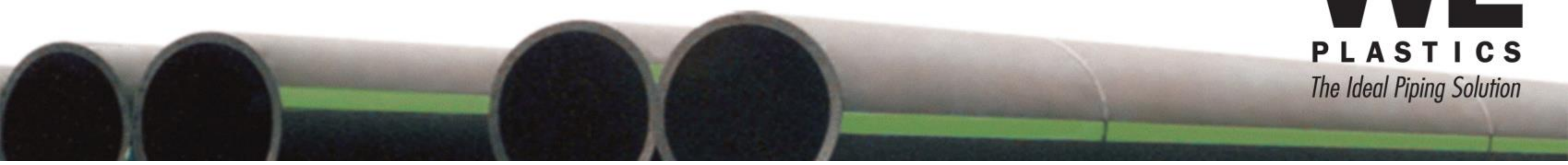
WL122 – WL Plastics PE4710 Performance



PE4710 – Third Generation High-Performance HDPE

HDPE Development

PE pressure piping entered the marketplace in the late 1960’s. High density PE3408 materials became available around 1980, and PE4710 around 2004. We can generally characterize pre-PE3408 PE piping as first generation, PE3408 (and later PE3608) as second generation and PE4710 as third generation materials. Each material generation is characterized by step-change improvements in polymer structure and piping performance. Each PE material generation also demonstrated continuing improvement; that is, continuing development yielded superior performing PE materials as the generation progressed. For example, PE3608 compounds are better performing materials compared to earlier PE3408 materials of the same generation.

As each PE material generation progressed, performance surveys and studies have revealed pressure piping performance. Early 1990’s surveys[1] show ductile iron water pipe failure rates at about 15.9 breaks per 100 miles, and PVC water pipe failures at about 1.2 breaks per 100 miles. A separate early 1990’s study[2] showed first generation PE pressure pipe at 1.3 leaks per 100 miles and PE3408 at about 0.1 leaks per 100 miles. Failures associated with iron pipes are predominantly related to circumferential cracking (cast iron) and corrosion (ductile iron). PVC piping failures are related to catastrophic axial splits, joint failure and tapping in roughly equal measure. PE piping leakage is generally associated with very small leaks from stress cracking. The failure rate of first generation PE is roughly comparable to current PVC water piping performance, but with minor leaks compared to catastrophic pipe bursting.

Stress cracking or slow crack growth (SCG) in PE pipe is a type of cracking that is driven very slowly through the pipe wall from stress such as internal pressure. Stress cracking does not cause the material to become brittle, and does not result from the material becoming brittle. In fact, tests show that aged PE pipe is just as ductile after decades of service as when it was produced. Stress cracking is driven by long-term applied stress. Over the years, improvements in PE materials are measured by reduced susceptibility to stress cracking.

SCG tests show that first generation PE materials typically demonstrated less than 1 to around 15 hours SCG resistance. Second generation PE3408/PE3608 materials show about 20 to more than 100 hours, and third generation PE4710 demonstrate from 500 to more than 10,000 hours. For practical purposes, PE4710 materials are not susceptible to stress cracking for at least 250 years in typical pressure applications.

PE4710 performance is explained below.

ASTM D2837 and PPI[3] TR-3[4] Requirements

Thermoplastic pressure piping materials are rated for internal pressure service in accordance with ASTM D2837 and PPI TR-3. ASTM D2837 is a procedure for conducting a series of sustained internal pressure tests for up to 10,000 hours, and then analyzing the data and determining a long-term hydrostatic strength (LTHS) that when categorized becomes the hydrostatic design basis (HDB) rating for the thermoplastic material. HDB is determined at a specific temperature such as 73°F or 140°F or 180°F, etc. ASTM D2837 includes the procedure for determining hydrostatic design stress (HDS), which is the HDB multiplied by a service (design) factor (DF) for an application such as water. For general applications, the PPI Hydrostatic Stress Board establishes DF and HDS values for thermoplastic materials in accordance with ASTM D2837 requirements. DF values are also established by regulatory authorities.

> *“5.5 Hydrostatic Design Stress—Obtain the hydrostatic design stress by multiplying the hydrostatic design basis by a service (design) factor selected for the application on the basis of two general groups of conditions. The first group considers the manufacturing and testing variables, specifically normal variations in the material, manufacture, dimensions, good handling techniques, and in the evaluation procedures in this test method and*

[1] Water Mains Break Data on Different Pipe Materials for 1992 and 1993, A-7019.1 Final, National Research Council Canada
[2] Controlling the Quality of PE Gas Piping by Controlling the Quality of the Resin, Brown and Lu, 1993
[3] Plastics Pipe Institute, 105 Decker Court, Suite 825, Irving TX, 75062
[4] TR-3 Policies and Procedures for Developing Hydrostatic Design Basis (HDB), Pressure Design Basis (PDB), Strength Design Basis (SDB), and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials or Pipe

in Test Method D1598 (Note 8). The second group considers the application or use, specifically installation, environment, temperature, hazard involved, life expectancy desired, and the degree of reliability selected (Note 9). Select the service factor so that the hydrostatic design stress obtained provides a service life for an indefinite period beyond the actual test period."

From the ASTM D2837 excerpt above, a design factor is the combination of two distinctly different groups of variables. The first group is directly related to the thermoplastic material, pipe, and testing. It addresses variability in manufacturing, material, and testing that affect the quality of the data used to determine the HDB rating of the thermoplastic material. The second group is based on the product application or use; that is, installation quality, operating pressure and temperature stability, and internal and external environment effects.

Regarding the first group of DF variables, ASTM D2837 LTHS data is developed using sustained internal pressure testing of pipe samples. Manufacturing tolerances will result in lot to lot variations in PE resins. Differences in pipe extrusion equipment and processing procedures introduce variability. Different laboratories conducting tests introduce variability through different laboratory equipment. That is, the resin, the pipe and testing are subject to variability. Higher quality, reduced variability data strengthens the material's HDB rating.

The second group addresses uncertainty in installation and operation for an application. Despite the best efforts of installers, installation quality will vary. Likewise operating conditions are seldom as benign as a test sample resting quietly in a laboratory test tank. The internal and external environment can include variability in temperature, internal pressure and dynamic loads and stresses such as varying water table or traffic loads.

PPI's Hydrostatic Stress Board first developed the ASTM and PPI procedures for thermoplastic pressure pipe material stress ratings in the 1960's. The HSB is an internationally recognized authority for thermoplastic material stress ratings and application design factors. The HSB developed the first design factor for thermoplastic water piping, which is the 0.50 DF that is has been used for over five decades for North American water pipe made from conventional materials such as PVC, CPVC, HDPE, ABS, etc. When higher performing PE materials were developed, the HSB developed additional material performance requirements to qualify for a higher DF. Only materials that meet additional performance requirements qualify for a 0.63 DF. Unqualified lower performing materials such as conventional PVC, CPVC, HDPE, ABS, etc., are restricted to 0.50.

PPI TR-3 is the PPI HSB policy for evaluating and listing long-term internal pressure strengths (HDB and HDS) for thermoplastic (and other) pressure piping materials. PPI listing is a third party evaluation of a product, and listing of that product based on compliance with TR-3 requirements.

PPI listing is based on ASTM D2837, but extends D2837 by requiring separate data sets from three commercial resin lots, and pipe from one of the lots must be manufactured by a commercial processor. These requirements for listing in PPI TR-4 apply to all listed thermoplastic materials and piping constructions.

In PPI TR-4, PPI lists materials that meet standard requirements and PE materials that meet requirements for higher performance, e.g., higher allowable design stress. PPI TR-3 Section F.7 sets additional requirements for higher performing PE compounds: (a) reduced pipe test data variability, (b) increased SCG resistance, and (c) substantiation at 50 years. Conventional thermoplastics and PE3408/PE3608 materials meet standard requirements, but do not meet the additional performance requirements; PE4710 materials meet both standard requirements and the additional high performance requirements.

Long-term Performance of PE3408/PE3608 Pressure Piping

Unlike metals, when subjected to constant stress, the strength of thermoplastic materials typically decreases as time under stress increases. This knowledge led to the development of ASTM D2837 in mid-1960. ASTM D2837 determines a long-term strength rating for a thermoplastic by evaluating long-term ductile strength data that is generated by testing pipe samples at different internal pressures. To determine long-term strength rating, a mathematical regression analysis is applied to the long-term test data. For a data set that covers a specified range of applied stresses, the regression analysis of ductile failure testing times up to 10,000 hours results in a predicted ductile strength rating at 100,000 hours. When categorized, this long-term predicted ductile strength rating is the material's hydrostatic design basis, or HDB.

PE pressure piping compounds (and many other conventional thermoplastics) were first introduced in the 1950's. Early pipe pressure ratings were calculated by applying a reduction (a safety factor) to the ductile tensile yield strength of the material. After a few years, however, some PE pipes began failing prematurely by a previously unknown failure mechanism. The assumption that ductile tensile yield strength could be used for PE pipe pressure rating was wrong. Research, testing and evaluation determined that the newly discovered failure mechanism was stress cracking or slow crack growth (SCG). Unlike ductile tensile failure where the material elongates and then fails in the elongated region, SCG is a different failure mechanism where stress drives cracks slowly through the pipe wall and there is virtually no ductile elongation. SCG is not material embrittlement. It is a cracking mechanism that arises from sustained tensile stress that is less than ductile tensile stress.

After the discovery of SCG susceptibility in PE, ASTM D2837 and PPI TR-3 were revised to include a validation procedure to assure that the onset of SCG is after the 100,000 hour strength rating, the HDB. The analysis for determining HDB is based on data from one failure type, ductile tensile failure. But SCG is not ductile; therefore, SCG data must be excluded from the HDB data. Research showed that the slope of the SCG data curve is steeper than the ductile data curve; that SCG could be accelerated by testing at elevated temperature, and that pipe internal pressure testing at several elevated temperatures could be used to predict the onset of SCG. The validation procedure that was added to ASTM D2837 requires elevated temperature sustained pressure testing and analysis to prove that SCG does not occur before the 100,000 hour intercept with the ductile tensile long-term HDB curve.

When ASTM D2837 data is plotted graphically, the regression analysis yields a straight line when plotted on log-stress vs. log-time coordinates. This graphical presentation is typically called a stress-rupture curve. We can show the onset of SCG on the stress-rupture curve because the SCG curve has a steeper slope compared to the ductile failure curve. Figure 1 shows the ductile curve for PE3408/PE3608 HDB (black line), and the *minimum* validation requirement for PE compounds (red line). A PE material does not validate if the SCG curve intersects the ductile curve before 100,000 hours. A PE material that does not validate does not qualify for HDB rating or PPI Listing, and is unsuitable for pressure piping.

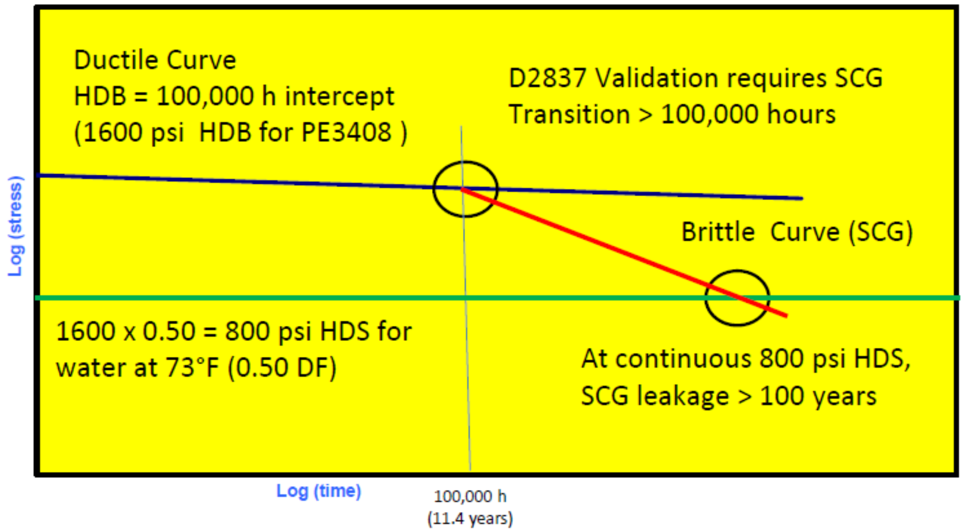
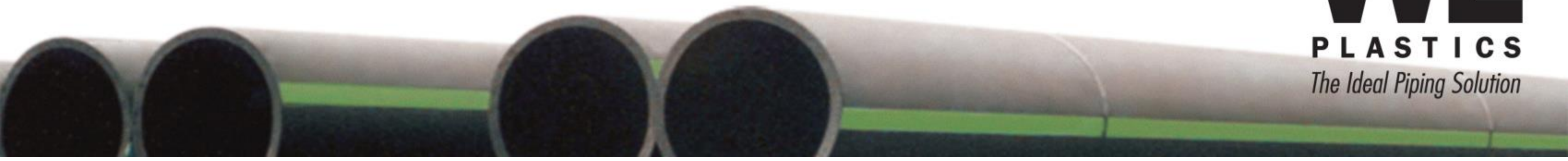


Figure 1 Stress Rupture Curve for PE3408/PE3608 for Water at 73°F

For validated, HDB rated PE materials, PPI TR-4 lists HDS ratings for water at 73°F by multiplying the HDB by the PPI DF for the application. For PE3408/PE3608 materials that meet standard ASTM D2837 and PPI TR-3 requirements, the PPI DF for water at 73°F is 0.50, which yields a HDS for water at 73°F of 800 psi.



For validated PE3408/PE3608 materials, the earliest time for SCG pipe wall leakage is when the HDS curve intersects the SCG curve. If the HDS for water service at 73°F is plotted on the stress rupture curve, we can estimate the potential service time before SCG leaks in PE pressure pipe. This is the intersection of the green line and the red line in Figure 1. For PE3408/PE3608 materials, this intersection is after 100 in-service years.

The PE3408/PE3608 depicted in Figure 1 is a minimum PE3408/PE3608 that just complies with HDB and validation requirements (black and red curves). The HDS operating conditions (green curve) are for a 73°F water system that operates continuously at maximum rated internal pressure. For PE3408/PE3608, the HDS at 100,000 hours (11.4 years) is HDB x 0.50. All PE3408/PE3608 materials exceed HDB and validation requirements so the red line is actually well to the right of the Figure 1 red line, and water systems seldom operate continuously at maximum pressure rating so for actual water systems, the green line is lower than the Figure 1 green line. Figure 1 illustrates a minimum PE3408/PE3608 operating at maximum allowable conditions.

The relationship between PE material stress rating, pressure rating, and pipe is described by the following equation. (Reference – ASTM D2837 Sections 3.1.8 and 3.1.8.1)

$$PR = \frac{2 \times HDS}{(DR - 1)} = \frac{2 \times HDB \times DF}{(DR - 1)} \qquad \text{Equation (1)}$$

Where
- PR = pressure rating (or Pressure Class, PC) for water at 73°F, psi
- HDS = PE material hydrostatic design stress for water at 73°F, psi
- DR = dimension ratio $= \frac{D_o}{t}$
- D_o = pipe outside diameter, in
- t = pipe minimum wall thickness, in
- HDB = PE material hydrostatic design basis, psi
- DF = service (design) factor for application such as water at 73°F

Although similar in appearance to Barlow's Formula[5] that is used to determine pipe bursting pressure, Equation (1) is not the same for two significant reasons.

- The allowable stress in Equation (1) is the material's long-term design stress rating, HDB. Barlow's Formula uses short-term tensile strength.
- In Equation (1), long term strength is reduced by a service (design) factor. In Barlow's Formula, tensile strength is reduced by a safety factor. A service (design) factor accounts for variability in material, pipe, testing, application and installation, and specifically addresses uncertainty in long term service. A safety factor is simply reduces a short-term property. For thermoplastics, short-term properties such as tensile strength do not address long term performance.

A half century ago, PE pipes that were pressure-rated using Barlow's Formula failed prematurely in service. From this field experience, Barlow's Formula has been shown to be an inadequate means for determining pressure rating for PE pressure pipes. Using Barlow's Formula for thermoplastic pipe pressure rating, which is a long term property, is a misapplication of Barlow's Formula.

In ASTM and AWWA PE piping standards (current and proposed), Barlow's Formula is incorporated in short-term requirements where the minimum bursting stress or hoop tensile for PE pipe must exceed 2900 psi for high density PE materials. Quick burst testing is conducted per ASTM D1599[6]. Hoop tensile testing for larger pipes is conducted per ASTM D2290[7].

[5] Appendix A is an excerpt from The Engineering Toolbox (www.engineeringtoolbox.com) that describes Barlow's Formula and its use for estimating the bursting pressure of (metallic) pipes and tubes at ideal room temperature conditions.
[6] D1599 Standard Test Method for Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings
[7] D2290 Standard Test Method for Apparent Hoop Tensile Strength of Plastic or Reinforced Plastic Pipe by Split Disk Method

Long-Term Performance of PE4710 Pressure Piping

PE4710 is not the same as PE3408/PE3608 for a number of reasons.

- PE4710 complies with PPI TR-3 Section F.7 requirements for higher performing PE materials; PE3408/PE3608 does not.
- PPI TR-3 Section F.7 requires substantiation at 50 years vs. validation at 100,000 h. PE4710 complies; PE3408/PE3608 does not. Substantiation requires that SCG cannot occur before 438,300 hours (50 years). ASTM D2837 validation is at 100,000 hours (11.4 years).
- A higher performing PE polymer structure is required to meet PPI TR-3 Section F.7 requirements. PE4710 has a higher performing polymer structure; PE3408/PE3608 does not. PE4710 materials must be more consistent because F.7 has tighter data quality requirements.
- PE4710 has higher density and meets higher SCG requirements compared to PE3408/PE3608.
  - 0.946 to 0.955 g/cm^3 for PE4710 vs. 0.941 to 0.945 g/cm^3 for PE3408/PE3608. Higher density improves mechanical strength.
  - Compliance with PPI TR-3 Section F.7 requires improved resistance against long-term SCG leakage – >500 h SCG resistance for PE4710 vs. >10 h SCG resistance for PE3408 and >100 h for PE3608.

Figure 2 illustrates PE4710 minimum performance requirements for internal water pressure service. The black line is the HDB ductile rupture curve for water at 73°F. Circled on the black line is the 100,000 intercept for a HDB rating of 1600 psi at 73°F. However, additional requirements for PE4710 require substantiation at 50 years; that is, that the onset of SCG must be after the 50 year intercept with the HDB curve, which shifts the red SCG curve for PE4710 to the right at least 38.6 years.

As in Figure 1, the green line is the HDS curve which is the maximum allowable continuous internal pressure stress for water at 73°F. Because PE4710 complies with PPI TR-3 Section F.7 requirements, the PPI recommended HDS for PE4710 is 1000 psi, 200 psi higher than is allowable for PE3408. Nevertheless, the PE4710 HDS (green line) intercept with the PE4710 SCG curve (red line), the point in time where SCG leakage may begin, is at least 150 years after the SCG intercept for PE3408/PE3608.

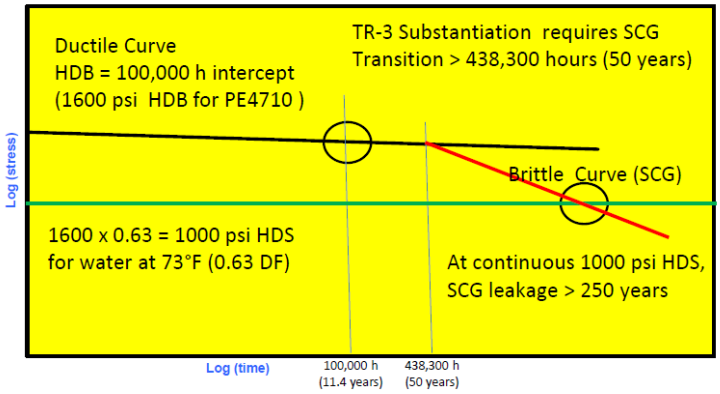


Figure 2 Stress Rupture Curve for PE4710 for Water at 73°F

The PE4710 depicted in Figure 2 is a PE4710 that just meets HDB and substantiation requirements (black and red curves), and the operating conditions (green curve) are for a 73°F water system that operates continuously at HDS internal pressure. Compared to PE3408/PE3608, PE4710 has higher HDS (HDB x 0.63); however, 50-year substantiation pushes the HDS-SCG intercept beyond 250 years. All PE4710 materials exceed HDB, validation and substantiation requirements so the red SCG line is actually well to the right of the Figure 2 red line. Water systems seldom operate continuously at maximum pressure rating so the green line for typical water system applications is actually lower than the Figure 2 green line.

Conclusions

1. PE4710 and PE3408/PE3608 have fundamentally different polymer structures. They are different in density, in SCG resistance, and in the requirements that must be met to qualify for classification as PE4710 or PE3408/PE3608. PE3408/PE3608 does not meet PE4710 requirements.
2. PE pipes are pressure-rated in accordance with ASTM D2837, not Barlow's Formula. Before ASTM D2837 existed, PE pipes that were pressure-rated in accordance with Barlow's Formula failed prematurely in the field. The fundamental differences are that Barlow's Formula does not address the long-term strength of PE materials, where ASTM D2837 does, and a safety factor does not address variability in materials, testing, application and installation that are addressed within a design factor.
3. In accordance with ASTM D2837, PE pipes are pressure-rated using a service (design) factor that is based on two groups of variables. The first group addresses variations in materials, manufacture and testing. The second group addresses application variables. Unlike the safety factor in Barlow's Formula that is a simple tensile strength reduction, the ASTM D2837 DF addresses long-term performance and field applications.
4. PE4710 materials must comply with additional performance requirements in accordance with PPI TR-3 Section F.7. To comply with Section F.7, PE4710 materials have a different polymer structure that provides higher density, reduced material variability, and significantly higher SCG resistance.
5. At 25% higher allowable internal pressure stress, the potential for the onset of SCG pipe wall leakage in PE4710 is at least 150 years beyond that of PE3408/PE3608.

Appendix A – Barlow's Formula

The Engineering ToolBox

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Resources, Tools and Basic Information for Engineering and Design of Technical Applications!

Bursting Pressure

Barlows Formula and bursting pressure of pipes and tubes

Barlow's formula can be used to estimate burst pressure of pipes or tubes.

$P = 2\, s\, t / (d_o\, SF)$ (1)

where

P = max. working pressure (psig)

s = material strength (psi)

t = wall thickness (in)

d_o = outside diameter (in)

SF = safety factor (in general 1.5 to 10)

The Barlow's estimate is based on ideal conditions at room temperature.

Material Strength

The strength of a material is determined by the tension test, which measure the tension force and the deformation of the test specimen.

- the stress which gives a permanent deformation of 0.2% is called the **yield strength**
- the stress which gives rupture is called the **ultimate strength**

Strength of some common materials:

Material	Yield Strength *(psi)*	Ultimate Strength *(psi)*
Stainless Steel, 304	30,000	75,000
6 Moly, S31254	45,000	98,000
Duplex, S31803	65,000	90,000
Nickel, N02200	15,000	55,000