In application, a material is evaluated by suitable laboratory testing to determine the values of K1 for which crack growth will occur. In brittle polymeric materials like polystyrene, crack growth (when it occurs) will be rapid and the specimen will fail immediately. In more ductile materials, like the pipe-grade polyethylenes, crack growth may proceed very slowly; e.g. at rates of 10^{-5} – 10^{-6} inches/hour. It is possible to observe both types of crack growth in the same material: i.e. under sufficient energy, a crack will grow slowly until its length is such that the value of K1 for the now longer crack exceeds the critical value $K1_c$ for the rapid crack growth in the material.

The phenomenon of rapid crack failure of polyethylene pipes has been studied extensively. Such failures are extremely rare, and methodologies exist to evaluate the potential conditions under which polyethylene could fail by such a mechanism(27).

In studies of slow crack growth behavior on resins that have been used for the production of polyethylene pipe, two types of behavior have been observed(31). Some older polyethylene materials have exhibited slow crack growth (SCG) field failures. For these materials, it has been possible to determine crack incubation times (time for slow crack growth to commence at a given K1) and crack growth rates as a function of K1 and relate the pipe failure time to in-service stresses(12,45). Newer polyethylene pipe resins are proving to be so extremely resistant to slow crack growth that more complex methods of non-linear analysis may be necessary(31).

Cyclic Fatigue Endurance

Fracture mechanics has also been utilized in evaluating fatigue fracture of polyethylene pipe(9). For fatigue loading, the rate of crack growth is expressed as:

$$da/dn = D(\Delta K_i)^d$$

WHERE

da/dn = crack growth per fatigue cycle

D, d = material constants

ΔK_i = difference in stress intensity at the crack tip between the highest and lowest stresses imposed during each fatigue cycle

Testing of polyethylene pipes via fatigue loading appears to also be a reasonable method of assessing the relative resistance of the newest resins to slow crack growth(11). Experimental evaluation of D and d in the above equation for a particular polyethylene pipe resin could permit prediction of field performance for pipe made from that resin if some estimate of applied stress and flaw size within the pipe can be made.

Each time a polyethylene pipe is pressurized, its circumference and length expand. For applications where the pressure is constant and below the pipe pressure rating, this small amount of expansion (strain) is not important. However, strain does become important when the pipe undergoes higher cyclic pressurization.

There is a maximum critical strain limit which, once exceeded, permanently changes the characteristics of the pipe. At high strain levels, microcracks can occur. Repeated straining that approaches the strain limit can cause the growth of flaws or microcracks that will propagate through the pipe wall, resulting in pipe failure. The effects of high strain levels are cumulative due to this non-reversible microcrack formation. As the critical strain limit is approached, there is a greater possibility that the pipe performance will be affected.

The typical pressure pipe in the field undergoes a strain of ½% to 1%. This is well below the critical strain limit of 6% to 7% for most polyethylenes. However, the actual value is a function of the material. Most field failures occur in the brittle mode, which indicate that crack propagation was the cause of the failure. Strain is not a factor in these cases. However, as the pressure increases so does the strain. Failures at high pressures (well above the pressure rating of the pipe) occur in the ductile mode, which is indicative of high strain conditions.

Predicting the service life under cyclic pressure conditions is not straightforward. It is a function of two parameters; Stress Level (Amplitude), and Frequency. By minimizing each of those items, the possibilities of failure by fatigue are reduced. See Figure 16 for a typical S-N curve. For more specific details on this subject, please see references(9,10,11).

Short-Term Mechanical Properties

Tensile Properties

Most short-term data is derived from a constant-speed tensile apparatus using test coupons as shown in Figure 17. The results from these tests are in the form of force and deformation data, which can then be transformed into stress-strain or elongation curves. The tests are usually conducted at a certain temperature, which is typically 73°F (23°C).

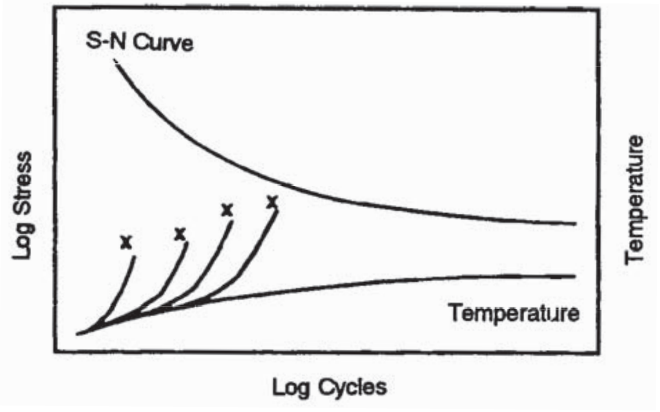


Figure 16 Typical S-N Curve, with Thermal Effects Which Sometimes Occur When Fatigue-Testing Plastics

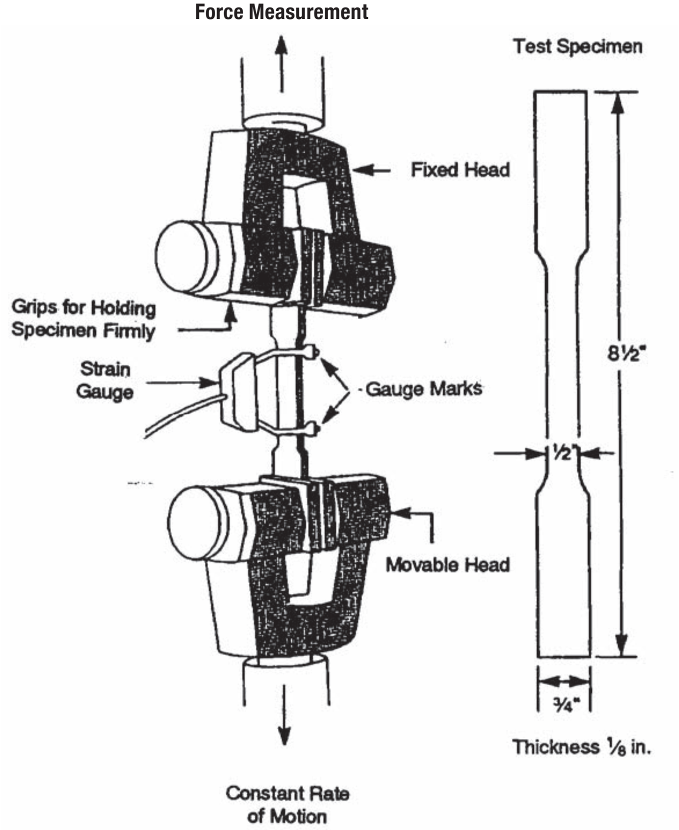


Figure 17 Typical Test Setup and Specimen

A material will deform whenever a force is applied(46). The amount of deformation per unit length is called strain, and the force per cross-sectional unit area is called stress. At very low stress levels, strain is nearly proportional to stress and is reversible. Once the stress is removed, the material returns to its original dimension. The Modulus of Elasticity (Young's Modulus) is the ratio between stress and strain in this reversible region. This strain is also referred to as elastic strain since it is reversible. However, in practice, there is not a region of a true, reversible strain for plastics.

At higher stress levels, strain is no longer directly proportional to stress and it is not reversible when the stress is removed. The term used to describe strain in this region is called plastic strain. (This term is used for all materials, not just for polymeric materials.) Figure 18 illustrates stress-strain curves for polyethylene.

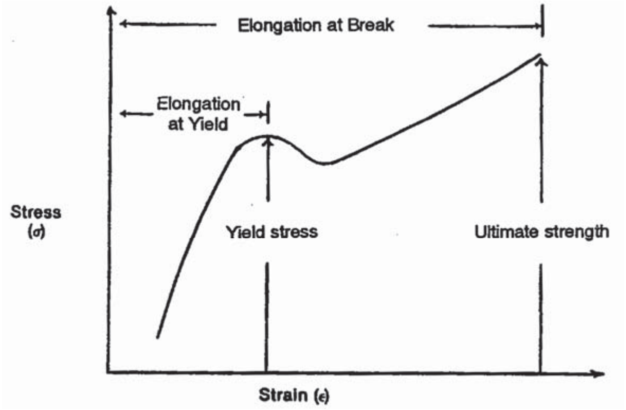
When testing plastics by using a typical constant crosshead rate tensile testing machine, two points should be noted that differ from results obtained from materials such as steel:

1. The stress-strain curve is usually not a straight line in the elastic region, as shown in Figure 18a. It is common to construct a secant line to a defined strain, usually 2% for polyethylene, and then read the stress level at that point(40).
2. The speed of the test will affect the elastic modulus. At slow speeds, the molecules have time to disentangle, which will lower the stress needed to deform the material and will lower the modulus. Conversely at higher crosshead speeds, the molecular entanglement requires a higher stress (force) for deformation and hence a higher modulus value as shown in Figure 18b. This is the reason the testing speed is specified in all test procedures.

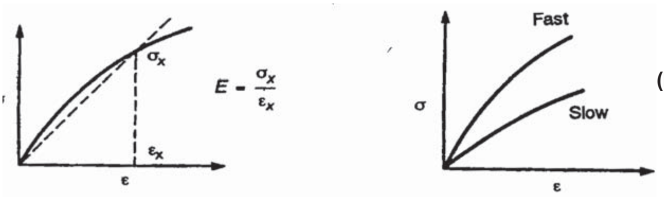
It is necessary to know the exact conditions by which test data are obtained. Slight changes in conditions can drastically alter the test values.

Tensile Strength

The point at which a stress causes a material to deform beyond its elastic region is called the tensile strength at yield. The force required to break the test sample is called the ultimate strength or the tensile strength at break. The strength is calculated by dividing the force (at yield or break) by the original cross-sectional area. ASTM D638(2), *Standard Test Method for Tensile Properties of Plastics,* is used to determine the tensile properties of polyethylene pipe resins. Figure 19 shows the various inflection points for a typical stress-strain curve for polyethylene.



(a) Plot of results of tensile (stress-strain curve)



(b) Stress versus strain at constant crosshead rate

Figure 18 Stress vs Strain Curves Under Specified Conditions

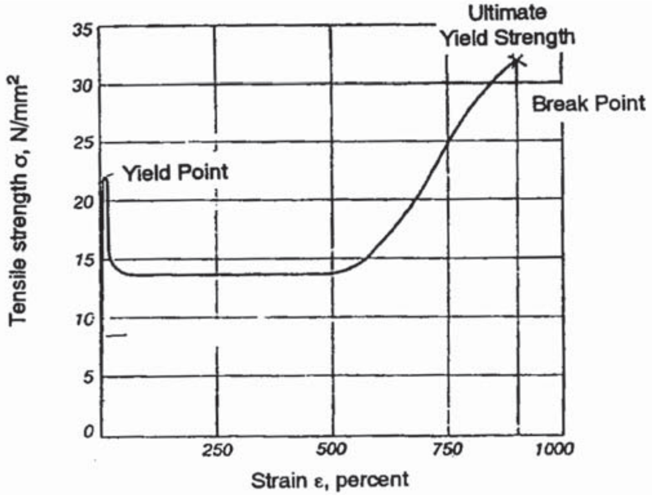


Figure 19 Stress/Strain Curve (Note: 1N/mm2 = 145 psi)

Test specimens are usually shaped as a flat “dog-bone,” but specimens can also be rod-shaped or tubular per ASTM D638. During the tensile test, polyethylene, which is a ductile material, exhibits a cold drawing phenomenon once the yield strength is exceeded. The test sample develops a “neck down” region where the molecules begin to align themselves in the direction of the applied load. This strain-induced orientation causes the material to become stiffer in the axial direction while the transverse direction (90° to the axial direction) strength is lower. The stretching or elongation for materials such as polyethylene can be ten times the original gauge length of the sample (1000% elongation). Failure occurs when the molecules reach their breaking strain or test sample defects, such as edge nicks, begin to grow and cause premature failure. Fibrillation, which is the stretching and tearing of the polymer structure, usually occurs just prior to rupture of a well-drawn sample.

Any stretching or compressing of a test specimen in one direction, due to uniaxial force (below the yield point), produces an adjustment in the dimensions at right angles to the force. A tensile force causes a small contraction, called lateral strain (d/d), to occur at right angles to the force, as shown in Figure 20. The ratio of lateral strain and tensile (longitudinal) strain (L/L) is called Poisson's ratio (v).

$$v = \frac{\text{lateral strain}}{\text{longitudinal strain}} = -\frac{d/d}{L/L}$$

ASTM E132^(6)^, *Standard Test Method for Poisson's Ratio at Room Temperature*, is used to determine this value. Poisson's ratio for polyethylene is between 0.40 and 0.45(20).

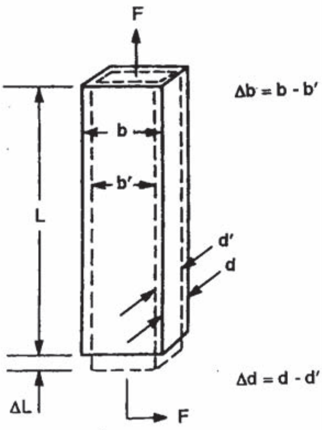


Figure 20 Loaded Tensile Strength Bar Showing Dimensional Change in Length and Width

Compressive Strength and Modulus

Compressive forces act in the opposite direction to tensile forces and can be measured on the same tensile testing machine. The sample is usually a solid rod rather than the tensile dog-bone specimen. The crosshead, instead of moving away from the test sample, moves into and compresses the sample. The deformation or strain is measured the same way as in a tensile test. Again, there is a region of the stress-strain curve in which the stress is proportional to the strain.

At small strains (up to 1–2%) the compressive modulus is about equal to the elastic modulus. However, at higher stress levels, the compression strain is lower than the tensile strain. Unlike the tensile loading, which results in a failure, stressing in compression produces a slow and infinite yielding which seldom leads to a failure. For this reason, it is customary to report compression strength as the stress required to deform the test sample to a certain strain. But even this is difficult to achieve. ASTM D695(2), *Standard Test Method for Compressive Properties of Rigid Plastics*, is used to determine this property.

Flexural Strength and Modulus

Flexural strength is the maximum stress in the outer fiber of a test specimen at rupture. The test is conducted using a specimen that is supported at each end with a load applied at the center. The distortion is measured as the load is increased. If the plastic does not break, as in the case of polyethylene, then the amount of stress is reported at a specified level of strain (usually at 2% or 5%).

Flexural strength is related to the density and, to a lesser extent, molecular weight. As the density increases, the polymer becomes stiffer since the molecules do not have as much space to move around one another. Also as the molecular weight increases, the entanglement of the molecules resists movement and therefore increases stiffness.

Using a tensile testing machine, a sample is bent while being held in a three- or four-point-contact holder. The amount of stress needed to deflect the outer surface of the sample a certain vertical distance (strain) is determined. Since most thermoplastics do not break in this test, the true flexural strength cannot be determined. Typically, the stress at 2% strain is used to calculate the flexural modulus. ASTM D790(2), *Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials* describes this test method.

Shear Properties

The best way to imagine shear stress is to slice a block of material into infinitesimally thin layers, as shown in Figure 21. If the block is subjected to a set of equal and opposite forces, Q, there is a tendency for one layer to slide past another one to produce a shear form of deformation or failure when the force is high enough. The displacement of one plane of molecules relative to another produces shear stresses.

The shear stress, γ, is defined as

$$\gamma = \text{shear load / area resisting shear}$$
$$= Q/A$$

The shearing strain, e, is the angle of deformation which is measured in radians.

The shear modulus, G, is defined as the shear stress divided by the shear strain for stresses below the yield strength.

G = shear stress/shear strain
= γ/ε

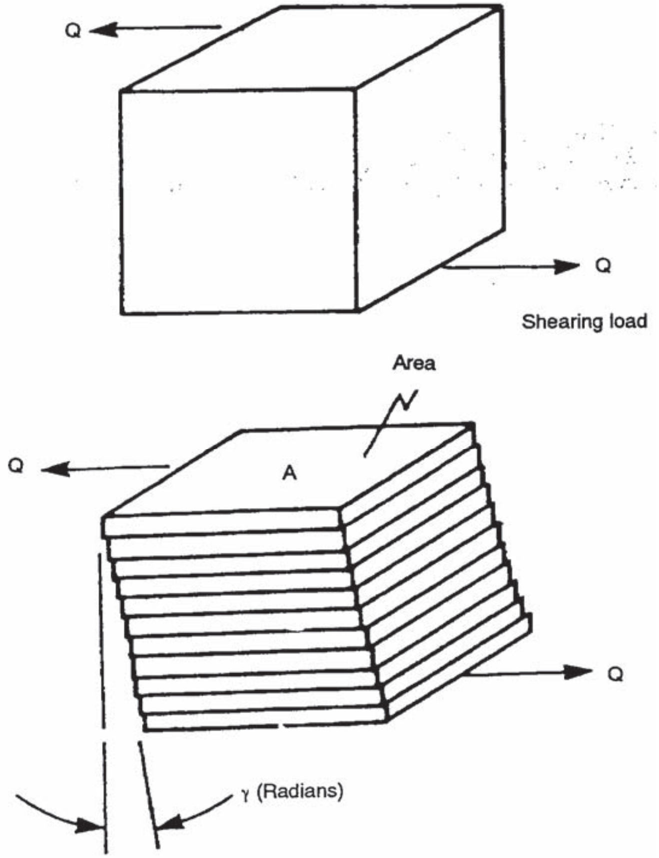


Figure 21 Shear Strain

General Physical Properties

Impact Strength

Impact strength measures the amount of energy that a material can absorb without breaking. The ability of a plastic part to absorb energy is a function of its shape and thickness and the molecular character of the resin. High-molecular-weight resins are very tough since they absorb more energy than lower molecular-weight resins.

The test results from these impact tests can only be used to rank the toughness or the notch sensitivity of similar materials. There are many factors that influence the results such as temperature, specimen orientation (compression or injection molded specimens give different results), and the shape and radius of the notch. The test results provide data for comparisons between the same types of resins (i.e., only polyethylenes to polyethylenes or acetals to acetals, etc.) under the same conditions of the test. Some very tough materials are notch-sensitive, such as nylons and acetals, and register very low notched impact values from this test.

There are several types of impact tests that are used today. The most common one in the United States is the notched Izod test. Izod specimens are tested as cantilever beams. The pendulum arm strikes the specimen and continues to travel in the same direction, but with less energy due to impact with the specimen. This loss of energy is called the Izod impact strength, measured in foot-pounds per inch of notch of beam thickness (ft-lb/in). The specimens can be unnotched or with the notch reversed with the results reported as unnotched or reverse notch Izod impact strength. (The impact test specimen is usually notched in order to have a controlled failure point.)

The Charpy impact test is widely used in Europe and is less common in the United States. The specimen is a supported beam, which is then struck with a pendulum. The loss of energy is measured in the same units as in Izod impact test. The specimens can be either notched or unnotched. Figure 22a illustrates the Izod and Charpy impact tests. ASTM D256(2), *Standard Test Methods for Impact Resistance of Plastics and Electrical Insulating Materials*, describes both test methods.

There is another type of test called the tensile impact strength test, which uses a swinging pendulum as shown in Figure 22b. It measures the amount of energy needed to break the specimen due to tensile impact loading.

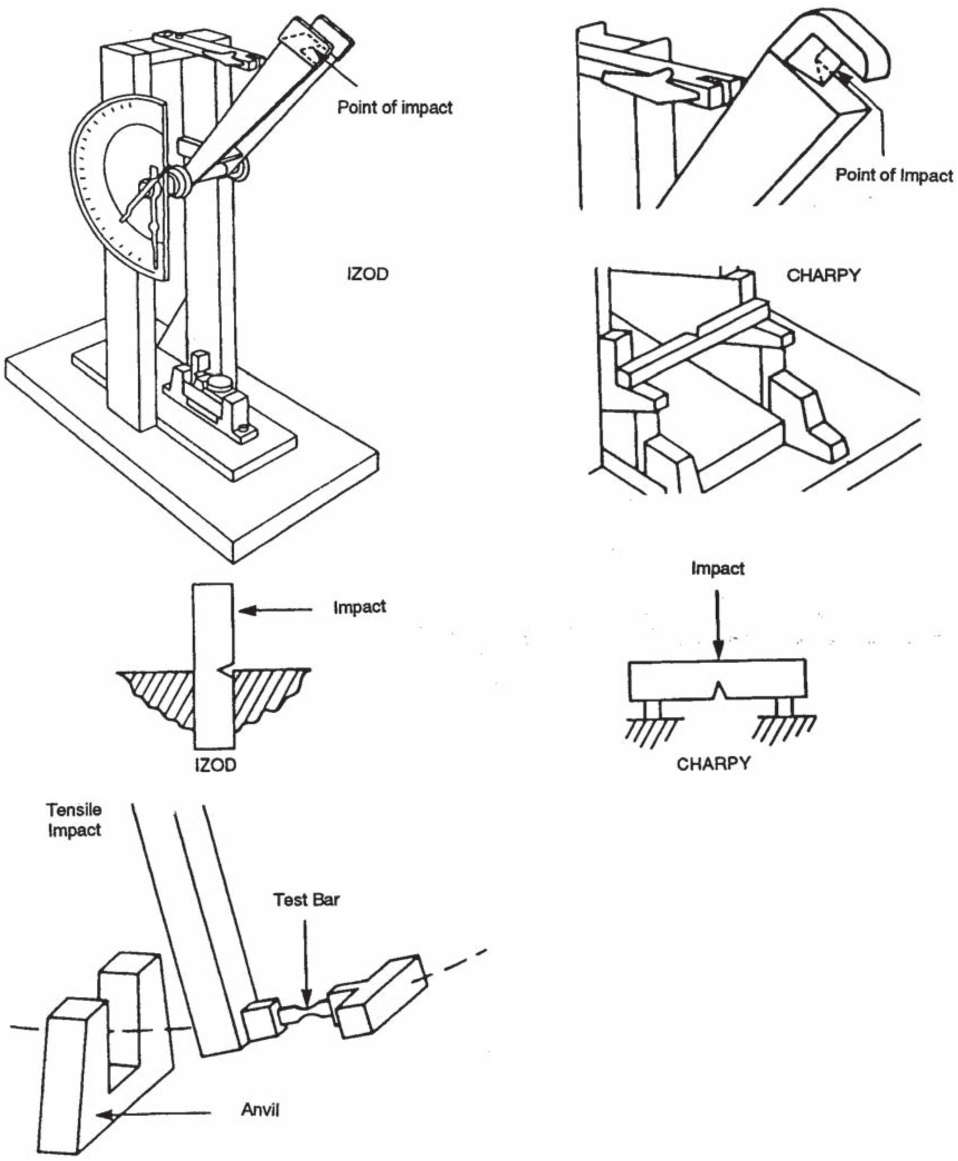


Figure 22 Impact Test Setups

Hardness

Hardness is the resistance of a material to penetration of its surface. It is related to the crystallinity and hence the density of the material. Figure 23 shows the relationship of density versus hardness. The typical hardness tests are either the Shore or the Rockwell. The hardness value depends on the shape, size, and time of the indenter used to penetrate the specimen. Depending upon the hardness of the material to be tested, each hardness test has several scales to cover the entire range of hardness. For polyethylene, the Shore D scale or Rockwell L scale is used. ASTM D785(2), *Standard Test Method for Rockwell Hardness of Plastics and Electrical Insulating Materials,* describes the Rockwell test, while ASTM D224(3), *Standard Test Method for Rubber Property-Durometer Hardness,* describes the Shore test.

For thermoplastics, the depth of indentation by the ball will be very dependent upon the amount of time that the specimen is under stress (due to the viscoelastic characteristics).

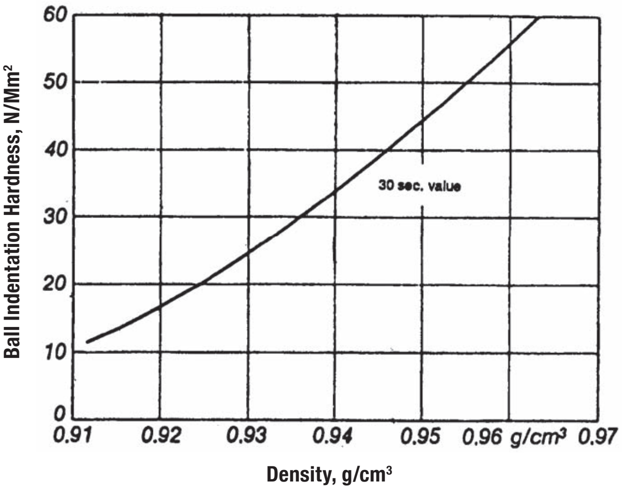


Figure 23 Ball Indentation of Hardness of Polyethylene as a Function of Density

Abrasion Resistance

The growth in the transportation of solids through hydraulic systems is increasing mainly due to the economic advantages of operating this type of system. More and more polyethylene pipe is being used to transport granular or slurry solutions, such as sand, fly ash and coal. The advantage of polyethylene in these applications is its wear resistance, which has been shown in laboratory tests to be three to five times longer than normal or fine-grained steel pipe at a typical velocity of under 15 ft/sec.

There are several factors that affect the wear resistance of a pipeline. The concentration, size and shape of the solid materials, along with the velocity, are the major parameters that will affect the wear resistance and thus affect the life of the pipeline. Some other factors include the angle of impingement and the type of flow characteristics (single- or two-phase flow)(41).

Permeability

The property of permeability refers to the passage of either gaseous or liquid materials through the plastic. Polyethylene has a low permeability to water vapor but it does exhibit some amount of permeability to certain gases and vapors. As a general rule, the larger the vapor molecule or the more dissimilar in chemical nature to polyethylene, the lower is the permeability.

The following gases are listed in order of decreasing permeability: sulfur dioxide, hydrogen, carbon dioxide, ethylene, oxygen, natural gas, methane, air and nitrogen.

Most of the permeability is through the amorphous regions of the polymer. It is related to density and, to a lesser extent, to molecular weight. An increase in density will result in a lower permeability. An increase in molecular weight will also slightly reduce the permeability. Table 3.3 shows permeation rate of methane and hydrogen through both MDPE and HDPE(1).

TABLE 3
Gas Permeation Rate Through Polyethylene

	Permeation Rate	
Resin	Methane	Hydrogen
Medium Density PE	$4.2\text{x}10^{-3}$	$21\text{x}10^{-3}$
High Density PE	$2.4\text{x}10^{-3}$	$16\text{x}10^{-3}$

Permeation from external reagents into the pipe can occur and should be properly addressed. Any pipe, as well as an elastomeric gasketed pipe joint, can be subjected to external permeation when the pipeline passes through contaminated soils. Special care should be taken when installing potable water lines through these soils regardless of the type of pipe material (concrete, clay, plastic, etc). The Plastics Pipe Institute has issued *Statement N - Pipe Permeation*(39) that should be studied for further details.

Thermal Properties

Thermal Expansion and Contraction

The coefficient of linear expansion for polyethylene is about 10 to 12 x 10^{-5} in./in./°F compared to steel at about 1 x 10-5 (42). The typical method to determine this value is described in ASTM D696(2), *Standard Test Method for Coefficient of Linear Expansion of Plastics*. This means that an unconstrained polyethylene pipe will expand or contract at least ten times the distance of a steel pipe of the same length. The main concern to the piping engineer is the amount of internal stress generated during expansion and contraction movements. For constrained polyethylene pipe, the stresses developed due to this movement are substantially lower than that of a steel line. This is due to the lower modulus of elasticity of polyethylene as compared to steel. Polyethylene pipe that is properly anchored should not be adversely affected by normal expansion or contraction. The chaper on above ground applications of polyethylene pipe in this Handbook provides further information about pipe constraining techniques.

The equation to calculate expansion or contraction is

$$\Delta L = L\alpha(\Delta T)$$

WHERE

ΔL = Change in length

L = Original length

ΔT = Change in temperature

α = Coefficient of linear expansion

A 10°F rise or fall in temperature will cause a 100-foot length of an unconstrained polyethylene pipe to move 1.0 to 1.2 inches. The same length of steel pipe will move about 0.10 inch but will generate larger internal stresses than the polyethylene pipe.

Thermal Conductivity

The amount of heat that a polyethylene pipe can convey through its wall is a function of thermal conductivity. Polyethylene has a thermal conductivity of 2.4 Btu/in./ft^2/hr/°F (0.43 W/m/°K) (42). The amount of heat transmitted through a polyethylene wall is calculated by the following equation:

$$q = (k/x)(T_1-T_2)$$

WHERE

q = heat loss, BTU/hr/ft of length

k = thermal conductivity, BTU/in./ft^2/hr/°F

x = wall thickness, inches

T_1 = outside temperature, °F

T_2 = inside pipe temperature, °F

This equation can be used to estimate the heat loss (or gain) from a polyethylene pipe.

The ASTM method commonly used to determine this value is ASTM C177(2), *Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus.*

Specific Heat

The specific heat is defined as the ratio of the heat capacity of the material to that of water (the specific heat of water is 1 cal/g/°C). The specific heat of polyethylene is a function of temperature that is shown in Figure 3.24(23).

For partially crystalline thermoplastics, a sharp maximum in the heat is observed in the melting point region. As the density increases, the specific heat maximum is higher and sharper. Once the polyethylene is in the molten state, the specific heat is independent of temperature and is the same value for all polyethylene resins.

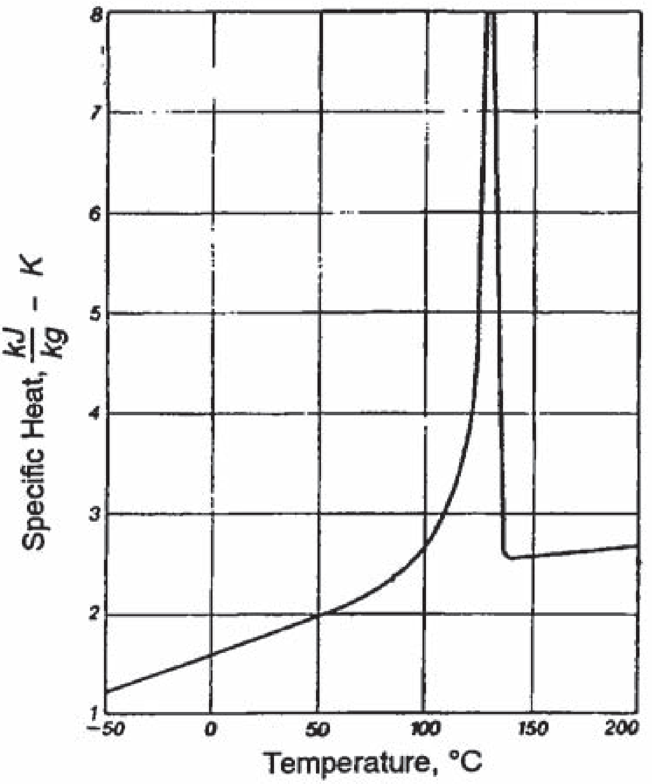


Figure 24 Specific Heat as a Function of Temperature

Glass Transition Temperature

The molecules that make up polyethylene are in constant motion. Even though the molecules are entangled, there is enough free space within the polymer to allow molecular movement. As the temperature falls below melting point, Tm, which is also called the crystallization temperature, there is a decrease in molecular movement and volume due to crystallization of part of the polymer. The structure now consists of crystalline regions separated by amorphous material. Within these latter regions, molecular motion still occurs. As temperature is decreased further, molecular movement and volume reduction in the non-crystalline areas continues. When the molecules cannot pack together any closer, any further decrease in temperature only allows molecular vibrations to occur. The temperature at which this occurs is called the glass transition temperature, Tg. Above the Tg temperature, polyethylene is flexible and ductile, and at temperatures below Tg it exhibits less ductility.

The following example illustrates the difference in polymer characteristics of polymers with different glass transition temperatures. Polyethylene has a Tg of -166ºF (-110ºC) and a Tm of +275ºF (+135ºC)(40). As a comparison, polystyrene has a Tg of +212ºF (+100ºC) and a Tm of +230ºF (+110ºC), which accounts for its more brittle-like behavior at room temperature.

Minimum/Maximum Service Temperatures

Polyethylene has very good characteristics, such as impact strength, at low temperatures. It is the preferred material for operating temperatures below 0ºF (-18ºC). The highest permissible service temperature for a polyethylene pipe depends upon the duration and magnitude of stresses upon the pipe. Generally, +140ºF (+60ºC) is the typical maximum service temperature. However, some non-pressure applications can be used up to +176ºF (+80ºC). The use of polyethylene at high temperature necessitates reducing the working pressure in order to obtain the same service life as that of a lower temperature application. Refer to PPI Technical Note TN-11(34), *Suggested Temperature Limits For Thermoplastic Pipe Installation And For Non-Pressure Pipe Operation*, for further details.

Deflection Temperature Under Load

This test gives the temperature at which a plastic will deflect under a certain load. It is not intended to be a guide to high temperature service limits but to serve as a comparison of high temperature behavior of various materials.

Figure 25 shows a schematic of the typical apparatus used in this test. ASTM D648(2), *Standard Test Method for Deflection Temperature of Plastics Under Flexural Load,* is the standard method used to determine this value.

A 0.5 in. by 0.5 in. by 5.0 in. beam is immersed in a heat transfer liquid and heated until the beam deflects 0.01 in. with a maximum flexural stress load of 264 psi or 66 psi.

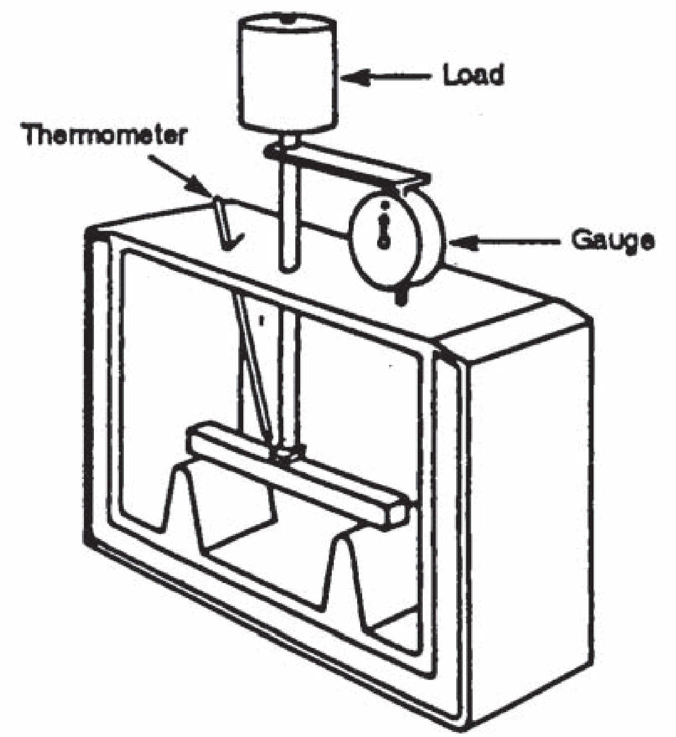


Figure 25 Test Apparatus for Deflection Temperature Under Load

Electrical Properties

Metals are very good electrical conductors due to their metallic crystal structure(13). The outermost electrons are loosely bound to the atoms and can be easily broken free to move among the crystal lattice. This flow of free electrons accounts for the ability of metals to conduct large amounts of electrical current. In plastics and glass, the outer electrons are tightly bound to the atoms and are not available to move among the lattice. This accounts for the inability of plastics to conduct electricity; therefore they are called insulators. Table 4 lists the typical electrical properties of polyethylene.

TABLE 4

Selected Electrical Property Ranges for MDPE and HDPE

Property	Unit	Test Method	Value
Volume Resistivity	Ohms-cm	–	$>10^{16}$
Surface Resistivity	Ohms	–	$>10^{13}$
Arc Resistance	Seconds	ASTM D495	200 to 250
Dielectric Strength	Volts/mil	ASTM D 149, 1/8 in. Thick	450 to 1000
Dielectric Constant	–	D150 – 60 Hz	2.25 to 2.35
Dissipation Factor	–	D150 – 60 Hz	>0.0005

Volume Resistivity

Volume resistivity is the resistance to current leakage through an insulator. It is related to temperature, moisture in the insulator, and the type of the insulator. The units of measurement are ohm-centimeters (ohm-cm). Higher values indicate a better resistance to breakdown or leakage.

Also, a volume resistivity of 10^{10} ohm-cm normally forms the dividing line between conducting and non-conducting materials. Since polyethylene has a volume resistivity of 10^{16} ohm-cm, it will accumulate a static charge.

Surface Resistivity

Surface resistivity is the resistance to current leakage along the surface of the insulator, measured in ohms. It actually measures the ability of the current to flow over the surface of the material. This value is a function of surface conditions and is not a true property of the material. The higher the value, the better the resistance to leakage.

Arc Resistance

Arc resistance is the measurement of the breakdown of the surface of an insulator caused by an arc. If an electrical arc is imposed upon the surface, the current will flow along the path of least resistance. The test measures the time it takes for the breakdown to occur along the surface. Higher values indicate better resistance to breakdown.

Dielectric Strength

Dielectric strength is the voltage that an insulator can withstand before breaking down and allowing current to pass. The voltage just prior to breakdown divided by the sample thickness defines this property. It is expressed in terms of a voltage gradient, volts/mil. The higher the value, the better the insulator. The thinner the insulation thickness, the greater the dielectric strength.

Dielectric Constant

Molecules will become polarized when an electrical field is applied across an insulator. If the voltage potential is reversed, the polarization of insulator molecules will also become reversed. The ease with which polarization takes place is measured by a material constant called permittivity. The ratio of permittivity to the negligible permittivity in a vacuum is called the relative dielectric constant. The value changes with frequency, temperature, moisture level, and part thickness. This value is important when plastics are used in high frequency applications.

Dissipation Factor

If polarization of the sample occurs at a very high rate, a certain amount of energy will be dissipated in the form of heat. The dissipation factor is the ratio of energy dissipated at a certain frequency (usually 1 MHz) to that transmitted. A low value is important when plastics are used as insulators in high frequency applications such as microwave or radar equipment.

Static Charge

Since plastics are good insulators, they also tend to accumulate a static charge. A static charge is a result of either an excess or deficiency of electrons in the molecular structure of the polymer. Depending on the type of polymer, the static charge can be either positive or negative electrically.

Polyethylene pipe can acquire a static charge through friction. Sources of friction can be simply the handling of the pipe in storage, shipping, or installation. Friction can also be caused by the flow of gas containing dust or scale or by the flow of dry material through the pipe. These charges can be a safety hazard if there is leaking gas or an explosive atmosphere and should be dealt with prior to working on the pipeline.

Since polyethylene is electrically non-conductive, the static charge will remain in place until a grounding device discharges it. A ground wire will only discharge the static charge from its point of contact. The most effective method to minimize the hazard of static electricity discharge is to apply a film of water to the work area prior to handling. Please refer to the pipe manufacturer for further details.

There are special grades of electrically conductive polyethylenes that are used to prevent the build-up of static charges in explosion-proof areas. These resins usually contain 7% to 9% carbon black, which prevents an accumulation of a static charge by decreasing surface resistivity. For further information, please contact a polyethylene resin producer.

Flammability and Combustion Toxicity

Flammability

Polyethylene ignites on contact with a flame unless it contains a flame retardant stabilizer. Burning drips will continue to burn after the ignition source is removed. The flash ignition and self ignition temperatures of polyethylene are 645°F (341°C) and 660°F (349°C) respectively as determined by using ASTM D1929(3), *Standard Test Method for Ignition Properties of Plastics.* The flash point using the Cleveland Open Cup Method, described in ASTM D92(7), *Standard Test Method for Flash and Fire Points by Cleveland Open Cup,* is 430°F (221°C)(16) .

During polyethylene pipe production, a certain amount of smoke may be generated. If smoke is present, it can be an irritant and as such should be avoided. Specific information and Material Safety Data Sheets (MSDS) are available from the polyethylene resin manufacturer.

Combustion Toxicity

The combustion of organic materials, such as wood, rubber, and plastics, can release toxic gases. The nature and amount of these gases depends upon the conditions of combustion. For further information on combustion gases, refer to *Combustion Gases of Various Building Materials* and *Combustion Toxicity Testing* from The Vinyl Institute(46,48).

The combustion products of polyethylene differ greatly from those of (poly)vinyl chloride (PVC). Polyethylene does not give off any corrosive gases such as hydrochloric acid, since it does not contain any chlorine in its polymer structure.

Chemical Resistance

Plastics are not subject to galvanic corrosion, as are metals, since they are nonconductors. However, plastics can be affected through direct chemical attack, strain corrosion or solvation. The extent of the resistance is a function of many items, including time, temperature and stress of contact.

Polyethylene is a non-polar high-molecular-weight paraffin hydrocarbon. It is very resistant to chemicals and other media such as salts, acids and alkalis. However, oils, fats and waxes will cause some slight swelling. Strong oxidizing agents tend to attack the molecules directly and lead to gradual deterioration of properties. Organic chemicals tend to be absorbed by the plastic through a process called solvation. The effects of solvation, which are very time-dependent, include swelling and softening of the polymer. Strain corrosion takes place under combined action of strain and a chemical environment. Another name for this phenomenon is environmental stress cracking (ESC).

Stress crack resistance increases as density decreases and also as the melt index (higher molecular weight) decreases. Copolymer type and placement on the polymer chain also greatly affect the ESC characteristics of a polymer. The following section describes various types of chemical resistance testing.

Immersion Testing

The chemical resistance information published by many polyethylene resin and pipe manufacturers was determined from immersion tests. These simple immersion chemical resistance tests use molded specimens that are immersed in the chemical media (under no stress) at two or three different temperatures. After a certain amount of time, the samples are removed, weighed, inspected and tested. The resistance is then determined by the amount of (or lack of) specimen swelling, weight loss and change in strength properties. The ratings are listed "generally resistant," "limited resistance," and "not resistant." Some test results are shown in Table 5. When using this type of data, special consideration must be made if the material is to be exposed to chemical, mechanical or thermal stresses. Consult PPI Technical Report TR19(38), *Thermoplastic Piping for the Transport of Chemicals,* for more complete information.

TABLE 5

Chemical Resistance of HDPE Pipe Resins

The following abbreviations are used in Table 5:

R Generally Resistant. (Swelling was less than 3% or observed weight loss less than 0.5%, and elongation at break was not changed significantly.)

C Has limited resistance only and may be suitable for some conditions. (Swelling between 3% and 8%, and/or observed weight loss between 0.5% and 5%, and/or elongation at break decreased less than 50%.)

N Is not resistant. (Swelling greater than 8% or observed weight loss greater than 5% and/or elongation at break decreased to greater than 50%.)

D Discoloration

The terms R to C, C to N, and R to N are used when disagreement exists in the literature.

Where no concentrations are given, the relatively pure material is indicated except in the case of solids, where saturated aqueous solutions are indicated.

* Indicates that this chemical resistance does not apply for weld joints.

(The complete Table 5 is included on the following pages.)

TABLE 5
Chemical Resistance of HDPE Pipe Resins

Chemical Name	Concentration	73°F	120°F	140°F
Acetaldehyde & Acetic Acid		R	—	—
Acetaldehyde (aqueous)	all	R to C	C	C to N
Acetamide		R	—	R
Acetic acid	100% (glacial)	R	C to N	C to N
Acetic acid	50%, 60%, 70%, 80%	R	C	R to C
Acetic acid	10%, 20%	R	—	R
Acetic acid vapor		R	R	==
Acetic anhydride	100%	R	—	C
Acetoacetic acid		R	—	—
Acetone, 100%		R to C	C	C
Acetophenone		R	—	—
Acetylene		R	—	—
Acids aromatic		R	—	R
Acronal® dispersons - usual	commercial	R	—	C
Acrylic acid emulsions		R	—	R
Acronitrile	technically pure	R	—	R
Adiptic acid, saturated sol.		R	—	R
Adiptic acid ester		R	—	C
Aktivin® (chloramine)(aqueous	1%	R	—	R
Alcohol, allyl		R	C	R
Alcohol, amyl	technically pure	R	C	R to C
Alcohol, benzyl		R to C	C	R
Alcohol, (n-butanol)		R	R	R
Alcohol (2-butanol)		R	R	—
Alcohol, ethyl		R	C	R to C
Alcohol, hexyl		R	R	R
Alcohol, isopropyl (2-propanol)		R	R to C	R to N
Alcohol, methyl		R	R	R to C
Alcohol, propyl (1-propanol)		R	R	R
Allyl acetone		R	—	R to C
Alums (aqueous)	all	R	R	R
Aluminum salts (chloride, flouride hydroxide, metaphosphate, sulphate)		R	R	R
Amino acids		R	—	R
Ammonia, gas		R	R	R
Ammonia, liquid		R	—	R
Ammonia (aqueous)		R	R	R
Ammonium salts (acetate, carbonate chloride, fluoride 10-25%, hydrosulphide, hydroxide, metaphosphate nitrate, phosphate, sulphate, sulphide, thiocyanate)		R	R	R
Amyl acetate	technically pure	R to C	C to N	C
Amyl chloride	100%	C	—	N
Amyl phthalate		R	—	C
Analine (aqueous)	all	R	C to N	C to N
Analine chlorhydrate		C	—	—
Analine hydrochloride (aqueous)	all	R to C	—	R
Analine dyes		C	—	—
Animal oils		R	—	R to C
Aniseed oil		C	—	N
Anisole		C	—	C to N
Antifreeze		R	—	R
Anthraquinone		C	—	—
Anthraquinone sulfonic acid		R	—	R
Antimony chloride, pentachloride		R	—	R
Antimony trichloride		R	R	R
Aqua Regia		N	N	N
Arsenic acid (anhydride)		R	—	R
Arsenic acid (aqueous)		R	R	R
Aryl sulfonic acid		R	—	—
Ascorbic acid		R	—	R
Asphalt		R	—	C
Aspirin		R	—	R
Barium salts	all	R	R	R
Barium hydroxide (aqueous)	all	R	R	R
Battery acid		R	—	R
Beater glue		R	—	R
Beer		R	R	R
Beet sugar liquor		R	—	—
Beeswax		R	C	C to N
Benzaldehyde (aqueous)	10%	R	—	C
Benzaldehyde in isopropyl alcohol	1%	R	—	R
Benzene	pure	C	C to N	C to N
Benzene Sulfonic acid	all	T ro C	—	R to C
Benzoic acid (aqueous)	all	R	R	R
Benzoyl chloride		C	—	N
Bichromate-sulphuric acid	concentrated	R	—	N
Bismuth salts		R	—	R
Bisulphite soution		R	—	R
Bitumen		R	—	C
Black liquor-paper		R	R	—
Bleach liquor (12.5% active chlorine)		R	N	N
Bleach liquor (5.5% active chlorine)		R	R	R
Bone oil		R	—	R
Borax		R	R	R
Boric acid (aqueous)	all	R	R	R
Boric acid methylester		R	—	C to N
Boron trifluoride		R	C	C
Brake fluid		R	—	R
Brandy - wine		R	—	—
Brine	saturated	R	R	R
Bromic acid		R	N	—
Bromine (gas)		N	N	N
Bromine (aqueous)		C	N	N
Bromine (liquid)		N	N	N
Bromochloromethane		N	—	—
Butanediol (aqueous)	all	R	R	R
Butadione		R	C	—
Butane tetrol (crythritol)		N	N	—
Butane, gas		R	R	R
Butanetriol (aqueous)	all	R	—	R
Butaxyl® (methoxylbutyl acetate)		R	—	C
Butter		R	—	R
Butyl acetate		R to C	C	C to N
n-Butyl acetate		R	—	C
Butyl acrylate		R	—	C
Butyl benzyl phthalate		R	—	R
Butylene glycol		R	—	R
Butylene		R	R	—
Butyl phenol		R to C	C	R
Butyric acid (aqueous)	all	R	C	C
Calcium chloride		R	R	—
Calcium salts (aqueous)		R	R	R to C
Camphor oil		N	—	N
Camphor (crystals)		R	C	C
Calcium hydroxide		R	R	R
Cane sugar liquors		R	R	R
Carbazole		R	—	R

TABLE 5
Chemical Resistance of HDPE Pipe Resins, continued

Chemical Name	Concentration	73°F	120°F	140°F
Carbolic acid		R	—	R
Carbolineum for fruit trees (aqueous)		R	—	C
Carbon bisulfide		C to N	N	N
Carbon dioxide (wet or dry)		R	R	R
Carbonic acid (aqueous)	all	R	R	R
Carbon monoxide		R	R	R
Carbon tetrachloride		C to N	N	N
Carnauba wax		R	—	R
Casein		R	C	—
Castor oil		R	C	R to C
Caustic potash (dry & solution)		R	R	R
Caustic soda (dry & solution)		R	R	R
Cellosolve		C	C	—
Cetyl alcohol (hexadecanol)		R	—	R
Cellosolve acetate		C	C	—
Chloral hydrate (aqueous)	all	R	R	RD
Chloramine		R	—	—
Chloroacetic acid		R to C	R to N	R to N
Chloric acid	20%	R	N	—
Chlorine, gaseous, dry		C to N	N	N
Chlorine, gaseous, moist		C to N	N	N
Chlorine, liquid		N	N	N
Chlorine, water		R to C	C	C to N
Chlorobenzene		C to N	C to N	N
Chlorocarbonic acid		R	—	C
Chlorobenzyl chloride		C	C	C
Chloroethanol	pure	R	—	RD
Chloroform	pure	C to N	C to N	N
Chloromethane	100%	C	—	N
Chloropicrin		R to C	—	N
Chlorosulphonic acid	100%	C to N	C to N	N
Chrome alum		R	R	R
Chrome anode mud		R	—	R
Chrome salts (aqueous)	all	R	—	R
Chromic acid	10%,30%,40%,50%	R	R to C	C to N
Chromic acid	80%	R	R to C	N
Chromium trioxide (aqueous*)	up to 50%	R	—	
Chromosulphuric acid		R	C	N
Cider		R	—	R
Citric acid (aqueous)	saturated	R	R	R
Clophen® A50 & A60		R	—	C to N
Coal-tar oil		RD	—	CD
Coconut oil		R	R to C	R to C
Cod liver oil		R	—	R to C
Coke oven gas (benzene free)		R	R	R
Coffee extract		R	—	R
Cognac		R	—	—
Cola concentrate		R	—	R
Copper salts (aqueous)		R	R	R
Copper chloride (aqueous)		R	R	R
Copper cyanide		R	—	R
Copper flouride (aqueous)		R	R	R
Copper nitrate (aqueous)		R	R	R
Copper sulphate (aqueous)	all	R	—	R
Corn oil		R	R to C	C
Corn syrup		R	R	R
Cranberry sauce		R	—	R
Coumarone resins		R	—	R
Creosote		R	R	RD
Cottonseed oil		R	C	R
Cresol	100%	R to C	R to N	CD
Cresol (aqueous)	diluted	R	—	RD
Crotonaldehyde	pure	R to N	N	C
Cresylic acid	50%	C	—	—
Cyclanone	usual commercial concentration	R	—	R
Crude oil		C	C	—
Cyclohexane		R	C	R to N
Cyclohexanol		R to C	C to N	N
Cyclohexanone		R to C	R to C	C to N
Decalin	pure	R	—	R
Detergents		R	R	R
Developer solutions (photographic)		RD	R	RD
Dextrin		R	R	R
Dextrose		R	R	R
Diazo salts		R	C	R
1;2-dibromoethane		C	—	N
Dibutyl ether		R to C	C	N
Dibutyl phthalate	pure	R	C	C
Dibutyl acetate		R	C	C
Dichloroacetic acid	pure	R	R	CD
Dichloroacetic acid	50%	R	—	CD
Dichloroacetic acid methyl ester		R	—	R
Dichlorobenzene		C	C to N	N
Dichloromethane		C	—	C
DDT (powder)		R	—	R
Dichloroethylene		C to N	C to N	N
Dichloropropane		C	—	N
Dichloropropene		C	—	N
Diesel fuel		R	C	C
Diethyl amine		C	C	—
Diethylene glycol		R	R	R
Diethyl ether		R to C	C	C to N
Di (2-ethylexyl) phthalate (DOP)		R	—	C
Diethyl ketone		R	-	C
Diglycolic acid (aqueous)	30%	R	R	R
Diisobutyl ketone	pure	R	R	C to N
Diisopropyl ether		R to C	—	N
Dimethylamine		R to C	C	C
Dimethyl formamide	pure	R	R	R to C
Dimethyl sulphoxide		R	—	R
Dioctyl phthalate		R to C	C	C to N
Dioxane 1,4		R	R	R
Diphenylamine		R	—	C
Diphenyl oxide		R	—	C
Disodium phosphate		R	R	R
Disodium sulphate		R	—	R
Dodecylbenzenesulphonic acid		R	—	C
Drinking water		R	—	R
Dyes		RD	—	RD
Electrolyte baths		R to C	—	C
Emulsifiers		R	—	R
Emulsions (photographic)		R	—	R
Emulsions (acrylic)		R	—	R
Ephetin (aqueous)	10%	R	—	R
Epichlorohydrin		R	—	R
Epsom salts	all	R	—	R
Esters, alphatic	pure	R	R	R to C
Ethane		R	—	R
Ether		R to C	C	C
Ethyl acetate	pure	R	C	C to R
Ethylbenzene	pure	C	—	—

TABLE 5
Chemical Resistance of HDPE Pipe Resins, continued

Chemical Name	Concentration	73°F	120°F	140°F
Ethyl chloride	pure	C	—	N
Ethyl ether		R to C	—	C to N
Ethylene		R	—	C
Ethyl esters		R	C	—
Ethyl halides		R	C	—
Ethylene diamine	pure	R	—	R
Ethylene diamine-tetraacetic acid		R	—	R
Ethylene dichloride		C to N	N	N
Ethylene chloride		C	—	C
Ethyl dibromide		C	—	N
Ethylene glycol		R	R	R
Ethylene oxide (gas)		R to C	C	R
2-Ethylhexanol		R	—	C
Euron● B		C	—	C
Euron● C		R	—	R
Fatty acids amides		R	—	C
Fatty acids		R	R	R to C
Fatty alcohols		R	—	C
Ferric chloride (aqueous)	all	R	R	R
Ferric and ferrous salts (aqueous)		R	R	R
Fertilizer salts (aqueous)	all	R	—	R
Film solutions		R	R	R
Fir wood oil		R	—	C
Fish solubles		R	—	R
Fluoboric acid		R	R	R to C
Fluorine, dry gas		C to N	N	N
Fluorine, wet gas		N	N	N
Fluorosilic acid	30%-40%	R	R	R
Formaldehyde	to 40%	R	R	R
Formamide		R	—	R
Formic acid (aqueous)	10%-50%	R	R to N	R
Formic acid (aqueous)	85%-100%	R	—	R
Freon - F11, 12, 113, 114		R to C	C	C to N
Freon - 21, F22		C	C	—
Fruit juices & pulp & fractose	all	R	R	R
Fuel oil		R	C	C
Furfural		C	C to N	C to N
Furfuryl alcohol		R	—	R to C
Gallic acid		R	—	—
Gas, coal, manufactured		R	R	R
Gas, natural, methane		R	R	—
Gasoline		R to C	C to N	C to N
Gelatin		R	R	R
Genantin●		R	—	R
Glucose		R	R	R
Glue		R	R	R
Glycerine (glycerol)(aqueous)	to 100%	R	R	R
Gylcerol chlorohydrin		R	—	R
Glycine		R	—	R
Glycol		R	R	R
Glycolic acid (aqueous)	up to 70%	R	R	R
Glycolic acid butyl ester		R	—	R
Glysantin		R	—	R
Grisiron 8302		C	—	C
Grisiron 8702		R	—	R
Halothane		C	—	C to N
Heptane		R	C	C to N
Heating oil		C	C	—
Hexane		R	C	C
Hexanetriol		R	—	R
Hexanol	R	R	R	
Honey		R	—	R
Hydraulic fluid		R	—	C
Hydrazine hydrate		R	—	R
Hydrobromic acid (aqueous)	up to 50%	R	R	R
Hydrobromic acid (aqueous)	100%	R	—	R
Hydrochloric acid	up to 100%	R	R	R
Hydrogen chloride gas wet & dry		R	—	R
Hydrocyanic acid	10%	R	R	R
Hydrfluoric acid	40%	R	R	C
Hydrofluosilicic acid (aqueous)	all	R	—	R
Hydrogen	100%	R	R	R
Hydrogen peroxide (aqueous)	10%	R	—	R
Hydrogen peroxide (aqueous)	30%	R	R	R
Hydrogen peroxide (aqueous)	50%	R	—	R
Hydrogen peroxide (aqueous)	90%	R	N	N
Hydrogen phosphide		R	—	R
Hydrogen sulphide	dry	R	R	R
Hydroquinone		RD	D	RD
Hydrosulphite	up to 10%	R	—	R
Hydroxylamine sulphate (aqueous)	12%	R	R	R
Hypochlorus acid		R	R	R to C
Ink		R	—	R
Iodine - in KI	3% (aqueous)	R	R	R
Iodine alcohol solution		C	C to N	N
Iodine (aqueous)	10%	C	C	—
Iron III chloride (aqueous)	all	R	—	R
Isobutyl alcohol		R	—	R
Isooctane		R to C	C	C
Isopropanol	pure	R	C	R to N
Isopropyl acetate	100%	R	—	C
Isopropyl ether	pure	R to C	C	N
Jam, jellies		R	—	R
Jet fuels, JP-4 & JP-5		R	C	—
Kerosene		C	C to N	C to N
Ketones		R to C	C	C to N
Kraft paper liquor		R	R	—
Labarraque's solution		R to C	—	
Lactic acid	10%-96%	R	R	R
Lactose		R	—	R
Lacquer thinners		C	C	—
Lanolin (wool fat)		R	—	R
Lard oil		R	R	—
Latex		R	—	R
Lauric acid		R	R	—
Lauryl chloride		R	R	—
Lauryl sulphate		R	R	—
Lead acetate (aqueous)	all	R	R	R
Lead salts		R	R	—
Lead tetraethyl		R	R	—
Lime		R	—	R
Lime sulphur		R	R	—
Lime water		R	—	R
Linseed oil		R to C	C	R to N
Liquor		R	R	R
Liqueur		R to C	R	N

TABLE 5
Chemical Resistance of HDPE Pipe Resins, continued

Chemical Name	Concentration	73°F	120°F	140°F
Liquid manure		R	—	R
Liquid paraffin		R	—	R
Liquid soaps		R	—	R
Lithium bromide		R	—	R
Lubricating oils		R to C	C	C
Lithium salts		R	R	—
Linoleic acid		R	R	—
Lysol		R	—	C
Machine oil		R	R	C
Magnesium salts		R	R	R
Magnesium carbonate		R	R	R
Magnesium chloride		R	R	R
Magnesium fluosilicate		R	—	R
Magnesium hydroxide		R	—	R
Magnesium iodide		R	—	R
Magnesium sulphate		R	R	R
Magnesium hydroxide		R	R	R
Magnesium nitrate		R	R	R
Maleic acid	50%-100%	R	R	R
Malic acid	50%	R	R	R
Manganese sulphate		R to C	R to C	R
Margarine		R	—	R
Mash		R	—	R
Mayonnaise		R	—	—
Menthol		R	R	C
Mercuric chloride		R	R	R
Mercuric cyanide		R	R	R
Mercurous nitrate		R	R	R
Mercuric salts		R	R	R
Mercury		R	R	R
Metallic soaps		R	R	R
Metallic mordants		R	—	—
Methacrylate		R	—	R
Methacrylic acid		R	—	R
Methane		R	R	—
Methanol	pure	R	R	R
Methyl acetate		C	C	—
Methyl bromide		C	C to N	N
Methyl cellosolve		C	C	—
Methyl chloride		C	C to N	N
Methyl chloroform		C	C	—
Methyl benzene		C	—	N
Methoxy butanol		R	—	C
Methoxybutyl acetate (Butozyl)		R	—	C
Methyl cyclohexane		C	C	N
Methyl cyclohexanone		R	C	—
Methyl methacrylate		R	C	R
Methyl salicylate		R	—	C
Methyl sulfate	50%	R	—	R
Methyl sulfuric acid		R	—	R
Methyl ethyl ketone		R to N	R	N
Methyl glycol		R	—	R
Methyl isobutyl ketone		R	—	C to N
4-Methyl2-pentanone		R	—	R to CD
Methyl propyl ketone		R	—	C
n-Methyl pyrrolidone		R	—	R
Methylene bromide		C	C	—
Methylene chloride*		C	C	C to N
Methylene iodide		C	C	—
Milk		R	R	R
Mineral oil		R to C	C	C to N
Molasses		R	R	R
Mixed acids (sulfuric & nitric)		N	N	—
Mixed acids (sulfuric & phosphoric)		R	C	—
Monochloroacetic acid		R	—	R
Monochloroacetic acid ethyl ester		R	—	R
Monochloroacetic acid methyl ester		R	—	R
Monochlorobenzene		C to N	C to N	N
Monoehtanolamine		—	—	—
Morpholine		R	—	R
Motor oil		R	R	R to C
Mowilith• polymer emulsions		R	—	R
Mustard		R	—	R
Nail varnish remover		R	—	C
Naphtha		R to C	C to N	C to N
Naphthalene		R	C	C
Nickel chloride		R	R	R
Nickel nitrate		R	R	R
Nickel salts		R	R	R
Nickel sulphate (aqueous)	all	R	—	R
Nicotine		R	—	R
Nicotine acid	diluted solution	R	—	R
Nitric acid	0-30%	R	R to C	R
Nitric acid	30-50%	R to C	C	N
Nitric acid	60%	C	N	N
Nitric acid	70%	C to N	N	N
Nitric acid	80%	N	N	N
Nitric acid	90%	N	N	N
Nitric acid	100%	N	N	N
Nitric acid fuming		N	N	N
Nitrobenzene		R to C	C	N
Nitrocellulose		R	—	—
Nitrotoluene		R	C	N
Nitrous acid		R	N	—
Nitrous oxide, gas		R	N	—
Nitroglycerine		R	C	—
Nitroglycol		—	—	—
Nitropropane		—	—	—
Nonyl alcohol		R	—	R
Octyl cresol		C	N	—
Oils and fats		R	R to C	C to N
Oils, vegetable		R to C	C	C
Oleic acid		R to C	C	C
Oleum		N	N	N
Olive oil		R	R	R
Optical brightners		R	—	R
Orange juice		R	—	R
Orthophosporic acid	50%	R	R	R
Orthophosporic acid	85%	R	R	C
Oxalic acid		R	R	R
Oxygen, gas		R	R	R
Ozone, gas		C	C	N
Palmitic acid	10%	R	R	R to C
Palmitic acid	70%	R	R	—
Palmityl alcohol		R	—	R
Paraffin		R to C	C	C
Palm kernel oil		R	—	R
Paraformaldehyde		R	—	R
Pentane		C	C	—
Pentanol		R	—	R

TABLE 5

Chemical Resistance of HDPE Pipe Resins, continued

Chemical Name	Concentration	73°F	120°F	140°F
Peppermint oil		R	—	—
Peracetic acid		R	—	—
Perchloric acid (aqueous)	up to 20%	R	R	R
Perchloric acid (aqueous)	20% to 50%	R	R	C
Perchloric acid (aqueous)	70%	R	R to C	N
Perchloroethylene		C	C	N
Perfume oils		C	—	C to N
Petroleum (sour, refined)		R	C	C
Petroleum ether		R	—	C
Phenol		R	C	RD
Phenolic resin molding materials		R	—	R
Phenylcarbinol		—	—	—
Phenyethylalcohol		R	—	R
Phenylhydrazine		C	C	C to N
Phenylhydrazine hydrochloride		R to C	C	R
Phenylsulphonate		R	—	R
Phenylsulphonate		R	—	R
Phosgene gas		C to N	C	—
Phosgene liquid		N	N	—
Phosphorus oxycloride		R	R	C
Phosphorus pemtoxide		R	R	R
Phosphorus trichloride		R	R	C
Phosphoric acid	50%	R	R	R
Phosphoric acid	80%-100%	R	—	CD
Phosphorus, yrellow		—	—	—
Phosphorus, red		—	—	—
Phosphates (aqueous)	all	R	R	R
Photographic developers		RD	—	RD
Phthalic acid (aqueous)	50%	R	R	R
Phthalic acid ester		R	—	R to C
Picric acid (aqueous)		R	R to C	C
Pineapple juice		R	—	R
Pine-needle oil		R	—	C
Plating solution, metals (many types)		R	C	R
Plasticizers		R	—	C
Polyester plasticizers		R	—	R to C
Polyester resins		C	—	R
Polyglycols		R	—	R
Potash		R	R	R
Potash aluminum (aqueous)		R	—	R
Potassium alkyl xanthates		—	—	—
Potassium bicarbonate (aqueous)	all	R	—	R
Potassium bichromate	40%	R	—	R
Potassium bisulphate (aqueous)	all	R	—	R
Potassium borate (aqueous)	1%	R	R	R
Potassium bromate (aqueous)	up to 10%	R	R	R
Potassium bromide (aqueous)	all	R	R	R
Potassium carbonate (aqueous)	all	R	R	R
Potassium chlorate (aqueous)	all	R	R	R
Potassium chloride (aqueous)	all	R	R	R
Potassium chromate (aqueous)	40%	R	R	R
Potassium cyanide (aqueous)	all	R	R	R
Potassium dichromate (aqueous)	all	R	R	R
Potassium ferricynaide (aqueous)	all	R	R	R
Potassium ferrocyanide (aqueous)	all	R	R	R
Potassium fluoride (aqueous)	all	R	R	R
Potassium hydroxide (aqueous)	all	R	R	R
Potassium hypochlorite		R	R	C
Potassium hydrogen carbonate		R	—	R
Potassium hydrogen sulfate	saturated	R	—	R
Potassium hydrogen sulfide		R	—	R
Potassium iodide		R	—	R
Potassium nitrate		R	R	R
Potassium orthophosphate	saturated	R	—	R
Potassium perchlorate		R	R	R
Potassium perborate		R	R	R
Potassium permanganate	up to 25%	R	R	R
Potassium persulphate (aqueous)	all	R	R	R
Potassium salts		R	R	—
Potassium sulphate		R	R	R
Potassium sulfide		R	R	R
Potassium sulfite		R	—	R
Potassium tetracyanocuprate		R	—	R
Potassium thiosulphate		R	—	R
Propane, gas		R	R	R
Propargyl alcohol (aqueous)	7%	R	—	R
Propionic acid (aqueous)	all	R	—	R to C
Propylene dichloride	100%	C to N	—	N
Propylene glycol		R	R	R
Propylene oxide		R	—	R
Prussic acid		R	R	R
Pseudocumene		C	—	C
Pyridine		R	C	C
Pyrogallic acid		—	—	—
Pulp mill water (red & black liquor)		R	R	—
Quinine		R	—	R
Quinol (hydroquinone)		R	—	R
Rayon coagulating bath		R	—	R
Rubber dispersions (latexes)		R	—	R
Sargrotan®		R	—	C
Salinec acid (aqueous)		R	—	C
Salicylic acid		R	R	R
Saturated steam concentrate		R	—	R
Sauerkraut		R	—	R
Salicylaldehyde		R	R	—
Sea water		R	R	R
Selenic acid		R	R	R
Sewage, residential		R	R	—
Silicic acid (aqueous)	all	R	R	R
Silicone, oil		R	R to C	R to C
Silver, acetate		R	R	R
Silver, cyanide		R	R	R
Silver, nitrate		R	R	R
Silver salts		R	R	R
Soap solutions (can be stress cracking agents)		R	R	R
Sodium acetate (aqueous)	all	R	R	R
Sodium aluminum phosphate		R	—	R
Sodium benzoate		R	R	R
Sodium bicarbonate		R	R	R
Sodium bisulphate		R	R	R
Sodium bisulphite (aqueous)	all	R	R	R
Sodium borate		R	R	R
Sodium bromide		R	R	R
Sodium carbonate (aqueous)	all	R	R	R
Sodium chlorate	saturated	R	R	R
Sodium chloride (aqueous)	salt	R	R	R
Sodium chlorite		R	R	R
Sodium chromate		R	—	R
Sodium cyanide		R	R	R
Sodium dichromate		R	—	R
Sodium dichromate, acid		R	C	—

TABLE 5
Chemical Resistance of HDPE Pipe Resins, continued

Chemical Name	Concentration	73°F	120°F	140°F
Sodium dodecylbenzenesulphonate		R	—	R
Sodium ferricyanide		R	R	R
Sodium ferrocyanide		R	R	R
Sodium fluoride		R	R	R
Sodium hexacyanoferrate		R	—	R
Sodium hydrogen carbonate		R	—	R
Sodium hydrogen phosphate		R	—	R
Sodium hydrogen sulfite		R	—	R
Sodium hydroxide, aqueous & solid	all	R	R	R
Sodium hypochlorite		R	R	R
Sodium nitrate (aqueous)	all	R	R	R
Sodium orthophosphate		R	—	R
Sodium perborate (aqueous)	all	R	—	R
Sodium perchlorate (aqueous)	R	R	—	R
Sodium peroxide	10%	R	—	R
Sodium peroxide (aqueous)	saturated	C	—	—
Sodium phosphate (aqueous)	saturated	R	—	R
Sodium salts (aqueous)		R	R	—
Sodium silicate		R	—	R
Sodium sulphate		R	R	R
Sodium sulfide		R	R	R
Sodium sulfite		R	—	R
Sodium thiosulphate		R	R	R
Soft soap		R	—	R
Soybean oil		R	—	R
Spindle oil		R to C	—	C
Stain removers		R to C	—	C
Stannic chlorides		R	R	R
Stannous chloride		R	R	R
Starch (aqueous)	up to 100%	R	R	R
Stearic acid		R	R	R to C
Styrene		C	—	N
Stoddard solvent		R	C	—
Succinic acid	50%	R	—	R
Sulfur dioxide, dry		R	R	R
Sulfur dioxide, wet		R	R	R to C
Sulfite liquor		R	R	—
Sulfur		R	R	R
Sulfuric acid	up to 50%	R	R	R
Sulfuric acid	50%-70%	R	R	R
Sulfuric acid	70%-90%	R	C to N	C
Sulfuric acid	90%	C to N	N	N
Sulfuric acid fuming		N	N	N
Sulfurous acid		R	R	R
Sulfuric ether		R to C	—	C
Sulfur trioxide		N	N	N
Sulfuryl chloride		N	—	—
Syrups & sugars		R	R	R
Tall oil		R	R	—
Tallow	pure	R	R	R
Tannic acid		R	R	R
Tanning liquors		R	R	—
Tartaric acid (aqueous)		R	R	R
Tetrabromoethane		N	N	N
Tetrachloroethane		C to N	C to N	N
Tetrachloromethylene		—	—	—
Tetraethyl lead		—	—	—
Tetrahydrofuran		C to N	N	N

Chemical Name	Concentration	73°F	120°F	140°F
Tetrahydronaphthalene		R	—	C to N
Thioglycolic acid		R	—	R
Thionyl chloride		N	N	N
Thiophene		C	—	N
Thread cutting oil		—	—	—
Terpineol		—	—	—
Titanium tetrachloride		R	R	—
Toluene		C to N	C to N	N
Toluene - kerosene	25%-75%	C	—	N
Transformer oil		R	R to C	R to C
Tributyl citrate		C	C	—
Tributyl phosphate		R to C	N	R
Trichloroacetic acid	pure	R	R	C to N
Trichloroacetic acid	50%	R	C	R
Trichloroethylene	pure	C to N	C to N	N
Trichlorobenzene		N	—	N
Tricresyl phosphate		R to C	C	R
Triethanolamine		R	C	R to CD
Triethylene glycol		R	—	R
Triethylamine		R	C	—
Triethyl borate		R	—	C to N
Trimethyl propane		C	C	—
Trimethyol propane (aqueous)		R	—	R
Tri-B-chloroethyl phosphate		R	—	R
Trioctyl phosphate		R	—	C
Trisodium phosphate		R	—	R
Turpentine		C	C to N	N
Tutogen● U		R	—	R
Tween● 20 & 80		R	—	N
Two-stroke engine oil		R	—	C
Urea	up to 33%	R	R	R
Uric acid		R	—	R
Urine		R	R	R
Vaseline		R to C	R	C
Vegetable oils		R	R	R
Vinegar		R	R	R
Vinyl acetate		R	—	R
Walnut oil		R	—	C
Water,distilled, fresh, mine, salt, tap		R	R	R
Wax alcohols		C	-	C
Waxes		R	—	R to C
Whey		R	—	R
Whiskey		R	R	R
Wine		R	R	R
Wood stains		R	—	R to C
Xylene		C to N	C to N	N
Yeast		R	R	R
Zinc carbonate		R	R	R
Zinc chloride		R	—	R
Zinc oxide		R	—	R
Zinc salts (aqueous)	all	R	R	R
Zinc sulfate		R	—	R
Zinc sludge		R	—	R
Zinc stearate		R	—	R

Chemical Resistance Factors

NOTE: This experimental method was developed in Europe but is not used in the United States. It is presented here only as a reference for the interested reader.

Since the experimental method uses compression-molded specimens immersed in the chemical media, the results can only be applied under the same conditions. When plastic parts come into contact with chemical agents, it is important to know how those parts will be affected. When a mechanical stress is superimposed on a chemical one, a plastic may exhibit a completely different behavior. The standard chemical resistance immersion tests that are conducted on compression-molded plaques are suitable only if the plastic part in question will not be under stress. Chemicals that do not normally affect the properties of a stress-free plastic part may cause cracking to occur when a stress is applied. Various chemicals can accelerate crack propagation and therefore cause early failures.

Realizing this need of information for pressure pipes, a task committee within the International Standards Organization (ISO/TC 138 WG 3) began to test HDPE and polypropylene pipe. It was decided to use the creep-rupture internal pressure test, which had been exhaustively investigated using water as the internal medium(14,26).

The creep rupture internal pressure test is usually conducted using water in the inside of the pipe. A graph showing typical failure times versus hoop stresses for HDPE and polypropylene, known as a creep-rupture curve, is shown in Figure 26. The creep rupture curves for pipes under stress with water are the basis for the determination of the chemical resistance factors.

A dimensionless ratio that quantifies the influence of a chemical medium to that of water is called the chemical resistance factor, $_{fcr.}$ By using the chemical as the internal medium, a new creep-rupture curve can be drawn and compared to the standard "water" curve. From these data, two chemical resistance factors are obtained. These indicate the service and the stress life of the pipe with the chemical compound as compared to the pipe with water.

Figure 27 illustrates the basis for determining the two resistance factors:

Chemical Resistance Time Factor, fcrt = tm / tw

Chemical Resistance Stress Factor,

$$fcp\sigma = \frac{\sigma m}{\sigma w}$$

WHERE

tm = service life using chemical medium

tw = service life using water

σm = hoop stress using chemical medium

σw = hoop stress using water

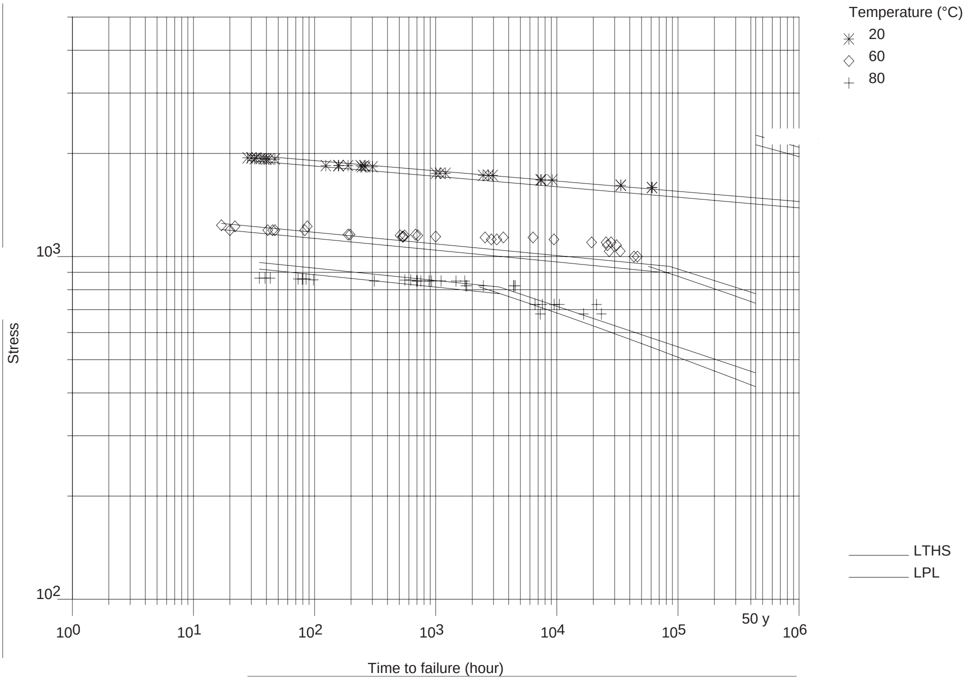
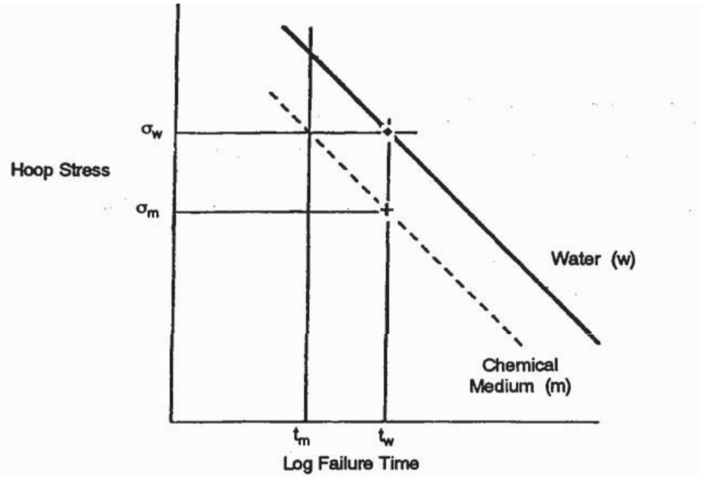


Figure 26 Typical Creep-Rupture Curve for HDPE Pipe



$fcr\sigma = \frac{\sigma_m}{\sigma_w}$ If the same failure time for both medium 1 and water is required, the hoop stress time of medium 1 is equal to the water curve hoop stress multiplied by fcrσ.

$fcrt = \frac{t_m}{t_w}$ If the same hoop stress for both medium 1 and water is required, the failure time of medium 1 is equal to the water curve failure time multiplied by fcrt.

Figure 27 Creep-Rupture Curve

The Time Factor is determined by dividing the failure time of the pipe with the chemical compound by the failure time using water; the same hoop stress must be used. Conversely, the Stress Factor is determined by dividing the hoop stress with the chemical compound by the hoop stress with water at the same failure time.

The chemical resistence stress factor indicates the level of stress to which the pipe containing the chemical compound can be subjected and still achieve the same service life as water. The chemical resistence time factor (fcrt) indicates what the service life of the pipe containing the chemical compound would be as compared to the pipe containing water at the same hoop stress. Table 6 lists some chemical resistance factors.

TABLE 6

Resistance Factors for Pipes Made from HDPE

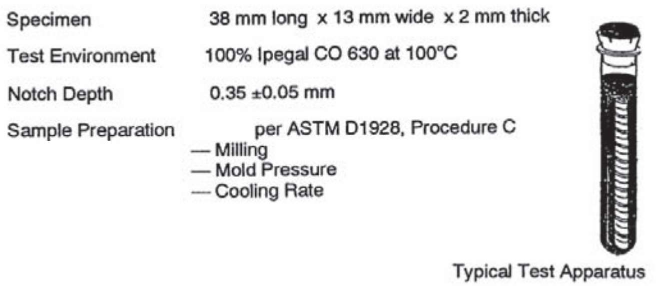
Medium	Concentration %	Temp. °C	Time Factor f_{crt}	Stress Factor f_{cr}
Air	100	80	10	1
Mains Water	100	80	1	1
Wetting Agent Solution, Aqueous	2	80	0.25	0.6
Sulphuric Acid	80	80	5	1
Common Salt Solution	25	80	9	1
Caustic Soda Solution	50	80	15	1
Sodium Hypochlorite	20	80	0.02	0.5
Chromic Acid	10	80	0.5	0.8
Chromic Acid	20	80	0.25	0.6
Nitric Acid	65	80	0.01	0.2
Hydrochloric Acid	33	80	0.35	0.7
Methanol	100	60	1	1
Octanol	100	60	0.3	0.8
Acetic Acid	100	60	0.07	0.3
Acetic Acid	60	60	0.4	0.4
Ethyl Acetoacetate	100	80	0.2	0.7
Fuel Oil	100	60	0.2	0.7
Unfractionated Crude Oil	100	60	0.04	0.4
Unfractionated Crude Oil	—	20	>0.5	>0.6
Petrol	100	60	0.01	0.3
Carbon Tetrachloride	100	60	0.025	0.5

Environmental Stress Crack Resistance (ESCR)

Under certain conditions of temperature and stress in the presence of certain chemicals, polyethylene may begin to crack sooner than at the same temperature and stress in the absence of these chemicals. This phenomenon is called environmental stress cracking (ESC). Stress cracking agents for polyethylenes tend to be polar materials such as alcohols, detergents (wetting agents), halogens and aromatics. The property of a material to resist ESC is called environmental stress crack resistance or simply ESCR. The mechanism has been fully researched over the years. Failures from ESC tend to be due to the development of cracks that slowly grow and propagate over time. Stress cracking can be avoided by using stress crack resistant materials and by limiting stresses and strains during pipe installation.

There are over 40 different ESCR test methods used to determine the chemical resistance of various materials. A standard test currently used in the polyethylene industry is the bent-strip test. It is also called the "Bell Test," since it was developed during the 1950's for wire and cable coatings for the telephone industry.

ASTM D1693[(3)], *Standard Test Method for Environmental Stress-Cracking of Ethylene Plastics,* describes the test method used to determine the ESCR value for polyethylene. Ten small compression-molded specimens are notched and bent and then placed into a holder. The holder is immersed into a tube of a surfactant, typically one such as Igepal C630 (from GAF Corp. NY, NY), at 212°F (100°C) and 100% concentration, and the time to failure is noted. The results are reported using the notation $_{\text{Fxx,}}$ where xx is the percentage of samples that have failed. For example, the statement F_{20} = 500 hours means that 20% of the samples have failed within 0 to 500 hours. Figure 28 illustrates the bent- strip ESCR test.



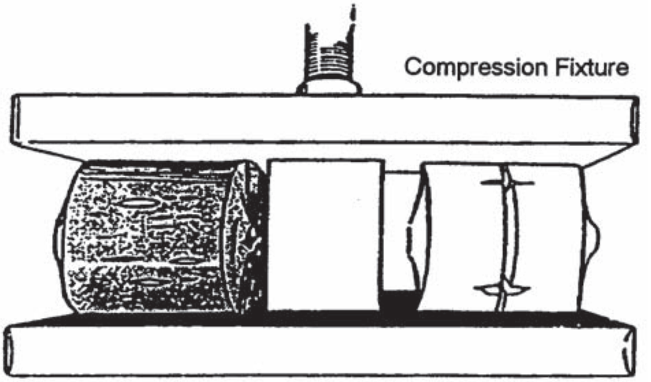
Specimen	38 mm long x 13 mm wide x 2 mm thick
Test Environment	100% Ipegal CO 630 at 100°C
Notch Depth	0.35 ±0.05 mm
Sample Preparation	per ASTM D1928, Procedure C — Milling — Mold Pressure — Cooling Rate

Figure 28 Details of the Bent Strip Test

This test was developed when the time to failure was less than 10 hours and the decay of stress did not affect the results. However, the current polyethylene pipe resins generally do not fail this test. This is due to the excellent stress crack resistance of modern resins, but it is also due to the fact that the stress, which is produced by bending the samples, decays over time. Therefore, the intensity of the test diminishes after a few hundred hours. This test is used mainly as a quality assurance test rather than providing definitive ranking of pipe performance.

Compressed Ring ESCR Test

ASTM test method, F1248[(5)], *Standard Test Method for Determination of Environmental Stress Crack Resistance (ESCR) of Polyethylene Pipe*, determines the polyethylene pipe's resistance to stress cracking in the presence of a stress crack agent at elevated temperatures. A ring specimen of pipe, having a controlled imperfection at one location, is exposed to a stress-cracking agent while compressed between two parallel plates. Figure 29 illustrates the apparatus used to conduct this test. The time to failure is recorded. This test is believed to be more realistic than the bent-strip ESCR test (ASTM D1693) since the test specimens are actual pieces of pipe rather than compression-molded specimens.



Specimen

Pipe Sample (actual production lot) cut to 1/2 in. length

Test Environment

25% Ipegal CO 630 at 50°C

Notch Depth

20% of minimum wall
(e.g., 0.043 in. for 2-in. SDR 11)

Notch Length

3/4 in.

Figure 29 Details of the Rader Compressed Ring ESCR Test

PENT Test

ASTM test method, F1473(5), *Notch Tensile Test to Measure the Resistance to Slow Crack Growth of PE Pipes and Resins (PENT test)*, is used to measure the slow crack growth properties of a polyethylene material under standard conditions. Specimens cut from either compression-molded plaques or pipe are precisely notched and then exposed to a constant tensile stress at elevated temperature in air. The test is generally performed at 80°C with an applied stress of 2.4 MPa, but may also be carried out at alternate temperatures and stresses. The time to failure is recorded. This test method can be used in place of the standard bent-strip test method for classifying a material's slow crack growth resistance in ASTM D3350.

Specimen Cut from plaque or pipe, 50 mm long, 25mm wide and 10 mm thick.
Test Environment 80°C, 2.4 MPa stress in air.
Notch Depth 3.5 mm.
Side Notches 1.0 mm.

Aging

Weatherability

Ultraviolet (UV) radiation and oxygen-induced degradation in plastics can alter its physical and mechanical properties(17). The function of UV stabilizers is to inhibit the physical and chemical processes of UV-induced degradation. The prime UV stabilizer used in the polyethylene pipe industry is finely divided carbon black, which is the most effective additive capable of stopping these UV-induced reactions.

The weatherability of plastic pipe used in outdoor applications is not just a function of the material's color. The colorant is only one part of a two-part package that protects the pipe from degradation due to the effects of UV radiation from the sun.

There are two separate issues when dealing with UV protection. The first is weatherability, which is defined as the capability of the resin to resist changes in the physical properties when exposed in an outdoor environment. The other parameter, which is often used to test the durability of a pigment system, is called color fastness. That test measures the time it takes for an article to fade or to change colors.

Since all plastics are susceptible to attack by UV light, the first step is to protect the plastic resin by using a UV stabilizer, of which there are many different types on the market. The type of UV stabilizer is the predominant factor affecting the service life of a part. The next step is to choose a colorant that will not decrease the effectiveness of the UV stabilizer package. Many colorants act in a synergistic manner with the UV stabilizer. The type of pigment may either increase or decrease the physical properties of the article.

It should be noted that the type of pigment selected also has an effect on the life-span of the product. For example, phthalo-cyanine blue provides better protection, using the same UV stabilizer package in polyethylene, than does ultramarine blue. Therefore, particular attention should be paid to the type of pigment used and not just the general color. Carbon black is considered to be the best color for outdoor articles because of its powerful UV absorptivity. It is also the least expensive pigment for plastics since it is a colorant and, at the same time, one of the best UV stabilizers for outdoor plastic articles. Some general guidelines concerning the weatherability of colorants are shown as follows.

TABLE 7
Relative Weatherability Of UV Stabilized Pigmented Polyethylene

Black	Best Protection
White, Blue	
Red (Inorganic)	
Yellow (Inorganic)	
Green	
Red, Yellow (organic)	
Natural (nonpigmented)	Least Protection

There are also other factors that can affect the life expectancy of a pipe. For further technical information, please refer to PPI Technical Report TR-18(37a), *Weatherability of Thermoplastic Piping.*

Stabilization

Stabilizers are added to the resin to prevent oxidation and the subsequent loss of physical properties. Free radical molecules combine with oxygen and form unstable compounds that continue to react with the polyethylene. This free radical chain process is controlled by using compounds that will react with the free radicals to form stable species incapable of further reaction.

A stabilizer system usually comprises a primary and a secondary antioxidant. It has been found that two different types of antioxidants can work synergistically and provide better protection using lower concentrations and therefore lower costs. The primary antioxidant is used to protect the resin during the extrusion process. Commonly used compounds include BHT, hindered phenols, and secondary amines. Since oxidation attack is a continuous process, secondary antioxidants protect the finished product from long-term oxidation during its service life. Compounds used for this purpose include phosphites and thioethers.

The high temperatures encountered during extrusion facilitate free radical formation. Therefore it is very crucial to protect the polymer during this step. Since there is a finite amount of antioxidant added to the polymer, high processing temperatures combined with a certain time factor could fully deplete the antioxidant ingredient. Once the antioxidant is depleted, the polymer will undergo degradative steps, such as chain scission and/or cross-linking. This degradation process will reduce the physical properties of the polymer so the pipe will not meet industry standards.

There are several tests that can be used to indicate the severity of processing that a polymer has undergone. Two common methods include Differential Scanning Colorimetry (DSC) and carbonyl index tests. DSC induction time or temperature measurements indicate the degree of stabilizer usage. The carbonyl index indicates the degree of oxidative degradation by measuring the type and amount of carbonyl (C=0) functionalities created during UV exposure.

Toxicological Properties

Health Effects

The Food and Drug Administration (FDA) issues requirements for materials that may contact food, either directly or indirectly, under the Code of Federal Regulations (CFR) Title 21, parts 170 to 199. Most natural polyethylene resins do comply with these regulations. Some grades of furnace carbon blacks are certified for compliance to these FDA requirements. If there are any questions concerning FDA compliance for carbon black pigment, contact the resin supplier.

Potable water piping materials, fittings, and pipe are currently tested according to the standards developed by the National Sanitation Foundation (NSF). The most recent standard to be written by the NSF is Standard 61 (30), *Drinking Water System*

Components - Health Effects. It sets forth toxicological standards for all potable water system components including plastics.

Many municipalities and other organizations have adopted the potable water standards that are administered by NSF. Those standards verify that physical, chemical, toxicological, taste and odor requirements have been met by any materials that bear the NSF mark. NSF enforces the standards by conducting unannounced visits to all companies that are listed with them. Non-compliance items are ordered withdrawn from the market place.

Biological Resistance

Biological attack can be described as degradation caused by the action of micro-organisms such as bacteria and fungi. Virtually all plastics are resistant to this type of attack. Once installed, polyethylene pipe will not be affected by micro-organisms, such as those found in normal sewer and water systems. Polyethylene is not a nutrient medium for bacteria, fungi, spores, etc.

Research has shown that rodents and gnawing insects are compelled to maintain their teeth in good condition by gnawing on objects. The surface of the pipe serves as a deterrent to gnawing rodents since their teeth slide off the round surface of the pipe. Rodents will gnaw at plastic simply because it is a soft material. Other materials such as wood, copper, lead, and all other plastics would fall prey to this phenomena if installed in rodent-infested areas.

Termites pose no threat to polyethylene pipe. Several studies have been made where polyethylene pipe was exposed to termites. Some slight damage was observed, but this was due to the fact that the plastic was in the way of the termites' traveling pathway. PPI Technical Report, TR-11(37), *Resistance of Thermoplastic Piping Materials to Micro- and Macro-Biological Attack*, has further information on this matter.

Conclusion

The information contained in this chapter should help the reader to understand the fundamental properties of polyethylene. A basic understanding of these properties will aid the engineer or designer in the use of polyethylene pipe and serve to maximize the utility of the service into which it is ultimately installed.

While every effort has been made to present the fundamental properties as thoroughly as possible, it is obvious that this discussion is not all-inclusive. For further information concerning the engineering properties of polyethylene pipe, the reader is referred to a variety of sources including the pipe manufacturers' literature, additional publications of the Plastics Pipe Institute and the References at the end of this chapter.

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