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Forensic Engineering Research and Testing of Building Copper Tube Water Piping System Freeze Failures

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Abstract

Forensic engineers investigating water loss incidents, caused by water leaking from damaged copper tube piping systems inside buildings, are tasked with determining if that damage is from the piping being exposed to subfreezing temperatures or some other cause. This paper provides guidance for such investigations and factual basis for such opinions, including presenting the results of experimental testing of water-filled copper tube piping systems exposed to subfreezing conditions. It also discusses piping standards and building codes. When ice forms a solid plug inside a pipe, the portion of the piping downstream of that plug becomes isolated. As the ice plug grows, the pressure in the isolated portion of the piping system increases dramatically from hydraulic pressure until the strength of the "weak link" is exceeded, which causes a rupture that relieves the pressure. Oftentimes, no significant water flows through the rupture at that time because the ice plug prevents water flow through the pipe. However, significant water flow occurs once the plug melts. This paper demonstrates why it is critically important for forensic engineers to understand this sequence of events.

Keywords

Water, freeze, ice, copper tube, pressure, rupture, damage, forensic engineering, testing, freeze failure, piping, plumbing

Introduction and Background

For forensic engineers to be permitted to testify in federal court on their opinions in a particular matter, their work is required to comply with Federal Rules of Evidence, Rule 702[1]. That rule requires that an expert witness' "testimony is based on sufficient facts or data." This paper provides facts and data for an expert to rely on when investigating a water damage incident involving copper tube plumbing systems.

The cost of frozen pipe water damage incidents is significant. In fact, approximately 250,000 buildings are damaged by frozen pipes every year. Other estimates indicate the average cost per incident is \$15,000[2]. This data suggests the annual cost is on the order of \$3.75 billion. The following hypothetical case study illustrates the various issues a forensic engineer may encounter when investigating a potential pipe freeze incident.

Case Study

A forensic engineer, retained to investigate a water damage incident to a single-family home, inspected the building and discovered a rupture in a length of copper tube water line. The water line extended from the basement upward through an exterior wall and horizontally through a second-floor joist space to a second-floor bathroom. The rupture was located in the horizontal tube 10 feet from the exterior wall. The engineer documented the outdoor temperature was well below freezing for days immediately before the date the water damage incident was discovered, and rose above freezing on the day of the incident. The engineer also documented the heating system inside the house was set low (but above freezing) during that time. The engineer concluded the temperature inside the house dropped below freezing, and the copper tube water line froze and burst, permitting a large volume of water to flow through the rupture and cause extensive water damage inside the house.

The forensic engineer was subsequently asked two questions by an attorney representing an adverse party during a deposition: 1) If the tube burst from freezing,

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why didn't the burst occur inside the exterior wall where it would have been first exposed to subfreezing temperatures and froze? 2) What caused the tube to burst 10 feet inboard of the exterior wall where it was surrounded by the warmer temperatures? This paper provides experimental test data that answers those questions.

Codes and Standards

A brief discussion of some codes and standards forensic engineers should be aware of when conducting this type of water damage incident follows. Building codes contain requirements for water service and distribution systems. For example, the International Residential Code (IRC) states the maximum allowable pressure for residential water piping systems is 80 p.s.i., and pressure-reducing valves are required when the pressure exceeds that number[3]. Thermal expansion control and water hammer arrestors may also be required. The IRC also specifies the allowable types of copper tube for water distribution systems are types K, L, and M[4]. The International Property Maintenance Code (IPMC) requires hot water to be supplied at a minimum temperature of 110ºF[5].

Requirements for components of copper tube water systems are contained in the following standards. These requirements include dimensions and tolerances, temperature and pressure ratings, and testing requirements.

- ASME B16.18 Cast Copper Alloy Solder Joint Pressure Fittings[6]
- ASME B16.22 Wrought Copper and Copper Alloy Solder-Joint Pressure Fittings[7]
- ASTM B32 Standard Specification for Solder Metal[8]
- ASTM B88 Standard Specification for Seamless Copper Tube[9]

Copper Tube Specifications

A popular choice for building domestic water and hydronic heating systems, copper tubing was introduced around 1927, and its use grew to include about 90 percent of indoor water piping. Currently, more than 5.7 million miles of copper tubing has been installed in homes and commercial buildings in the United States[10]. Piping systems of other materials include galvanized pipe and plastic pipe (PVC, CPVC, and PEX) to name a few. However, this paper focuses on copper.

A well-known excellent conductor of electricity and heat energy, copper has low thermal resistance (inverse of thermal conductivity) when compared to other piping materials. For comparison purposes, the thermal conductivity of copper is about 10 times the value for steel and more than 2,000 times the value for PVC[11,12,13]. Consequently, water inside copper tube will cool and freeze quickly. Ice plugs will form earlier in a freezing event when compared to other piping materials.

The wall thickness of the allowable types of copper tube for water distribution systems varies by type (for ½ in. tube): Type K = 0.049 in.; Type L = 0.040 in.; and Type M = 0.028 in., which correlates with their rated pressures. **Figure 1** provides basic copper tube specifications, including rated and burst pressures[14]. The rated and burst pressures decrease with increased pipe size. Information printed on the tube is color coded to the Type. Copper tube is available in annealed and drawn products. Since the allowable maximum pressure for residential and light commercial building water supply is 80 p.s.i., the lowest rated pressure for drawn tube is at least 10 times the expected water pressure in a piping system, and the burst pressure is at least 75 times. Straight lengths of pre-cut individual tube are typically drawn but may be annealed. Coiled tube is annealed only. Drawn tube is stiffer and has a greater rated pressure, while annealed tube is more ductile. The use of solder having a lead content greater than 0.2 percent has been banned for potable water systems since 1986.

Pipe Freeze Failure Mechanism

When a water-filled piping system is subjected to subfreezing conditions, portions of the system may freeze when one or more ice plugs form and expand in the piping. Water expands as it freezes to ice, which causes the water pressure in "closed" portions of the system to increase dramatically. If the piping or components have insufficient strength to withstand the pressures they encounter, they will fail at the weakest points and relieve the pressure.

If the pressure can be relieved, then a pipe rupture may be avoided. Accordingly, the practice of opening a faucet to maintain minimal water flow during cold spells permits the pressure in the piping system to dissipate without reaching damaging levels.

Air chambers or air pockets in the piping system may protect the system from freeze failures. The water being displaced by the growing ice plug can partially fill the air space, thereby limiting the pressure rise. However, piping ruptures can occur when the water occupies enough

Type	Color Code	Nominal Size/Dia. (in.)	O.D. (in.)	Wall Thickness (in.)	Rated Pressure (P.S.I.)		Burst Pressure (P.S.I.) @ Room Temperature	
					Annealed	Drawn	Annealed	Drawn
K	Green	½	.625	.049	891 @ 100F 446 @ 400F	1534 @ 100F 1400 @ 400F	4535	9840
		¾	.875	.065	852 @ 100F 426 @ 400F	1466 @ 100F 1338 @ 400F	4200	9300
		1	1.125	.065	655 @ 100F 327 @ 400F	1126 @ 100F 1028 @ 400F	3415	7200
L	Blue	½	.625	.040	722 @ 100F 361 @ 400F	1242 @ 100F 1133 @ 400F	3885	7765
		¾	.875	.045	582 @ 100F 291 @ 400F	1002 @ 100F 914 @ 400F	2935	5900
		1	1.125	.050	494 @ 100F 247 @ 400F	850 @ 100F 776 @ 400F	2650	5115
M	Red	½	.625	.028	494 @ 100F 247 @ 400F	850 @ 100F 776 @ 400F	n/a	6135
		¾	.875	.032	407 @ 100F 204 @ 400F	701 @ 100F 639 @ 400F	n/a	4715
		1	1.125	.035	337 @ 100F 169 @ 400F	701 @ 100F 639 @ 400F	n/a	3865
Source: Copper Tubing Handbook								

Figure 1
Table of copper tube specifications.

volume of the original air space to compress the air to the piping burst pressure.

When a water-filled piping system is exposed to subfreezing conditions, heat energy transfers from the water through the piping wall to the environment, cooling the water to 32°F (0°C). The water in the piping freezes at one or more locations, with an ice plug forming inside the pipe at each location. Copper tube has low thermal resistance when compared to other piping options, so it provides minimal insulating value to resist the heat loss of the water inside the tube.

Ice plugs may form at different locations where the piping system is exposed to subfreezing temperatures in the building, such as in an inadequately insulated exterior wall, floor/crawl space, ceiling/attic, or near an area with air infiltration (e.g., door, window, crack in a wall, or other opening). Portions of the system downstream of the ice plugs become isolated and closed. Increased pressure in the portion of the system upstream of the plug may dissipate backward toward the water source. Ice plugs inside the tube expand longitudinally within the pipe as more water freezes. A 9 percent volumetric expansion of the ice in a closed portion of the piping system causes the water pressure in that section to increase dramatically, creating very high hydraulic pressures.

The pressures increase until the burst pressures of the weakest points in the closed sections are exceeded, causing piping component failures. Ruptures are typically not due to direct contact with ice plugs[15]. There may not be any significant water leakage at the time of rupture because the ice plugs prevent water flow through the pipes. When the piping containing the ice plugs warms above freezing, the ice plugs melt, and water flows through the ruptures, causing water damage.

As the pipe is cooled, the water temperature decreases by several degrees below 32°F, supercooling the water. Supercooling is based on a concept that the ice nucleation temperature is different than the phase change equilibrium temperature[16]. Supercooling may last for an extended period of time, and has been documented in testing to last up to 80 consecutive hours[12]. The metastable (marginally stable) water initiates ice nucleation, and ice crystals begin to form on the inner surface of the tube wall, growing in the dendritic form[12,13]. Ice nucleation is the point where the phase change begins when water freezes to ice. When ice begins to form, the temperature abruptly increases to the phase change equilibrium temperature and remains there during the freeze process. The noted abrupt increase in temperature is caused by the initiation of the phase transition from water to ice. This process releases energy (latent heat of fusion), which increases the temperature. The latent heat of fusion is the heat energy needed to change the state of a substance from a solid to a liquid. The abrupt temperature increase indicates the point of dendritic ice formation, resembling the branches of a tree (**Figure 2**). Once the water has fully phase changed from water to ice, the temperature then progressively decreases as the ice gets colder.

As water undergoes the phase transition to ice during a freezing process, the density decreases and the volume increases, which is why ice cubes float in a glass of water. When water freezes to ice at 0°C, the densities are 0.9998 g/cm^3 for water and 0.9167 g/cm^3 for ice, revealing the change in volume is 1.091. Likewise, at -10°C, those values are 0.9993 and 0.9196, for a change in volume of 1.087[17]. Accordingly, there is a 9 percent increase in volume when water freezes to ice. **Figure 3** presents this information in tabular form.

Figure 2
Photo of dendritic ice formation on needles on a tree.

An ice structure then grows from the tube wall inward at the phase change temperature until it has formed a plug when all the water in the area has frozen solid. However, the tube typically does not fail at the plug. This condition is the basis of pipe freeze kits used to intentionally freeze sections of pipes (forming ice plugs) to isolate and drain downstream portions of the piping and perform maintenance work[18].

Flash freezing of water (where water instantly freezes to ice) at the pipe rupture location has been documented. This condition is caused by the high system pressure depressing the phase change temperature. Then, when the rupture occurs, the pressure suddenly drops to atmospheric, causing a flash freeze of the water discharging from the opening in the pipe. This phenomenon is explained by the phase diagram for water (**Figure 4**)[19]. The negative slope of the boundary line between the solid and liquid phases is significant because it indicates the freeze temperature decreases as the pressure increases, and vice versa. For example, the phase change temperatures at 14.7 p.s.i. (1 atmosphere) and 14,504 p.s.i. are 32.0°F and 15.8°F, respectively[17].

Temperature	**Water Density**	**Ice Density**	**ΔV**
0°C	0.9998 g/cm^3	0.9167 g/cm^3	0.09
-10°C	0.9993	0.9196	0.09

Figure 3
Table of water and ice densities.

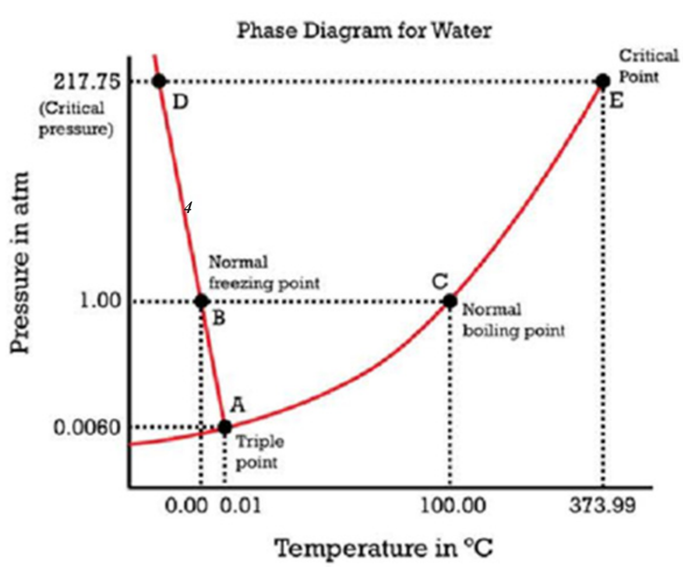

Figure 4
Phase diagram for water.

The pressure that is developed is dependent on the size of the ice plug and the volume of the closed portion of the piping system downstream of that plug. Since water is essentially incompressible, the volume of the water displaced by the ice toward the closed end of the system causes the pressure increase. The increased pressure causes the piping to expand both radially and longitudinally. This increased volume of the piping compensates for some of the ice expansion. However, the piping ruptures when the stress exceeds the ultimate strength of the material.

The length of closed portion of the piping system, downstream of the ice plug, is a key factor in whether a rupture will occur. If the volume of the closed portion of the piping is sufficiently large relative to the size of the ice plug, the burst pressure will not be reached, and the piping will not rupture. A rupture occurs when the change in volume of the fluid exceeds the allowable change in volume of the piping. The critical length of the piping to cause a rupture can be calculated as follows[15].

The change in volume of the fluid is:

$$\Delta V_f = I L_f d^2 \frac{\pi}{4}$$

Where: ΔV_f = the change in fluid volume

I = volume increase from water freezing to ice (9 percent)

L_f = the length of pipe frozen beyond the initial freeze

d = the inside diameter of the pipe

The change in volume of the pipe to cause a rupture is:

$$\Delta V_p = l d^2 \frac{\pi}{4} \left[(1+\sigma_{hoop}/E)^2 (1 + \sigma_{axial}/E) - 1\right]$$

Where: ΔV_p = change in pipe volume

l = length of pipe not frozen beyond the initial freeze plug

σ_{hoop} = hoop stress corresponding to the critical "burst" pressure of the piping

σ_{axial} = axial stress corresponding to the critical "burst" pressure of the piping

E = modulus of elasticity

The critical length is found by solving for L_f when ΔV_p equals ΔV_f at the critical pressure:

$$L_f = \frac{l}{I} \left[(1+\sigma_{hoop}/E)^2 (1+\sigma_{axial}/E) - 1\right]$$

Experiments

Physical experiments were performed in a laboratory on ½-inch nominal diameter copper tube assemblies exposed to subfreezing conditions to:

1. Evaluate downstream pressures generated from ice plugs forming and growing inside a piping system, including the pressures necessary to fail copper tube, copper fittings (elbows and caps), solder joints, push-connect components, and compression components.

2. Determine whether the failures occur at the point of the ice formation (ice plug) where the tube was in direct contact with the ice or in liquid filled closed portions of the system due to increased water pressure from ice plug growth inside the piping.

3. Investigate the process of ice plug formation inside copper tube.

Three experiments were conducted. The first utilized copper tube assemblies connected to a refrigerated galvanized pipe test apparatus where temperatures and water pressures were recorded. The second utilized "U"-shaped copper tube assemblies open at both ends (filled with water and frozen inside the freezer). Only temperatures were recorded. The first and second test apparatuses were generally consistent with test apparatuses utilized in similar water pipe freeze testing[13,15]. The third test utilized a straight section of copper tube extending through a cold chamber. Windows were present on the ends of the tube, and the tube was filled with water. The formation of ice inside the tube was documented, and temperatures were recorded. Distilled water was used during the testing to control variations in the freeze temperature from minerals and impurities in the water. The initial pressure in all tests was atmospheric.

Ice Plug Expansion Pressure Experiment

Tests were performed on a closed piping system of galvanized pipe and copper tube (**Figures 5** and **6**). The test apparatus was in the shape of an inverted "L" of ¾-inch galvanized pipe. Galvanized pipe was used because it had a significantly higher burst pressure than copper tube to assure any failures occurred within the copper tube system. The piping was carefully filled completely with water to eliminate any air entrapment. A new and calibrated 10,000 p.s.i. pressure transducer (error +/- 0.05 FS) and data logger was located in the branch port of a tee fitting of the galvanized pipe. A ½-inch reducer bushing was threaded into the end of the short leg, and the ½-inch copper tube test assemblies were screwed into the test apparatus there. The vertical leg was insulated with a progressively thicker layer starting with no insulation on the lowermost 6 inches and stepped up thicker layers every 6 inches, progressing toward the top.

The vertical leg was placed inside an electric freezer and projected out the top of the freezer (**Figure 7**). The copper tube assembly was positioned horizontally above the freezer in the room environment, and remained well above freezing during the testing.

This configuration assured an ice plug formed near the bottom of the vertical leg and grew upward, progressively increasing the water pressure above the ice. The pressure within the liquid portion of the system was recorded along with various temperatures. New K-type thermocouples (accuracy +/-2°F) were installed on the lower portion of the galvanized pipe vertical leg where no insulation was present (T1), on the copper tube piping assembly (T2), inside the freezer measuring the air temperature (T3), and

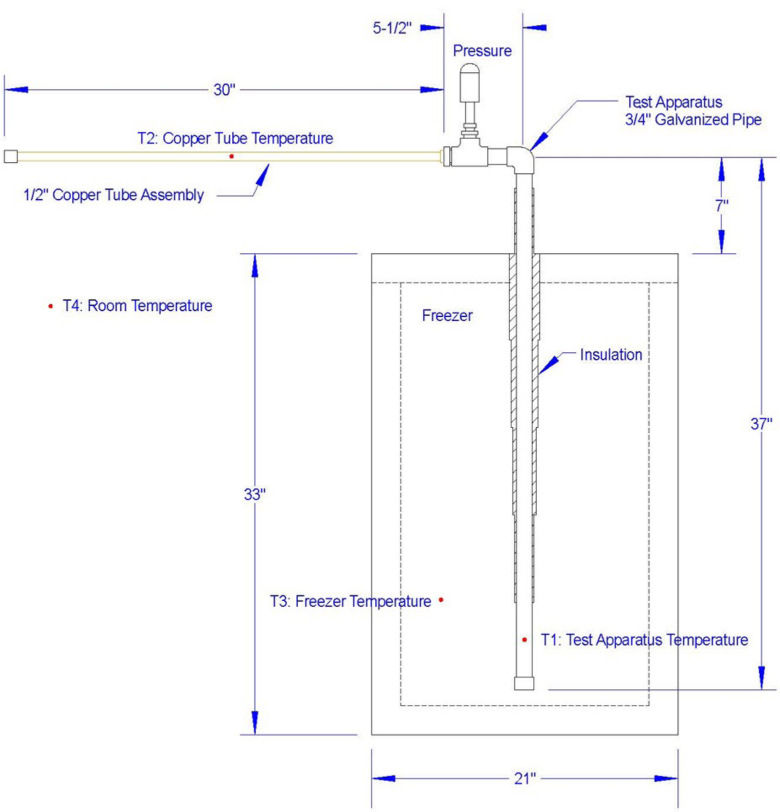

Figure 5
Diagram of ice plug expansion test apparatus.

Figure 6
Photo of the galvanized pipe test apparatus, showing pressure transducer and copper tube test assembly attached. Different configurations of copper tube assemblies were tested. Accordingly, this copper tube assembly is different than the one illustrated in **Figure 5**.

Figure 7
Photo of the test setup, showing test apparatus installed in freezer.

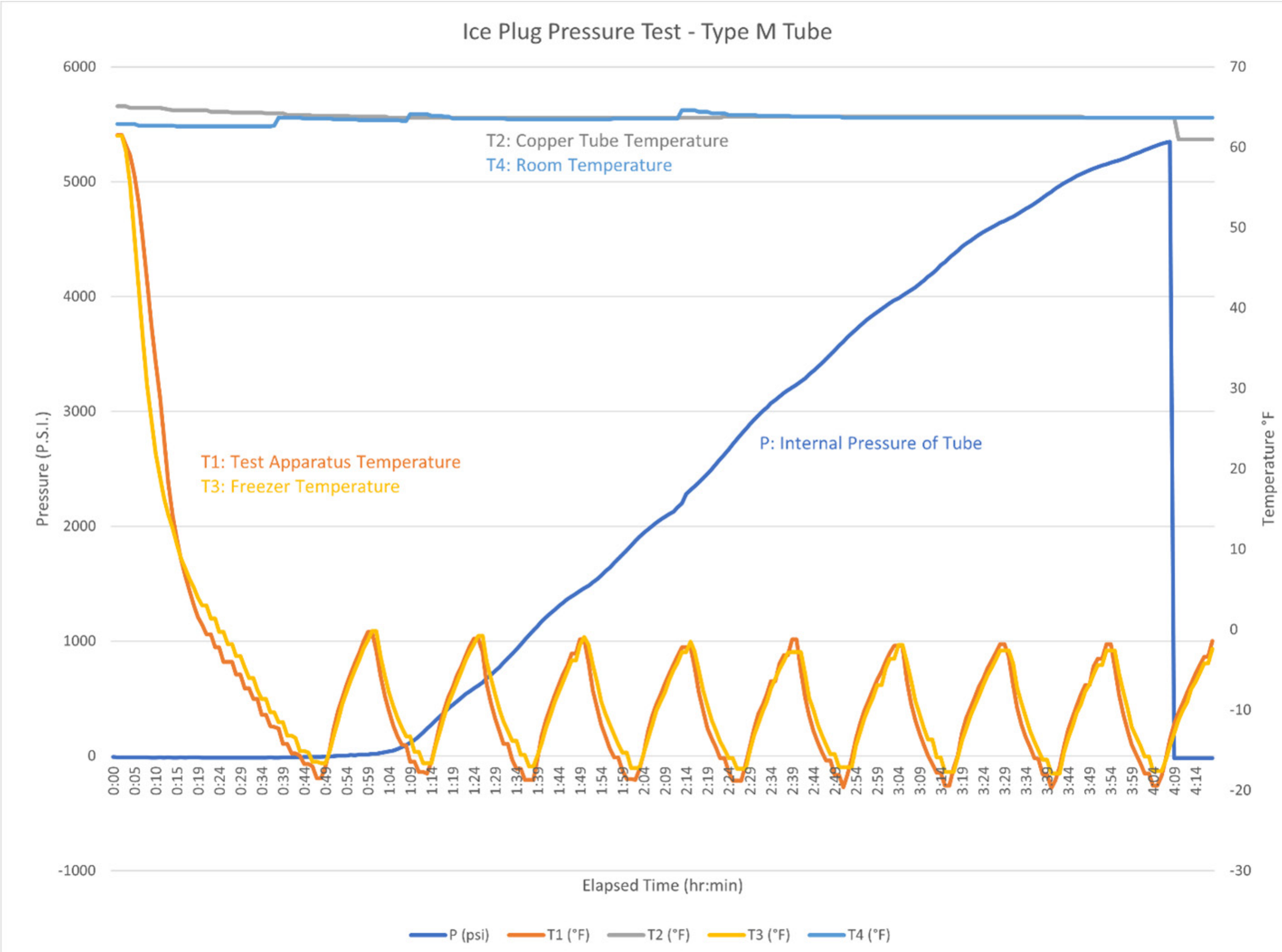

Figure 8
Graph of pressure and temperature data from Type M copper tube test.

measuring the room temperature (T4). The pressure transducer measured the water pressure in the upper portion of the test apparatus, which remained water filled. **Figure 8** illustrates the pressure and temperature data for a test run.

The test apparatus temperature (T1) closely followed the freezer temperature (T3). Likewise, the copper tube temperature (T2) closely followed the room temperature (T4). The pressure began to increase approximately 1 hour into the test and then increased fairly consistently for about 3 hours where it then dropped suddenly back to atmospheric pressure when the tube ruptured. The maximum pressure attained was approximately 5,300 p.s.i.

Group 1 tests: Caps and threaded male adapters were soldered onto straight sections of Type M copper tube. Lead-free silver bearing solid wire solder (complying with ASTM B32) was utilized in all tests. The tube was attached to the test apparatus and carefully filled with distilled water to prevent air pockets. The freezer was then turned on, and the temperatures/pressures were recorded every minute. The copper caps ruptured in "fish-mouth"-type failures at an average pressure of 5,048 p.s.i. (**Figure 9**). Burst pressure readings from different trial runs were within 3 percent of each other. The burst

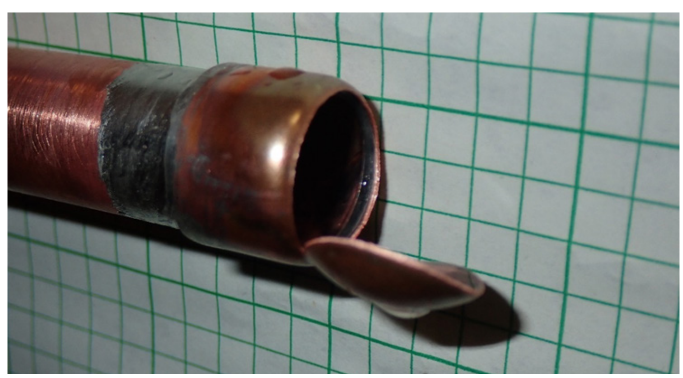

Figure 9
Photo of a "fish-mouth" rupture of copper cap.

pressures may have been lowered when the annealed strength of the material was reduced from the heat of the torch during the soldering process, where the rupture locations were within the heat-affected zones of the fittings.

Group 2 tests: The cap was replaced with a second male adapter and a galvanized cap, permitting higher pressures to be developed inside the tube. The tube was again attached to the test apparatus, filled with water, and the freezer was turned on. The Type M copper tube split longitudinally at an average pressure of 5,373 p.s.i. (**Figure 10**). Burst pressure readings from different trial runs were within 2 percent of each other. The splits generally occurred in the middle of the tube well away from any potentially heat-affected areas at the ends where the adapters had been soldered to the tube.

Group 3 tests: The copper tube configuration was the same as the Group 2 tests except the Type M copper tube was replaced with Type L (greater wall thickness). No failures occurred, and the maximum pressure attained was 7,133 p.s.i. Note: At those high pressures, small, slow drip-type leaks developed in threaded joints in the galvanized pipe assembly, which permitted enough water loss to limit any further pressure increases.

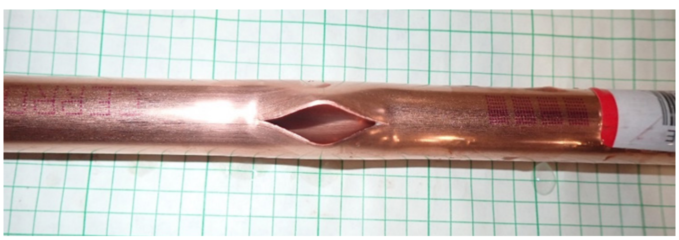

Figure 10
Photo of a longitudinal rupture in Type M copper tube.

Figure 11
Photo of a longitudinal rupture in copper elbow fitting.

Group 4 tests: "L"-shaped copper tube assemblies with a copper 90° elbow fitting and a capped threaded adapter on the end were attached to the test apparatus. All ruptures occurred at the elbow fittings in longitudinal-type failures at an average pressure of 4,682 p.s.i. (**Figure 11**). Burst pressure readings from different trial runs were within 5 percent of each other.

Group 5 tests: Push-to-connect caps were fully pressed onto the ends of copper tube so there was full engagement. The caps began to drip water at an average pressure of 1,029 p.s.i. (**Figure 12**). Failure pressure readings from different trial runs were within 30 percent of each other. Some movement of the caps on the tube was observed. In later tests, the caps were installed on copper tube and frozen solid (**Figure 13**). During those tests, the metal outer caps were pushed off the tube by the expanding ice. However, the inner plastic components remained on the tube.

Group 6 tests: Compression stop valves were installed onto the ends of the copper tubes, so there was full engagement with the tube. Brass ferrule rings were used in the compression joints. The stop valves were in the closed position during the tests, and the outlet ports of the valves were capped. Drips developed at the valve outlet port caps.

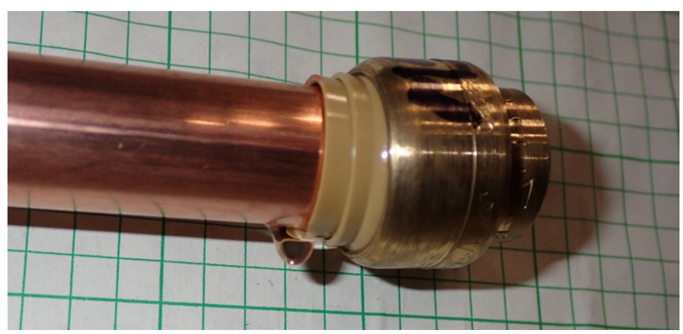

Figure 12
Photo of a push-to-connect cap dislocated on copper tube.

Figure 13
Photo of a push-to-connect cap separated from frozen solid copper tube.

The maximum pressure obtained averaged 1,365 p.s.i. (**Figure 14**). Failure pressure readings from different trial runs were within 26 percent of each other. An audible pop was observed immediately prior to the dripping, suggesting the internal valve mechanisms may have failed. There was no visible movement of the valve on the tube. The stop valve may have been pushed along the tube, including being pushed off by expansion of the ice if all the water in the tube froze.

Figure 15 summarizes the test results in tabular form. At no time did any of the solder joints fail, including exposure to internal pressures exceeding 7,000 p.s.i. Each test was repeated at least once, and the results were compared to evaluate repeatability.

Tube Rupture in Water or Ice Section Experiment

Tests were performed to observe whether the ruptures occurred in areas that were frozen solid at ice plugs or in areas of liquid water trapped in closed sections isolated by the ice plugs. A "U"-shaped copper tube assembly was comprised of three straight tube sections and two elbows (**Figures 16** and **17**). The vertical legs were 14 inches long, and the horizontal leg was 13 inches long. The top ends of the two vertical legs were open, and the middle horizontal leg of the tube was insulated. A thermocouple was installed at the middle of each straight section (T1, T2, and T3), and the freezer air temperature was measured (T4).

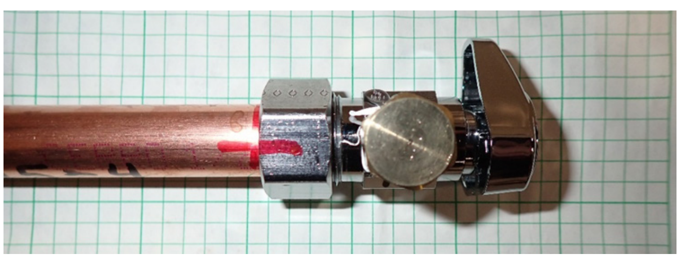

Figure 14
Photo of a compression stop valve installed on copper tube.

The tube was filled with water and placed upright inside the freezer (**Figure 18**). The insulation was utilized to cause the two vertical legs to freeze first, thereby creating a closed section between the two ice plugs. **Figure 19** illustrates the data from a U-shaped tube freeze test.

The temperatures of the three legs of the test U-tube

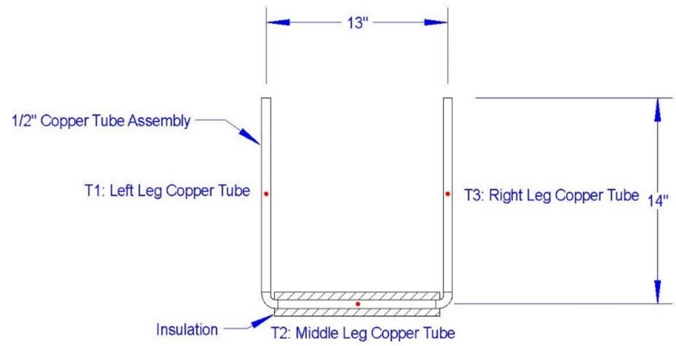

Figure 16
Diagram of U-shaped copper tube rupture location test apparatus.

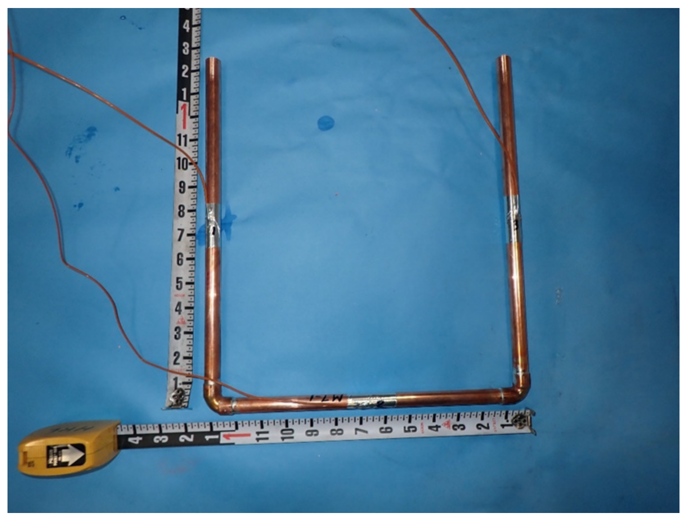

Figure 17
Photograph of the U-shaped copper tube test apparatus, without insulation, showing thermocouple locations.

Failed Component	Failure Pressure (p.s.i.)	Failure Mode
Copper cap fitting	5048 +/- 3%	Fish-mouth rupture
Type M copper tubing	5373 +/- 2%	Longitudinal rupture
Tyle L copper tubing	7133 max	No failure
Copper 90° elbow fitting	4682 +/- 5%	Longitudinal rupture
Push-to-connect cap	1029 +/- 30%	Water drip, no visible failure
Compression stop valve	1365 +/- 26%	Water drip at valve outlet, no visible failure

Figure 15
Table summarizing test results from ice plug pressure tests.

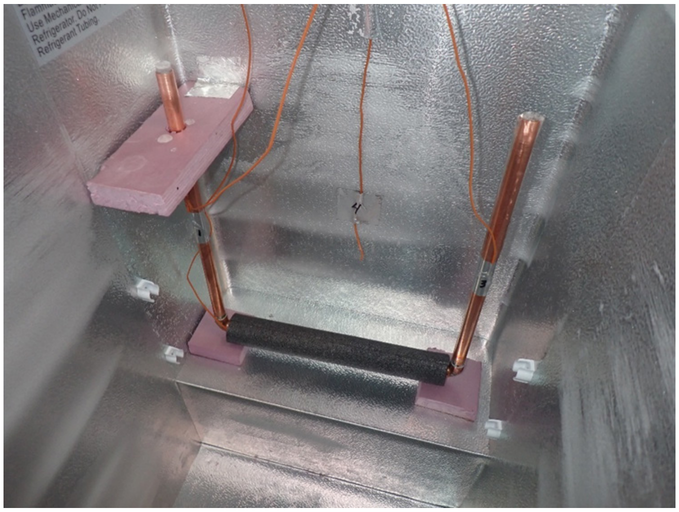

Figure 18
Photo of U-shaped copper tube test apparatus installed in freezer.

(T1, T2, and T3) all decreased gradually until the water in became supercooled. The middle leg (T2) decreased less due to the insulation. Freezing started when dendritic ice began to form, and the temperature of all three legs abruptly increased to 32°F. The temperature then remained roughly constant as the water froze. The two vertical legs (T1 and T3) froze solid first, trapping liquid water in the horizontal leg. As the ice plugs grew, the water pressure in the horizontal leg increased until the tube ruptured.

The tube burst was documented by a sudden increase in temperature. The equilibrium freeze temperature was reduced with increased pressure. For example, at 2,000 p.s.i., the temperature is reduced about 1.8°F (1.0°C). Likewise, at 4,600 p.s.i., the temperature is reduced about 4.3°F (2.4°C)[12]. When a burst occurs, the pressure in the area of the rupture instantly drops to atmospheric, causing the freeze temperature to suddenly jump to 32°F (0°C). The cause of this effect is apparent in the negative slope of the boundary line between the solid and liquid area of the phase diagram.

During trial runs, the horizontal legs ruptured generally near the middle in longitudinal hoop stress type

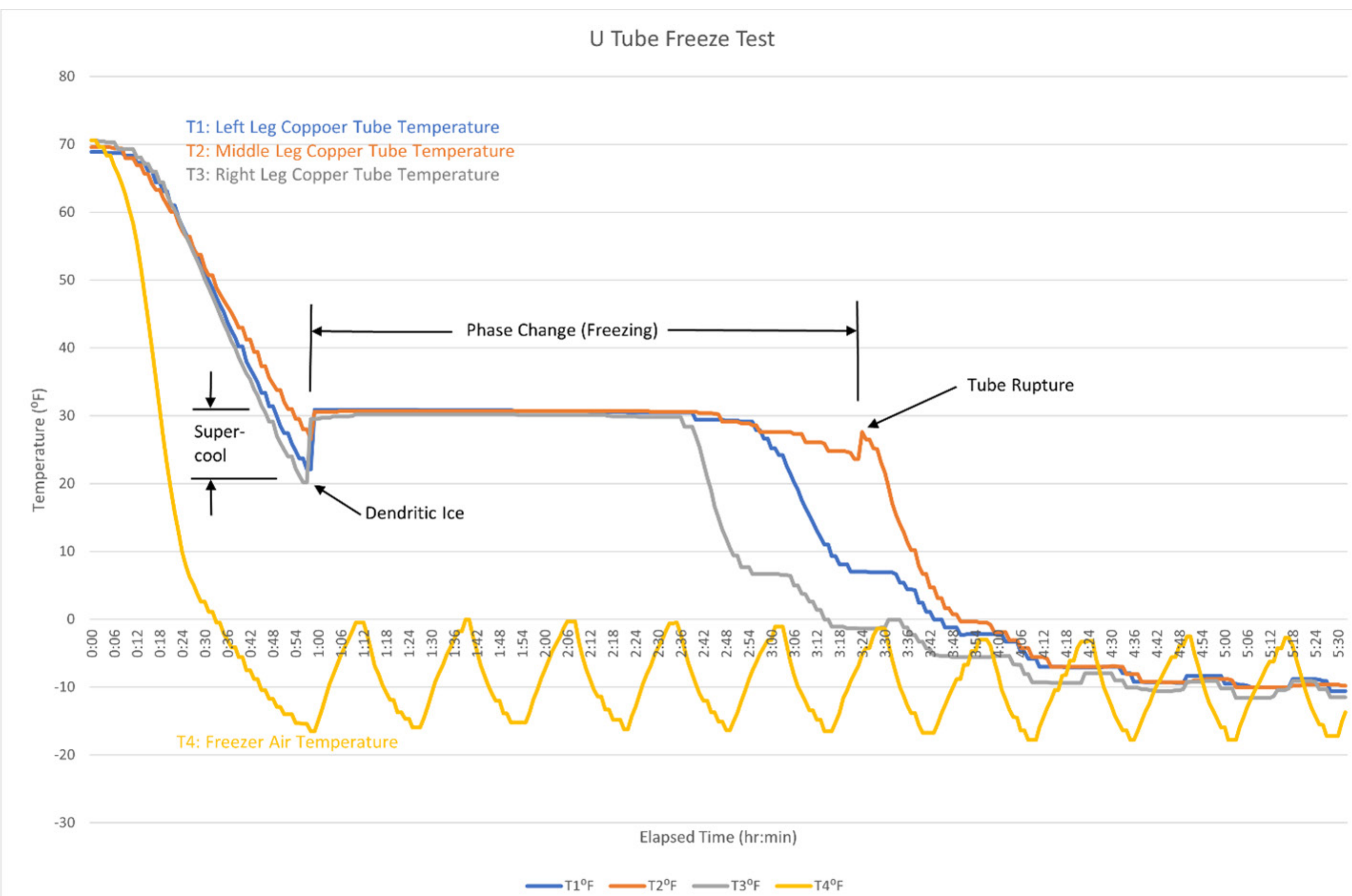

Figure 19
Graph of U-shaped tube freeze test data.

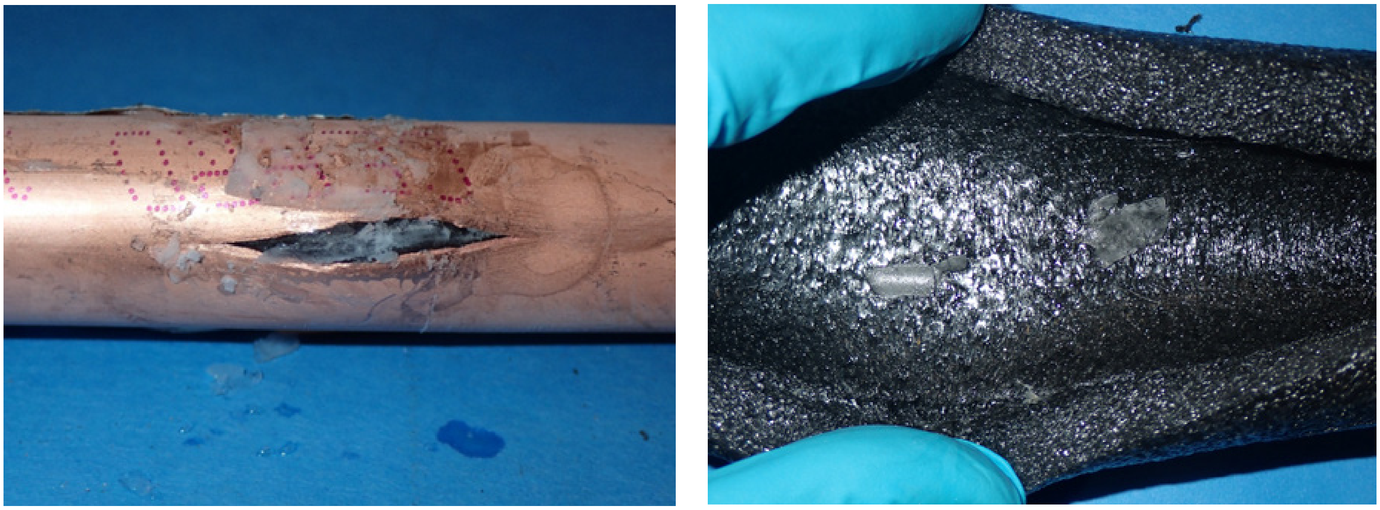

Figure 20
Photographs of ice that formed in the annual space between the tube and insulation.

failures (**Figure 20**). A thin layer of ice was observed to have formed on the outer surface of the tube and the inner surface of the insulation at the rupture, indicating liquid water had flowed out of the rupture and into that annular space where it froze.

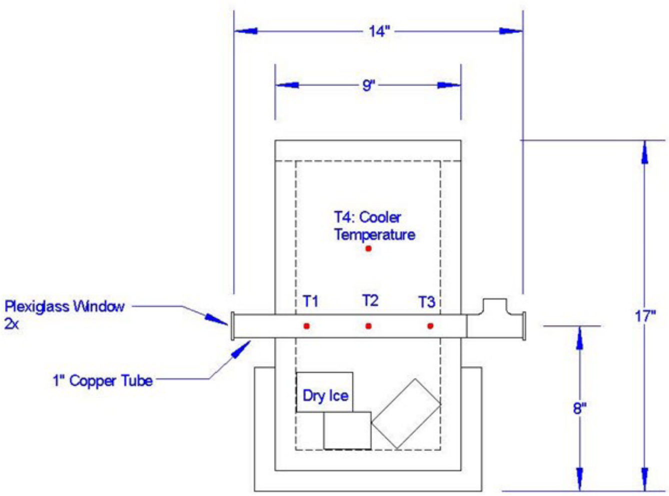

Figure 21
Diagram of ice plug formation test apparatus.

Ice Formation Process in Tube Experiment

A test was performed to observe the formation of an ice plug in a section of copper tube (**Figures 21, 22** and **23**). A horizontal straight length of 1-inch copper tube with plexiglass windows on the ends was positioned horizontally through a cold chamber so that both ends extended through the walls and were located outside the chamber. Thermocouples were installed on the portion of the tube located inside the chamber (T1, T2, and T3). The freezer air temperature was also measured (T4). The tube was filled with distilled water, and the dry ice was placed inside the chamber with an air space of several inches between the tube and ice, assuring no contact between the two. A video camera was positioned at the front window to view the interior of the pipe, and lighting was positioned at the rear window to illuminate the interior of the tube. **Figure 24** illustrates the temperature data for a test run.

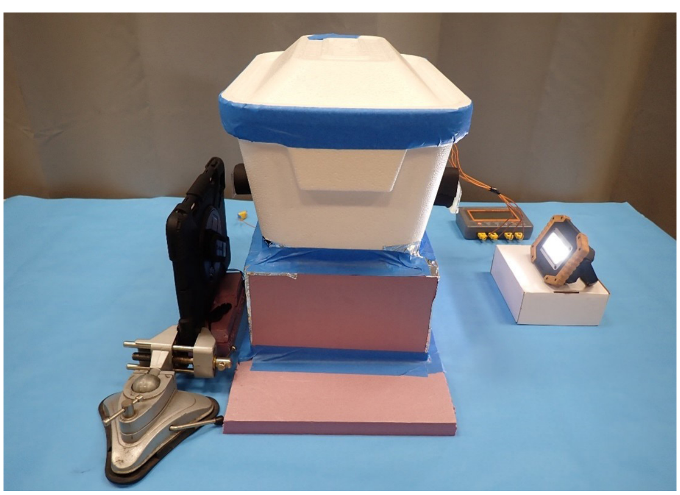

Figure 22
Photograph of ice plug formation test apparatus.

The cold chamber air temperature ranged between approximately 15°F and 22°F. As expected, the temperature of the copper tube decreased from room temperature with the center of the tube being the coldest, since it was in the middle of the chamber. The temperature of the center of the tube decreased below 32°F at an elapsed time of 56 minutes. The liquid water in the tube became supercooled at that point and remained in a supercooled state until an elapsed time of 3 hours and 6 minutes. Accordingly, the supercooled period lasted for 2 hours and 10 minutes.

At the 3 hour and 6 minutes point, dendritic ice began to form on the interior of the tube wall. Ice was observed initially forming on the upper-left quadrant wall and growing circumferentially along the wall in both directions (clockwise and counterclockwise). At the same time, the ice layer began to grow longitudinally along the tube toward the camera. This initial part of the process occurred over a 17-second period after the first ice was observed. The ice growth then accelerated significantly in both the circumferential and longitudinal directions. The layer grew into a solid plug, completely obstructing the tube. This second part of the process, which occurred over a 5-second period, was recorded on video. The total elapsed time was 23 seconds. Screen shots of the video are presented in **Figure 25**.

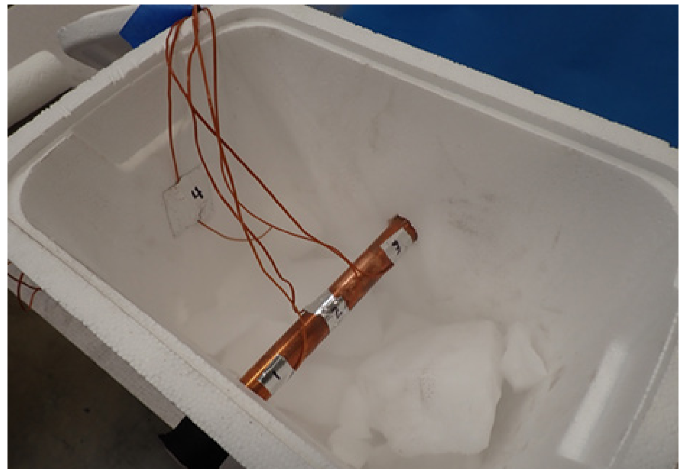

Figure 23
Photographs of ice plug formation test apparatus.

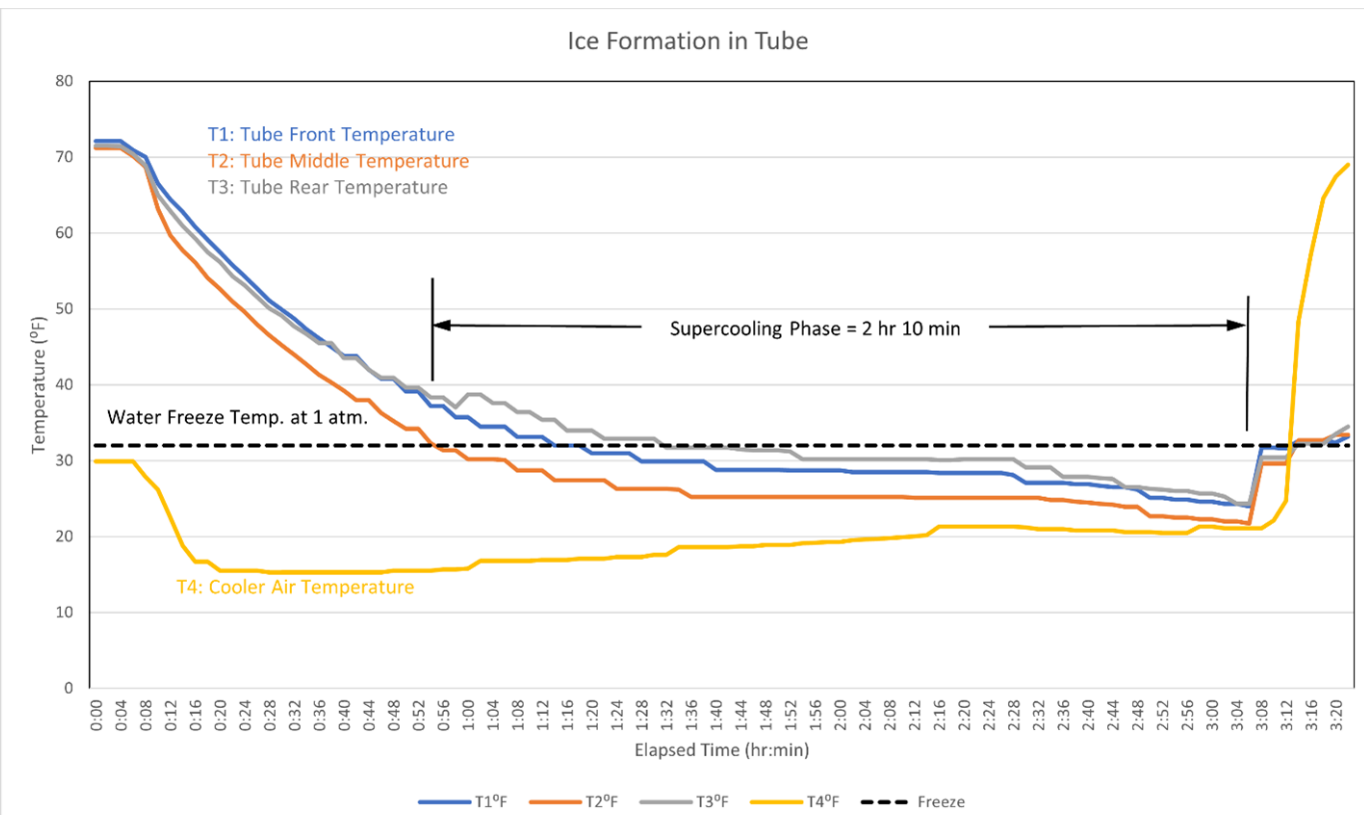

Figure 24
Graph of ice plug formation test data.

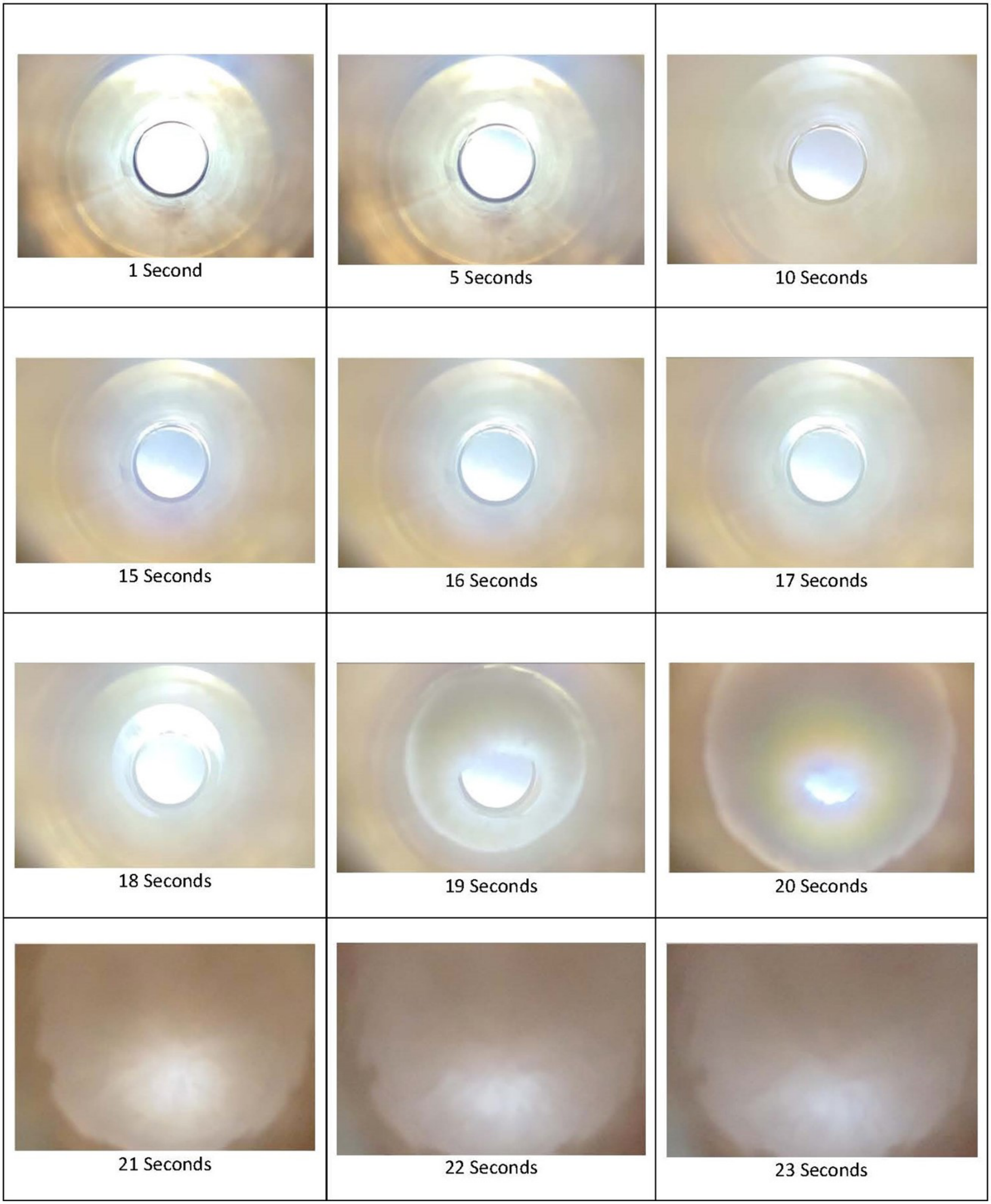

Figure 25
Screen shots of video depicting ice plug formation inside copper tube.

Conclusion

Experimental testing was performed to investigate three basic issues related to a building copper tube water piping system freeze failure investigation:

- Downstream pressures generated from ice plugs forming and growing inside a piping system were investigated. The pressures necessary to fail copper tube, copper fittings (elbows and caps), solder joints, push-to-connect components, and compression components were included in that investigation. Pressures as great as 7,133 p.s.i. were developed in the liquid water-filled portion of the test apparatus, including the copper tube assemblies, at temperatures that were well above freezing. The pressures were great enough to burst/rupture common components of copper tube water systems, including Type M tube, solder fittings, push-to-connect fittings, and compression fittings.

- The ½-inch Type M copper tube ruptured at an average pressure of 5,373 p.s.i. (see **Figure 15**), which was 88 percent of the published burst pressure of 6,135 p.s.i. (see **Figure 1**). The ½-inch Type L copper tube was pressurized to 7,133 p.s.i. without failure, which was less than the published burst pressure of 7,765 p.s.i.

- The push-to-connect fittings and compression fittings leaked but did not burst.

- The locations of the failures were investigated to determine if they occurred at the point of the ice formation (ice plug) where the tube was in direct contact with the ice or in liquid-filled closed portions of the system due to increased water pressure from ice plug growth inside the piping. When water-filled copper tube assemblies were subjected to freezing, the failures occurred in areas that were insulated, and froze later in time than the non-insulated areas. The ruptures occurred in liquid-filled areas as evidenced by liquid water flowing out of the rupture into the annual space between the tube and insulation (and freezing there) and a recorded spike in the temperature at the moment of the failure caused by the sudden drop in water pressure from the rupture in the area of the rupture.

- The process of the formation of an ice plug inside copper tube was investigated. The interior of a water-filled copper tube inside a cold chamber was observed and recorded. The temperature of the copper tube decreased from room temperature and became supercooled for a period of 2 hours and 10 minutes. At that point, dendritic ice formed on the interior of the tube wall. Ice was observed initially forming on the inner surface of the tube wall and grew circumferentially along the wall in both directions (clockwise and counterclockwise). At the same time, the ice layer began to grow longitudinally along the tube toward the camera. The ice growth then accelerated significantly in both the circumferential and longitudinal directions. The layer grew into a solid plug, completely obstructing the tube. The elapsed time of ice formation was 23 seconds.

- No solder joints failed during the testing, indicating those joints were not the weak points of the piping system. Failed solder joints found by investigators in the field would be inconsistent with this testing. Additional analysis of those failed joints may be warranted to determine if they had been properly soldered when they were made or became damaged before the freeze event.

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