Plastic Failure Labs

6004 Camelot
Midland, MI 48640
Ph: 877-PLA-FAIL

Why Do PVC and CPVC Pipes Fail?

By Dr. Duane Priddy, Plastic Failure Labs, Midland, MI

Introduction

Both PVC and CPVC pipes are utilized extensively in plumbing systems due to their relative low cost and ease of installation. CPVC is preferred over PVC in some applications where improved fire and heat resistance are required.

However, failures of PVC and CPVC pipes and fittings are quite common. We have seen everything from hairline 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. The causes of failure that we have identified and the tests used to diagnose the causes are summarized in Table 1.

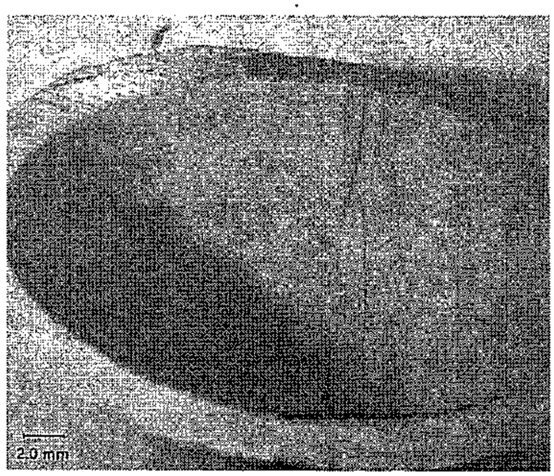

Figure 1. Environmental stress-cracks on inside of CPVC pipe

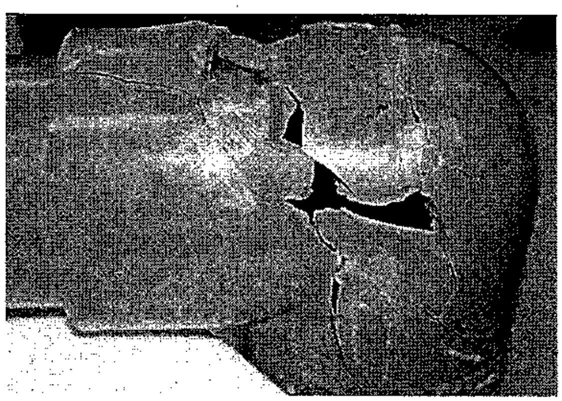

Figure 2. Reconstructed PVC elbow that disintegrated during use

Table 1. Causes of pipe failure and testing required for diagnoses

Type of Failure	Root Cause of Failure	Tests
Resin Defects	MW too low	MI
	crystallinity too low	DSC
	filler content too high	TGA
Manufacturing Defects	incomplete fusion of resin particles	ASTM D2152 & ISO9852
	voids or particulates in pipe/fitting	OM
Improper Installation	excessive glue inside pipe	pipe inspection
	clamps too far apart	site inspection
	clamps too tight	out-of-round measurement/OM
	wrong clamps/contact with other pipes	site inspection
	no allowance for thermal expansion	site inspection
	wrong antifreeze	GC-MS/IR
	pipes not aligned	site inspection
	ESC due to contamination	GC-MS/IR
	short insertion	OM
	over-insertion (overbelling)	ASTM 2321 Section 7.4.1
Improper Operation	water hammer	SEM
	over pressurization	SEM
	area contamination	GC-MS/IR
Abuse by Distributor	stored in sun	OM/IR
	damaged during handling/transport	OM
MI = melt index		
OM = optical microscopy		
IR = infrared spectroscopy		
TGA = thermal gravimetric analysis		
DSC = differential scanning calorimetry		
SEM = scanning electron microscopy		
ESC = environmental stress cracking		
GC-MS = gas chromatography-mass spectroscopy		

Our forensic investigations show that the most common cause of failure in PVC and CPVC pipes is exposure to 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 inside the pipes.

Resin Defects

PVC and CPVC are sold by the resin producers as particles. The resin particles have a specified set of properties. The key resin properties that control the performance are its polymer melt index, resin crystallinity, and the filler content. The quality of the resin can be assessed using ASTM testing.

Pipe Defects

Plastic pipe is manufactured by extrusion of molten PVC and CPVC resin through a circular die with a mandrel held in place with thin metal webs. As the molten resin flows through the die, it is sliced by the 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 have no recognizable initiation point.

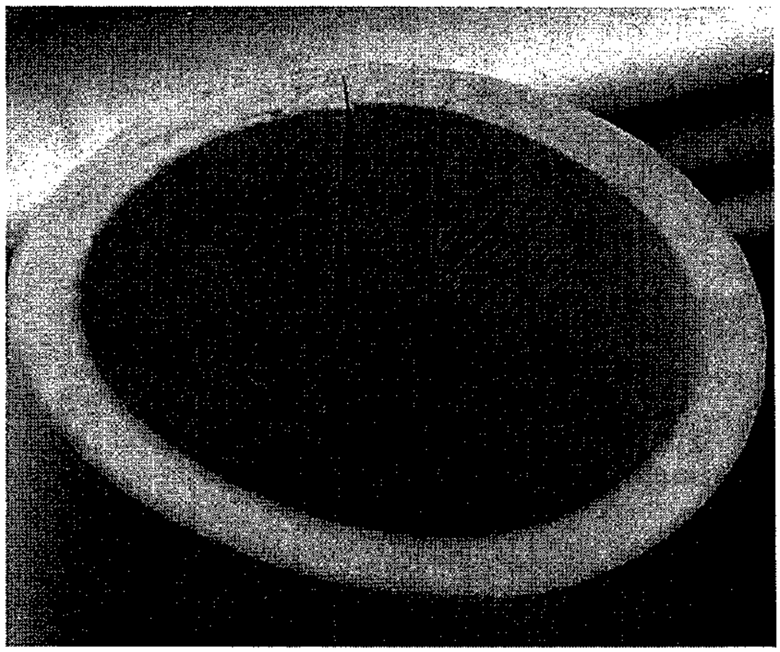

Figure 3. Weak extrusion knit-lines on the inside surface of a CPVC sprinkler system pipe resulting in the formation of perfectly parallel straight line cracks upon exposure to trace organic contaminants

Actually, 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 apposed 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. Since these pipes are intended for use in handling aqueous environments, one would think that exposure to ESC agents would be rare; however this is not the case. By rinsing inside surfaces of failed pipes (that show evidence of ESC) with a solvent and analyzing the rinse we have identified a multitude of organic contaminants. 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. The presence of trace hydrocarbon contaminants 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 by being improperly supported.

Improper Installation

Excessive glue use: Another 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).

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.

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.

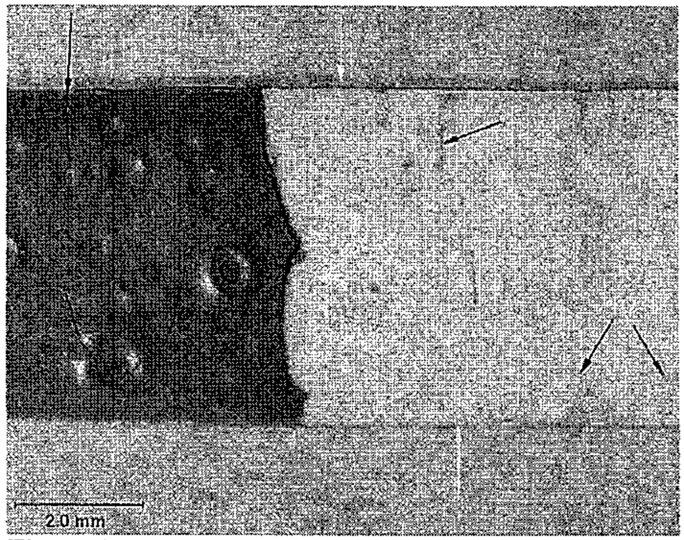

Figure 4. Glue dribble on inside of CPVC pipe with hairline cracks found underneath the dribble.

Thermal expansion: Plastic pipes have a much higher coefficient of linear thermal expansion (CLTE) than other materials. The high CLTE of PVC and 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.

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 PVC and 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.

Over insertion (Overbelling)

Large diameter PVC pipes (i.e., 16 inch) are frequently used for underground transportation of sewage. These pipes are very heavy and are thus difficult to handle. The pipe sections are generally 20 feet in length and the pipes are installed by insertion of the male end into the female end of the adjacent pipe which contains an elastomeric seal.

ASTM 2321-05 ("Standard Practice for Underground Installation of Thermoplastic Pipe for Sewers and Other Gravity-Flow Application", Section 7.4.1 for Elastomeric Seal Joints) is to be followed exactly for proper installation. The male pipe is to be inserted into the female (bell) to the mark on the male pipe. Insertion of the male too far into the bell will result in over-assembly or over-belling of the female section which results in the male putting too much force on the female end creating high stress resulting in creep failure and cracking of the pipe as shown in Figure 5.

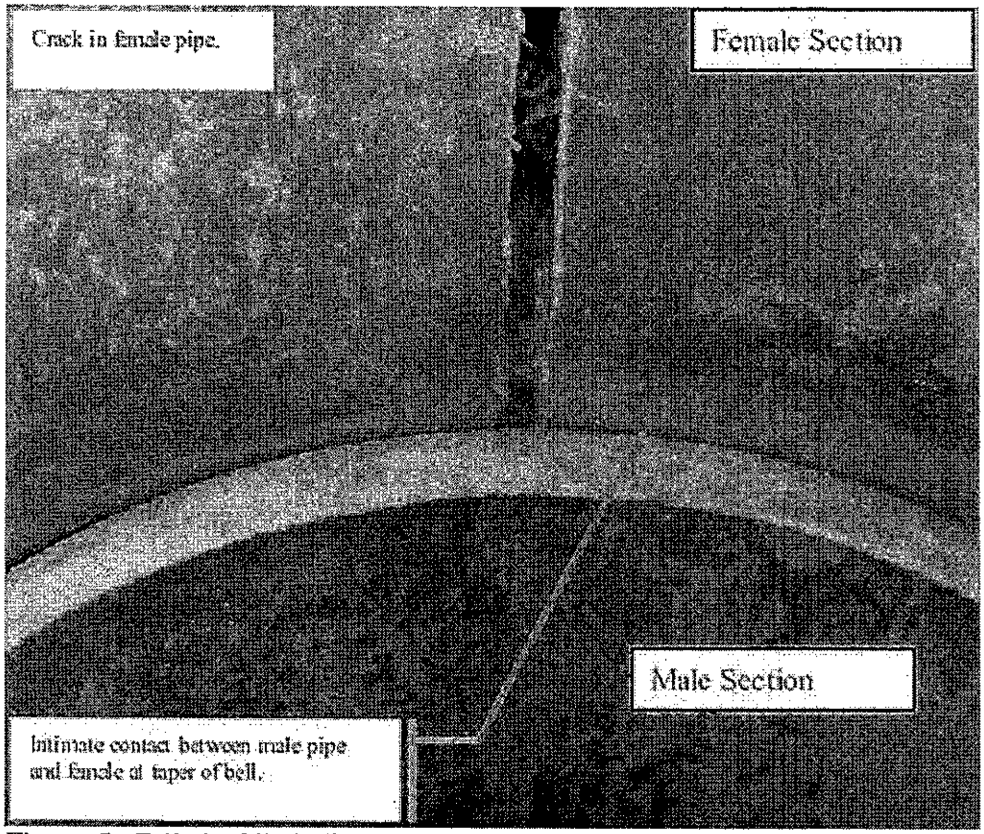

Figure 5. Failed 16 inch diameter PVC sewer transport pipe caused by over-insertion (over-belling) of male end into the female end.

<u>Contamination</u>: CPVC sprinkler systems are commonly installed in combination with metal pipes. Since metal pipes are threaded on-site with the use of thread-cutting oils, these oils end up contaminating the CPVC pipes if not washed off the threads before connecting to the CPVC fitting. Since the sprinkler system is under static pressure, the hydrocarbon contaminants that end up inside the pipes remain there. Since oils have a very low solubility in water, they deposit onto the inside pipe surface and slowly absorb into the pipe initiating ESC failure. A tell tale sign of this kind of failure is when the crack in the CPVC pipe is located on the top of the pipe. This is because the oils are lighter than water and float to the top. Another observation that is frequently associated with ESC is a "cracked mud" appearance (Figure 6) on the inside surfaces of the pipe.

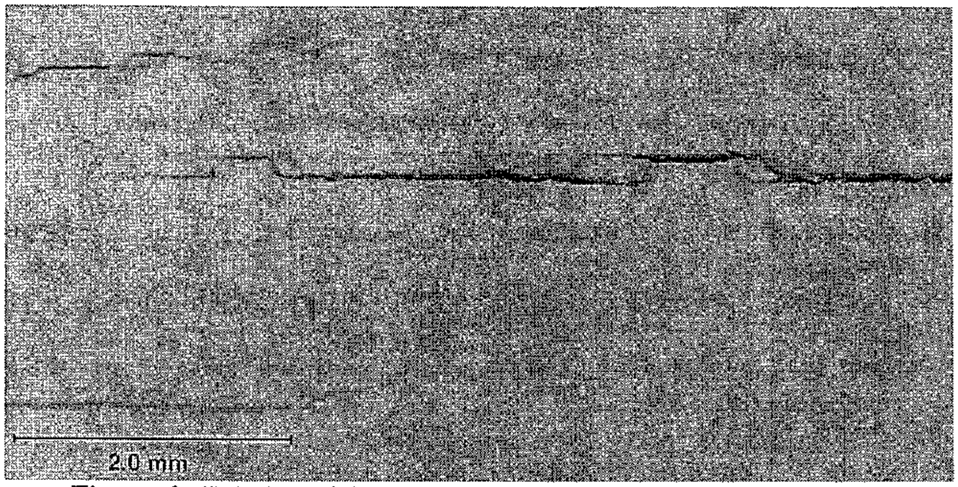

Figure 6. "Mud crack" pattern on inside of CPVC pipe due to ESC

Importance of Cleaning Metal Pipes before Connection to Plastic Pipes

Metal pipes are often contaminated with hydrocarbons, many of which may be incompatible with PVC and CPVC pipes. The list includes corrosion inhibitors, and thread cutting oils. Metal pipes should be cleaned before they are connected to the CPVC piping system. Antibacterial lined metal pipe (ABF) should not be used in fire sprinkler water supply lines that supply water to CPVC sprinkler pipes. ABF linings contain amine antimicrobials that chemically react with and degrade CPVC pipes. The gas chromatogram showing the identity of extractible hydrocarbons present in an ABF pipe is shown in Figure 7.

Petroleum based hydrocarbons (e.g., oils) are generally hydrophobic (water hating) and are repelled by water. Thus flushing plain water through metal pipes only partially removes oils. Complete removal of hydrocarbons 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.

Table 2 list the compatibility of a variety of hydrocarbon materials with CPVC. This table was assembled by considering published data*** on the compatibility of CPVC with organic chemicals. I highlighted the different classes of chemicals in the table by color. From the table, I drew the following generalized conclusions. Please note that there may be exceptions to these generalizations:

1) Most hydrocarbon based chemicals are not compatible with CPVC.
2) Chlorinated hydrocarbons are incompatible with CPVC.

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* see http://www.plastemart.com/upload/literature/CPVC.asp

** see http://www.pep-plastic.com/manufacturers/nibco/chemvlvgde.pdf

*** see http://www.pep-plastic.com/manufacturers/spears/pdf/cpvcchart.pdf

3) Phthalates are incompatible with CPVC.
4) Aromatics are incompatible with CPVC.
5) Amines are highly incompatible with CPVC.
6) Most esters are incompatible with CPVC.
7) Most ethers are incompatible with CPVC.
8) Many alcohols are incompatible with CPVC unless diluted to low concentrations in water.
9) Most ketones are incompatible with CPVC unless diluted to low concentrations in water.
10) Most saturated hydrocarbons (molecular formula fits the equation CnH2n+2) are compatible with CPVC.
11) Most unsaturated hydrocarbons (molecular formula contains less H atoms than 2n + 2 the number of C atoms) are incompatible with CPVC.

Table 2. The compatibility of a variety of hydrocarbon materials with CPVC

Hydrocarbon Name		Hydrocarbon Name		Hydrocarbon Name		Hydrocarbon Name		Hydrocarbon Name	
Acetaldehyde	I	Butyric Acid, pure	I	Dichloroethylene	I	Heptane	U	Propanol, < 0.5%	C
Acetic Acid, < 10%	C	Cane Sugar Liquors	C	Diethylamine	I	Hydrazine	I	Propanol, > 0.5%	U
Acetic Acid, > 10%	C	Caprolactam	I	Diethyl Ether	I	Isopropanol	U	Propionic Acid, < 2%	C
Acetic Acid, pure	I	Caprolactone	I	Dill Oil	I	Ketones	I	Propionic Acid, > 2%	U
Acetic Anhydride	I	Carbitol	I	Dimethylformamide	I	Lemon Oil	I	Propionic Acid, pure	I
Acetone, < 5%	C	Carbon Disulfide	I	EDTA, Tetrasodium	C	Limonene	I	Propylene Dichloride	I
Acetone, > 5%	U	Carbon Tetrachloride	I	Esters	I	Linseed Oil	I	Propylene Glycol, < 25%	C
Acetone, pure	I	Castor Oil	I	Ethanol, < 5%	C	Methanol, < 10%	C	Propylene Glycol, > 25%	U
Acrylic Acid	I	Cellosolve, all types	I	Ethanol, > 5%	U	Methanol, > 10%	U	Propylene Oxide	I
Acrylonitrile	I	Chlorinated Solvents	I	Ethers	I	Methanol, pure	I	Pyridine	I
Adipic Acid, sat'd	C	Chlorobenzene	I	Ethyl Acetate	I	Methyl Cellosolve	I	Silicone Oil	C
Alcohols	U	Chloroform	I	Ethyl Acrylate	I	Methyl Chloride	I	Soaps (ionic surfactants)	C
Allyl Alcohol	U	Citric Acid	C	Ethyl Benzene	I	MethylEthylKetone (MEK)	I	Soybean Oil	I
Allyl Chloride	I	Citrus Oils	I	Ethyl Chloride	I	Methyl Formate	I	Starch	C
Amines	I	Coconut Oil	I	Ethyl Ether	I	Methyl Isobutyl Ketone	I	Stearic Acid	C
Ammonia	I	Corn Oil	I	Ethylene Bromide	I	Methyl Methacrylate	I	Styrene	I
Amyl Acetate	I	Corn Syrup	C	Ethylene Chloride	I	Methylamine	I	Sugar	C
Amyl Alcohol	U	Cottonseed Oil	I	Ethylene Diamine	I	Methylene Chloride	I	Tall Oil	U
Amyl Chloride	I	Creosote	I	Ethylene Glycol, < 50%	C	Mineral Oil	C	Tartaric Acid	C
Aniline	I	Cresol	I	Ethylene Glycol, > 50%	C	Monoethanolamine	I	Terpenes	I
Aromatic Hydrocarbons	I	Crotonaldehyde	I	Ethylene Oxide	I	Motor Oil	I	Tetrahydrofuran	I
Benzaldehyde	I	Cumene	I	Formaldehyde	I	Naphthalene	I	Toluene	I
Benzene	I	Cyclohexane	I	Formic Acid, < 25%	C	Olive Oil	I	Tributyl Phosphate	I
Benzoic Acid, sat'd	C	Cyclohexanol	I	Formic Acid, > 25%	U	Oxalic Acid, Sat'd	C	Trichloroethylene	I
Benzyl Alcohol	I	Cyclohexanone	I	Freons	U	Palm Oil	I	Turpentine	I
Benzyl Chloride	I	Detergents	U	Fructose	C	Paraffin	C	Urea	C
Bromobenzene	I	Dextrin	C	Gasoline	I	Peanut Oil	I	Vegetable Oils	I
Bromotoluene	I	Dextrose	C	Glucose	C	Phenylhydrazine	I	Vinegar	C
Butanol	U	Dibutyl Phthalate	I	Glycerine	C	Picric Acid	I	Vinyl Acetate	I
Butyl Acetate	I	Dibutyl Ethyl Phthalate	I	Glycol Ethers	I	Pine Oil	I	WD-40	U
Butyl Carbitol	I	Dichlorobenzene	I	Halocarbon Oils	I	Polyethylene Glycol	I	Xylene	I

Key and Grouping Color Codes
Compatible = C   Incompatible = I   Uncertain = U

Generalizations: (please note that there are exceptions to these generalizations)
1) Chlorinated hydrocarbons are incompatible with CPVC
2) Phthalates are incompatible with CPVC
3) Aromatics are incompatible with CPVC
4) Amines are highly incompatible with CPVC
5) Most esters are incompatible with CPVC
6) Most ethers are incompatible with CPVC
7) Most alcohols are compatible with CPVC in low concentrations in water
8) Most ketones are incompativle with CPVC
9) Most saturated hydrocarbons (molecular formula fits the equation C_nH_{2n+2}) are compatible with CPVC
10) Most unsaturated hydrocarbons (molecular formula contains less H atoms than 2n + 2 the number of C atoms) are incompatible with CPVC

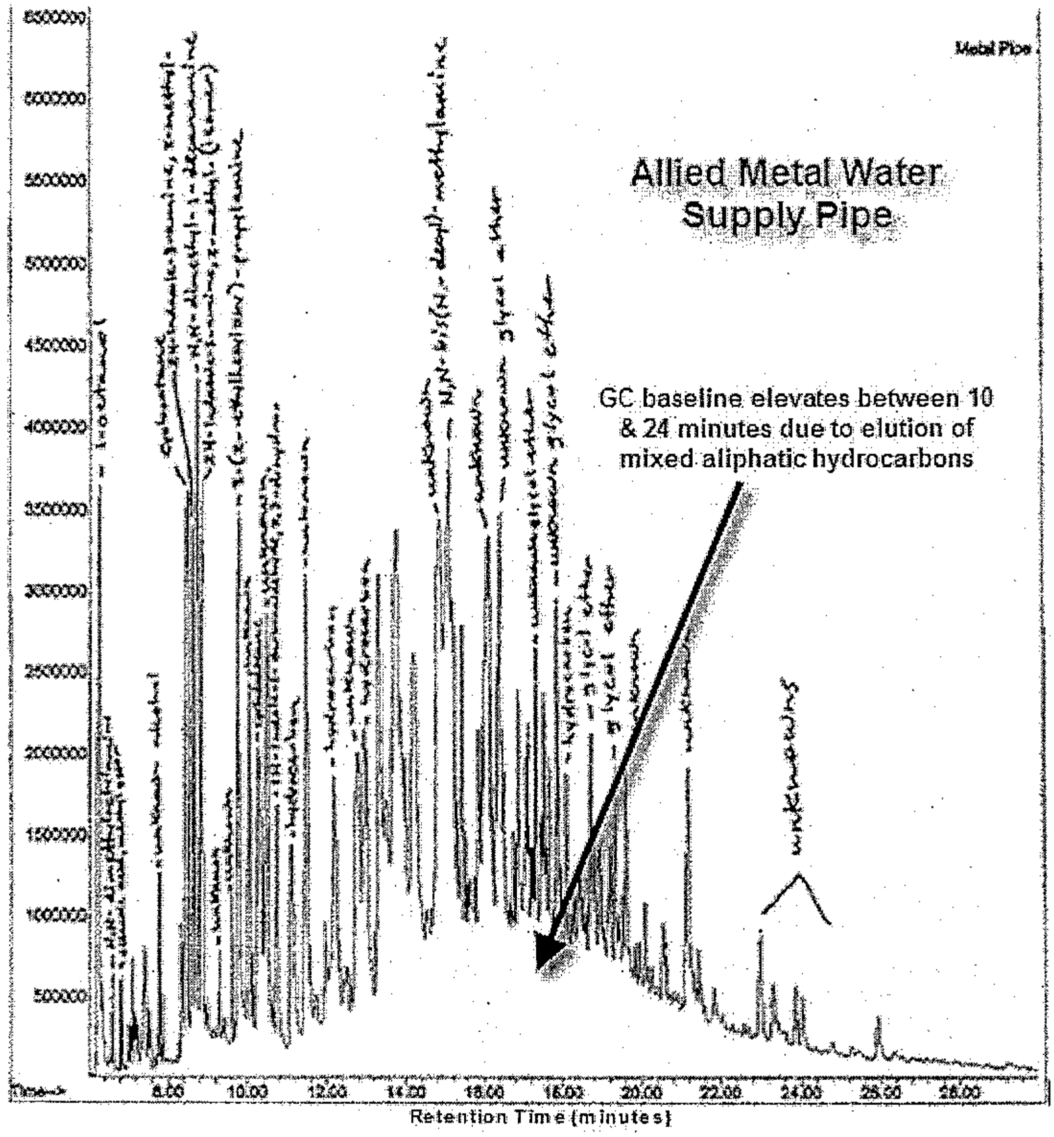

Figure 7. GC-MS analysis of hydrocarbons present inside ABF lined metal pipe

The procedure that we developed to analyze CPVC and PVC pipe samples to identify the hydrocarbon contaminants involves rinsing the inside surfaces of a pipe sample with pure hexane and then injecting a small sample of the hexane rinse into a gas chromatograph (GC) that is equipped with a mass spectrometer (MS). The contaminants are separated by boiling point and then the pure compounds are transferred into the MS where they are identified. Once the identity of the contaminants is known, they can be assessed based upon their known compatibility as described in Table 2. However, many hydrocarbon compounds are not found in Table 2 forcing one to compare the chemical structure of contaminant found inside the pipe and predict its propensity toward being an ESC agent for CPVC.

Figure 8 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 a mixture of aliphatic hydrocarbons and an amine. The amine was also identified in the ABF lined metal pipe that supplied the water to the CPVC sprinkler piping system. Amines are especially potent bad for CPVC because they chemically react with and degrade the CPVC.

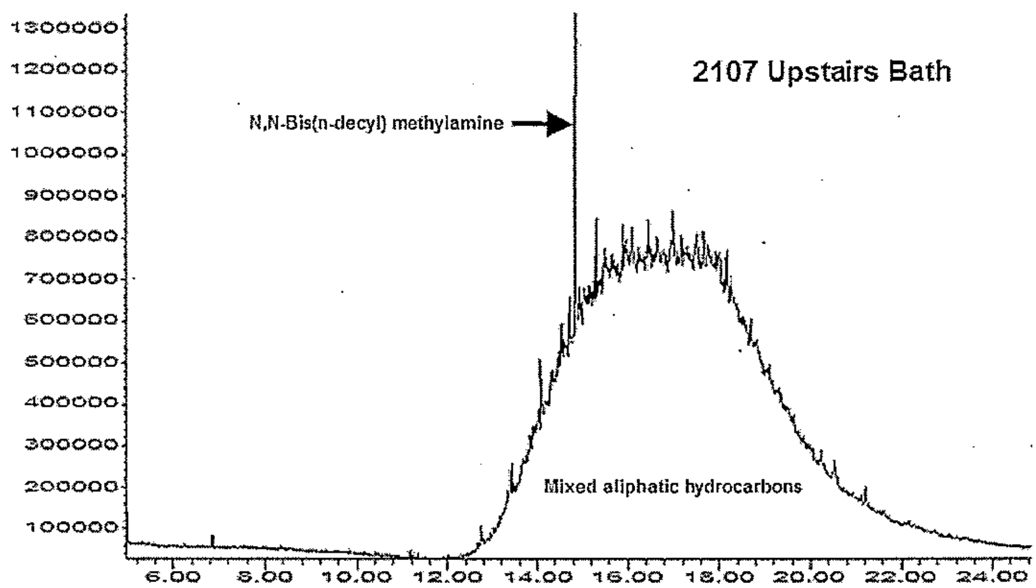

Figure 8. Contaminants found inside a failed CPVC sprinkler pipe. The source of the N,N-bis(n-decyl)methylamine was the ABF lined metal water supply piping through which the water flowed before entering the CPVC sprinkler piping system.

Improper Operation

Building owners are obligated to maintain and operate their plastic piping systems according to recommendations. Things that some building owners do that cause pipes to fail include:

1) painting plastic pipes with paints that are not compatible with the pipes;
2) using/storing chemicals near pipes;
3) allowing pipes to be exposed to high internal pressure during maintenance operations;
4) dropping heavy objects that fall onto pipes causing external damage.
5) spraying insecticides or other chemicals into wall cavities where plastic pipes are located without checking to see if there are compatibility issues.

Forensic Failure Analysis Process

If you are having a cracking problem with PVC or 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

People tend to think that plastics can take a lot of abuse and bounce back. They are wrong! Distributors and installers have been known to break bundles of pipe open by beating on the strap holding the bundle together with a hammer. Then grab a pipe and drag it along the ground to transport it to the installation point leaving scrapes and gouges in the outside of the pipe. This kind of treatment is totally unacceptable. Plastic pipe should be treated gently and installed only by certified technicians trained in proper installation techniques. Before hiring a plumbing subcontractor to install plastic pipe it is very important to confirm that they are a certified plastic pipe installer.

Duane Priddy, Sr. is the founder and CEO of Plastic Failure Labs, Inc. in Midland, MI. 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 failure for over 30 years. He holds a Ph. D. in Organic Chemistry. For article feedback, contact Dr. Priddy by phone (989.385.2355) or email at info@plasticfailure.com.