COMMON INSTALLATION FAILURE MODES FOR IN-SERVICE PLASTIC PIPING COMPONENTS AND SYSTEMS

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Abstract

Plastic pipe components are generally constructed into high integrity, high durability systems. However, some poor installation practices occur with sufficient frequency that they have been noted by the authors as recurring as the root cause upon completion of failure analyses. These installation based root causes differ with the application environment and the material of construction. This paper will address poor installation practices for polyethylene, poly vinyl chloride and chlorinated poly vinyl chloride based piping systems.

Introduction

Plastic piping systems have gained substantial market-share into infrastructure based on three significant factors; 1) plastic pipe is cost effective when compared to archaic materials, especially when lifetime costing analyses are applied rather than narrowly focusing on initial costs 2) plastic pipe is relatively easy to install with low sensitivity to a number of field installation practices with the recent advances in trenchless technology emphasizing this point and 3) when properly installed, plastic pipe is very durable with low failure rates per mile of installation per decade.

In a truly ironic way, the strengths of plastic pipe sometimes become its weakness. Because plastic pipe is comparatively low cost and easy to install, this seems to encourage the hiring of unskilled, under-trained or uninformed workers resulting in poor installation practices or procedures specifically recommended against in industry literature. It is common for plastic pipe system failures to occur due to installation practices and procedures that are in direct contradiction to industry recommended practices. Due to the long history of failure analysis of plastic piping systems and components in our laboratory, we have observed that some installation practices provide recurrent failure modes. This paper will look at three common failure modes based on poor installation practices; incompatible chemicals in make-up water causing environmental stress-cracking of chlorinated poly vinyl chloride pipe, rock impingement from native back-fill resulting in point loading stresses, and severe curvature contributing to reduced service life.

Environmental Stress Cracking Failure of Chlorinated Poly Vinylchloride (CPVC) Pipe from Chemicals in Makeup Water

The sensitivity of CPVC pipe to a growing variety of environment stress cracking (ESC) agents now documents termiticides[1], polyol ester lubricant oils[2], Dioctyl Phthalate[3], and a variety of glycols[4].

Industry documents indicate that pressure rated CPVC 4120 meets the cell classification requirements[5] of ASTM D1784, *Standard Specification for Rigid Poly(Vinyl Chloride) (PVC) Compounds and Chlorinated Poly(Vinyl Chloride) (CPVC) Compounds*, for a 23447 compliant material. This provides several key details about the CPVC material used. For example, this indicates that the material is a chlorinated Poly(Vinyl Chloride) with the formulated compound containing at least 80% CPVC in addition to compounding ingredients such as lubricants, stabilizers, non-PVC resin modifiers, pigments or inorganic fillers. The compound exhibits more than 80.1 Joules / m impact resistance[6] when tested in accordance with ASTM D256. The deflection temperature under load[7] when measured by ASTM D648 exceeds 100°C. Finally, the minimum tensile strength of the compound exceeds 7000 psi and a modulus of elasticity[8] that exceeds 360,000 psi when tested in accordance with ASTM D638.

Numerous samples of CPVC piping and fittings were received from the client exhibiting signs of brittle fracture. A typical appearance of a CPVC pipe that has suffered exposure to ESC agents and subsequently failed in service is shown in Figure 1. The sample shows signs of localized crazing upon initial visual examination.

The same specimen from Figure 1 was then examined under low magnification light microscopy as shown in Figure 2. Under these conditions, multiple independent inner wall initiating “thumbnail” features are evident confirming identification of the failure as ESC.

In addition to the numerous samples of CPVC pipe and fittings, two system makeup water samples were provided and tested per EPA SW-846 Method 8270C[9]. Analysis of the resulting data included both the standard required compounds as well as library identification and approximate quantification of “tentatively identified

Figure 1: Digital image displaying a section cut from CPVC pipe with obvious brittle fracture zone. For scale, the pipe wall thickness is approximately 0.075 inches.

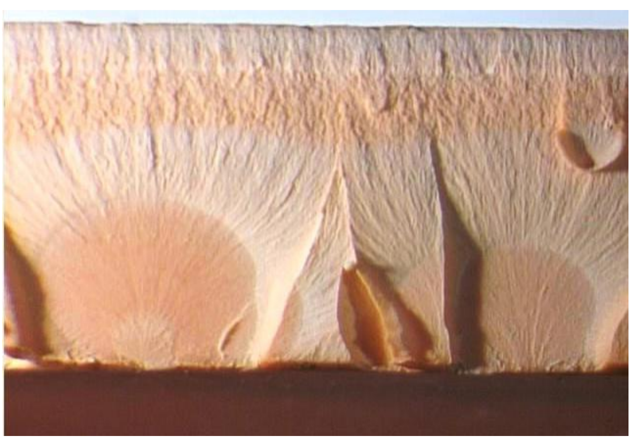

Figure 2: Digital close-up image of the full thickness of the fractured CPVC pipe surface displayed above. Note that each "thumbnail" in the fracture represents a single fracture initiation, indicating that multiple initiations are present.

compounds" present in the water. EPA SW-846 Method 8270C is known to be a useful test method for the identification of semi-volatile organic compounds in a water matrix. Numerous compounds were tentatively identified in the two system makeup water samples. The highest estimated concentration in both makeup water samples was tentatively identified as cyclohexanone. THF, MEK, and cyclohexanone are expected to be present in the makeup water due to their presence in the primer and solvent cement used to assemble the piping system. While the specific compounds listed are only tentatively identified (i.e. they do not have specific chemical standards which were run concurrently with the test samples), a compound chemically similar to the tentatively identified compound is assuredly present. Other compounds that were tentatively identified in both makeup water samples include; cyclohexanol, 3, 5, 5 trimethyl hexanoic acid, 1-decanol, N, N dimethyl octylamine, and 2-butenedioic acid dibutyl ester among many others. Note that none of the tentatively identified compounds were detected for a supplied sample of tap water.

These compounds include ketones, alcohols, carboxylic acids, amines and esters – many of which are known or suspected to be ESC agents to CPVC. The identification of ketones, alcohols, carboxylic acids, amines and esters as ESC agents for CPVC is obtained from numerous sources. Highly detailed information[10] regarding ESC agents for PVC is available. It seems reasonable that ESC agents for PVC identified in this reference are also ESC agents for CPVC. This is additionally supported by numerous public domain chemical compatibility documents for CPVC pipe materials promulgated by resin and pipe manufacturers. When requested by clients, confirmatory testing can be undertaken through exposure[11] of pipe or plastic specimens to the suspect ESC chemicals in accordance with ASTM D543 or other test methods.

Rock Impingement on PVC Pipe Results in RCP Failure

During sample recovery, it was established that a rock was in direct contact with the top of a 6" nominal ASTM D2241 SDR21 PVC pipe[12], with a larger rock on top of the impinging rock at the location of the fracture initiation (see Figure 3). The linear dimensions of large rock were obtained and the volume exceeded 1000 cubic inches. The mass of the rock was estimated to exceed 100 pounds. The printline of the pipe identified that at the time of removal from service, the pipe had been installed for less than 7 years.

The manufacturer of the pipe indicated that the PVC material used meets the cell classification requirements[5] of ASTM D1784 for a 12454 compliant material. This provides several key details about the PVC material used. For example, this indicates that the PVC material is a homopolymer with the formulated compound containing at least 80% PVC in addition to compounding ingredients such as lubricants, stabilizers, non-PVC resin modifiers, pigments or inorganic fillers. The compound exhibits more than 34.7 Joules / m impact resistance[6] when tested in accordance with ASTM D256. The deflection temperature under load[7] when measured by ASTM D648 exceeds 70°C. Finally, the minimum tensile strength of the compound exceeds 7000 psi and a modulus of elasticity[8] that exceeds 400,000 psi when tested in accordance with ASTM D638.

Based on macrofractography, the overall fracture network in the sample is macroscopically brittle, although there is some amount of ductility visible on the outer surface near the initiation area. The fracture initiated near the outer wall of the pipe at a location coincident with the area of rock impingement (see Figure 3).

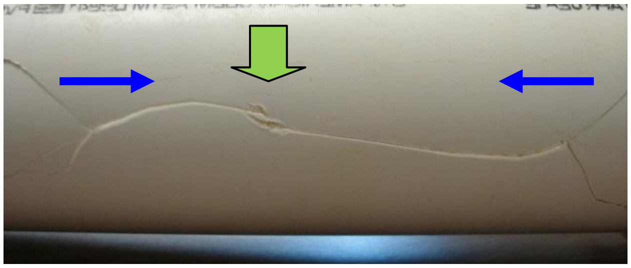

Figure 3: Digital image displaying the general fracture initiation area based on macrofractography, with previously-established rock-impingement location identified by the green arrow. The blue arrows denote "TOP" location (12 o'clock) in trench.

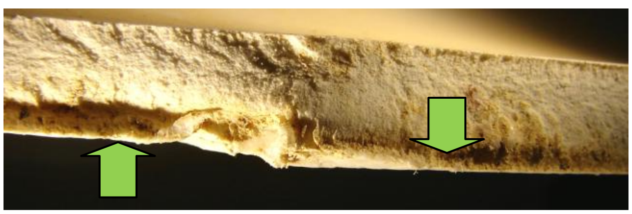

Figure 4: Digital image displaying the exterior rock impingement and fracture initiation area sectioned for SEM inspection. The rock-impingement location is generally bounded by the green arrows along the outside edge of the pipe which is down as shown in this photo. Note approximately 10-25% (thickness) penetration of the rock into the PVC pipe wall in wedge-like fashion.

The fracture morphology in the initiation area is microscopically ductile, and is typical of time-dependent (slow) crack growth in PVC piping materials. As shown in Figure 5, the initiation site and area near the impingement at the outer pipe wall show significant ductility when viewed by low magnification SEM imagery. These ductile features at the outer wall give way to microscopically brittle features in the mid-wall as shown in Figure 6.

Within this fracture initiation area, the fracture propagates radially through the pipe wall due to the impinging rock acting as a "wedge", followed by axial propagation. The fracture then branches on each side of the impingement area and propagates generally axially via fast fracture, due to the stress field resulting from internal pressurization. The total fracture length was greater than 18 inches. There was no evidence of manufacturing defects such as voids, inclusions, or contamination present in the fracture surface. The fracture was a result of time-dependent overload caused by rock impingement followed by fast fracture, and does not display any evidence of cyclic fatigue failure mode.

It is important to note that numerous installation standards provide prescriptive language regarding the impingement of rocks upon thermoplastic pipes. For example, ASTM D2774 (originally approved[13] in 1969) states "The particle size of material in contact with the pipe shall not exceed the following: ½ in. for pipe to 4 in., ¾ in. for pipes 6 to 8 in.; 1 in. for pipes 10 to 16 in.; and 1½ in. for larger pipes."

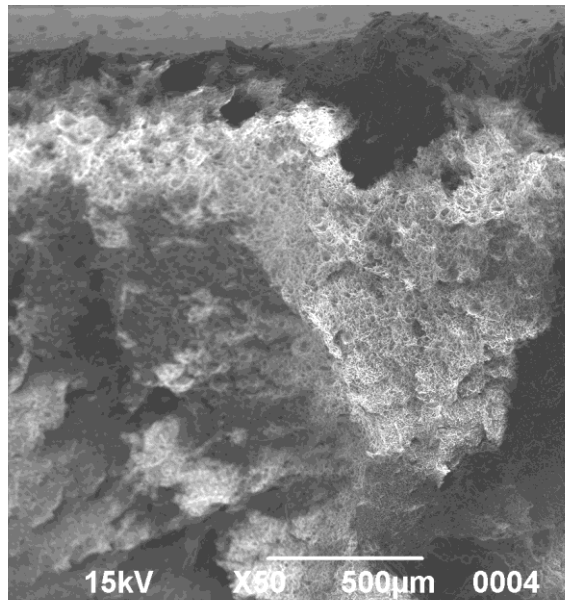

Figure 5: Low Magnification SEM digital image displaying the fracture surface near the outer wall initiation. Note microscopically ductile morphology.

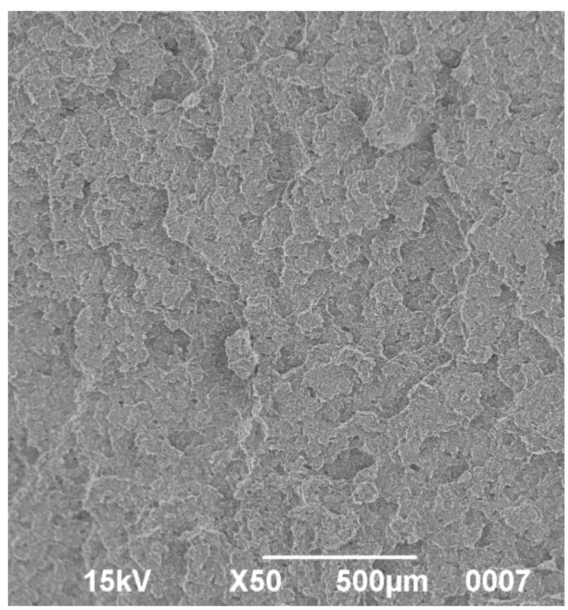

Figure 6: Low Magnification SEM digital image displaying the fracture surface in the mid-wall. Note microscopically brittle morphology.

ESC and Radius of Curvature Reduce Polyethylene (PE) Tubing Service Life

The Failed Sample was received from the client as unpigmented small diameter PE tubing greater than 4 feet in length with an interior "stain" adjacent to the through-wall fracture. The Failed Sample contained an axially oriented through-wall fracture approximately 1 inch in length (as shown in Figure 7) co-located with a significantly reduced radius of curvature. No manufacturing defects were present within the fracture surface. During visual inspection and optical microscopy, a second incipient fracture was observed near to the through-wall fracture. Additionally, an Exemplar Sample of similar unpigmented polyethylene (PE) tubing greater than 30 inches in length was received from the client.

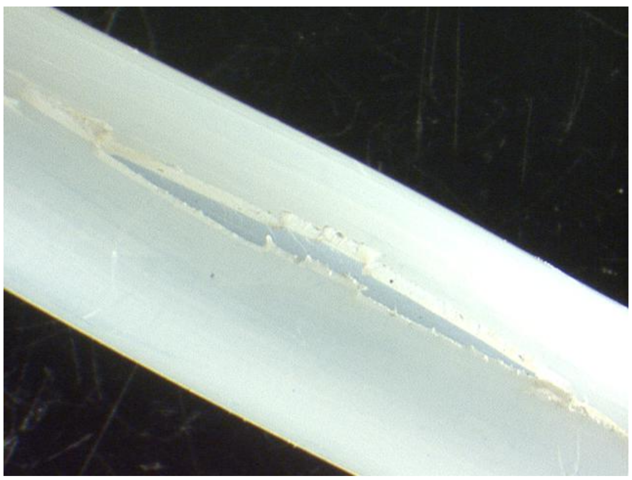

Figure 7: Digital image of the Failed Sample showing the through-wall stepped fracture indicating multiple fracture initiations.

The density of the Failed Sample was determined in accordance[14] with D1505 as <0.925 g/cm^3 which meets the definition[15] of low-density polyethylene plastics (LDPE) provided in ASTM F412-12 "those branched polyethylene plastics having a standard density of 0.910 to 0.925 g/cm^3".

The through-wall fracture in the Failure Sample is macroscopically brittle and co-located within an area that displays reduced radius of curvature with multiple adjacent fracture initiations along the inner wall of the tube that join to form the through-wall fracture. There are no manufacturing defects present within the approximately 1 inch long fracture surface. The overall fracture network is typical of an environmental stress cracking failure mode, with multiple inner wall fracture initiations and through-wall propagation via slow crack growth (See Figure 8).

A test specimen of the stain material was directly removed, transferred to a mirror, and pressed thin. The pressed material was analyzed by Fourier Transform Infrared (FTIR) spectrometry using a Thermo Nicolet 560 FTIR with a Thermo Nicolet Continuum microscope attachment, according[16] to ASTM E334. The base material of the tubing was identified using the ATR-FTIR (Attenuated Total Reflectance) technique. Only poor quality matches for the stain material were generated by comparison to Biorad and/or locally-generated infrared spectral libraries with possible and/or partial matches including various amines, amides, alcohols, and glycol esters. Although a conclusive match was not obtained, the stained area clearly included other compositions aside from PE (see Figure 9).

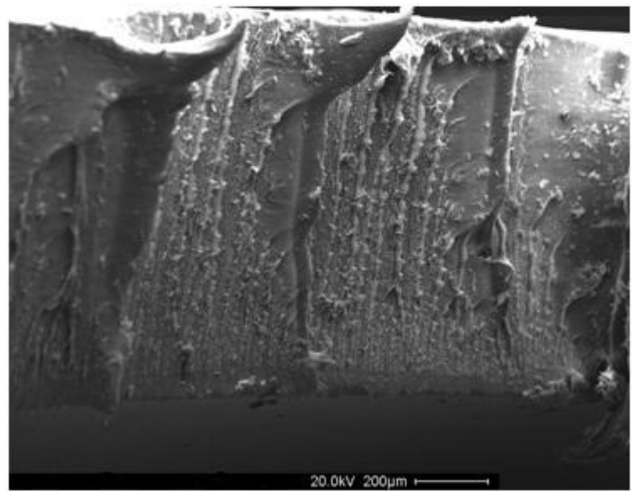

Figure 8: Digital SEM image of the fracture surface for the Failure Sample. Note stepped fracture indicating multiple fracture initiations, and progression from inner (at bottom of image) to outer wall (at top).

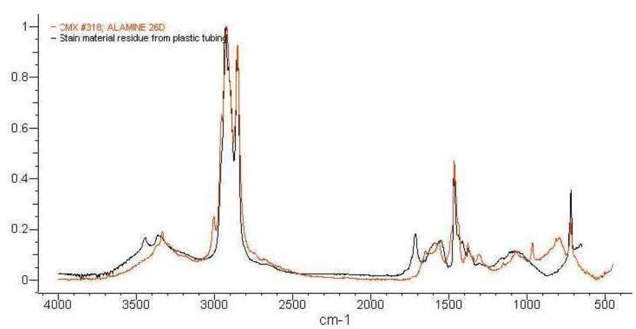

Figure 9: FT-IR spectrum resulting from the stain material (in black) combined with an overlay of a reference material "Alamine 26D" (in orange). Note the similarity of the spectral features at the higher wavenumbers.

A section of the tubing with the stain present was sequentially rinsed with various solvents, none of which appeared to visually dissolve the stain. Each rinsing step included gathering the rinse solution into a vial and then evaporating the solvent, followed by the next rinsing into the same vial. Finally, a tetrahydrofuran extraction was conducted and accompanied by sonication for 15 minutes. A Hewlett Packard 7673 autosampler was used to inject 1μL onto a DB-5MS column in a Hewlett Packard 5890 Series II GC with Hewlett Packard 5972 Series Mass Selective Detector. Mass spectra were scanned from 35 to 500 AMU. No compounds were detected during this GC/MS testing indicating the stain has either no soluble components and/or no volatile components that were detectable by GC/MS.

A short section of the Failure and Exemplar Sample were capped using standard Swage-Lok compression fittings. These capped tubes were then pressure tested[17] at 80°C in a water/water environment with internal pressure of 39 psi in accordance with ASTM D1598. Details of the pressure testing and time-to-failure results are presented in Table 1. It is important to note that both the Failure and Exemplar Sample failed in a brittle manner during this hydrostatic testing. The hydrostatic testing of the Failure Sample resulted in failure due to multiple axially oriented slow crack growth fractures on the complete inner tube surface. The hydrostatic testing of the Exemplar Sample resulted in failure via a single axially oriented slow crack growth fracture typical of elevated temperature failure in PE tubing. This critical difference indicates that the Failure Sample has been compromised over its entire interior surface with an ESC agent, whilst the Exemplar Sample failed as expected by simple slow crack growth failure mode.

Sample ID	Wall Stress (psi)	Time to failure (hrs)
Failure	223	45.9
Exemplar	204	334.8

Table 1: Summary data table associated with testing of the Failure and Exemplar samples of tubing. Note that the well known ISO equation was used to calculate the wall stresses indicated using the minimum wall thickness and average outside diameter of the samples.

PE failure times and stresses in MDPE and HDPE materials can be used to approximate failure times at a different temperature than the reference temperature based on the time- and stress shift-factors developed by Carl Popelar[18]. The shift factors developed by Popelar for shifting from 80°C to 20°C indicate an approximate 700-fold increase in the time-to-failure.

Therefore, simple multiplication by 700 of the measured time-to-failure at 80°C of 45.9 hrs for the Failure Sample and 334.8 hrs for the Exemplar Sample provide estimated service lifetimes at 20°C of >32,000 hours and > 200,000 hours, respectively. Although these estimates are approximations only, they clearly illustrate that the anticipated long-term durability in pressure service of the Failure Sample – sampled outside of the area of the stain – has been reduced by nearly an order of magnitude from the Exemplar Sample. Moreover, secondary mechanical stresses such as those resulting from bending of the tubing would be predicted to further reduce service life.

In summary, the Failure Sample failed by inner-wall initiating environmental stress cracking (ESC) failure mode co-located with reduced radii of curvature and hence mechanical stresses. A stain on the tubing interior was analyzed by various methods to attempt to identify a chemical responsible for ESC failure mode. Although the results were not sufficient to implicate a single chemical species, the FTIR test results clearly indicate that a residue illustrates the presence of chemical contamination. Results of 80°C hydrostatic pressure testing indicate that the Failed Sample has reduced residual service life expectations when compared to the Exemplar Sample. The reduction of service life and the multiple fracture initiation failure mode within the Failure Sample suggests that the Failed Sample has been compromised by the combination of the elevated stresses created by the reduced radius of curvature in combination with an environmental stress cracking agent.

Discussion and Conclusions

Commercial laboratories that are actively engaged in failure analysis for plastic piping components and systems share a responsibility with the manufacturers, installation workers and end-users to assist in educating the community regarding common failure modes. Only through the responsible sharing of this accumulated knowledge will the industry achieve continuous improvement that drives down the (already low) incidences of failure. Sharing of best practices for installation and end-use design goes hand-in-hand with the illustrations provided here for the types of failures resulting from flawed procedures and discredited practices.

References

1. J. A. Smith, J. Saunders; P. G. Koehler, *Pest Management Science*, **64**, 147 (2008).
2. D. Priddy, B. Arnold, K. Battjes, *Plastics Engineering*, **68**, 4 (2012).
3. M. Hoffman; M. Reitman; S. Donthu; P. Ledwith, *ANTEC Proceedings*, (2010).
4. R. Hauser, *ANTEC Proceedings*, (2009).
5. ASTM D1784-11, "Standard Specification for Rigid Poly(Vinyl Chloride) (PVC) Compounds and Chlorinated Poly(Vinyl Chloride) (CPVC) Compounds" *2011 Annual Book of ASTM Standards, Volume 08.01, Plastics*, ASTM International, West Conshohocken, PA.
6. ASTM D256-10, "Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics" *2010 Annual Book of ASTM Standards*,

Volume 08.01, *Plastics*, ASTM International, West Conshohocken, PA.
7. ASTM D648-07, "Standard Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position" *2007 Annual Book of ASTM Standards, Volume 08.01, Plastics,* ASTM International, West Conshohocken, PA.
8. ASTM D638-10, "Standard Test Method for Tensile Properties of Plastics" *2010 Annual Book of ASTM Standards, Volume 08.01, Plastics,* ASTM International, West Conshohocken, PA.
9. The most currently updated method is EPA Method 8270D "Semivolatile Organic Compounds By Gas Chromatography/Mass Spectrometry (GC/MS) Revision 4", [Online] Available at http://www.epa.gov/epawaste/hazard/testmethods/sw846/pdfs/8270d.pdf.
10. D. Wright, *Environmental Stress Cracking of Plastics*, Rapra Technology Ltd., Shawbury, United Kingdom (1996).
11. ASTM D543-06, "Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents" *2006 Annual Book of ASTM Standards, Volume 08.01, Plastics,* ASTM International, West Conshohocken, PA.
12. ASTM D2241-09, "Standard Specification for Poly(Vinyl Chloride) (PVC) Pressure-Rated Pipe (SDR Series)" *2009 Annual Book of ASTM Standards, Volume 08.04, Plastics,* ASTM International, West Conshohocken, PA.
13. ASTM D2774-08, "Standard Practice for Underground Installation of Thermoplastic Pressure Piping" *2008 Annual Book of ASTM Standards, Volume 08.04, Plastics*, ASTM International, West Conshohocken, PA.
14. ASTM D1505-10, "Standard Test Method for Density of Plastics by the Density-Gradient Technique" *2010 Annual Book of ASTM Standards, Volume 08.01, Plastics,* ASTM International, West Conshohocken, PA.
15. ASTM F412-12, "Standard Terminology Relating to Plastic Piping Systems" *2012 Annual Book of ASTM Standards, Volume 08.04, Plastics,* ASTM International, West Conshohocken, PA.
16. ASTM E334-01 (2007) "Practices for General Techniques of Infrared Microanalysis" *2007 Annual Book of ASTM Standards, Volume 03.06, Molecular Spectroscopy; Surface Analysis* ASTM International, West Conshohocken, PA.
17. ASTM D1598-02 (2009) "Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure" *2009 Annual Book of ASTM Standards, Volume 08.04, Plastics,* ASTM International, West Conshohocken, PA.
18. C. H. Popelar, "A Comparison of the Rate Process Method and the Bidirectional Shifting Method" *Thirteenth Plastic Fuel Gas Pipe Conference Symposium.* 1993

Key Words: Failure Analysis, Pipe, CPVC, PVC, HDPE, Environmental Stress Cracking, Rock Impingement, Reduced Radius of Curvature.