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Why Do CPVC Pipes Fail?

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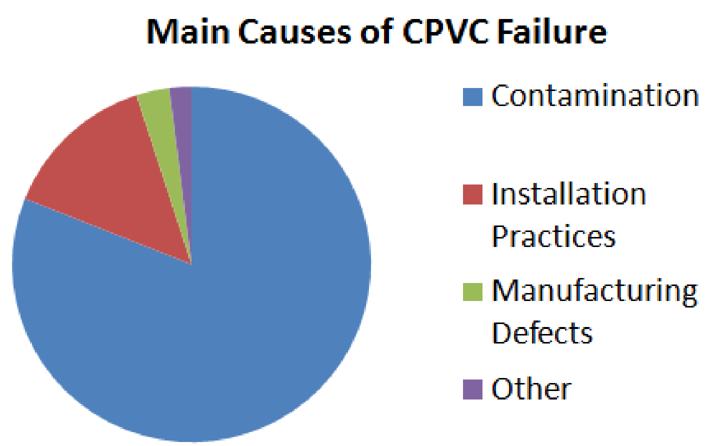
Summary
For over 30 years CPVC pipes have been extensively utilized in fire sprinkler systems due to ease of installation, corrosion resistance, and relatively low failure rate. However, in the past 18 months the failure rate of CPVC pipes and fittings has increased. Plastic Failure Labs has been extensively involved in trying to determine the cause behind the failure increase. In the past 18 months our investigations indicate that contamination is the root cause of most (>80%) of the failures. The second most common cause of failure is poor installation practices followed by manufacturing defects in pipes and fittings.



Until recently we (like most forensic labs) utilized infrared spectroscopy (IR) for contaminant identification in failed CPVC pipe samples. However, IR was not detecting anything unusual inside the failed pipes even though the failure mode was clearly environmental stress cracking (ESC) due to contamination on the inside of the pipes. We therefore explored alternate forensic contaminant identification techniques. We found that GC-MS worked exceptionally well and we successfully developed a protocol for pipe and water sample analysis. Using GC-MS we successfully determined the root cause for the sudden increase in failures of CPVC pipe and fittings; i.e., the main contaminants responsible for most of the ESC failures were amines. In 2008, whenever GC-MS detected amines inside of failed CPVC samples that we analyzed, we discovered that Allied ABF metal pipe was also used in the water supply system. Our discovery of the amines and the Allied ABF source has not been without controversy, primarily because most other forensic labs were not detecting the chemicals. However, we continued to communicate our findings because of our scientific certainty. Currently the controversy is beginning to wane as recent evidence collected by others supports our findings. This article is being written to help educate the Fire Sprinkler Industry about the amine contamination issue. Also we are trying to help educate installers about installation errors and Forensic Failure Scientists about the benefits of GC-MS for contaminant analysis.

Introduction

Plastic Failure Labs is an independent forensic laboratory. We have been conducting forensic failure analyses for several years. In that time we have carried out hundreds if forensic failure analysis investigations of CPVC fire sprinkler pipes and fittings at the request of insurance companies, installers, general contractors, condominium associations, and private owners. We have seen everything from hairline branched cracks in pipes (Figure 1) to fittings that have totally disintegrated (Figure 2). Our failure analysis investigations have revealed that there are many potential causes of failure (summarized in Table 1). However, we have found that the overwhelming/most common cause of failure is contamination of the CPVC pipes and fittings with incompatible chemicals. The combination of pipes under stress plus the exposure to incompatible chemicals, leads to what is generally called environmental stress cracking or ESC. This is especially the case with CPVC sprinkler system piping because the system is static so contaminants that were swept into the piping system during the original pressurization remain trapped inside the pipes.

Figure 1. Environmental stress-cracks on inside of CPVC pipe

Pipe Defects

Plastic pipe is manufactured by extrusion of molten CPVC resin through a circular die with a mandrel held in place with thin metal webs. While passing through the die, the molten resin is sliced by the mandrel webs but then should fuse back together again to produce a solid pipe. If the extrusion conditions are not optimized, incomplete fusion results leading to straight longitudinal knit lines the entire length of the pipe wall. These longitudinal knit lines are more susceptible to penetration of trace organic contaminants that may be present in the water being transported or held inside the pipes leading to environmental stress cracking (ESC). Cracks originating from the knit lines appear as straight-line cracks running longitudinally and parallel down the pipe (Figure 3) and they display no single initiation point.

The pipe extrusion process itself results in the production of pipes under inherent mild stress. As the polymer molecules flow through the die they become aligned with each other. After they exit the die, the plastic is immediately cooled and the molten plastic is solidified resulting in the polymer molecules becoming frozen in alignment rather than in their natural random state. Since the pipe walls are frozen in an unnatural state, they are under a low level of stress before ever being installed. Since the pipe is in a stressed state, it is looking for opportunities to relax to relieve the stress. Things that allow it to relax include heat and exposure to certain organic contaminants that soften the plastic. If exposed to certain organic or hydrocarbon chemicals, the pipe surface absorbs the chemicals and softens allowing it to relax in an effort to relieve the stress. This process results in the formation of hairline cracks which generally run longitudinally down the pipe in the direction of polymer molecule alignment. As opposed to straight-line cracking described in the preceding paragraph, these cracks are generally more random. If the installer places the pipe under additional stress by clamping it tightly or installing it in a slightly bent state, the additional stress exponentially increases the sensitivity of the pipe to exposure to ESC agents.

Figure 2. Disintegrated CPVC elbow caused by over-pressurization.

Table 1. Six causes of pipe failure of CPVC in order of occurrence and testing required for diagnoses

Type of Failure	Root Cause of Failure	Tests
ESC	Contamination from ABF pipe	GC-MS
Improper installation	Excessive glue	OM
	Insufficient glue	OM
	Clamps too far appart	Site inspection
	Clamps too tight	Out of round/clamp marks
	Wrong clamps used	Site inspection
	No allowance for thermal expansion	Site inspection
	Wrong antifreeze	IR
	Pipes not aligned	Site inspection
	ESC due to contamination by installer	GC-MS
	Short insertion	OM
Manufacturing defects	Pipe dimensions wrong	ASTM F441
	Resin not consolidated	ASTM F442
	Weak knit lines	ASTM F442
	Voids or particulates	OM/SEM/EDS
Resin Defects	Resin molecular weight too low	MI
	Resin crystallinity too low	DSC
	Filler content wrong	TGA
Improper operation	Water hammer	OM/SEM
	Over pressurization	OM/SEM
	Area contamination	GC-MS/IR
	Freezing	OM
Abuse by distributor	store in sun	IR
	damage during handling/transport	OM
MI = melt index		
OM = optical microscopy		
IR - infrared scectroscopy		
TGA = thermal gravimetric analysis		
DSC = differential scanning calorimetry		
SEM = scanning electron Microscopy		
EDS = Electron dispersive spectroscopy		
GC-MS = gas chromatogrphy-mass spectroscopy		

Improper Installation

Excessive glue use: A common installation problem that we commonly see is the use of excessive glue. Glue itself is an ESC agent. The organic solvents in glue soften the surface of the pipe and fittings allowing the polymer molecules to intertwine to form a permanent bond. The organic solvents in the glue are volatile and quickly evaporate so that they are only around long enough to do their intended job but not long enough to cause the pipe to crack. The problem is that many installers utilize too much glue resulting in glue dribbles running down the inside of vertical runs of pipe. The glue dribble is a spongy material and it serves as a place where contaminants can be absorbed and trapped underneath. Peeling back the glue often reveals hairline cracks underneath (Figure 4).

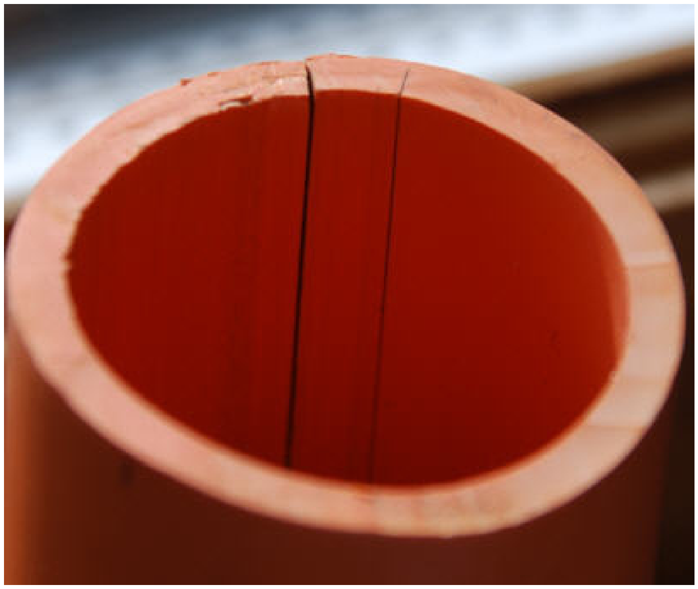


Figure 3. Weak extrusion knit-lines on the inside surface of a CPVC sprinkler system pipe resulting in the formation of perfectly parallel straight line cracks upon exposure to contaminants

When excessive glue is used on the outside of pipe it is not as much of a problem as on the inside. This is because, on the outside, the organic solvents quickly evaporate. However, on the inside of the pipe, the organic solvents are trapped allowing more exposure time of the plastic to the solvent. Also, the glue dribble is porous and acts like a sponge providing a place where trace hydrocarbon contaminants can be absorbed from the water inside the pipes. The hydrocarbon laden glue dribble is in constant contact with the inside pipe surface providing the perfect site for crack initiation (Figure 4).

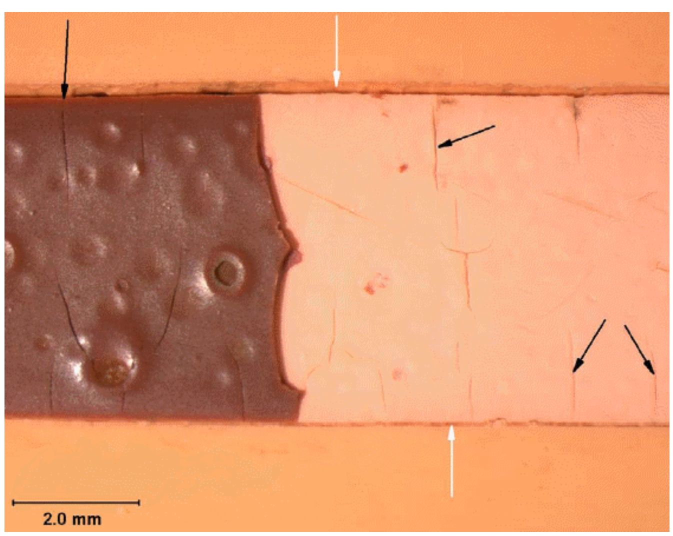


Figure 4. Glue dribble on inside of CPVC pipe with hairline cracks found underneath the dribble.

Insufficient glue use: Sufficient glue must be applied to end up with complete coverage of the end of the pipe and the inside of the fitting so that a contiguous film of glue is formed between the pipe and fitting surfaces. If insufficient glue is applied, voids may form between the pipe and fitting. The presence of the voids results in a weakened fitting which lowers the burst pressure of the fitting. So, you may ask the question "how do I ensure that I use enough but not too much glue?" Most CPVC installation manuals recommend the following procedure for glue application:

> *"Apply a heavy, even coat of cement to the outside pipe end. Apply a medium coat to the fitting socket. Apply a second cement application on the pipe end. It is important to insure sufficient penetration of the solvent cement into the pipe and fitting surface(s) by wiping the cement with the dauber until the pipe markings have been removed from the pipe surface. Usually 3-5 rotations around the pipe with the dauber are sufficient to achieve proper softening. Immediately insert the pipe into the fitting socket completely to the stop, while rotating the pipe 1/4 turn."*

It is alright to end up with excess glue on the outside of a pipe/fitting but it is not alright to end up with excess glue on the inside of the pipe/fitting. By applying the excess glue to the end of the pipe, but not the fitting, when the pipe is inserted into the fitting, the excess glue is pushed down the outside of the pipe. If excess glue is applied to the inside of the fitting, the excess ends up remaining in the fitting and either pools inside the fitting (Figure 5) or else runs down the pipe (Figure 4). It is generally quite easy to spot whether a fitting was assembled using sufficient glue versus an insufficient amount of glue as shown in Figure 6.

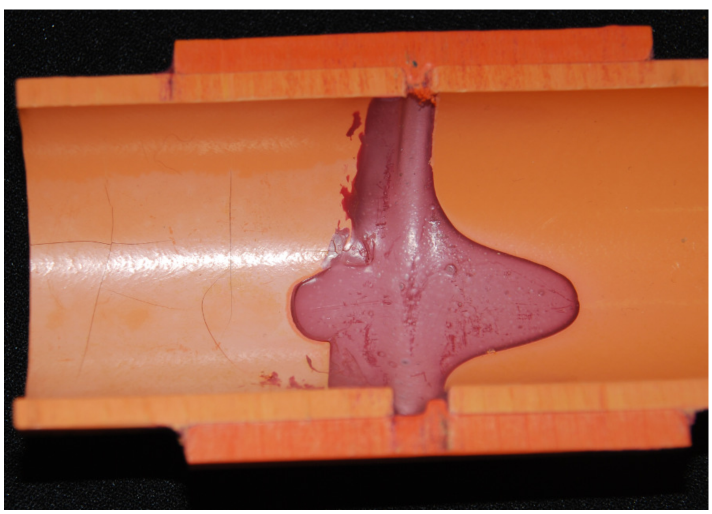


Figure 5. Pooling of excess glue inside of fitting. Notice mud cracking of the inside surface to left of glue.

Clamps/conduit: Another very common cause of failure is clamping pipes too tightly causing them to go out-of-round or using the wrong type of clamp. Also placing pipes in contact with electrical conduit or other pipes is a problem. These practices place tremendous external stress on pipes which will likely lead to eventual failure.

Thermal expansion: Plastic pipes have a much higher coefficient of linear thermal expansion (CLTE) than other materials. The high CLTE of CPVC pipes must be compensated for during installation, especially in environments where large temperature changes are likely. The normal way to allow for thermal expansion is by installation of expansion loops in long runs of piping and loose fitting hangars that allow for slippage.

Figure 6. Photos showing the external appearance of a bad (top) and a good (bottom) joints.

Wrong antifreeze: In very cold northern climates where sprinkler pipes are likely to be exposed to freezing temperatures, the water that is charged into the sprinkler system must contain an antifreeze. Regular automotive (ethylene glycol) and RV (propylene glycol) not acceptable for use with CPVC as they may initiate stress cracking over time, especially at concentrations greater than 30%. Instead, a special antifreeze based upon glycerin must be used.

Pipe alignment: Pipes must be installed without any bending moment. If installed in a bent configuration, the pipes are under stress making them susceptible to ESC.

Short insertion: When small diameter CPVC pipes are inserted into fittings they should be inserted all of the way until the end of the pipe hits the stop. If they are short inserted, a pocket remains between the end of the pipe and the stop. This is a place where we commonly see failures occur. What happens is glue accumulates in the pocket. The sponge effect of the glue in the pocket acts as a place for trace organics to accumulate and eventually ESC of the fitting takes place.

Contamination - Exterior: Care must be taken not to allow CPVC pipes to contact other non-metallic materials. Figures 7 and 8 show examples of failure due to contact of CPVC with other materials that contain plasticizers. Figure 7 was a condominium where a worker sealed all of the openings in walls using a fire caulk. A drop of excess fire caulk fell down onto a CPVC fire sprinkler pipe resulting in failure of the pipe underneath the fire caulk.

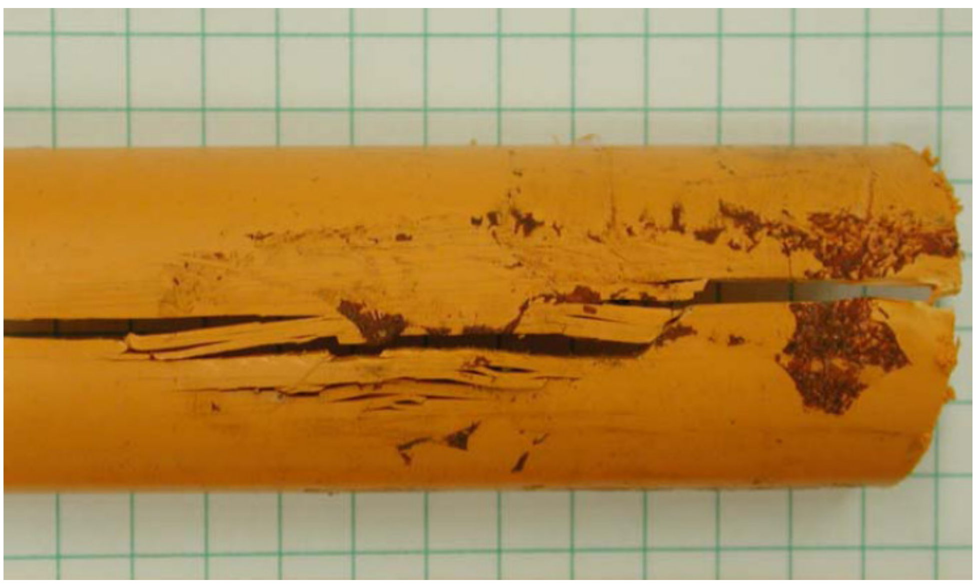


Figure 7. Failure of CPVC fire sprinkler pipe due to fire caulk contamination on the exterior surface of the pipe. The fire caulk contained phthalates and phosphate esters which migrated from the caulk and into the CPVC.

Figure 8 shows an example where a black grommet was used to seal the hole in the concrete floor through which a CPVC pipe ran. It was known that black grommets are not compatible with CPVC so metal foil tape was applied to the pipe to isolate the grommet from contacting the pipe surface. However, the phthalate plasticizers in the grommet migrated from the grommet down the tape and into the pipe resulting in softening of the pipe wall.

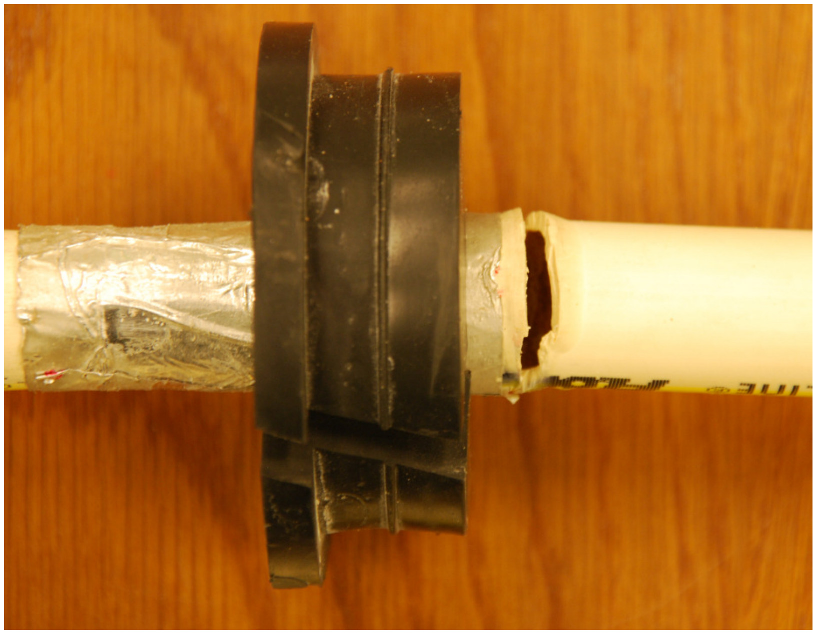


Figure 8. Failure of CPVC pipe due to migration of phthalate plasticizer from Proset grommet down metal foil tape used to isolate pipe. Phthalates were absorbed into the pipe resulting in softening and failure of the pipe wall.

<u>Contamination – Interior:</u> CPVC pipe is for use with water, not for hydrocarbons. CPVC is not compatible with most hydrocarbons. Unfortunately, hydrocarbon contaminants are everywhere and care must be exercised during installation to make sure that contaminants are not introduced. . The most common sources of contaminants are metal pipe thread cutting oils, pipe thread sealants, and coatings placed on the inside surfaces of metal water supply pipes connected to the plastic pipes. These coatings may have been placed inside the metal pipes to inhibit corrosion, inhibit bacterial growth, etc. As already mentioned, CPVC sprinkler systems are especially vulnerable because they are pressurized and held under fairly constant static pressure (hoop stress) over long periods of time. Trace hydrocarbon contaminants present in the water slowly absorb into the pipe initiating stress cracking especially in locations where the pipes were placed under additional stress by being slightly bent to fit through holes in drywall or at hangar assemblies where the weight of the water filled pipes is supported.

Based upon analysis of over 400 CPVC pipe and water samples, we have assembled a data base of chemicals that we have found inside of contaminated fire sprinkler systems. Metal piping may contain significant levels of hydrocarbon contaminants including corrosion inhibitors, pipe thread cutting oils, pipe thread sealants, and antimicrobial coatings. Some antimicrobial coatings contain amines. Amines (primary, secondary, and tertiary) are especially aggressive ESC agents for CPVC because amines chemically react with chlorinated hydrocarbons including CPVC. Theoretically the only amine that may possibly be compatible with CPVC would be quaternary. However, more testing must be done to confirm. Allied Tube calls their antimicrobial lined pipe ABF which stands for antibacterial film. We first began discovering failures in condominiums where the water supply piping utilized Allied ABF pipe in the Fall of 2007. Our extensive forensic analyses indicated that the primary contaminants in the failed CPVC piping contained amines. Our forensic investigation to locate the source of the amines led us to the Allied ABF piping, which we discovered contained the same amines. Since that time we have been involved in many CPVC pipe failures in other condominiums. Whenever amines are identified as the contaminant that caused the failure, we also find that the water supply piping is Allied ABF pipe. This evidence caused us to post an alert of the problem in early 2008.

The method that we use to analyze failed pipe samples and water drained form failed fire sprinkler system piping to identify the contaminants is gas chromatography equipped with a mass spectrometer detector (GC-MS). GC-MS is the only analysis we have found that provides isolation and identification of amines. Most other forensic labs rely on infrared spectroscopy (IR) for conducting contaminant analysis. The levels of amine contaminants in the failed CPVC pipes is generally below the detection limit for IR and therefore often go undetected. Unfortunately not all labs that work on forensic failure analysis of plastics have GC-MS capability. Those labs that have GC-MS lack experience on its use for contaminant analysis of pipe and water samples. The use of IR for contaminant analysis and the lack of experience with GC-MS for pipe/water contaminant analysis has caused significant controversy over our pioneering discovery of the ABF / CPVC failure connection. Fortunately the controversy is waning as new data is becoming available which supports our findings. For example, Victaulic recently performed ESC testing showing that exposure of CPVC to water from antibacterial lined pipe accelerates ESC failure of CPVC (see Victaulic communication dated September 12th, 2008 located at http://www.nfsa.org/news/CPVCCompatibility.pdf). Also, in early 2009 Lubrizol posted a communication about the problem at http://www.systemcompatible.com/other-compatibility-concerns.asp#SteelPiping.

Figure 9 shows an example of a GC-MS analysis of a CPVC sprinkler pipe sample removed from a condominium. The pipe sample was found to contain didecylmethylamine. The amine was also identified in the hexane wash of the Allied ABF lined metal pipe that supplied the water to the CPVC sprinkler piping system.

In an effort to communicate our findings and gain peer review, we decided to present our work at a Fire Sprinkler Association conference and publish our work in a peer reviewed Fire Sprinkler Industry journal. Recently (October 2008) we presented the work at the annual technical conference of the Society of Fire Protection Engineers. Also, we submitted our findings to the Journal of Fire Protection Engineering for publication. In December 2008 we received acceptance of the paper. The paper entitled "Systematic Approach to Contaminant Analysis of CPVC Fire Sprinkler System Piping and Development of Cleaning Technology for Elimination of Contaminants" will appear in the journal sometime in 2009.

Diagnosing Failure Due to ESC/Contamination on Interior: Failure of CPVC piping by ESC is generally diagnosed by high magnification analysis of the crack surfaces by a professional experienced in fracture surface analysis. Figure 10 shows a fracture surface typically found in pipe samples that have failed due to contamination.

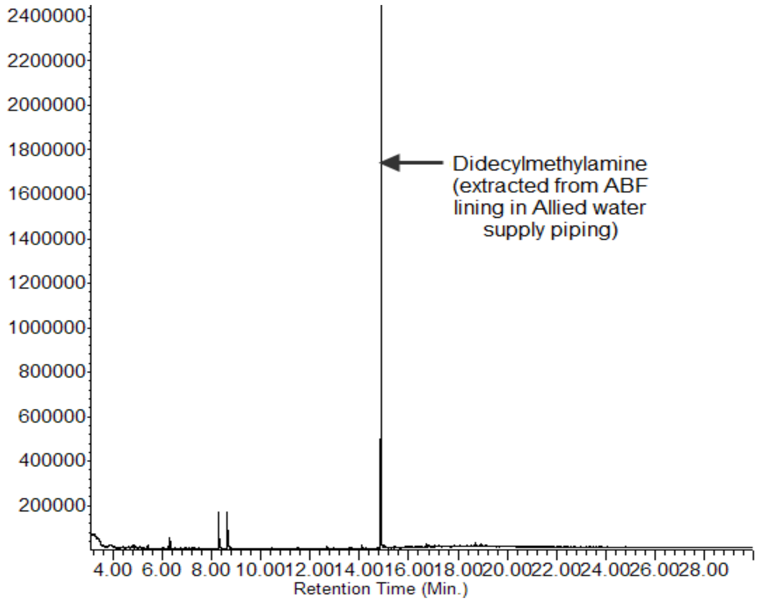


Figure 9. GC-MS analysis of contaminants identified inside of a failed CPVC pipe. The contaminant found in highest concentration was didecylmethylamine which was extracted from the ABF lining in Allied pipe and deposited into the CPVC sprinkler pipe.

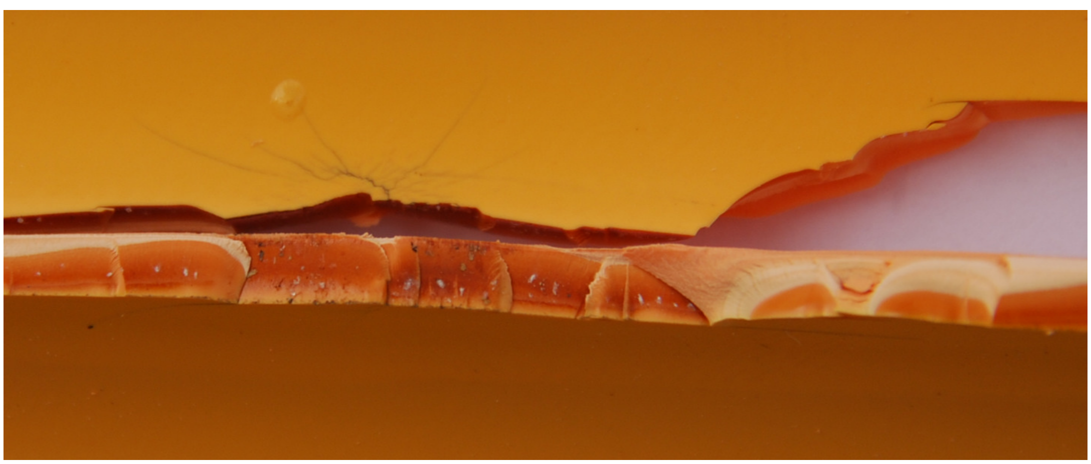


Figure 10. Fractographic analysis of the crack surfaces confirms failure due to ESC.

Importance of Cleaning Metal Pipes before Connection to Plastic Pipes

Metal pipes that are connected to CPVC pipes should be thoroughly cleaned before they are connected to the CPVC piping system. Unfortunately most of the contaminants are hydrophobic (water hating) and are repelled by water. Thus flushing plain water through metal pipes is not very effective for contaminant removal. Removal of hydrocarbons generally requires that a surfactant (soap) be added to the water being flushed through the metal pipes. Surfactants compatibilize the hydrophobic oils with the water allowing the oil to become emulsified so that it can be flushed from the metal pipe surfaces. After the soapy water flush, the metal pipes should be thoroughly rinsed with pure water to remove all of the soap residues from the metal pipes as some concerns have been expressed about the potential for even surfactants (especially non-ionic surfactants) to cause environmental stress cracking.

We have partnered with Coastal Environmental and performed research aimed at the development of pipe washing protocols to ensure that metal water supply pipes are contaminant free before they are connected to CPVC piping. We have been successful and we now offer metal pipe cleaning services.

Forensic Failure Analysis Process

If you are having a cracking problem with CPVC pipes, Plastic Failure Labs can analyze the pipes and/or the installation and diagnose the root cause of the problem. We are also highly experienced providing expert witness services should the pipe failure lead to litigation.

Our goal is to diagnose the cause of failure efficiently and quickly. In general, we carry out a laboratory examination of the pipes including measurement of pipe dimensions, examination of the pipe surfaces for physical damage, examination of the pipe surfaces for the presence of contaminants, examination of the crack fracture surfaces, and ASTM testing of resin used to make the pipes to see if a defective resin was used.

In Closing

CPVC pipe is a great product but it is unforgiving when it comes to contamination. Since the primary source for introduction of contaminants into the CPVC are metal pipes, installers should make sure the metal pipes are clean and contaminant free before connecting them to the CPVC portion of the fire sprinkler system. We offer pipe cleaning and contaminant analysis services and we can assist you in minimizing the chances of CPVC pipe failure due to internal contamination.

Duane Priddy, Sr. is the founder and CEO of Plastic Failure Labs. The company is a leading provider of plastic consulting, expert witness, and plastic failure analysis services. Prior to starting Plastic Failure Labs, Dr Priddy was a Principal Scientist for Dow Plastics where he was involved in helping solve problems with plastic manufacture and plastic failure for over 30 years. Partially due to Dr. Priddy's pioneering forensic investigations of CPVC failure, he was recently awarded "Fellow" of the Society of Plastic Engineers. Please feel free to contact Dr. Priddy anytime by phone (989.385.2355) or email at duane@plasticfailure.com.