A Discussion of PVC Pipe Under Vacuum

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From time to time, we receive questions concerning the effects of a vacuum on PVC pressure pipes. More specifically, can PVC pressure pipe withstand a vacuum pressure, and if so, to what extent?

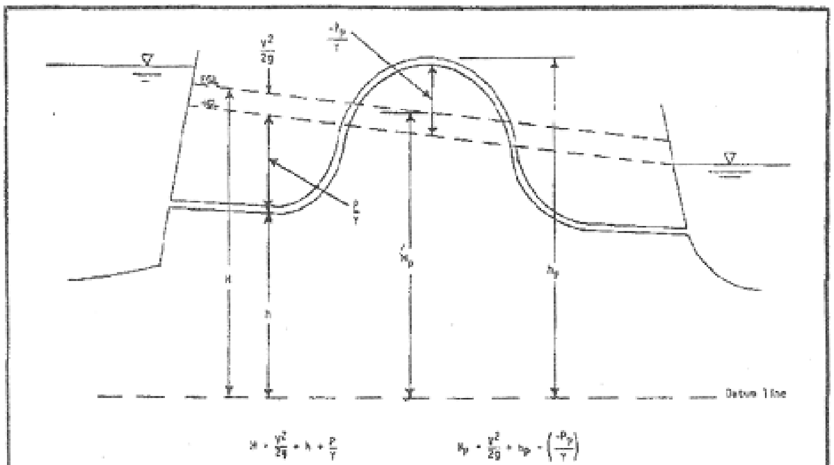
Before discussing PVC's ability to withstand vacuum pressures, perhaps a review of the basics of a vacuum is appropriate. In order to understand what a vacuum pressure is, we must understand the difference between absolute and gauge pressures. Gauges commonly used to measure pressures in distribution and transmission lines measure pressure in excess of atmospheric pressure. These are called gauge pressures. When a gauge pressure device measures zero, there is actually one atmosphere of pressure on the line. While atmospheric pressure depends on altitude above sea level, it is commonly taken as 14.7 psi. An absolute pressure measurement on the line would, therefore, be 14.7 psi when the gauge pressure measurement reads zero.

A vacuum is created when pressure in the line is reduced below atmospheric pressure or zero gauge. While a vacuum pressure is a positive absolute pressure, between zero and 14.7 psi, it is a negative gauge pressure because it is below zero gauge. Vacuum gauges are often incremented in inches of mercury (Hg) with a maximum reading of 30 inches of Hg. Thirty inches of mercury is equivalent to 14.73 psi or 33.9 feet of water. The pressure in a vessel cannot be reduced below zero absolute, which constitutes a complete vacuum.

There are several situations which may result in vacuum pressures in a pipeline. One may be caused as a result of scheduled maintenance or repair. Periodically, pipelines are drained for routine maintenance or repair. As water flows out through drain valves, a vacuum may be created inside the pipeline.

Another is the result of column separation. This may occur when boundary conditions are such that upstream pressure is reduced, thereby sending a negative wave pulse down the pipeline reducing velocity. The resulting velocity differential between portions of flow in the pipe can put the column in tension causing reduction in pressure until vapor pressure is reached. At this point, a vapor cavity forms in the pipe. Normally this occurs at a high point along the line.

Another situation which may lead to negative or vacuum pressures is one of geography. Long pipelines laid to transport water from one reservoir to another usually follow the local contour of the land. Portions of the line sometimes are placed at an elevation above the local hydraulic gradient. By reviewing the figure below and remembering that the total energy head (H) must equal the vertical distance between the datum and the energy grade line (EGL) at any location along the pipeline, it becomes obvious that negative pressures may exist. At the high point (Hp), the elevation hp is given and the velocity head $V^2/2g$ is also a fixed positive value. The sum $V^2/2g + h_p$ can be larger than Hp. When this is the case, the pressure head P_p/γ can only be negative. Once again, by negative we mean less than atmospheric.



Can PVC withstand vacuum pressures? The answer to this question is yes. To what extent? This part of the question requires further elaboration.

Within Appendix A of AWWA C900-81, "Standard for Polyvinyl Chloride (PVC) Pressure Pipe, 4 In. Through 12 In., for Water," is section A.7.3 entitled, "Negative or vacuum pressure." It states, "According to the experiments conducted at Utah State University, negative (vacuum) pressures cannot collapse an underground plastic pipe that is properly encased in a soil envelope and exposed to normal service temperatures. However, if the temperature of a plastic pipe becomes excessive because of the temperature of the fluid it is conveying, then the application of a negative pressure can cause the pipe to collapse."

Research conducted by R.K. Watkins, Professor of Civil and Mechanical Engineering, Utah State University, on the "Effects of Spacing of Stiffener Rings on Flexible Pipes at Collapse Vacuum," provides a method of determining to what extent flexible pipes can withstand vacuum pressures. The following relationship between flexible pipes and collapse pressures was demonstrated.

$$\left(\frac{E}{P'}\right) = f \left[\left(\frac{D}{t}\right), \left(\frac{X}{D}\right)\right]$$

Where:
P' = vacuum at collapse
E = modulus of elasticity
D = diameter of ring
t = thickness of wall
X = spacing of rings

Professor Watkins points out that theoretically when X approaches infinity the following equation holds:

$$\frac{P'}{E} = 2\left(\frac{t}{D}\right)^3$$

While the bell of a PVC pipe is much stiffer than the wall of the pipe, it is not considered a ring stiffener. Therefore, assuming infinite spacing of stiffeners is appropriately conservative.

With this equation the vacuum collapse pressure may be determined. Realizing that t/D is also 1/DR we may rewrite the equation as:

$$P' = 2\left(\frac{1}{DR}\right)^3 E$$

For a circular ring subjected to a uniform external pressure or internal vacuum, the critical buckling pressure (Pcr) is defined by Timoshenko as:

$$P_{cr} = \frac{3EI}{r^3}$$

Where:
E = modulus of elasticity
I = moment of inertia
r = mean pipe radius, in.

With the moment of inertia described as $t^3/12$ (t = wall thickness, in) this equation becomes:

$$P_{cr} = \frac{2E}{(DR-1)^3}$$

PVC pipe manufactured in accordance with pressure standards AWWA C900 and ASTM D2241 with a cell classification of 12454A, B or C, as well as pipe manufactured to sewer standard ASTM D3034, have a minimum allowable modulus of elasticity (E) of 400,000 psi.

Armed with this information, we may solve the above equations for vacuum collapse pressure. The following results are obtained for the specific dimension ratios (DR) listed at 73.4° F.

DR	P' (psi)	Pcr (psi)
35	18.6	20.3
25	51.2	57.8
18	137.1	162.8
14	291.5	364.1

In each case above, collapse pressure is greater than atmospheric pressure (14.7 psi). This indicates that each of the pipes evaluated could withstand a complete vacuum. This being zero absolute, negative 14.7 psi or 30 inches of Hg.

In an actual buried application, the vacuum pressure is combined with both the dead (earth load) and live loads to create the total load on the pipe. In pressure pipe applications, this load is usually much less than internal pressure on the pipe. In buried applications, the embedment soils provide some resistance against buckling/collapse and deflection. These equations do not take this resistance into account. For additional information see pages 184-186 of the Uni-Bell *Handbook of PVC Pipe: Design and Construction*, second edition, or pages 160-163 of the first edition.

Now, what about the question of excessive temperatures? Wall temperatures in a buried PVC system seldom exceed 73°F. When they do, the modulus of elasticity decreases.

For instance, at 100°F the modulus of elasticity is approximately 84 percent of that at 73°F. Therefore, P' for DR 25 at 100°F would be 43.0 psi. While it is still above atmospheric pressure, other physical characteristics of the pipe have also changed. For this reason, special consideration must be given when designing for elevated temperature applications. For more information on loss of modulus at elevated temperatures, see page 171 or 148, first and second edition respectively, of the aforementioned *Uni-Bell Handbook*.

As you can see, the PVC pipe wall can withstand negative or vacuum pressures. Having satisfied concern for the pipe, it is appropriate to turn our attention to how the joint will stand up under negative pressures. PVC pressure pipe is required by ASTM Standard D3139, "Standard Specification for Joints for Plastic Pressure Pipes Using Flexible Elastomeric Seals," to undergo a vacuum test. The assembled joint is required to withstand a vacuum of 22 in. of Hg for one hour with no leakage while in an axially deflected position. PVC sewer pipes are required to undergo similar vacuum testing under ASTM Standard D3212.

While PVC pipe can withstand vacuum pressures, good design should consider the consequences of a vacuum on the rest of the system. Common practice would require that pressure at all points in the pipeline remain above the vapor pressure of water or the fluid being transported. When the pressure in a pipe drops below this value, the water may vaporize locally forming pockets. These pockets can collapse in regions of higher pressure causing transient surges and other unfavorable side effects. They also reduce cross sectional flow area, consequently reducing hydraulic efficiency.

Vacuum pressures are generally not considered a favorable occurrence in water distribution systems consisting of any pipe material. However, if the effects on the entire system are taken into consideration, PVC offers adequate strength and safety to withstand negative or vacuum pressures.

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