Update to Designing, Operating, and Maintaining Piping System Using PVC

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The use of PVC in the irrigation industry is extensive, but there are some potential problems in designing PVC pipelines if the designer does not give due consideration to damage pressure changes can cause on the pipelines. Modern irrigation systems use electronic controls for turning valves on and off, and in doing so, pressure surges can occur.

Bliesner (Bliesner, 1987) lists several causes of pressure surges in irrigation systems. The most common is due to valve closure. As a valve closes, the kinetic energy of the moving water is converted to pressure in a phenomenon known as water hammer. Most valves are designed to close slowly—perhaps as long as 10 seconds. However, most valves are closed by porting water into the bonnet, and the rate of closure depends on the pressure drop through the valve. The closer the valve is to closing, the faster it closes. Bliesner suggests a rule of thumb that 75% of the fluid flow stoppage occurs in the last 25% of the closure time. That is one of the reasons that the recommended maximum design velocity in the lines is 5 fps.

Air entrapped in system lines can cause significant pressure surge. The flow rate through a restriction—a nozzle for example—depends upon the density of the fluid. (The flow rate is inversely proportional to the square root of the density). Because water is about 100 times as dense as air in pressurized systems, the flow rate of air (and hence the velocity) through a nozzle is about 10 times that of water. [1] As a pocket of air passes through a restriction, the flow rate will accelerate to the flow rate of the air, but when water hits the restriction, the rate must slow to the flow rate of water. This sudden change in velocity results in significant surges in pressure. A reflected wave results from the sudden velocity change, and the wave results in a pressure surge. The following equations have been well-established for calculating the pressure surge. (for a more complete discussion, refer to a hydraulics textbook).

$$a = \frac{4660}{\sqrt{1 + \frac{KD_i}{Et}}}$$

[1] Bliesner wrote, "Water is about 5 times more dense than air at 100 psi… when water reaches the opening, the velocity suddenly decreases, since air escapes about 5 times faster than water at 100 psi". That statement is incorrect, but the point is the same. Air can cause water hammer.

Where: a = wave velocity, ft/s
K = fluid bulk modulus, (300,000 psi for water)
D_i = pipe inside diameter, in
E = modulus of elasticity of the pipe, (400,000 psi for PVC)
t = pipe wall thickness, in.

In plastic pipe, DR, dimension ratio is generally used. DR is the outside diameter (D_o) over the thickness, and D_o = D_i + 2t, so the equation becomes:

$$a = \frac{4660}{\sqrt{1 + \frac{k}{E}(DR - 2)}}$$

The maximum pressure surge is then given by:

$$\mathrm{P} = \frac{\mathrm{a}\ (\Delta \mathrm{V})}{2.31\ \mathrm{g}}$$

Where

ΔV = maximum velocity change, ft/s
g = acceleration due to gravity, 32.2 ft/s^2
P = pressure surge, psi

As an example, if a flow of 5.0 ft/s is suddenly stopped in a 6 inch class 150 (DR 18) PVC pipe, the surge pressure would be as follows.

$$a = \frac{4660}{\sqrt{1 + \frac{30{,}000}{40{,}000}(18 - 2)}}$$

So a = 1292 ft/s.

Then,

$$\mathrm{P} = \frac{1292\ (5.0)}{2.31\ (32.2)} = 87\ psi$$

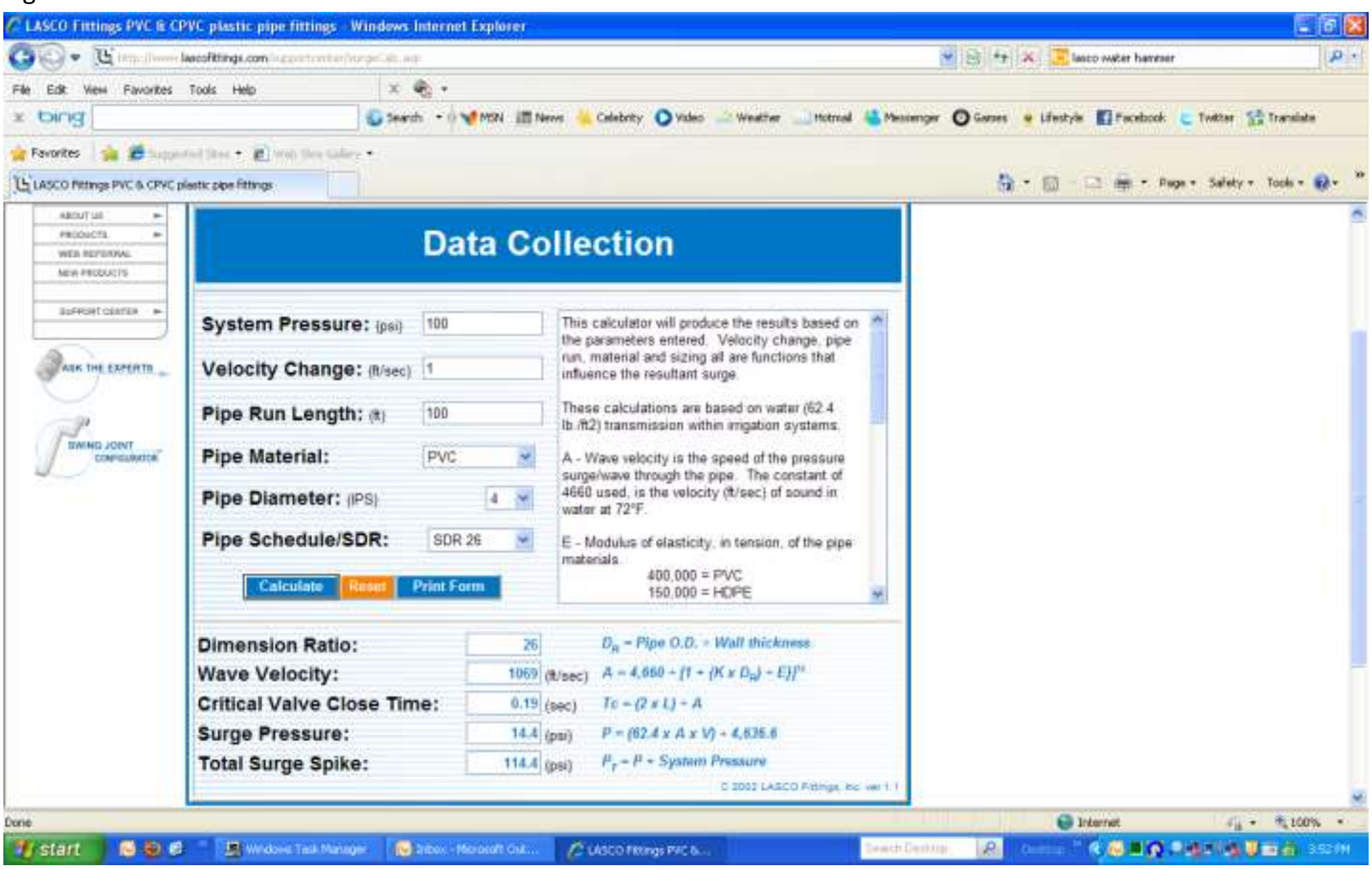
With this methodology, a table of pressure surges for each dimension ration can be developed. Table 1 below shows the values for one foot per second. Values for higher velocities can be obtained by multiplying the one foot per second value by the velocity.

Table 1. Pressure surges from instantaneous flow stoppage for one foot per second

Dimension Ratio	Pressure Surge, psi
51	10.8
41	11.4
32.5	12.8
26	14.4
25	14.7
21	16.0
18	17.4
14	19.8
13.5	20.2

The LASCO fittings web page has a handy water hammer and surge pressures calculator. The inputs are system pressure, velocity change, pipe run length, pipe material, pipe diameter, and SDR. It returns the wave velocity, critical valve close time, surge pressure and total spike. The URL is: http://www.lascofittings.com/supportcenter/surgeCalc.asp. A screen capture for 26 SDR is shown below. According to Moser and Folkman (2008), a good rule of thumb for surge pressure rise in pressure rated pipe is 16 psi per foot per second of velocity change.

Figure 1. LASCO water hammer on-line calculator



PVC Pipe Design

Bliesner reported a design technique based upon work done by Vinson (Vinson, 1981). Uni-Bell funded follow-up research at Utah State University which was done by Jeffrey, Moser, and Folkman [JMF](2004). Vinson's equations were developed assuming fatigue was a function of peak stress alone. Later researchers contested this assumption, and JMF showed that Vinson's work led to very conservative designs. JMF showed that mean stress and stress amplitude together influence PVC fatigue, and they developed a new set of design equations. A design graph relating mean stress, cycles to failure and stress amplitude. That graph is reproduced below.

Figure 2. Jeffrey, Moser, Folkman Design Graph

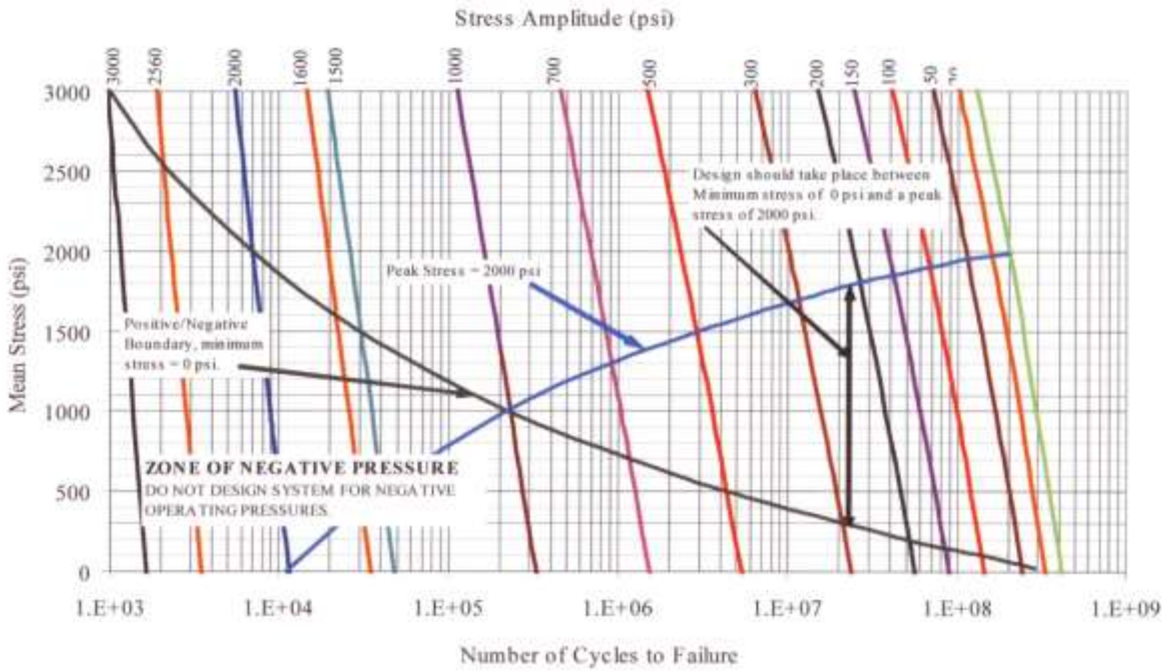


Figure 14. Cyclic design graph

For most irrigation designers, this graph is a bit overwhelming. The process is iterative in that one must first assume a dimension ratio and check it. Then based on the result, a new dimension ratio is assumed. The process continues until there is no change between the assumed and calculated dimension ratio. JMF provided the equations from which the design graph was developed, and those have been solved for typical irrigation design scenarios and are shown in Table 2 below.

Table 2. PVC SDR selection for assumed operating pressure and lifetime cycle.

Recommended SDR PVC pipe for operating pressure and number of cycles

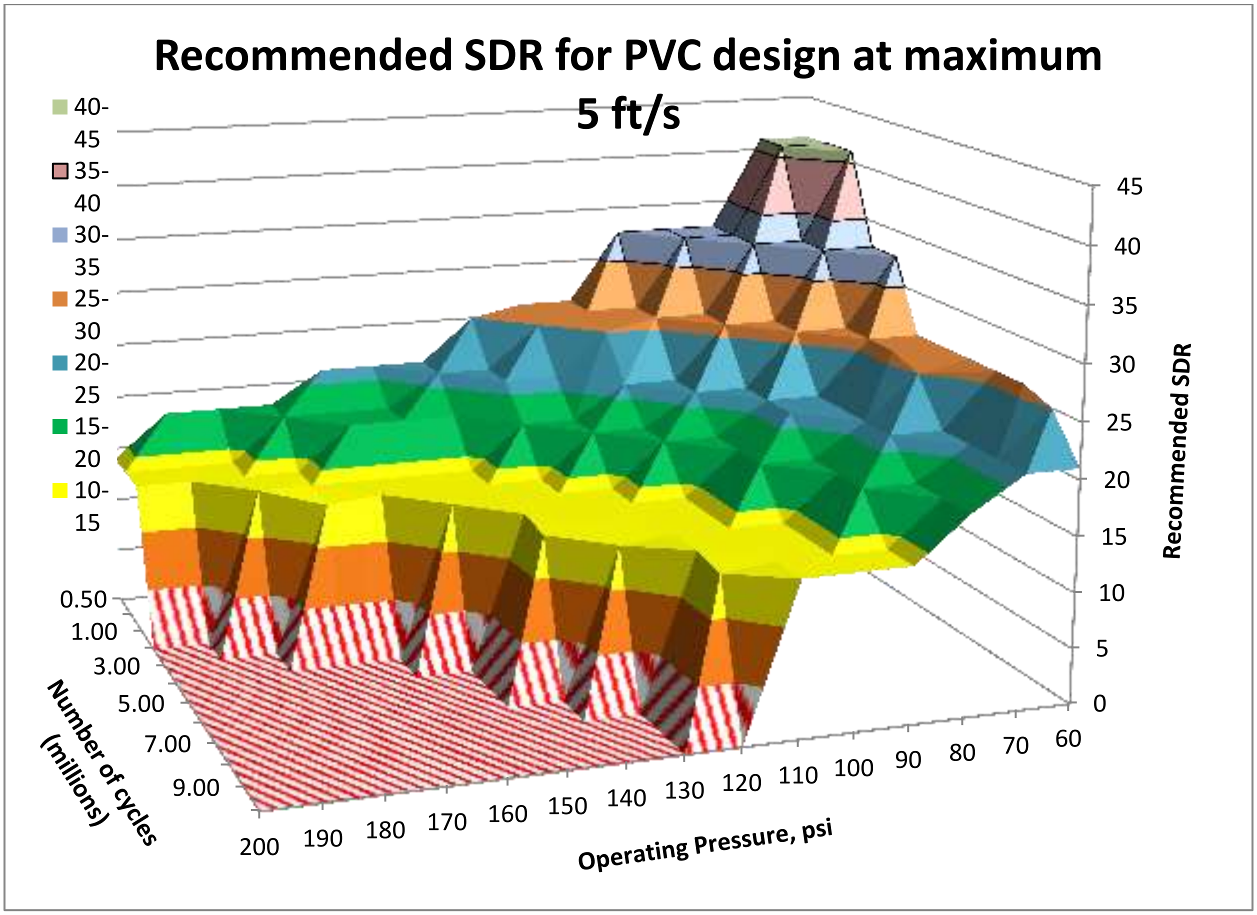
Maximum velocity 5 feet per second

Cycles, millions	Pressure, psi														
	60	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**	**160**	**170**	**180**	**190**	**200**
0.50	**41**	41	32.5	32.5	32.5	26	26	25	21	21	21	18	18	18	14
0.75	41	41	32.5	32.5	26	26	25	21	21	18	18	18	14	14	14
1.00	41	32.5	32.5	26	26	25	21	21	18	18	18	14	14	14	14
2.00	32.5	32.5	26	26	21	21	18	18	14	14	14	14	14		
3.00	32.5	26	26	21	21	18	18	14	14	14	14	13.5			
4.00	26	26	21	21	18	18	14	14	14	14					
5.00	26	26	21	21	18	14	14	14	14						
6.00	26	25	21	18	18	14	14	14	13.5						
7.00	26	21	21	18	14	14	14	13.5							
8.00	26	21	18	18	14	14	14								
9.00	25	21	18	14	14	14	13.5								
10.00	21	21	18	14	14	14									

SDR for 0.50 million cycles at 60 psi is dictated by short-term pressure rating, not cyclic life

Table 2 is used to select the proper SDR given the estimated number of cycles of a system over the lifetime of the system and the operating pressure. For example, if it is anticipated that there will be 2 million cycles over the lifetime of a system with an operating pressure of 100 psi and maximum velocity of 5 fps, the recommended SDR is 21. For the regions shown in red, there are no valid PVC choices. The only case shown where short term pressure governs rather than cyclic pressure governs is 0.5 million cycles at 60 psi. Using cyclic pressure, one could pick SDR of 51, but it will not withstand the pressure surge, so 41 is selected. It will withstand the pressure surge. How the SDR varies with cycles and operating pressure is graphically shown in Figure 2 below.

Figure 3. Graphical representation of SDR selection for operating pressure and lifetime cycles.



PVC Fitting Design

For a variety of reasons, PVC fittings are not nearly as durable as is PVC pipe. One reason cited (Edwards, et.al. 1992) is that fittings typically are molded from lower molecular weight material than pipe resulting reduced strength. A second reason is that the shape of the fittings—primarily tees—results in stress concentrations. After testing 6-inch schedule 40 PVC, they concluded that the Vinson design equations were applicable only if the pressures were de-rated for fittings. They proposed de-rating to 60% of rated pressure. Vinson found that the cycles to failure, C, could be found by:

$$C = (5.05\ x\ 10^{21})S^{-4.906}$$

where S is the stress, psi.

The stress can be found using the following equation:

$$S = [P(DR - 1)]/2$$

where P is the maximum pressure including the surge, psi, and

DR is the design ratio.

Using a 60% de-rating and substituting S_f for S, the equation becomes:

$$S_f = \frac{[P(DR-1)]}{2\,x\,(0.60)} = \frac{[P(DR-1)]}{1.2}$$

This de-rating results in reducing the number of cycles the fittings can sustain to about $1/12^{th}$ of that of the pipe. Table 3 below shows the recommended SDR for pressures from 50 to 100 psi and cycles from 500,000 to 3 million. PVC fittings are not recommended for cycling systems with operating pressures in excess of 100 psi.

Table 3. Recommended Pipe Fitting SDR for given number of cycles, operating pressure, and velocity.

Cycles, M	**Operating Pressure, psi**																	
	50			60			70			80			90			100		
0.5	**21**	**18**	**13.5**	**18**	**14**	**14**	**18**	**14**	**13.5**	**14**	**14**		**14**	**13.5**		**14**		
1.0	**18**	**14**		**14**	**14**		**14**	**13.5**		**14**			**13.5**			**13.5**		
1.5	**18**	**14**		**14**	**13.5**		**14**											
2.0	**14**	**13.5**		**14**			**13.5**											
2.5	**14**																	
3.0	**14**																	

Black is for 3 fts velocity, blue is for 4 ft/s, and red is for 5 ft/s.

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