A Study of the Freezing Phenomena in PVC and CPVC Pipe Systems

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Abstract

Residential and commercial piping systems often experience complex failures from freeze events. In this paper the freezing failures are studied by replicating pipe freezing conditions in a laboratory setting. Testing was performed on ½ inch (12.5mm) PVC and CPVC pipes. Pressure and temperature during the freeze event were monitored and the fracture modes of failed pipes were examined. Freeze events result in excessively high pressures. It has been shown that during a freeze event, the properties of plastic pipes are advantageous over other more rigid piping systems. In this study, it was observed that PVC and CPVC pipes were able to sustain over thirty times the typical household water pressure before bursting occurred.

Introduction

Chlorinated poly(vinyl chloride) (CPVC) and poly(vinyl chloride) (PVC) pipes are two of the most commonly used materials for piping systems. Plastic is a popular alternative to steel piping due to lower cost and easier installation. Plastic piping can also reduce noise by as much as four times over copper of comparable size. There are also fewer problems associated with condensation and corrosion of plastic pipes. Additionally, there is a significant difference between mechanical and thermal properties of metal and plastic pipes.

During a high-pressure event, a plastic pipe will expand to absorb increases in pressure such as those found in a freeze event. Plastic pipes also have thicker walls and greater thermal resistance than metal pipes. For comparison, the thermal conductivity (k) of PVC pipe is $1.3\text{x}10^{-4}$-$1.9\text{x}10^{-4}$ kW/m-K while for copper it is 0.39 kW/m-K. The high conductivity of copper corresponds to a thermal resistance that is basically negligible [1]. Copper pipes will in turn cool faster when exposed to lower temperatures resulting in an earlier freeze event. Nevertheless, plastic pipe freezing failures are a problem commonly experienced in residential and commercial buildings. These failures are primarily attributed to improper pipe/building insulation and controlled interior temperatures. The problem is greater in the southern states where warmer winters are more common and some builders/plumbers use inadequate insulation to protect pipes from occasional sub-freezing temperatures [2].

Ice Formation in a Piping System

As water undergoes a phase transition from liquid to solid the density decreases. The orientation of molecules in ice results in a structure that occupies more volume than liquid water. According to the phase transition into ice, as water freezes a net expansion in volume of approximately 9% occurs. This net expansion in volume ultimately causes the bursting of plastic pipes. However, failure often occurs at a remote section of pipe through an indirect mechanism generated by the actual phase change expansion at the freeze point.

A freeze event in a plastic water piping system is a complex phenomenon. PVC and CPVC pipe filled with water, sealed and placed in a freezing environment typically will not crack. The pipes will expand to absorb the net volumetric expansion of ice. Since the volume in a pipe is proportional to the square of the diameter, a 9% volumetric expansion will result in a net diameter expansion of approximately 3%. Performing a linear elastic mechanical analysis for a thin-walled closed cylinder results in hoop and axial strain values of 3.5% and 1.75%, respectively [3]. Both PVC and CPVC have the ability to expand and withstand the resulting pressure generated by this change in volume. However, if localized freezing in a water piping system occurs and results in the formation of an ice plug the system will become closed. Any additional freezing that occurs downstream of the plug will create a pressure rise in the system. As ice continues to form, the pressure in the remaining water will rise until the plastic pipe fails.

Freezing of water in a pipe occurs in different stages. Figure 1 shows a schematic that describes the different stages of freezing. Initially, the pipe is exposed to a subfreezing temperature and the heat transfers from the water through the pipe wall and any insulation layers. This will reduce the temperature of the water. The water temperature can fall below the phase change temperature of 0°C and reach a supercooling stage without ice formation [1, 4, 5]. This supercooling stage can last for extensive periods of time and reach temperatures significantly below the phase change temperature. At some point during the supercooling stage, the water will initiate ice nucleation. At this moment, ice crystals in the dendritic form will immediately begin to grow. The dendritic ice formation is a quick event that ends when the water stabilizes at the phase change temperature. A solid ice structure then grows inward. The temperature during this period remains constant until all the water in the region has frozen. Because the dendritic ice nucleates on the walls of the pipe and grows inward it results in a strong plug that can withstand extremely high pressures. For a closed piping system further ice formation results in an extreme pressure rise that can generate failure. In some occasions variation in the growth of dendritic ice against the wall combined with the high downstream pressure may cause the plug to slide back lowering the system pressure.

Experimental

Based on the knowledge that bursting of water pipes does not occur directly from the physical pressure applied by the growing ice but by the excessive water pressure generated from ice formation, an experimental setup was developed where a pipe could be exposed to subfreezing temperatures to cause an adjacent pipe to fail. Figure 2 shows a schematic of the setup. The setup consisted of a 24 inch long, 1 inch diameter metal pipe. The pipe was insulated with a tapered layer that increased in thickness from the bottom upward. The insulation aided in controlling the location of the ice formation. The lower end of the metal pipe was capped to create a completely closed system. Therefore, the formation of a solid plug was not necessary to create a positive pressure. The metal pipe was inserted into a freezer maintained at a temperature of -25°C. The upper end of the metal pipe passed through an insulation layer and out of the freezer. On the exterior, the test section of plastic pipe was connected to the metal pipe using a metal transition fitting. The plastic pipe was also capped at the end. A pressure gauge was used to monitor system pressure and thermocouples were connected to the lower metal end cap and plastic pipe to monitor surface temperatures.

Three different pipes were used in the analysis. Two ½ inch PVC pipes manufactured by J-M Manufacturing in 2006 and 2009, respectively; and a ½ inch CPVC Flow Guard Gold® pipe manufactured by Charlotte Pipe and Foundry in 2009. The pipes were cut into 18 inch sections. Cementing of the fittings followed ASTM standard D 2855 and the sections were given adequate time to fully dry prior to testing. Tap water from a hot water source was used for the tests and the system was carefully filled to avoid air entrapment. Initial conditions from filling and capping produced a starting pressure between 100-500 psi (690-3450 kPa).

An alternative setup was also used where the plastic and metal pipes were both placed inside the freezer. In this case, the plastic pipe was heavily insulated while the metal pipe had minimal insulation. This setup permitted an analysis of the behavior of the plastic pipe at temperatures lower than room temperature (24°C).

Results and Discussion

Exposure of the metal pipe to subfreezing temperatures resulted in burst failures of the ½ inch CPVC and PVC pipes. A larger metal pipe was used because the plastic would expand during freezing, allowing a significant amount of volumetric expansion to take place prior to failure. In these experiments an ice plug was not required to create a pressure rise since the system is fully closed. However, the overall behavior of the ice formation and pressure rise were similar to that observed in a residential setting after an ice plug formed [1]; the primary difference being the time at which the pressure rise occurred. Figure 3 and Figure 4 show graphical results of pressure and temperature obtained for PVC and CPVC, respectively. The temperature of the plastic was monitored on the exterior surface to provide a reference value to relate to the stiffness of the material. Due to the reduced size of the experimental setup the temperature of the plastic pipe would also drop slightly over time. The curve “Temperature metal” refers to the surface temperature measured on the lower end cap of the metal pipe. As shown in the figures, a sudden rise in temperature occurs at the same time the pressure increases. This sudden rise results from the latent heat of fusion and generates dendritic ice (Figure 1). Since the temperature recorded is not the actual internal water temperature, but that of the exterior metal surface, the sudden rise in temperature does not stabilize at the phase transformation temperature. For a situation where an ice plug needs to form to create a closed system, the pressure will also rise rapidly. However, the pressure rise does not occur during the first ice formation but after a complete ice plug has formed.

Figures 5 and 6 show results obtained with a different experimental setup in which both the plastic and metal pipes where located inside the freezer. In this case, a thin insulation layer was placed over the upper portion of the metal pipe while the entire plastic pipe was covered with heavy insulation. The insulation layers prolonged the heat release from the plastic pipe section and allowed freezing to initiate on the lower end of the metal pipe. Similar to Figures 4 and 5, the pressure reached a maxima followed by yielding and permanent plastic deformation. This eventually led to catastrophic failure. PVC shows greater levels of expansion than CPVC prior to failure–an effect clearly noticeable when examining the fracture modes.

Table 1 shows a summary of results obtained for various trials. As shown, the CPVC undergoes a smaller pressure drop between the maxima and failure. This pressure drop is directly related to the amount of bulging or permanent deformation after yield. Figure 7 shows the fractured PVC and CPVC pipes. The temperature of the plastic pipe when maximum pressure occurred is shown in each image. The PVC pipe showed significant bulging in comparison to the CPVC. As expected, plastic pipes exposed to lower temperatures showed less ductility and greater stiffness. Consequently, these low temperature failures exhibited higher maximum pressure and the parts showed less bulging with significantly more crack propagations.

Figure 8 shows micrographs of the fracture surfaces. All fractures showed similar features to those observed in Figure 8. The initiation region of PVC shows a very rough surface that becomes smoother as the energy is released and the crack expands around the circumference. Crack bifurcations also show signs of high energy release and indications of rapid axial crack expansion. CPVC pipe had multiple initiation sites on the interior diameter and a rougher and jagged crack behavior on the interior wall.

The mode of failure of the pipes presented in this report was compared to pipes that failed in residential settings. The pipes that failed in residential settings show significantly larger crack propagations, more bifurcations, and less pipe bulging. Figure 9 shows an image of a freeze failure for a CPVC pipe in a residential setting. This pipe has significantly larger cracks and numerous bifurcations. In the laboratory setup, a similar fracture behavior was obtained on the PVC pipe manufactured in 2006, Figure 10. This fracture mode occurred only when the plastic pipe was also exposed to subfreezing temperature. The fracture shows no significant bulging and large crack expansions. In this case, the temperature of the pipe was sub-freezing and resulted in a higher material stiffness. However, the PVC pipe manufactured in 2009 did not show this fracture behavior when tested under the same subfreezing condition (refer to Figure 7, PVC subfreezing temperature burst). The 2009 pipe showed a bulging behavior at subfreezing temperatures comparable to what was observed for both pipes near room temperature.

Many different variables may have influenced the experimental results and caused differences from the typical failure modes observed in residential settings. Some of these variables may include material formulation, length of the piping, variation in temperature along the pipe, and aging effects. It is generally mentioned that failures in hot water lines are more prevalent than in cold water lines. The proposed theory to describe this effect is based on the fact that over heated water may have less air and greater amounts of dissolved minerals that can promote ice nucleation [7]. For plastic pipes, the aging effect of pipes exposed to higher temperatures may be another factor. Based on the results, further research is required to better understand the modes of failure observed in actual residential and commercial systems.

Conclusions

The freezing phenomena in PVC and CPVC piping systems was studied in this research. It was observed that the plastic materials possess excellent properties that can help prevent a freezing failure from occurring. The observed failures of PVC pipes showed significant material bulging prior to failure. Only one PVC pipe manufactured in 2006 exposed to sub-freezing temperatures showed a failure with less bulging and multiple long axial bifurcations. The CPVC showed failures with less bulging than the PVC and several initiation sites over the main axial crack. The mode of failure for most pipes tested in this research did not accurately replicate the modes of failure typically observed in residential and commercial settings. It is possible that variables such as material formulation, pipe length, and aging effects could have caused the difference in the results. Further testing should extend into considering these variables in order to accurately replicate the typical modes of failure observed in service.

References

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Keywords

PVC, CPVC, pipe, freezing, ice formation, burst, failure, fracture

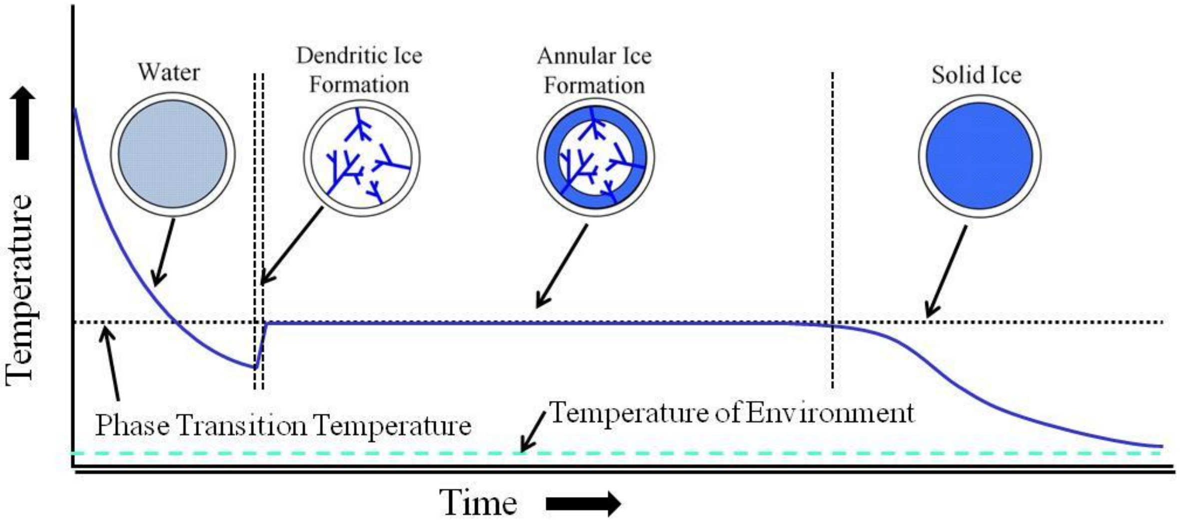

Figure 1: Schematic of ice formation in a piping system.

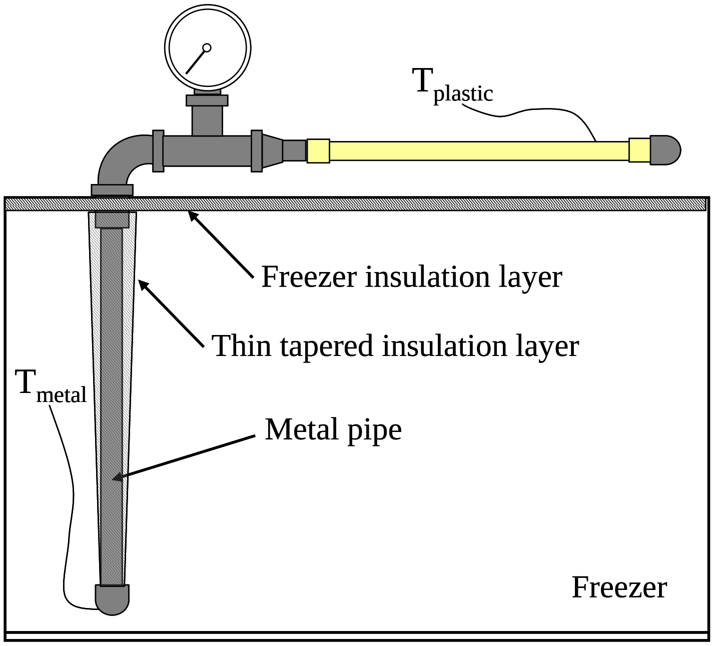

Figure 2: Generalized schematic for the experimental system setup.

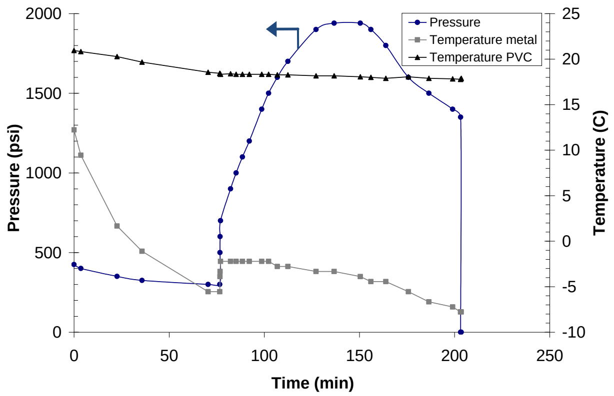

Figure 3: Pressure* and temperature during a freezing event for a ½ inch (12.5mm) PVC pipe.

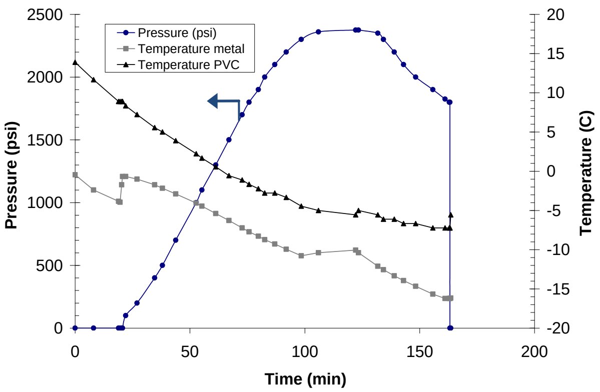

Figure 5: Pressure* and temperature during a freezing event for a ½ inch (12.5mm) PVC pipe insulated and exposed to subfreezing temperature.

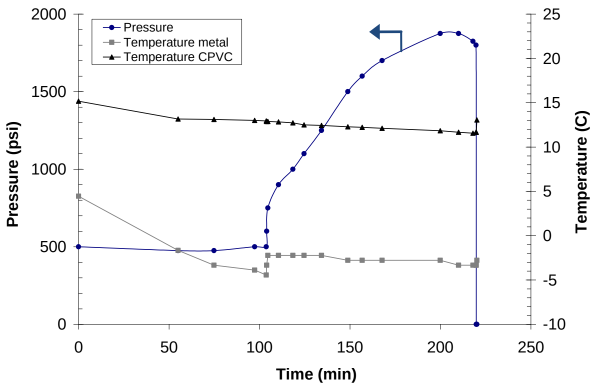

Figure 4: Pressure* and temperature during a freezing event for a ½ inch (12.5mm) CPVC pipe.

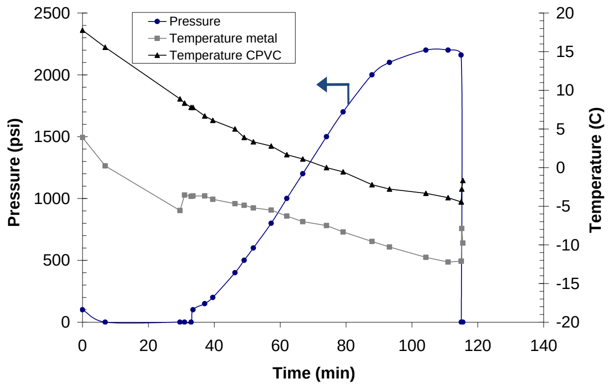

Figure 6: Pressure* and temperature during a freezing event for a ½ inch (12.5mm) CPVC pipe insulated and exposed to subfreezing temperature.

* The graphical representations shows US customary units in order directly relate to ASTM standards which serve as specifications for these piping systems. (1 psi = 6.89 kPa)

Table 1: Summary of several results obtained during PVC and CPVC freeze events.

Material	Trials	Temperature @ maxima [ºC]	Pressure max psig (MPa)	Temperature @ failure [ºC]	Pressure @ failure psig (MPa)	ΔP (P_{max}-P_{fail}) psig (MPa)
PVC 2009	1		1800 (12.41)		1250 (8.62)	550 (3.79)
	2	8.6	2150 (14.82)	7.9	1830 (12.62)	320 (2.20)
	3	-5.6	2375 (16.36)	-7.2	1800 (1241)	575 (3.96)
PVC 2006	1	18.1	1940 (13.38)	17.7	1350 (9.31)	590 (4.07)
	2	-6	2575 (17.75)	-2.9	2100 (14.48)	475 (3.28)
CPVC	1	11.8	1875 (12.93)	11.6	1800 (12.41)	75 (0.52)
	2	10.7	2000 (13.79)	10.1	1925 (13.27)	75 (0.52)
	3	-3.3	2200 (15.17)	-4.4	2160 (14.89)	40 (0.28)

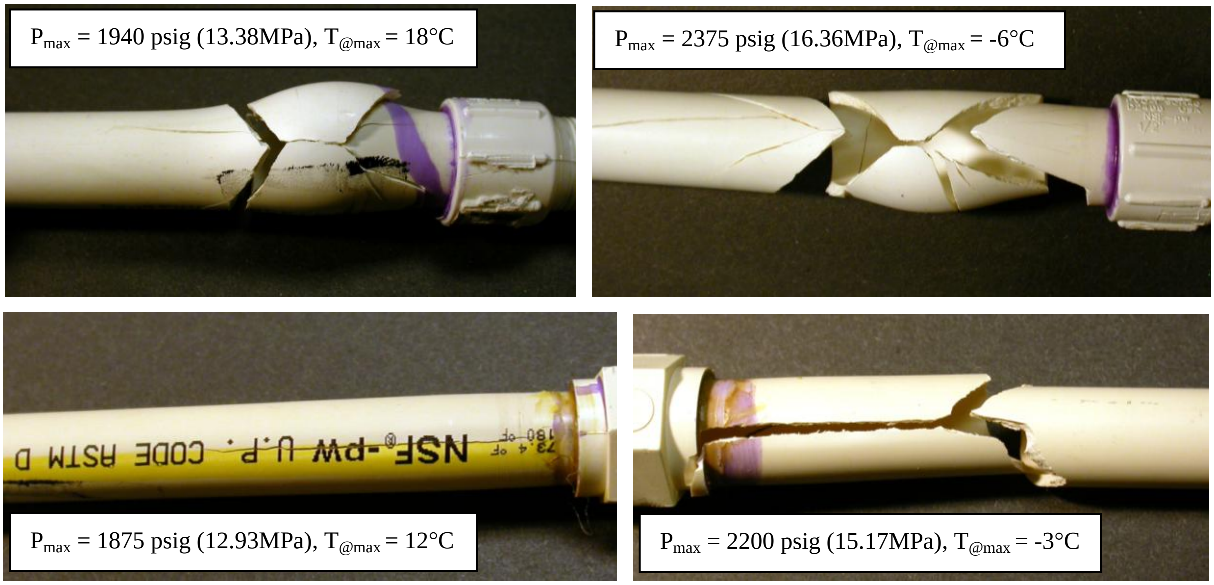

Figure 7: View of freezing failures for PVC and CPVC pipe sections (top: PVC, bottom: CPVC, left: pipes exposed to room temperature, right: pipes exposed to subfreezing temperature).

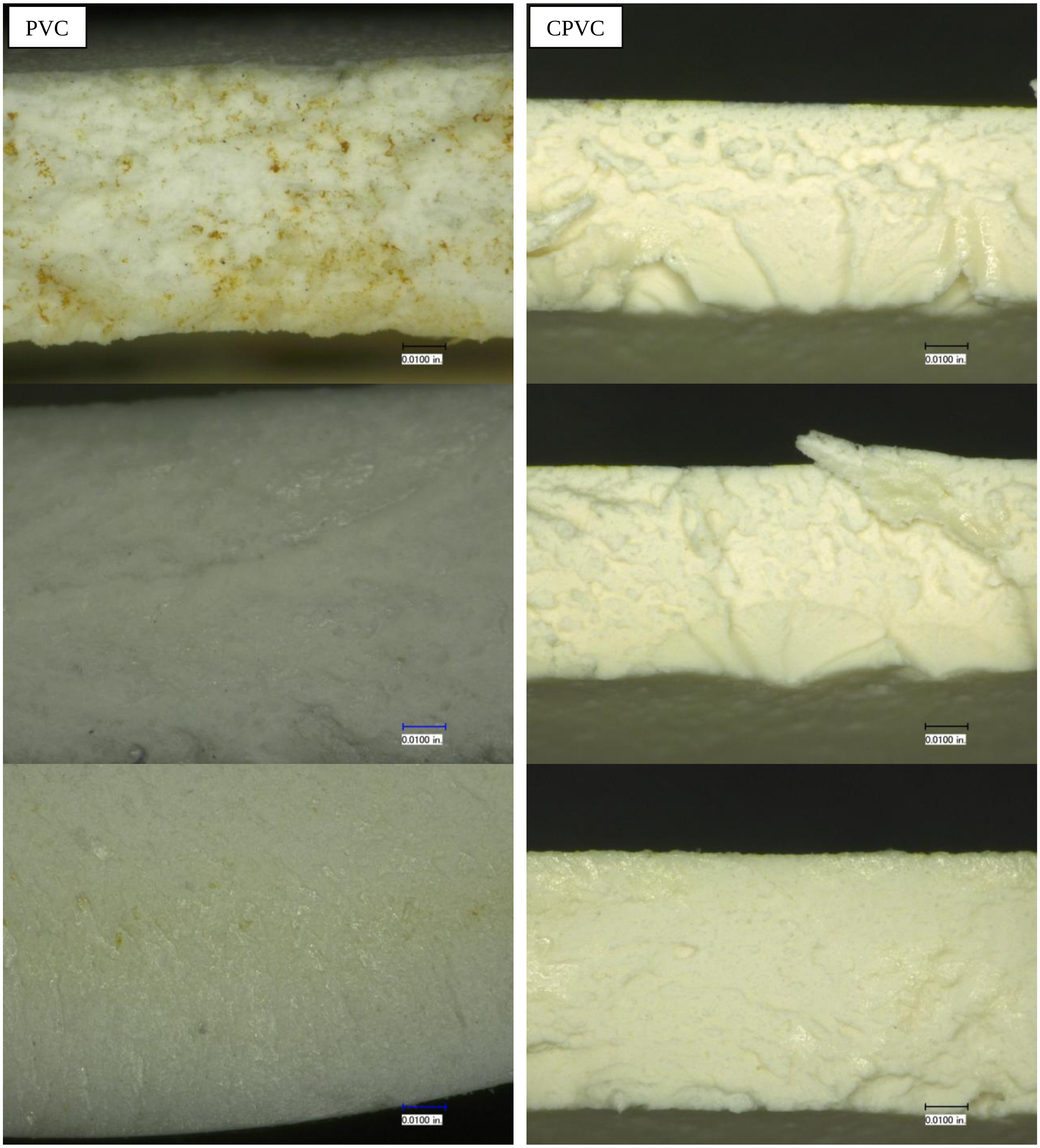

Figure 8: Micrographs of fracture surfaces for PVC and CPVC pipes.

Figure 9: View of a freezing failure of a CPVC pipe in a residential setting.

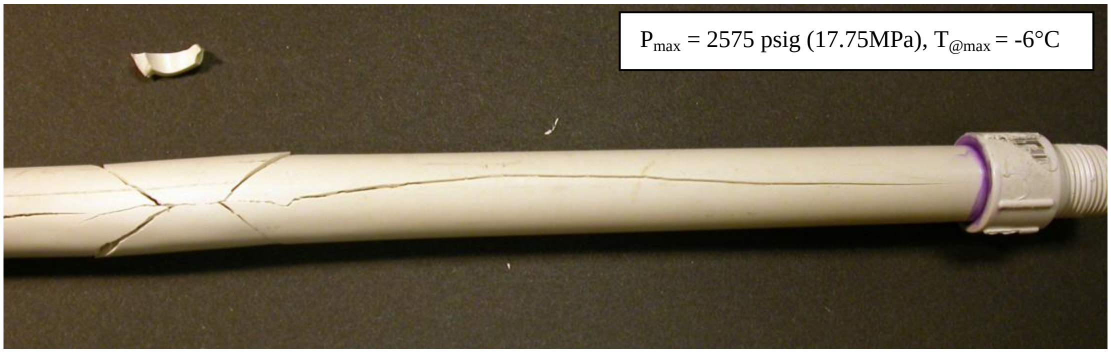

Figure 10: View of a freezing failure for a ½ inch (12.5mm) PVC pipe manufactured in 2006 exposed to subfreezing temperature.