# TABLE OF CONTENTS

INTRODUCTION .................................................................................................................. 1
MATERIAL SELECTION ......................................................................................................... 1
HYDRAULIC DESIGN ............................................................................................................ 2
PVC PRESSURE PIPE DESIGN ........................................................................................... 3
  Long-Term Strength .......................................................................................................... 3
  Short-Term Strength ......................................................................................................... 4
  Cyclic Strength .................................................................................................................. 6
PVC PRESSURE PIPE DESIGN EXAMPLE ........................................................................ 8
  Check Long-Term Strength ............................................................................................... 9
  Check Short-Term Strength .............................................................................................. 10
  Check Cyclic Strength ...................................................................................................... 10
  Cyclic Check, Step-by-Step ............................................................................................ 10
  Cyclic Life ........................................................................................................................ 11
ADDITIONAL DESIGN CONSIDERATIONS .................................................................... 12
  Common Surge Control Techniques .............................................................................. 12
  Entrapped Air .................................................................................................................. 14
  Reflected Pressure Waves .............................................................................................. 16
  External Load Design ...................................................................................................... 18
INSTALLATION PROCEDURES ....................................................................................... 18
ACCEPTANCE TESTING .................................................................................................... 19
ADDITIONAL REFERENCES ............................................................................................... 19
APPENDIX A: CYCLIC CUMULATIVE DAMAGE----------------------------- 21

Applying Miner’s Rule----------------------------------------------------------- 22

References Cited in Appendix A-------------------------------------------------- 25

APPENDIX B: LIST OF EQUATIONS--------------------------------------------------- 26

APPENDIX C: AVERAGE INSIDE DIAMETERS--------------------------------------------- 28

ASTM D2241, IPS--------------------------------------------------------------- 28

AWWA C900, CIOD--------------------------------------------------------------- 28

AWWA C905, CIOD--------------------------------------------------------------- 29
Introduction

Due to the high cost of wastewater collection systems, engineers are continually re-evaluating old ideas concerning wastewater collection. Gravity-flow collection systems normally offer the most practical and cost-effective solution to a community’s collection needs. However, the gravity flow solution is sometimes economically impractical or physically impossible. To overcome these problems, engineers may elect to install pump stations and force mains.

A force main is defined as a piping system that transports sanitary sewage with internal pressure. High pressure is created at the system’s intake point by a pump. This pump station “forces” the wastewater to the discharge, or low-pressure point, in the system.

While a wealth of information exists on pump-station design, examples and design guidelines for sewer force mains are often inadequate. Uni-Bell has chosen to produce a design manual which deals directly with the issues surrounding a force main sewer installation using PVC. Although the following design manual will briefly touch on pump design requirements, pump-station design is not included.

Material Selection

Upon selecting PVC pressure pipe for force main design, the designer forms a solid foundation for the short- and long-term success of the project. Polyvinyl Chloride (PVC) piping material has withstood the test of time. Extensive performance records have been compiled proving PVC is the piping material of choice for sanitary sewer applications.

There are numerous reasons for PVC’s success in sanitary sewer applications, the first and foremost being PVC’s ability to resist corrosion. PVC’s inert nature is attributed to the fact that vinyl is a non-conductor of electricity, making it immune to electrochemical reactions caused by acids, bases, and salts. This inert characteristic is very important for sanitary sewer installations, where aggressive environments exist both outside and inside the system.

PVC’s ability to resist corrosion is an advantage not shared by traditional pressure-piping materials. By specifying PVC pipe for force-main design, the designer has chosen to eliminate the possibility of corrosion-induced pipe failure.

PVC pipe also offers other distinct advantages. An immediate benefit will be construction cost savings through PVC’s light weight and ease of installation. Appreciable financial savings can be realized during any project’s construction phase by eliminating the heavier equipment needed to install traditional piping materials. In addition to initial savings, PVC’s superior hydraulic characteristics will often result in lower lifetime costs for pumping and maintenance of the system.
The major total costs of a pumping system include the cost of pumps, pipes, installation, operation and maintenance (O&M), and energy. A larger diameter pipeline (higher initial cost) will result in lower friction head loss and require a smaller total pumping head with lower horsepower pumps and less energy (lower lifetime cost). A PVC pipeline offers the same lower lifetime costs without the expenditure of high initial material costs by providing competitive initial costs, long service life, low maintenance costs, and lower friction head loss achieved through its hydraulic smoothness.

Hydraulic Design

Hydraulic research and analysis have shown that flow conditions in PVC pressure piping systems can be designed conservatively using the Hazen-Williams equation. Flow conditions may also be designed with more detailed analysis using the Darcy-Weisbach equation.

The Hazen-Williams flow formula is most widely accepted and used in the calculation of pressure pipe flow conditions.

**EQUATION 1**

\[ V = 1.318 \, C \left( R_h \right)^{0.63} \left( S \right)^{0.54} \]

Where:
- \( V \) = flow velocity, ft/s
- \( C \) = flow coefficient
- \( R_h \) = hydraulic radius, ft
  
  Note: The hydraulic radius is defined as the flow area divided by the wetted perimeter in the interior of the pipe.
  
  Note: \( R_h = 1/4(D_i) \) for pipe flowing full or half full
- \( S \) = hydraulic slope, ft/ft
- \( D_i \) = pipe inside diameter, ft

Research has established that the Hazen-Williams flow coefficient, or “C” factor, is commonly defined in a range of values from 155 to 165 for both new and used PVC pipe. The Hazen-Williams “C” factor, therefore, has been established conservatively at \( C = 150 \) for the design of PVC piping systems.

Pipe sizing and pump design and selection are topics covered in many civil engineering textbooks. The intent of this document is not to repeat this material. Rather, the intent is to give details on the specifics of PVC pressure-pipe design and installation, as well as highlighting design considerations that the textbooks sometimes lack.
Some of the basic details the designer gathered when optimizing the pipe and pump details are listed below:

- Pipe material (PVC)
- Projected wastewater flows
- Pipe profile and stationing

Once the designer has determined the basic hydraulic components for the project, the pump curve and system curve are used to determine the pressures and flows within the system for various operating conditions. The designer then establishes the hydraulic profile for the project. At that point, the designer has the information needed to specify the appropriate class of PVC for the pressure requirements of the project.

**PVC Pressure Pipe Design**

Consistent with all thermoplastic materials, PVC has three distinct strength limits. These are: (a) Long-Term Strength, (b) Short-Term Strength, and (c) Cyclic Strength. The sewage force main designer must select a PVC pipe that is within the limits of all three strength categories.

The design approach presented in this manual will include three separate design checks, listed below:

- The system’s operating pressure will establish the required long-term pressure rating (PR) of the PVC pipe, based on a Factor of Safety of 2.0 against the Hydrostatic Design Basis.

- The worst-case, non-recurring surge experience will establish the required short-term pressure rating (STR) of the appropriate PVC pipe, based on a Factor of Safety of 2.0 against the quick-burst strength.

- A cyclic fatigue check, using the design tools developed through research conducted by Utah State University, will establish a fatigue life that meets or exceeds the desired design life.

**Long-Term Strength**

This is the design step that is familiar to most engineers. The operating pressure is compared to the PR of the pipe. The PRs for various dimension ratios of PVC pipe are listed in Table 1. (With the latest revision of the AWWA C900 standard, the Pressure Class (PC) is now the same as the Pressure Rating (PR) for a given dimension ratio.) Mathematically, the Standard Dimension Ratio (SDR) is the same as the Dimension Ratio (DR). Both are defined in Equation 2.
### TABLE 1
Pressure Ratings for PVC Pipe

<table>
<thead>
<tr>
<th>SDR or DR</th>
<th>PR or PC, psi (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
<td>80 (0.55)</td>
</tr>
<tr>
<td>41</td>
<td>100 (0.69)</td>
</tr>
<tr>
<td>32.5</td>
<td>125 (0.86)</td>
</tr>
<tr>
<td>26</td>
<td>160 (1.10)</td>
</tr>
<tr>
<td>25</td>
<td>165 (1.14)</td>
</tr>
<tr>
<td>21</td>
<td>200 (1.38)</td>
</tr>
<tr>
<td>18</td>
<td>235 (1.62)</td>
</tr>
<tr>
<td>14</td>
<td>305 (2.11)</td>
</tr>
</tbody>
</table>

### EQUATION 2

\[
SDR = DR = D_0 + t_{\text{min}}
\]

Where: \( D_0 \) = average outside diameter
\( t_{\text{min}} \) = minimum wall thickness, same units as \( D_0 \)

The PR selected must exceed the normal operating pressure determined by the hydraulic design of the system.

**Short-Term Strength**

An inherent property that PVC pipes have always offered is higher pressure capacity as the duration of the applied pressure is decreased. This is why the quick-burst and sustained-pressure test values used for quality-control purposes far exceed a PVC pipe's Pressure Rating. An SDR41 product, with a 100 psi Pressure Rating, serves as an example. For the sustained-pressure test, an SDR41 must hold 210 psi in excess of 1,000 hours. For the quick-burst test, the pressure causing the pipe to burst must exceed 315 psi, where the time to burst is calibrated to be in the 60 to 70 second range.
TABLE 2
STR Values for PVC Pipe

<table>
<thead>
<tr>
<th>SDR or DR</th>
<th>STR, psi (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
<td>128 (0.88)</td>
</tr>
<tr>
<td>41</td>
<td>160 (1.10)</td>
</tr>
<tr>
<td>32.5</td>
<td>203 (1.40)</td>
</tr>
<tr>
<td>26</td>
<td>256 (1.77)</td>
</tr>
<tr>
<td>25</td>
<td>264 (1.84)</td>
</tr>
<tr>
<td>21</td>
<td>320 (2.21)</td>
</tr>
<tr>
<td>18</td>
<td>376 (2.60)</td>
</tr>
<tr>
<td>14</td>
<td>488 (3.40)</td>
</tr>
</tbody>
</table>

For non-recurring pressure surges, such as those resulting from a power outage, select an STR that exceeds the peak pressure (including surge).

If better data are not available from transient analysis software, a conservative estimate for a non-recurring pressure surge may be calculated using Equation 3 and Table 3. This assumes that the surge resulted from an operation that instantaneously stopped the column of wastewater.

EQUATION 3

\[ P_{\text{peak}} = P_{\text{op}} + V(P_{s}') \]

Where:
- \( P_{\text{peak}} \) = peak pressure from non-recurring surge event, psi
- \( P_{\text{op}} \) = normal operating pressure, psi
- \( V \) = maximum flow velocity, ft/s
- \( P_{s}' \) = surge for a 1 ft/s velocity change (Table 3), psi
Table 3
Pressure Surge versus Dimension Ratio
(In Response to a 1 ft/s (0.3 m/s) Instantaneous Flow Velocity Change)

<table>
<thead>
<tr>
<th>SDR or DR</th>
<th>Pressure Surge, $P_s'$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>psi (kPa)</td>
</tr>
<tr>
<td>51</td>
<td>10.8 (74)</td>
</tr>
<tr>
<td>41</td>
<td>11.4 (79)</td>
</tr>
<tr>
<td>32.5</td>
<td>12.8 (88)</td>
</tr>
<tr>
<td>26</td>
<td>14.4 (99)</td>
</tr>
<tr>
<td>25</td>
<td>14.7 (101)</td>
</tr>
<tr>
<td>21</td>
<td>16.0 (110)</td>
</tr>
<tr>
<td>18</td>
<td>17.4 (120)</td>
</tr>
<tr>
<td>14</td>
<td>19.8 (137)</td>
</tr>
</tbody>
</table>

Cyclic Strength

The Utah State University (USU) research on the cyclic capabilities of PVC pressure pipe [Jeffrey, 2004] confirmed that predicting the fatigue capabilities of PVC is much like that of any other material. It is a function of two variables: the average stress and the stress amplitude. (See Equations 4 and 5.) The design chart developed by the USU research is shown in Figure 1.

EQUATION 4

$$\sigma_{\text{avg}} = \frac{(P_{\text{max}} + P_{\text{min}})(\text{DR} - 1)}{4}$$

Where:
- $\sigma_{\text{avg}}$ = required average hoop stress, psi
- $P_{\text{max}}$ = maximum recurring pressure, psi
- $P_{\text{min}}$ = minimum recurring pressure, psi
- DR = dimension ratio of the pipe

EQUATION 5

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

Where:
- $\sigma_{\text{amp}}$ = required design stress amplitude, psi
Figure 1: Design Chart for the Cyclic Strength of PVC Pressure Pipe

The successful design will result in a cyclic life ($C$) that exceeds the total number of cycles ($C'$) that occur throughout the design life. Figure 1 is used to determine $C$, while Equation 6 is used to calculate $C'$. Note that Equation 6 uses the total number of cycles per day, not the number of cycles per hour. By using a total daily number, both heavy and light periods of sewage flows are accounted for. The worst case design condition would be based on the design number of starts per hour, which is part of the pump selection and wet well design.

**EQUATION 6**

$$C' = (N \text{ cycles/day}) (365 \text{ days/year}) (\text{Design Life in Years})$$
PVC Pressure Pipe Design Example

This design example will demonstrate the various design checks for PVC pressure pipe. The pipe under consideration is a 14-inch SDR41 AWWA C905 pipe, with a CIOD diameter regimen. The design flow is 3.03 cfs. It is estimated that the pump will have 58 starts and 58 stops each day. Once the steady-state-operating flow has been achieved, the operating pressure is 27 psi. During start-up or shut-down, the pressure amplitude may be as large as 20 psi. The force main discharges into a manhole at atmospheric pressure at the upstream end. The desired design life is 50 years. An analysis of transients using design software has not been conducted.

EQUATION 7

\[ D_i = D_o - 2t' \]

Where:
- \( D_i \) = inside diameter, in
- \( D_o \) = outside diameter, in
- \( t' \) = \( t_{min} + 0.5t_{tol} \), in
- \( t_{min} \) = minimum wall thickness, in
- \( t_{tol} \) = tolerance on the minimum wall thickness, in

EQUATION 8

\[ A_x = \frac{(\pi \div 4)(D_i)^2}{144} \]

Where:
- \( A_x \) = flow cross sectional area, ft²

EQUATION 9

\[ V = Q \div A_x \]

Where:
- \( V \) = flow velocity, ft/s
- \( Q \) = flow, ft³/s
- \( A_x \) = flow cross sectional area, ft²

The following information may be found in Table 2 of the AWWA C905 standard.

\( D_o = 15.300 \) in
\[ t_{min} = 0.373 \text{ in} \]
\[ t_{tol} = +0.052 \text{ in} \]

With that information and Equation 7, the average inside diameter may be computed.

\[ t' = 0.373 + (0.5) (0.052) = 0.399 \text{ in} \]
\[ D_i = 15.300 - 2 (0.399) = 14.502 \text{ in} \]

Next, find the flow cross sectional area using Equation 8 and the fluid velocity using Equation 9.

\[ A_x = \left( \frac{\pi \div 4}{(14.502)^2} \right) / 144 = 1.147 \text{ ft}^2 \]
\[ V = \left( 3.03 \right) \div (1.147) = 2.64 \text{ ft/s} \]

Routine pressures the force main experiences are as follows:

- \( P_{op} \) = Operating pressure = 27 psi (Known)
- \( P_{amp} \) = Pressure amplitude = 20 psi (Known)
- \( P_{max} \) = 27 + 20 = 47 psi
- \( P_{min} \) = 27 - 20 = 7 psi

Hoop stresses from the routine pressures may now be calculated using Equations 4 and 5.

\[ \sigma_{avg} = \left[ \frac{(47 + 7)(41 - 1)}{4} \right] = 540 \text{ psi} \]
\[ \sigma_{amp} = \left[ \frac{(47 - 7)(41 - 1)}{4} \right] = 400 \text{ psi} \]

The number of cycles per day (\( N \)) may be determined from the known information. Equation 6 may be used to determine the number of cycles that occur throughout the design life.

\[ N = 58 \text{ starts} + 58 \text{ stops} = 116 \text{ cycles / day} \]
\[ C' = (116)(365)(50) = 2.12 \times 10^6 \text{ cycles} \]

This system experiences 42,340 cycles per year.

**Check Long-Term Strength**

Is the operating pressure less than or equal to the PR of the SDR41 selected?

\[ P_{op} \leq \text{PR?} \]
\[ 27 \text{ psi} \leq 100 \text{ psi (From Table 1)} \]
Yes. The first design check is passed.
Check Short-Term Strength

Equation 3 will be used to estimate the worst-case, non-recurring pressure. Table 3 lists the $P_s'$ for SDR41 as 11.4 psi.

$$P_{\text{peak}} = 27 + (2.64)(11.4) = 57 \text{ psi}$$

Now the adequacy of the SDR41’s short-term strength may be checked.

Is the peak pressure less than or equal to the STR of the SDR41 selected?

$$P_{\text{peak}} \leq \text{STR?}$$

$58.7 \text{ psi} \leq 160 \text{ psi}$ (From Table 2)

Yes. The second design check is passed.

Check Cyclic Strength

Is the cyclic capacity greater than the anticipated number of cycles expected for the force main over its design life?

$$C' \leq C?$$

$2.12 \times 10^6 \leq 9 \times 10^6$ (From Figure 1)

Yes. The third and last design check is passed. The design is satisfactory.

Cyclic Check, Step-by-Step

The manner by which the $9.0 \times 10^6$ value for $C$ was determined is now further detailed. Refer to Figure 2. First note that it is a semi-log chart. The $x$-axis has a logarithmic scale. One of the two independent variables, average stress, serves as the chart’s $y$-axis. The second independent variable, stress amplitude, is represented by the black diagonal lines that overlay the chart. Each line represents a different stress amplitude. As one moves from left to right across the chart, the stress amplitudes represented by the black lines decrease. The $x$-axis is the dependent variable, and it denotes the cyclic life ($C$) of the PVC pressure pipe.

In this example, the first independent variable, $\sigma_{\text{avg}}$, has a value of 540 psi. In Figure 2, that value is shown in green on the $y$-axis. A green line extends right from that value until it intersects the second independent variable, $\sigma_{\text{amp}}$. In the example, $\sigma_{\text{amp}}$ has a value of 400 psi. However, the design chart does not have a line for a 400 psi $\sigma_{\text{amp}}$. There are $\sigma_{\text{amp}}$ lines for 300 and 500 psi. Since 400 falls halfway between those two values, a purple line was added to the chart midway between those values to represent the 400 psi $\sigma_{\text{amp}}$ line. At the intersection of the green line and the purple line, the tail of a blue line is shown. The blue line is extended downward until it hits the $x$-axis. The value for $C$ in this example is $9.0 \times 10^6$.
$10^6$, which is read from the x-axis of the chart at the point of intersection of the arrowhead of the blue line and the x-axis.

![Stress Amplitude (psi) Chart]

**Figure 2: Using the Design Chart for the Design Example**

**Cyclic Life**

At 42,340 cycles per year, what is the cyclic life for the pipe in this design example?

\[
\text{Cyclic Life} = \frac{9.0 \times 10^6}{42,340} \text{ cycles / year} = 213 \text{ years}
\]

Note: Large pressure swings have been greatly reduced in recent years with the use of “soft-start / soft-stop” pumps in force main applications. The pressure swing shown in this example could be further reduced by taking full advantage of this technology or other surge control devices. There have also been improvements in variable speed pumping, which has increased its popularity. If variable-speed
pumping were employed, the number of starts and stops shown in this example would be greatly reduced as would the pressure swings.

**Additional Design Considerations**

**Common Surge-Control Techniques**

Pressure-control devices serve multiple tasks within a force main. Their primary function is to minimize pressure fluctuations created when a change in fluid velocity occurs within the system. A change in flow velocity within a closed conduit causes elastic waves to travel upstream and downstream from the point of origin. These elastic waves cause an increase or decrease in pressure as they travel along the line. These pressure changes are referred to as water hammer, surge pressure, or transient pressure.

Where either the magnitude or frequency of surges is judged to be the limiting parameter in a pipeline design, there are practical means of reducing them to acceptable levels. In general, the first objective is to keep the upsurge and downsurge (the maximum positive and negative surges) at minimum values. Within this minimized transient pressure envelope, even at a fixed-cycle frequency (i.e., where C is not a controllable variable), the operation of the pipeline may often proceed because the cyclic strength of the system is shown to be sufficient. Due to the wide variety of surge conditions possible, positive or negative pressures, transient or oscillatory, there is no general solution applicable to the control of surge conditions.

There are various means of controlling, reducing, or withstanding surge pressure in pressure systems. One method is to use variable speed pumps, which allow the pumping operation to be continuous for varying flow conditions, thereby greatly reducing the amount of on/off cycles. Other options are sketched in Figure 3 and are described below:

- **Controlled Closing Check or Pump Control Valve:** Slowly opening and closing check valves or pump control valves are an effective way of controlling pressure surges during normal pump starts and stops. (This arrangement is often referred to as a "soft start / soft stop" pump.) The rate of opening and closing will be a function of the pipe length. Another factor in the design is the minimum flow required by volute-casing-centrifugal pumps. The pump manufacturer should be consulted for the flow required to relieve the high radial thrusts this type of pump generates. (See Figure 3a.)

- **Air Exhaust and Air Inlet Valves:** The air exhaust valves will serve two purposes. The first will be to vent air at the high points when the
line is slowly filled for its acceptance testing after installation. The second purpose will be to vent the entrained air that comes out of the wastewater between pump cycles. Air inlet valves will admit air when the pressure drops below atmospheric pressure in order to prevent a vacuum from occurring. (See Figure 3b.) This is discussed further in the next section.

- **Pressure Surge Relief Valves**: Spring-loaded valves which release and vent pressures in excess of a pre-set value. When activated, the wastewater discharged is piped back to the wet well. (See Figure 3c.)

- **Closed or Pressurized Surge Tanks**: A closed unit containing air and wastewater occasionally separated by a diaphragm or a bladder. The air is under pressure allowing control of both positive and negative surges in high-pressure systems by allowing flow into and out of the unit. (See Figure 3d.)

- **Surge Tower**: A tank open to the atmosphere that functions in a manner similar to a surge tank for low pressures. (See Figure 3e.)

- **Pump and Driver Inertia**: Pumps which decelerate slowly in the event of a power outage, which minimizes the downsurge on the wastewater column. (See Figure 3f.)

Proper maintenance of the surge control devices and other system appurtenances is necessary for the system to continue to operate as designed.

PVC force mains can utilize some or all of the methods listed above, and Figure 3 illustrates these approaches. Additional discussion is provided in “Design of Wastewater and Stormwater Pumping Stations,” [WEF MOP FD-4, 1993].
Figure 3: Surge Reduction Methods [WEF MOP FD-4, 1993]

Entrapped Air

Air in piping systems will tend to collect at high points in the line when flow velocities are low. “Recommended Standards for Sewage Works” [GLUMRB, 2004] states that automatic air-release valves should be placed at high points along the force main to prevent the accumulation of entrapped air. “Air-Release, Air/Vacuum, and Combination Air Valves” [AWWA M51, 2001] has recommendations for the type of valve and where it should be located. The applicable recommendations are:
• **High Points:** Combination air valves should be installed at pipeline high points to provide venting while the force main is filling, during normal operation, and for air inflow and vacuum protection while the pipe is draining.

• **Increased Downslope:** A combination air valve should be considered at abrupt increases in downslope.

• **Decreased Upslope:** An air/vacuum valve or a combination air valve should be considered at abrupt decreases in upslope.

• **Long Ascents and Long Descents:** An air/vacuum valve or combination air valve should be considered at intervals of a quarter mile to a half mile along ascending sections of pipelines.

• **Horizontal Runs:** Combination air valves should be considered at the beginning and end of long horizontal sections, and air-release valves or combination air valves should be considered at intervals of a quarter mile to a half mile along horizontal sections of pipelines. It is difficult to evacuate air from a long horizontal pipeline at low-flow velocities.
Figure 4: Locating Air and Vacuum Valves on a Typical Force Main

Refer to AWWA M51 (2001) for the design approach for sizing the valve or consult the valve manufacturer. Proper sizing of air valves and other surge control devices can also be obtained by using transient-analysis computer software. Figure 4 shows a typical force main and locations of air valves. Consultation with the valve manufacturer is recommended whenever the force main projects above the hydraulic grade line.

Reflected Pressure Waves

In the PVC pressure-pipe design example, no secondary or tertiary pressure waves are generated during a pump start-up or shut-down because the system is vented to the atmosphere. If the system were a closed system, and if surge
pressures were able to be reflected, additional analysis using Miner’s Rule would be needed to determine the system’s cyclic life. (See Appendix A.)

The cyclic life is now recalculated with the following assumptions:

- The system is closed and the surge pressure wave is reflected throughout the pipeline.
- The attenuation of the secondary and tertiary waves follows a dampened sinusoidal pattern as shown in Figure 5.

![Graph showing stress over time](image)

**Figure 5: Typical Surge Pattern**  
Pressure Decay is Represented by a Dampened Sinusoidal Pattern

The first step is to represent the pressure pattern with the equivalent number of primary pressure waves. Jeffrey (2004) shows that the secondary and tertiary waves have the fatigue equivalent of 0.55 primary waves. So, the number of cycles per year must be increased by 55% to account for the pressure pattern generated by reflected surge pressure waves.

Primary Cycles per Year = (1.55) (42,340)  
Primary Cycles per Year = 65,600 cycles/year

Cyclic Life = \( C \div \text{Anticipated Number of Primary Cycles per Year} \)
Cyclic Life = $9.0 \times 10^6 \div 65,600$ cycles/year
Cyclic Life = 137 years

The design is again shown to be more than satisfactory from a cyclic fatigue point-of-view. Appendix A and the article by Fisher (2004) show more of the intermediary steps used for deriving the 55% value given by Jeffrey (2004).

External Load Design

The external load design requirements for PVC force main design do not vary from what is required of any PVC pressure piping system. Methods of external load design have been extensively covered and Uni-Bell offers the documents referenced below as recommended external load design practices for force main installations:


Installation Procedures

Proper installation procedures are critical for ensuring the longevity of the sewer force main. Research has established best practices for the installation of PVC potable water distribution and transmission pipelines. Uni-Bell offers the guidelines referenced below as recommended practices for the installation of PVC force-main pipe:


**Acceptance Testing**

To ensure the system has been installed properly, the installer should perform hydrostatic testing of the completed system. Deflection testing is not typically performed on PVC force sewer main installations. Hydrostatic test procedures have been established previously for clean water distribution and transmission and are applicable for acceptance testing of force main installations. Uni-Bell offers the guidelines referenced below as recommended practices for the acceptance testing of PVC force main installations:


The prudent engineer may wish to confirm the hydraulic design by recording actual pressures with a pressure transducer data-logger after the line is put in service. To accommodate the installation of a pressure transducer, a fitting with the appropriate threaded port should be installed downstream of the pump and just past the check valve. In the event that unusual pressure surges are recorded, remedial transient analysis may be done to identify the appropriate surge controls to rectify the situation.

**Additional References**


APPENDIX A

Cyclic Cumulative Damage

The following discussion was adopted from portions of Appendix A of Jeffrey (2004).

Cyclic Cumulative Damage

For cyclic pressures where the amplitude is variable, a method for determining the influence that each amplitude has on the total cyclic life is necessary. The linear-cumulative-damage rule, or Miner’s Rule, has come into common use following its publication by M. A. Miner in 1945. The linear-cumulative-damage rule assumes that the total life can be estimated by adding up the percentage of life consumed by each stress cycle.

Miner’s Rule is expressed by Equation A1 [Juvinall, 1967], in which \( n_1, n_2, \ldots, n_k \) represent the number of cycles at specific stress levels and \( N_1, N_2, \ldots, N_k \) represent the life (in cycles) at these stress levels, as taken from the S-N curve (Figure 1).

\[
\frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdots + \frac{n_k}{N_k} = 1 \quad \text{or} \quad \sum_{j=1}^{k} \frac{n_j}{N_j} = 1
\]

Tests cited by T. J. Dolan, et al., [Dolan, 1949] for progressively decreasing stress cycles show Miner’s Rule to produce conservative results. On the other hand, tests reported in the same publication show the rule produces non-conservative results for progressively increasing stress cycles. Sines (1959) states, that for random stress amplitudes, Equation A1 gives “reasonably accurate” results. Stress fluctuations encountered in practice are usually random in nature, and under these conditions, the linear law appears to give predictions in the right range. Typical surge pressures in pipelines produce a damped wave with progressively decreasing stress cycles. Therefore, Miner’s Rule will produce reasonably accurate results - but on the conservative side.

Kirby (1980) reported that surge events in pressurized sewer systems typically have the appearance of the wave shown in Figure A1. This is essentially a damped sine wave. For the case shown, the amplitude of the tenth cycle is between three and four percent of the initial cycle. The amplitudes of cycles after
the tenth cycle are small and their influence on the cyclic life is negligible and can be disregarded.

![Graph showing pump pressure wave over time](image)

**Figure A1: Pump Pressure Wave [Kirby, 1980]**

### Applying Miner's Rule

Table A1 gives the stress amplitudes for the first ten cycles in Figure A1. The average stress in Figure A1 is 725 psi. The cycles to failure for each average stress / stress amplitude combination are also shown and were derived from Figure 1. The method for using Figure 1 to determine \( N_i \) was presented in the section titled “Cyclic Check, Step-by-Step” as part of the PVC pressure pipe design example.

In the example in this Appendix, \( k \) is equal to ten. Moreover, every time there is a primary cycle (which has the subscript of one), the complex pressure wave has nine additional cycles (each having its own subscript ranging from two to ten). This known information is captured in Equation A2.

\[
\text{EQUATION A2}
\]

\[
    n_1 = n_2 = n_3 = n_4 = n_5 = n_6 = n_7 = n_8 = n_9 = n_{10} = n
\]

The design objective is to solve for \( n \) and determine the effect that the smaller cycles that accompany every primary cycle has on the pipe’s cyclic life.
Table A1
Cycles to Failure for the Ten Cycles in Figure A1

<table>
<thead>
<tr>
<th>Cycle Number (n_i)</th>
<th>Stress Amplitude (psi)</th>
<th>Average Stress (psi)</th>
<th>Cycles to Failure from Figure 1 (N_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>652</td>
<td>725</td>
<td>1.4E+06</td>
</tr>
<tr>
<td>2</td>
<td>452</td>
<td>725</td>
<td>4.0E+06</td>
</tr>
<tr>
<td>3</td>
<td>313</td>
<td>725</td>
<td>1.5E+07</td>
</tr>
<tr>
<td>4</td>
<td>217</td>
<td>725</td>
<td>3.0E+07</td>
</tr>
<tr>
<td>5</td>
<td>151</td>
<td>725</td>
<td>6.0E+07</td>
</tr>
<tr>
<td>6</td>
<td>104</td>
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</tr>
<tr>
<td>7</td>
<td>72</td>
<td>725</td>
<td>1.4E+08</td>
</tr>
<tr>
<td>8</td>
<td>50</td>
<td>725</td>
<td>1.9E+08</td>
</tr>
<tr>
<td>9</td>
<td>35</td>
<td>725</td>
<td>2.3E+08</td>
</tr>
<tr>
<td>10</td>
<td>24</td>
<td>725</td>
<td>2.5E+08</td>
</tr>
</tbody>
</table>

The information known in Equation A2 allows Equation A1 to be further simplified as shown below in Equation A3.

\[
\frac{n}{N_1} + \frac{n}{N_2} + \cdots + \frac{n}{N_{10}} = 1 \quad \text{or} \quad \sum_{j=1}^{10} \frac{n}{N_j} = 1 \quad \text{or} \quad n \left( \sum_{j=1}^{10} \frac{1}{N_j} \right) = 1
\]

Equation A3 is solved for \( n \). The result is shown below in Equation A4.

\[
\frac{n}{N_1} + \frac{n}{N_2} + \cdots + \frac{n}{N_{10}} = 1 \quad \text{or} \quad \sum_{j=1}^{10} \frac{n}{N_j} = 1 \quad \text{or} \quad n \left( \sum_{j=1}^{10} \frac{1}{N_j} \right) = 1
\]

Equation A3 is solved for \( n \). The result is shown below in Equation A4.

\[
n = \frac{1}{\sum_{j=1}^{10} \frac{1}{N_j}}
\]

The summation in the denominator of Equation A4 is calculated in Table A2.
Table A2
Application of Miner’s Rule for Surge Event of Figure A1

<table>
<thead>
<tr>
<th>Cycle Number (subscript i)</th>
<th>Cycles to Failure from Figure 1 ($N_i$)</th>
<th>$1 / N_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4E+06</td>
<td>7.14E-07</td>
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<tr>
<td>2</td>
<td>4.0E+06</td>
<td>2.50E-07</td>
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<tr>
<td>3</td>
<td>1.5E+07</td>
<td>6.67E-08</td>
</tr>
<tr>
<td>4</td>
<td>3.0E+07</td>
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<td>1.00E-08</td>
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<tr>
<td>7</td>
<td>1.4E+08</td>
<td>7.14E-09</td>
</tr>
<tr>
<td>8</td>
<td>1.9E+08</td>
<td>5.26E-09</td>
</tr>
<tr>
<td>9</td>
<td>2.3E+08</td>
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</tr>
<tr>
<td>10</td>
<td>2.5E+08</td>
<td>4.00E-09</td>
</tr>
</tbody>
</table>

\[
\sum_{i=1}^{10} \frac{1}{N_i} = 1.11E-06
\]

As shown in Equation A4, the value for $n$ is the inverse of the summation calculated in the last row of Table A2. Thus, $n$ is equal to $9.0 \times 10^5 \times (1 + 1.11E - 6)$.

For the primary wave, which has an average stress of 725 psi and a stress amplitude of 652 psi, the cycles to failure ($N_1$) is $1.4 \times 10^6$. When each primary wave is immediately followed by nine additional - but smaller - waves as shown in Figure A1, the pipe’s cyclic life is reduced to $9.0 \times 10^5$. Applying Miner’s Rule shows that the secondary and tertiary waves that accompany the primary pressure wave may be represented as $0.55$ primary cycles ($1.4 \times 10^6 + 9.0 \times 10^5 = 1.55$). The use of this multiplier was demonstrated in the section titled “Reflected Pressure Waves” in the discussion on additional design considerations in the body of this report.

The fatigue of this system from the complex pressure wave shown in Figure A1 serves as an upper bound. The $1.55$ multiplier may be used with confidence for analysis.

Please note that a properly designed system will not experience surge pressures with amplitudes of this magnitude. However, if such conditions are present in a system, the above procedure may be used to determine if corrective actions in the system are necessary to ensure a sufficient design life.
References Cited In Appendix A


APPENDIX B

List of Equations

Equation 1
page 2

\[ V = 1.318 \ C \left( R_H \right)^{0.63} \ (S)^{0.54} \]

Equation 2
page 4

\[ SDR = DR = D_o + t_{min} \]

Equation 3
page 5

\[ P_{peak} = P_{op} + V(P_s') \]

Equation 4
page 6

\[ \sigma_{avg} = \frac{(P_{max} + P_{min})(DR - 1)}{4} \]

Equation 5
page 6

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

Equation 6
page 7

\[ C' = (N \ cycles/day) \ (365 \ days/year) \ (Design \ Life \ in \ Years) \]
Equation 7
page 8

\[ D_i = D_o - 2t' \]

Equation 8
page 8

\[ A_x = \frac{(\pi + 4)(D_i)^2}{144} \]

Equation 9
page 8

\[ V = Q + A_x \]

Equation A1
page 21

\[ \frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdots + \frac{n_k}{N_k} = 1 \quad \text{or} \quad \sum_{j=1}^{k} \frac{n_j}{N_j} = 1 \]

Equation A2
page 22

\[ n_1 = n_2 = n_3 = n_4 = n_5 = n_6 = n_7 = n_8 = n_9 = n_{10} = n \]

Equation A3
page 23

\[ \frac{n}{N_1} + \frac{n}{N_2} + \cdots + \frac{n}{N_{10}} = 1 \quad \text{or} \quad \sum_{j=1}^{10} \frac{n}{N_j} = 1 \quad \text{or} \quad n \left( \sum_{j=1}^{10} \frac{1}{N_j} \right) = 1 \]

Equation A4
page 23

\[ n = \frac{1}{\sum_{j=1}^{10} \frac{1}{N_j}} \]
APPENDIX C

Average Inside Diameters

The average inside diameters listed in this Appendix were calculated using Equation 7.

<table>
<thead>
<tr>
<th>Nominal Diameter (in)</th>
<th>Average OD (in)</th>
<th>SDR 17 Average ID (ft)</th>
<th>SDR 17 Average ID (ft)</th>
<th>SDR 21 Average ID (ft)</th>
<th>SDR 26 Average ID (ft)</th>
<th>SDR 32.5 Average ID (ft)</th>
<th>SDR 41 Average ID (ft)</th>
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<td>0.337</td>
<td>0.344</td>
<td>0.351</td>
<td>0.356</td>
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</table>

Table C2

AWWA C900, CIOD

<table>
<thead>
<tr>
<th>Nominal Diameter (in)</th>
<th>Average OD (in)</th>
<th>DR 14 Average ID (ft)</th>
<th>DR 15 Average ID (ft)</th>
<th>DR 18 Average ID (ft)</th>
<th>DR 18 Average ID (ft)</th>
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<td>0.353</td>
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<tr>
<td>Nominal Diameter (in)</td>
<td>Average OD (in)</td>
<td>DR 18 Average ID (ft)</td>
<td>SDR 21 Average ID (ft)</td>
<td>DR 25 Average ID (ft)</td>
<td>SDR 32.5 Average ID (ft)</td>
<td>SDR 41 Average ID (ft)</td>
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<td>----------------------</td>
<td>-----------------</td>
<td>-----------------------</td>
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</table>
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