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A SUSTAINABLE 100-YEAR DESIGN LIFE WITH HDPE PRESSURE PIPE

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SUMMARY

Piping systems must be designed for all types of failure mechanism, not just pressure. Most materials used to make pipes have more than one mechanism, but usually one that is dominate and will ultimately determine “end-of-life” for that system. Today’s PE4710 compounds are uniquely designed to withstand all major failure mechanisms for 100+ year design life, when proper installation and operating conditions are followed. This paper will review these major failure mechanisms and how today’s HDPE pipe provides for a 100+ year design life.

KEYWORDS

Polyethylene, Design Life, Sustainable

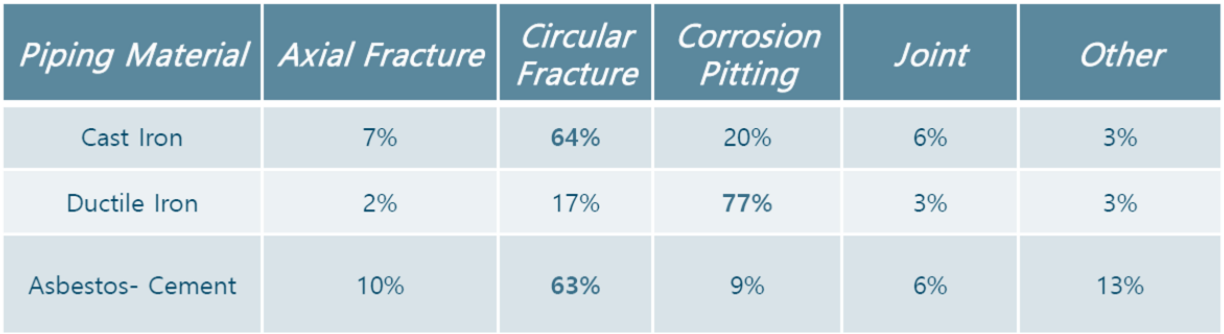
ABSTRACT

Pipes and piping systems are long-term engineered systems designed to avoid failure by various mechanisms. High-density polyethylene (HDPE) pipe has been used for over 60 years and advancements in material performance now enable designing for all known failure mechanisms to ensure a design life of 100 years or more. Achieving a sustainable 100-year design life for HDPE pipe involves addressing potential failure modes such as pressure, slow crack growth (SCG), corrosion/oxidation, and cyclic fatigue. Improved materials and design criteria, particularly with the advent of PE4710 compounds, have effectively mitigated these risks, ensuring performance beyond 100 years. Furthermore, HDPE pipe offers significant environmental benefits throughout its lifecycle, including responsible material sourcing, low energy manufacturing, recyclability, reduced transportation emissions, and the enablement of low-impact installation methods like horizontal directional drilling (HDD). The resilience of HDPE piping systems to natural disasters also contributes to sustainable infrastructure. This paper discusses the identified failure mechanisms for HDPE pipe and how modern materials and design practices provide a sustainable solution capable of achieving a 100+ year design life.

INTRODUCTION

Long-term engineered systems like piping must focus on the specific material properties and limit the potential for failure via known mechanisms. Utilizing the unique properties of a material system ensures that failure occurs beyond the intended design life, which is defined as the timeframe accounted for in the design to assure failure does not occur before that time. Of course, this is predicated on the design accounting for all potential failure mechanisms as well as the system being installed and operated within the appropriate design parameters (see Figure 1).

Service life is the timeframe these systems *can* perform their intended function, which is not truly known until observed over time. This can be longer or shorter than the design life depending on how the system is operated within it's environment. The goal is to achieve a sustainable design life of 100 years or more with HDPE pipe. This provides a sustainable solution and protects society and natural resources.



Piping Material	Axial Fracture	Circular Fracture	Corrosion Pitting	Joint	Other
Cast Iron	7%	**64%**	20%	6%	3%
Ductile Iron	2%	17%	**77%**	3%	3%
Asbestos- Cement	10%	**63%**	9%	6%	13%

Figure 1 – Typical Failure Mechanism for Various Piping Material

Identified Failure Mechanisms for HDPE Pipe

Pipes and piping systems can fail through a multitude of failure mechanisms. For HDPE, the identified potential failure mechanisms are:

- Pressure – internal and external
- Slow crack growth (SCG) – long-term stress intensifications
- Corrosion/Oxidation – such as oxidizing disinfectants
- Cyclic Fatigue – pressure surges / water hammer

The improved material performance of HDPE PE4710 now allows designing for all these mechanisms to ensure a 100+ year design life against all potential mechanisms,

Pressure

Unlike metals, the long-term hydrostatic strength of HDPE cannot be determined solely from short-term tensile tests due to its viscoelastic response to stress, which is dependent on the level and duration of stress. Standard test methods such as ASTM D2837 and ISO 9080 were developed to better forecast the long-term strength of thermoplastic materials that exhibit visco-elastic behavior. Similar to the way high temperature steel is evaluated.

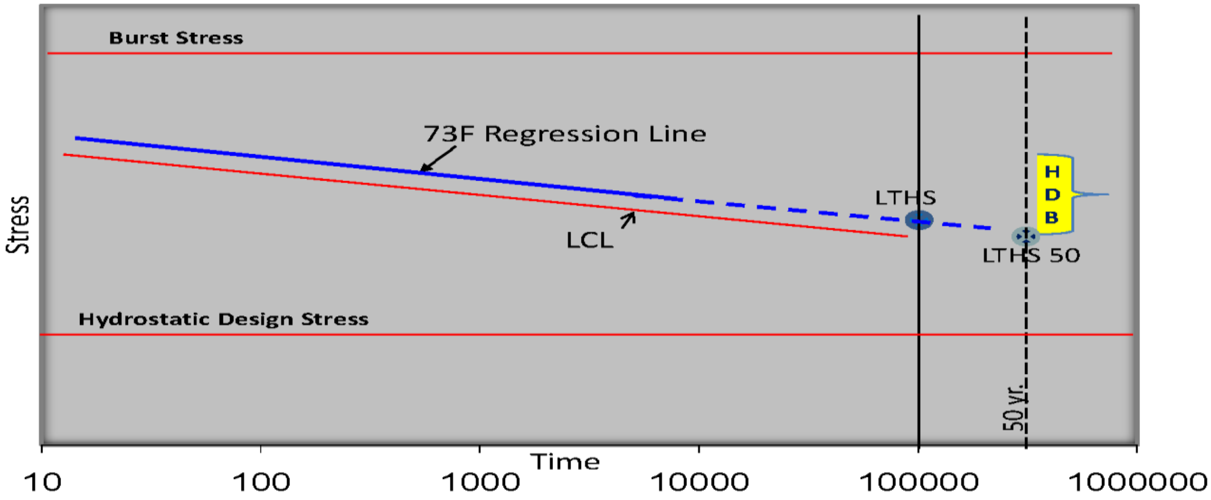


Fig. 2 – Graphical Representation of ASTM D2837 Stress Regression Evaluation

Older generation PE materials exhibited stress regression curves that showed a transition to from a ductile failure mechanism to a "brittle" type failure. According to ASTM D2837 only the ductile failure slope can be used to forecast the long-term strength of the material. However, it is also important to make sure the extrapolation of the ductile regression curve remains linear beyond the actual test time of 10,000 hours. This led to using elevated temperature testing to accelerate any potential ductile/brittle transition (see Fig 3) and Rate Process based evaluation methods.

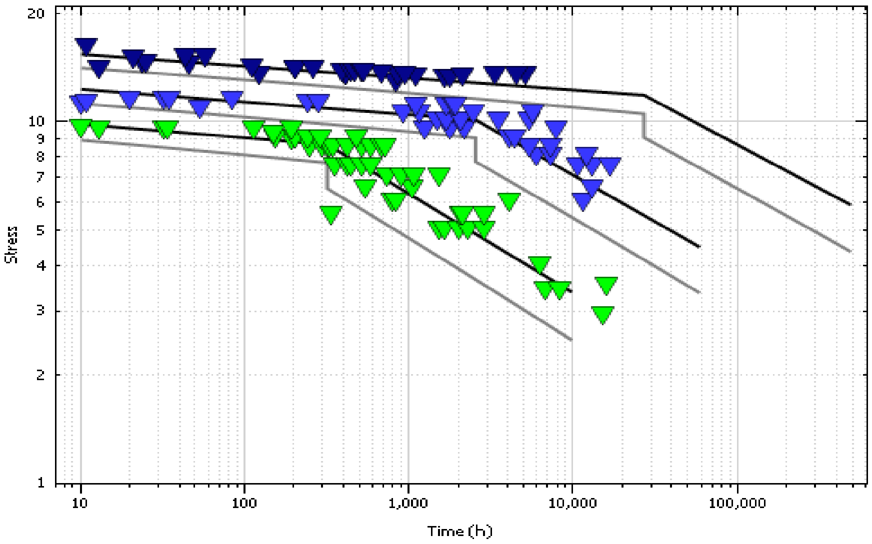


Fig. 3 – Example of multiple temperature regression lines with ductile/brittle transition

HDPE has evolved significantly over the decades. PE4710 is referred to as the "4th generation" of HDPE for pipe under the ASTM system of standards.

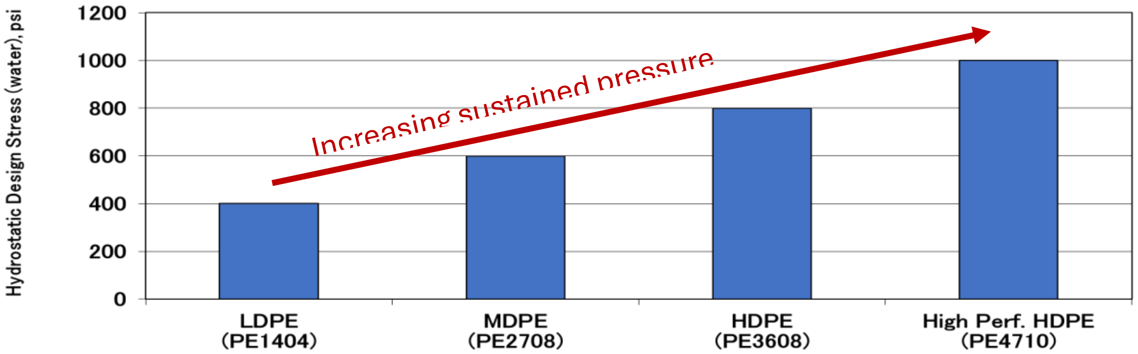


Fig. 4 – Progression of Pipe HDPE Resin Types in North America

These 4th generation HDPE compounds – PE4710 - had vastly superior slow crack growth resistance where the ductile/brittle transition was pushed far into the future. Figure 5 shows how there is no D/B transition exhibited even at elevated temperature conditions.

Establishing a maximum design stress for PE4710 compounds is based on stringent criteria introduced in 2004 that recognized the increased level of performance. Key properties were identified that allowed for a higher design stress. The criteria include:

1. **50 year substantiation**.
    - This provides further assurance the stress regression curve used to establish the long-term hydrostatic strength remain linear beyond 50 years.
2. **90% LCL/LTHS ratio**.
    - To establish a long-term strength and categorized hydrostatic design basis the stress regression data must have at least a 85% LCL/LTHS ratio This assures the extrapolation is appropriate. Tightening this requirement to 90% provides even further assurance the data is “well behaved” and results in a higher level of confidence.
3. **500 hours SCG Performance using PENT ASTM D1473**.
    - Correlations available in the early 2000s indicated that 500 hours of PENT performance would essentially assure slow crack growth would not occur before 100 years due to stress from internal pressure.

These criteria contribute to an indefinite design, effectively 100+ years, against the effects of internal stresses – i.e. pressure.

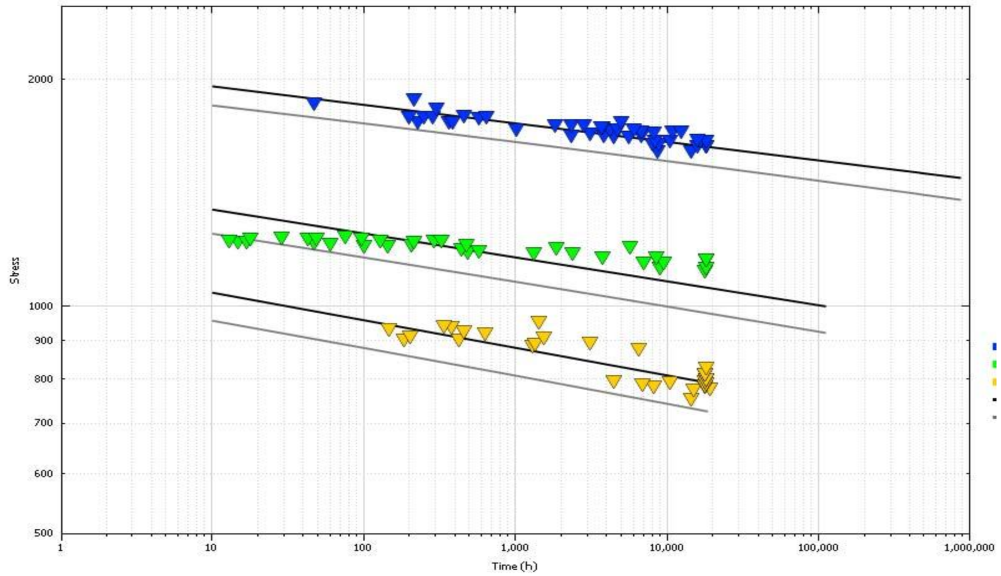


Fig. 5 – Stress regression for 4th generation PE4710 Compounds

Slow Crack Growth (SCG)

Slow crack growth has long been a known potential failure mechanism for polyethylene. Early tests like the ASTM D1693 Bent Strip ESCR had a minimum requirement of 192 hours using high temperature (80C) and an aggressive surfactant (Igepal). Eventually, pipe grade HDPE achieved performance greater than 10,000 hours, necessitating new test methods. PPI TR-3 validation requirements specify no ductile/brittle (D/B) transition for 100,000 hours, and substantiation requirements for PE4710 compounds stipulate no D/B transition before 50 years (438,000 hours).

A new SCG test was developed by Dr. Brown at the University of Pennsylvania - The PENT (Pennsylvania Notched Tensile) test, a notched tensile test at elevated temperatures. This test revealed that earlier PE grades ranged from 1 to thousands of hours on this new test, with most HDPE compounds - 2nd generation PE3408 - achieving 30-100 hours. The medium density (MDPE) monomodal compounds, still in use today, had several 1000s of hours PENT test performance. Introduction of bimodal technology led to the development of the PE4710 material category. PE4710 established a minimum of 500 hours PENT. Based on comparison testing using elevated temperature hydrostatic testing indicated the ductile/brittle transition occurs beyond 100 years. Continued material development has led to materials achieving 10,000+ hours of PENT requiring the development of even more aggressive test methods such as CRB, FNCT, and Strain Hardening to properly evaluate this advanced performance.

As a result of these material improvements and testing methods, SCG is no longer a failure mechanism for 100+ years under most design operating conditions.

Oxidation / Corrosion

Polyethylene does not corrode like metallic materials. However, any carbon-based polymer can oxidize. A combination of antioxidants and thermal stabilizers are added to HDPE compounds to provide both short-term and long-term protection against oxidation.

OIT (Oxidation Induction Time) and IT (Induction Temperature) testing have been standard requirements in material and product standards for decades to demonstrate enhanced resistance to oxidation in PE pipe compounds through the use of thermal stabilizers and antioxidants. Degradation from oxidation effects can lead to a decrease in properties, such as chain scission, and a decrease in ductility, potentially causing microcracking.

In most applications the OIT requirements were sufficient to demonstrate resistance to oxidation over the life of the pipe. However, in potable water systems disinfectants, such as chlorine are used. These disinfectants are strong oxidizers and can under a certain combination of factors can attack some materials leading to premature degradation. A multi-year study was conducted to develop models and test criteria for the long-term performance of PE4710 compounds against the oxidizing effects of chlorine disinfectants. This study utilizes actual water conditions, including chlorine (Cl) concentration, water pH, average water temperature, and operating pressure to assess the aggressiveness of the water and operating conditions within the system. The study resulting in the development of a model to forecast the oxidation resistance lifetime of PE compounds using the actual operating conditions they will see using free chlorine and chloramines but excluding ClO_2. PPI TN-44 specifically addresses the “Long-Term Resistance of AWWA C906 Polyethylene (HDPE) Pipe to Potable Water Disinfectants”. ASTM D3350 provides testing criteria for Chlorine Resistance Categorization: CC1, CC2, and CC3.

Table 1: Resistance to Residual Disinfectants using PE4710 CC3 for AWWA C906-21 Pipe

US and Canadian Utilities	**Ontario**	**Indiana Utility-1**	**Indiana Utility-2**	**North Carolina**	**California Utility-1**	**California Utility-2**
Disinfectant type*	Chlorine	Chloramine	Chlorine	Chlorine	Chloramine	Chlorine
Average Disinfectant Residual (ppm)	1.1	1.6	1.4	0.9	1.9	0.9
Average pH	7.5	7.7	8.8	8.6	9.0	7.9
Estimated ORP (mV)[5]	775	650	740	680	650	750
Average Annual Water Temperature (°F)[6]	59	57	54	68	61	64
Pipe DR and Pressure Class, PC (psi)	DR21 PC100	DR21 PC100	DR21 PC100	DR21 PC100	DR21 PC100	DR21 PC100
Average Working Pressure (psig)	100	70	70	70	65	77
Projected Oxidative Resistance under the specific operating conditions	≥100 years					

Based on this research and material development, oxidation from disinfectants is no longer a potential failure mechanism for 100+ years. AWWA C906 now requires PE4710-CC3 compounds for all municipal water transmission, distribution potable water applications. AWWA C901 requires PE4710-CC3 and DR 9 only for municipal water service line applications.

Surge and Cyclic Fatigue

Fatigue became a recognized potential failure mechanism, notably displayed by the Liberty ships in WWII, which contributed to the birth of the study of Fracture Mechanics. In pipelines transporting liquids the effects of pressure transients, such as water hammer and cyclic fatigue must be considered in the design.

Pipes are designed for transporting fluids under pressure, not just as a pressure vessel. While the pipe may be rated for a certain long-term pressure, this does not take into account these types pressure transients. When this column of fluid stops instantaneously, such as with a valve closure, this kinetic energy will be converted to potential energy in the form a pressure wave, or water hammer effect. The actual pressure increase caused by this event is directly proportional to the elastic modulus of the piping material – see Fig. 6. Since HDPE has a relatively low elastic modulus compared to other materials the resulting pressure spike.

$$a = \frac{4{,}660}{\sqrt{1 + \frac{K}{E_d}(DR - 2)}}$$

where:

a = wave velocity (celerity), ft/s
K = bulk modulus of fluid at working temperature (300,000 psi for water at 73°F)
E_d = dynamic instantaneous effective modulus of pipe material (150,000 psi for PE pipe)
DR = pipe dimension ratio

$$P_s = a\left(\frac{\Delta v}{2.31\mathrm{g}}\right)$$

where:
P_s = transient surge pressure, psig
a = wave velocity (celerity), ft/s
Δv = velocity change occurring within the critical time $2L/a$, in s, where L is the pipe length, ft
g = gravitational acceleration, 32.2 ft/s^2

Fig. 6 – Formulas for wave speed and pressure surge

PE4710 HDPE is designed to withstand surge and cyclic fatigue. Studies support that PE4710 HDPE pipe has the capacity to withstand pressure surges of 1.5x the MOP of the pipe for recurring surges and 2.0x MOP for occasional surges. This design has been incorporated into the American Water Works Association (AWWA) M-55 Design and Installation Manual for PE Pipe.

A design example for surge with DR 17 with MOP of 125 psi pipe operating at 125 psi and experiencing a 5 fps velocity leading to a 56 psi surge pressure shows no cyclic fatigue for >4 Million cycles. This demonstrates a 100+ year design against surge and cyclic fatigue.

Sustainability and Environmental Impact of HDPE Pipe

Beyond its long design life, HDPE pipe offers significant environmental advantages, contributing to sustainable infrastructure.

Polyethylene is traditionally made from natural gas feedstocks, but there is a transition occurring towards utilizing bio-feedstocks and recycled Post-Consumer Resin (PCR). No harmful emissions are produced during the processing of HDPE into pipe. HDPE is a thermoplastic, meaning there is no waste as it can be reprocessed several times. Residual pipe segments can also be reclaimed for recycling into various consumer products.

Life Cycle Assessment (LCA) and CO_2 Reductions

LCA studies for HDPE pipe estimate that the total energy consumption is approximately 95 MJ per kg of pipe (approx. 26 kWh per kg of pipe). HDPE pipe has the lowest projected environmental impact due to its low energy consumption during manufacturing, reduced product weight, superior shipping efficiencies, ease of installation, and outstanding material durability characteristics.

HDPE pipe significantly reduces CO_2 emissions. This is particularly evident in:

- Shipping: Due to its lighter weight compared to alternative materials, more HDPE pipe can be shipped per truck. Fewer trucks required for transportation result in less CO_2 emissions to deliver the pipe to the job site. A project example, the Great

Salt Lake project (redirecting a wastewater treatment plant effluent using 33,000 ft of 63” HDPE pipe), required 460 fewer trucks, resulting in an estimated 184 metric tons of CO_2 reduction. The calculation provided is 400,000 mm x 0.46 kg CO_2/mm = 184,000 kg CO_2.

- HDD and Trenchless Installation: HDPE pipe is widely used in horizontal directional drilling (HDD), with a survey by Underground Construction indicating that over 60% of all HDD utilizes HDPE pipe. Studies have shown that HDD can achieve a more than 2/3 reduction in CO2 emissions compared to open cut trenching. Reduced traffic delays associated with trenchless methods also significantly lower societal costs and CO2 emissions.

Resilience

HDPE piping systems demonstrate resilience against changing climate conditions and natural disasters such as floods, droughts, hurricanes, and earthquakes. AWWA M-55 recognizes the earthquake resilience of HDPE piping systems. The use of fully restrained HDPE heat fused joints, fittings, saddles, and electrofusion joints ensures that the system will not fail during these events. Many examples demonstrate that HDPE piping systems remain functional during natural disasters and changing weather patterns.

CONCLUSION

Achieving a sustainable 100+ year design life for HDPE pipe infrastructure is now possible due to significant improvements in material science and engineering design criteria. By specifically addressing the identified failure mechanisms—pressure, slow crack growth, corrosion/oxidation, and cyclic fatigue—modern PE4710 compounds meet performance standards that ensure resilience and integrity well beyond a century. The material properties and design methodologies provide an indefinite design life for pressure, 100+ years for slow crack growth, 100+ years against oxidation from disinfectants, and 100+ years against surge and cyclic fatigue.

In addition to its long-term durability, HDPE pipe offers substantial environmental benefits, including responsible sourcing, energy-efficient manufacturing, recyclability, and significant reductions in CO2 emissions through optimized transportation and trenchless installation methods. The inherent resilience of fused HDPE systems further contributes to robust and sustainable infrastructure capable of withstanding natural disasters. The combined advancements in material performance, design standards, and environmental stewardship position HDPE pipe as a sustainable choice for infrastructure requiring a 100+ year design life.

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