Pipeline Rehabilitation with Expanded and Oriented PVC

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ABSTRACT

Open-cut installation of C900/C905 PVC for new potable water systems has been a proven methodology for many years. Creating PVC pipe with improved hydrostatic stress rating through expansion and orientation of the polymer (PVCO) is likewise established technology. Sliplining existing pipelines with butt-fused sections of polyethylene pipe is also a familiar technology. Advantages of each of these technologies are captured in a new rehabilitation system: PVC pipe which is butt fused, inserted into a pipeline, and then expanded and oriented in place. The resulting product is a structural, NSF-61 certified, pressure capable renewed water line accomplished with a trenchless approach.

Development of this product and system required three technical accomplishments: producing consistent, high-strength fusion joints; expanding the inserted fused sections to the inside diameter of the host pipe; and quantifying the strength increase obtained to rationally assign a pressure rating to the expanded-and-oriented pipe. Data supporting these developments is presented.

INTRODUCTION

Pipe made from polyvinyl chloride (PVC) has been a major success story for the plastics industry for at least three decades. This product is widely used for potable water and wastewater in sizes from ½-inch nominal to more than 30 inches diameter, joined with bell-and-spigot gasketed or solvent-cement joints. There are ASTM International (ASTM) Standard Specifications[1] and American Water Works Association (AWWA) Specifications[2] that cover these products, including the tests and calculations needed to assign a pressure rating to the finished pipe product.

Unlike polyethylene pipe, which is generally joined by heat fusion techniques, PVC pipe has until now been limited to applications that can be serviced with bell-and-spigot joints. This limitation has restricted use of PVC pipe in sliplining rehabilitation applications. Sliplining is an effective method of pipeline rehabilitation where pipe sections with diameter slightly smaller than the deteriorated existing pipeline are sequentially butt-fused and inserted into the existing pipeline. Lack of formulations and techniques for achieving butt-fused PVC joints with strength approaching that of the PVC material itself has been the primary barrier to using PVC in these applications. This paper discusses the testing used to identify PVC formulations and fusion techniques that overcome this barrier.

Successful rehabilitation requires some means of achieving close fit between the original pipeline and the liner pipe. This can be achieved by swaging polyethylene pipe to temporarily achieve a slight reduction in diameter, which memory-driven expansion later eliminates. In other applications, an annular space is left between the pipes, and is then filled with grout. In all sliplining applications, reduction of the pipeline capacity by reducing diameter is a major concern and limitation. Inserting PVC pipe, which is inherently stronger than PE pipe at the same thickness, and then expanding the inserted pipe to match its outside diameter to the inside diameter of the original pipeline, minimizes this capacity reduction. This paper discusses the techniques and equipment used to accomplish this expansion within a pipeline.

One valuable characteristic of PVC pipe is that it can be circumferentially expanded, increasing its diameter while decreasing its wall thickness. PVC pipe expanded in this manner becomes oriented, with enhanced mechanical property levels in the circumferential direction: the pipe becomes capable of sustaining greater hoop tensile stress without failing. Quantifying the strength increase achieved in any given pipe expansion, and capturing this increase in a pressure rating for the rehabilitated pipeline, is the first topic discussed in this paper.

ORIENTATION OF PVC: PVCO

An ASTM Standard[3] was published in 1993 describing the materials, requirements, and method of pressure rating PVC, and assigning to that product the material designation PVCO, for oriented PVC. The Standard acknowledges that circumferential expansion of a PVC pipe results in orientation of the polymer molecules. This increases hoop tensile strength, which in the plastic pipe industry typically is measured by hydrostatic pressure rupture regression testing. Test procedures are given in that Standard for determining a categorized measure of the long-term hydrostatic strength of the PVCO material (called Hydrostatic Design Basis). A pressure rating is assigned to the pipe itself based on wall thickness, diameter, and Hydrostatic Design Basis.

The Standard further indicates that a relationship exists between the expansion ratio and wall thickness ratio of the expanded pipe, and the long-term hydrostatic strength of the product. Wall thickness ratio refers to the ratio of the starting pipe wall thickness to that of the finished PVCO pipe; expansion ratio is the ratio of the original to finished outside diameters. So uniform expansion from a diameter of D to a diameter of 2D, with no change in material density, requires a thickness change from T to T/2. The expansion ratio in this case is 0.50, and the wall thickness ratio is 2.0.

Hydrostatic Design Basis (HDB) is the term used in the plastic pipe industry for the categorized long-term hydrostatic strength of a piping material. There are two PVCO materials designated in the ASTM Standard, PVCO 1135 and PVCO 1131, with HDBs of 7100 psi and 6300 psi respectively. The Standard, however, does not indicate what expansion or wall thickness ratios may be associated with these HDBs; that is left for a manufacturer to determine on a proprietary basis.

FUSION OF PVC

The process of butt fusing PE pipe has been practiced for over 30 years. Fusion of PVC pipe with a butt fuse technique has recently been developed to the point of practical field application. This technique allows for the joining of multiple pipe sections into a continuous gasketless length that can then be expanded inside a deteriorated host pipe.

Two advancements make this possible. First, a specific material formulation, or recipe, had to be developed that was compatible with high-strength fusion bonds. The plastic pipe industry has previously established generic formula that is acceptable for the production of pressure-rated PVC pipe. This generic formulation is defined in a document designated PPI TR-2.[4] The PVC compound used for Duraliner starting stock complies with the requirements of this generic formulation. However, experience has shown that not all PVC pressure pipe compounds that comply with the generic formulation are suitable for fusing and expanding. Therefore a specific proprietary formulation which meets all of the requirements of the generic formulation, but is more restrictive and specific than the generic formulation, had to be defined. This starting stock therefore meets all of the requirements of AWWA C900/905 (as well as comparable ASTM Specifications). Because it complies with the generic formulation limits, it also meet the requirements of NSF Standard 61[5] for transport of potable water.

The second advancement is the development of the specific procedural steps for the fusion joint. The procedure involves seven critical steps: clamping, facing, aligning, heating, joining, holding, and surface finishing. Specific procedures and operational limits for each of these steps needed to be determined, based on mechanical testing of the fusion joint obtained. A combination of conventional tensile testing and high-speed tensile impact testing was performed on both unexpanded and expanded fused joints. Although fusion of PVC does not in general achieve 100% of the strength of the parent material, it is possible to approach this value by careful control of the fusion process. The techniques developed have been shown to produce joints with nearly the strength of the parent material.

The joining process for Duraliner utilizes joining equipment readily available in the industry. It is recommended that fusion equipment that has the capability to record data generated from each fusion joint be used. This is to assure that the proper steps have been followed that produce the quality results.

Fusion can be done either at surface grade of the site or at the elevation of the host pipe within the access pit. Depth of the host invert and the bending radius of the pipe are factors in determining where best to do the fusion. If the fusion is done within the access pit, it is recommended that fusion equipment with a detachable carriage be used. This allows the power source to be remote from the fusion area producing a better work environment.

The key parameters of heat temperature, joining pressure, hold times, and cool down are different than polyethylene pipe. Experience has shown that using a procedure optimized for polyethylene to join PVC pipe will produce poor quality joints. A fusion process specifically designed and verified for a specific PVC formulation must be used in order to obtain acceptable fusion joints.

During the fusion process, an inspection of the starting stock is done for any surface scratches or defects that may affect expansion.

Because PVC is a harder material than polyethylene, facing blades wear more quickly. Carbide tipped blades have been developed that provide longer life when used with PVC. Warming the unfaced ends with indirect heat softens the material and has been found to make facing easier.

After fusion, the external bead is removed with a high speed rotary tool. This allows for easier pull in of the joined starting stock.

IN-PLACE ORIENTATION OF INSERTED PVC

In-place orientation of the PVC starting stock is accomplished by application of heat and pressure to the material. Prior to this, there are several steps in the process that must be completed.

The host pipe is exposed through the excavation of access pits. A small section of line is then removed. With this done, the host is then cleaned to remove any build up of mineral deposits or corrosion. The cleaning is done to meet the desired inside diameter of the host. The expanded PVC pipe does not adhere to the host. The host acts as a form for the expansion.

After cleaning, the host is then video inspected to verify cleaning and to be sure that there are no sharp protrusions that could effect the PVC material during expansion.

Insertion of the starting stock is the next step. This usually is done in parallel with the fusion process. Insertion is done usually using a constant tension winch. This allows for control of pulling force maintaining a safe value within the capabilities of the cross-section of the pipe. Other precautions include soft guides on the inlet of the host pipe.

After insertion, the end expansion hardware is installed and the internal distribution system inserted. The internal distribution system evenly distributes the hot water in the most effective manner for starting stock heating.

The end expansion hardware consisting of an expansion collar, a transition collar, a sizing sleeve and end restraints are then installed. The expansion and sizing collars allow the starting stock to expand longitudinal and provides a smooth transition from host pipe inside diameter to end outside diameter. The sizing sleeve limits the exposed end expansion to the desired outside diameter for the requested reconnection hardware. The ends can be expanded to a variety of diameters. The most common is to expand the ends to a CIOD or IPS size that is closest to the original host. This allows standard readily available fittings for reconnection of the rehabilitated line to the system. The end restraints are applied externally and internally to hold the end with no movement during processing. This allows end connections with ports and taps for instrumentation and water flow to installed.

After end cap installation ,internal and external instrumentation is added for process control. This is done to both ends of the line to be processed.

Expansion is done through the use a specially designed and constructed Mobile Expansion Vehicle. This is a self-contained, self sufficient vehicle that contains all necessary equipment to properly expand the starting stock. An initial pressure test is done to insure system integrity and circulation of the water in the system is initiated.. Then, the heating unit is engaged and water in the system is brought slowly to processing temperature. Upon reaching processing temperature, a second pump is used to provide added pressure for expansion as well as to provide volume increase while at temperature and pressure. Expansion is monitored throughout the duration of processing. Completion of expansion is determined by measuring the needed volume to achieve expansion and pressure increase indicating contact with the host pipe. After completion of expansion, cool down is initiated by introducing cool water to the circulation loop while under pressure.

With processing complete, the hardware is removed and the ends trimmed to length for reconnection.

STRESS RATING OF EXPANDED AND ORIENTED PRODUCT

Conventional PVCO pipe, expanded in the controlled conditions of a manufacturing plant, can be uniformly expanded to tightly controlled outside diameter and wall thickness. This uniformity allows the pipe to be pressure-rated based on a limited number (two at present) of HDBs based on consistent and predictable outside diameter and minimum wall thickness. Obviously, no field-based expansion within an existing deteriorated pipeline will be quite so predictable: there will be variability in the outside diameter obtained, due to variability in the inside diameter of the original pipe; and the thickness of the expanded-in-place pipe may be less uniform, because the field expansion process introduces new variables.

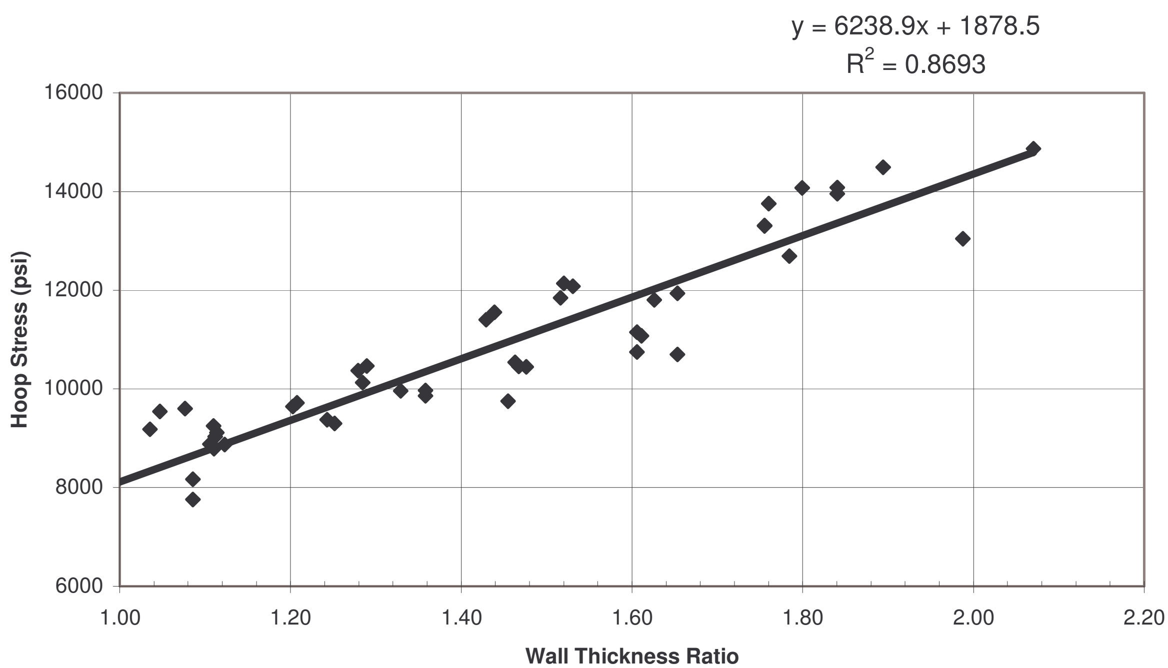
It is possible to deal with this variation and still take advantage of the hoop tensile strength increase obtained by expansion. Expansion ratio, based on average outside diameters, does not capture the variation in wall thickness that can occur when a pipe is expanded. A non-uniformly expanded length of pipe will have one expansion ratio, but many different wall thickness ratios.

Measuring the hoop tensile strength of a piping material by hydrostatic stress-rupture testing of pipe is an established and effective technique.[6] It is, however, a cumbersome and cost-ineffective way of determining the relationship between hoop tensile strength and degree of expansion, and especially so if the expansion was not highly uniform. A pipe sample several feet in length which is internally pressurized to failure (burst test), will fail at its weakest point, providing strength information only for that point. With non-expanded, non-oriented pipe, the weakest point will be along a longitudinal line of minimum thickness. We cannot make the same assertion for expanded, oriented pipe without prior knowledge of the relationship between hoop tensile strength and thickness ratio. Hydrostatic bursting of a PVC pipe in the lab is a rather violent and destructive event, making it impossible to determine the thickness of the failure point after the fact.

The alternate means of determining hoop tensile strength of a pipe is a split-disk tensile test.[7] This has several advantages. A test can be performed on about 2 linear inches of pipe, and the failure location can be pre-selected around the circumference. The pre-selected failure area can be carefully measured, so the wall thickness ratio associated with the hoop tensile strength measured can be precisely determined. A single expanded pipe length can be sampled to provide specimens covering a range of wall thickness ratios.

Hauser Laboratories performed hoop tensile testing including pipes with three diameters, and two expansion ratios, with wall thickness ratios ranging from 1.11 to 2.07. Figure 1 displays the data; the relationship between wall thickness ratio and strength is clearly apparent.

Figure 1: Hoop Tensile Stress vs. Wall Thickness Ratio.



These results show that the short-term hoop tensile strength is strongly correlated with wall thickness ratio. Knowing the slope of the strength vs. wall thickness ratio line gives us the information we need to confirm that hydrostatic bursting of a pipe section will, even in a non-uniformly expanded pipe, occur at the location coincident with the minimum wall thickness, as the following calculation illustrates. The relationship between the pressure in a pipe and the hoop tensile stress in the pipe wall is commonly called the ISO equation[8]:

$$2S/P = (D_0/t) - 1$$

Where:	S	= hoop tensile stress
	P	= pipe internal pressure
	D_0	= average outside diameter
	t	= wall thickness

Rearranging the equation to give pressure as a function of the other variables gives:

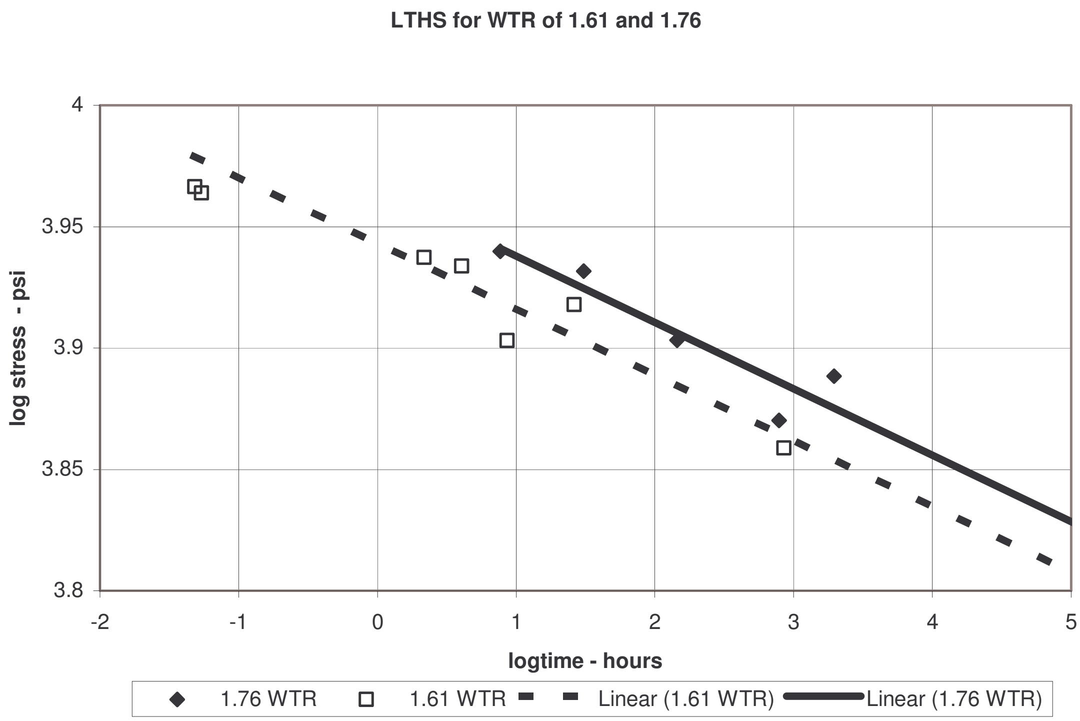
$$P = 2St / (D_0 - t)$$

For a pipe burst test, P is the burst pressure and S is the hoop tensile strength. For oriented pipe, we can express S as a function of wall thickness ratio, giving:

$$P = 2\,(1879+6239 \cdot WTR) / (D_0 - t).$$

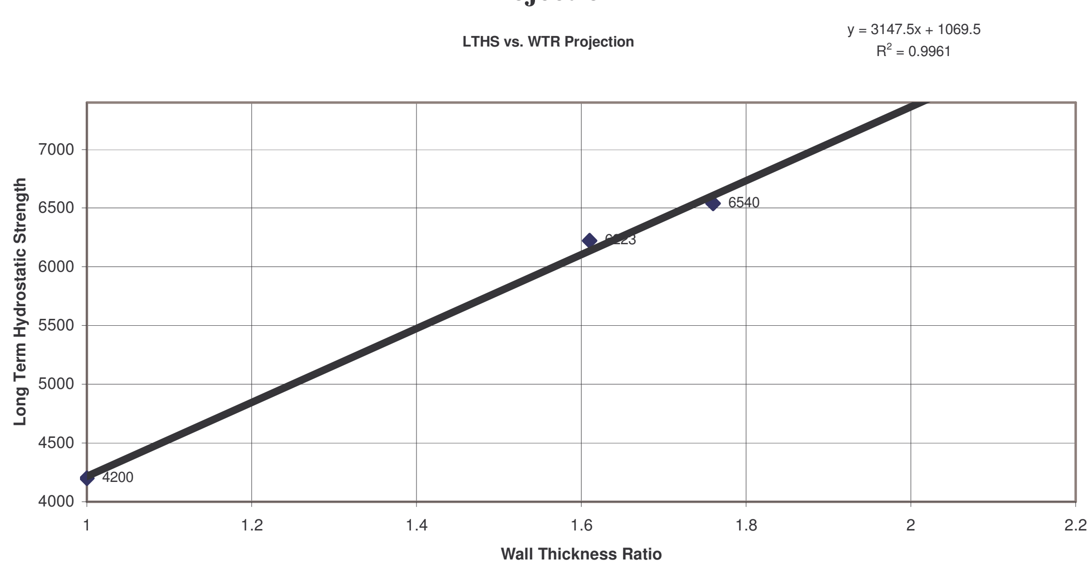
The above equation allows us to calculate the short-term failure pressure for an expanded and oriented pipe, knowing only the final outside diameter, the starting thickness, and the minimum final thickness. It does not, however, allow us to calculate the long-term failure pressure; for that, we need a long-term failure stress: and HDB. For oriented pipe, we need HDB as a function of wall thickness ratio. Having confirmed that the failure even in oriented pipe will occur at the minimum wall thickness, we can select groups of specimens that have approximately the same unexpanded dimensions, expanded outside diameter, and minimum thickness (and therefore approximately the same wall thickness ratio. Testing these specimens in accordance with the accepted Accelerated Regression Test[9] gives an HDB for that wall thickness ratio. Figure 2 shows the results of two such determinations.

Figure 2: Long Tern Hydrostatic Strength vs. Wall Thickness Ratio



Repeating this testing using specimen sets with different wall thickness ratios allows us to plot HDB as a function of wall thickness ratio for a specific PVC formulation and expansion process. Figure 3 gives a projection based on the data currently available.

Figure 3: Long-Term Hydrostatic Stress vs. Wall Thickness Ratio Projection



CURRENT APPLICATIONS AND LIMITATIONS

Current applications are being implemented in municipal water distribution and transmission systems. Fire loops are another prominent application. Beyond the water pressure areas, another application is for the rehabilitation of sewerage force mains. Industrial uses such as the rehab of cooling tower lines, brine line, etc. are also actively being developed. Because of the structural nature of the finished product, current projects include gravity sewers where enhancement of the structural qualities of the conduit are desired.

The product will negotiate most sweeps and bends in a water line. It cannot be inserted through 22.5, 45, or 90 degree fittings.

While lengths over 650 feet have been processed on projects, the norm is in the 500 LF range and will vary with fittings, diameter, and access points.

Presently residential taps must be done externally requiring excavation. Developments are being made to provide a method to renew taps without excavation.

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[1] Annual Book of ASTM Standards 2003, Vol. 8.04, Plastic Pipe and Building Products, ASTM International, West Conshohocken, PA 19428

[2] AWWA Standards, American Water Works Association, Denver, CO 80235

[3] ASTM F1483, "Standard Specification for Oriented Poly(Vinyl Chloride), PVCO, Pressure Pipe," Annual Book of ASTM Standards 2003, Vol. 8.04, Plastic Pipe and Building Products, ASTM International, West Conshohocken, PA 19428

[4] PPI TR-2/2003, "PPI PVC Range Composition Listing Of Qualified Ingredients," Plastics Pipe Institute, 1825 Connecticut Ave NW, Suite 680, Washington, DC 20009

[5] NSF/ANSI 61, "Drinking Water System Components – Health Effects", NSF International, 789 North Dixboro Rd, Ann Arbor, MI 48113

[6] ASTM D1599, "Standard Test Method for Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings," Annual Book of ASTM Standards 2003, Vol. 8.04, Plastic Pipe and Building Products, ASTM International, West Conshohocken, PA 19428

[7] ASTM D2290, "Standard Test Method for Apparent Hoop Tensile Strength of Plastic or Reinforced Plastic Pipe by Split Disk Method," Annual Book of ASTM Standards 2003, Vol. 8.04, Plastic Pipe and Building Products, ASTM International, West Conshohocken, PA 19428

[8] ASTM D2241, "Standard Specification for Poly(Vinyl Chloride) (PVC) Pressure-Rated Pipe (SDR Series), 3.2.3, Annual Book of ASTM Standards 2003, Vol. 8.04, Plastic Pipe and Building Products, ASTM International, West Conshohocken, PA 19428

[9] ASTM F1483, *op cit*, 7.5.