RESISTANCE OF PE4710 PIPING TO PRESSURE SURGE EVENTS IN FORCE MAIN APPLICATIONS

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ABSTRACT

Keywords: PE, Pressure Surge, Force Main

Force mains, by the nature of their operation, commonly generate cyclic loading conditions which, in some cases, can be quite severe. Consideration of these cyclic loads is, therefore, a critical component of force main piping design. This paper examines the demands of force main applications and the projected performance of PE4710 piping materials to the repetitive surge events in these applications. The potential magnitude and frequency of surge loads in force mains is examined along with the current design approaches for PE materials for addressing these loads. The results of cyclic loading testing of PE4710 piping, both with and without butt-fusion joints, are then examined to assess the validity of the design approaches. Currently, the Dura-Line PE4710 piping has surpassed 4.2 million cycles between 0 and 1.5x's the Pressure Class without failure (testing is on-going). The fatigue resistance of PE4710 materials is seen to be excellent, and shows these materials are capable of providing for essentially unlimited fatigue resistance under the operating conditions of force main systems. The current design approaches for both occasional (short-term) surge resistance and repetitive (long-term) fatigue resistance for PE4710 materials are conservative and justified based on the data.

BACKGROUND

In general, the cyclic fatigue resistance of PE piping materials has not been a design issue or concern. [*Marshall et al (1); Bowman (2)*] The high fatigue resistance of PE materials in general allowed some simple fatigue design rules-of-thumb to be developed during the introduction of PE piping. The general adequacy and utility of these practices, to some extent, has limited the need and the motivation to develop more detailed or precise practices for PE fatigue design. This is particularly true for the effects of internal pressure surges on PE water pipe.

The PE design practices for preventing pressure surge fatigue failures in water pipe have a long and very successful history. These practices were developed based on the older generation PE materials. Since this time there has been considerable evolution in the performance of PE pipe and the introduction of a new classification of high performance PE4710 materials. This study conducted an assessment of the current design approaches to determine their continued suitability for PE4710 piping systems.

PRESSURE SURGES IN FORACE MAIN APPLICATIONS

Surges are the result of a rapid change in liquid velocity within a pipeline which causes the stored energy in the flowing fluid to be converted to pressure energy, caused for example by rapid valve closure or a pump tripping. [*Brad (3); V.-M.V.a.M.C.Institute (4)*] They are short-term events (on the order of seconds) that result in either an initial rapid increase or decrease in pressure above or below the steady state pressure. The resulting pressure wave travels down the pipeline at the speed of sound, traveling in the transport fluid (which for water piping systems is the speed of sound in water) until it hits a barrier and is reflected back. The resulting pressure changes, commonly referred to as transients, hydraulic surges, hydraulic transients, and water hammer are an important consideration in the design of force main piping systems.

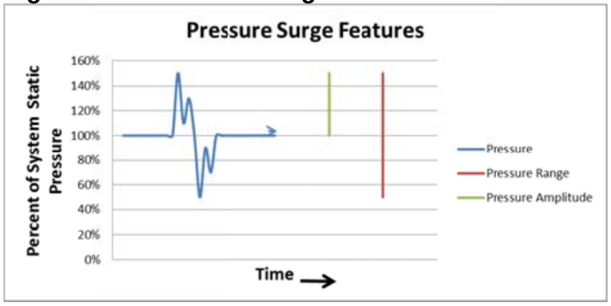
Surges are typically addressed through two separate design approaches; the first dealing with the immediate (short-term) effects of the pressure surge event (occasional surges) and the second dealing with the impact of recurring surge events (repetitive surges). The first of these is addressed in this section and the second in the following section. As the literature and design guidelines are not always consistent regarding terminology, the following precise definitions are presented for the purpose of this paper:

> *Occasional Pressure Surges:* Peak pressure surges caused by events outside normal operations of the pipeline (e.g. power outage causing tripping of all system pumps).
>
> *Recurring Pressure Surges:* Peak pressure surges caused by normal pipeline operation (e.g. pumps turned off and on, valves opening and closing) that occur at a frequency of greater than once per day.

Surge Basics

The general characteristics and behavior of surges in pipelines is well understood. The usual cause is a rapid change in the velocity of the fluid flowing in the pipe, which can be produced by valves operating, pump start-up and shut-down, air venting, fluid column separation, and other operations. [*Brad (3); V.-M.V.a.M.C.Institute (4)*] The kinetic energy of the flowing water column is converted to a pressure wave that travels the length of the pipeline, moving at a constant speed (essentially, the speed of sound in the fluid) until it encounters a boundary or barrier. Reflected waves propagate back down the pipeline, interfering with the incident wave, creating reinforced peaks and troughs that may have greater amplitude than the simple incident wave. The general features of the pressure surge waveform are illustrated in **Figure I**.

Figure I: Generalized Surge Event



Pressure cycle amplitude is defined as the maximum pressure, including all transients, minus the average or baseline pressure. The difference between the maximum and minimum pressures is the pressure cycle range. Note that some analysts have used the range as defined here and called it the amplitude; therefore, comparison of surge design procedures must take the terminology into account.

Because of the potential complexity of the surge pressure events, characterizing the pressure surges present in an operating piping system is typically done by a special engineering transient analysis. [*McPherson and Haeckler (5); Jung et al (6)*] The purpose of a transient pressure analysis is to determine the surge environment as it would be experienced by the piping components, so that failures related to surges can be avoided by proper material selection and component sizing. Extreme cases of system failure can lead to a single-event catastrophic pressure surge that damages the piping or other system components by short-term overstress if this is not considered in the design stage.

While full transient analysis is recommended, a basic understanding of the potential peak pressures in surge events can be obtained through use of the Joukowsky Equation [*V.-M.V.a.M.C.Institute (4)*], which describes the relationship between the key characteristics of a pressure surge event. On a pressure basis, the equation is expressed as:

$$P_s = a(\Delta V/2.31g) \qquad (1)$$

where:

P_s = surge (psi or bar)
ΔV= change in velocity (ft/s or m/s)
g = acceleration due to gravity (32 ft/s^2 or 9.8 m/s^2)
a =wave velocity (ft/s or m/s)

For water pipelines, the wave velocity (or celerity) can readily be estimated from the known properties of the fluid and the modulus of the piping material [*V.-M.V.a.M.C.Institute (4)*]:

$$a= 4660/((1+(K_{bulk}/E_d)*(DR-2))^{1/2}) \qquad (2)$$

where:

a = average velocity (ft/s or m/s)
K_{bulk} = Fluid bulk modulus (300,000 psi (2070 MPa) for water at 73°F (23°C))
E_d = Dynamic instantaneous effective modulus of pipe material (typically 150,000 psi (1030 MPa) at 73°F (23°C) for PE, 400,000 psi (2760 MPa) for PVC, and much higher for metals)

Water Velocity Changes and Pressure Surge Loads

To determine the pressure surge for a given pipe (specific material and DR), the only unknown in the Joukowsky equation is ΔV, the change in velocity. This value depends on the specific design of the pipeline network, the specific event that triggers a velocity change, and the water flow velocity. The maximum change in velocity is a full stoppage of flow (In this case ΔV is equal to the water flow velocity). Ignoring the potential for more complex reinforcement wave patterns (which can be assessed in a full transient analysis) and water column separation (which can be addressed through proper system design), this would result in the maximum possible pressure surge in the system.

As a single surge event can lead to failure (it is the short-term resistance to over pressurization that is being considered here), for design purposes the resistance to peak surges should be based on the maximum design velocity (or maximum anticipated water flow velocity) for the pipeline. While the pipeline could potentially endure many lesser surge events, it is the maximum event over the course of the pipe design lifetime that needs to be considered for surge resistance. While a full transient analysis should be considered for the pipeline, a full flow stoppage at the maximum flow velocity in the pipeline provides a good basis for considering surge events.

Force main pumping systems vary widely in their specific operating conditions and, consequently, in the operating flow velocities. For general reference, velocities in force main pipelines directly connected to the pump station are often in the order of 10 fps (3 m/s). [*Larsen (7)*] The maximum recommended force main velocity at peak conditions in the EPA Wastewater Technology Fact Sheet is also 10 fps (3 m/s). [*EPA (8)*] Ten (10) fps (3 m/s), therefore, represents a reasonable upper limit for design considerations. For self-cleaning of deposits from the pipeline, a general rule of thumb is to have a minimum velocity of 2 to 3 fps (0.6 to 0.9 m/s). [*Larsen (7)*] EPA reports that typically velocities are 2 to 8 fps (0.6 to 2.4 m/s) and 6 to 9 fps (1.8 to 2.7 m/s) for short force (<2000 ft or <610 m). [*EPA (8)*] Typical operating conditions would be expected to fall in the general range of 2 to 10 fps (0.6 to 3.0 m/s).

Resistance of PE4710 Piping to Pressure Upsurges

With an idea of the maximum flow velocity changes that can be anticipated in water piping systems, the resistance of PE4710 to the potential pressure surges resulting from a sudden flow stoppage at these velocities can be considered.

Thermoplastics like PE respond to fast loading rates (such as encountered in a surge event with the rapid pressure rise) by exhibiting greater strength and stiffness. [*IGN (9)*] At high pressurization rates, therefore, these materials are better able to resist the higher stress levels generated by surge, with the strength of both materials increasing with higher and higher rates of loading. [*IGN (9)*] Pressure surge events on thermoplastic piping systems typically occur at a rate of 14.5 to 145 psi/s (1 to 10 bar/s). [*Bowman (10)*] At these loading rates, the short-term strength of these materials is, therefore, many times higher than the long-term strength used in Pressure Class (PC) design. For PE materials, the strain from an occasional pressure surge of short duration is met with an elastic response that is reversed on removal of the load, [*Szpak and Rice (11)*] and that has no adverse effect on the long-term strength of the pipe. For occasional peak surge events, therefore, it is only the short-term ability of the piping system to resist the surge that needs to be considered.

Surge Allowance Design Practices for PE4710

For PE4710 piping materials, the maximum allowable pressure for an occasional surge event per AWWA M55 is defined by [*AWWA (12)*]:

$$P_{(MAX)(OS)} = 2 \times PC \quad (3)$$

where:

$P_{(MAX)(OS)}$ = maximum allowable surge pressure
PC = Pipe Pressure Class

The resulting allowable peak design pressures for PE4710 piping for various PCs are provided in **Table I**. The maximum allowable sudden change in velocity, assuming the pipeline is operated at its full pressure rating, is also presented.

Table I: Surge Capacity of PE4710 Pipe and Resultant Allowable Sudden Change in Velocity

PE4710 Dimension Ratio	Allowance for Occasional Surges, psi (bar)	
	Allowable Peak Pressure, psig (bar)	Maximum Allowable Sudden Change in Velocity, fps (m/s)
13.5	320 (22.1)	12.4 (3.78)
17	250 (17.2)	11.2 (3.41)
21	200 (13.8)	10.0 (3.05)
26	160 (11.0)	8.9 (2.71)
32.5	128 (8.8)	8.0 (2.44)

For PE4710 piping systems, the maximum flow velocities are typically at or above the range of 2 to 8 fps (0.6 to 2.4 m/s) reported by the EPA as typical of force main applications, even when the pipelines are operated at full design pressure (PC rating). These allowable peak pressure surges are well below the short-term material strengths. For example, PE4710 materials are required to have a minimum short-term pressure strength of 3200 psi (22 MPa), well above the maximum peak stress of 2000 psi (14 MPa). Overall, therefore, based on the short-term strength of PE, the US design approaches for PE4710 are seen to provide reasonable, technically defensible and conservative approaches for determining the allowable peak surge resistance.

The above consideration of allowable peak surges did not consider the impact of surge on the joints within the piping network. For PE materials butt fusion is the most common joining method. Studies have shown that properly prepared butt fusion joints have pressure strengths equal or greater to those of the pipe material [*Bowman (10)*] and, therefore, they can be used at the peak surge pressures for the pipe.

CYCLIC LOADING IN FORCE MAIN PIPING SYSTEMS

In addition to the magnitude of pressure surges, the total number of pressure surges over the lifetime of a piping system is the other primary factor in determining the potential for damage to the piping components. The impact of repetitive or cyclic loading events on piping materials is typically referred to as fatigue. For some materials, the performance lifetime in fatigue can be significantly below the static pressure long-term material strength, and the impact of cyclic loading on piping systems is, therefore, an important design consideration. [*AWWA (13)*] As they operate by different mechanisms and on different time scales, analysis for fatigue resistance is completely separate from that for resistance to peak surge events.

Overall it is seen that PE4710 materials are highly fatigue resistant and that the current US design approaches appear conservative and appropriate.

Review of Fatigue Resistance Data for PE Pipe Materials

The PE fatigue literature is extensive, though primarily focused on accelerated testing methodologies as fatigue is not generally considered to be a design limiting factor of PE piping. An overview is provided of the fatigue data for PE.

Overview of Existing PE Fatigue Data

The fatigue resistance studies for PE materials can be grouped into three primary categories:

1. Fatigue studies on PE4710/PE100 high slow crack growth resistant pipes.
2. Fatigue studies on older generation PE pipes.
3. Highly accelerated fatigue studies to assess slow crack growth resistance, typically using stress concentrators (sharp notches) and/or elevated temperature, for material ranking and development.

One of the key findings of the literature search was a complete lack of reported PE pipe fatigue failures in service. It is a failure mode that does not appear to occur in service. This has certainly impacted the nature of the fatigue studies conducted. As fatigue has not been considered a significant issue for PE pipe materials, limited studies have been conducted to examine the actual fatigue resistance of PE pipe. Most of the studies that have been conducted have been for the early generation PEs. Even for these older generation materials, good fatigue resistance is observed. In a study on fatigue resistance of early 1980s MDPE pipe resins, Bowman projected a service life of >670 years under fatigue loading conditions where failures of uPVC (rigid PVC) pipe were projected in 14 to 66 years. [*Bowman (2)*] The studies also demonstrated that fatigue failures in accelerated testing occurred in the pipe and not the fusion joints [*Bowman (2)*], indicating the joints are not a point of weakness.

The bulk of the studies fall into category three and are focused on accelerated testing of notched molded specimens. [*Strebel and Moet (14); Parsons et al (15); Haager et al (16)*] The driver of these studies is the creation of highly accelerated environments to examine the long-term slow crack growth resistance of PE pipe materials, which, due to the evolution in PE performance, has become increasingly difficult to assess with standard testing (due to the high performance and corresponding extremely long test times). Through these studies the fatigue response of PE pipe resins has been well characterized. As it was not their intent to project fatigue resistance at end-use conditions in water systems, the results of these studies are difficult to apply directly in forecasting performance. What the studies do show, however, is that PE materials are extremely fatigue resistant. [*Marshall et al (1); IGN (9)*] There has also been a clear correlation established between the slow crack growth resistance of PE resins and their resistance to fatigue with higher slow crack growth resistance leading to better fatigue response. [*Mamoun (17); Zouh (18)*] This data clearly shows that current generation materials, such as PE4710 and PE100 resins, have significantly higher resistance to fatigue than previous generation PE materials (which themselves have not been known to experience fatigue in service, as discussed above). [*Marshall et al (1); IGN (9)*]

The UK water industry [*IGN (9)*] examined the fatigue resistance of modern PE materials (PE80 and PE100 materials) with high slow crack growth resistance. The results and conclusions of the findings were reviewed and endorsed by the British Plastics Federation and UK consultants and academics involved in the fatigue testing of plastics. [*IGN (9)*] The study concluded that "the new high toughness PE materials are apparently not affected by repeated cyclic loading". The testing was conducted at stress ranges (peak stress minus minimum stress) of roughly 1500 psi (10 MPa) and higher to over 10,000,000 cycles. For US design approaches for PE4710 materials, a stress range of 1500 psi (10 MPa) is equivalent to testing at 1.5 times the PC, which is the current design approach for PE materials. (Note: While PE4710 and PE100 have different specific meanings, they are generally referring to the current generation, high slow crack growth resistant PE materials and, in terms of fatigue resistance and this analysis, the terms are, therefore, treated as synonymous).

Testing of PE100 pipes was also conducted by the Swedish National Testing and Research Institute at the pressure rating ± 50% surge at 23°C (73°F) for over one million cycles with no failure. [*Janson (19)*] The hoop stress was 1160 ± 580 psi (8 ± 4 MPa), which in the US rating system is equivalent to testing at 1.16 times the pressure class ± 58% of the pressure class for a peak pressure 1.74 times the PC. While generally supportive of the high fatigue resistance of PE materials, testing would need to be continued well beyond this number of cycles to validate the current design approaches.

Accelerated fatigue testing was conducted on a series of US PE pipe materials of varying slow crack growth resistance in order to examine the potential for cyclic load testing of pipes at elevated temperatures as an accelerated material ranking and validation tool. [*Mamoun (17)*] The testing demonstrated a clear correlation between the fatigue resistance and slow crack growth resistance (as measured by PENT and elevated temperature sustained pressure testing) of the resins. One of the resins studied had a compression molded PENT value just above the 500 hour minimum required for PE4710 materials. At 90°C (194°F) the stress in the pipe samples was cycled between 100 and 900 psi (mean stress of 500 psi) (0.7 to 6.2 MPa, mean stress of 3.4 MPa). This would be equivalent to cycling well beyond the 1.5 times the PC at 23°C (73°F). In order to obtain an estimate of how this data would translate into fatigue performance at end-use conditions in water systems, the data from this study was extrapolated to end use conditions through two different methods. The relationship between number of cycles to failure and test temperature developed by Bowman [*Bowman (2)*] for mid 1980s materials was used, and an approach employing the general rule of thumb for temperature acceleration of a doubling in reaction rate for every 10°C (18°F) increase in temperature (typically very conservative when applied to slow crack growth (SCG) type mechanisms) was also used. The resulting analysis projected that fatigue lifetimes at 20°C (68°F) were 1.6×10^9 (over 1 billion) cycles and 4.2×10^7 (42 million) cycles, respectively. While this is a very crude approximation, it does indicate the potential for essentially unlimited fatigue life for PE4710 materials at end-use conditions.

Bimodal PE4710 pipes have exceptionally high slow crack growth (SCG) and fatigue resistance. The Dura-Line PE4710 is currently undergoing fatigue testing with pressures cycling between 0 and 1.5 times the PC and has surpassed 4.2 million cycles with no failures (testing is on-going). Testing is being conducted for both straight pipe and pipe with butt fusion joints. Given the excellent SCG resistance of this material relative to the minimum 500 hour PENT requirement and the fatigue performance of the materials presented above, PE4710 pipes are projected to be fatigue resistant.

Overall, the existing PE fatigue literature suggests:

- PE materials are highly fatigue resistant.
- The fatigue resistance increases with increased SCG resistance.
- Current generation PE4710/PE100 materials have the potential for essentially unlimited fatigue cycling at end-use conditions in water systems.
- The butt fusion joining method does not impact fatigue resistance.
- The Dura-Line PE4710 pipe material is fatigue resistant.

Number and Magnitude of Cyclic Loading Events in a Pipeline Lifetime

Design lifetimes for piping systems vary. However, it is increasingly common for pipeline owners and designers to establish 50 to 100-year service life expectations. Long service lives require significant resistance to fatigue, even if the daily number of surges is relatively small**. Table II** shows the cumulative events for 50 and 100-year service lives for events tallied on a daily and hourly basis.

Table II: Pressure Surges in 50 and 100-year Service Lives

Surges per day	Approximate Surges per hour	Surges per 50 years	Surges per 100 years
1	0.04	18,263	36,525
10	0.42	182,500	365,000
40	2	730,000	1,460,000
75	3	1,368,750	2,737,500
150	6	2,637,500	5,475,000
250	10	4,562,500	9,125,000
300	13	5,478,750	10,957,500

The actual number of surge events experienced by a pipeline is dependent on the specific pipeline design and operating conditions and varies even within a given pipeline system. Resistance to cyclic loading must, therefore, consider the total number of expected surge events based on an analysis of the specific system.

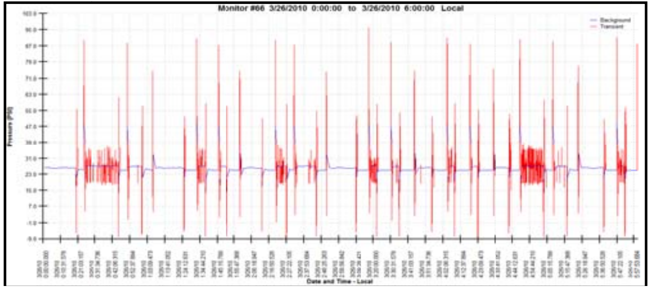
A primary pressure transient, however caused, will decay exponentially to a number of minor secondary pressure cycles. The effect of each minor cycle can be related to the primary cycle in terms of the number of cycles which would produce the same crack growth as one primary cycle. Joseph [*Joseph et al (20)*] calculates that a typical exponentially decaying surge is equivalent to two primary cycles. Thus design for surge fatigue should be based on the primary cycle amplitude, with the actual surge frequency doubled.

Force main piping systems vary widely in their design and operation. To develop a range of potential operating conditions, a literature search was conducted, consultations with engineering design firms were held, and actual field measured transients in force main systems were obtained.

The general engineering approach for force mains systems is to design for 2 to 4 pump starts per hour (producing a corresponding surge event) at peak operation. It is then typically assumed that the number of pump starts over a 24 hour period is the pump starts per hour times 24 hours times 0.6. This results in an average number of primary surge events of 1.2 to 2.4 per hour, which, for design purposes, would translate to 2.4 to 4.8 equivalent surges per hour based on Joseph’s 2 times factor.

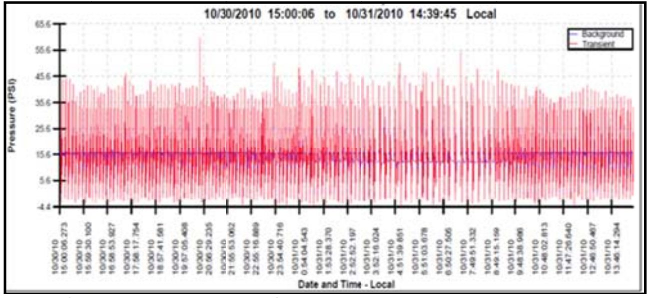
Actual field measured transients in operating force mains were obtained for three different systems. The measured pressure surges are provided in **Figures II** (System A), **III** (System B - 24 hours), **IV** (System B - 2 hours) and **V** (System C).

Figure II: Measured Surge Events in Force Main System A



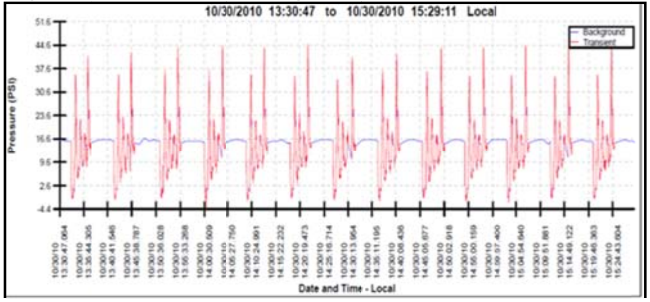
Note: Sewage Force Main System A - 6 Hour Period

Figure III: Measured Surge Events in Force Main System B



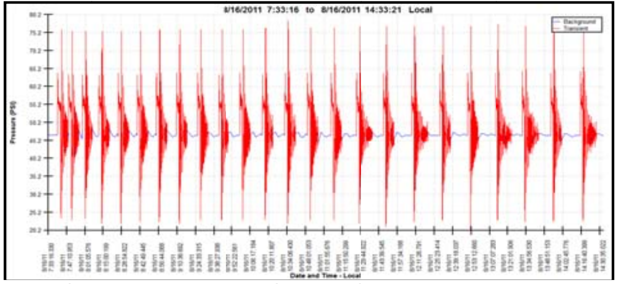
Note: Sewage Force Main System B - 24 Hour Period

Figure IV: Measured Surge Events in Force Main System B



Note: Sewage Force Main System B - 2 Hour Period

Figure V: Measured Surge Events in Force Main System C



Note: Sewage Force Main System C - 7 Hour Period

For System A, if the small amplitude (approximately 15 psi (1 bar)) surges are ignored, there is a surge frequency of approximately 6.5 surges per hour. Similarly for System B, surges occur approximately 6 times per hour. For system C, primary surges are observed approximately 3.5 times per hour.

Williams measured pressure surges in a force main system and reported 5 surges per hour. [*Williams (21)*] Larsen reports that pump stops in force mains occur at least once per hour which he equates to roughly 500,000 stops over a 50 year period for an estimated 10^6 to 10^7 equivalent surges over the design life of a pipeline, when secondary surges are accounted for. [*Larsen (7)*] Henderson reports a surge frequency of five surges per hour in their investigation of PVC force main failures. [*Henderson et al (22)*]

Overall, therefore, the expected number of surges in force main applications is likely to lie between 1 and 7 surges/hour. The total number of surges expected for a force main over a 100-year design life based on this range is summarized in **Table III**. The equivalent number of surge events for design purposes based on both the 1.5 times and 2 times factors are also provided.

Table III: Expected Surges over a 100-year Design Life for Force Main Piping Systems

Primary Surges per hour	Total Primary Surges in 100 year Design Life	Total Equivalent Surges for Design
		2 x's Factor
1	876,000	1,752,000
2	1,752,000	3,504,000
3	2,628,000	5,256,000
4	3,504,000	7,008,000
5	4,380,000	8,760,000
6	5,256,000	10,512,000
7	6,132,000	12,264,000

PE Pipe Fatigue Design Practices

The current US PE pipe design practice for pressure and pressure surges is documented in AWWA C901 [*AWWA (23)*], C906 [*AWWA (24)*], M55 [*AWWA (12)*] and the Plastic Pipe Institute Handbook of PE Pipe [*Plastics Pipe Institute (25)*]. The pipe pressure rating (Pressure Class (PC)) is calculated using the Recommended Hydrostatic Design Stress (HDS) and the standard ISO equation. For recurring surge events, the allowable peak surge pressure is limited to 1.5 times the PC. The number of recurring surges that are acceptable is not limited. The peak repetitive surge pressure is, therefore:

$$P_{(MAX)(RS)} = 1.5 \times PC \qquad (5)$$

where:

$P_{(MAX)(RS)}$ = allowable peak repetitive surge pressure
PC = Pipe Pressure Class

The maximum allowable peak repetitive surge pressures for various PCs are provided in **Table IV**.

Table IV: Allowable Peak Repetitive Surge Pressures for PE4710 Pipe

PE4710 Dimension Ratio	$P_{(MAX)(RS)}$ psi (bar)
13.5	240 (16.5)
17	188 (13.0)
21	150 (10.3)
26	120 (8.3)
32.5	96 (6.6)

It is important to note that the allowable peak repetitive surge pressures are independent of the number of surge events per hour, and that the surge amplitude is limited only by $P_{(MAX)(RS)}$. It is also important to note that the design life of the pipeline is not defined by the fatigue resistance of the pipeline.

SUMMARY

The fatigue resistance of PE4710 materials in force main applications is seen to be excellent. Both the current design approaches for occasional (short-term) surge resistance and for repetitive (long-term) fatigue resistance for PE4710 materials in force main applications are conservative and appear appropriate.

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