Occasional and Recurring Surge Design Considerations for HDPE Pipe

Larry J. Petroff[1]

[1]Plastic Pipe Consultant, 139 Imperial Way, Bogart, GA 30622; PH (706) 208-1031; email: lpetroff@charter.net

ABSTRACT

The current generation of High Density Polyethylene (HDPE) pipe materials, classified as PE4710 by U.S. standards and PE100 by ISO standards, has greatly improved toughness characteristics over previous generation materials. Most noteworthy is an increased resistance to slow crack growth and fatigue.

In the U.S., PE4710, PE3608, and PE3408 (a previous generation material) pipes are used in water mains and forcemain sewers. These pipelines daily experience numerous pressure surges above their standard pumping pressure. For pipes operated at their rated pumping pressure, AWWA C901 and C906 allow “recurring” pressure surges equal to 0.5 times the pipe’s Pressure Class (PC) and “occasional” surges to equal the pipe’s Pressure Class. Thus, the surge allowance results in a total pressure (combined pumping pressure plus surge pressure) equal to 1.5 x PC during recurring surges and 2.0 x PC during occasional surges. While all three materials have the same long-term hydrostatic design basis of 1600 psi, a higher design factor for PE4710 pipe allows it to operate at a pressure 25% higher than either PE3408 or PE3608 pipe. This paper addresses the question, Does the higher surge pressure resulting from operating PE4710 pipe at a higher pressure compromise PE4710 pipe’s performance?

This paper gives an overview of design procedures for water and forcemain sewers given in current standards. It discusses considerations for a reasonable safety factor against over-pressurization during transient surge and shows that this factor is met by PE4710 material when designed in accordance with AWWA and ASTM standards. Aside from the pressurization itself, repetitive surge may lead to fatigue. This paper references studies wherein PE4710 material has a fatigue life in the millions of cycles when operated at its pressure rating and subject to recurring surge equal to 0.5 x PC.

Introduction

Polyethylene pipe’s service and process water usage dates back nearly five decades. Over the years, polyethylene resin manufacturers continually improved polyethylene compounds introducing several new generations. Much of the focus in development has been in improving the pipe’s durability through increased resistance to slow crack growth (SCG). In fact, the latest generation materials (PE4710’s) have such an increased SCG resistance (by up to 50 times) that the pipes carry a higher pressure rating than previous generations.

Pressure Rating

ASTM and AWWA publish methods for pressure rating HDPE pipes. ASTM D2837, "Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials or Pressure Design Basis for Thermoplastic Pipe Products" is used to establish the "hydrostatic design basis" (HDB) of a HDPE pipe material [1]. The HDB is a categorized value of the material's (or compound's) long-term hydrostatic strength, LTHS. The HDB for PE4710 as well as PE3608 (and the older PE3408) is 1600 psi. The hydrostatic design stress (upon which the pressure rating is based) is determined by multiplying a design factor (DF) times the HDB. The Plastics Pipe Institute's Hydrostatic Stress Board, after considerable review of testing data and performance, assigns DF values to various thermoplastic piping materials including HDPE and PVC. The assigned DF values are intended to allow the pipe to function under typical service conditions at design pressure and temperature <u>indefinitely</u>. (Failure is not anticipated for hundreds of years.) However, severe stress concentrations, impingements, defects, and other localized stresses intensifications in a system could limit pipe life. These stress intensification conditions can ultimately damage pipe through slow crack growth development. A high resistance to SCG reduces crack development and, thus, helps provide a long service life.

Resistance to SCG in HDPE is measured by ASTM F1473, "Notch Tensile Test to Measure the Resistance to Slow Crack Growth of HDPE Pipe and Resins" (PENT test) [1]. Early HDPE materials, like PE3306, had PENT values of less than a few hours even though many of these materials have lasted for decades in pipe service. In late 2005, ASTM reclassified PE3408 material primarily on the basis of PENT values. The material was split into three categories, PE3408 (PENT $\geq$10 hrs), PE3608 (PENT$\geq$100 hrs), and PE4710 (PENT $\geq$ 500 hrs). The PE3408 and PE3608 classifications were for the older materials and PE4710 for the newer. PE4710 has additional SCG resistance requirements including tighter tolerances on the stress rupture curve and linearity of the stress rupture curve for at least 50 years. Recognizing the importance of SCG resistance in regard to the pipe's service capabilities, the Hydrostatic Stress Board assigned a DF of 0.63 to PE4710 material, whereas older generation PE3408 material and current PE3608 material are assigned a DF of 0.5. The result is that the pressure rating for PE4710 pipe is 25% higher than the rating for pipe having the same dimension ratio (DR) but made from PE3408 or PE3608 material, even though all three materials have a 1600 psi HDB. The hydrostatic design stress (HDS) for PE4710 is 1000 psi while for PE3608 (and PE3408) it is 800 psi. The higher pressure rating for PE4710 means that the pressure during surge (for the same flow velocity and DR as for PE3408 pipes) will be higher. The following sections will discuss surge pressure ratings and show that PE4710 can safely withstand the higher surge pressures.

(*One note before we proceed to that discussion: The pressure rating (PR) equals the pressure at which the pipe's hoop stress equals the HDS. ASTM F714 gives pressure ratings for PE4710 pipes using a DF of 0.63 [1]. AWWA publishes two standards for HDPE pipe: AWWA C901 for water service pipe and tubing and AWWA C906 for distribution and transmission pipes [2]. AWWA uses the term Pressure Class (PC)* *instead of Pressure Rating (PR). The terms result in the same hoop stress other than PC is given for 80°F and PR for 73°F.* ***AWWA C901 assigns a rating to PE4710 pipe based on a DF of 0.63.*** *Due to a lag in the AWWA process at the time of this writing AWWA C906-12, which also rates PE4710 based on a DF of 0.63, is in public review and is therefore not yet active. In the active standard, C906-07, PE4710 pipe is considered as a PE3408 material and thus has a DF of 0.5.)*

Surge Pressure Allowance

During operation, hydraulic transients result in the total pressure (pumping plus surge) exceeding the steady-flow pumping pressure. AWWA standards give HDPE pipe an allowance for surge pressure above its PC. The same allowance applies to F714 pipes. For occasional surges, the result of emergency conditions, equipment malfunction, or fire-flow, the surge allowance equals 1.0 x PC. For pipe being pumped at its PC, this allows a total pressure (pumping plus surge) equal to 2.0 times the pipes PC. (If the pipe is operating at less than the PC, higher surge pressures can be tolerated as long as the combined pumping plus surge pressure does not exceed 2.0 x PC.) This limits the hoop stress during an occasional surge to 2000 psi for PE4710. On the other hand, most water and forcemain systems operate daily with numerous surges due to pump starts and stops and valve openings and closures. AWWA's allowance for frequent recurring surges at the pipe's rated pressure is 0.5 x PC. It is reduced from the occasional surge value in consideration of fatigue. See Table 1.

Table 1. Surge Allowance for PE4710 Pipe (80°F) based on 0.63 DF

Frequency	Working Pressure	Surge Allowance	Total Pressure During Surge (WP + P_S)	Total Stress During Surge
Occasional	PC	1.0 x PC	2.0 x PC	2000 psi
Recurring	PC	0.5 x PC	1.5 x PC	1500 psi

Note: PC per AWWA C906-12. For ASTM F714 rated pipe substitute PR for PC.

Basis for AWWA Surge Pressure Allowance

The surge pressure allowance is based on the material's ability to withstand a sudden stress increase to 1500 psi or 2000 psi without altering the material's long-term strength and to withstand repeated surges without fatigue failure. This paper will exam (1) the safety factor against peak pressure and then (2) fatigue resistance.

I. Transient Surge and the Safety Factor against Peak Pressure

The Plastics Pipe Institute's (PPI) *Handbook of HDPE Pipe* [3] states that "the surge pressure lasts for only a few seconds at their longest." Transient surges are essentially impulse events, lasting only a few seconds and having very rapid rates of pressurization. The pressure rise can be in excess of 100 psi/sec. See Fig 1. The duration of the peak pressure is generally less than a second followed by a series of monotonically decreasing secondary pressure rises of lower amplitude and lower pressurization rates until the "ringing" ceases.

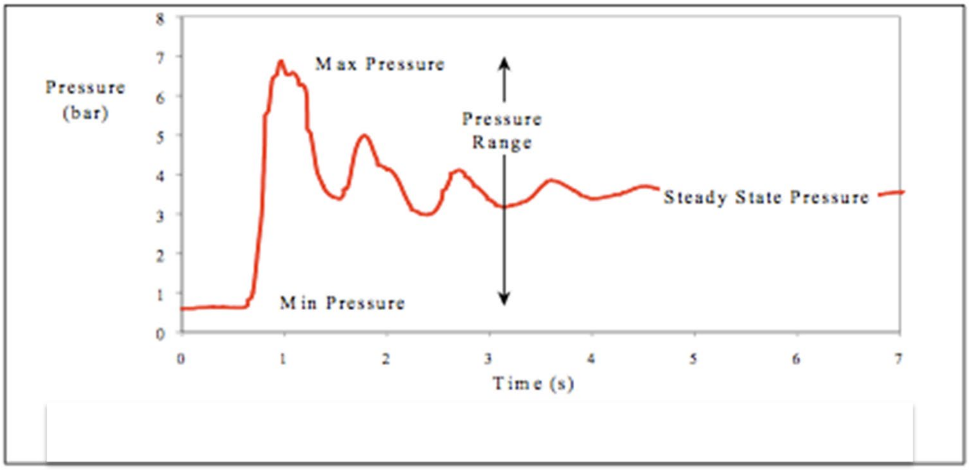

Figure 1. Typical Fluctuation for Sudden Valve Closure in DR11 PE Pipe
(Reprinted with permission from "Evaluation of the Surge and Fatigue Resistance of PVC and PE Pipeline Materials for use in the U.K. Water Industry" [4])

Safety Factor For Transient Surges
While the duration of load application (strain rate) normally has negligible impact on the design of metallic pipes, it is a major consideration for plastic pipe. Polymers and thermoplastic pipes in specific are viscoelastic. Viscoelastic materials undergo both viscous and elastic deformation when loaded. Elastic deformation is instantaneous and completely recoverable. Viscous deformation is time-dependent; the longer a load is applied, the more deformation occurs. For instance, the Long Term Hydrostatic Stress is based on HDPE's viscous (sometime referred to as creep) strength. The material is under constant stress and undergoes continuous (albeit extremely slow) hoop expansion until rupture. For thermoplastics, the ratio of applied

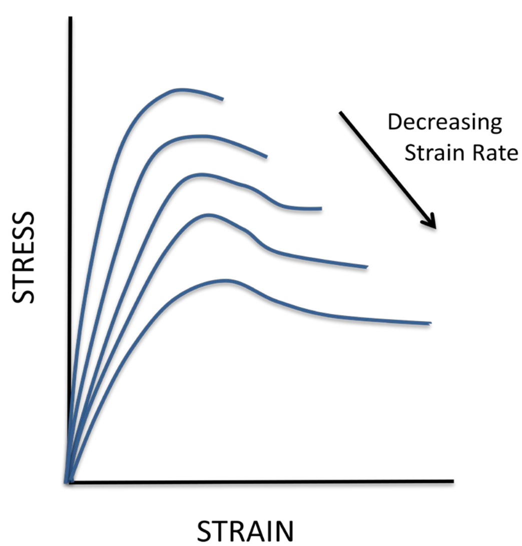

Figure 2. Stress vs Strain

stress to strain is referred to as the "apparent modulus of elasticity", because the ratio is not a fixed value but varies with the rate and amplitude of loading (as well as temperature). Increasing the load rate causes an increase in strength and stiffness. Load-deflection testing at various strain rates generates a family of stress-strain curves. See Fig. 2. Both the increase in modulus and strength at increasing load rates occur because of HDPE's morphology. The HDPE solid consists of stiff crystalline lamellae and flexible amorphous tie-molecules that connect the lamellae "plates". Slow straining separates lamellae (in tact) by unwinding and stretching tie-molecules. This results in large strains and low energy at rupture. At high strain rates, fracture occurs due to breaking lamellae which requires high force but pre-fracture strain is low.

Transient surges occur at very rapid rates (a few seconds). Under these conditions, PE4710 resists deformation with its "dynamic" modulus of elasticity of 150,000 psi [3]. Whereas the long-term (50 years) modulus is 29,000 psi, thus the material is effectively five times stiffer during surge. Similarly, strength increases under rapid load. Burst testing per existing standards are at pressurization rates slower than typical transients. Therefore they are not useful for establishing a safety factor against surge. For example, ASTM D1599 burst test calls for a pressurization rate causing burst in 60 to 90 seconds [1]. (F714 calls for a minimum burst of 2900 psi. Actual values run higher. Typical D1599 burst stress values for PE4710 reported to the author exceed 3400 psi.) The so called 5-second test in F714, is not a burst in 5 seconds, but requires the manufacturer to pressurize the pipe to 3200 psi (at any desired rate) and hold for 5 seconds without leakage. Therefore it cannot be used for establishing a safety factor. Tensile bar tests which are at higher strain rates (2 in/min) may be more indicative of surge strength. The ASTM D638 tensile strength for PE4710 resins having a D3350 cell classification of 445574C (most commercial materials comply) is 3500 psi to 4000 psi [1]. Perhaps the closest test to a sudden pressurization is ASTM F2634, tensile-impact test. Specimens are strained at either 4 in/sec or 6 in/sec, depending on size. Steve Sandstrum of McElroy Mfg. reported to the author that "a good minimum yield strength at both strain rates is in the range of 4500-4600 psi". This arguably gives a safety factor in excess of 2:1 for 2000 psi. While this illustrates PE4710's strength at a rapid load rate, it is still not a burst test.

To establish a safety factor for surge against burst stress, the burst test must be done at a similar rate of loading to the surge, in other words a burst in 2 or 3 seconds. This is practically difficult to accomplish. And what would be a desirable safety factor? AWWA Manual M-11 states "for steel pipe produced to meet AWWA standards, the increased hoop stress should be limited to 75 percent of the specified yield strength, but should not exceed the mill test pressure". In other words, M-11 permits a safety factor against yield of 1.33. This establishes that AWWA does not believe you need a 2 to 1 safety factor for surge events. In fact the safety factor against burst may be irrelevant. What is important is that the quick straining (lasting a few seconds) be limited to a value that does not lead to a significant accumulation of strain during the limited number of occasional surge events. A "significant accumulation of strain" would be measured by its affect on the pipe's long-term creep expansion/strength.

Grann-Meyer [5] states, "During surge, defined as 'short term condition', the PE pipe acts perfectly elastic and the E-Modulus becomes the initial Modulus of Elasticity", assuming the surge pressure does not exceed a critical value that alters the material. He considers a stress of half the yield stress lasting less than 10 minutes to be a short-term condition. Thus, a surge of 1.5 x PR (or 1500 psi stress) for PE4710 pipe is elastic and has an insignificant affect as virtually every method of measuring yield stress for PE4710 material mentioned in the preceding paragraph exceeds 3000 psi. This leaves the question, what about occasional surges at 2.0 x PR (or 2000 psi stress)? Can they be treated as a 'short term condition'? The answer is 'Yes'. The strain during occasional surge is approximately 1.33% (2000 psi/150,000 psi). Yield strain per D638 is 10% to 12% [6]. Several thousand cycles of such low level strain lasting for only a few seconds will not have a significant cumulative affect on creep expansion. Lamborn and Petroff [7] shows that even when high levels of strain (5% to 7%) are applied for several hours, upon removal of stress the residual strain drops significantly (in their tests, to approximately 1%).

The Fourth Generation--PE4710 and PE100

HDPE material has evolved over the years and many people consider today's material to be Fourth Generation material. The newer materials tend to have a bimodal molecular weight distribution and high resistance to slow crack growth (and fatigue). ISO classifies this material as PE100, whereas in the U.S. it is classified as PE4710. PPI says "The physical properties of PE100 and PE4710 materials are extremely similar" [8]. There are some differences, for instance stress rupture for PE100 is based on 50 year LTHS rather than 100,000 hours, while PE4710 has a minimum PENT requirement of 500 hours, whereas PE100 can be either 10 hours or 500 hours.

U.K. Surge Testing

G.P. Marshall, S. Brogden, and M.A. Shepherd have thoroughly addressed the affects of surge pressure on PE100 pipes [4]. Figure 3 shows the result of high-speed burst testing of PE100 pipe, comparable to surge pressure load rates. At a rate of 8 bars/sec (which they indicate was the maximum surge pressurization rate observed in a field study), the burst pressure of DR11 pipe is 60 bar (870 psi). Arguably their results apply to PE4710 material and show a SF of 2.2 for an occasional surge pressure to 2 x PC (2000 psi). See Fig. 3 and Table 2.

II. Recurring Surge and Safety Factor Against Fatigue Failure

Most water and forcemain sewer pipelines experience frequent (recurring) surges throughout the day. These are mainly due to the normal operation of pumps and valves that result in sudden flow velocity changes. For HDPE pipes, AWWA allows the total pressure within the pipe to equal 1.5 x PC (1.5 x PR) during recurring surge. As discussed in a preceding paragraph the pipe's creep growth will not be affected in any significant way by the surge pressure. However, the repetitive application of the surge (sudden expansion and contraction of the circumferential diameter) may lead to fatigue damage of the pipe wall. Therefore the number of surge cycles safely permitted at a given pressure is limited by the pipe's fatigue strength.

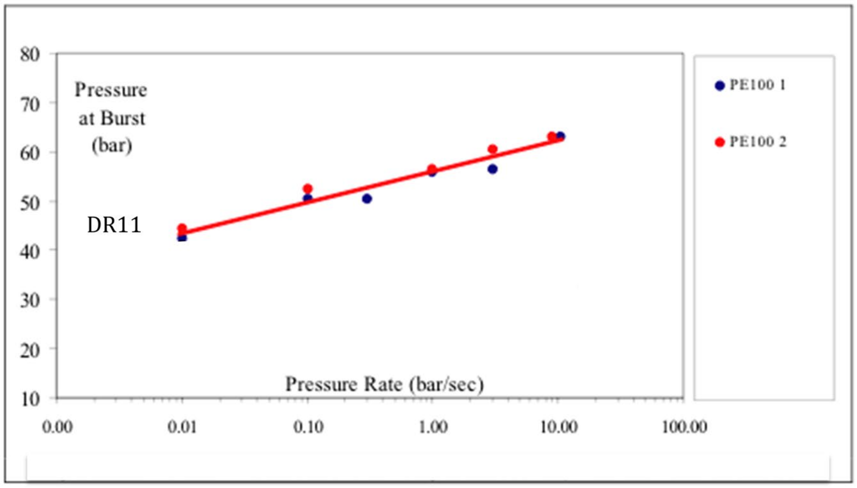

Figure 3. Effect of Pressure Rise Rate on Strength of Pipes Containing a 100 mm Notch to 10% of the Wall Thickness

(Reprinted with permission from "Evaluation of the Surge and Fatigue Resistance of PVC and PE Pipeline Materials for use in the U.K. Water Industry" [4])

Table 2. High Speed Burst Test SF When Compared to PE4710 Ratings

DR	PC	High Speed Burst Pressure	High Speed Burst Stress	Occasional Surge Stress	
				2.0 x PC	S.F.
11	200	870 psi	4350 psi	2000 psi	2.2

Note: PC per AWWA C906-12. For ASTM F714 rated pipe substitute PR for PC.

Anticipated Cycles

In a typical pipeline, the number of surge cycles varies daily. The author is not aware of a standard design value for the number of cycles, but AWWA C900 and C905 use a daily rate of 55 cycles (~2 per hour) in their examples. At this rate, the pipe would be subject to 2 million cycles over 100 years. Since the surge pressure "rings", as illustrated in Fig. 1, a higher number of daily surges is likely to occur. A more conservative design value is a daily rate of 96 cycles (4 per hour), which results in 3,500,000 cycles in 100 years. Historically, cyclic fatigue has not been a problem for HDPE pipe. Crabtree and Oliphant (2011) reports, "One of the key findings of the literature search was a complete lack of reported PE pipe fatigue failures in service" [9]. In 1999, Becht Engineering cycled Third Generation material (PE3408) which included a branch saddle, pipe, and a flange adapter to 1.5 x PC for 10,003,931 cycles without failure. UK Water Industry (IGN 4-37-02) states, "the new high toughness PE materials are apparently not affected by repeated cyclic loading."[10]

Fatigue Testing

Marshall et al [4] and more recently Crabtree and Oliphant [9] have undertaken to establish the fatigue life of PE100 and PE4710 material, respectively. Marshall used three-point bending tests conducted at 0.5 Hz to develop a regression line of stress versus cycles to failure for PE100 material. At 1.5 x PC (or 1500 psi stress), Marshall's curve predicts a failure intercept of 7,200,000 cycles. Crabtree and Oliphant cycled 4" DR17 (PC125) PE4710 pipes from 0 psi to 1.5 x PC. The four specimens, originally reported on in Crabtree and Oliphant, have since been cycled 10,000,000 times (0 to 1.5 PC) without failure (11). Two of the specimens contained heat fused joints. A fifth specimen was cycled 6,750,000 times (0 to 1.5 PC) without failure. All five specimens were then tested for at least an additional 2500 cycles from 0 to 2.0 PC (2000 psi) with no failures. These results exceed the number of cycles at 1.5 x PC predicted by Marshall and essentially confirm the applicability of Marshall's tests to PE4710 pipe. Equations 3 and 4, developed by Karl Lawrence, match Marshall's regression line and can be used to predict cycles to failure for various peak pressures for PE4710 and PE100 pipes. Table 3 shows the projected safety factor for recurring surge at 1.5 PC is 3.6 for 100 years based on 55 surges/day.

$$\text{Number of Cycles} = 10^{((1.708-\log_{10}(\text{Peak Stress}/145))/0.101)} \qquad \text{Eq. 3}$$

$$\text{Peak Stress} = (P_{PUMPING} + P_{SURGE})*(DR-1)/2 \qquad \text{Eq. 4}$$

Table 3. Cycles to Failure for PE4710 and PE100

Working Plus Surge Pressure ($WP + P_S$)	Peak Stress (psi)	Cycles to Failure	Fatigue Life (Years) @ 55 surges/day	SF for 100 years @ 55 surges/day
1.1 x PC	**1100**	**160,000,000**	**7970**	**80**
1.2 x PC	**1200**	**66,000,000**	**3288**	**33**
1.3 x PC	**1300**	**30,000,000**	**1494**	**15**
1.4 x PC	**1400**	**14,000,000**	**697**	**7**
1.5 x PC	**1500**	**7,200,000**	**359**	**3.6**

Note: PC per AWWA C906-12. For ASTM F714 rated pipe substitute PR for PC.

Eq. 3 gives the fatigue life for 2000 psi (surge pressure of 2 x PC) as 424,000 cycles. This well exceeds what anyone had in mind when they defined occasional surge and supports the argument that occasional surge has little impact on creep expansion.

PPI-PACE

The Plastics Pipe Institute publishes an on-line program, called PPI-PACE (Pipeline Analysis and Calculation Environment) that performs preliminary design calculations for HDPE pipes. It also calculates the pipe's design fatigue life.

Pressure and Surge Design

The selection of the proper DR for an application depends on many factors such as pumping pressure, flow, and external loading. AWWA M-55, PE Pipe—Design and

Installation, M-11, Steel Pipe: A Guide for Design and Installation, and M-23, PVC Pipe—Design and Installation use the Joukowsky equation for finding the transient surge pressure. (The overall piping network can influence pressure transients. They may exceed those calculated for a single pipe. Where the geometry and boundary conditions of a system are complicated, an engineered analysis may be required.)

Once the surge pressure is determined, the process for checking the DR is fairly straightforward. The primary considerations are pumping pressure, temperature, occasional surge pressure, and recurring surge pressure.

Step One: The working pressure of the system (steady flow pumping pressure) should be less than or equal to the pipe's Pressure Rating (or Pressure Class for AWWA systems) adjusted for the application temperature.

Step Two: The occasional surge pressure plus the working pressure should be less than 2 x PR (or 2 x PC for AWWA systems).

Step Three: The recurring surge pressure plus the working pressure should be less than 1.5 x PR (or 1.5 x PC for AWWA systems.)

Table 4 gives a design example using DR21 PE4710 pipe for a 100 psi pumping pressure. Surge pressure was calculated using equations 4-2 and 4-3 in AWWA M-55. For velocities less than 5 fps the pumping pressure, occasional surge pressure, and recurring surge pressure are all within allowed limits. At a velocity of 6 fps, the sum of the working (pumping) pressure and recurring surge pressure exceeds the allowance. For 6 fps a lower DR is required. In this case DR17 would work.

Table 4. DR21 Pressure Design Example for PE4710 Pipe at 73ºF

Working Pressure (psi)	DR/PR		Design Flow Velocity (fps)	Surge Pressure (psi)	Working Pressure + Surge (psi)	WP + Occasional Surge Allowance	WP + Recurring Surge Allowance
	DR	PC				PC+ 1.0PC	PC+ 0.5PC
100	21	100	4	40	140	200	150
	21	100	5	50	150	200	150
	21	100	6	60	160	200	150

Notes: 1) Surge pressure calculated per Eq 4-2 and 4-3 from M-55. 2) For temperatures >73ºF see M-55 3) Pressure ratings for distribution and transmission waterworks pipes per ASTM F714 4) PC per AWWA C906-12. *For ASTM F714 rated pipe substitute PR for PC.*

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Table 4 shows the effect of flow velocity on surge pressure. As the velocity increases, lower DR (thicker wall) pipes may be required to handle the surge pressure. What is a reasonable design velocity? Oliphant et al. [12] reports on a survey of 51 utilities and found an average normal flow velocity in water lines of 6.7 fps and an average fire flow velocity of 11.6 fps. The paper also states that the AWWA operator training documents indicate 5 fps as a typical limit for normal flow and AwwaRF "Guidance manual for Maintaining Distribution System Water Quality" recommends "a velocity of 5 fps or greater to remove biofilm, promote scouring and removal of loose deposits, and to reduce disinfection" [12]. ASTM F645 and EPA consider 5 fps to be a safe upper limit for a design water velocity for a thermoplastic piping system. UPC considers this to be 8 fps. These reports suggest that generally a design velocity of a least 5 fps should be considered. (Even higher velocities may occur in sewer forcemains. The EPA recommends 10 fps as a limiting velocity.)

Summary

The latest generation of HDPE material has exceptionally high slow crack growth and fatigue resistance. This material is characterized as PE100 by ISO and PE4710 in the U.S and Canada. The recommended hydrostatic design stress for this material is 1000 psi at 73°F. This paper has shown that during occasional surge PE4710 pipes can safely withstand a total stress (pumping plus surge) of 2000 psi (or pressure of 2 x PC). Marshall et al's rapid pressurization rate burst tests show the safety factor to be at least 2 against over-pressurization. During occasional surge the virtually elastic behavior of the pipe, the minimal strain at 2000 psi stress, and the occasional occurrence result in the surge having little significant affect on the pipe's creep expansion. As for recurring surge, testing shows PE4710 pipe can withstand 3.6 million cycles to 1.5 x PC (or 1500 psi stress) with a 2 to 1 safety factor. For 100 years at 55 cycles per day, the safety factor for recurring surge at 1.5 x PC is 3.6.

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