

Technical Note PP 841-TN Pressure Capability of HDPE PE4710 and PVC Pipe

Too frequently, the comparison between High Density Polyethylene (HDPE) and Polyvinyl Chloride (PVC) pipe is made primarily on pressure class (PC). However, there are fundamental material differences between HDPE and PVC that should be considered during design. When both hydrostatic stress and cyclic fatigue from hydraulic transients are correctly accounted for, HDPE pipe has several notable advantages. This Technical Note will provide a basis for a more appropriate comparison of the pressure capability of HDPE PE4710 and PVC pipes.

Key Points

- Pipes of different materials should not be compared based on pressure class (PC).
- Working pressure rating (WPR) is more appropriate to account for pressure surge.
- Fatigue strength should be evaluated for pipelines that will undergo frequent surge.
- The allowable operating pressure in PVC pipe may be limited well below the pressure class when considering surge and fatigue.
- The PC of PE4710 pipes accounts for the pumping and surge pressures that occur in typical municipal water pipes.

Pressure Class (PC)

Both PVC and HDPE utilize a maximum hydrostatic (constant) stress as the basis for their pressure class.

$$PC = \frac{2 \cdot \sigma_s}{DR - 1} \quad (Eq 1)$$

σ_s = Allowable long-term hydrostatic stress

2000 psi for PVC at 73°F

1000 psi for PE4710 at 73°F

DR = pipe dimension ratio = $\frac{\text{outside diameter}}{\text{wall thickness}}$

Table 1: PC Values for PVC and PE4710 Pipe

PVC Pipe		PE4710 Pipe	
DR 14	PC305	DR 9	PC250
DR 18	PC235	DR 11	PC200
DR 21	PC200	DR 13.5	PC160
DR 25	PC165	DR 17	PC125

Based on PC alone, one might assume that DR 21 PVC is comparable to DR 11 PE4710. However, PC only considers static or constant pressure. Typical pressure pipelines undergo fluctuating pressures in addition to static pressure. A comparison of only PC neglects key considerations that may result in a mistaken and biased design basis.

Working Pressure Rating (WPR)

A change in flow velocity in a pipeline converts kinetic energy to elastic energy resulting in pressure fluctuations from the steady state pressure. These pressure fluctuations from flow velocity changes are commonly termed hydraulic transients or surge pressures. Working pressure rating (WPR) is the pipe's design capacity to resist the sustained operating pressure (working pressure) with sufficient capacity for anticipated surge pressures above working pressure. The magnitude of the surge and the ability of the pipe to tolerate surge differs by material.

Analyzing surge events in multipart piping networks may be performed through specialized engineering analysis. Though a basic understanding of the potential pressures can be realized using the following relationships:

$$P_s = a \frac{\Delta V}{2.31g} \quad (Eq 2)$$

P_s = transient surge pressure (psi)

ΔV = sudden velocity change (ft./s)

g = acceleration due to gravity (32.2 ft./s²)

a = wave velocity (ft./s)

$$a = \frac{4660}{\sqrt{1 + \frac{K_{bulk}}{E_d} (DR - 2)}} \quad (Eq. 3)$$

K_{bulk} = bulk modulus of fluid

300,000 psi for water at 73°F

E_d = dynamic apparent modulus of pipe material

150,000 psi for HDPE at 73°F

400,000 psi for PVC at 73°F

Assuming ΔV in equation 2 equal to the maximum flow velocity in the pipeline provides a reasonable and conservative design basis. Normal water flow velocities are shown to range from three to ten ft./s and a range of five to seven ft./s occurs in many systems.¹

HDPE and PVC can both tolerate some occasional surge above their respective PC. Though HDPE can also tolerate *recurring* surges above its PC. For recurring surges such as those from normal pump start-up/shutdown, normal valve operation, etc., the WPR for PE4710 is the lesser of:

$$WPR_{PE} = PC_{PE} \cdot F_T \quad (Eq. 4)$$

or

$$WPR_{PE} = 1.5 \cdot PC_{PE} \cdot F_T - P_{RS} \quad (Eq. 5)$$

PC_{PE} = PE4710 Pressure Class (Eq. 1)

F_T = multiplier for temperature

1.0 for ≤ 80°F; see PP501 for higher temperatures

P_{RS} = recurring surge pressure per Eq. 2 (psi)

For PVC pipe design, recurring surge magnitudes must be subtracted from the pressure class to determine the working pressure rating per AWWA C900 and C905.^{2,3}

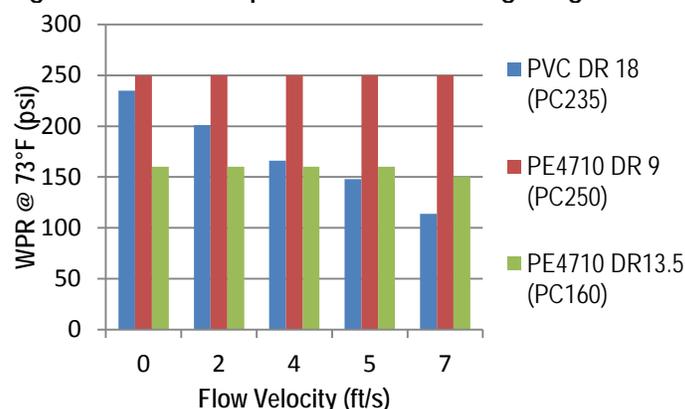
$$WPR_{PVC} = PC_{PVC} F_T - P_{RS} \quad (Eq. 6)$$

PC_{PVC} = Pressure Class of PVC pipe per AWWA C900 or C905

F_T = multiplier for temperatures > 73°F (See AWWA C900-07 or C905-10)

As illustrated in Figure 1, the static stress based PC of PVC pipe is not a sound technical basis for determining the required DR or PC for PE4710 pipe due to the different tolerance the materials have for recurring surge events. The WPR of DR 13.5 PE4710 is more comparable to DR 18 PVC at common flow velocities of four to five ft./s. As discussed below, the DR difference may be even less when other factors are considered.

Figure 1: WPR Comparison for Recurring Surge



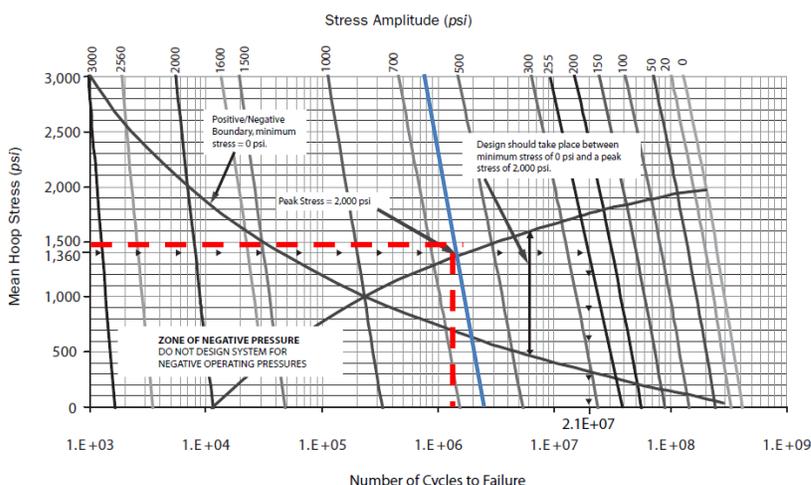
Design for Fatigue Loading

A 'fatigue' failure may occur from a load that is below the material's static or yield strength but repeated multiple times. Municipal water systems and force main piping generally have frequent surges due to pump starts and stops or valve openings and closures. AWWA C900 for PVC states "Recurring surge pressures may occur up to millions of times in a piping system's lifetime."² Hence, in addition to the surge considerations addressed by WPR, the design should consider the pipe's capacity for fatigue.

PE4710 has tremendous resistance to fatigue and reduction of PE4710 pipe's pressure rating for surge fatigue is not necessary.^{1,4} Empirical data demonstrates that current high performance PE such as PE4710 can withstand over seven million cycles to 1500 psi peak stress.⁵ So even at a surge event every fifteen minutes to the full 1.5-PC surge allowance, the projected fatigue

life of PE4710 pipe would be in excess of one hundred years.

Figure 2: PVC fatigue design from AWWA C900 Appendix B



Fatigue life design for PVC is in the appendices of AWWA C900 and C905 which present a graphical solution (Figure 2). The PVC fatigue life design is a function of mean stress, stress amplitude and cycles to failure (N). A primary factor that affects PVC pipe fatigue life is the stress amplitude from surge pressure; a relatively small change in stress amplitude has a large effect on cycles to failure making flow velocity a significant design parameter. AWWA C900 and C905 show a safety factor of 2 applied to the solution for N. To guard against the possibility of fatigue failure in PVC pipe from frequent surge, the working pressure may be limited significantly below the PVC pressure class.

Consider DR 18 PVC (PC235) operating at four ft./s design condition that results in recurring stress amplitude of 591 psi. From Figure 1, the WPR of DR 18 at these conditions would be 166 psi (not 235 psi) which corresponds to a mean hoop stress of roughly 1400 psi. Hence, the cycles to failure from Figure 2 would be approximately 1.6 million. As mentioned above, to convert to allowable surge events, divide the value by 2 to account for secondary pressure fluctuations associated with a surge event.⁴ The design engineer

would compare this value (800,000) with the anticipated surge events over the design life of pipe.

If one million surge events (requiring $N \geq 2MM$) were anticipated over the pipe's service life, the mean stress at the above conditions would need to be limited to around 960 psi per Figure 2 corresponding to an allowable operating pressure of roughly 113 psi in DR 18 PVC.

As PE4710's pressure class requires no consideration for de-rating to accommodate fatigue loads, DR 17 PE4710 would meet and exceed the 113 psi rating at these conditions and hence the materials compare roughly DR to DR.

Table 2 summarizes a DR to DR comparison based on these concepts. Higher or lower expected surge cycles over the pipe service life would alter the values shown.

Table 2: DR Comparison Considering One Million Surge Events over 50 Years

Maximum Working Pressure (psi)	Flow Velocity (ft/s)	Required DR	
		PVC	PE4710
80	2	DR 32.5	DR 26
	3	DR 25	DR 26
	4	DR 18	DR 26
	5	- ³	DR 21
100	2	DR 32.5	DR 21
	3	DR 25	DR 21
	4	DR 18	DR 21
	5	- ³	DR 21
150	2	DR 21	DR 13.5
	3	DR 21	DR 13.5
	4	DR 14	DR 13.5
	5	- ³	DR 13.5

1. Values consider pressure and surge only at 73°F. Other project parameters may alter the required DR
2. PVC DR's evaluated per guidance in AWWA C900-07 Appendix B.
3. Conditions exceed fatigue design window guidance in AWWA C900-07.

REFERENCES

1. Pipeline Analysis & Calculation Environment (PACE) [Software], Beta 1.0, eTrenchless Group, Inc. 2012.
Available at www.plasticpipe.org
2. American Water Works Association, C900-07: *AWWA Standard for Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 4 In. Through 12 In. (100mm through 300mm), for Water Transmission and Distribution*, 2006.
3. American Water Works Association, C905-10: *AWWA Standard for Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 14 In. Through 48 In. (350mm through 1200mm)*, 2009.
4. Jana Laboratories, *Fatigue of Plastic Water Pipe: A Technical Review with Recommendations for PE4710 Pipe Design Fatigue*, 2012
5. Marshall, G.P., Brogden, S., Shepherd, M.A. (1998) "Evaluation of the Surge and Fatigue Resistance of PVC and PE Pipeline Materials for use in the U.K. Water Industry", *Plastics Pipe X*, Goteburg, Sweden.

Example Calculation:

Given: An engineer is designing a water system that operates at 100 psi at 60°F and flow velocity is at 4 ft/s. It is estimated the pipeline may undergo 2 surge events per hour. What is the required DR for PE4710 and PVC for a 50 year design life?

Solution: PVC DR 25 (PC165 psi) is initially evaluated. The maximum design flow velocity of 4 ft/s is used to estimate recurring surge pressure:

$$a = \frac{4660}{\sqrt{1 + \frac{K_{bulk}}{E_d} (DR - 2)}} = \frac{4660}{\sqrt{1 + \frac{300,000 \text{ psi}}{400,000 \text{ psi}} \cdot (25 - 2)}} = 1091 \text{ ft/s}$$

$$P_s = a \frac{\Delta V}{2.31g} = 1091 \frac{4}{2.31 \cdot 32.2} = 59 \text{ psi}$$

$$WPR_{PVC} = PC_{PVC} F_T - P_{RS} = 165 \cdot 1 - 59 = 106 \text{ psi}$$

WPR > 100 psi working pressure and is therefore sufficient.

Next, consider fatigue. For a 50 year design life with 2 surges per hour, the pipeline should be designed to withstand 876,000 surge events and hence a required cycles to failure of $2 \times 876,000 = 1,752,000$ cycles to account for secondary pressure fluctuations associated with each surge event.

Stress Amplitude is calculated as:

$$\sigma_a = \frac{P_s (DR - 1)}{2} = \frac{59 \text{ psi} \cdot (25 - 1)}{2} = 708 \text{ psi}$$

The fatigue life curve in Appendix B of C900-07 shows there is no intercept of 708 psi stress amplitude with 1.8 MM cycles and hence a thicker DR is required. Evaluating DR 21 (PC200) also shows it is insufficient for 100 psi at the assumed conditions. DR 18 (PC235) results in:

$P_s \sim 70$ psi and $\sigma_a = 591$ psi. At 1.8MM cycles the allowable mean stress is determined from Figure in AWWA C900-07 Appendix B as roughly 1,300 psi. The corresponding pressure capacity for fatigue is:

$$P = \frac{2 \cdot \sigma_m}{DR - 1} = \frac{2 \cdot 1300 \text{ psi}}{18 - 1} = 153 \text{ psi}$$

153 psi considering fatigue for DR 18 is greater than the design operating pressure of 100 psi and therefore sufficient for the design assumptions above.

For PE4710, DR 21 PE4710 PC100 is evaluated. 4 ft/s change in flow velocity in DR 21 PE4710 results in P_s of 40 psi. WPR for PE4710 is the lesser of: $WPR = PC \cdot F_T = 100 \text{ psi} \cdot 1$

$$WPR = 1.5 \cdot PC \cdot F_T - P_{RS} = 1.5 \cdot 100 \cdot 1 - 40 \text{ psi} = 110 \text{ psi}$$

Hence the WPR = 100 psi which is sufficient for the design conditions. Fatigue is generally not a design consideration for PE4710, but the engineer verifies this with the equations in PPI PACE at www.plasticpipe.org which shows $N \sim 14,000,000$ cycles and more than sufficient for the design conditions.

The engineer elects to specify DR 21 PE4710 and DR 18 PVC.

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