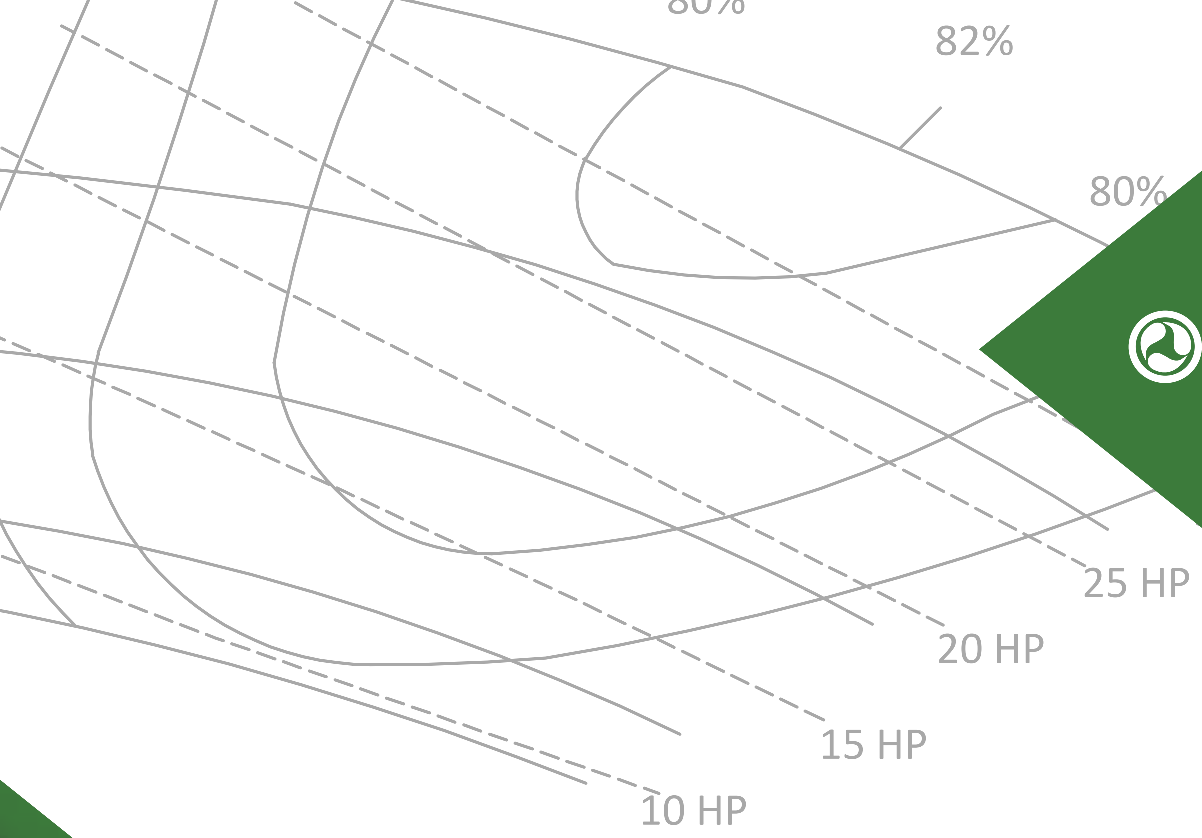
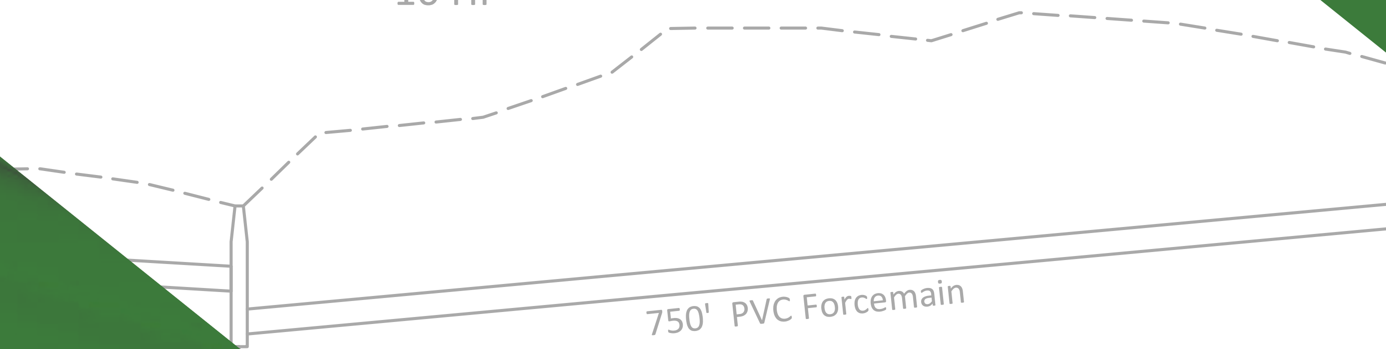
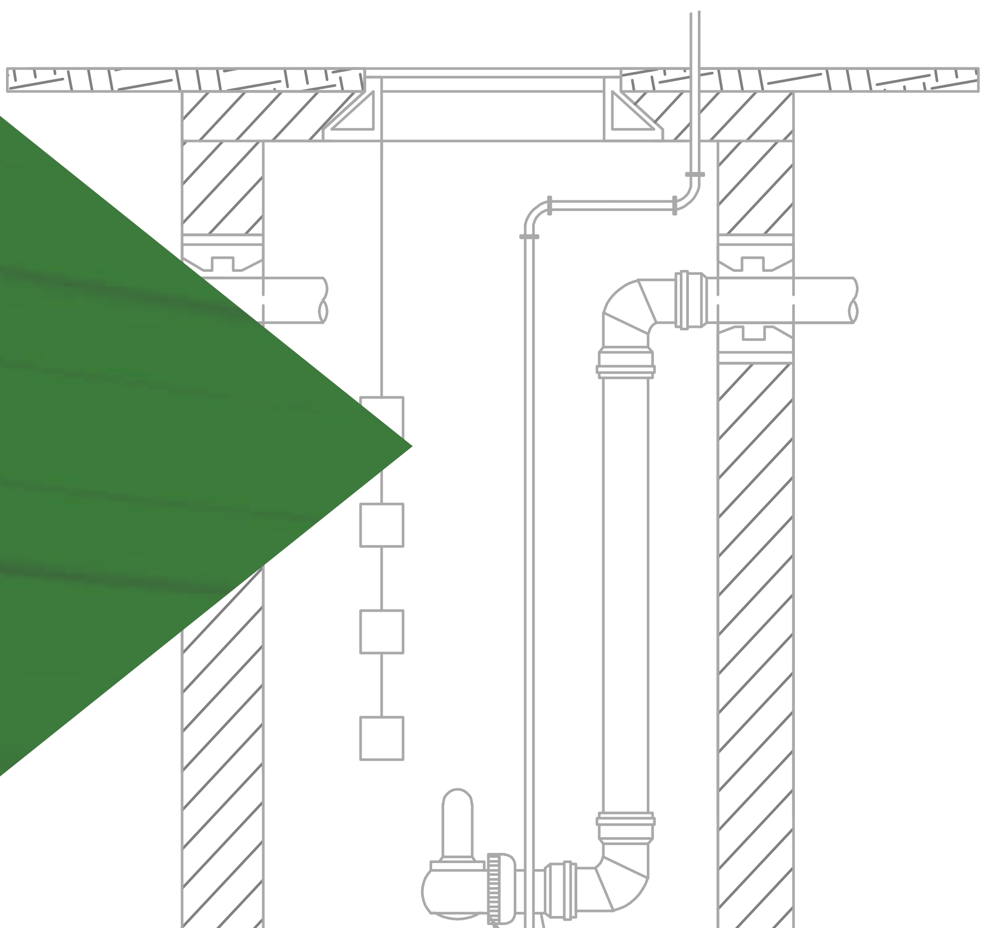






PVCPIPE association

FORCE MAIN DESIGN GUIDE

FOR PVC PIPE

TABLE OF CONTENTS

INTRODUCTION

WASTEWATER SYSTEMS

Wastewater conveyance generally falls into two categories: gravity flow and pressure flow. The most common way to transport wastewater is through downward-sloped pipe by gravity flow. When gravity sewers are not possible or economically practical, pressure from a lift station is used to convey wastewater through a pipe known as a "force main."

This document specifically addresses internal-pressure design of PVC force mains. Design of lift stations is not included, although both single-pump and multiple-pump scenarios are addressed.

PVC PRESSURE PIPE – OVERVIEW

HISTORY: PVC pipe has had a successful track record in municipal applications in North America since the 1950s. It has been used for force mains from the 1970s, with more than 40,000 miles in service today.

CORROSION: One of the many reasons for PVC pipe's success is its corrosion resistance. PVC is not affected by aggressive environments inside wastewater pipes (such as hydrogen sulfide gas) that cause premature failure in other pipe materials. The use of PVC pipe for force main systems eliminates corrosion failures.

HYDRAULICS: Due to a combination of low hydraulic friction characteristics and large inside diameter, PVC pipe provides low pumping costs over time. Additionally, the friction characteristics do not degrade with time. This means that lift station designs of PVC systems do not need to account for lower C Factors caused by "old" or "degraded" pipes — as a result, fewer or smaller pumps can be used.

LONGEVITY: Studies on the longevity of PVC pressure pipe show that properly designed and installed pipe can be expected to operate in excess of 100 years. Figure 1 shows a 24-inch PVC force main installed in 1989 and excavated in 2009, which successfully passed all AWWA standards requirements for new pipe.[1]

CYCLIC PRESSURES

Due to the nature of lift stations, cyclic pressures are more often a consideration in force mains than in water mains. PVC pipe has demonstrated exceptional resistance to cyclic pressures, both in laboratory testing and in pressure sewer systems. Testing has shown that PVC pipe is able to withstand over 10 million pressure cycles without failure.[2] Additionally, almost 50 years of use in North America confirm PVC pipe's suitability for force mains. This guide shows users how to design a PVC force main while taking into account cyclic pressures and required design life. To further assist the industry, the Uni-Bell PVC Pipe Association (PVCPA) has developed an online design calculator for cyclic pressures experienced in force main systems (**Online Cyclic-Life Calculator**).

Note: Phrases in green and bold refer to sections in this document – see Table of Contents for locations.

FIGURE 1: 20-YEAR-OLD PVC FORCE MAIN THAT MET AWWA STANDARDS FOR NEW PIPE

PVC PRESSURE PIPE – DESIGN ELEMENTS

HYDRAULIC DESIGN

One step in hydraulic design is to determine friction head-loss by using either of these equations:

1. **Darcy–Weisbach Equation**
   The Darcy-Weisbach Equation is found in many hydraulic textbooks but is not included in this guide. The pipe-material parameter in this equation is called "absolute pipe roughness." A pipe roughness value of 7.0×10^{-6} feet should be used for PVC pipe.
2. **Hazen–Williams Equation**
   Research has shown that the Hazen-Williams flow coefficient (or "C Factor") for PVC pipe is between 155 and 165.[3] A conservative value of C = 150 should be used for design of PVC pipe systems.

Unlike many other materials whose coefficients reduce over time, PVC pipe's Hazen-Williams and Darcy-Weisbach coefficients remain unchanged. For more information on both equations, see the "Hydraulics" chapter of the *Handbook of PVC Pipe Design and Construction*.[4]

Design engineers use the following to optimize sizing of pipes and pumps:

- Pipe dimensions
- Pipe material friction factors
- Projected wastewater flows
- Pipe profile and stationing

After basic hydraulic parameters for the project have been established, pump and system curves are used to determine pressures and flows within the system for various operating conditions. The hydraulic profile is then established. This information enables the designer to specify the pressure class (PC) or pressure rating (PR) of PVC pipe to meet project requirements.

INTERNAL PRESSURE DESIGN CHECKS

To design PVC pipe for internal pressures, there are three design checks that a selected PC or PR must meet. These checks ensure that the pipe can accommodate maximum operating pressure, recurring surge pressure (cyclic surge, such as pump start-up/shut-off), and occasional surge pressure (worst-case surge, such as power failure). The PCs of AWWA C900 and PRs of ASTM D2241 include a safety factor of 2.0.[5,6]

Note: in the following design checks, the AWWA notation "PC" is used. For ASTM pipe, "PR" is substituted for "PC." An online calculator developed by PVCPA is available for these design checks (Internal Pressure Design Calculator).

These design checks are given below:

$$WP_{max} \leq PC \times F_T \quad \text{(First Design Check)}$$

$$P_{rs(max)} = WP_{normal} + P_{rs} \leq PC \times F_T \quad \text{(Second Design Check)}$$

$$P_{os(max)} = WP_{max} + P_{os} \leq 1.6 \times PC \times F_T \quad \text{(Third Design Check)}$$

Where:

WP_{max} = working pressure during maximum pump operations, psi

WP_{normal} = working pressure during normal pump operations, psi

P_{rs} = recurring surge pressure, psi (from typical pump on/off operation)

$P_{rs(max)}$ = maximum pipe pressure from a recurring surge event, psi

P_{os} = occasional surge pressure, psi (worst-case transient scenario, e.g., power failure)

$P_{os(max)}$ = maximum pipe pressure from an occasional surge event, psi

PC = pressure class, psi (Appendix Table B.1)

F_T = thermal derating factor, dimensionless. If sustained operating temperatures are above 73°F, a thermal derating factor should be applied. (Appendix Table B.2)

The WP subscripts in the design checks are for multiple-pump operations.

For lift stations that operate only on a single pump, the design checks are modified as follows:

$WP_{max} = WP_{normal}$ because only one pump is operating.

CYCLIC PRESSURE DESIGN CHECK

Cyclic pressures (also called "recurring surge pressures") are typically not frequent enough or large enough in water transmission or distribution mains to be a design consideration. In contrast, surge pressures occur at high frequencies in force mains due to pumps operating to empty small-capacity wet wells. This means that a fourth design check is required for force-main applications.

Utah State University has performed cyclic-pressure research and analysis to develop an improved method for determining cyclic life for PVC pipe. The research involved testing numerous samples of PVC pipe to failure and then analyzing the number of cycles and the pipe wall stresses. The result is the "Folkman Equation."[7]

If the number of surge cycles the pipe will experience is known, the result of this equation can be used to determine the life of the pipe ("cyclic life") from these recurring surge pressures. The calculated cyclic life should exceed the specified design life, as shown in the design check below.

$$\text{Cyclic Life} \geq \text{Design Life} \quad \text{(Cyclic Design Check)}$$

Cyclic life refers to the number of years PVC pipe can withstand cyclic pressures and is not an overall life expectancy. Rather, it is the amount of years PVC pipe will endure recurring surge pressures alone.

DETERMINING PVC PIPE CYCLIC LIFE:

1. Stress amplitude is found using maximum and minimum pressures from a surge event (Equation 1)
2. Number of cycles to failure is calculated (Equation 2)
3. Cyclic life is obtained by dividing number of cycles to failure by number of surge occurrences (or cycles) per year (Equation 3)

EQUATION 1

$$\sigma_{amp} = \frac{[P_{rs(max)} - P_{rs(min)}](DR - 1)}{4}$$

Where:

σ_{amp} = amplitude of pipe wall hoop stress from cyclic pressures, psi

$P_{rs(max)}$ = maximum pipe pressure from a recurring surge event, psi

$P_{rs(min)}$ = minimum pipe pressure from a recurring surge event, psi

DR = pipe's dimension ratio, dimensionless = OD/t

EQUATION 2 (FOLKMAN EQUATION)

$$N = 10^{-4.196 log(\sigma_{amp}) + 17.76}$$

Where:

N = number of cycles to failure

EQUATION 3

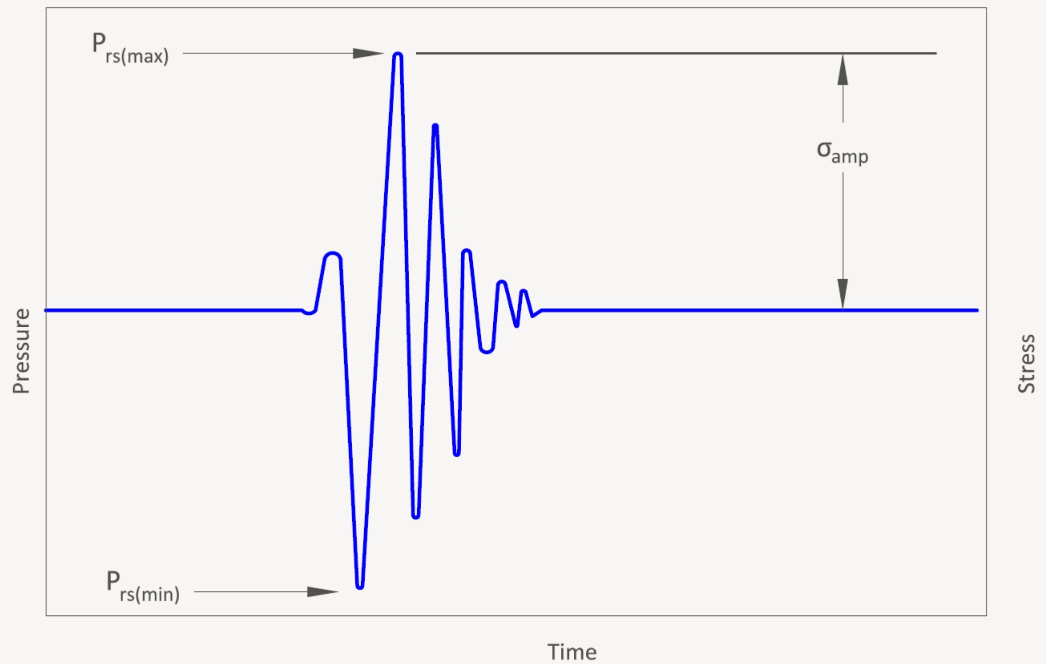
$$Cyclic\ Life\ (years) = \frac{N}{n}$$

Where:

n = number of cycles per year from pump operations

Figure 2 illustrates maximum and minimum recurring-surge pressures and resulting stress amplitude during a surge event.

FIGURE 2: TYPICAL SURGE PRESSURE AND STRESS BEHAVIOR IN A SEWER FORCE MAIN



In summary, the cyclic life of PVC pipe depends on:

1. Number of surge occurrences
2. Magnitude of these recurring surges
3. Pipe wall thickness (DR)

Methods for determining surge pressures for PVC pipe are discussed in the next section. See **Design Example** for how these design checks are used.

DETERMINING SURGE PRESSURES

JOUKOWSKY EQUATION: Surge pressures in PVC pipe are typically determined using the Joukowsky Equation, which is based on the pressure wave speed through the pipe and instantaneous change in flow velocity. Table 1, derived from the Joukowsky Equation, provides surge pressures caused by a change in velocity of 1 foot per second (ft/s) for each representative DR. The following is an example of how the table is used: if design velocity in a DR 21 pipe is 5 ft/s, anticipated surge pressure is 16.0 psi/(ft/s) × 5 ft/s = 80 psi.

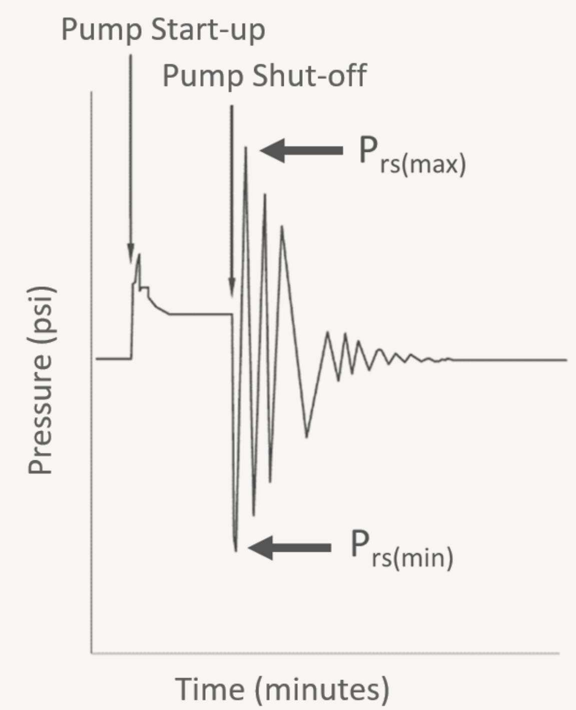
TRANSIENT ANALYSIS: Using the Joukowsky Equation may result in conservative pressures which may lower the calculated cyclic life.[8] Alternatively, transient analysis software can be used to determine surge pressures. This method provides more accurate results, especially for complex pipe systems and operations. Scenarios for normal pump on/off operations and for worst-case surge events (such as a power failure) can be used for the PVC pipe design checks mentioned in **Internal Pressure Design Checks**. Figure 3 is an example of a graph produced using transient analysis software to model a PVC force main.

TABLE 1: PRESSURE SURGE FROM A 1 FT/S INSTANTANEOUS CHANGE IN FLOW VELOCITY

Values from the Joukowsky Equation		
DR	PC/PR (psi)	Surge Pressure (psi)
51	80	10.8
41	100	11.4
32.5	125	12.8
26	160	14.4
25	165	14.7
21	200	16.0
18	235	17.4
14	305	19.8

Note: For values where DR is not shown, the pipe manufacturer should be consulted.

FIGURE 3: TRANSIENT MODEL OF NORMAL PUMP ON/OFF OPERATION



When appurtenances (i.e., air valves or surge-control devices) are used in a piping system, transient software is generally preferable, regardless of pipe material. Pump station and pipeline design manuals provide specific conditions when transient modeling is recommended. If such software is not available, use of the pressure surge values from Table 1 is typically valid and conservative. The design example in the next section shows how to use both methods for determining surge pressures.

DESIGN EXAMPLE

The following analysis shows how to determine surge pressures using the Joukowsky Equation (Solution A) or a transient analysis model (Solution B) for the design of a PVC force main.

Given:

- Pipe size: AWWA C900 20-inch CIOD
- Pump information: Normal pump operation is one pump (lead) delivering the design flow, while two pumps (one lag and one backup) are used only for high-flow events. The wet well has a fill time of 12 minutes and an emptying time of 3 minutes under normal one-pump operation.
- Operating temperature: 70°F
- Design life: 100 years

Determine:

- Dimension ratio / pressure class that will provide a 100-year design life.

The selected DR or PC must satisfy four design checks as shown below:

$$WP_{max} \leq PC \times F_T$$ (First Design Check)

$$P_{rs(max)} = WP_{normal} + P_{rs} \leq PC \times F_T$$ (Second Design Check)

$$P_{os(max)} = WP_{max} + P_{os} \leq 1.6 \times PC \times F_T$$ (Third Design Check)

$$\textit{Cyclic Life} \geq \textit{Design Life}$$ (Cyclic Design Check)

Design Steps:

Step 1: Select initial DR/PC.

Step 2: Develop pump and system curves to determine operating pressures and velocities.

Step 3: Determine occasional and recurring surge pressures.

Step 4: Conduct first three design checks.

If any design check is not met, select next lower DR (thicker wall) / higher PC, and repeat **Steps 2-4** until all design checks are satisfied.

Step 5: Use the Folkman Equation (Equation 2) to determine number of cycles to failure.

Step 6: Using pump cycles (or surge occurrences) per year from wet-well design, calculate cyclic life.

Step 7: Conduct cyclic design check.

If cyclic design check is not met, select next lower DR (thicker wall) / higher PC, and repeat **Steps 2-3** to determine new velocity and recurring surge pressures. Repeat **Steps 5-7** until cyclic design check is satisfied.

SOLUTION A: USING THE JOUKOWSKY EQUATION

The design engineer has elected to use the Joukowsky Equation to determine surge pressures. A transient model will not be used.

Assumptions:

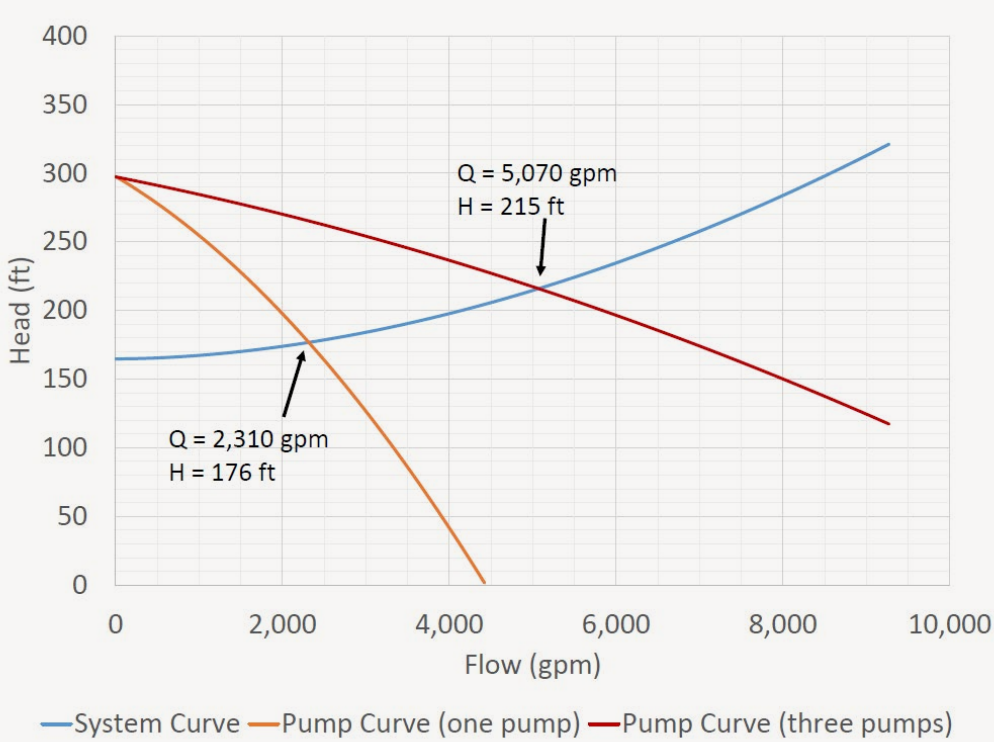
- Surge events occur from instantaneous stoppage in flow velocity.
- No surge-control equipment or variable-frequency drive (VFD) pumps are used.
- During normal pump on/off operations, only the pump shut-off will produce considerable recurring surge pressures.[a]

Step 1: Choose pipe DR/PC. Initial selection is DR 32.5 / PC 125 pipe.

Step 2: Develop pump and system curves to provide pressures and velocities (Figure 4).

Appendix Table A.1 gives the inside diameter for a 20-inch DR 32.5 pipe which is 1.69 feet. This dimension is used to develop the pump and system curves and to calculate flow velocities.

FIGURE 4: PUMP AND SYSTEM CURVES FOR 20-INCH DR 32.5 PIPE



Operating Points:

Normal Operation Flow = 2,310 gpm ➔ v = 2.30 ft/s
Normal Operating Head = 176 ft = 76 psi

Maximum Flow = 5,070 gpm ➔ v = 5.04 ft/s
Maximum Head = 215 ft = 93 psi

[a] Malekpour, et al., provide an example of a typical force main with transient models that show pump start-up surge is insignificant.[8] See **Multiple Surge Events** for validity of this assumption and for more information.

Step 3: Determine occasional and recurring surge pressures.

From Table 1, for a DR 32.5 pipe, a surge pressure of 12.8 psi results from a 1 ft/s instantaneous change in velocity. The occasional surge is found from the maximum velocity produced by the pump station, thus

$$P_{os} = 12.8\ \frac{psi}{ft/s} \times 5.04\ ft/s = 65\ psi$$

The recurring surge is based on the velocity change occurring from normal pump operation.

$$P_{rs} = 12.8\ \frac{psi}{ft/s} \times 2.30\ ft/s = 29\ psi$$

Since the operating temperature is less than 73°F, F_T = 1.0 (Appendix Table B.2)

Step 4: Conduct first three design checks.

$$WP_{max} \leq PC \times F_T \qquad \text{(First Design Check)}$$
$$93\ psi \leq 125\ psi \times 1.0$$
$$93\ psi < 125\ psi\ \checkmark$$

$$P_{rs(max)} = WP_{normal} + P_{rs} \leq PC \times F_T \qquad \text{(Second Design Check)}$$
$$76\ psi + 29\ psi \leq 125\ psi \times 1.0$$
$$105\ psi < 125\ psi\ \checkmark$$

$$P_{os(max)} = WP_{max} + P_{os} \leq 1.6 \times PC \times F_T \qquad \text{(Third Design Check)}$$
$$93\ psi + 65\ psi \leq 1.6 \times 125\ psi \times 1.0$$
$$158\ psi < 200\ psi\ \checkmark$$

DR 32.5 satisfies the first three design checks. Because force main applications have a high frequency of surge pressures, the cyclic check will now be conducted.

Step 5: Use the Folkman Equation (Equation 2) to find cyclic life.

- Determine maximum and minimum recurring surge pressures as follows:

$$P_{rs(max)} = WP_{normal} + P_{rs} = 76 + 29 = 105\ psi$$

$$P_{rs(min)} = WP_{normal} - P_{rs} = 76 - 29 = 47\ psi$$

- Stress amplitude may now be calculated using $\boxed{\textbf{EQUATION 1}}$:

$$\sigma_{amp} = \frac{[P_{rs(max)} - P_{rs(min)}](DR-1)}{4} = \frac{(105-47)(32.5-1)}{4} = 457\ psi$$

- Now the **FOLKMAN EQUATION (EQUATION 2)** can be used:

$$\mathcal{N} = 10^{-4.196log(\sigma_{amp})+17.76} = 10^{-4.196log(457)+17.76} = 3.97 \times 10^6 \; cycles \; to \; failure$$

Step 6: Pump cycles (or surge occurrences) per year must be known. As previously stated in the assumptions, recurring surges occur from pump shut-offs only. From the given information, it is known that the wet well has a fill time of 12 minutes and an emptying time of 3 minutes under normal pump operations. This leads to a pump shut-off every 15 minutes. The cycles per year can be calculated as follows:

$$n = \frac{1 \; cycle}{15 \; minutes} \times \frac{60 \; minutes}{1 \; hour} \times \frac{24 \; hours}{1 \; day} \times \frac{365 \; days}{1 \; year} = 35{,}040 \; cycles/year$$

Cyclic life is then determined from **EQUATION 3**:

$$Cyclic \; Life \; (years) = \frac{\mathcal{N}}{n} = \frac{3.97 \times 10^6 \; cycles}{35{,}040 \; cycles/year} = 113 \; years$$

Step 7: Conduct cyclic design check.

$$Cyclic \; Life \geq Design \; Life \qquad \text{(Cyclic Design Check)}$$

$$113 \; years > 100 \; years \; \checkmark$$

DR 32.5 meets all design checks and should be selected for this project. If this DR had not met the cyclic design check, then the next lower DR (thicker wall) would be selected and Steps 5-7 would be repeated. It is important to recognize that with a different DR, the recurring surge pressures needed for Step 5 would change.

For a discussion on applying a factor of safety to this result, see **Conservatism in PVC Pipe Cyclic Design**.

SOLUTION B: USING TRANSIENT MODELING

The design engineer has elected to run a transient model.

Assumptions:

- No surge-control equipment or variable-frequency drive (VFD) pumps are used.
- Valve closure time is 30 seconds.

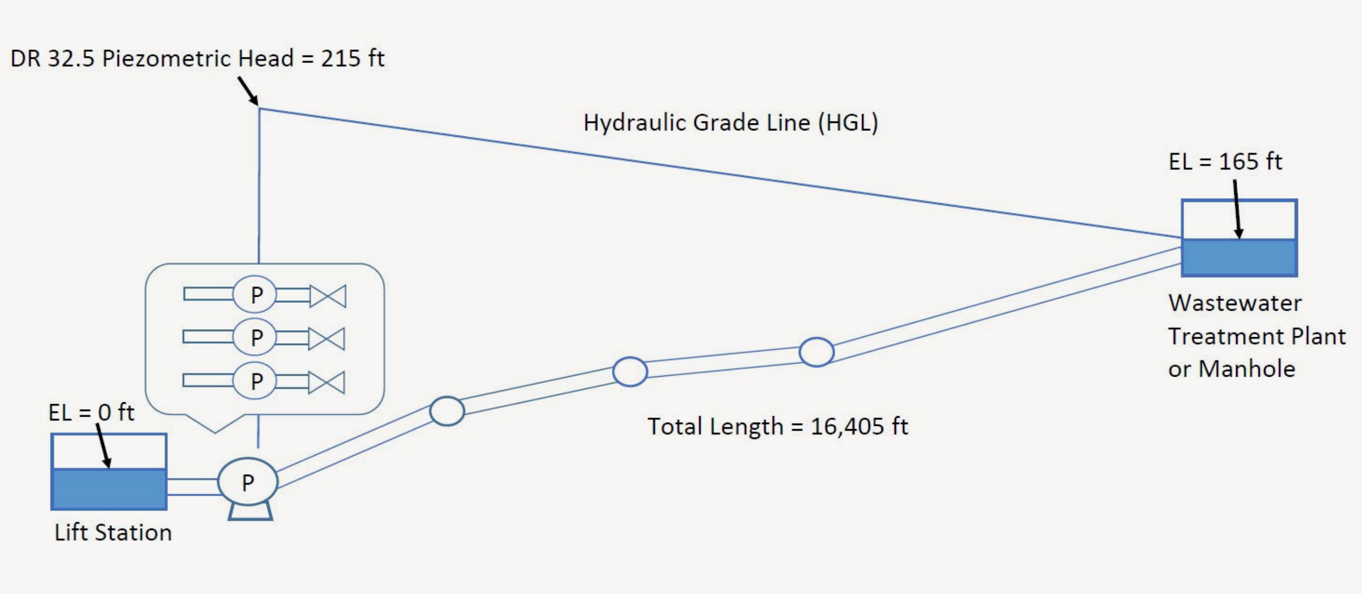
Step 1: Develop transient models for DR 32.5 / PC 125 pipe.

Steps 2-3: Use pressures provided by transient models to perform design checks.

- For the first design check, the hydraulic grade line (HGL) in Figure 5 provides the WP_{max}.

$$WP_{max} = Maximum \; Head = 215 \; ft = 93 \; psi$$

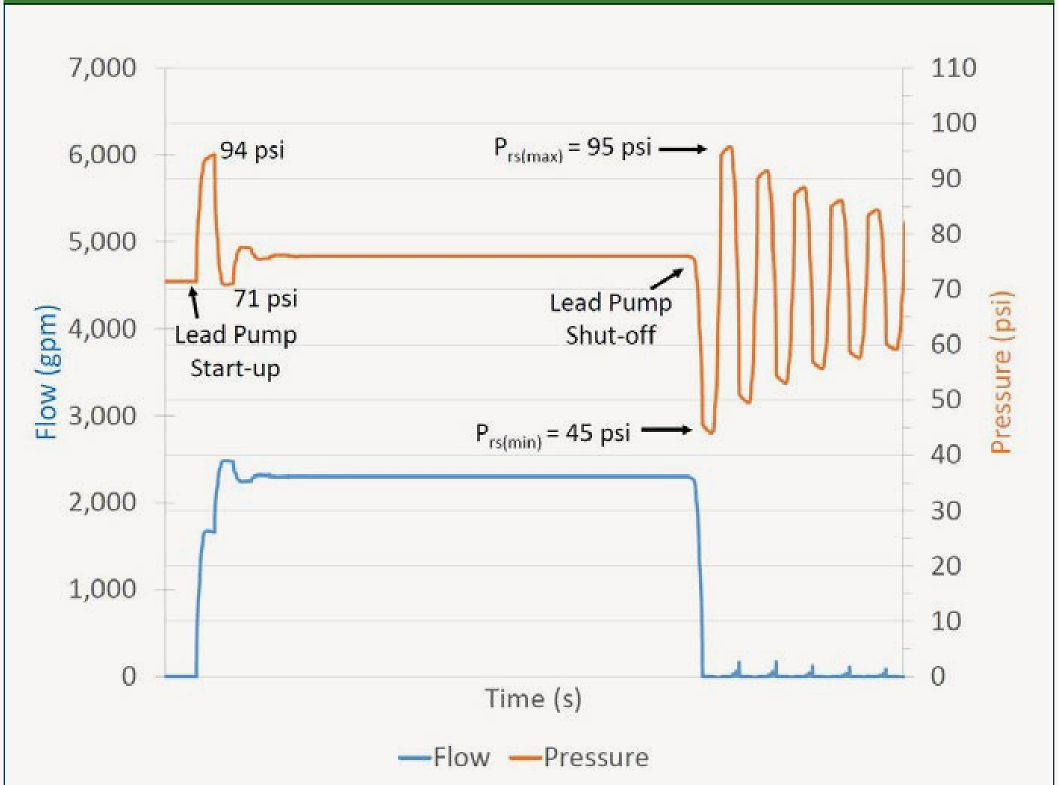
FIGURE 5: FORCE MAIN PROFILE



- For the second design check, a model of normal pump on/off operation is shown in Figure 6. Maximum recurring surge occurs during pump shut-off. It is also important to note that the surge-pressure amplitude during pump start-up (left side of Figure 6) is of such a small magnitude that fatigue life is essentially unaffected. More information on pump start-up effects is discussed in **Multiple Surge Events**.

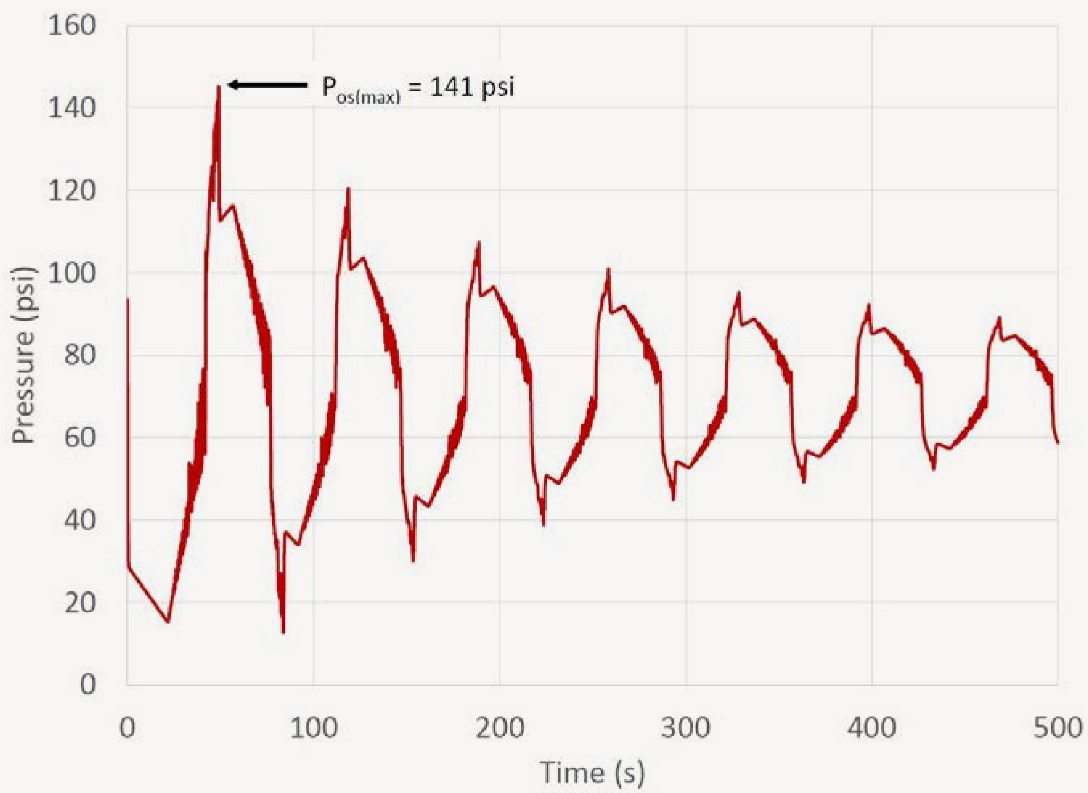
$$P_{rs(max)} = 95\ psi$$

FIGURE 6: FLOW AND PRESSURE vs TIME



- For the third design check, a power failure model for a simultaneous shut-down of all pumps is shown in Figure 7.

FIGURE 7: PRESSURE vs TIME FOR SIMULTANEOUS POWER FAILURE OF ALL PUMPS



- The pressure needed from Figure 7 is as follows:

$$P_{os(max)} = 141\ psi$$

Step 4: Conduct first three design checks.

$$WP_{max} \leq PC \times F_T$$ (First Design Check)

$$93\ psi \leq 125\ psi \times 1.0$$

$$93\ psi < 125\ psi \quad \checkmark$$

$$P_{rs(max)} \leq PC \times F_T$$ (Second Design Check)

$$95\ psi \leq 125\ psi \times 1.0$$

$$95\ psi < 125\ psi \quad \checkmark$$

$$P_{os(max)} \leq 1.6 \times PC \times F_T$$ (Third Design Check)

$$141\ psi \leq 1.6 \times 125\ psi \times 1.0$$

$$141\ psi < 200\ psi \quad \checkmark$$

Step 5: Use the Folkman Equation (Equation 2) to find cyclic life.

- See Figure 6 for maximum and minimum recurring surge pressures:

$$P_{rs(max)} = 95\ psi$$

$$P_{rs(min)} = 45\ psi$$

- Stress amplitude may now be calculated using **EQUATION 1**:

$$\sigma_{amp} = \frac{[P_{rs(max)} - P_{rs(min)}](DR - 1)}{4} = \frac{(95 - 45)(32.5 - 1)}{4} = 394\ psi$$

- Now the **Folkman Equation (Equation 2)** can be used:

$$N = 10^{-4.196 log(\sigma_{amp}) + 17.76} = 10^{-4.196 log(394) + 17.76} = 7.40 \times 10^6\ cycles\ to\ failure$$

Step 6: Pump cycles (or surge occurrences) per year must be known. It is assumed that recurring surges occur from pump shut-offs only. From the given information, the wet well has a fill time of 12 minutes and an emptying time of 3 minutes under normal pump operations. This leads to a pump shut-off every 15 minutes. The cycles per year can be calculated as follows:

$$n = \frac{1\ cycle}{15\ minutes} \times \frac{60\ minutes}{1\ hour} \times \frac{24\ hours}{1\ day} \times \frac{365\ days}{1\ year} = 35{,}040\ cycles/year$$

Cyclic life is then determined from **EQUATION 3**:

$$Cyclic\ Life\ (years) = \frac{N}{n} = \frac{7.40 \times 10^6\ cycles}{35{,}040\ cycles/year} = 211\ years$$

Step 7: Conduct cyclic design check.

$$Cyclic\ Life \geq Design\ Life$$ (Cyclic Design Check)

$$211\ years > 100\ years\ \checkmark$$

For both Solutions A and B, DR 32.5 is selected. While both solutions provide the same pipe wall thickness, the cyclic lives are different. When surge pressures are calculated with the Joukowsky Equation, the result is a conservative cyclic life of 113 years. A transient analysis provides a more accurate cyclic life, which in this case is 211 years. For additional information, see **Conservatism in PVC Pipe Cyclic Design**.

DISCUSSION OF DESIGN EXAMPLE

INCREASING CYCLIC LIFE

The design example illustrates how different variables affect cyclic life. When designing PVC force mains, engineers can use one or more of the following options to increase cyclic life and ensure an economical design:

- Select lower DR (which increases pressure class / pressure rating) and update $P_{rs(max)}$ and $P_{rs(min)}$ (from the Joukowsky Equation table or a transient analysis).
- Lower the number of pump cycles in lift-station or wet-well design.
- Decrease surge-pressure amplitude (i.e., the difference between $P_{rs(max)}$ and $P_{rs(min)}$) by adding surge-control equipment. This is discussed in more detail in **Surge-Control Techniques**.

If thicker-walled pipe (e.g., DR 21, 18, 14) were used in the design example, the resulting cyclic life would be too conservative (for example, >>200 years). In this scenario, a high cyclic-life value means that fatigue from cyclic pressures would not be a concern for PVC force main longevity.

CONSERVATISM IN PVC PIPE CYCLIC DESIGN

There is inherent conservatism in many of the assumptions used in PVC pipe cyclic design:

- Use of the Joukowsky Equation usually produces lower cyclic-life values compared to transient modeling. As shown in **Determining Surge Pressures**, performing a transient analysis provides more accurate pressures and cyclic life. This is illustrated in the differences in cyclic life between Solutions A and B.
- The Folkman Equation also includes built-in conservatism. During cyclic testing to develop the equation, some of the pipe samples did not fail over a run time of approximately 2 years. To illustrate this, if a DR 41 PVC pipe experiences surge pressures oscillating between 82 psi and 123 psi for 10 cycles per minute, the Folkman Equation predicts 6.9 million cycles to failure. In contrast, in the testing laboratory, several DR 41 pipe samples reached 11 million cycles under the same conditions without failing while several pumps and valves had to be replaced.[9]

Thus, the design procedure shown provides a conservative result.

However, if the engineer chooses to apply an additional factor of safety to account for variations in project design assumptions, a value of 2.0 may be used:

$$Cyclic\ Life \div 2.0 \geq Design\ Life$$

If a factor of safety of 2.0 is applied to the design example, it is shown that for Solution A, DR 32.5 pipe does not meet the cyclic check:

$$Cyclic\ Life \div 2.0 \geq Design\ Life \rightarrow 113 \div 2.0 = 56.5\ years < 100\ years\ ✘$$

Repeating the analysis with the appropriate system curve, DR 21 pipe would be selected. However, as shown for Solution B, after a transient analysis is performed, DR 32.5 pipe still meets the design check:

$$Cyclic\ Life \div 2.0 \geq Design\ Life \rightarrow 211 \div 2.0 = 106\ years > 100\ years\ ✓$$

This demonstrates that using the Joukowsky Equation and applying an additional factor of safety of 2.0 results in a very conservative DR selection.

Alternatively, if conservative design assumptions are used (e.g., higher values for pressures and pump cycles), an additional factor of safety may not be warranted.

OTHER CONSIDERATIONS

SURGE-CONTROL TECHNIQUES

One method of controlling surges in force main systems is to use variable-speed pumps, which allow pumping operations to be continuous for fluctuating flow conditions. For more information see Water Environment Federation (WEF) Manual of Practice (MOP) FD-4, *Design of Wastewater and Stormwater Pumping Stations.*[10]

ENTRAPPED AIR

AWWA Manual M51 *Air Valves: Air Release, Air/Vacuum, and Combination* states:

> Air and wastewater gases entrainment is much greater in wastewater force main systems than in other pumped liquid transmission systems owing to their unique design and operational characteristics... Because of the cyclic operation of force main systems, sections of the force mains empty out at the end of each pumping cycle, drawing air and wastewater gases into pipes. At the entrance to sewage lift stations, air and wastewater gases are entrained from plunging jets of sewage.[11]

Refer to AWWA M51 for information on design, maintenance, and operation of air valves, or consult the valve manufacturer. Proper sizing and location of air valves and other surge-control devices can also be determined with transient-analysis software.

MULTIPLE SURGE EVENTS

In force main pipelines, recurring surges are typically caused by regular pump shut-offs, which was shown in the design example. However, other surge events can take place. For example, pressure increases can occur during pump start-ups, though these are typically insignificant. Nevertheless, there are cases where this warrants consideration.[b] Additionally, different valves may close routinely during pipeline operation, creating pressure surges. To determine cyclic life caused by multiple surge events, Miner's Rule can be used.[13]

MINER'S RULE: The common form of Miner's Rule to predict failure is:

$$\sum \frac{n_i}{N_i} = 100\%$$

Where:

n_i = number of cycles per year for a particular surge event

N_i = number of cycles to failure for a particular surge event

[b] Jones, et. al, state "Pump start-up can cause… an undesirable surge, but usually is not a problem unless the… specific speed in U.S. customary units exceeds approximately 7,000."[12]

The left-hand side of Miner's Rule represents the fraction of life consumed by a surge event. Cyclic life is then determined by:

EQUATION 4

$$Cyclic\ Life = \frac{1}{\sum \frac{n_i}{N_i}}$$

USING MINER'S RULE: An online calculator is available that can perform Miner's Rule (**Online Cyclic-Life Calculator**). To illustrate how to use Miner's Rule for the previous design example, see Table 2. Inputs for this table are as follows:

Surge Events

- Pump shut-off and start-up events are chosen and shown in Figure 8 (taken from **Design Example**).
- As part of ongoing maintenance, a surge from closing a plug valve occurring once every three months is assumed.

$P_{rs(max)}$; $P_{rs(min)}$; Folkman Equation (N_i)

- Maximum and minimum recurring surge pressures from pumps turning on and off are shown in Figure 8.
- Maximum and minimum recurring surge pressures from a plug-valve closure are assumed to be equivalent to a pump shut-off.
- The Folkman Equation (Equation 2) can be used for each surge event.

Cycles per Day

- The wet well has a fill time of 12 minutes and an emptying time of 3 minutes under normal pump operations. Thus, a pump shut-off occurs every 15 minutes (96 times per day).
- A pump start-up also occurs every 15 minutes (96 times per day).

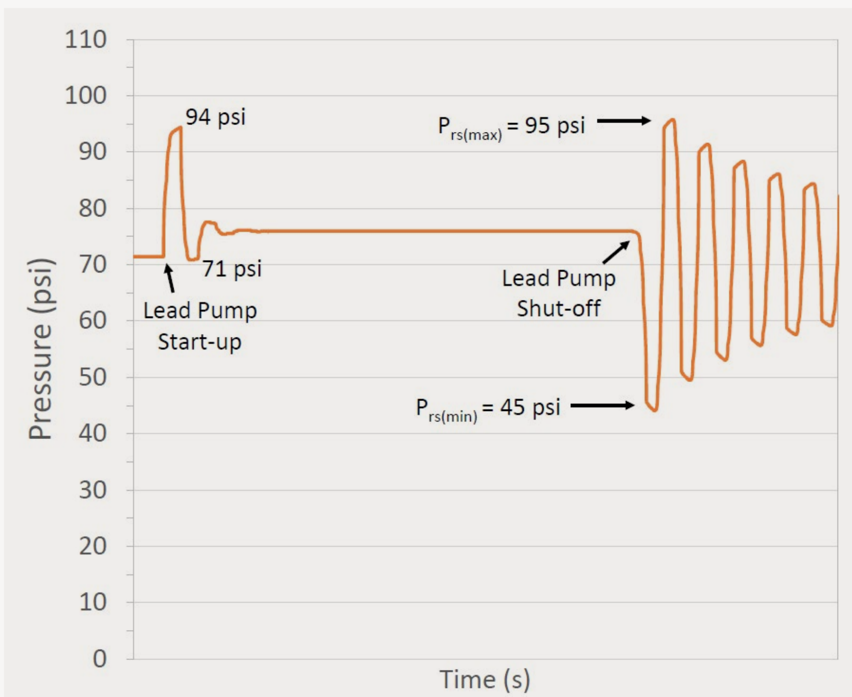
Cycles per Year (n_i)

- Pump on/off operation occurs 365 days per year.
- Plug-valve closure occurs 4 times per year.

The expression n_i/N_i provides the fraction that each surge event contributes to the overall cyclic life. The reciprocal of the sum of all n_i/N_i values is then taken to calculate cyclic life.

TABLE 2: APPLYING MINER'S RULE TO COMBINE DIFFERENT SURGE PRESSURES							
Surge Event	**$P_{rs(max)}$ (psi)**	**$P_{rs(min)}$ (psi)**	**N_i per Folkman Equation (cycles × 10^6)**	**Cycles per Day**	**n_i (cycles per year)**	**Fraction of Life Consumed per Year (n_i/N_i)**	**Percent of Life Used**
Pump Shut-off	95	45	7.42	96	35,040	0.0047	96.3%
Pump Start-up	94	71	192	96	35,040	0.0002	3.72%
Plug-valve Closure	95	45	7.42	—	4	5.4E-07	0.01%
			Sum =			0.0049	
			Cyclic Life (reciprocal of Sum) =			204 years	

FIGURE 8: PRESSURE vs TIME FOR NORMAL PUMP OPERATION



Note: For reflected waves following pump shut-off, see **Reflected Pressure Waves**.

As shown in Table 2, surge-pressure amplitude caused by pump start-ups contribute an insignificant amount (only about 3.7%) to cyclic life for this example. Plug-valve closures contribute even less (under 0.1%) to cyclic life. Other occasional surges such as power outages are also considered insignificant over the life of the force main.

When pump start-ups are included, the cyclic life result declines slightly from 211 years (Solution B from **Design Example**) to 204 years. Thus, the design example's assumption is valid: only pump shut-offs need to be considered.

Miner's Rule can be used to determine cyclic life for multiple anticipated surge events or varying pump cycles. However, this is typically not necessary for the design of PVC force mains. As shown in Table 2, cyclic life is primarily driven by regular pump operation which causes maximum surge amplitude (i.e., single pump shut-off).

REFLECTED PRESSURE WAVES

Transient analysis may also model surge pressure waves reflecting throughout the pipeline which can occur following the last pump (lead) shut-off and act as additional surge events (Figure 8). Miner's Rule can be used to account for these waves.

- When information on reflected pressure waves is unavailable or a transient analysis has not been undertaken, the recommendations presented in **Conservatism in Cyclic Design** should be followed to account for these additional waves.
- Where reflected pressure waves are minimized or non-existent (e.g., discharge into manhole vented to atmosphere), further analysis is not needed.
- Where surge pressures are reflected during pump shut-off (i.e., due to pipe plan, profile, closed discharge conditions, valve closure time, etc.), additional analysis using Miner's Rule may be warranted to determine the system's cyclic life.

NEGATIVE PRESSURES

It is possible for zones of negative pressure to occur along the length of a force main. Their locations can be identified by hydraulic or transient models. It is good design practice to prevent negative pressures in pipelines and appurtenances, no matter what pipe material is used. Surge-control equipment can prevent negative pressures from occurring near the pump station during a transient event (**Surge-Control Techniques**).

PVC pressure pipe is capable of withstanding negative pressures without buckling, collapse, or loss of joint integrity.[14] Resistance to buckling is discussed in the "Design of Buried PVC Pipe" chapter of the *Handbook of PVC Pipe Design and Construction*.[15] Additionally, PVC pipe joints undergo quality assurance vacuum and internal pressure tests per AWWA C900 and ASTM D2241. Compliance to these standards ensures that PVC pipe has a leak-free, water-tight joint design.

INSTALLATION PROCEDURES

Proper installation helps ensure the longevity of a sewer force main, regardless of pipe material. Installation is outside the scope of this guide. However, some key considerations for gasketed pipe are:

- For joint insertion, see technical brief "Gasketed PVC Pipe: The Importance of Insertion Lines."[16]
- Follow manufacturers' recommended joint deflection limits and procedures.[17]

Additional resources on installation of PVC pipe are:

- Pipe manufacturers' installation guides
- Uni-Bell PVC Pipe Association, *Installation Guide for Gasketed-Joint PVC Pressure Pipe*, UNI-PUB-9
- American Water Works Association (AWWA) Standard C605 "Underground Installation of Polyvinyl Chloride (PVC) and Molecularly Oriented Polyvinyl Chloride (PVCO) Pressure Pipe and Fittings"
- Uni-Bell PVC Pipe Association, *Contractor's Guide for Installation of Gasketed PVC Pipe for Water*
- Uni-Bell PVC Pipe Association, *Handbook of PVC Pipe Design and Construction*

ADDITIONAL RESOURCES

ONLINE CYCLIC-LIFE CALCULATOR

The PVC Pipe Association (PVCPA) has developed an online calculator for cyclic design (Cyclic-Life Calculator). Inputs include:

- Pipe DR
- Maximum recurring surge pressures
- Minimum recurring surge pressures
- Number of surge occurrences per day

The output provides the cyclic life. Multiple surge events can be added, which the calculator can combine to provide resulting cyclic life. Up to four surge events can be included.

The calculator assists designers to quickly perform the cyclic design check and to change variables to see how cyclic life is affected. For example, designers can compare the cyclic life of a PVC force main with or without surge-control equipment (which changes maximum and minimum recurring surge pressures). Note that if pipe DR is changed, corresponding maximum and minimum recurring surge pressures should be updated.

PVCPA does not recommend use of online calculators from other organizations for design of PVC pipe. These tools limit the user's ability to accurately design a pipeline project. Using the cyclic procedure provided in this guide enables a thorough analysis of a PVC force main project.

CONDITION ASSESSMENT

While this guide provides the design procedure for new PVC force mains, the Folkman Equation (Equation 2) may also be used to approximate remaining useful life of an existing PVC force main. Pressure monitoring can be set up to measure the maximum and minimum recurring surge pressures. These values are then used in the Folkman Equation (as shown in Step 5 of **Design Example**) to determine cyclic life. The remaining useful life is then found by:

EQUATION 5

$$Remaining\ Useful\ Life = Cyclic\ Life - Pipe\ Age$$

APPENDIX A: PVC PRESSURE PIPE DIMENSIONS

The average inside diameters listed are in feet and are based on OD – (2 × t_{min} × 103%). These dimensions are used for design purposes only. If actual values are needed for field installation purposes, contact the manufacturer.

TABLE A.1: APPROXIMATE INSIDE DIAMETERS FOR CIOD PIPE — AWWA C900

Nominal Diameter (in)	Average OD (in)	DR 14 Average ID (ft)	DR 18 Average ID (ft)	DR 21 Average ID (ft)	DR 25 Average ID (ft)	DR 32.5 Average ID (ft)	DR 41 Average ID (ft)
4	4.800	0.341	0.354	0.361	0.367	—	—
6	6.900	0.490	0.509	0.519	0.528	—	—
8	9.050	0.643	0.668	0.680	0.692	—	—
10	11.10	0.789	0.819	0.834	0.849	—	—
12	13.20	0.938	0.974	0.992	1.01	—	—
14	15.30	1.09	1.13	1.15	1.17	1.19	1.21
16	17.40	1.24	1.28	1.31	1.33	1.36	1.38
18	19.50	1.39	1.44	1.47	1.49	1.52	1.54
20	21.60	1.54	1.59	1.62	1.65	1.69	1.71
24	25.80	1.83	1.90	1.94	1.97	2.01	2.04
30	32.00	2.27	2.36	2.41	2.45	2.50	2.53
36	38.30	—	2.83	2.88	2.93	2.99	3.03
42	44.50	—	3.28	3.35	3.40	3.47	3.52
48	50.80	—	—	—	3.89	3.97	4.02
54	57.56	—	—	—	4.40	4.49	4.56
60	61.61	—	—	—	4.71	4.81	4.88

Note: Sizes for some DRs not listed may be produced. Contact manufacturer for availability.

TABLE A.2: APPROXIMATE INSIDE DIAMETERS FOR IPS OD PIPE — ASTM D2241						
Nominal Diameter (in)	Average OD (in)	DR 17 Average ID (ft)	DR 21 Average ID (ft)	DR 26 Average ID (ft)	DR 32.5 Average ID (ft)	DR 41 Average ID (ft)
4	4.500	0.330	0.338	0.345	0.351	0.356
6	6.625	0.407	0.418	0.427	0.434	0.440
8	8.625	0.485	0.498	0.508	0.517	0.524
10	10.750	0.632	0.648	0.662	0.673	0.683
12	12.750	0.787	0.808	0.825	0.839	0.851

Note: Sizes and DRs not listed may be produced. Contact manufacturer for availability.

APPENDIX B: PVC PRESSURE PIPE DESIGN TABLES

TABLE B.1 DIMENSION RATIOS (DR), PRESSURE CLASSES (PC), AND SHORT-TERM RATINGS (STR)		
DR	PC/PR (psi)	STR (psi)
51	80	128
41	100	160
32.5	125	203
26	160	256
25	165	264
21	200	320
18	235	378
14	305	488

Note 1: The third design check requires comparing the maximum occasional surge pressure to 1.6 × PC/PR. The value of 1.6 × PC/PR is known as STR.

Note 2: DRs not listed may be produced. Contact manufacturer for availability.

TABLE B.2 THERMAL DERATING FACTORS	
Sustained Service Temperature (°F)	Temperature Coefficient
<73	1.00
80	0.88
90	0.75
100	0.62
110	0.50
120	0.40
130	0.30
140	0.22

Note 1: Multiply PC/PR by factor shown.
Note 2: Interpolate between the temperatures listed to calculate other factors.

APPENDIX C: DESIGN EXAMPLE ALTERNATE SCENARIO – HIGH-FLOW EVENT

Since cyclic life is primarily dependent on daily pump operations, this operating state was used in the design example. However, a force main may see high-flow events (such as heavy rain) for a portion of its life, which can result in changes in the number of pump cycles. For this scenario, a high-flow event is defined as one that causes all three pumps (lead, lag, and standby) to run.

Solution B of **Design Example** is used to show typical operating conditions, but with the addition of a high-flow event occurring for a portion of the year. For this example, high-flow events are assumed to occur for 80 days per year.

Assumptions:

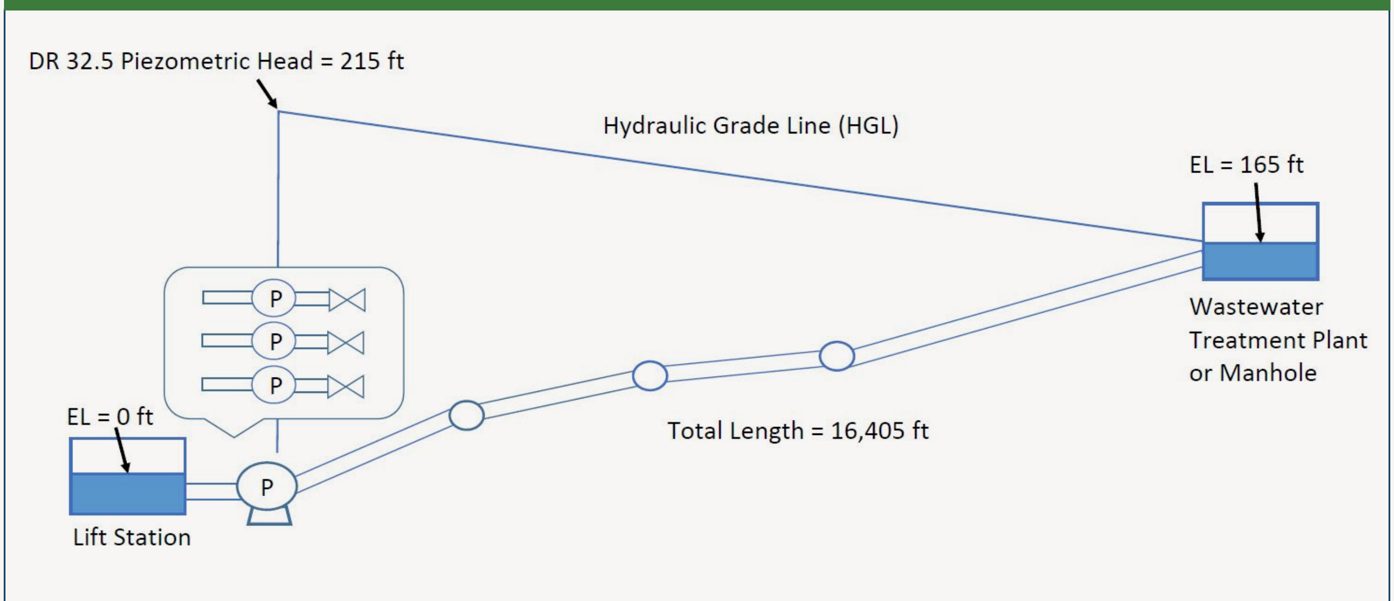
- The cyclic design assumes that all pumps are running for 80 days per year (maximum flow), and a single pump is running 285 days per year (normal flow).
- Other assumptions are the same as those listed in **Design Example**, Solution B.

To complete all four design checks for DR 32.5 PVC pipe, the following hydraulic and transient models are used:

- The HGL in Figure C.1 provides the maximum working pressure (WP_{max}).

$$WP_{max} = 215\ ft = 93\ psi$$

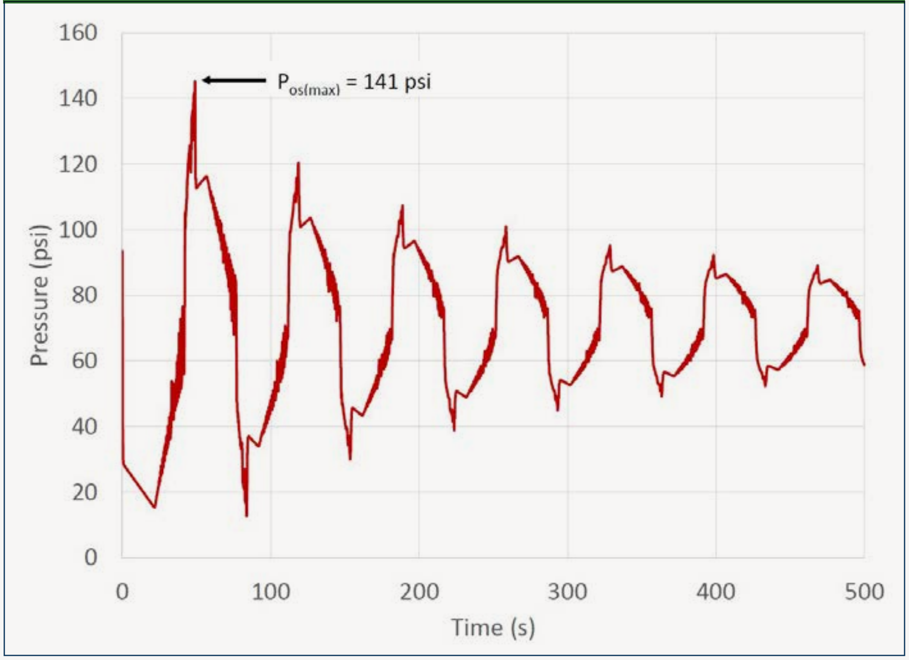
FIGURE C.1: FORCE MAIN PROFILE



- For maximum occasional surge ($P_{os(max)}$), Figure C.2 simulates a power failure where all pumps shut off simultaneously.

$$P_{os(max)} = 141\ psi$$

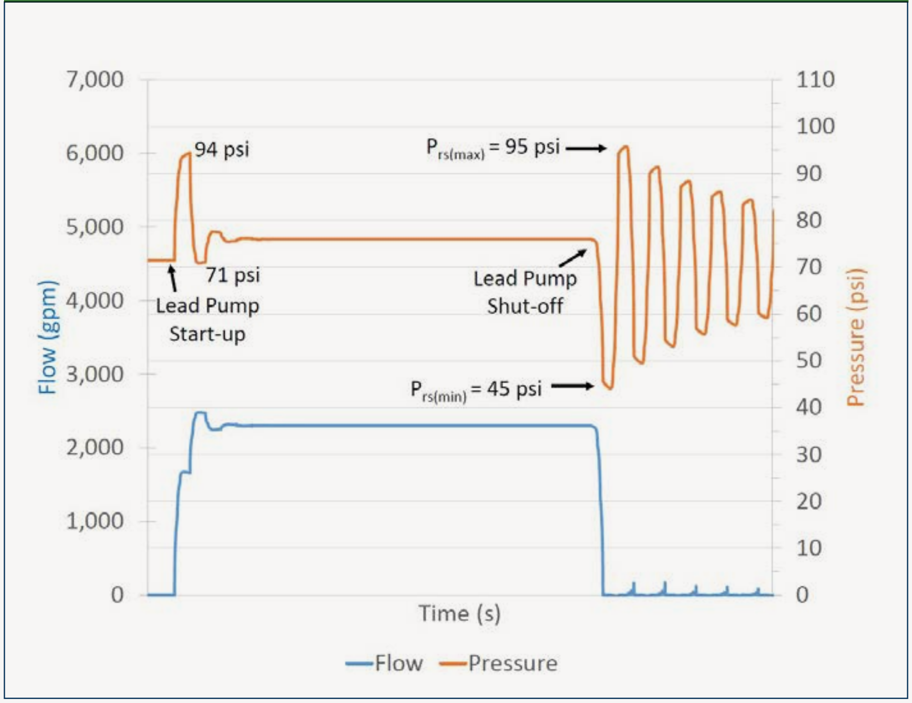
FIGURE C.2: PRESSURE vs TIME FOR SIMULTANEOUS POWER FAILURE OF ALL PUMPS



- Figure C.3 represents recurring surge ($P_{rs(max)}$) for the single-pump operation.

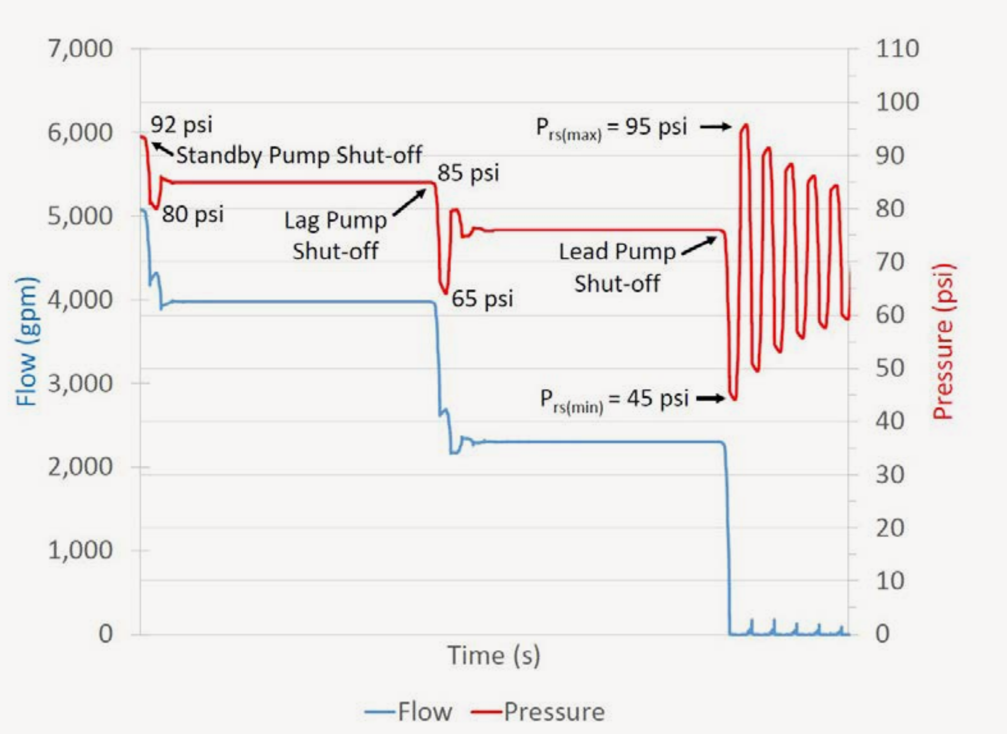
$$P_{rs(max)} = 95\ psi$$

FIGURE C.3: FLOW AND PRESSURE vs TIME



For recurring surge when all pumps are running, a new model shows all three pumps shutting off sequentially. A model with sequential start-up is not provided, since the effects of the surge-pressure amplitudes are negligible.

FIGURE C.4: FLOW AND PRESSURE vs TIME FOR THREE-PUMP OPERATION



Note: For reflected waves following pump shut-off, see **Reflected Pressure Waves**.

The step-downs in pressure correspond to each pump shutting off in sequence. When Figures C.3 and C.4 are compared, the values of $P_{rs(max)}$ = 95 psi and $P_{rs(min)}$ = 45 psi do not change. In other words, whether a single pump or multiple pumps turn(s) on/off, maximum and minimum recurring surge pressures do not change.

The first three design checks are as follows (same as **Design Example**, Solution B):

$$WP_{max} \leq PC \times F_T$$ (First Design Check)

$$93\ psi \leq 125\ psi \times 1.0$$

$$93\ psi < 125\ psi \quad \checkmark$$

$$P_{rs(max)} \leq PC \times F_T$$ (Second Design Check)

$$95\ psi \leq 125\ psi \times 1.0$$

$$95\ psi < 125\ psi \quad \checkmark$$

$$P_{os(max)} \leq 1.6 \times PC \times F_T$$ (Third Design Check)

$$141\ psi \leq 1.6 \times 125\ psi \times 1.0$$

$$141\ psi < 200\ psi \quad \checkmark$$

- For the cyclic design check, Miner's Rule must be used since the number of pump cycles varies throughout the year. For this scenario, Table C.1 provides the inputs for Miner's Rule:

TABLE C.1: MINER'S RULE TABLE FOR VARYING PUMP CYCLES PER YEAR

Surge Event	$P_{rs(max)}$ (psi)	$P_{rs(min)}$ (psi)	N_i per Folkman Equation (cycles × 10^6)	Cycles per Day	n_i (cycles per year)	Fraction of Life Consumed per Year (n_i/N_i)
Lead Pump: shut-off from single-pump operation (typical flow)	95	45	7.42	96	96 cycles/day x 285 days = 27,360	0.0037
Lead Pump: shut-off from three-pump operation (high flow)	95	45	7.42	48	48 cycles/day x 80 days = 3,840	0.0005
			Sum =			0.0042
			Cyclic Life (reciprocal of Sum) =			238 years

In this example for high-flow events, cyclic life is 238 years. Inputs for this table are as follows:

Surge Event

- Surges from pump start-ups are ignored, since resulting surge-pressure amplitudes produce almost no fatigue.
- For single-pump operation, only pump shut-off is considered.
- For three-pump operation, down-surges from the first two pump shut-offs (standby and lag) produce almost no fatigue. Only the third pump (lead) shut-off is included.

$P_{rs(max)}$; $P_{rs(min)}$; Folkman Equation (N_i)

- Maximum and minimum recurring surge pressures are 95 psi and 45 psi, respectively, for both operations as shown in Figures C.3 and C.4.
- Use Folkman Equation (Equation 2).

Cycles per Day

- For single-pump operation: a shut-off occurs every 15 minutes (96 times per day).
- For three-pump operation: to determine number of times the last pump (lead) shut-off occurs, wet-well size and inflow rate are needed. The last pump will shut off when the inflow rate reduces to a value less than the single pump's flow rate. For simplicity, this example assumes the last pump shuts off every 30 minutes due to fill and empty time for the wet well. This equates to 48 occurrences per day, which is considered a large number of cycles during high-flow events.

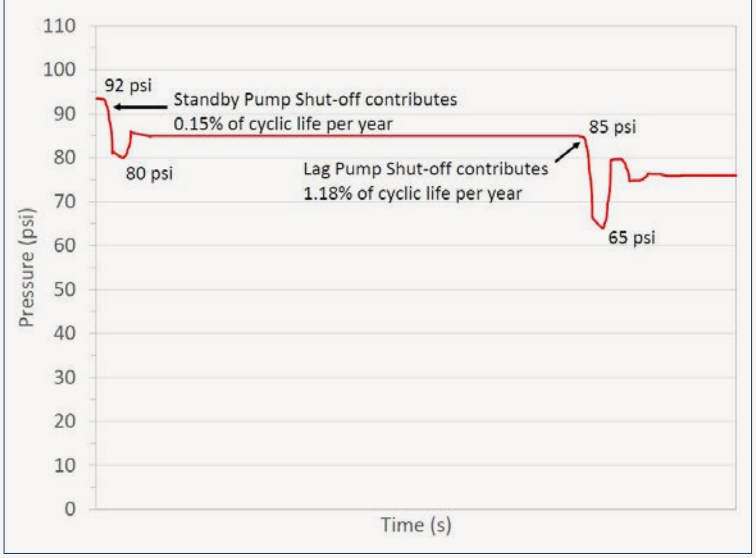
Cycles per Year (n_i)

- Assume single-pump operation occurs 285 days per year.
- Assume three-pump operation occurs 80 days per year.

SUMMARY: HIGH-FLOW EVENTS HAVE MINIMAL EFFECT ON CYCLIC LIFE

Cyclic life is higher when accounting for high-flow days. In this example, the resulting cyclic life is 238 years. In contrast, in the design example, which is based on a single-pump operation for 365 days a year, cyclic life is 211 years. This may seem counterintuitive at first but can be explained. High-flow events are often associated with greater surge pressures due to increased velocity changes. However, the transient model in Figure C.4 shows that there is a minor down-surge each time the standby pump or the lag pump turns off, but a major down-surge when the lead pump turns off. If lag pump and standby pump down-surges were included in Table C.1, calculations would show that the impacts on cyclic life are negligible (Figure C.5).

FIGURE C.5: SMALL DOWN-SURGES FROM SHUT-OFFS OF FIRST TWO PUMPS



Summary:

- Surges caused by lag pump and standby pump shut-offs produce almost no fatigue.
- Surges caused by all three pump start-ups also cause almost no fatigue.
- Therefore, only the one-pump (lead) shut-off surge must be taken into account.
- The surge from this last pump shut-off is the same as for the one-pump operation.
- For the lead pump, cycles occur fewer times per day with multiple pumps operating. In effect, the other two pumps reduce the demand on the lead pump because it takes more time for the wet well to fill and empty.

Conclusion:

- In the **Design Example**, a surge pressure between 45 psi and 95 psi occurs 96 times per day for 365 days per year.
- In this high-flow scenario, the same surge pressure and frequency occur only 285 days per year. For the remaining 80 days, this surge from lead pump shut-off occurs at a lower frequency of 48 times per day (as compared to 96 times per day).
- The result is a longer cyclic life of 238 years for the high-flow scenario compared to 211 years for single-pump operation.

For multiple-pump operations, high-flow events do not require additional analysis because they are not design-limiting. Design of PVC force mains should be based on regular pump operation that causes maximum surge amplitude (which occurs during lead pump shut-offs), as shown in **Design Example**, Solution A or B.

Bottom line: high-flow events with multiple pumps do not govern cyclic life of PVC force mains.

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Note: clickable links are blue and underlined.

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