An Investigation into Freezing and Bursting Water Pipes in Residential Construction

By

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PROPERTY LOSS REDUCTION

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#### 1. Introduction

Damage from burst residential water pipes because of freezing is widespread and costly. The Insurance Institute for Property Loss Reduction (IIPLR) estimates that the cost of insured freeze-related losses over the past decade exceeds \$4 billion.

The problem is particularly acute in the southern states where generally warm winter temperatures encourage builders to employ building practices that are inadequate to protect water pipes from occasional severe sub-freezing temperatures. Individual weather incidents leading to losses in the hundreds of millions of dollars have been documented in the Gulf coast states. Most recently, on December 22/23, 1989, an acute cold spell caused massive damage from Texas to Florida resulting in literally hundreds of thousands of insurance claims.

In 1994 and 1995, under sponsorship from the State Farm Fire and Casualty Company, the Building Research Council investigated the phenomena of freezing and bursting water pipes. The research focused on developing a sound understanding of the phenomena, with an eye toward identifying potential loss prevention strategies. The research was conducted in two phases:

The first phase of the research in 1994 featured laboratory tests of water pipes subjected to subfreezing temperatures. In Phase 1, water pipes were placed in a freezer apparatus, and the variables of pipe composition, pipe diameter, insulation level, freezer temperature, and water source were studied. This work provided a good understanding of the freezing and bursting phenomena, and led to initial recommendations of potential burst protection strategies.

At the heart of the second phase of the research were field tests of water pipes subjected to winter temperatures during the first three months of 1995. The field tests took place in a residential attic setup. A primary goal was to confirm, and hopefully expand upon, the basic knowledge of the pipe bursting

phenomena found during Phase 1 of the research. The tests were specifically designed to test air chambers and insulation levels as burst protection strategies.

This report provides a summary of both phases of the research. It is not intended as a detailed engineering report, but as a discussion of the research methods, findings, and opportunities for hazard mitigation.

The first part of the report describes the *Test Methods* for the Phase 1 and Phase 2 research projects.

The *Overview* section consists of four parts. Initially it presents the graphic form of the data from Phase 1. An overview of the freezing process is then provided based on the Phase 1 research data. The graphic form of the Phase 2 data is then presented, incorporating temperature profiles and pressure readings. Finally, an overview of the bursting process is provided based on the Phase 2 data. In total, the Overview section offers a less detailed summary of the larger research report.

The *Findings* section presents the research results in more detail. A section on *Thermal* effects looks at the variables affecting heat loss and freezing, and discusses the roles of convective heat loss and conduction from the interior space. A section on *Hydraulic Pressure and Bursting* looks at the findings relating to the excessive pressures associated with bursting.

The report concludes with a discussion of the **Loss Prevention Strategies** and opportunities for **Mitigation Efforts**. These strategies are viewed through the opportunities available in building practices, public education, and the pursuit of potential technical developments.

In summary:

Pipe bursting due to freezing is a severe problem in the US. Insurance company estimates show that more than \$4 billion has been spent in repairs due to pipe bursting in the last ten years. The problem is more severe in the

southern US than in the northern US, where more effective and consistent measures are taken for plumbing pipe protection.

This research shows how pipe bursts occur. A commonly held view, that ice growth simply pushes against pipe walls, is not correct. Pipe bursting occurs when 1) freezing temperatures create ice blockages in water pipes, then 2) further ice growth applies dangerously high pressures to a confined water volume. This understanding of the rupture mechanism has been confirmed in two years of laboratory and field studies.

**Pipe bursting is preventable.** As always, placement of water pipes in conditioned, heated spaces remains the principal strategy for preventing bursting. Because pipe bursting is shown to be due to elevated water pressure, several other prevention approaches can be taken:

- pipe insulation, which has benefits extending far beyond the benefit of delaying the onset of freezing temperatures,
- air chambers, which, when sized and placed appropriately, can accommodate elevated fluid pressures due to freezing

- · pressure relief fixtures,
- · changes to building codes,
- · weather alerts, and
- public education, consisting of guidelines for residents and for the trades.

### 2. Test Methods

#### 2.1 Phase 1

An investigation into the pipe freezing and bursting phenomena was done in a series of tests conducted inside a commercial freezer. The freezer was an upright model, with a triple insulated glass door that allowed for viewing of the pipes during testing. *Figure 1* provides a graphic view of the test setup.

Water lines were brought to the freezer from overhead, where they branched into four separate lines. Two water lines entered the freezer from each side, and a total of four pipes could be installed in the freezer per test. Where the water lines entered the freezer, the pipe material changed from copper to 3/4" steel. The steel pipes penetrated 4 inches into the interior of the freezer, where they were insulated and ended in a threaded

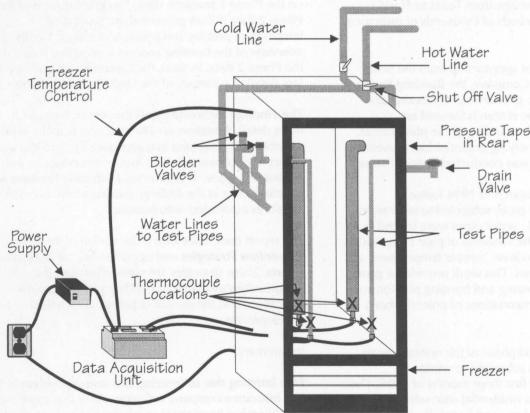


Figure 1. Freezer test apparatus.

female elbow. The test pipes were then easily installed and replaced on the four lines with a male threaded connector. The purpose of the 4" steel pipe and elbow was twofold: to prevent a burst failure at this point in the apparatus, and to provide a "quick-change" capability in the testing.

Data were recorded on a Campbell Scientific CR10 data acquisition unit. Temperatures were sampled with type T thermocouples. Each thermocouple had an identical 6' wire length. A Campbell Scientific 10TCRT thermistor served as the thermocouple reference at the datalogger. Data were sampled on a 30-second interval, with five minute averages recorded. Some later tests employed one and two minute recording intervals.

The thermostat preinstalled in the freezer to control interior temperature was disconnected and replaced with a solid-state relay connected to the datalogging unit. Temperature control in the tests was achieved through monitoring the freezer temperature on a 30-second interval, and sending a 5-volt signal to the

relay from the datalogger. This arrangement allowed for a tight ambient temperature range during the tests. A fan installed in the ceiling of the freezer operated continually during the tests to mix the interior air, and achieve an even vertical temperature distribution throughout the freezer.

For the Phase 1 research, thermocouples were placed directly in the water of the test pipes. *Figure 2* shows the assembly used to achieve this installation.

A rubber stopper was sized to fit a threaded connection on the end of the test pipe. A small hole was drilled through the stopper and the thermocouple wire forced through the hole. The end of the thermocouple protruded 6" into the pipe. A silicon sealant was applied to each end of the stopper around the wire and allowed to cure. The thermocouple wire was also threaded through a larger hole in a plastic end cap. Once the sealant was cured, the stopper was installed in the pipe, and the end cap threaded onto the pipe connection, which served to drive the stopper firmly into the end of

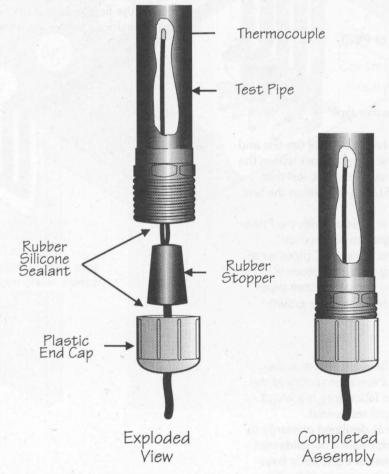


Figure 2. Thermocouple mounting in a water pipe, Phase 1 research.

the pipe. Later in the research, vertical temperature profiles in a pipe were obtained with an identical assembly featuring four thermocouple wires piercing the stopper.

As the importance of hydraulic pressure was recognized in the Phase 1 research, water pressures were recorded during later tests. Bourdon tube pressure transmitters were installed in the water lines at the back of the freezer, one transmitter for each pair of test pipes. Pressures were sampled and recorded on the same intervals as the temperature data. The pressure transmitters were rated up to 300 psi (pounds per square inch), well short of the pressures (4000 psi and up) associated with bursting water pipes. During pressure tests, the tests were monitored to allow for the release of pressure by opening the main water valve to protect the transmitters. In this report, the data associated with the full range of hydraulic pressures associated with bursting will be from the Phase 2 research.

The Phase 1 tests examined the effect upon the freezing process of five variables:

- 1. Design temperature,
- 2. Pipe composition, (copper or PVC),
- 3. Insulation level,
- 4. Pipe diameter (1/2" or 3/4")
- 5. Water source (cold or hot water tap).

Each test was identified by the Julian Date of the test and a postscript number showing the pipe number within the test. For instance, "JD145.P2" represents the test that took place on day 145 (May 25), pipe #2 within the test.

Two additional activities were associated with the Phase 1 freezer tests. Both were designed to observe ice formation. On several occasions, clear PVC pipes were installed in the freezer, allowing for direct observation of ice growth. On other occasions, partially frozen pipes were cut into sections in 4" intervals and ice growth documented.

### 2.2 Phase 2

The Phase 2 research featured field tests done at the Building Research Laboratory, a research facility of the Building Research Council. The laboratory is a wood frame structure employing typical residential construction techniques, and was designed primarily to study thermal and moisture performance of residential structures. The laboratory consists of eight study bays and two control bays, each bay measuring 8' by 20'. Through an arrangement with the sponsor of the

laboratory, CertainTeed Corporation, one study bay was used for the Phase 2 pipe freezing research. *Figure 3* provides a perspective view of the basic setup of the pipe freezing field tests.

The laboratory has water service to supply the humidifiers installed in each study bay. For the purposes of the field tests, a water line was run through the crawl space, and into bay 1 through the floor by the west wall. At this point the water line split into five separate lines 4" on center, each line entering the attic through the ceiling by the west wall. A total of five pipe configurations could be tested anytime. The water lines crossed the attic to the east end of bay 1 before reentering the room. Unions were provided at each end of the straight run through the attic to allow for replacing the pipes in the attic as required by burst pipe events. The field tests employed both 1/2" and 3/4" Type M copper pipe. The attic of bay 1 is of truss construction, vented with soffit and ridge vents, with a nominal 9 1/2" of fiberglass batt insulation installed between the bottom chords of the trusses. The water lines were installed above this existing building insulation. With this placement, the field tests featured water pipes that were in a very hazardous winter environment.

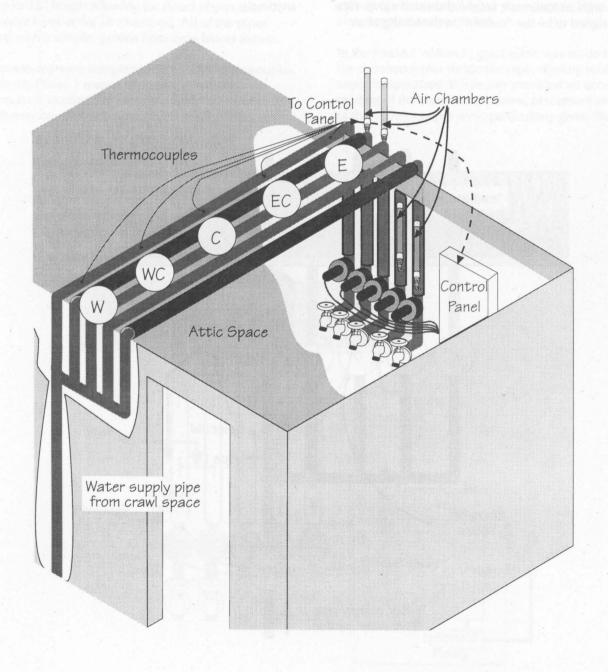


Figure 3. Layout of the Phase 2 pipe freezing field tests in study bay 1 of the Building Research Laboratory.

Figure 4 provides an elevation of the pipe layout along the west wall of bay 1.

A shut-off valve was installed on the main supply pipe entering from the crawl space. After dividing into five separate lines, each line was provided a separate shut-off valve on the west wall. In this way, each water line could be recharged individually during the field tests. The northernmost line (Pipe 1) in the array was provided with an automatic solenoid shut-off valve. Pipe 1 was designed to be the "control" in the testing of air

chambers, and was the only pipe that was not protected by an air chamber. Therefore, it was expected that Pipe 1 would be the most vulnerable to bursting, and that burst incidents with Pipe 1 were very likely over the winter. To forestall flooding of the research laboratory, the solenoid valve was connected to a relay from the test datalogger, which was programmed to examine pipe pressures every 30 seconds, and to shut off the supply to Pipe 1 if there was a dramatic pressure loss (burst pipe) anytime.

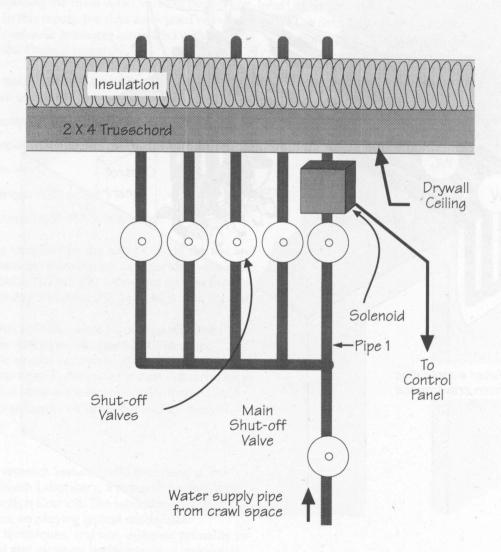


Figure 4. Elevation of west wall, Phase 2 field tests.

Figure 5 provides an elevation view of the east wall of bay 1, including the control panel.

Pipe 2 and Pipe 3 (from the north wall) were outfitted with air chambers located in the attic. Pipe 4 and Pipe 5 were outfitted with air chambers inside the room of bay 1. The air chambers were fabricated at the BRC from 3/4" clear PVC pipe and standard white PVC fittings. Each clear PVC air chamber was graduated and marked along its 12" length allowing for direct observation of the water level in the air chambers. All of the pipes ended with a simple, garden hose-type faucet fixture.

Temperatures were sampled with type T thermocouples. While the Phase 1 research generally featured one temperature reading per pipe, the field tests employed five thermocouples per pipe. The thermocouples were

evenly spaced along the length of the pipe in the attic, from west to east. Each thermocouple was given a specific designation by pipe and placement on the pipe; for example: the thermocouples on Pipe 1 were designated west to east as 1W, 1WC, 1C, 1EC, and 1E (see Figure 3). Temperature profiles along the length of the pipes were vital components of the Phase 2 research. Each thermocouple was fabricated with an identical wire length despite placement. Outdoor temperature, attic temperature, and bay 1 room temperature were also sampled and recorded.

In the Phase 1 research, great effort was made to place the thermocouples inside the pipe, directly recording water temperature. While this provided an accurate reading of the water temperature, placement and sealing of the thermocouple wire, particularly given elevated

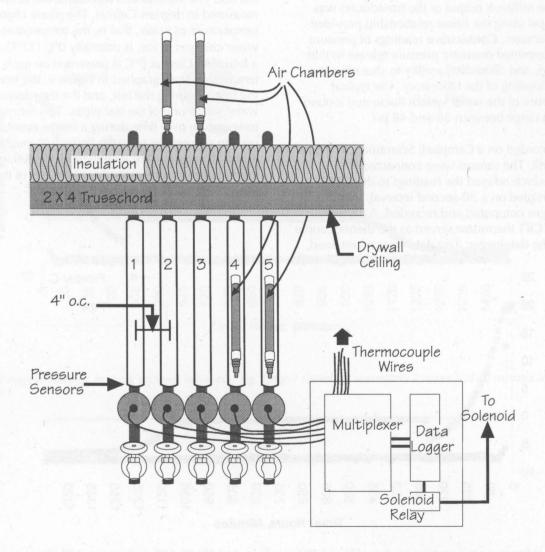


Figure 5. Elevation of east wall, Phase 2 field tests.

water pressures, was difficult, leading to leaks and subsequent downtime in the tests. For Phase 2 research, alternate methods of thermocouple installation were explored. Trials using the Phase 1 freezer apparatus showed that the thermocouples could be placed directly on copper pipes and covered with a small patch of insulation. Given the great conductivity of copper, this method of thermocouple placement proved sufficient for the Phase 2 field tests and offered precise temperature readings. The distinct temperature progression relating to phase change within water pipes was always clear.

Hydraulic pressure in each pipe was measured with Setra 206 pressure transducers. As with temperatures, the pressures were sampled every 30 seconds, and five minute averages computed and recorded. The pressure transducers have a working range from zero to 5000 pounds per square inch (psi). For the data presented in this report, the millivolt output of the transducers was converted to psi using the linear relationship provided by the manufacturer. Consecutive readings of pressure on Pipe 1 determined dramatic pressure release in that pipe (bursting), and controlled a relay to shut off water and prevent flooding of the laboratory. The typical ambient pressure of the water system fluctuated around 42 psi, with a range between 36 and 48 psi.

Data were recorded on a Campbell Scientific CR10 data acquisition unit. The sensors were connected to a multiplexer, which relayed the readings to the CR10. Data were sampled on a 30-second interval, with five minute averages computed and recorded. A Campbell Scientific 10TCRT thermistor served as the thermocouple reference at the datalogger. Test data were maintained

on spreadsheets, identified by the Julian Date (JD) of the test.

#### 3. Overview

This section of the report presents an overview of the freezing and bursting process, and introduces the graphs that illustrate that process.

3.1 Phase 1 Data Presentation
The graph in *Figure 6* displays a typical freeze event inside a water pipe.

Figure 6 charts data from the tests done as part of Phase 1 of the research, and shows the water temperature inside a pipe over time. The horizontal axis represents the time, in hours and minutes, since the start of the test. For example, "950" is nine hours and 50 minutes into the test. The vertical axis represents the temperature measured in degrees Celsius. The phase change temperature of water, that is, the temperature at which water changes to ice, is normally 0°C (32°F). Therefore, a horizontal line at 0°C is presented on each graph. Two temperatures are graphed in Figure 6: the temperature of the freezer during the test, and the temperature of the water inside one of the test pipes. This format, graphing temperature over time during a freeze event, will be used to present the research findings throughout the report. The graphs are identified by the Julian Date of the test (JD139 represents the 139th day of the year, or May 19th).

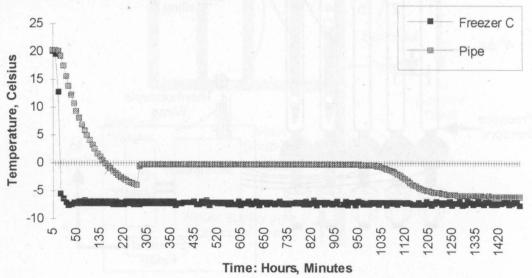


Figure 6. Typical freeze event in water pipe. From Phase 1 BRC database. Test JD139, 1/2" copper pipe, 1/2" fiberglass insulation, cold water tap, -6.67°C freezer (20°F).

# 3.2 The Freezing Process Freeze events within a water pipe can be subdivided into four distinct stages:

- 1. initial cooling through supercooling,
- 2. dendritic ice formation,
- 3. annular ice formation, and
- 4. final cooling to ambient temperature.

Using the test displayed above as an example, *Figure 7* illustrates the first stage of the freezing process.

When a water pipe is exposed to subfreezing temperatures, heat is transferred from the water, through

the pipe wall and any insulation layers, to the subfreezing air. The temperature of the water begins to fall in a steep decline. This is *Stage 1* of the freezing process. Remarkably, the water in the pipe does not immediately begin to freeze when it reaches the phase change temperature of 0°C, but continues to fall and approach the temperature of the surrounding air. This process is known as *supercooling*. It is possible for water in a pipe to supercool for a considerable length of time before any ice forms. As the pipe cross section in Figure 7 shows there is no ice formation during Stage 1, the pipe contains only water. The temperature at which ice begins to form is known as the *ice nucleation temperature*. The term *nucleation* implies a starting point, or a nucleus, for ice formation.

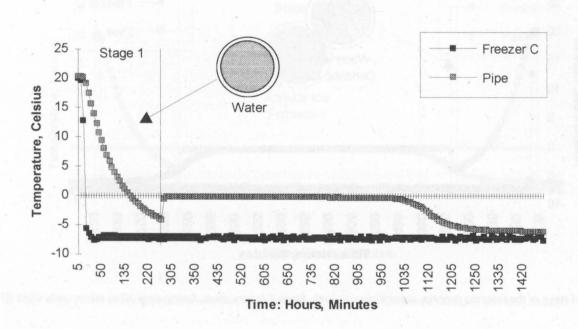


Figure 7. First stage of the pipe freezing process, initial cooling. Stage 1 lasted approximately 2 hours and 20 minutes in this test. Data JD139, Phase 1.

Figure 8 illustrates the second stage of the freezing process.

At some point below 0°C, at the end of the first stage of the freezing process, ice nucleation occurs and ice crystals begin to form in the supercooled water. This initiates *Stage 2*, the formation of dendritic ice. Dendritic ice is made up of thin, plate-like, feathery crystals interspersed with the water. As the dendritic ice forms, the heat of fusion from the ice formation is absorbed by the supercooled water, raising the water's temperature. When the water has returned to the phase change temperature, 0°C, the formation of dendritic ice is complete. It follows that the extent of dendritic ice

formation is a function of the amount of supercooling. The formation of dendritic ice occurs quickly, and appears on the graphs as a sudden rise in temperature. In the Phase 1 tests with clear PVC pipes, dendritic ice formation was observed to be completed between 30 seconds and 60 seconds in a 34-inch long pipe.

In the late 1970's, R.R.Gilpin did detailed studies of ice formation in water pipes focusing on dendritic ice. Gilpin showed that the volume fraction of ice was around 2 percent for shallow supercooling above 2.5°C, and up to 6 percent for longer supercooling in the 4° to 5°C range. With slight supercooling the dendritic ice formation is confined to the walls of the pipe. With deep

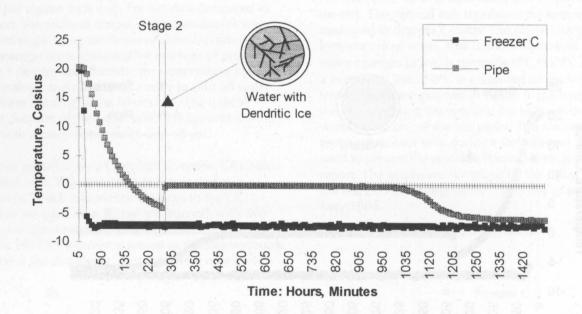


Figure 8. Second stage of the freezing process, dendritic ice growth. Stage 2 is very short, lasting only 30 to 60 seconds. Data JD139, Phase 1.

supercooling the dendritic ice can form a matrix throughout the diameter of the pipe. Gilpin showed that such a dendritic ice matrix can lead to a flow blockage at typical residential water pressures.

Only after the dendritic ice growth is complete can the third stage of the freezing process, the growth of annular ice, begin. *Figure 9* presents the third stage of the freezing process.

When the water in a pipe has completed dendritic ice formation and returned to 0°C, *Stage 3*, the growth of

annular ice begins. Annular ice is the familiar, dense form of ice, and it grows from the outside walls of the pipe inward. It is during annular ice growth that the remaining 94 percent to 98 percent of the water turns to ice. As seen in the pipe cross section in Figure 9, the existing dendritic ice is incorporated into the denser annular ice. A section of pipe that is freezing will remain at phase change temperature until all of the water has turned to ice. Graphically, Stage 3 appears as a steady horizontal line at or near 0°C.

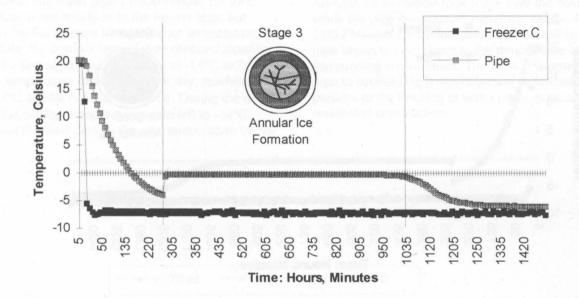


Figure 9. Third stage of the freezing process, annular ice formation. Stage 3 lasted around 8 hours in this test. Data JD139, Phase 1.

Figure 10 illustrates the fourth and final stage of the freezing process.

When all of the water in a pipe has frozen, the pipe cools below phase change temperature and eventually approaches the temperature of its environment. This is *Stage 4* of the freezing process. (For the purposes of this report, the temperature of the pipe's environment is called the *ambient* temperature.) When the water pipe has reached the same temperature as the surrounding air the freezing process is complete. In stage four the pipe

no longer contains water, but is blocked completely by a solid annulus of ice. The water in a pipe will remain in equilibrium with its environment until the temperature of the ambient air rises above the phase change temperature. If this occurs, then the freezing process reverses, and the pipe goes through much the same process, less the dendritic ice growth stage. Again, there is an extensive phase change stage as the pipe thaws and the ice reverts to liquid water.

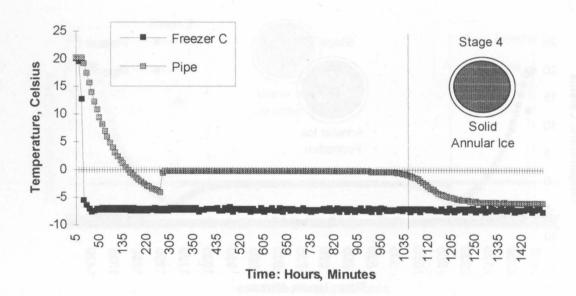


Figure 10. Fourth stage of the freezing process, cooling to ambient temperature. Data JD139, Phase 1.

# 3.3 Phase 2 Data Presentation Figure 11 presents an example of data from the Phase 2 field tests.

The graphs of the Phase 2 research are of the same form as the Phase 1 results. The horizontal axis again represents time, though in Phase 2 "time" is actual time of day. Figure 11 presents data from February 5 (JD36), starting at midnight (12:00 AM) and ending at 10:00 PM the following night. The vertical axis again represents temperature in degrees Celsius.

Three temperatures are being tracked over time in Figure 11: (1) outdoor temperature (TCod), (2) attic temperature (Attic C), and (3) the temperature at the center of the pipe (3C). The principal difference compared to the Phase 1 tests is the nature of the water pipe's environment. The water pipe's environment, the attic temperature, is not steady as in the freezer tests, but subject to the fluctuations in the outdoor temperature. On this date, the outdoor temperature dropped steadily through the first night, reaching a low of -14°C at 7:30 AM. The temperature rose through the day, reaching a high of -9°C at 3:00 PM that afternoon. During the next evening the outdoor temperature again fell to -14°C. Throughout this time period, the attic temperature tracks

the outdoor temperature closely, between 1.5° and 3.5° warmer. This was typical of the field tests, and shows the severity of the conditions that the field tests produced. The water pipes were installed outside the building insulation, and thus the temperature of the water pipes' environment was much closer to outside conditions than indoor conditions.

While the Phase 2 field tests represented different environmental conditions from Phase 1, the water pipe's response to subfreezing temperatures is strikingly familiar. The temperature of the pipe during this freeze event displays the same four phases shown in Phase 1: supercooling, dendritic ice formation, annular ice formation, and final cooling. On this date, the pipe supercooled to -6°C at 2:40 AM, and then guickly returned to the phase change temperature of 0°C. Annular ice formation took place over the next 11 hours while the pipe temperature remained steady. At around 2:00 PM, annular ice formation was complete, and the pipe began to cool down to the temperature of the surrounding environment. The basic response of a water pipe to subfreezing temperatures as described above pertains to the freezing of water pipes in actual residential construction.

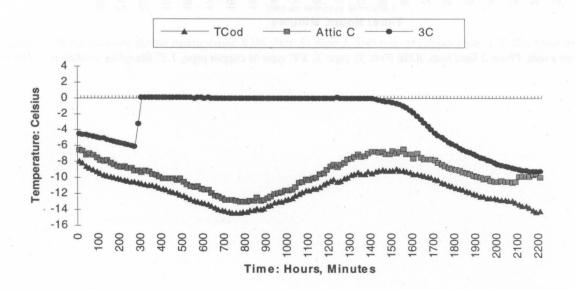


Figure 11. Typical freeze event, Phase 2 field tests. JD36 (Feb. 5), pipe 3. 3/4" type M copper pipe, 1.5" fiberglass insulation.

As described in the section, *Test Methods*, temperatures were sampled in five locations along the length of each water pipe. *Figure 12* displays this same freeze event as Figure 11, but tracking all five temperatures.

By looking at temperatures along the length of the pipe, one can establish a more detailed understanding of the freeze event. During supercooling, the center of the pipe (3C) is coldest. To the east and west of center (3EC & 3WC), the pipe is about 1°C warmer than the center.

The ends of the pipe (3E & 3W) are between 4° and 5° C warmer. Once dendritic ice forms at 2:40 AM, all sections of the pipe rise to the phase change temperature of 0°C, and remain at that temperature during annular ice formation. Ice formation is complete throughout the center of the pipe around 2:00 PM, as all three locations (3C, 3WC, and 3EC) begin the descent to the attic temperature at about the same time. Ice growth continues toward the ends of the pipe (3W & 3E), which finally finish freezing about 6 hours later, around 8:00

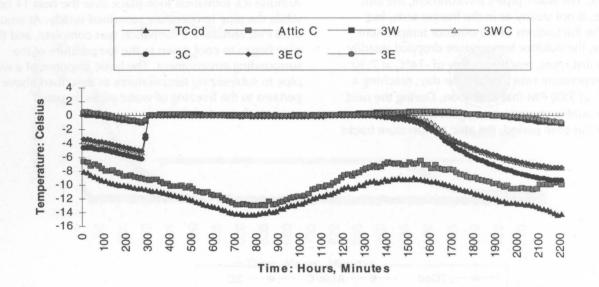


Figure 12. Typical freeze event, Phase 2 field tests. JD36 (Feb. 5), pipe 3. 3/4" type M copper pipe, 1.5" fiberglass insulation.

PM. Once the pipe is completely frozen, only the very center of the pipe (3C) reaches the attic temperature. Again, just east and west of the center the pipe (3WC & 3EC) temperatures stabilize at 2°C warmer, and the very ends of the pipe (3W & 3E) stabilize at 6°C warmer. This graph clearly shows a water pipe freezing from the center of the pipe outward toward the ends.

There is another piece of data available from the Phase 2 field tests: water pressure within the pipe. Unlike the Phase 1 research, Phase 2 tests provide full range pressure measurements throughout each test. *Figure 13* 

shows the pressure during this same freeze event example.

In this graph, the vertical axis is now pressure, measured in lbs/in² (psi). The pressure throughout most of the freeze event remains at the starting pressure of the water system, around 40 psi. The pressure starts to rise at 3:20 PM, ultimately climbing to around 150 psi. It is possible to put all of the data on one chart, and examine both

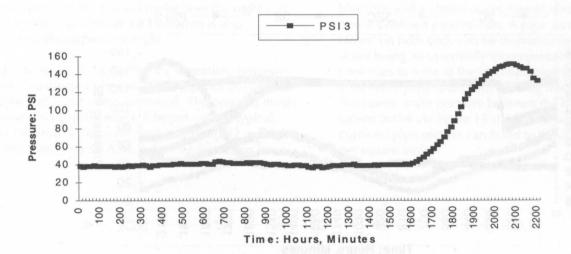


Figure 13. Water pressure during freeze event. JD36 (Feb. 5), pipe 3. 3/4" type M copper pipe, 1.5" fiberglass insulation, air chamber in attic.

pressure and temperatures at the same time. *Figure 14* combines this data, and puts a second vertical axis for pressure on the right side of the graph.

Figure 14 offers a full representation of the data available from the Phase 2 field tests. An understanding of freezing and bursting in water pipes is derived from examining the interplay between temperatures and pressures during pipe freezing events. The graphs contained in this report will be in this format, and will

use some or all of the available data for a particular freeze event to present the research findings.

# 3.4 The Bursting Process

Water is denser than ice. At 0°C, pure water has a density of 62.42 lb./cubic foot, while the density of ice is 57.5 lb./cubic foot. These relative densities imply that as water freezes to ice, it expands by about 8 percent by volume. It is commonly understood that it is this volumetric expansion from freezing that ultimately leads

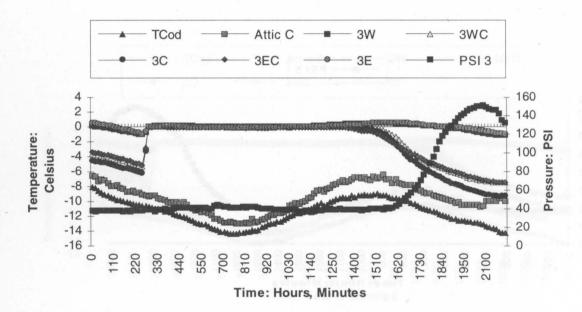


Figure 14. Typical freeze event with temperatures and water pressure, Phase 2 field tests. JD36 (Feb. 5), pipe3. 3/4" type M copper pipe, 1.5" fiberglass insulation, air chamber in attic.

to bursting of water pipes. This common understanding, however, is not a complete understanding. *Figure 15* illustrates the data from a burst pipe event from the Phase 2 attic field tests.

Figure 15 looks at test pipe 1 from 8:00 PM on February 13 until Noon on February 14. Four temperatures are graphed (Outdoor, 3W, 3C, &3E) along with the water pressure.

From our overview of the freezing process, the temperature graph of the water pipe looks familiar. As the temperature fell on the evening of the 13th, the water temperature in the pipe fell below freezing around 11:30 P.M., and entered the supercooling stage (Stage 1). Indeed, the water supercooled for well over an hour, finally entering Stage 2, dendritic ice formation, around 1:00 A.M. As we have seen, annular ice formation (Stage 3) begins immediately afterwards. As the outdoor temperature continues to fall throughout the night and into the morning, annular ice formation is also continuous throughout the night.

The pressure graph during this ice formation, however, shows no increased pressure in the pipe for the first two and one half hours of ice formation. The pressure inside the pipe stays exactly where it began - at the typical water pressure of the water system (around 42 psi at the test site). Only at 3:30 A.M., when ice formation is

complete at the west end of the pipe (1W), does the pressure within the pipe start to grow. At that point it grows dramatically, ultimately leading to a burst event.

This shows the central, and often least understood, fact about burst water pipes: freezing water pipes do not burst directly from physical pressure applied by growing ice, but from excessive water pressure. Before a complete ice blockage, the fact that water is freezing within a pipe does not, by itself, endanger the pipe. When a pipe is still open to the water system upstream, ice growth exerts no pressure on the pipe because the volumetric expansion caused by freezing is absorbed by the larger water system. A pipe that is open on one end cannot be pressurized, and thus will not burst.

Once ice growth forms a complete blockage in a water pipe the situation changes dramatically. The downstream portion of the pipe, between the ice blockage and a closed outlet (faucet, shower, etc.) is now a confined pipe section. A pipe section that is closed on both ends can be dramatically pressurized, water being an essentially incompressible fluid. If ice continues to form in the confined pipe section, the volumetric expansion from freezing results in rapidly increasing water pressure between the blockage and the closed outlet. As figure 15 shows, the water pressure in a confined pipe section can build to thousands of pounds per square inch.

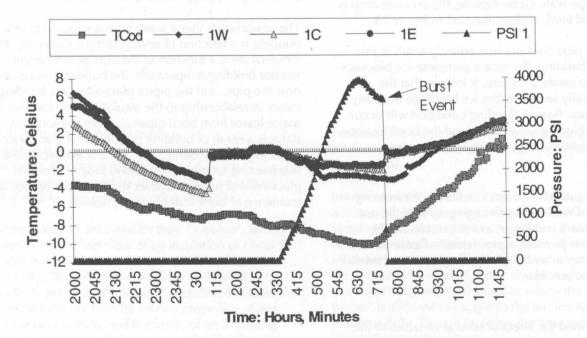


Figure 15. Burst pipe event. JD 44 & JD45. 3/4" Type M copper, no insulation, no air chamber.

It is at these dramatically elevated pressures that burst pipes and other failures occur. Because the entire pipe section downstream of the ice blockage experiences the same elevated pressures, the failure can occur at any point in the system, and the weakest link will be found. Besides pipes themselves, failures involving solder joints, elbows, and fixtures themselves can also occur. Ironically, because burst events arise from water pressure and not from the ice itself, failures can occur in a part of the pipe section where almost no ice has formed, even within the heated space of a building.

In the case of the burst event in Figure 15, it was the copper pipe that burst. Upon blockage, the pressure builds rapidly and consistently. Through this initial pressure rise to the apex of the pressure curve, the pipe is still "elastic". Whatever deformation resulting from the increased pressure, the pipe retains the capability of returning to its initial shape. A major change occurs at the point when the pressure reaches its maximum 4000 psi. At this point, the pipe is said to go "plastic". Deformation because of the excessive pressure is permanent once the pipe material reaches its elastic limit and goes plastic. Examination of a burst pipe shows that a sizable "bulge" in the pipe wall appears at the point of the rupture. The pressure drop following the maximum pressure represents the creation of this deformation in the pipe: the pipe is stretching in response to the pressure, resulting in a thinner pipe wall at the location of the deformation. Once the bulge is created, the pipe is subject to rupture at the location of the thinner pipe wall. Upon rupture, the pressure drop is immediate and total, as demonstrated in Figure 15.

A burst water pipe does not immediately result in the flooding of a building. Because a complete ice blockage is necessary to create a rupture, it follows that the rupture is initially sealed by the ice blockage from any substantial water flow. A flooding condition will occur when the ice blockage thaws out, and the burst location is back in communication with the water system.

# 4. Findings

The overview provides an introduction to the freezing and bursting of water pipes through graphs of the test data from Phase 1 and Phase 2 of the research. The *Findings* section provides a more detailed examination of this phenomena, and illustrates the impacts of several variables to the process.

#### 4.1 Thermal

Phase 1 examined the effect of several variables to the thermal performance of water pipe assemblies.

# 4.1.1 Ambient Temperature

During the Phase 1 research in the controlled environment or the freezer, tests were done at three freezer temperatures: 20°F (-6.67°C), 10°F (-12.22°C), and 0°F (-17.78°C). The tests produced many matched triplets to study this effect, and the results were similar and consistent. Typical freezing response to ambient temperature is shown in *Figure 16*. Again, "ambient temperature" is the temperature of the air that constitutes a water pipe's environment. In the tests, ambient temperature is the temperature inside the freezer during a test.

Figure 16 illustrates tests on three identical pipes, the only difference being the freezer temperature during the test. The effect of the ambient temperature on Stage 1 of the freezing process, the descent from room temperature through supercooling, is small - about 35 minutes over the temperature range. The effect on the formation of annular ice and the complete blockage of the pipe (Stage 3), however, is significant. At 20°F (-6.67°C), the pipe formed a blockage in 11-1/2 hours. Subjected to 10°F (-12.22°C), the same pipe formed a blockage in 6 1/2 hours, a difference of five hours. At the coldest temperature of 0°F (-17.78°C), time to blockage is seen to be around 4-3/4 hours. As we have seen, the formation of a complete ice blockage is the critical point in a pipe bursting event. The temperature of a water pipe's environment is a principal factor in determining the time it takes to form a complete ice blockage, and thus set up the potential for a burst event.

The temperature that a water pipe is exposed to in a building is a function of several factors. Generally, that temperature is a function of the outside temperature, the interior building temperature, the building insulation near the pipe, and the pipe's placement in a building cavity in relationship to the insulation. The fact that the major losses from burst pipes are from the southern states is a result of building practices that place water pipes in jeopardy during rare, but occasional, severe sub-freezing temperatures. Sound judgment on the placement of pipes in houses would greatly reduce the incidence of burst water pipes in houses.

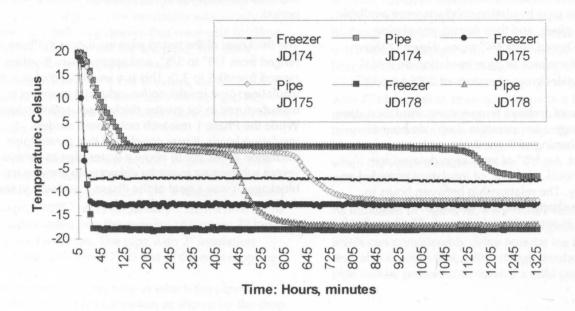


Figure 16. Effect of ambient temperature on freezing. Tests # JD174 , JD175, and JD178. Each test is 1/2" PVC pipe, cold water tap, 3/8" foam insulation.

4.1.2 Pipe Insulation Level
If a water pipe does experience sub-freezing temperatures, the rate of heat loss, and thus ice formation, can be slowed by insulating the pipe itself. This is a well-known pipe protection strategy.

Insulating materials are rated by their "R-value", which is the resistance to heat flow of an insulation of certain thickness. Sometimes, materials may be rated by their conductivity, "k", which is a measure of thermal conductivity per inch of insulating material. Resistance and conductivity are directly related properties. If one knows the conductivity and thickness of an insulating material, it is not difficult to figure out the R-value. The greater the R-value, or the smaller the conductivity, k,

the better the insulating value of the material of a given thickness, and thus the slower the heat transfer through the material.

Insulating materials affect ice formation in several ways: a minor effect involves retarding the heat flow due to simple temperature difference between the water temperature and ambient temperature. A major effect of insulation occurs because the phase change of water to ice generates heat and the rate at which phase change occurs will depend on the rate at which the "heat of fusion" is allowed to escape to the air. Insulation retards that heat flow. Thus, it prolongs the time during which phase change takes place.

A variety of over-the-counter pipe insulation was purchased for Phase 1 study. For 1/2 inch copper pipes, six kinds of pipe insulation were tested. Fewer over-the-counter pipe insulation products were available for 3/4" copper pipes, and thus three types of pipe insulation were tested with 3/4" pipes. *Figure 17* shows the thermal performance of pipe insulation on a 3/4" copper pipe at a design temperature of 20°F (-6.67°C).

As with the case of ambient temperature, insulation does not affect the Stage 1 temperature drop - an hour at most. The lengthening of Stage 3 phase change was again significant. An 1/8" of insulation delayed ice blockage by 3 hours, and 5/8" of insulation provided an eight-hour delay. The relationship between hours to complete phase change and the conductivity of the insulation level is approximately inverse. The benefit of

pipe insulation is clearly in its ability to slow the phase change within a water pipe, and thereby reduce the likelihood of an annular ice blockage before a warming period.

The thickness of the tested pipe insulation in Phase 1 ranged from 1/8" to 5/8", and approximate R-values ranged from 0.5 to 3.0. This is a small band of possible insulation; pipe insulation for industrial purposes is manufactured in far greater thicknesses and R-values. While the Phase 1 research only tested modest insulation levels, it was concluded that greater pipe insulation levels could allow a water pipe to survive a severe subfreezing event by delaying an annular ice blockage. It was a goal of the Phase 2 research to test the impact of greater insulation levels.

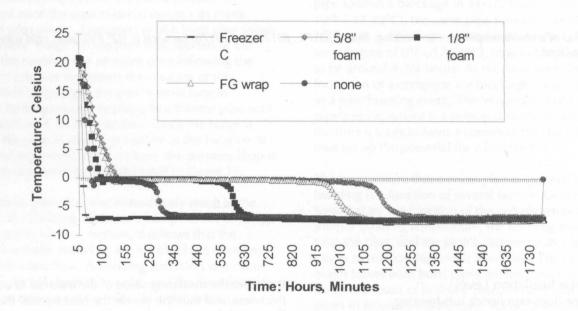


Figure 17. Comparison of Pipe Insulation. JD174. 3/4" copper pipe, cold water tap, -6.67 °C design temperature (20 °F).

The Phase 2 field tests featured test pipes insulated at three levels: 1", 1.5", and 2" of insulation. In each case, the insulation was a molded fiberglass insulation with a plastic outer wrapping. This insulation was locally available in 3 feet long sleeves that were split to allow the insulation to slip over the test pipe. The listed conductivity for this insulation was  $k = 0.25 \text{ Btu*in/hr*ft}^2\text{F°}$ . The R-values, which are the inverses of conductivity, were then R4, R6, and R8, respectively. *Figure 18* shows a comparative result of the insulation tests.

Figure 18 shows a 48-hour period, beginning at 8:00 AM on the morning of January 22, and ending at 8:00 AM on the morning of January 24. It features a severely cold night (-10°C, 14°F) on January 22/23. Three of the pipes supercooled into the evening of January 22 before starting ice formation. The pipe with 2" insulation supercooled until about 7:00 AM of the next morning.

The main concern is the time at which the pipes completed annular ice formation as shown by the drop from the phase change temperature of 0°C. It is at this

point that a blockage was complete, and increased pressure and potential bursting was imminent. The pipe with no insulation became blocked at around 5:30 AM on the 23rd. The pipe with 1" insulation showed a blockage around 3:00 PM that next afternoon, a delay of 9-1/2 hours. The pipe with 1.5" of insulation does not become blocked until 2:30 the morning of 24th, a full 23 hours after the uninsulated pipe. Finally, the pipe with 2" of insulation does not complete a blockage. Indeed, here a warming trend in the outdoor temperature led to thawing in this pipe before a blockage was ever completed. There were occasions when the lesser insulation levels, 1" and 1.5", also prevented a blockage.

As indicated in Figure 18, the Phase 2 field tests confirmed that, by slowing heat loss, greater insulation levels can considerably delay annular ice blockage. The tests also confirm that, with enough insulation, a water pipe can be protected to survive a cold period of limited duration.

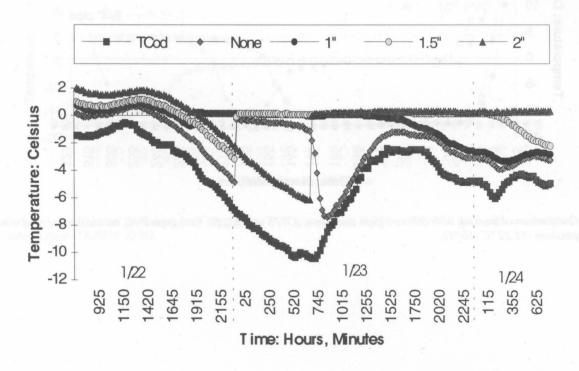


Figure 18. Comparative insulation study, Phase 2 field tests. JD 22 to JD24. Insulation as indicated. Temperatures taken from the center (C) of the pipe in each case.

### 4.1.3 Pipe Diameter

Residential water distribution systems generally employ 1/2" and 3/4" water lines. Both diameters were tested, allowing for direct comparison of the survivability of different diameter pipes. *Figure 19* illustrates typical freezing curves for uninsulated copper pipes.

Complete growth of annular ice during phase change is dependent upon how much water is contained in the pipe. A 3/4" copper pipe holds approximately twice the water of a 1/2" copper pipe, 17.6 cubic inches as compared to 8.6 cubic inches in the 34" long test pipes used in Phase 1. Based on this fact, it should be expected that a 3/4" pipe will take twice as long to freeze as a 1/2" pipe.

Moderating the difference in volume is the fact that, with the same levels of insulation, the heat loss is greater in a 3/4" pipe than in a 1/2" pipe due to greater surface area. However, the influence of this greater heat loss is minor compared with the difference in volume. Figure 19 shows that the 1/2" pipe completed ice growth in 75 minutes, which is 62 percent of the 120 minutes required in the 3/4" pipe.

The determination of pipe diameter in a plumbing system is based on necessary service demands and flow requirements. For these reasons, an attempt to reduce the burst pipe incidents through the specification of pipe diameter is of negligible value.

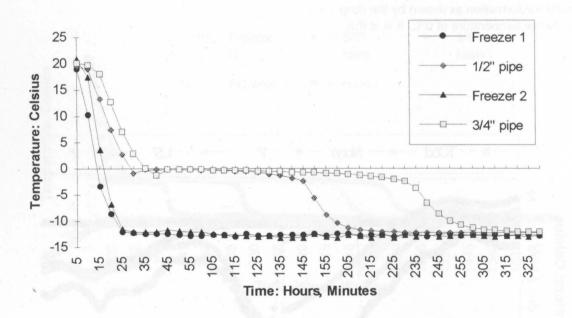


Figure 19. Comparison of freezing with different pipe diameters. JD175 and JD209. Each pipe PVC, no insulation, cold water tap, design temperature -12.22 °C (10 °F).

4.1.4 Pipe Composition

There is a difference in the thermal properties of copper and PVC pipes. Plastic pipes have both thicker walls and greater resistance to heat flow. The Plastic Pipe Industry lists the conductivity of PVC pipe as k = 0.9 to 1.3 Btu\*in/hr\*°F\*ft², which corresponds to an R-value of between 0.77 and 1.1 for each inch of thickness. ASHRAE Fundamentals lists the conductivity of copper as k = 2700 Btu\*in/hr\*°F\*ft². This means that copper water pipes have virtually no resistance to heat flow, and have an R-value that is negligible. This difference in the thermal properties of the pipes is noticeable when the pipes go through a freeze process. Figure 20 illustrates the difference in time of phase change at 0°F (-17.78°C).

All matched pairs of similar pipe assemblies, comparing copper and PVC pipes, showed a similar difference, with plastic pipe outperforming copper pipe in thermal resistance.

While PVC water pipes display measurably better thermal performance compared to copper pipes, the difference is not overwhelming. Only in marginal cases would the added thermal resistance of plastic pipes prevent annular ice blockage in comparison to copper.

No bursts occurred in any of the PVC pipe tested. Further tests will be necessary to determine the role of plasticity of pipe materials in preventing bursting under freezing conditions.

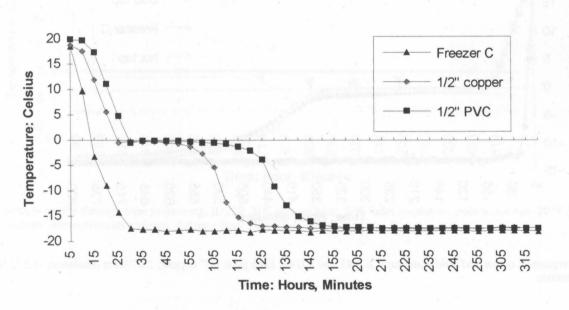


Figure 20. Comparison of thermal performance of copper and PVC water pipes. JD151 and JD178. Each pipe uninsulated, cold water tap, design temperature -17.78 °C (0 °F).

4.1.5 Hot vs. Cold Water Source
It has been often claimed that, when subjected to identical conditions, a hot water line will burst before a cold water line. References to this alleged phenomena can be traced back as far as 1916. A definitive, widely-accepted explanation has yet to be proposed. One theory holds that premature bursting is a result of greater dendritic ice formation in hot water pipes than in cold water pipes.

During Phase 1, tests were done on pipes with water drawn from both cold and hot water taps, allowing analysis of several matched pairs. *Figure 21* provides the temperature profile for one of those matched pairs. As this example shows, when water pipes begin to cool

from identical temperatures toward identical temperatures, it makes no difference if the water was drawn from a cold water source or a hot water source. The freezing process is identical. In the other matched pairs the difference between the freezing of the cold water pipe and the hot water pipe was rarely more than ten minutes. If hot water lines tend to burst before cold water lines, it is not due to the water's response to the subfreezing temperature and the time to complete phase change. More likely, a tendency for hot water pipes to burst before cold water pipes might be due to the distribution of entrapped air in residential water systems because of the water heating process. The current research did not investigate this possibility, and further research is required.

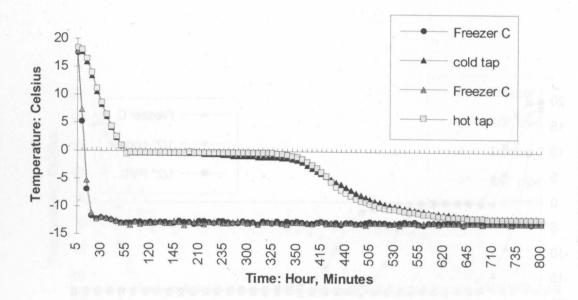


Figure 21. Comparison of hot and cold water taps. JD145 and JD146. Each pipe 1/2" copper, 1/2" foam insulation, -12.22 °C (10 °F) design temperature.

# 4.1.6 Conductive Heat Gain

On several occasions, clear PVC pipes were installed in the freezer and the freezing process and resultant ice formation was observed. Two of the significant observations were:

- 1. Annular ice growth went from the outside walls inward, as expected.
- 2. Completed annular ice growth went from the bottom of the pipe upwards.

Having observed that complete freezing of the pipe occurred from the bottom up, a series of tests was done with four thermocouples inserted into the pipe, providing a vertical temperature profile. *Figure 22* illustrates a typical vertical temperature profile during a freeze event. The graph shows the point at which the temperature of each pipe section falls below the phase change temperature, which is the point at which annular ice formation is complete. The graph clearly shows the growth of annular ice from the bottom of the pipe toward the top.

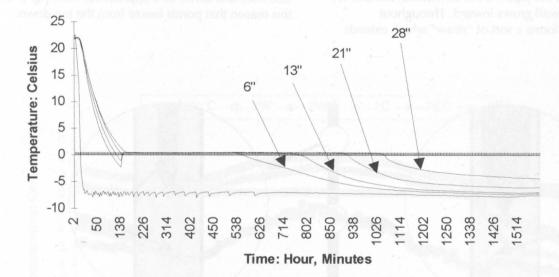


Figure 22. Vertical profile through pipe in freezing. JD259. 3/4" copper pipe, 5/8" foam insulation, cold water tap, 20 °F (-6.67 °C) design temperature. Measurements indicate distance from the bottom of 34" pipe.

To further examine ice growth, several pipes were cut into 4" sections during freezing, and the ice formation examined. *Figure 23* illustrates the observations.

At the time the bottom 6 inches is leaving phase change, there is a solid annulus of ice at the bottom of the pipe. The frontier of the ice growth forms a sharp "V" shape about 3/4" to 1" long, making a transition to a very thin layer of ice, about 1/16" thick, along the pipe wall. This was determined by cutting a pipe that was undergoing annular ice formation into small sections. These ice layers ascend nearly perpendicular to the pipe wall, with only the slightest taper. Water in liquid form extends nearly the whole length of the pipe.

As the pipe continues to freeze, the "V" at the ice/water frontier climbs in the pipe. At the same time, annular ice against the pipe wall grows inward. Throughout freezing, the ice forms a sort of "straw" which extends

down to the ice/water frontier. With a 3/4" pipe, when annular ice has been completed about half way up the pipe, ice along the pipe walls is approximately 1/4" thick, with a 1/4" column of water extending down through the center. Again, the ice layers above the "V" are nearly perpendicular to the pipe walls with only a slight taper measurable in a few hundredths of an inch. This pattern appears to continue until the pipe has completely frozen solid. In the tests, annular ice grew both upward and inward.

While it may be intuitive to attribute the upward progression of ice growth in the Phase 1 tests to the density of water (that is, the colder water sinking to the bottom of the pipe), this is not the case. Unlike air, the maximum density of water occurs at 4°C, and in fact becomes less dense as it approaches freezing. It is for this reason that ponds freeze from the top down.

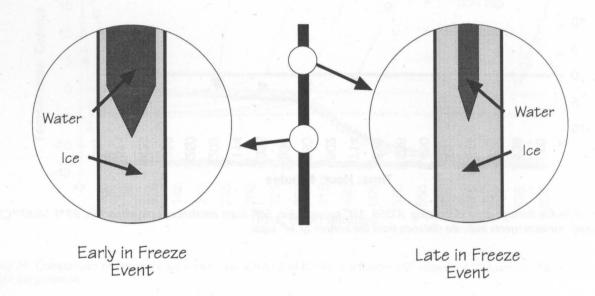


Figure 23. Ice formation pattern in vertically oriented test pipe. Phase 1.

Rather, the upward ice growth is a result of conductive heat gain from the warmer, "indoor" space. The test pipes penetrated the freezer at the top. Both the pipe and the water have little resistance to thermal transfer, so it is expected that there would be heat added to the top of the pipe from outside the freezer. Indeed, the pipes that protruded from the freezer were cold during a test, confirming this heat transfer. At the same time, while the pipe in the freezer was insulated along its entire length, no insulation was applied to the bottom of the pipe. It should be expected that heat loss will be greatest at the very bottom of the pipe assembly. These two factors worked in unison, with the thermal influence spreading throughout the pipe, and causing the stratification of annular ice growth. One would expect a similar ice growth pattern, from a cold space toward a

warm "indoor" space, in a horizontal pipe. This was confirmed during the Phase 2 field tests, as shown in *Figure 24*.

During this freeze event, the ends of the pipe (2W & 2E) were significantly warmer than the center section of the pipe. Even after the center section entered phase change at 4:35 AM, the pipe ends were not freezing but in fact responding to the warmer daytime temperatures in the attic. Only after the center of the pipe froze solid at 1:30 AM (first at 3C, then quickly after that at 3W and 3E) did the pipe ends start to freeze in response to a declining temperature in the attic. The temperature profile in Figure 24 is clearly a result of conductive heat gain along the length of the pipe from the room below.

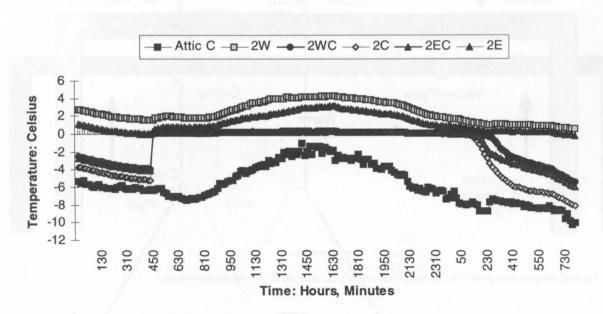


Figure 24. Conductive heat transfer through the pipe ends. JD 23 and JD24. 1/2" Type M copper, 1" fiberglass insulation.

In order for water to freeze into ice, heat must be transferred from the water to the environment. Specifically, 143.5 Btu/lb, the *heat of fusion*, must be transferred to the environment. As the tests show, heat transfer associated to residential water pipes is not one way. Conductive heat transfer from a conditioned interior space along the length of the pipe results in a heat gain. Freezing in any specific pipe section, then, is a matter of *net* heat loss: the heat loss from the pipe in a cold unconditioned space *less* the conductive heat gain from the conditioned space. As we have seen, the conductive heat gain has the greatest impact on the ends

of the pipe closest to the interior. This results in a typical temperature profile as illustrated in *Figure 25*.

All residential water lines that may be subject to freezing (whether placed in an attic, crawl space, or exterior wall) ultimately pass from a warm environment, to a subfreezing environment, and back to a warm environment. Barring any convective heat loss effects (wind chill), the profile illustrated in Figure 25 represents a typical temperature profile in a residential water pipe.

#### Cold Attic

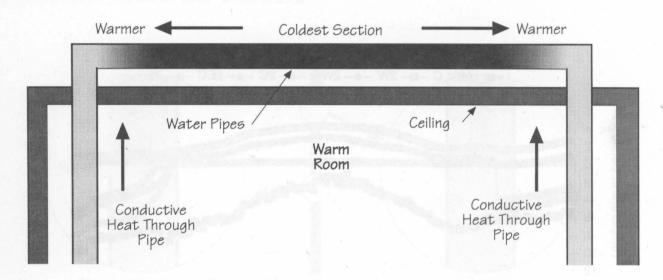


Figure 25. Typical temperature profile in a residential water pipe subject to a cold environment.

4.1.7 Convective Heat Loss / Wind Chill In the graphs of Phase 2 freeze events examined to this point, annular ice formation is seen to begin in the center of the test pipes and continue outward to the ends. In fact, the completion of annular ice growth is seen to occur throughout the center section (WC, C, &EC) almost consecutively (Figure 24). In order for a pipe to burst, it is necessary to continue to freeze water downstream of an annular ice blockage, resulting in greatly increased water pressure in the pipe. Because of the short length of the test pipes and the warming of the pipe end, the potential for extensive freezing following blockage was seen to be limited early in the testing period. To promote the potential for burst pipe events in the tests, it was necessary to create conditions that led to differential cooling. That is, it was necessary to promote freezing and ice blockage at the west end of the test pipes first, followed by continued freezing toward the east. One approach was to create a condition of

increased *convective* heat loss at the west end of the pipe.

The discussion to this point has centered around conductive heat transfer: conductive heat loss through the pipe wall and insulation layer to the attic environment, and conductive heat gain through the pipe itself from the room to the attic. Convection is another heat transfer mechanism dealing with the heat transfer resulting from a moving fluid, such as moving air. From common experience, we know that cold air moving across a warm surface will have a greater cooling effect than cold still air. People recognize this phenomenon as wind chill. One method to promote differential cooling in the test pipe was to establish an increased convective heat loss at the west end of the pipe. Figure 26 illustrates the device fabricated to accomplish this, which will be called the wind chill generator.

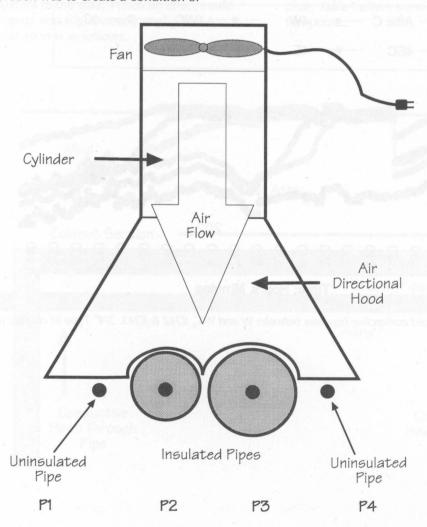


Figure 26. Wind chill generator, Phase 2 field tests.

The wind chill generator consisted of a small fan attached to a 6" diameter cylinder 7" long. The cylinder was attached to a truss chord above the test pipes between locations W and WC. A cardboard hood was fabricated and attached to the bottom of the cylinder, which spread the airflow across the first four test pipes, and focused the flow to an air stream 1" wide just above the pipes. As Figure 26 shows, pipes 1 and 4 were uninsulated, and pipes 2 and 3 were insulated with 1" and 1.5" of fiberglass insulation, respectively. To determine air speed, the wind chill generator was tested with a velometer that showed that the device generated a breeze of 8 mph at the location of the pipes.

The results achieved with the wind chill generator were immediate and dramatic. *Figure 27* provides a typical response on an uninsulated pipe.

The importance of the results in Figure 27 lie in the order in which freezing was completed, that is, when the temperature at each location of the pipe leaves phase change and falls toward the attic temperature. Freezing is first completed at 4W, followed less than an hour later by 4WC. A considerable length of time passes before freezing is complete at 4C, followed eventually by 4EC, and then 4E. Clearly, the growth of annular ice is directly from west to east. The tendency of the pipe to

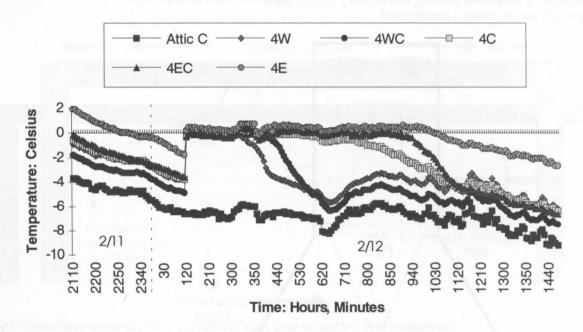


Figure 27. Freeze event with enhanced convective heat loss between W and WC. JD42 & JD43. 3/4" Type M copper, uninsulated.

freeze from the center outward has been entirely overridden by the effect of enhanced convective heat loss at the west end. Furthermore, the effect is dramatic, with the west end completing ice formation in about 1/3 the time of the center. Convective heat loss can change the temperature profile, as typically seen in Figure 25, to the temperature profile illustrated in *Figure 28*.

Differential cooling accomplished with the wind chill generator became an important tool in the Phase 2 field tests. The tests that ultimately featured excessive hydraulic pressure and bursting were accomplished using this technique.

The dramatic results featured in Figure 28 pertain to uninsulated pipes. The effect on the two insulated pipes that were subject to the wind chill generator was not nearly as dramatic. Often, there was no discernible wind chill effect apparent in the data. When an effect could be seen, the impact was slight, nearly negligible. A simplified explanation is as follows.

Total heat loss is a function of the thermal resistance (R-values) of a system. With water pipes, this includes the thermal resistance of the pipe wall, the pipe insulation, and the ice itself as it grows on the inside of the wall. Surface effects, including convection, can also be expressed as thermal resistance. Calculating total heat loss involves adding up the component thermal resistance. When a pipe is insulated, the comparatively great thermal resistance of the insulation becomes the dominant factor in the heat loss equation, dwarfing the other factors. Changes in the wind chill on the outside on the insulation, or the amount of ice on the inside of the pipe, will have only a modest effect on the total heat loss. If a pipe is uninsulated, however, the surface conditions, particularly convective heat loss, becomes the dominant factor in the heat loss equation. Any changes in the surface conditions such as wind speed will have a dramatic effect on the overall heat loss of the pipe. Table 1 offers some sample calculations that show this point.

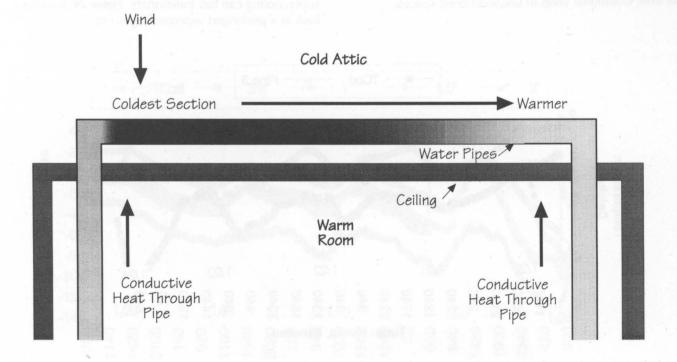


Figure 28. Temperature profile with wind chill effect.

It is clear from Table 1 that for an uninsulated pipe, the impact of wind speed on heat loss is tremendous. At the same time, a pipe with 1" of insulation will see only a minor increase in heat loss. The field test results from the Phase 2 research agree with this finding.

Table 1. Sample Heat Loss (Btu/hr) Variable Wind Speed			
Part year to ye	1 MPH	8 MPH	20 MPH
No Insulation	58.27	129.27	198.80
1" Insulation	14.34	15.13	15.37

Table 1. Sample heat loss calculations with varying wind speeds. 1

The impact of convective heat loss on uninsulated water pipes, the wind chill effect, is one of the significant findings of the Phase 2 research project. Many of the burst pipe losses are probably associated with wind and air leakage on uninsulated pipes, either from unintentional air leakage through the building envelope, or from intentional vents in unconditioned spaces.

4.1.8 Supercooling

In the Overview we introduced the phenomena of supercooling. In the Phase 1 freezer tests, the test pipes typically showed a shallow supercooling of -1° to -2°C. Occasional tests exhibited a deeper, colder supercooling. In the Phase 2 field tests this trend was reversed. Prolonged supercooling was the norm, with only occasional tests exhibiting a shallow supercooling. Typical ice nucleation temperatures were between -3.5° and -6°C. Only five of the 49 freeze events in the field tests exhibited an ice nucleation temperature above -3°C. Gilpin's research shows that the presence of nucleation sites, or starting points, is central to the amount of supercooling a pipe will experience. It is possible that in placing the thermocouple wire inside the water pipes during the Phase 1 tests, a nucleation site was introduced, leading to generally shallow supercooling temperatures. The exterior method of thermocouple mounting in the field tests provided a condition more representative of actual conditions. Based on the field tests, a prolonged supercooling and low ice nucleation temperature is typical in residential water pipes.

In the Phase 1 tests, pipes supercooled up to three hours before ice formation. The field tests showed that, in fact, supercooling can last indefinitely. *Figure 29* provides a look at a prolonged supercooling event.

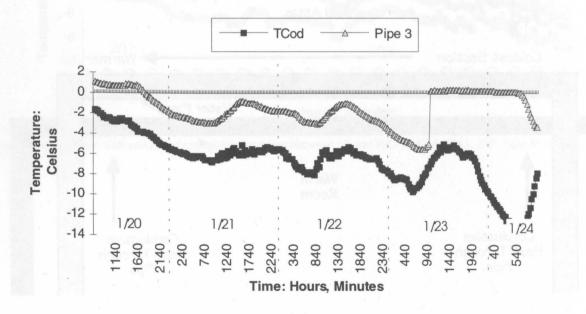


Figure 29. Prolonged supercooling. JD20 through JD24. Temperatures measured at the center of the pipe.

<sup>&</sup>lt;sup>1</sup>Table 1 is based on the following assumptions: Convection coefficient determined using equation from ASTM C680. 3/4'' Type M copper pipe. Air temperature of 20°F. Phase change temperature of 32°F. Conductivity of insulation, k = 0.25 Btu\*in/hr\*ft²\* F°. Conductivity of copper, k = 227 Btu/hr\*ft\* F°=2700 Btu\*in/hr\*ft²\*°F.

Figure 29 presents data from a four-day period when the outdoor temperature was below freezing both day and night throughout the period. This cold spell produced an uninterrupted subfreezing temperature in the insulated pipe shown in the graph. Despite the prolonged cold spell, ice formation did not occur for the first three days of the four-day period. That is, the pipe underwent supercooling for those three days. In the Phase 2 field tests, supercooling was seen to last for up to 80 hours at a time.

#### 4.1.9 Insulation Revisited

Figure 29 looked at a pipe experiencing prolonged supercooling. By looking at all of the pipes during this time period, additional observations on the benefit of pipe insulation can be made.

Figure 30 illustrates that all four pipes underwent a prolonged supercooling over this four-day period. During the supercooling phase, the temperature of the pipes track the outdoor temperature closely. In so doing, they also are aligned by the level of insulation. The pipe with the least insulation is coldest, while the pipe with the greatest insulation is warmest. The likely explanation

for this alignment results from the conductive heat gain through the pipe ends from the room. All four pipes, being of the same diameter and composition, experience nearly the same conductive heat gain through the ends. Due to different insulation levels, however, they have different heat loss rates to the attic. It takes longer for the better insulated pipe to dissipate the conductive heat gain. As a result, the pipes establish different equilibrium temperatures in relation to their environment. A better insulated water pipe maximizes the conductive heat gain from the conditioned space.

In Figure 30, three of the four pipes leave the supercooling phase and begin to form ice during the morning hours of January 23. The pipe with 2" of insulation supercools for another 24 hours. In fact, all three of the other pipes have formed an annular ice blockage by the time this pipe is just starting ice formation. As happens in Figure 18, the pipe with 2" of insulation never formed a blockage before the onset of warmer weather. In the field tests, the pipe with the most insulation supercooled longer and required a colder outside temperature to begin ice formation.

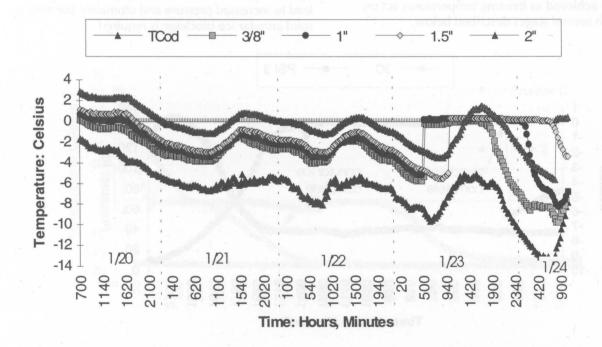


Figure 30. Prolonged supercooling. JD20 through JD24. Temperatures measured at the center of the pipe.

In summary, the Phase 1 research identified the principal advantage of insulation as a burst protection strategy: by slowing the rate of heat loss, insulation delays the completion of an ice blockage, and thus delays the potential for bursting. Phase 2 field tests confirm this finding. Additionally, the Phase 2 field tests identified three related advantages:

- 1. Pipe insulation maximizes the conductive heat gain through the pipe ends, leading to warmer equilibrium pipe temperatures.
- Pipe insulation can lead to longer supercooling, requiring a colder environmental temperature to initiate ice formation, delaying the completion of an ice blockage.
- As seen in the section Convective Heat Loss, insulation greatly reduces the potential for isolated convective heat loss, or wind chill effect, which is likely a major factor in burst pipe losses.

The sum of these advantages is significant. Requiring a respectable level of insulation (R6 to R8) for water pipes in unconditioned spaces would have a positive impact on reducing the extent of burst pipe losses.

4.2 Hydraulic Pressure and Bursting
The principal findings of this research is that pipe
bursting results from elevated fluid pressures which are
the result of the growth of ice blockage. Elevated fluid
pressures are achieved as freezing temperatures act on
water through several stages described below.

#### 4.2.1 Dendritic Ice Formation

As previously noted, the field tests generally showed close to maximum supercooling and low ice nucleation temperatures. This implies that the dendritic ice formation typically developed as a dense matrix inside the pipe. Gilpin showed that a dense matrix of dendritic ice could prevent flow and the loss of service through a water line. If a dense matrix of dendritic ice can create a blockage preventing flow, it is appropriate to ask whether a dendritic ice blockage could also lead to elevated pressures downstream, and possibly create bursting potential before the completion of an annular ice blockage. Based on Gilpin's studies, it would seem that a dense dendritic ice matrix would not have the structural integrity to withstand the pressures associated with burst pipe incidents. The Phase 2 field tests proved this conclusion to be the case. Figure 31 shows the inability of dendritic ice to constrain a pipe section, and lead to elevated hydraulic pressure.

The case in Figure 31 represents the coldest ice nucleation temperature observed during the field tests, -6.23°C. As such, this case likely represents the greatest percentage, and densest matrix, of dendritic ice formation. This initial ice formation does not lead to increased hydraulic pressure in the pipe. Only after the completion of a solid annular ice blockage is the pressure seen to increase. The Phase 2 field tests showed no incidence of dendritic ice resulting in increased hydraulic pressure. To isolate a pipe section, which can lead to increased pressure and ultimately bursting, a solid annular ice blockage is required.

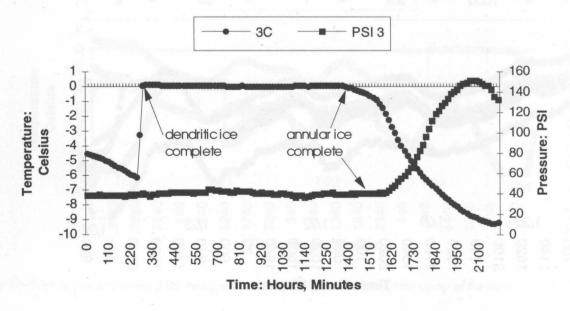


Figure 31. Freeze event with temperature and water pressure, Phase 2 field tests. JD36 (Feb. 5), pipe3. 3/4" type M copper pipe, 1.5" fiberglass insulation, air chamber in attic.

# 4.2.2 Phase Change Temperature at Elevated Pressures

While the phase change temperature of water is typically 0°C (32°F), the temperature at which water freezes falls with increasing pressure. The Clausius-Claypeyron equation expresses the reduction in equilibrium freezing temperature with respect to pressure. The change in freezing temperature is about .0075 K (°C) per atmospheric pressure. At 2000 psi the freezing point of water is reduced about 1 degree C. At 4700 psi, in the range of pipe burst pressures, the freezing point of water is reduced by 2.4°C. Upon bursting, excessive pressure in a pipe is relieved, and the equilibrium freezing temperature reverts to 0°C. These phenomena appeared in the data from both phases of the research. In the freezer tests, bursting was shown by a small jump in the temperature within the pipe. Figure 32 displays the temperature graph of two pipes that burst during the same test.

During the field tests, similar temperature jumps were witnessed upon bursting in those sections of pipe that still contained water at the time of the rupture. Referring back to Figure 15 in the overview of bursting, one can

note that when the pipe ruptured, the temperature at locations 1C and 1E, which were still in the process of freezing, returned to 0°C. The pipe section at 1W, which was the location of the blockage and thus frozen solid, did not experience a similar rise in temperature.

# 4.2.3 Burst Types and Locations

As part of the Phase 1 research, test pipes were sectioned in 4" segments to examine the interior of the pipe immediately following bursting. Examination of burst events showed that there were two types of burst events based on the location of the rupture and the associated pressure relief.

As previously stated, ice growth in the freezer tests went from the bottom of the pipe upwards toward the warmer interior space. In all but one pipe bursting incident, the burst location occurred in the pipe within an inch or two from the top of the pipe. Examination of these events showed that there was very little ice at the location of the rupture, often only 1/16" on the interior of the pipe wall. On a couple of occasions the burst event was witnessed, and pressure relief upon bursting was seen to be sudden, violent, and complete.

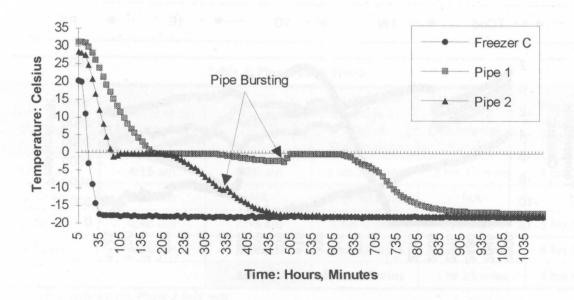


Figure 32. Two burst pipe events. JD165. Both pipes 3/4" copper, hot water tap, design temperature -17.78 °C (0 °F). Insulation as indicated.

The Phase 2 field tests documented only three burst events. (The reason for the limited number of burst events will be discussed later). Two out of the three events were of the same type. That is, the blockage was induced by the wind chill generator at the west end of the pipe, and the rupture occurred at the east end, in a section that had little ice growth. The event presented in figure 15 in the Overview is an example, and shows that pressure relief upon bursting was sudden and complete.

A second type of burst event was witnessed in one case during Phase 1. In that event, a rupture occurred lower in the pipe, near the ice/water interface. This pipe was sectioned and an examination made of the burst site. In this case the excessive pressure, pushing down on the ice and out on the pipe walls, had caused a cross-sectional hairline fracture in the ice at the location of the interface. Water had apparently moved by capillary action, no doubt aided by the pressure, through the hairline crack to the outside of the pipe where it was subject to freezing. Expansion from freezing then resulted in a rupture at this point. Because the burst location was not immediately in communication to the pressurized water in the pipe, the burst event was seen to be far less violent, with water oozing out of the rupture and refreezing on the outside of the pipe.

One of the three burst events during the field tests also was of this type. *Figure 33* graphs the pressures during

this event, and provides a distinct contrast to the type 1 burst event of Figure 15.

The temperature data in Figure 33 again shows west to east ice growth, with the initial blockage on the west end. Again, the phase change temperature drops about 2°C in response to the increased pressure. The pressure increase because of ice growth shows a typical elastic range response. Once the pipe goes plastic, the period of pipe deformation is much longer than seen in the previous example. When the rupture does occur, the pressure release, while initially sudden, takes place over a period of 45 minutes. Furthermore, the pressure release is not total, but rather a pressure of 800 psi is maintained after the pressure release, and the pressure begins to climb again. An examination of the pipe showed that the burst occurred in the center of the pipe, and not at the east end. This is clearly a case of the second type of burst event as described above. The extended deformation of the pipe, and the lack of total pressure release, resulted from the water being required to pass through a hairline crack. Rather than "exploding", the water only "oozed" from the rupture. In fact, this process allowed the escaping water to refreeze on the outside of the pipe, sealing the rupture before complete pressure release and allowing the pressure to build again. The phase change temperature at the center and east end increased upon rupture and pressure relief, but not all the way back to 0°C, as the pressure in the

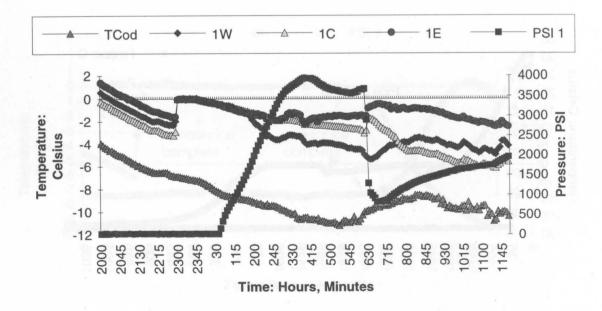


Figure 33. Type 2 burst event in center portion of pipe. Pipe 1, JD 41 & JD 42. 3/4" Type M copper, no insulation, no air chamber.

pipe was still elevated. The center of the pipe at the ice/water interface where the rupture occurred was soon frozen solid.

While the second type of burst event is interesting, it should be noted that it occurs at exactly the same elastic limit of the pipe. Consequently, it does not change any of the considerations of potential burst protection strategies.

What does merit consideration in the second type of burst event is the subsequent pressure buildup. Because the pipe was resealed at the rupture by freezing water on the exterior of the pipe, the downstream pressure started to rise again. Over the next day, ongoing ice formation continued to generate higher pressures, nearly approaching the burst strength of the pipe a second time, and thus nearly resulting in a second burst event. While a warming trend induced thawing before a second burst event here, the potential clearly exists for one water line to show more than one burst location.

An insufficient number of burst events occurred during the Phase 2 field tests. Therefore it could not be determined which burst event type was more common. During the Phase 1 freezer tests, the first type of burst event was far more common.

In both phases of the research, pipe failures occurred in the test pipes themselves. It is possible for pressure relief to alternatively occur through the failure in other parts of a water line, including elbows, "tees", solder joints, or within a fixture itself.

**Table 2** provides the elapsed times of the burst pipe events that occurred in the Phase 2 field tests.

It was previously stated that there were three burst events. The fourth event in Table 2 (JD44) involved a pipe that experienced a pressure that took it past the elastic limit, and initiated a deformation of the pipe. By coincidence, a sudden warming temperature thawed the pipe at the same time and released the pressure before bursting.

The pipes in each case were 3/4" Type M copper pipes. The elapsed time from blockage to the start of pipe deformation was somewhat consistent, with an average of 3 hours and 27 minutes. There was a greater spread regarding the elapsed time from the start of deformation to bursting. This is primarily due to the event of JD42, which we have seen involved the type 2 burst event. The other two burst events (JD 45 & JD 62) were quite similar, both within five minutes of an hour from deformation to bursting. There are undoubtedly several variables that influence time to bursting, with heat loss rate and rate of ice formation the principal variables. Based on the Phase 2 research one can expect, for 3/4" Type M copper pipes, that a pipe will begin deformation around three hours after annular ice blockage, and burst around four hours after blockage.

Table 2. Pipe 1 Burst Events							
	Time: Initial Blockage	Time: Start of Deformation	Time: Bursting	Elapsed time: Blockage to Start of Deformation	Elapsed Time: Start of Deformation to Bursting	Elapsed time: Blockage to Bursting	
JD42	12:40 am	4:15 am	6:20 am	3 hrs 35 mins	2 hrs 15 mins	5 hrs 50 mins	
JD44	3:50 am	7:40 am	NA	3 hrs 50 mins	NA	NA	
JD45	3:40 am	6:40 am	7:35 am	3 hrs 0 mins	55 mins	3 hrs 55 mins	
JD62	1:15 am	4:25 am	5:30 am	3 hrs 10 mins	1 hr 5 mins	4 hrs 15 mins	
129 0 CAS Sentration 20			Average	3 hrs 27 mins	1 hr 25 mins	4 hrs 40 mins	

Table 2. Elapsed time of burst events, Phase 2 field tests

## 4.2.4 Burst Strength Tables

It was not the intention of the research to identify and document the burst strengths of commercially available water pipes. Following are the working pressures and burst pressures as listed by the manufacturer's associations.

The Copper Development Association lists the working pressures and burst pressures of residential copper pipes as shown in *Table 3*.

Clearly, 1/2" copper pipes have a greater burst strength than do 3/4" copper pipes, and the thicker Type L copper pipe has a greater burst strength than the thinner Type M. The research was consistent with this table, as Type M copper was the most likely to burst.

The Plastic Pipe Institute (PPI) provides a different, time dependent, measure for the burst strength of PVC water lines. That is, PVC pipe can withstand some pressures for short periods of time that would be sufficient to burst the pipes over longer periods of time. *Table 4* lists the working pressures and burst pressures as defined by PPI.

In the Phase 1 tests there were no failures with plastic PVC pipes. The time of exposure to high pressures was limited to overnight time periods of about 12 hours, which is typical of burst pipe situations. The relatively mild winter during the Phase 2 test period limited the number of tests that could be done, and testing plastic pipes was not a part of the Phase 2 research. The above listed pressures, which rate PVC burst pressure on a par with type L copper, does not overstate the burst pressures based on PVC's survivability in the Phase 1 tests.

# 4.2.5 Air Chambers

It was concluded following the Phase 1 research that properly placed air chambers could provide burst protection in residential water systems. The volumetric expansion of water freezing to ice is approximately 8%. Because water is virtually non-compressible, it is this expansion that results in excessive water pressure within a water pipe, and ultimately bursting. By introducing a reservoir of highly compressible gas to a water system, an air chamber can provide a cushioning effect for the virtually non-compressible water. One of the principal goals of the Phase 2 research was to test the effectiveness of air chambers under field test conditions.

Table 3. Working Pressures and Burst Pressures of Copper Pipes						
	Type L		Туре М			
	Working Pressure	Burst Pressure	Working Pressure	Burst Pressure		
1/2" Copper	1362 PSI	7765 PSI	932 PSI	6135 PSI		
3/4" Copper	1099 PSI	5900 PSI	769 PSI	4715 PSI		

Table 4. Working Pressures and Bursting Pressures of PVC Pipe				
nim 22 gad 8.12 sassanawayatawana ka	PVC Type 1120			
min 2 and 4 Has 15 min	Working Pressure	Burst Pressures		
1/2" PVC	600 PSI	6 minutes: 7418 PS		
3/4" PVC	480 PSI	1 hour: 6783 PSI		
water byport on a sector of the property		10 hours: 6202 PSI		

Figure 33 showed a burst event in a pipe unprotected by an air chamber. *Figure 34* provides the data from an identical pipe over the same time period, but with an air chamber installed in the room of bay 1.

Throughout the tests, pipe 1 and pipe 4 were a matched pair for the study of air chamber effectiveness. On this night both pipes were 3/4" type M copper with no pipe insulation. As with pipe 1 on this night (Figure 27), the growth of ice is from the west end of the pipe to the east because of the wind chill generator. There is a rapid completion of an annular ice blockage at the west end at 2:40 AM, which immediately leads to increasing

pressure. By 10:00 AM the pipe has frozen solid all the way to the east end, when the pressure growth is seen to slow somewhat. The maximum water pressure of 140 psi is significant. As we have seen, the identical pipe without the air chamber was subjected to more than 4000 psi, and ultimately burst. Over the winter test period, 140 psi is the maximum water pressure experienced by the pipe having an air chamber installed in bay 1. In every case the Phase 2 field tests confirmed the conclusion that air chambers are effective in limiting excessive pressures and potential bursting caused by freezing in water pipes.

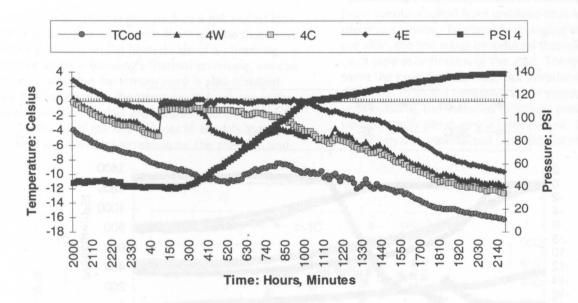


Figure 34. Freeze event with an air chamber in room. Pipe 4, JD42 & JD 43. 3/4" type M copper, no insulation.

Pipe 2 and pipe 3 in the field tests were equipped with identical air chambers installed in the attic as compared to an installation in the heated space of bay 1. For the first half of the winter, the air chambers were insulated at the same level as the pipes (1" and 1.5", respectively). In these cases it was seen that the air chambers were subject to freezing which limited their effectiveness in reducing water pressures. For the second half of the test period these air chambers were insulated with 1/2" more insulation than the pipes (1.5" and 2", respectively). Despite the extra insulation, the installation in the cold attic space continues to prove problematic. *Figure 35* shows a typical response of a water pipe with an air chamber installed in the attic space.

As previously indicated, the wind chill generator did not affect insulated pipes, as happened in this instance. Annular ice formation was completed throughout the center of the pipe (3WC, 3C, & 3EC) at about the same time, and the pipe froze from the center outward toward

the east and the west. The pressure readings during the early stages of pressure increase are erratic. There are several instances of increasing pressure followed by sudden pressure drops. Finally, at 8:30 PM, the pressure builds without interruption to a level greater than 1300 psi. The water pressure stabilizes only after ice formation is complete through the entire length of pipe. Apparently, the erratic pressure readings early in the event are a result of freezing within the air chamber itself. Because there is air above the water in the air chamber, it is possible that an ice blockage inside the air chamber could shift in response to increased pressure in the line. This appears to occur several times during the freeze event. By 8:30 PM the water at the bottom of the air chamber has frozen to such an extent that further dislocation of ice in the air chamber was not possible. and pressure was allowed to build unprotected by the air chamber.

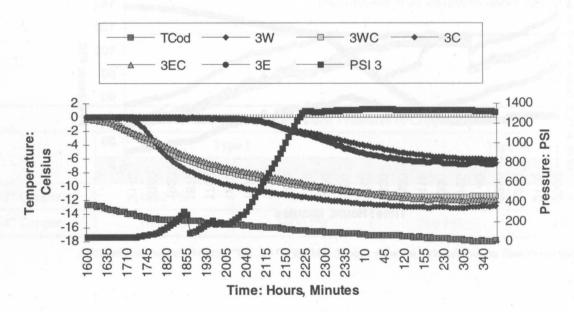


Figure 35. Freeze event of water pipe with an air chamber installed in the unconditioned attic. Pipe 3, JD 43 & JD 44. 3/4" type M copper pipe, 1.5" insulation on pipe, 2" insulation on air chamber.

Erratic behavior by the air chambers installed in the unconditioned attic was typical in the Phase 2 field tests. While no pipes with this type of installation burst, unacceptably high pressures were common. To ensure adequate and dependable burst protection through the use of air chambers, the air chambers should be installed in the conditioned space as compared to the unconditioned space.

The ideal gas law states:

PV = RT

where:

P = pressure

V = volume

R= gas constant

T = temperature

For any given quantity of gas, such as a gas sealed into an air chamber, R is a constant. If we assume that an air chamber is placed on the heated side of a plumbing system, or inside a building's thermal envelope, we can roughly assume that the temperature is also constant. Under this assumption, the pressure and volume of the gas inside an air chamber are inversely proportional. In this case, the *ideal gas law* reduces to *Boyle's Law*: if a gas is kept at a constant temperature, the pressure and

the volume are inversely proportional, or have a constant product.

In the field tests, the air chambers were constructed at the BRC of clear PVC calibrated so that the water level could be visually observed, and the volume of air determined both before and after a freeze event. Pressures were recorded throughout the tests. When the water levels were visually recorded, the pressure × volume product could be determined for the conditions both before and after the freeze event. Analysis of these results shows that Boyle's law applies quite well to the performance of air chambers during the field tests. With this knowledge, it is fairly easy to size an air chamber for a particular length of pipe that travels through an unconditioned space.

#### 4.2.6 Pressure Relief Fixtures

As was noted, there were only three burst events during the field tests. A principal reason for this low number of burst events resulted from unintentional leaks in the plumbing system. To simplify changing of the pipes in the attic, the test setup introduced threaded junctions for each pipe at both ends of the attic. These junctions did serve the purpose intended, but introduced another difficulty. With the excessive water pressures associated with bursting, the threaded junctions provided a potential leak site during a freeze event. On several occasions the unprotected pipe did not experience burst

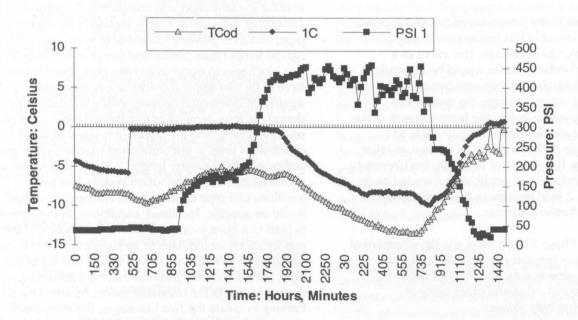


Figure 36. Pressure relief through the plumbing fixture. JD 24 & JD 25. 1/2" Type M copper, no insulation, no air chamber.

pressures due to leakage, and thus pressure relief, at the junction. This was not, however, the only potential leak site. *Figure 36* provides a pressure graph from a second leak site.

The temperature profile of this freeze event is familiar. As can be seen by the pressure readings, a blockage first occurred at 9:30 AM on the morning of January 24. The initial pressure rise slowed during the middle of the day in response to warmer outdoor temperatures; the pipe simply stopped freezing. The next night was again very cold (-14°C, 7°F), freezing restarted and the pressure began to rise swiftly. It was expected that the pressure in this pipe would continue to rise and approach the burst pressure through this cold overnight period. Instead the pressure in the pipe rose to 450 psi and then fluctuated for 14 hours, regularly reaching but never exceeding 450 psi.

The pipe was examined the morning of January 25. The faucet at the end of this pipe in bay 1, a typical garden hose faucet, showed a drip at the outlet. Below the faucet, the floor displayed a wet spot indicating continual dripping (14 hours worth) from the previous night. The fixture discharged water at a specific pressure, in this case 450 psi, well below the burst pressure, and in so doing prevented a burst event. The faucet handle was tightened for the next evening, but the faucet continued to function as a pressure-relief fixture, although at a higher pressure. Only when the faucet was replaced were burst pressures realized in subsequent tests.

This finding leads to the possibility of the development of a potentially valuable loss prevention strategy: pressure-relief plumbing fixtures. The intent of a pressure-relief plumbing fixture would be to provide pressure relief through an intentional bypass in the fixture, allowing water to escape the system at a predetermined pressure below the burst pressure of the water line. The case illustrated in figure 36 is an excellent example of the principle of a pressure-relief plumbing fixture. Based on this research, the University of Illinois has filed a patent application founded on this idea. The Phase 2 field tests show the application of pressure-relief plumbing fixtures.

Throughout the Phase 2 test period, the development of leaks at high water pressures created difficulties in producing burst pipe events. The Phase 2 field tests confirm the potential value and practicality of pressure-relief plumbing fixtures.

## 5. Conditions Leading to Two Ice Blockages

As we have seen, burst pipe events occur when ice growth continues within a confined pipe section. Up to now, we have defined that confined pipe section being bounded by an initial annular ice blockage and a closed plumbing fixture downstream. In the Phase 2 field tests, all incidents of extreme pressure occurred in this manner. The previous two sections of this report, discussing air chambers and pressure-relief plumbing fixtures, address the problem using this definition of the confined pipe section.

One must consider the possibility of a second type of confined pipe section: one bounded by two annular ice blockages. If a water pipe experienced two separate and concurrent blockages, and there was enough unfrozen water in the intervening pipe section, the intervening pipe section could experience elevated pressures and a potential burst event because of continued freezing within the pipe section. In that case, methods aimed at providing pressure mitigation or relief at the downstream end would prove ineffective. During the Phase 2 field tests, such an incident did not occur, and thus provided no positive evidence on the possibility of this type of incident. The knowledge gained from the research does allow us to speculate on the conditions that could lead to this possibility.

During the field tests, (not including those tests where a wind chill was induced), the temperature profile of the water pipes showed the coldest area throughout the center region and warming toward the ends. When annular ice formation was completed, it appeared to be completed throughout a large section of the center of the pipe, and then growing toward both ends. This is likely a typical temperature profile and freeze event. In order for two blockages to occur in a water pipe, there would have to be two atypical places where there was significant differential cooling. While this did not occur during the tests, remember that the test pipes were only seven feet long, and the layout of residential water distribution lines in unconditioned spaces is often more elaborate and of greater length. It might be possible, in an elaborate water distribution system, that two locations in a pipe could witness differential cooling based on specific, localized, conditions. In this scenario, to lead to a burst event, the differential cooling at the two locations would have to be significant. That is, they would need to freeze solid well before the rest of the pipe, for the scenario assumes that the intervening pipe section is also in the unheated space. As annular ice is forming to create the two blockages, the intervening pipe section is also forming ice. There must be enough water left unfrozen, following the completion of the two

blockages, to result in excessive pressure. Furthermore, once the two blockages are complete, the intervening pipe section will be reinforced with annular ice on the pipe walls. Only when the two blockage locations are freezing significantly faster would it be likely that this scenario could result in a burst incident.

The research showed that significant differential cooling can be caused by a wind blowing on a section of a pipe, (though even then it was observed that between 55 percent and 66 percent of the remaining downstream water had already turned to ice at the time of the accelerated blockage). If burst events from two ice blockages is possible, it would likely be a result of two separate locations witnessing an accelerated convective heat loss.

This presents another argument for pipe insulation. As we have seen, pipe insulation greatly decreases heat loss from convection, and would ensure that the amount of unfrozen water available following the blockage would be insufficient to burst the pipe. A properly insulated pipe probably cannot experience two blockages leading to a burst event.

However, an improperly insulated pipe might cause the condition. If pipe insulation is poorly installed, leaving gaps in the insulation, the poor quality of the insulation job could possibly cause differential cooling. That is, if part of a pipe is insulated, and other parts not insulated, this becomes a formula for differential cooling rather than a solution. Any recommendation for pipe insulation should stress a thorough insulation installation, without gaps, covering the pipe all the way to the heated space. A poor pipe insulation job could be more hazardous than no insulation at all.

While one can speculate on the probability of burst events from two separate ice blockages, the research field tests provided no evidence for such an event. It is likely that the continued freezing of a confined pipe section between an initial ice blockage and a closed plumbing fixture is the principal scenario for pipe bursting events, and represents most of the burst events that occur.

6. Loss Prevention Strategies

The combined research provided a good understanding of the freezing and bursting phenomena. Throughout the research, emphasis was placed on the identification and analysis of potential loss prevention strategies.

Three basic loss prevention strategies for burst water pipes can be identified based on the research:

- Prevent water pipes from ever encountering freezing temperatures through **placement** in the conditioned space of a building. Placement is meant to include the avoidance of air leakage through the building near water pipes.
- Accept some subfreezing temperatures, but provide sufficient pipe insulation to reduce heat loss to the point where an annular ice blockage cannot occur.
- Accept both subfreezing temperatures and annular ice blockage, but provide the water lines with devices to moderate the excessive pressures associated with bursting pipes. Potential protective devices include air chambers and pressure-relief plumbing fixtures.

The first strategy is designed to prevent water pipes from encountering sub-freezing temperatures, and thus avoid any potential for ice blockage and subsequent bursting. The second strategy is designed to prevent or substantially delay the formation of an ice blockage, and in so doing, prevent the excessive pressures that lead to bursting. The third strategy allows total freezing, and thus the temporary loss of water service, but prevents burst pipe losses by relieving the pressures that lead to bursting. Strategy 3 would require testing and probable development of existing technology (air chambers), or the development and testing of a new technology (pressure-relief plumbing fixtures).

# 7. Mitigation Efforts

Mitigation measures addressing burst pipe losses from freezing can be categorized into three areas: building practices, public education, and development of new technologies.

# 7.1 Building Practices

To the extent that residential building practices are governed at all, they are governed by local and state building codes through local code enforcement officials. State and localities generally employ model codes developed by one of the three model code agencies active in the United States, though local amendments are common. One method for moving toward loss prevention would be through improvements to the existing building codes.

#### 7.1.1 Code Review

During Phase 1 of the research, a review was conducted of the existing building and plumbing codes in relation to freeze protection of water pipes. The review focused on the codes presently in effect in the southern states.

The 1991 Standard Plumbing Code of the Southern Building Code Congress governs most of the southern states. The guidelines in this code regarding freezing are typical of most of the building codes:

## 407.4 Freezing

A water, soil, or waste pipe shall not be installed or permitted outside of a building, or concealed in outside walls or in any place where they may be subjected to freezing temperature, unless adequate provision is made to protect them from freezing.

This is the entire reference to freezing in the plumbing code. Other building codes are as brief, and contain essentially the same wording. The 1993 BOCA Plumbing Code adds the phrase "by insulation or heat or both" to the end of the statement, but is essentially no more definitive. The striking quality of these guidelines is that they are non-prescriptive. They provide the necessity of protecting water pipes from freezing, but no prescriptive formula to accomplish the protection. Both "subject to freezing" and "adequate protection" are left to interpretation. When this is the case, no means of verification or enforcement emerges.

To address the freezing and bursting pipe problem through amendments to building codes, it will be necessary to provide greater definition to the code. "Subject to freezing" should be specifically defined by conditions and building placement. "Adequate protection" should be prescribed by specified levels of insulation or other protective measures. A level of specificity would provide local code enforcement officials with the tools required to ensure adequate protection of water pipes.

The Phase 1 review of the building codes did discover one building code that offers prescriptive methods to water pipe freeze protection. This is the 1994 North Carolina State Building Code, which comprises the 1988 Standard Plumbing Code (Southern Building Code Congress) with North Carolina amendments. In the following discussion of potential prevention strategies and code amendments, the specifics of the North Carolina amendments will be examined.

#### 7.1.2 Building Cavities

Residential wall, floor, ceiling and attic cavities are typically used to distribute water to individual fixtures. When exterior cavities are used, the pipes may be subject to freezing. The placement and care taken in installation of water pipes in exterior wall cavities are critical to their vulnerability to freezing temperatures. The present code language does not directly address

proper installation. Following are recommended additions to the code language. Water pipes in ceiling cavities are included in the recommendations.

- "Pipes installed in a wall exposed to the exterior shall be located on the heated side of the wall insulation." (NC-1994).
- 2. When pipes are installed between two floors, the perimeter enclosure of those cavities shall be insulated with R-19 insulation, and the pipes located on the heated side of the insulation when entering the cavity. Pipes installed in floor cavities over unheated spaces, such as a garage, shall be placed on the heated side of the floor insulation.
- 3. In any building cavity containing water pipes, all penetrations in exterior walls, top plates, and bottom plates, shall be sealed.

The first recommendation is quoted from the North Carolina code, and is critical to the protection of water pipes in wall cavities. Technically, this amendment disallows blown-in insulation in wall cavities containing water pipes, as blown-in insulation would place a water pipe in the middle of the insulation layer as compared to "the heated side of the wall insulation."

The second recommendation extends the concern over pipe placement to ceiling cavities, and attempts to assure that ceiling cavities are thermally protected. There is anecdotal evidence showing that water pipes have frozen in ceiling cavities between floors, as well as in ceiling cavities over unheated garages.

The third recommendation is directed toward convective heat loss. Phase 2 research shows that convective heat loss, or wind chill, can have a dramatic impact on pipe freezing. Fiberglass insulation has little resistance to air movement, and convective heat loss from a penetration in a building cavity can accelerate pipe freezing even while the cavity is insulated. The requirement to seal penetrations through top and bottom plates is also an existing fire code requirement.

#### 7.1.3 Water Pipe Insulation

Pipe insulation is a secondary prevention strategy that is particularly applicable to the protection of water pipes placed in unconditioned spaces. The Phase 1 research identified the principal advantage of insulation as a burst protection strategy: by slowing the rate of heat loss, insulation delays the completion of an ice blockage, and thus delays the onset of elevated water pressures and the subsequent potential for bursting. Phase 2 field tests confirmed this finding, and provided examples of pipe

insulation levels providing satisfactory protection from freezing overnight temperatures. Additionally, the Phase 2 field tests identified three related advantages:

- 1. Pipe insulation maximizes the conductive heat gain through the pipe ends, leading to warmer equilibrium pipe temperatures.
- 2. Pipe insulation leads to colder and longer supercooling, requiring a colder environmental temperature to initiate ice formation.
- 3. Pipe insulation greatly reduces the potential for isolated convective heat loss, or wind chill effect, which is likely a major factor in burst pipe losses.

The sum of these advantages is significant, and presents the opportunity to reduce burst pipe losses through existing technology.

Most pipe insulation on the market has a thermal conductivity (k) of around k = 0.25 Btu\*in/hr\*ft<sup>2</sup>\*F°. Pipe insulation commonly sold to homeowners in hardware centers and home centers range in thickness from 1/8" to 5/8". This range of thickness provides a range of thermal resistance (R, the inverse of k for a known thickness) between R-0.5 to R-2.5. Pipe insulation of more substantial thickness and R-values are common in industrial applications, and are also readily available. Phase 2 field tests employed fiberglass pipe insulation with thicknesses of 1", 1.5" and 2" (thermal resistance of R-4, R-6, and R-8, respectively). The value of the additional thickness of insulation was shown during the field tests. For those regions where water pipes are located in unconditioned spaces, requiring a respectable level of insulation (R-6 to R-8) for these water pipes would have a positive impact on reducing the extent of burst pipe losses.

- "Water piping installed in an unconditioned attic or unconditioned utility room shall be insulated with an insulation having a minimum R factor of 6.5 determined at 75°F in accordance with ASTM C-177.
- NOTE: These provisions are minimum requirements that have been found suitable for normal weather conditions. Abnormally low temperatures for extended periods may require additional provisions to prevent freezing. (NC-1994).
- Pipe insulation sections shall be tightly butted, and the seams between sections taped. There shall be no gaps in pipe insulation throughout an unconditioned space.

The first recommendation is from the 1994 Revisions of the North Carolina Code. It is interesting to note that the 1993 Revisions called for insulation "having a minimum R factor of 7.4." That more stringent requirement was obviously reduced in 1994 to R-6.5. Inquiries to state code officials in North Carolina indicated that the reduction in R-value was made to address current manufacturing capability and the availability of insulation products. While "more is better" when it comes to pipe insulation, it would be expected that code amendments addressing insulation levels will be subject to limitations similar to the experience in North Carolina. A thermal resistance of R-6.5, as currently stated in the North Carolina Code, is a major improvement over typical residential pipe insulation values. In using the North Carolina Code as a model in this issue, the provision should be extended to all unconditioned spaces, including crawl spaces.

The note following the first recommendation is also from the 1994 North Carolina Code, and its message is pertinent. While greater insulation levels will reduce burst pipe losses significantly, pipe insulation will not eliminate all burst pipes. For any insulation level there exists conditions of "abnormally low temperatures for extended periods" which can render the insulation in some cases ineffective. At the same time, greater regional insulation levels would reduce the scale of any catastrophic loss event by providing adequate protection for a large number of marginal cases.

The second recommendation addresses the installation quality of pipe insulation. The purpose is to avoid gaps in insulation that can lead to *differential cooling*, or the freezing of an isolated section of pipe far before the rest of the pipe. As the research shows, differential cooling can lead to burst pipe situations.

Additional requirements relating to future technical developments are presently premature, but could be of great value. Potential technical developments are discussed below.

## 7.2 Public Education

Eliciting a widespread change in building practices would require a long-term effort. Most immediately, a program of public education could have a positive impact on hazard mitigation in the existing housing stock. This is particularly true in the southern tier of states, where catastrophic losses have occurred and remain a threat every few years.

7.2.1 Current Homeowner Recommendations A basic understanding and awareness of the pipe freezing process are essential. Homeowners should be alert to the problem, and have an awareness of where

water pipes run to reach their outlets, particularly the vulnerable pipes passing through unheated spaces. Therefore, the following advice and recommendations can be made to homeowners based on the recent research. The recommendations are mostly familiar:

Let the Faucet Drip. This is common advice and good advice. It is usually thought that providing flow in a pipe will prevent it from freezing. Water flow will delay freezing, but it may not prevent it in all cases. By opening a tap even slightly, pressure relief has been provided at the furthest downstream point that will prevent pressure buildup and ultimately bursting. Hot and cold water are brought to fixtures in separate lines, each of which could be subject to freezing, so it is necessary that each line contributes to the induced flow. Homeowners who let the faucet drip should be advised to keep the faucet in the slightly open position, even if the ice blockage causes the dripping to stop or slow down.

**Pipe Insulation.** The research verifies the advantages of pipe insulation. Commercial pipe insulation with thicknesses measuring 1", 1-1/2", and even 2" is commonly available from plumbing and insulation supply houses, and will outperform the thinner hardware store variety. Emphasis should be placed on careful installation to avoid gaps.

Heat Tapes. The present research did not involve investigation into the use of heat tapes or heating cables. Clearly, a safe supply of heat to a pipe will be an effective freeze prevention measure. Emphasis should be placed on using a high quality heating cable with heavy wire insulation and a built-in thermostat, and following manufacturers' instructions. Heat tapes and cables will not work, of course, in the case of a power outage.

Interior Temperature. The temperature of the interior of a house is a principal variable to the likelihood of freezing. It is common for homeowners to turn down their thermostats when leaving home for a few days. If already vulnerable pipes exist in this case, the likelihood of freezing is multiplied. Care should be taken not to turn down the thermostat too far, otherwise the homeowner should follow the next recommendation when leaving home in the winter.

**Shut Down the Water System.** It is not a difficult task to shut off the water to a residence. A main shut-off valve is usually found where the water first enters a home. Shutting off the valve and opening the various outlets will drain most of the water out of the system and introduce large quantities of air. With the water supply

shut off, the valves can remain open, and the possibility of burst pipes eliminated. One does not have to leave home to take advantage of this procedure, which can protect a home from severe overnight lows until morning.

7.2.2 Temperature Alert Threshold Alerting the public of ways to help protect the water pipes in their homes from freezing could prove quite beneficial in preventing losses due to burst water pipes. To have the greatest impact, such an alert could be implemented just before a dangerous cold spell. The temperature at which to carry out an alert can be defined as the "temperature alert threshold." It was a principal concern of the research sponsor to determine an appropriate temperature alert threshold for the southern states.

Several factors determine the temperature of a pipe in a house, and thus the point at which the pipe is subject to freezing. The major factors are:

- The temperature outside.
- · The placement of the pipe in the building shell.
- The amount of insulation in that portion of the building, and the placement of the pipe in relation to the building insulation.
- Wind speed, and whether there is a hole or crack in the building shell that would affect the pipe.
- The amount of insulation on the pipe itself, if any.
- · The temperature on the inside of the building.

Most of these factors deal with the building and plumbing system rather than with the conditions outside. This is why the southern states have more catastrophic losses from burst pipes; building practices in the south do not protect pipes from occasionally severe weather. For any specific pipe in a specific house these building factors are known, and the research into the freezing process would allow us to make a reasonable determination of the actual outdoor temperature from direct calculation. Establishing this temperature threshold for an entire region, however, would require extensive knowledge of building practices and the distribution of pipe placements within buildings. This knowledge is not available.

While determining a temperature alert threshold is problematic, the recent research into the pipe bursting phenomena does provide some information that is pertinent to establishing a temperature alert threshold for

the southern states. The field tests performed at the BRC through the winter of 1995 featured pipes installed in an unconditioned attic. The first step toward a burst pipe incident is the initiation of freezing, and the start of ice formation. *Table 5* shows the outdoor temperature and the attic temperature when the most vulnerable, uninsulated pipe started to freeze during the Phase 2 field tests.

There is a remarkable consistency to the temperature at which the pipe started to freeze: just at or below 20 °F. Simply put, whenever the outside temperature fell below twenty and into the teens, the uninsulated pipe was immediately in jeopardy. This is clearly below the commonly known freezing temperature of water of 32°F: supercooling and the slightly elevated temperature from being in the attic produced this consistent result.

This data represents the "worst case" scenario. The pipe was uninsulated, and on the outside of R-30 fiberglass attic insulation in a vented attic. The last column shows the temperature difference between the outside and the attic: a slim 3.2°F. Short of placing a pipe on the outside of a building altogether, this is about as vulnerable as a

residential water pipe can get. Given the extent of pipe freezing losses seen in the southern states, it may be prudent to base the temperature alert threshold on this "worst case" scenario. Based on this analysis, a temperature alert threshold could be established at 20°F for the southern United States.

It is expected that isolated, infrequent, freezing incidents will occur at overnight temperatures above the threshold, between 20 and 32 °F. Holes in the exterior shell of a house can play a major role for pipes that would otherwise appear protected. The temperature alert threshold of 20 °F should, however, address the vast majority of burst pipe incidents, and provide the best value returned in a public education investment.

# 7.3 Potential Technical Developments The research showed two potential developments that could reduce the incidence of burst pipe losses: air chambers and pressure-relief plumbing fixtures. Both developments address the problem by moderating the excessive water pressures associated with the freezing and bursting of water pipes.

Date	Outdoor Temperature F	Attic Temperature F	Difference: Outdoor to Attic Temperature F	
23-Jan	16.5	21.0	4.5	
29-Jan	19.4	20.8	1.4	
5-Feb	19.9	23.5	3.6	
7-Feb	18.1	20.2	2.1	
9-Feb	15.4	19.5	4.1	
11-Feb	19.6	23.4	3.8	
14-Feb	19.2	23.9	4.7	
1-Mar	19.0	21.4	2.3	
3-Mar	19.6	23.5	4.0	
8-Mar	19.8	22.5	2.7	
9-Mar	20.1	22.3	2.2	
Average	18.8	22.0	3.2	

7.3.1 Air Chambers for Burst Protection
The Phase 1 research determined that air chambers
could be effective in moderating the extreme pressures
associated with frozen water pipes, and in so doing,
prevent bursting. The benefit of air chambers is not in
the prevention of freezing in a water pipe, but in the
accommodating of the subsequent pressure following
freezing. The Phase 2 field tests confirmed this finding.
In all cases, the use of air chambers in the field tests
prevented bursting of frozen water pipes.

The air chambers used in the field tests were constructed specifically for the test, and did not incorporate a seal separating the air and the water in the chamber. This "home-made" design is not recommended. Experience has shown that air chambers without a seal between the air and the water eventually lose their charge of air, and would become ineffective for burst protection. Commercially available air chambers are manufactured with this seal in place, and are expected to hold their charge indefinitely.

Air chambers are manufactured as "water hammer arrestors", intended to address the problem of water hammer, which is the pressure-induced knocking of water pipes when a quick closing valve is shut. Current testing of these devices are designed to test their endurance during numerous, momentary pressure surges. For burst protection, it would be necessary to determine the viability of these products under sustained pressure of 12 to 24 hours as compared with numerous pressure surges. An established, safe working pressure will need to be established. For any given run of pipe, determining the proper size for a burst-protecting air chamber is a trade off between volume and pressure rating. Research and development aimed at developing air chambers with the specific requirements for burst protection is needed. It does not seem, however, that the existing market is far away from these requirements. It is possible that existing designs can meet the requirements for burst protection devices. The development of this technology could be accomplished with the existing manufacturers.

The use of air chambers on water pipes that run through unconditioned spaces could greatly reduce the incidence of burst water pipes. Economical air chambers that could be easily retrofitted to existing residential plumbing systems would be particularly beneficial in addressing the existing risk exposure.

7.3.2 Pressure Relief Plumbing Fixtures
The most promising and elegant burst prevention
strategy is based on pressure-relief plumbing fixtures. As

with air chambers, this strategy accepts the completion of an ice blockage, but provides pressure relief to avoid the excessive pressures associated with bursting. Rather than providing a chamber of air, pressure-relief plumbing fixtures would discharge water from the line at a specified pressure well below the burst pressure of the line. Discharge would be through the fixture into the existing drain basin (sink, bathtub, etc.). The Phase 2 field tests showed the practicality of this principle.

Widespread adaptation of pressure-relief plumbing fixtures could virtually eliminate the burst water pipe phenomena at marginal additional cost. They would require no maintenance, and no more labor to install than a standard fixture. One can envision pressure relief becoming a standard feature of plumbing fixtures.

The concept of plumbing fixtures with pressure-relief designed into the fixture is a novel idea. There are no such fixtures presently being marketed. There are many types of plumbing fixtures based on several types of basic, functional design. The basic designs are often specific to the manufacturer. Each type of fixture would require design modifications equally specific. Given this fact, the development of pressure-relief fixtures would be best accomplished in cooperation with, and with the design resources of, the existing plumbing fixture manufacturers.

Based on the recent research, the University of Illinois has submitted a patent application covering the concept of pressure-relief plumbing fixtures.

#### 8. Conclusions

## 8.1 Phase 1

The major conclusions from Phase 1 of the work are:

- Water pipes freeze in several stages: 1) water cools to a temperature below freezing, 2) dendritic ice forms as the supercooled water warms back to 0°C, 3) over an extended period of time, the remaining water changes to dense annular ice, and 4) the ice temperature cools to the temperature of the surrounding air.
- In the initial cooling of the first stage, the temperature of a water pipe falls rapidly to the freezing point, and even falls below the freezing point (supercools) prior to any ice formation. Following supercooling, as much as six percent of the water forms into dendritic ice. Complete annular ice formation occurs much later in the freezing process. While other researchers have shown that den-

dritic ice can lead to a flow blockage, it is likely that only annular ice is capable of creating a blockage to contain the excessive pressures of a burst event. The formation of an annular ice blockage is the critical point leading to a ruptured water pipe.

- The formation of annular ice (phase change) proceeds in a consistent, predictable fashion. The principal controlling variables during phase change are ambient temperature (the temperature of the air surrounding the pipe) and insulation level. For moderate subfreezing temperatures and durations, it is possible to specify an insulation level that would delay phase change to the extent of preventing annular ice blockage and bursting.
- The composition and diameter of the pipe have a lesser, though measurable, impact on the time it takes to complete annular ice formation. Whether water in a pipe was drawn from a cold water source or a hot water source did not appear to have any bearing on the time to complete phase change.
- Burst pipes result from excessive fluid pressure caused by an 8 percent volumetric increase of water as it turns to ice. A pressure increase requires a confined pipe section. During freezing, rupturing only occurs between a complete annular ice blockage and a closed, downstream outlet. There is no confinement, and thus no rupturing, upstream from an ice blockage.
- Once an annular ice blockage occurs, continued freezing leads to an immediate increase in pressure in the confined pipe section. The amount of air in the water and ice probably plays a major role in the ability of the pipe assembly to absorb the increased pressure.
- If the water pressure from ice expansion reaches the burst strength pressure of the water pipe, a rupture will occur. Pipe bursting is not due to outward (radial) expansion of ice, but from excessive water pressure. The rupture generally occurs in a portion of the pipe that has seen little ice formation.

#### 8.2 Phase 2

The major conclusions from Phase 2 of the work are:

 Long and deep supercooling of the water pipes in the field tests was typical, with supercooled temperatures at or approaching the maximum temperature depression of -6°C. As a result, freeze

- events in which dendritic ice formation was of the maximum density were common. In no cases did a dense dendritic ice formation result in increased hydraulic pressure in a pipe. Dendritic ice formation does not have the structural integrity to withstand the elevated pressures associated with the burst pipe phenomena. A blockage of annular ice is required.
- Supercooling of water pipes can last indefinitely.
  Freeze events were recorded that featured supercooling of up to 80 hours. As a result, the initiation of ice formation, and ultimately an ice blockage, can be greatly delayed as a result of supercooling.
- In residential construction, water pipes subject to freezing temperatures run from a warm space, into the unconditioned subfreezing space, and then back into a warmer conditioned space. Conductive heat gain through the water and pipe material from the warmer spaces at each end of the pipe plays an important role in the freezing process. This results in a typical temperature profile with the coldest section of pipe in the center, and warmer sections toward each end. Barring significant convective heat loss, pipes typically freeze at the center of the unconditioned space, with ice growth proceeding towards the ends.
- Convective heat loss, or the wind chill effect, is a result of wind and air leakage on water pipes. The wind chill effect can have a dramatic impact on pipe freezing. The effect is greatest on uninsulated pipes, and minimal on pipes with insulation. It is probable that many of the burst pipe losses are associated with wind and air leakage on uninsulated pipes, either from unintentional air leakage through the building envelope, or from intentional vents in unconditioned spaces.
- Pipe insulation plays a major role in the freezing of water pipes, and represents a legitimate burst protection strategy. The principal advantage of pipe insulation is that, by slowing the rate of heat loss, insulation delays the completion of an ice blockage, and thus delays the potential for bursting. The phase 2 field tests confirm that it is possible to protect a water pipe through a cold spell of limited duration with pipe insulation.

- Beyond its principal advantage, pipe insulation provides three additional advantages relating to other findings in the phase 2 research:
  - a. Pipe insulation maximizes the conductive heat gain through the pipe ends, leading to warmer equilibrium pipe temperatures.
  - Pipe insulation can lead to colder and longer supercooling, requiring a colder environmental temperature to initiate ice formation.
  - c. Insulation greatly reduces the potential for isolated convective heat loss, or wind chill effect, which is likely a major factor in burst pipe losses.

The sum of these advantages is significant. Requiring a respectable level of insulation (R6 to R8) for water pipes in unconditioned spaces would have a positive impact on reducing the extent of burst pipe losses.

- Pressure-relief plumbing fixtures would be a practical and effective strategy in reducing burst pipe losses. Pressure-relief plumbing fixtures have yet to be developed.
- Air chambers are an effective strategy in preventing burst pipe losses. Air chambers intended for burst protection must be installed in the conditioned (heated) space, or on the heated side of building insulation in a building cavity, close to the faucet or outlet of the water line. The performance of air chambers designed for burst protection can be analyzed by Boyle's Law. The current

market for air chambers is based on their use as "water hammer arresters". In order to specify air chambers for burst protection, tests should be performed aimed at their ability to withstand sustained pressure.

## 8.3 Strategies

Four loss prevention strategies for burst water pipes can be identified based on the research:

- Prevent water pipes from ever encountering freezing temperatures through **placement** in the conditioned space of a building. Placement is meant to include the avoidance of air leakage through the building, and the wind chill effect.
- Accept some subfreezing temperatures, but provide sufficient insulation to reduce heat loss to the point where an annular ice blockage cannot occur.
- Accept both subfreezing temperatures and annular ice blockage, and install air chambers to moderate the excessive pressures required for bursting.
- 4. Accept both subfreezing temperatures and annular ice blockage, and install pressure-relief plumbing fixtures to provide protection at a pressure below the burst pressure of the water pipe.

The third and fourth strategies allow total freezing, and thus the temporary loss of water service, but prevent burst pipe losses. Strategy 3 would require testing and probable development of existing technology. Strategy 4 would require the development and testing of a new technology.

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