TECHNICAL REPORT

FATIGUE OF PLASTIC WATER PIPE: A TECHNICAL REVIEW WITH RECOMMENDATIONS FOR PE4710 PIPE DESIGN FATIGUE

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Fatigue of Plastic Water Pipe: A Technical Review with Recommendations for PE4710 Pipe Design Fatigue

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Abstract

The purpose of this project was to conduct an Engineering Assessment of the resistance of HDPE pipe to fatigue loading situations encountered in North American water distribution and transmission applications, particularly as they relate to PE4710 materials. The assessment specifically included an engineering comparison of the literature regarding the relative fatigue resistance of plastic potable water pipe materials: PE and PVC. It also included a literature review and utility survey to confirm design fatigue loads and surge velocities. In addition, the data to support the current proposed fatigue design practices for PE4710 pipe were reviewed. Recommendations were developed for obtaining limited additional data to provide additional experimental support for the current design practices and for future changes to design practices.

The primary findings of the study were:

- The fatigue resistance of PE4710 materials, based on the available data, is excellent and shows these materials are capable of providing for essentially unlimited fatigue resistance under the operating conditions of water transmission and distribution systems.
- The current design approach for occasional (short-term) surge resistance for PE4710 materials is conservative and appears appropriate.
- The current design approach for repetitive (long-term) fatigue resistance for PE4710 materials is conservative and appears justified based on available data.
- The US design approach for PE4710 materials is more conservative than that of the UK for both occasional and repetitive surge events.
- PVC materials are seen to be susceptible to fatigue under the operating conditions of water transmission and distribution systems.
- The current design approach for occasional (short-term) surge resistance for PVC materials appears justified.
- The current design approach for repetitive (long-term) fatigue resistance for PVC materials appears justified based on available data.
- The US design approach for PVC materials is less conservative than that of the UK for repetitive surge events.
- PE4710 materials are seen to exhibit superior fatigue resistance to PVC piping materials.
- Given the high fatigue resistance of PE4710 materials, the development of limited additional cyclic fatigue data would provide justification for increasing the allowable repetitive surge pressure and, at the very least, would provide additional experimental support of the design approach. While fatigue testing has been done on PE fusion joints, it is recommended that joints be included in any additional testing to acquire additional information on performance of newer materials.
- Similarly, the development of additional fatigue data within the PVC design envelop would provide confirmation and, potentially, refinement of the current design approach. It is recommended that testing of this nature include both bell and spigot and fused PVC joints.

1.0 Purpose

The purpose of this project was to conduct an Engineering Assessment of the resistance of HDPE pipe to fatigue loading situations encountered in North American water distribution and transmission applications, particularly as they relate to PE4710 materials. The assessment specifically included an engineering comparison of the literature regarding the relative fatigue resistance of plastic potable water pipe materials: PE and PVC. It also included a literature review and utility survey to confirm design fatigue loads and surge velocities. In addition, the data to support the current proposed fatigue design practices for PE4710 pipe were reviewed. Recommendations were developed for obtaining limited additional data to provide further experimental support for the current design practices and for future changes to design practices.

2.0 Background

The cyclic fatigue resistance of PE piping materials has not been a design issue or concern[1, 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 so for the effects of internal pressure surges on PE water pipe.

The fatigue resistance of PVC piping has always been considered to be a significant limiting factor in PVC pressure pipe design[1, 3]. Within the last decade, the PVC piping industry has promulgated newer fatigue design recommendations and tools[4]. These guidelines suggest PVC pipe will perform adequately under certain service conditions that were once considered too severe for PVC pipe, based on fatigue life design. The guidelines also demonstrate that there remain many applications where PVC piping will rapidly fail by fatigue. The current PVC pipe surge pressure design tool is very specific and precise and thus may appear to some users to be more “scientific” than the very broad general surge allowances promulgated for PE.

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. With the introduction of these materials, questions have been raised around the suitability of the current design practices. This study conducted an assessment of the current design approaches to determine their continued suitability with the introduction PE4710 materials. Comparison was also made with the current US fatigue design approaches for PVC along with an examination of other international design practices.

3.0 Report Structure

The report is structured in eight Sections as detailed below:

- **1.0 Purpose**
- **2.0 Background**
- **3.0 Report Structure**
- **4.0 Pressure Surges in Water Transmission and Distribution Piping**
  - 4.1: Surge Basics
  - 4.2: Water Velocity Changes and Pressure Surge Loads
  - 4.3: Resistance of PE and PVC Piping to Pressure Upsurges
    - 4.3.1 Surge Allowance Design Practices for PE4710 and PVC
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- **5.0 Cyclic Loading in Water Transmission and Distribution Systems**
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    - 5.1.2: Crack Initiations and Propagation with Acceleration by Cyclic Loading
      - 5.1.2.1:Observed Fracture Mechanism in Fatigue Acceleration of Brittle Cracks
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- **7.0 Summary**
- **8.0 References**

4.0 Pressure Surges in Water Transmission and Distribution Piping

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[5, 6]. They are a short term event (on the order of seconds) that results 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 water transmission and distribution 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 Section 5. As the literature and design guidelines are not always consistent regarding terminology, the following precise definitions are presented for the purpose of this report:

> *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) occurring at a frequency of > once per day.

In considering the potential short-term impact of surge pressures, the following factors need to be addressed:

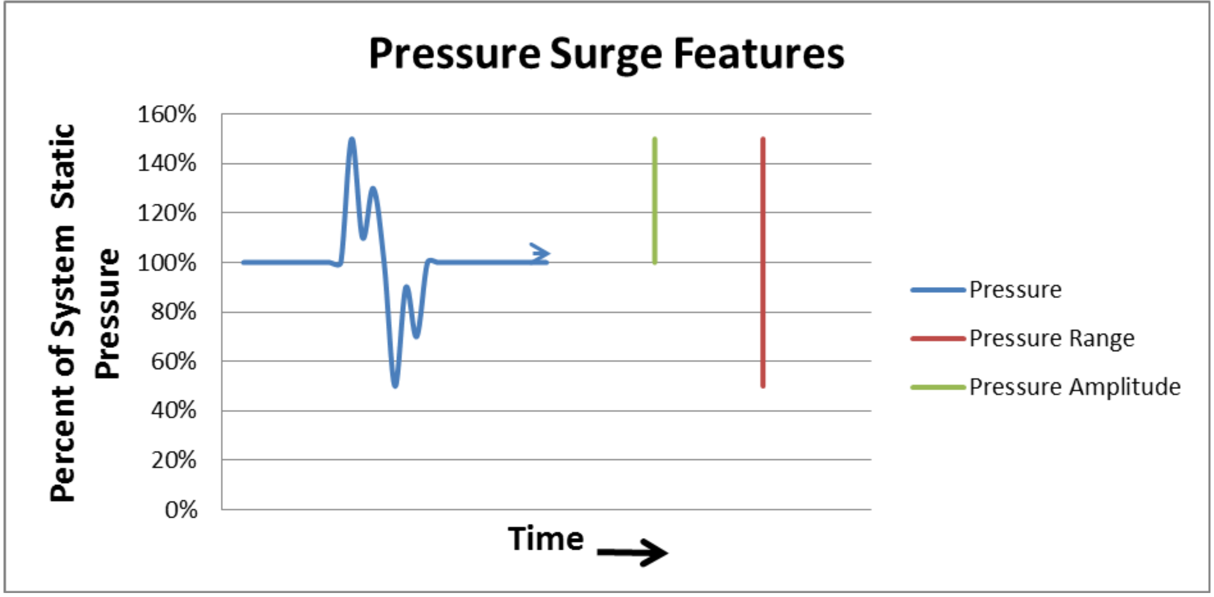
1. Upsurges (pressure increase):
    a. Over pressurization of the pipeline leading to pipe damage or rupture
    b. Damage to system components (gasket blowout, pump damage, etc)
2. Downsurges (pressure decreases):
    a. Pipe collapse
    b. Groundwater infiltration (at leakage points such as joints)

After a general discussion of surge basics to lay the foundation for the discussions to follow, each of these factors is addressed for design of PE4710 and PVC piping systems for US water transmission and distribution applications. Overall, the US design approaches for surge for PE and PVC appear to be suitable.

4.1 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[5, 6]. 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 4.1**.

Figure 4.1: 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 so 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[7, 8]. 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[6] which describes the relationship between the key characteristics of a pressure surge event. On a pressure basis the equation is expressed as[6]:

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

where:

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

For water pipelines, the wave velocity can readily be estimated from the known properties of the fluid and the modulus of the piping material[6]:

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

where:

a=wave velocity (ft/s)
K_{bulk}= Fluid bulk modulus (300,000 psi for water at 73°F)
E_d= Dynamic instantaneous effective modulus of pipe material (typically 150,000 psi at 73°F for PE, 400,000 psi for PVC, and much higher for metals.)

Therefore a DR17 pipe with the typical PE material modulus of 150,000 psi will have pressure surges that travel at 837 feet per second. Stiffer, higher modulus materials will all have proportionately higher surge velocities.

The final parameter of concern in surge analysis is the critical time, which is essentially how long it will take the incident pressure wave to be reflected and return to the source. This parameter is significant in that if the critical time is longer than the duration of the incident event, there will be no destructive interference at the source and the full pressure surge will occur. If the critical time is shorter than the incident event then some reduction in the full pressure surge will occur.

The critical time can be estimated as:

$$\mathbf{T_{CR} = 2L/a} \qquad \mathbf{(3)}$$

where:

T_{CR} = critical time, (seconds)
L = distance within pipeline pressure wave moves before reflected by boundary (ft)
a=wave velocity (fps)

Continuing with the example of DR 17 PE piping, a 500 ft length of pipe would have a critical time of: 2 x 500 ft/837 fps = 1.2 seconds. Any event (eg. Pump trip, rapid valve closure) occurring faster than this would result in a full pressure surge as given by the Joukowsky equation (Equation 1).

4.2 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 (e.g. UK IGN 4-37-02[9] for guidance on design of PE and PVC pipelines in the UK recommends "for identification of the peak surge, the worst case anticipated event (e.g. emergency trip of all pumps) should be considered"). 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.

There are no set, standardized, design velocities for piping systems. Utilities typically provide maximum design velocities for the normal operation of their systems and for fire flow based on their specific system requirements. **Table 4.1** provides a summary of the design guidelines obtained by random sampling of fifty-seven water utilities through phone surveys and published design guidelines[10].

The reported values of maximum design velocities for normal flow are shown in **Figure 4.2** and for fire flow in **Figure 4.3**. The average value for normal flow is 6.7 fps and for fire flow is 11.6 fps. These values are in general alignment with AWWA operator training documents that indicate 5 ft/s as a typical limit for normal operations with higher velocity expected during "fire flow conditions" and the AWWA Research Foundation *Guidance Manual for Maintaining Distribution System Water Quality*[11], which recommends a velocity of 5 ft/s or greater to remove biofilm, promote scouring and removal of loose deposits, and to reduce disinfection demand and a velocity of 12 ft/s for removing sand from siphons. These values, as maximum design values, may be in excess of the actual system operating flow velocities and, while they are instructional and used here to provide a design example (Section 4.3), it is the true maximum system velocity change anticipated during the pipe lifetime that should be used for system specific design (including the potential impact of reinforcement wave patterns which could exceed the pressures predicted by the Joukowsky equation).

Table 4.1: Municipal Design Flow Rate Survey Results

Ref.	Utility Name	City	Maximum Design Flow Rate
1	(city utility)	Flagstaff	5 ft/s at 130 psig, 10 ft/s at 20 psig
2	(city utility)	Mooresville	6 ft/s
3	Mukilteo Water District	Mukilteo	8 ft/s
4	Global Water	Phoenix	8 ft/s
5	Municipal Authority of Westmoreland County	Westmorland	20 or 30 ft/s
6	(city utility)	Woodland	10 ft/s
7	LCRA	Austin	5 or 10 ft/s
8	(city utility)	Saskatoon	5 or 8.2 ft/s
9	(city utility)	Blacksburg	6.4 ft/s (fire)
10	(city utility)	Seminole	6.8 or 8 ft/s (fire)
11	Lubbock Water Utilities	Lubbock	3/4, 10 or 14 ft/s (fire)
12	Marysville Public Works	Marysville	6.4 ft/s (fire)
13	Harvest-Monrovia Water & Sewer Authority	Harvest	4.8 ft/s (fire)
14	Salem Department of Public Works	Salem	3/5 ft/s (normal), 10 ft/s (fire)
15	(city utility)	Medicine Hat	6 ft/s (normal), 8 ft/s (fire)
16	(city utility)	Nanaimo	5 (normal), 10 ft/s (fire)
17	New Kent County Public Utilities	New Kent	6.4 or 9.6, 11.4 or 17 ft/s (fire)
18	(city utility)	Buffalo	11.4 or 14.2, 17 or 19.9 ft/s (fire)
19	Water Resources Department City of Asheville	Asheville	5.7, 11.4 ft/s (fire)
20	Utah Division of Drinking Water	Salt Lake City	5 ft/s (normal)
21	(city utility)	Kent	8 ft/s (normal)
22	(city utility)	Fife	5 ft/s (normal),r 9 ft/s (fire)

Table 4.1 Continued: Municipal Design Flow Rate Survey Results

Ref.	Utility Name	City	Maximum Design Flow Rate
23	American Water	Voorhees	7 ft/s (normal), 10 ft/s (fire)
24	Dublin San Ramon Services District	Dublin	5 ft/s (PVC) and 7 ft/s
25	Helix Water District	La Mesa	8 ft/s (normal), 15 fps (fire)
26	Lakeside Water District	Lakeside	8 ft/s (normal), 15 fps (fire)
27	Otay Water District	Spring Valley	8 ft/s (normal), 15 fps (fire)
28	Padre Dam Municipal Water District	Santee	8 ft/s (normal), 15 fps (fire)
29	San Dieguito Water District	Encinitas	8 ft/s (normal), 15 fps (fire)
30	Ramona Municipal Water District	Ramona	8 ft/s (normal), 15 fps (fire)
31	Santa Fe Irrigation District	Rancho Santa Fe	8 ft/s (normal), 15 fps (fire)
32	Sweetwater Authority	Chula Vista	8 ft/s (normal), 15 fps (fire)
33	(city utility)	Central Saanich	6.5 ft/s (normal), 9.8 ft/s (fire)
34	(city utility)	Colwood	6.5 ft/s (normal), 9.8 ft/s (fire)
35	(city utility)	Esquimalt	6.5 ft/s (normal), 9.8 ft/s (fire)
36	(city utility)	Highlands	6.5 ft/s (normal), 9.8 ft/s (fire)
37	(city utility)	Langford	6.5 ft/s (normal), 9.8 ft/s (fire)
38	(city utility)	Metchosin	6.5 ft/s (normal), 9.8 ft/s (fire)
39	(city utility)	North Saanich	6.5 ft/s (normal), 9.8 ft/s (fire)
40	(city utility)	Oak Bay	6.5 ft/s (normal), 9.8 ft/s (fire)
41	(city utility)	Saanich	6.5 ft/s (normal), 9.8 ft/s (fire)
42	(city utility)	Sidney	6.5 ft/s (normal), 9.8 ft/s (fire)
43	(city utility)	Sooke	6.5 ft/s (normal), 9.8 ft/s (fire)
44	(city utility)	Victoria	6.5 ft/s (normal), 9.8 ft/s (fire)
45	(city utility)	View Royal	6.5 ft/s (normal), 9.8 ft/s (fire)
46	(city utility)	Allen	5.4 ft/s (normal)
47	(city utility)	Arlington	5.3 ft/s (normal)
48	(city utility)	Rowlett	5.3 ft/s (normal)
49	(city utility)	Prosper	5 ft/s (normal)
50	Dallas Water Utilities	Dallas	5 ft/s (normal)
51	(city utility)	Frisco	5 ft/s (normal)
52	(city utility)	Pilot Point	5 ft/s (normal)
53	(city utility)	Melissa	5 ft/s (normal)
54	(city utility)	North Richland Hills	5 ft/s (normal)
54	(city utility)	Baton Rouge	4.5 ft/s (normal)
56	(city utility)	Aledo	4.6 ft/s (normal)
57	Luella Water Supply Corp	Luella	4.3 ft/s (normal)

Note: Data obtained from published Utility design guidelines or directly from utility through a telephone survey

Figure 4.2: Summary of Reported Maximum Design Velocities for Normal Flow

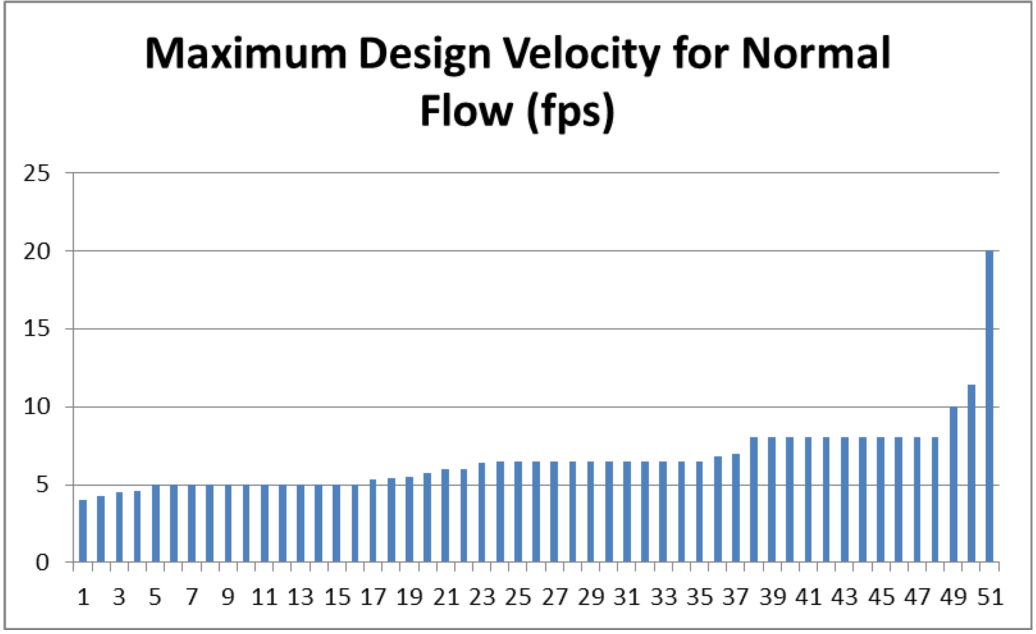
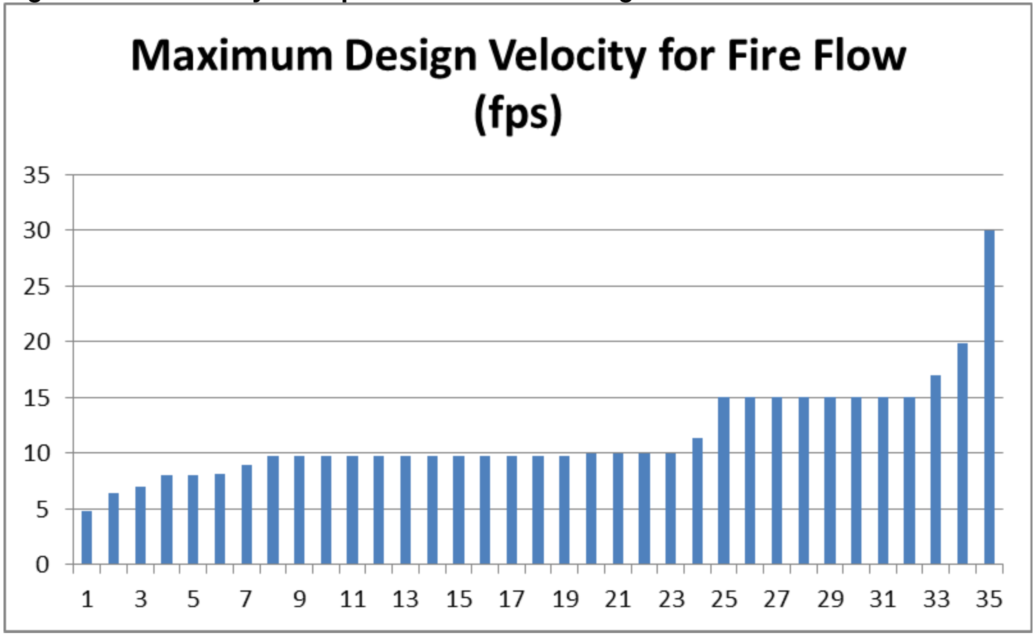


Figure 4.3: Summary of Reported Maximum Design Velocities for Fire Flow



4.3 Resistance of PE and PVC 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 and PVC piping to the potential pressure surges resulting from a sudden flow stoppage at these velocities can be considered.

Thermoplastics like PVC and PE respond to fast loading rates (such as encountered in a surge event with the rapid pressure rise) by exhibiting greater strength and stiffness[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[9]. Pressure surge events on thermoplastic piping systems typically occur at a rate of 14.5 to 145 psi/sec[12]. 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 (and likely equally applicable to PVC 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[13] 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.

The allowable peak pressures, due to a surge event, that are allowed by different design practices are compared for US, UK and Australian design practices for PE4710 and PVC. These values are then compared to expected maximum pressure surges based on the maximum design flow velocities presented in Section 4.2.

4.3.1 Surge Allowance Design Practices for PE4710 and PVC

The US[14-17], UK[9] and Australian[18, 19] PE and PVC pipe design practices all give consideration to design for peak surge events. In comparing the different design approaches, it is important to realize that they are based on different design stresses depending on the long-term strength rating practices of each region. **Table 4.2** provides a comparison of the applicable design stresses. It should be noted that the PVC design stress used in the US is 25% higher than those for the UK and Australia while that for PE is 16% lower than the UK and Australia (based on PE100 materials). This needs to be taken into consideration in comparing the allowable surge stresses between the different rating methods. For this reason the analysis has been conducted on the basis of allowable stress and converted to PC (Pressure Class) where appropriate.

Table 4.2: Design Stresses Used to Derive Maximum Surge Pressure Tolerance

Material	Design Stress (psi)		
	US	UK	Australia
PE4710/PE100	1000[1]	1160[2]	1160[2]
PVC	2000	1595	1595

Note 1: PE4710
Note 2: PE100

Table 4.3 provides the maximum allowable short term stresses for PE4710/PE100 and PVC piping materials based on the respective design practices of each region, compensated for the respective design stresses used. The US and UK approaches are similar with essentially equal surge allowance for PVC and 16% higher surge allowances for PE in the UK than the US. The Australian practice is considerably more conservative, though for PE materials it does provide allowance for higher surge pressures with pressure testing of the system to the desired pressure for surge allowance[18] (this option is not provided for PVC[19]). The allowable surge for PVC is 50% lower than the US and 27% lower for PE (with standard PE pipeline pressure tests).

In all cases, the allowable peak surge stress is well below the short term material strengths for PE and PVC. For example, PE4710 materials are required to have a minimum short term pressure strength of 3200 psi, well above the maximum peak stress of 2000 psi. The UK surge allowances for PE and PVC are based on test data and application of a 0.67 effective design factor, to ensure that the allowable peak pressure stress is safely below the short-term strength of the materials[9]. Conversely, the Australian design practices[18, 19] recognize the increase in short term strength exhibited by PE and PVC materials yet do not provide for this and the design is based on the pressures to which newly installed pipe systems are tested to in the field. The ratings are, therefore, not based on the material's resistance to short term loading but on convention.

Overall, therefore, based on the short term strength of PE and PVC, the US design approaches for PE4710 and PVC are seen to provide reasonable, technically defensible and conservative approaches for determining the allowable peak surge resistance.

Table 4.3: Allowable Upsurge in PE and PVC Pipelines

	Maximum Short Term Surge Stress (psi)		
Material	US[1,2]	UK[3]	Australia[4,5]
PE4710/PE100	2000	2320[6]	1450[7]
PVC[9]	3200	3190[6]	1595[8]

Notes (1) PE rating based on 2 x's PC,(2) PVC Rating based on M23, (3) IGN 4-37-02, (4) Pipa POPO10A, (5) Pipa POP101, (6) Minimum, higher values allowed based on loading rates, (7) Minimum – higher values allowed if pressure testing of system conducted at higher pressures, (8) No provision provided for surge beyond the design stress, (9) Pressure surge may also be limited so that subatmospheric pressure not obtained due to potential for groundwater ingress at gaskets.

Based on the US design approach for PE4710 and PVC, the maximum allowable ΔV or sudden change in velocity as a function of PC was calculated. The data is tabulated in **Table 4.4** and **Table 4.5** for PE4710 and PVC, respectively, and plotted in **Figure 4.4**. The allowable ΔV at comparable pressure classes is similar for both materials, though, as shown in **Figure 4.4**, consistently higher for PE4710 materials.

Table 4.4: Surge Capacity of PE4710 Pipe and Resultant Allowable Sudden Change in Velocity

DR	Pressure Class (PC) for water at 73°F	Allowance for Occasional Surges (psi)	
		Allowable Peak Pressure (psig)	Maximum Allowable Sudden Change in Velocity, fps
7.3	320	640	17.4
9	250	500	15.4
11	200	400	14.0
13.5	160	320	12.4
17	125	250	11.2
21	100	200	10.0

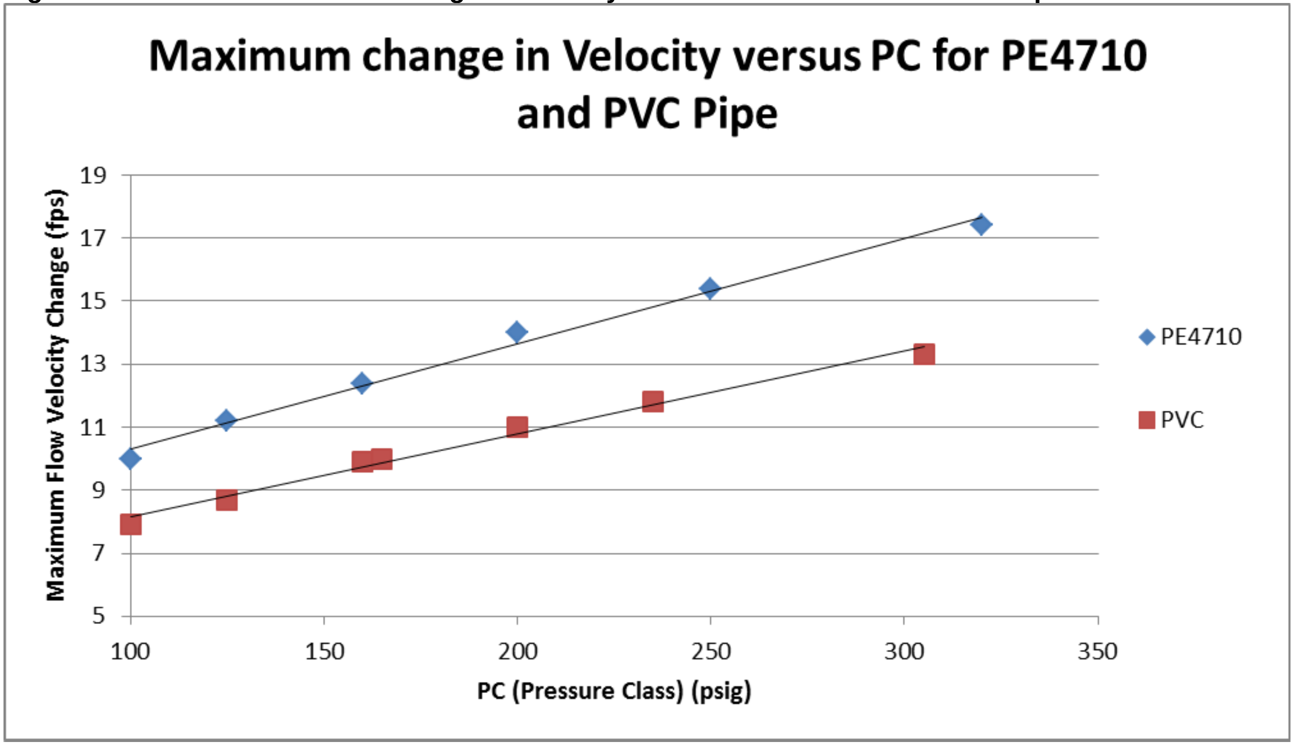
Note: Data calculated based on allowable 2 times PC allowable peak pressure for pipe operating at maximum rated pressure.

Table 4.5: Surge Capacity of PVC Pipe and Resultant Allowable Sudden Change in Velocity

DR	Pressure Class (PC) for water at 73°F	Allowance for Occasional Surges (psi)	
		Allowable Peak Pressure (psig)	Maximum Allowable Sudden Change in Velocity, fps
14	305	488	13.3
18	235	376	11.8
21	200	320	11.0
25	165	264	10.0
26	160	256	9.9
32.5	125	200	8.7
41	100	160	7.9

Note: Data calculated based on allowable 1.6 times PC allowable peak pressure and surge data from C900/C905 for pipe operating at maximum rated pressure.

Figure 4.4: Allowable Sudden Change in Velocity versus PC for PE4710 and PE Pipe



Note: Data for PE4710 calculated based on allowable 2 times PC allowable peak pressure. Data for PVC calculated based on allowable 1.6 times PC allowable peak pressure and surge data from M23 Table 5-6.

The allowable maximum velocity changes can be compared to the maximum design velocities reported in Section 4.2 to determine the appropriate PC of pipe. Below flow velocities of 7.9 fps, PVC PC 100 or greater pressure class piping can withstand a sudden complete flow stoppage. Similarly, below 10 fps, PE4710 PC 100 or greater pressure class piping can withstand a complete flow stoppage. Beyond these flow velocities, **Figure 4.4** can be used to determine the appropriate PC of pipe. For example, at the average maximum design velocity of 11.6 fps, PC 160 PE4710 or PC 235 PVC piping would provide appropriate resistance to peak surge stresses.

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[12] and, therefore, they can be used at the peak surge pressures for the pipe. For PVC pipe materials, bell and spigot joints are the most common. The potential for gasket dislodgment may need to be considered at high surge pressures[20]. Specific studies on the impact of peak surge on this joint type for PVC were not found through the literature search conducted, although pressure testing of joints is required in PVC standards. For PVC piping joined by butt fusion, no studies regarding the impact of peak surge of the joint were found in the open literature.

4.4 Resistance of PE and PVC Piping to Pressure Downsurges

In addition to pressure upsurges, pressure downsurges must also be considered. Pressure downsurges, if they are sub-atmospheric, have the potential to collapse pipelines (which has been observed in steel pipelines) or lead to ingress of groundwater (which can cause potential contamination of drinking water[20]) into the piping system. In general, pressurized pipelines are designed to avoid sub-atmospheric pressures. If such an event does occur, however, it is important to understand the potential impact on the piping system.

Both PE 4710[21] and PVC[22] are resistant to collapse at full vacuum. With a butt fusion joining method, both materials are also immune to groundwater ingress (as the monolithic pipe structure essentially has no 'joints' for leakage to occur). For bell and spigot PVC piping materials sub-atmospheric pressures do, however, provide the potential for groundwater ingress into the system and this should be considered during the design process.

4.5 Section Summary

Proper surge design involves estimating the peak surge event that will occur over the pipe lifetime and ensuring that the piping material is resistant to that level of stress. For both PE and PVC, the US pipe design practices appear reasonable and supported by the available data. The same design approach also appears suitable for PE fusion joints. No direct information on the surge resistance of PVC bell and spigot or fusion joints was found in the open literature and this remains an area in need of future research.

5.0 Cyclic Loading in Water Transmission and Distribution 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[22]. 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. In this section the response of PE and PVC materials to fatigue and the observed mechanisms are reviewed, followed by an overview of the fatigue resistance data for each material. An examination of the fatigue design practices for PE4710 and PVC, the appropriateness of the approaches based on the available fatigue data and a comparison of fatigue performance is also presented.

Overall it is seen that PE4710 materials are highly fatigue resistant and that the current US design approaches appear conservative and appropriate. PVC materials are seen to be susceptible to fatigue and, hence, fatigue is an important design consideration. The current US design approaches appear justified based on available fatigue data. PE4710 materials are seen to have significantly better fatigue resistance than PVC.

5.1 Responses of PE4710 and PVC to Cyclic Loading

There are three primary models for fatigue damage to thermoplastic materials, depending on the type of loading[2]:

- Self-heating with induced localized melting;
- A cumulative damage model;
- A crack propagation model with acceleration by cyclic loading, which may be further subdivided into:
    - Pure fatigue
    - Combined creep and fatigue

Of these, the first can be wholly discounted as a mechanism in water pipelines due to the high thermal heat sink of the water and soil and the relatively low surge frequencies. The other two mechanisms are briefly reviewed in this section along with an assessment of the expected impact of the higher slow crack growth resistance of PE4710 materials on fatigue performance.

5.1.1 Cumulative Damage Model

The cumulative damage model is applied to situations where the ultimate failure mode is macroscopically ductile[2]. The loading scenarios that can cause macroscopically ductile failure in plastic materials vary. Most plastics can be made to fail by ductile yielding in monotonic tensile tests if tested at a sufficiently slow rate and sufficiently high temperature. Most plastics, if loaded to slightly less than that yield stress, will fail ductily in a short time. At a still lower stress, the time to failure will be longer. The same plastics, if repeatedly and rapidly loaded and unloaded to that stress, will fail ductily after some number of cycles. For cyclic loading that produces macroscopically ductile failures, the time to failure is dependent on the cumulative time at peak stress, not on the number of cycles[2]. This behavior characterizes (essentially, defines) the cumulative damage model: ductile failures (those which occur by necking and thinning and other post-yielding behaviors) occur when the cumulative time at peak stress is equal to the time that would cause failure in a constant-load creep test[2]. Essentially, one cannot speed-up a ductile failure test (static or dynamic) by cycling the stress unless one increases the peak stress. In other words, there are no macroscopically ductile failures that are true fatigue failures: they are stress-rupture failures caused by multiple intermittent overstress events.

The critical value is regarded as the time for failure to occur at a constant stress equal to the peak cyclic stress. That is, the total time to failure at peak stress in cyclic loading will be equal to the total time to failure for static loading at the same stress. In this model the number of events to failure can be calculated as[2]:

$$\mathbf{N_f = (t_{sr}/t_{max})_{T,\sigma}} \qquad \textbf{(4)}$$

where:

N_f = number of cycles to failure
t_{sr}= time to stress rupture
t_{max}= time of each cycle at stress
T = temperature
σ = stress

The model has been shown to be applicable to PVC and to PE[2] for failures in either material that are macroscopically ductile in accelerated cycling loading. Under these scenarios the materials do not experience fatigue weakness.

This mechanism is different from that expected in many piping applications where the pressure surges are of short duration with time for material relaxation between surges. Under these conditions the surges have been projected not to impact the long term strength and the mean pressure determines design[13]. The cyclic loading region where each of these different mechanisms operates has not been clearly defined for PE or PVC materials and remains an opportunity for further research.

5.1.2 Crack Initiation and Propagation with Acceleration by Cyclic Loading

Many plastics will cease to exhibit this response as the peak load is decreased and the number of cycles to fail increases. Those materials will transition to a macroscopically brittle failure mode, with very different failure morphology and failure arithmetic. Macroscopically brittle failures are an artifact of crack initiation followed by crack propagation[23-25]. Under cyclic loading conditions this mechanism is prone to fatigue weakness[26-28]. Unlike in the ductile regime where the cumulative damage model applies, the total time at peak stress is typically lower under cyclic fatigue than under static loading at the same conditions.

Crack initiation and propagation failures depend on the number of cycles, the loading rate, the peak stress, and the stress amplitude. Crack propagation is accelerated by cyclic loading. Thus, brittle failures that occur under cyclic loading conditions are fatigue failures (or they are at the very least fatigue-assisted failures). Fatigue failures can occur with some materials in a few weeks to months even when the peak cyclic stress is less than 50% of the extrapolated long-term creep-rupture stress. Other materials can sustain essentially unlimited cycles to a much higher fraction of their long-term creep-rupture stress[1, 9].

For plastic pipes in water applications, loading scenarios that cause ductile failure are extremely rare. It takes gross under-design, a significant temperature excursion beyond design limits, or a very significant pressure excursion beyond design limits to produce a ductile failure. Loading scenarios that produce brittle failures are uncommon, but much less so than those for ductile failures. Depending on the crack-initiation and crack-propagation resistance of the material, brittle failures in pipe can be induced by point loads (such as from rock impingement), by average stress combined with long times (for materials with inadequate slow crack growth (SCG) resistance), or by fatigue from the cyclic system stress (for materials with inadequate fatigue resistance).

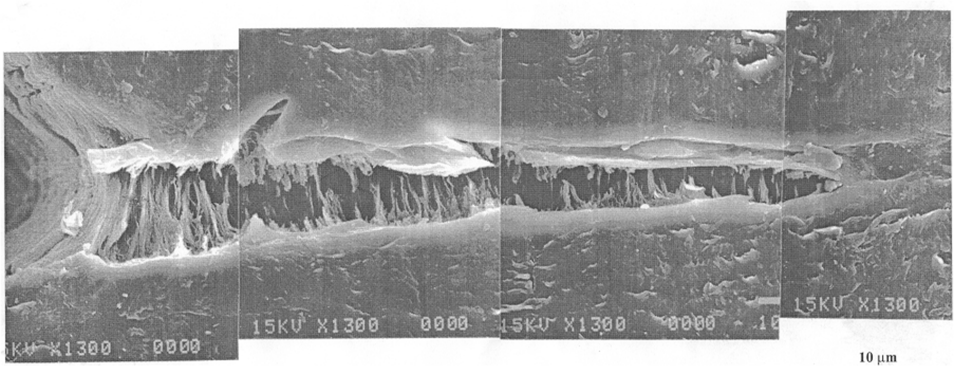
Limited studies[2] suggest that there may be an impact of both creep and fatigue on the long term strength of older generation PE materials under cyclic load.

5.1.2.1 Observed Fracture Mechanisms in Fatigue Acceleration of Brittle Cracks

Crack initiation and crack propagation have been studied for many plastic materials including PE[29-31] and PVC[32, 33]. In PE, there is only one characteristic slow crack growth morphology (SCG) regardless of the temperature or load cycle. In PE, the crack tip progresses in a stepwise advance-arrest sequence, behind a progressing single linear craze[25]. PVC exhibits that same morphology under certain conditions: faster stress cycles, lower temperature, and higher amplitudes favor this morphology and mechanism[34]. Slower cycles, higher temperature, and lower amplitudes produce a different morphology and mechanism[34]. In this second mechanism, there are multiple crazes with multiple initiation points that coalesce to the final fracture. Craze density measurements have been made in the vicinity of the advancing crack tip and the craze density was found to increase with temperature and to decrease with increasing cycle frequency[34].

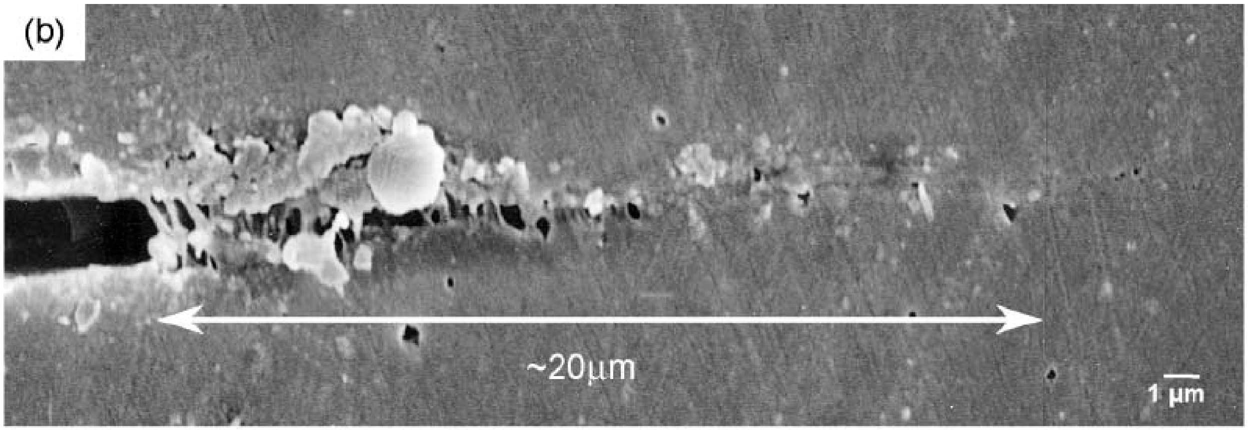
Investigation of field samples of PE and PVC piping materials has provided observations and experience that illustrate the practical significance of these mechanisms. Field failures in older generation PE that have occurred by slow crack growth always show fracture morphology consistent with the stepwise progression of a single linear craze-crack process. This is true whether the SCG initiates at a stress concentration from localized external impingement, from distributed external stress, from excessive localized bending, or from an internal flaw. **Figure 5.1** provides a detail of an advancing crack showing the detailed morphology. The microfibrals spanning the crack face in the process zone restrain the advancement of the crack until they are drawn down, elongate and rupture. In cyclic loading the fibrils creep at peak stress and are ‘bent’ when the stress is relaxed due to the contractive stresses created in the bulk material around the advancing crack. It is this bending mechanism which causes fatigue acceleration beyond pure static creep loading. An important aspect of fatigue for PE materials is that this mechanism only occurs under conditions where a crack can form, it is not operable in the ductile mode. This is why an increase in the slow crack growth resistance of PE materials results in a corresponding increase in fatigue resistance[35, 36] to the point, as shown in Section 5.2, where current generation high slow crack growth materials appear to exhibit almost unlimited fatigue resistance[1, 9] under the loading conditions found in potable water applications.

Figure 5.1: SCG Mechanism in PE Pipe



Field failures in PVC sometimes show similar fracture morphology[34] as shown in **Figure 5.2**. Those fractures typically are associated with concentrated point loads such as impingement by a single rock point. The SCG fracture pattern in those failures closely resembles that of a PE failure. The more common PVC pipe field fracture morphology is one that derives from the simultaneous incubation and initiation of multiple crazes that grow into a coalescing dominant crack. These fracture surfaces are significantly rougher and more irregular than the single-craze type, often with macroscopic shear steps or jumps where small cracks join. This morphology is generally found when the external stress is significant but spatially distributed, such as a pipe bedded on hardpan. It is also found when failures occur by fatigue in the absence of concentrated external stress.

Figure 5.2: Fatigue Slow Crack Growth in PVC



This fatigue mechanism appears to be the limiting mechanism for PVC in applications with high cyclic stress (frequent pressure surges of significant amplitude). In those applications the long-term static strength of the PVC pipe becomes irrelevant; PVC pipe design in those applications becomes design against fatigue failure. This is incorporated into U.S. and international design practices for PVC. As the following sections explain, designing to prevent pipe fatigue failure is relatively more complex for PVC than for PE4710. This is a consequence of the susceptibility of PVC to fatigue and the high fatigue resistance of modern high slow crack growth resistance PE materials.

5.2 Review of Fatigue Resistance Data for PE and PVC Pipe Materials

Literature searches were conducted to collect the available fatigue resistance data for PE and PVC piping materials. Significant fatigue studies have been conducted for PVC piping materials as fatigue is recognized as a potentially design limiting phenomenon in many applications. The PE fatigue literature is also 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 and PVC along with a comparison of the fatigue performance of the two materials. Overall, the fatigue resistance of PE materials is acknowledged to be vastly superior to that of PVC[1, 2, 9].

5.2.1 Overview of Existing PE Fatigue Data

Detailed literature searches of the existing fatigue studies for PE pipe were conducted. This section provides a summary of the findings and a discussion of the most pertinent studies. In general, PE materials, particularly current generation high slow crack growth resistant materials, are seen to be extremely fatigue resistant.

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.

The bulk of the studies fall into category three and are focused on accelerated testing of notched molded specimens[29-31]. 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, however, 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[1, 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[35, 36]. 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[1, 9].

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 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[2]. The studies also demonstrated that fatigue failures in accelerated testing occurred in the pipe and not the fusion joints[2], indicating the joints are not a point of weakness.

The UK water industry[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[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 and higher to over 10,000,000 cycles. For US design approaches for PE4710 materials, a stress range of 1500 psi is equivalent to testing at 1.5 times the PC, which, as discussed in Section 5.3.2 to follow, 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 for over one million cycles with no failure[37]. The hoop stress was 1160 +/- 580 psi, which in the US rating system is equivalent to testing at 1.16 times pressure class +/- 58% of 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[35]. 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 the stress was cycled between 100 and 900 psi (mean stress of 500 psi) for unnotched pipe samples. This would be equivalent to cycling well beyond the 1.5 times PC at 23°C. 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[2] for mid 1980s materials was used as well as employing the general rule of thumb for temperature acceleration of a doubling in reaction rate for every 10°C increase in temperature (typically very conservative when applied to SCG type mechanisms). The resulting analysis projected that fatigue lifetimes at 20 °C 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.

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

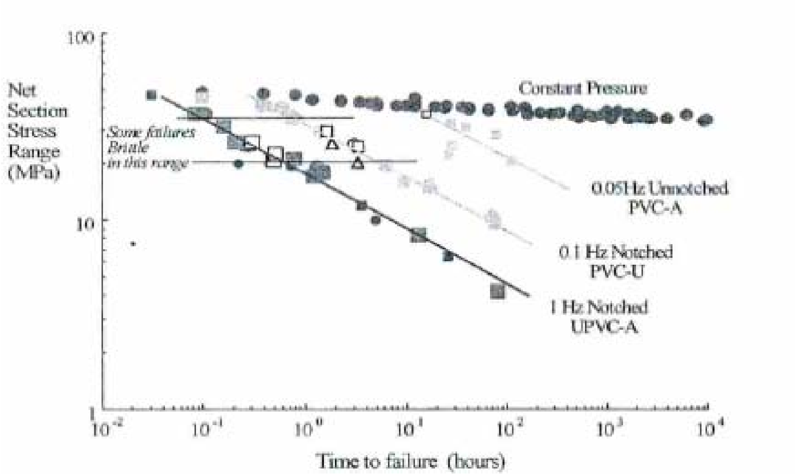
These conclusions could be verified through a simple, well designed testing program as detailed in the Recommendations section.

5.2.2 Overview of Existing PVC Fatigue Data

Detailed literature searches of the existing fatigue studies for PVC pipe were conducted. This section provides a summary of the results and a discussion of the most pertinent studies. In general, PVC materials are susceptible to fatigue and design for the fatigue loading characteristics of the application is an essential component of ensuring performance.

The literature recovered for PVC related to fatigue is generally focused on the reality of fatigue failure in PVC piping[1, 3], and design strategies to avoid it[9, 19]. The primary studies are those of Moser[4], Leevers and Joseph[38], Vinson[39], Marshall[40], Bowman[41, 42], Hitch[43] and Whittle[3]. It is clear from the literature that fatigue failures can be predicted in PVC pipe, with the number of cycles to failure dependent on the stress amplitude (primarily) and the mean stress (less so). The impact of fatigue on PVC pipe can be seen in **Figure 5.3** where the decrease in long-term strength under fatigue relative to the constant load long-term strength is clearly shown

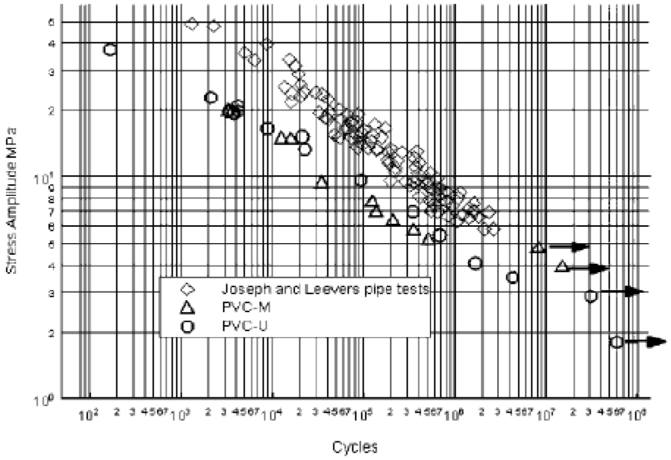
Figure 5.3: Impact of Fatigue on Long-Term Strength of PVC



Note: Figure from Reference 1

In general, all PVC formulations have similar fatigue resistance[38] and so performance may be generalized for design purposes. **Figure 5.4** shows a compilation of data from studies from Brogden and leevers on rigid PVC pipe[3] (uPVC in European terminology). The literature data for PVC seems generally consistent in the projection of fatigue performance. The literature is also consistent in the recognized need for consideration of fatigue and the potential for de-rating in the design of PVC piping. The differences lie in the interpretation of the data and development of a methodology to account for fatigue performance. This is examined in Section 5.3.

Figure 5.4: Compilation of PVC Fatigue Performance Data



Note: Figure from Reference 3

5.3 General Fatigue Design Approaches for Thermoplastic Piping Materials

Fatigue design for pipelines follows the general approach of estimating the required PC of pipe based on the long-term pressure and surge requirements of the application, estimating the number and magnitude of cyclic surge events (through transient modeling of the system) and then applying a de-rating, where it is required, to account for the impact of the cyclic surge events on the specific piping material.

As there is no universal, global, approach for accounting for the impact of fatigue in water transmission and distribution for thermoplastic piping materials, this section examines and compares the US, UK and Australian design approaches for both PE and PVC piping, along with the data supporting each approach, to make an assessment of the appropriateness of the US design approaches. The potential number and magnitude of cyclic loading events in water transmission and distribution systems is examined and a basis is selected for comparison of the design approaches. The design approaches for PE4710 and PVC are then each examined separately. The section concludes with a comparison of the fatigue design of PE4710 and PVC.

5.3.1 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 for municipal potable water systems. Long service lives require significant resistance to fatigue, even if the daily number of surges is relatively small**. Table 5.1** shows the cumulative events for 50 and 100-year service lives for events tallied on a daily and hourly basis.

Table 5.1: Pressure Surges in a 100-year Service Life

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	4562,500	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.

As in end-use applications there is a wide variation in the number and stress amplitude of surge events, it is not possible to characterize them all in this paper. A basis for analysis was selected, therefore, that would allow examination of the appropriateness of the design approaches and comparisons of material performance. This approach was developed based on available literature on measured surge events in operating pipelines (of which there is little), knowledge of expected flow velocities and potential surge frequencies from **Table 5.1**. The result is an analysis grid that covers a broad range of potential end-use operating conditions that is believed to provide a sound basis for the analysis objectives of this report.

Two analysis scenarios were examined (labeled Analysis #1 and Analysis #2). In Analysis #1, the impact of a surge frequency of 55 surge events per day (approximately 2 surge events per hours or 1,000,000 surges over 50 years is examined for a variety of operating pressures and flow velocities. In Analysis #2, the impact of different surge frequencies is examined for a variety of flow conditions and an operating pressure of 125 psig.

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[38] 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. This practice is not universally specified.

For both scenarios, pressure surges were estimated based on an assumed velocity change and the Joukowsky Equation[6] (Equation 1). For recurring pressure surges it is the standard operational pressure surges and not the peak pressure of worst case events that is of primary interest and, therefore, the actual operating flow velocity that should be considered in the analysis. This approach is consistent with that presented in UKWIR IGN 4-37-02[9] which states, in terms of fatigue design that worst case surges should not be often repeated events and need to be considered only in the surge design. Based on the utility data presented in Section 4.2, and general industry reference to flow velocities, systems were considered with flow velocities ranging from 2 fps to 7 fps. The resulting calculated pressure surges are presented in **Table 5.2** and **Table 5.3** for PE4710 and PVC, respectively. Based on this data, the cyclic loading scenarios presented in **Table 5.4** were devised for Analysis #1. This data is used in the subsequent analysis to examine the fatigue design approaches for PE4710 and PVC pipeline based on the US[14-17], UK[9] and Australian[18, 19] design approaches.

To broaden the analysis, a grid of conditions was analyzed (Analysis #2). This grid covers flow velocities from 2 fps (commonly used in design examples for PVC materials) through to 6.7 fps, the average velocity found in the utility survey conducted (Section 4.2). Actual velocities examined are 2, 3, 4, 5, 6 and 6.7. The analysis also covers surge frequencies from **Table 5.1**, providing a relatively complete coverage of potential surge situations. The analysis is conducted at an operating pressure of 125 psig.

Table 5.2: Estimated Pressure Surges for PE4710 Pipe

DR	Pressure Class (PC) for water at 73 °F	Estimated Pressure Surge (psi)		
		With 2 fps Velocity Change	With 5 fps Velocity Change	With 7 fps Velocity Change
7.3	320	37	92	129
9	250	32	81	113
11	200	29	72	101
13.5	160	26	64	90
17	125	22	56	79
21	100	20	50	70

Table 5.3: Estimated Pressure Surges for PVC

DR	Pressure Class (PC) for water at 73 °F	Estimated Pressure Surge (psi)		
		With 2 fps Velocity Change	With 5 fps Velocity Change	With 7 fps Velocity Change
14	305	40	99	139
18	235	35	87	122
21	200	32	80	112
25	165	29	74	103
26	160	29	72	101
32.5	125	26	64	90
41	100	23	57	80

Table 5.4: Cyclic Loading Scenarios Considered for Analysis 1

Maximum Standard Operating Pressure (psi)	Effective Velocity Change (fps)[1]
125	2
	3
	4
	5
	6
	6.7[2]
100	2
	3
	4
	5
	6
	6.7[2]
80	2
	3
	4
	5
	6
	6.7[2]

Notes: 1: Effective velocity change is defined as the velocity change occurring to cause the fatigue event, this may be lower than the actual operating flow velocity. 2: 6.7 fps was the average design velocity found from a survey of Water Utilities (see Section 4.2)

5.3.2 PE Pipe Fatigue Design Practices

A brief summary of the US, UK and Australian fatigue design approaches is provided, followed by a comparison of the different approaches. PE4710 materials are analyzed in this section, PVC materials in Section 5.3.3 and a comparison of the two materials is provided in Section 5.3.4.

The current US PE pipe design practice for pressure and pressure surges is documented in AWWA C901[14], C906[15], M55[21] and the Plastic Pipe Institute Handbook of PE Pipe[44]. 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 current UK approach, as detailed in UKWIR IGN 4-37-02[9], does not require fatigue de-rating for PE100 materials meeting the UK performance standards and, therefore, allows for an unlimited number of fatigue events. The allowable maximum stress for surge amplitude is effectively the design stress (which for PE materials translates to 1160 psi) which translates into a maximum total peak surge of 2 x PC.

The Australian approach, as detailed in PIPA POP010A[18], requires the cyclic peak pressure to be below the design pressure and provides for fatigue de-rating of PE100 materials for greater than 300,000 total cycles. The de-rating factors, or 'fatigue load factors', are based on the number of cycles. The allowable pressure is calculated from the pressure range (peak pressure minus minimum pressure) divided by the fatigue load factor to obtain an equivalent operating pressure. The allowable maximum peak surge stress for cyclic loading is, therefore, effectively the design stress (which for PE materials translates to 1160 psi) for below 300,000 cycles and the design stress times the appropriate fatigue load factor for greater than 300,000 load cycles.

For Analysis #1 with 1,000,000 surges in fifty years and 2,000,000 surges in 100 years (which translates to 2,000,000 and 4,000,000 cycles, respectively, using the two times factor introduced in Section 5.3.1) the resulting estimated pressure surges and required pipe DRs are presented for a range of PCs in **Table 5.5** for the US design approach and **Table 5.6** for the UK design approach. No de-rating is required based on the UK design approach. Note also, that the PCs for a given DR are higher (16%) than those allowed based on the US design approach and, therefore, PC100 would be usable for all design scenarios. For the US design approach, de-rating is required when the total peak surge is greater than 1.5 times the PC as shown in **Table 5.5**. The US fatigue design approach for PE4710 materials is considerably more conservative than the UK design approach.

Table 5.5: Required PC for Various Repetitive Surge Situations for PE4710 Materials per US Design Methodology Based on Analysis #1

Maximum Standard Operating Pressure (psi)	Effective Velocity Change (fps)	Resultant Repetitive Surge Pressure (Surge Amplitude) (psi)	Required DR[3]			
			50 year Fatigue Design Life[1]		100 year Fatigue Design Life[2]	
			DR	PC	DR	PC
125	2	23	17	125	17	125
	3	34	17	125	17	125
	4	45	17	125	17	125
	5	56	17	125	17	125
	6	77	13.5	160	13.5	160
	6.7	86	13.5	160	13.5	160
100	2	20	21	100	21	100
	3	30	21	100	21	100
	4	40	21	100	21	100
	5	50	21	100	21	100
	6	68	17	125	17	125
	6.7	75	17	125	17	125
80	2	18	26	80	26	80
	3	27	26	80	26	80
	4	36	26	80	26	80
	5	50	21	100	21	100
	6	60	21	100	21	100
	6.7	67	21	100	21	100

Note: 1: Based on 1,000,000 x 2 cycles for 50 years
Note 2: Based on 2,000,000 x 2 cycles for 100 years
Note 3: All values calculated per AWWA C901/C906 Surge Procedures

Table 5.6: Required PC for Various Repetitive Surge Situations for PE4710 Materials per UK Design Methodology Based on Analysis #1

Maximum Standard Operating Pressure (psi)	Effective Velocity Change (fps)	Resultant Repetitive Surge Pressure (Surge Amplitude) (psi)	Required DR[3]			
			50 year Fatigue Design Life[1]		100 year Fatigue Design Life[2]	
			DR	PC	DR	PC
125	2	32	21[4]	100[5]	21[4]	100[5]
	3	48				
	4	64				
	5	80				
	6	96				
	6.7	107				
100	2	32	**21[4]**	**100**	**21[4]**	**100**
	3	48				
	4	64				
	5	80				
	6	96				
	6.7	107				
80	2	32	**21[4]**	**100**	**21[4]**	**100**
	3	48				
	4	64				
	5	80				
	6	96				
	6.7	107				

Note 1: Based on 1,000,000 x 2 cycles for 50 years
Note 2: Based on 2,000,000 x 2 cycles for 100 years.
Note 3: All values calculated per UK WIR IGN4-37-02
Note 4: Low DR and PC could be used based on UK design if available,
Note 5: PC100 would only be required based on UK design as higher allowable HDS for PE100 materials

For the Australian design approach de-rating of the pipe would be required as the peak surge pressure is not to exceed the design stress. This is considerably more conservative than both the US and UK design approaches.

The results of Analysis #2 are presented in **Table 5.7**. There is no need for fatigue de-rating of PE4710 for the full range of surge scenarios examined. At flow velocities above 5 fps the 1.5 times PC requirement results in a need for a higher PC at these conditions.

Table 5.7: Pressure Class Requirements for Repetitive Surge Situations for PE4710 per US Design Based on Analysis #2 Grid for 125 psi Operating Pressure

Daily Surges	Approximate Surges per hour	Required Pressure Class As a Function of Effective Flow Velocity (fps)											
		2		3		4		5		6		6.7	
		DR	PC	DR	PC	DR	PC	DR	PC	DR	PC	DR	PC
1	0.04	17	125	17	125	17	125	17	125	13.5	160	13.5	160
10	0.4												
40	2												
75	3												
150	6												
250	10												
300	13												

PE4710 materials, based on current design approaches, would, therefore, not generally require any pressure de-rating for the broad range of conditions examined until flow velocities start to exceed 5 fps. The US design approach is also seen to be significantly more conservative than the UK approach. The Australian approach is considerably more conservative than the UK and US approaches.

5.3.3 Summary of Supporting Documentation for PE Fatigue Design

An examination of the PE fatigue data supporting the US, UK and Australian design approaches was conducted to assess their validity. As discussed previously, it is seen that the US approach is conservative relative to the UK design approach for high slow crack growth resistant materials and that current fatigue data supports the US approach. With more specific data development (see Recommendations section) there may be room to closer align the US and UK approaches by increasing the allowable fatigue design limits in US design. The Australian approach is seen to be overly conservative for PE materials based on available fatigue data. This has been recognized by the Australian industry and efforts to revise the approaches are being promoted[45].

The US design approach was developed based on an analysis of then available information for the fatigue resistance of PE materials. Since this time, the slow crack growth resistance and, based on the available test data, fatigue resistance of PE materials has improved considerably. This advancement in material performance has been captured in the UK standards which do not require any fatigue de-rating for PE100 materials but has not been captured in the current US design approaches (which applies the same design approach to all PE materials).

As discussed in Section 5.2.1, the UK water industry examined the fatigue resistance of modern PE materials (PE80 and PE100 materials with high slow crack growth resistance) and 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 and higher to over 10,000,000 cycles. For US design approaches for PE4710 materials, a stress range of 1500 psi is equivalent to testing at 1.5 times the PC. This data, therefore, supports the current US design approach for PE4710 materials. Additionally, as also reported in Section 5.2.1, accelerated fatigue testing was conducted on a resin with a compression molded PENT value just above the 500 hour minimum required for PE4710 materials. At 90^{o}C the stress was cycled between 100 and 900 psi (mean stress of 500 psi) for un-notched pipe samples. This would be equivalent to cycling well beyond the 1.5 times PC at 23^{o}C. As discussed previously, this is estimated to correspond to projected fatigue lifetimes at 20 ^{o}C between 1.6 x 10^9 (over 1 billion) to 4.2 X 10^7 (42 million) cycles. While the approximation is crude, it does, combined with the UK data, support the current US design approach for PE4710 materials.

The Australian design approach does not present any fatigue data that would indicate an identified fatigue weakness for high slow crack growth resistant PE materials. The overly conservative approach appears to be a remnant of past practices and is under pressure for revision by the Australian industry.

Overall, therefore, the current US design approach for PE4710 materials is supported by the available fatigue data. Based on the UK design approach, there may even be the potential to increase the cyclic loading allowance for PE4710 materials. Recommendations for testing to examine this opportunity are presented in Section 6.

5.3.4 PVC Pipe Fatigue Design Practices

The US, UK and Australian design approaches were also examined for PVC along with a comparison of the different approaches based on Analysis #1.

The current AWWA PVC pipe design practice for pressure and pressure surges is in AWWA C900-07 and C905-10 . The pipe pressure rating (Pressure Class) is calculated using the Recommended Hydrostatic Design Basis (HDB) and the standard ISO equation. The Pressure Class must exceed the sum of the average pressure (static pressure) plus the amplitude of the recurring surge. All recurring surge pressures, therefore, reduce the Working Pressure Rating of the PVC pipe to something less than the Pressure Class. The recurring surges are assumed to be sinusoidal around the average pressure, with a stress range equal to twice the stress amplitude. Thus, a pipeline operating at an average pressure of 100 psig with recurring surges of 50 psig would require pipe with a pressure class of 150 psig or higher.

An additional calculation must be performed to check the anticipated number of cycles during the design life against the design fatigue limit of the PVC pipe. The design fatigue limit is determined from a Cyclic Design chart with input variables of mean stress and stress amplitude for the recurring surges (**Figure 5.5**). The number of primary surges is multiplies by two to provide the number of surge events considered for design. While the AWWA design approach for PVC states the primary number of cycles is multiplied by 2 to provide a ‘safety factor’, the findings of Joseph discussed earlier suggest that this is just good practice to account for the decaying pressure waves generated by the surge event and does not actually represent a safety factor as presented.

The required DRs for Analysis #1 based on the US design approach are presented in **Table 5.8** for various static line pressure and repetitive surge pressure combinations. At low stress amplitude, the design approach projects high fatigue resistance of PVC pipe materials. As the magnitude of the repetitive surge increases, the required DR decreases, requiring higher pressure class piping.

The same calculations were conducted based on the UK design approach, as presented in **Table 5.9**. The lower HDS (hydrostatic design strength) allowed under the UK approach (26% lower than the allowable US HDS) is included in the calculation. The UK approach is noticeably more conservative that the US design approach across the full range of end-use conditions examined.

Figure 5.5: Excerpted PVC fatigue design chart, Figure B2 from AWWA C905-10

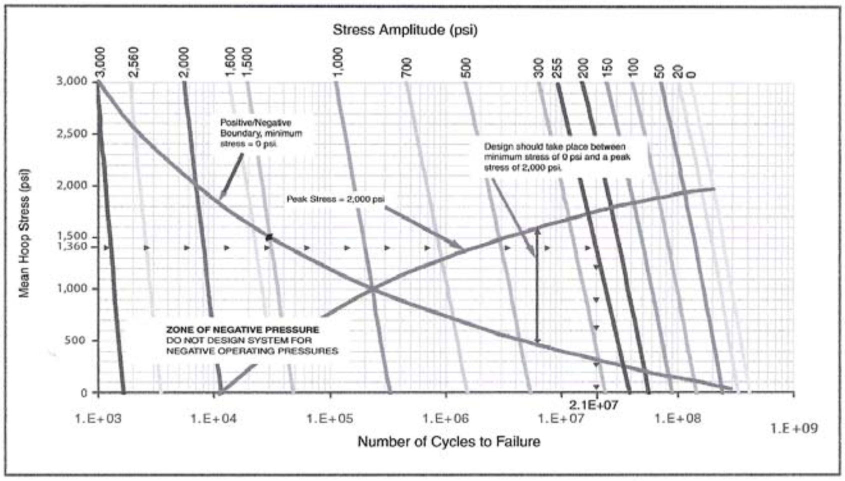


Figure B.2 Cyclic design curves

Table 5.8: Required PC for Various Repetitive Surge Situations for PVC Materials per US Design Methodology Based on Analysis #1

Maximum Standard Operating Pressure (psi)	Effective Velocity Change (fps)	Resultant Repetitive Surge Pressure (Surge Amplitude) (psi)		Required DR[3]			
				50 year Fatigue Design Life[1]		100 year Fatigue Design Life[2]	
		50 yr DR	100 yr DR	DR	PC	DR	PC
125	2	29	29	26	160	26	160
	3	48	52	21	200	18	235
	4	79	-	14	305	-	-
	5	-	-	-	-	-	-
	6	-	-	-	-	-	-
	6.7	-	-	-	-	-	-
100	2	26	26	32.5	125	32.5	125
	3	43	52	26	160	21	200
	4	70	-	18	235	-	-
	5	-	-	-	-	-	-
	6	-	-	-	-	-	-
	6.7	-	-	-	-	-	-
80	2	26	26	32.5	125	32.5	125
	3	43	48	26	160	21	200
	4	70	-	18	235	-	-
	5	-	-	-	-	-	-
	6	-	-	-	-	-	-
	6.7	-	-	-	-	-	-

Note 1: Based on 1,000,000 x 2 cycles for 50 years
Note 2: Based on 2,000,000 x 2 cycles for 100 years
Note 3: All values calculated per AWWA C900/C905 Surge Procedures

Table 5.9: Required PC for Various Repetitive Surge Situations for PVC Materials per UK Design Methodology

Maximum Standard Operating Pressure (psi)	Effective Velocity Change (fps)	Resultant Repetitive Surge Pressure (Surge Amplitude) (psi)	Required DR[3]			
			50 year Fatigue Design Life[1]		100 year Fatigue Design Life[2]	
			DR	PC	DR	PC
125	2	28	21	200	21	200
	3	47	14	305	14	200
	4	63	-[4]	-[4]	-[4]	-[4]
	5	84	-[4]	-[4]	-[4]	-[4]
	6	101	-[4]	-[4]	-[4]	-[4]
	6.7	128	-[4]	-[4]	-[4]	-[4]
100	2	25	21	200	21	200
	3	42	14	305	14	200
	4	63	-[4]	-[4]	-[4]	-[4]
	5	78	-[4]	-[4]	-[4]	-[4]
	6	94	-[4]	-[4]	-[4]	-[4]
	6.7	128	-[4]	-[4]	-[4]	-[4]
80	2	25	21	200	21	200
	3	38	14	305	14	200
	4	56	-[4]	-[4]	-[4]	-[4]
	5	70	-[4]	-[4]	-[4]	-[4]
	6	94	-[4]	-[4]	-[4]	-[4]
	6.7	128	-[4]	-[4]	-[4]	-[4]

Note: 1: Based on 1,000,000 x 2 cycles for 50 years
Note 2: Based on 2,000,000 x 2 cycles for 100 years
Note 3: All values calculated per UK WIR IGN4-37-02
Note 4: Not usable in available DR range (< DR 14 required)

Table 5.10 provides the results of Analysis #2 for PVC. The Table clearly demonstrates that fatigue becomes a significant issue for PVC as flow velocities approach 5 fps (lower at higher surge frequencies) and with increasing surge frequency (> 3 surges per hour).

Table 5.10: Pressure Class Requirements for Repetitive Surge Situations for C900/C905 PVC per US Design Based on Analysis #2 Grid for 125 psi Operating Pressure, 50 years (#design surges = #surges x2)

Daily Surges	Approximate Surges per Hour	Required Pressure Class As a Function of Effective Flow Velocity (fps)					
		2	3	4	5	6	6.7
1	**0.04**	160	200	200	235[1]	235[1]	305[1]
10	**0.4**	160	200	200	235[1]	235[1]	305[1]
40	**2**	160	200	235[1]	305[1]	-[2]	-[2]
75	**3**	160	200	305[1]	-[2]	-[2]	-[2]
150	**6**	160	305[1]	-[2]	-[2]	-[2]	-[2]
250	**10**	200	-[2]	-[2]	-[2]	-[2]	-[2]
300	**13**	200	-[2]	-[2]	-[2]	-[2]	-[2]

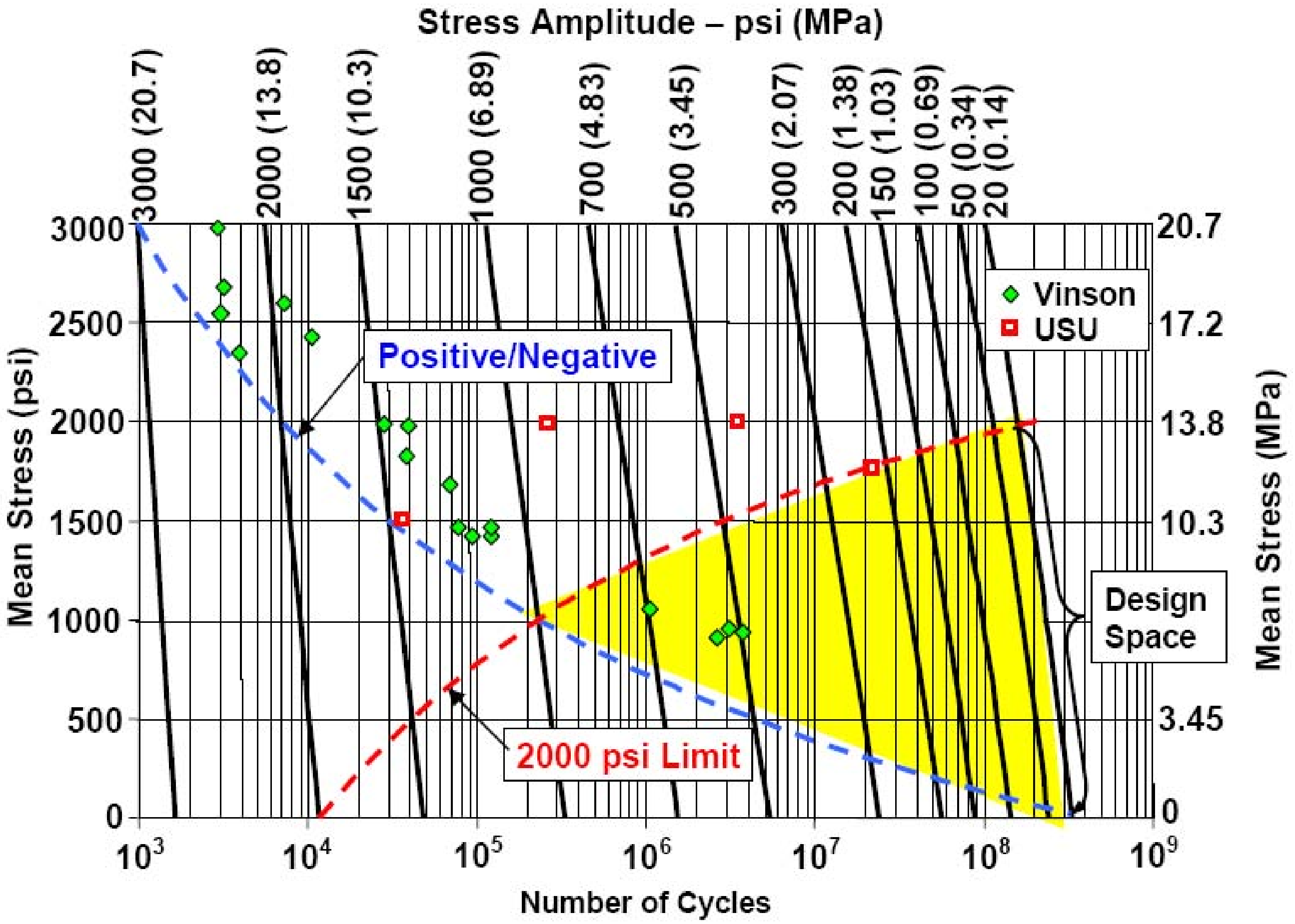
Notes: 1: This PC not specified in all pipe diameters in C900/C905, 2: Beyond PC in C900/C905

The Australian design approach, similar to the case for PE, is considerably more conservative than both the US and UK design approaches as it is based on a HDS of 1595 and more stringent fatigue limitations.

5.3.5 Summary of Supporting Documentation for PVC Fatigue Design

The US PVC design approach is based on the work of Moser et al at Utah State University and the work of Vinson. Moser took the data of Vinson and reanalyzed it to create a plot of mean stress versus cycles to failure with the stress amplitude lines overlaid, similar to that presented in AWWA C900 and C905. Moser then conducted additional research on the fatigue resistance of PVC and, with this and Vinson's data, created the final plot provided for design in AWWA C900 and C905 (**Figure 5.6**).

Figure 5.6: AWWA C900 and C905 Design



Moser supplies the data used to generate the ultimate design guidelines for PVC[4]. The data of Vinson as presented in Moser's paper was examined and compared to the data developed by Moser. If the Vinson data is plotted based on log(stress amplitude) versus log(cycles to failure) (the general UK approach) a straight line is obtained with an r^2 of 0.974, indicative of excellent fit of the data, as shown in **Figure 5.7**. When Moser's data is added to that of Vinson, an excellent agreement between the datasets is observed as shown in **Figure 5.8**. The r^2 of the combined datasets is 0.973, almost identical to that of the original Vinson data on its own. This shows that the Moser data is in excellent agreement with the Vinson data and fits the same log(stress amplitude) – log(cycles to failure) model. The plots also show that using a log(stress amplitude) – log(cycles to failure) model provides a generally good fit to the experimental data, although the resulting equation appears to over predict fatigue lifetime at low stress amplitude. The data also shows that it is the stress amplitude that primarily controls the fatigue lifetime of PVC, consistent with the findings of Moser and others.

Figure 5.7: Original Vinson Data Shows Excellent Fit on Log-Log plot of Stress Amplitude versus Cycles to Failure

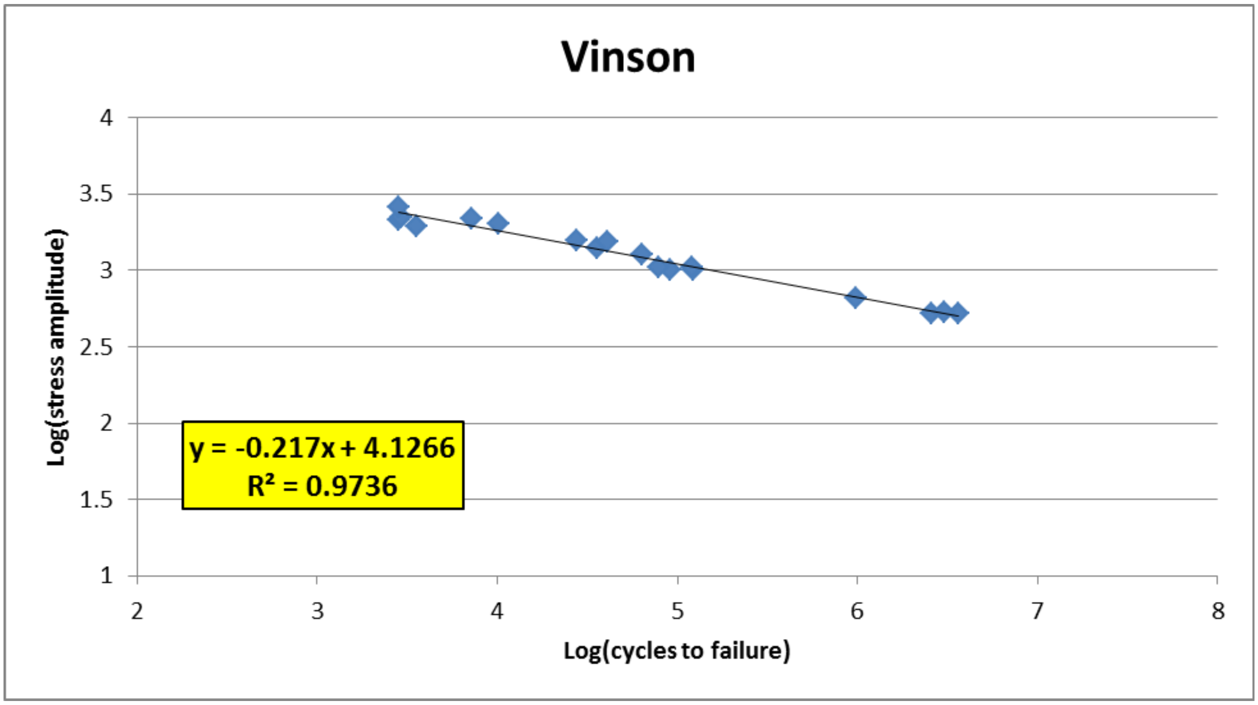
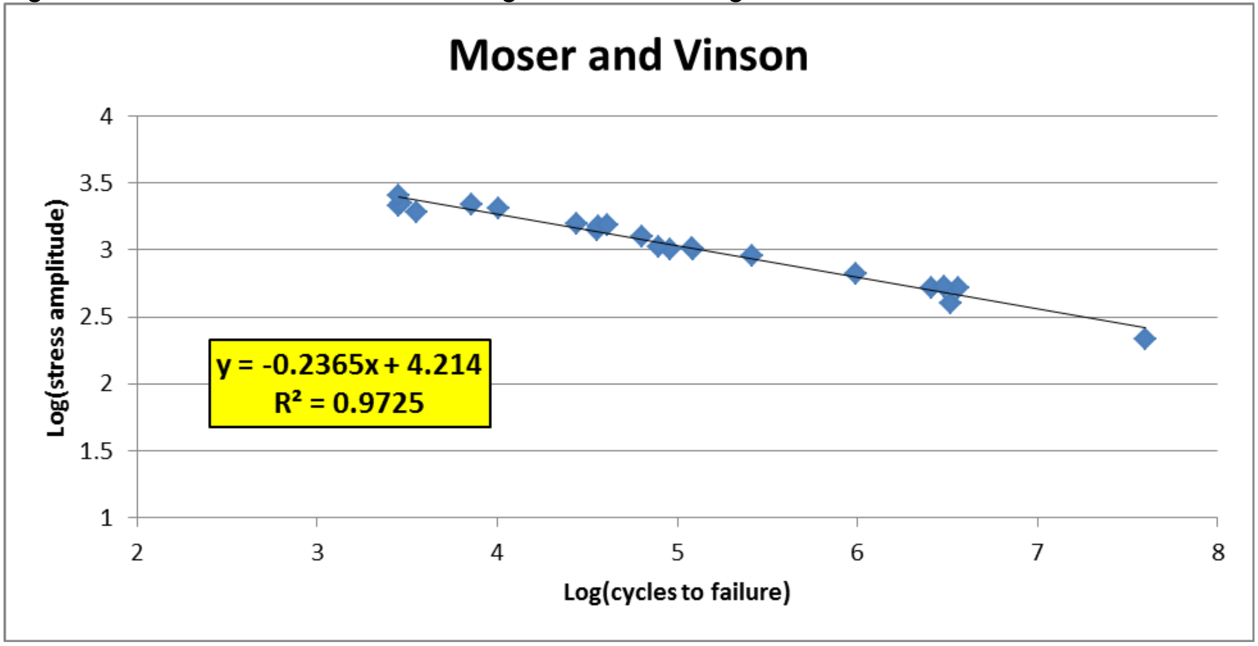


Figure 5.8: Moser Data is in Excellent Agreement with Original Vinson Data



As a general check of the Moser design approach, the projected cycles to failure of the Moser approach was compared to the projected cycles to failure based on the equation derived from a best fit to the log(stress amplitude) versus log (cycles to failure data) from **Figure 5.7**. The analysis confirms the general design approach presented by Moser.

While the Moser paper that presents the current AWWA design approach states "because the fatigue failure data is very limited, Equations 2 and 3 are still in the developmental stage and should only be used as a guide" and recommendations for additional testing to refine the proposed design approach are also provided, the approach does appear to provide reasonable projections of fatigue resistance based on the current data. Additional data developed in the design window would provide confirmation of the overall approach.

5.3.6 Comparison of PE4710 and PVC Fatigue Performance

The fatigue resistance of PE4710 and PVC materials was compared based on the available literature data, the design approaches and the justification for the design approaches. Overall, PE4710 is seen to demonstrate noticeably superior fatigue resistance compared to PVC, in agreement with other published comparison studies.

The available fatigue data for PE4710 and PVC materials were examined in sections 5.2.1 and 5.2.2. PE4710 pipe is not projected to demonstrate fatigue weakness under the operating conditions of water transmission and distribution systems. PVC materials are known to be susceptible to fatigue weakness under these conditions when the number of cycles in service is high and/or the stress amplitude of the cycles is large.

A comparison of the PC requirements based on current US fatigue design practices for PE4710 and PVC materials is presented in **Table 5.11** for Analysis #1. PVC materials require a higher (and sometimes noticeably higher) pressure class under all the scenarios examined. Given that the design approaches for both materials appear appropriate, this would again suggest significantly better fatigue resistance for PE4710 materials in potable water systems and the ability to operate with lower PC piping.

Table 5.11: Required PC for Various Repetitive Surge Situations for PE4710 Materials per US Design Methodology Based on Analysis #2, 125 psi Operating Pressure, 50 years

Daily Surges	Approximate Surges per Hour	Required Pressure Class As a Function of Effective Flow Velocity (fps)											
		2		3		4		5		6		6.7	
		PVC	PE4710	PVC	PE4710	PVC	PE4710	PVC	PE4710	PVC	PE4710	PVC	PE4710
1	0.04	160	125	200	125	200	125	235[1]	125	235[1]	160	305[1]	160
10	0.4	160		200		200		235[1]		235[1]		305[1]	
40	2	160		200		235[1]		305[1]		-[2]		-[2]	
75	3	160		200		305[1]		-[2]		-[2]		-[2]	
150	6	160		305[1]		-[2]		-[2]		-[2]		-[2]	
250	10	200		-[2]		-[2]		-[2]		-[2]		-[2]	
300	13	200		-[2]		-[2]		-[2]		-[2]		-[2]	

Note: 1: This PC not specified in all pipe diameters in C900 or C905, 2: Beyond PC in C900 or C905, Data based on calculated values presented in Table 5.7 and Table 5.10

6.0 Recommendations

6.1 General Design Recommendations

The current design approaches for PE4710 and PVC materials appear to be justified based on the available fatigue data and there is no data that suggests an immediate change to these approaches is required. There is the potential, with the appropriate supporting data development, to expand the allowable fatigue design window for PE4710 materials.

6.2 Recommendations for Cyclic Loading Studies

Given the high fatigue resistance of PE4710 materials, the development of limited additional cyclic fatigue data would provide justification for increasing the allowable repetitive surge pressure and, at the very least, would provide additional experimental support of the design approach.

The data that would be most immediately and directly useful in supporting and potentially increasing the current surge pressure design allowances for PE would be cycles-to-fail data for modern PE pipe, performed with cycles of 0 psig to 150% of Pressure Class, and 0 psig to 200% of Pressure Class, at approximately 73°F, without notches and without chemical accelerants.

It is anticipated that current PE water pipes would withstand several million cycles without failure in the 150% tests and would fail in a very large, but possibly measurable, number of cycles in the 200% tests. It is further recommended that fusion joints be included in the testing to verify their resistance to cyclic loading.

Similarly, the development of additional fatigue data within the PVC design envelop would provide confirmation and, potentially, refinement of the current design approach. It is recommended that testing of this nature include both bell and spigot and fused PVC joints.

7.0 Summary

The purpose of this project was to conduct an Engineering Assessment of the resistance of HDPE pipe to fatigue loading situations encountered in North American water distribution and transmission applications, particularly as they relate to PE4710 materials. The assessment specifically included an engineering comparison of the literature regarding the relative fatigue resistance of plastic potable water pipe materials: PE and PVC. It also included a literature review and utility survey to confirm design fatigue loads and surge velocities. In addition, the data to support the current proposed fatigue design practices for PE4710 pipe were reviewed. Recommendations were developed for obtaining limited additional data to provide additional experimental support for the current design practices and for future changes to design practices.

The primary findings of the study were:

- The fatigue resistance of PE4710 materials, based on the available data, is excellent, and shows these materials are capable of providing for essentially unlimited fatigue resistance under the operating conditions of water transmission and distribution systems.
- The current design approach for occasional (short-term) surge resistance for PE4710 materials is conservative and appears appropriate.
- The current design approach for repetitive (long-term) fatigue resistance for PE4710 materials is conservative and appears justified based on available data.
- The US design approach for PE4710 materials is more conservative than that of the UK for both occasional and repetitive surge events.
- PVC materials are seen to be susceptible to fatigue under the operating conditions of water transmission and distribution systems.
- The current design approach for occasional (short-term) surge resistance for PVC materials appears justified.
- The current design approach for repetitive (long-term) fatigue resistance for PVC materials appears justified based on available data.
- The US design approach for PVC materials is less conservative than that of the UK for repetitive surge events.
- PE4710 materials are seen to exhibit superior fatigue resistance to PVC piping materials.
- Given the high fatigue resistance of PE4710 materials, the development of limited additional cyclic fatigue data would provide justification for increasing the allowable repetitive surge pressure and, at the very least, would provide additional experimental support of the design approach. While fatigue testing has been done on PE fusion joints, it is recommended that joints be included in any additional testing to acquire additional information on performance of newer materials.

- Similarly, the development of additional fatigue data within the PVC design envelop would provide confirmation and, potentially, refinement of the current design approach. It is recommended that testing of this nature include both bell and spigot and fused PVC joints.

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