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Northward Market Extension For Passive Solar Water Heaters by Using Pipe Freeze Protection with Freeze-Tolerant Piping

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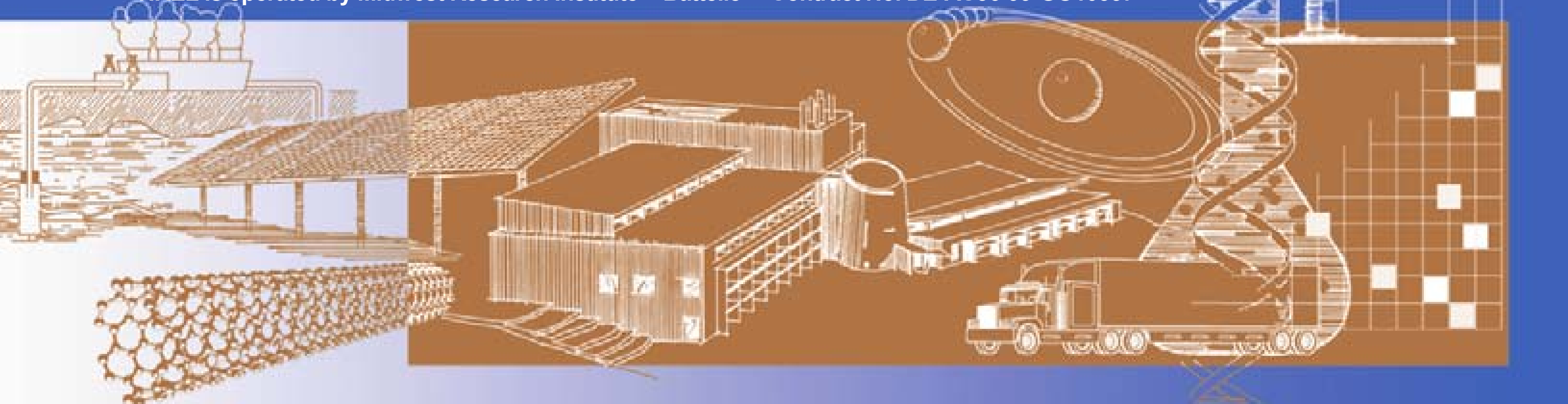

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NORTHWARD MARKET EXTENSION FOR PASSIVE SOLAR WATER HEATERS BY USING PIPE FREEZE PROTECTION WITH FREEZE-TOLERANT PIPING

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ABSTRACT

Combining a freeze protection method with fail-safe, freeze-tolerant cross-linked polyethylene (PEX) piping may provide a means to significantly extend the market northward for passive solar water heaters. Stress-strain data on PEX piping materials indicate that the 3.5% hoop strain from uniform freezing is likely tolerable for many cycles, but data are not definitive because it is not clear where permanent deformation starts occurring. Four PEX piping systems were freeze-thaw-cycled ~450 times. One brand showed no freeze tolerance, whereas two other brands appear freeze-tolerant, with no bursts in lengths greater than 7" or less than 2". Two geometries were identified that promote nonuniform freezing and that should be avoided: 1) nonuniform insulation increasing from ends toward the middle of the pipe in longer sections; and 2) pipes of ~4" in length with metal connectors on both ends. All metallic fittings have survived, but several polymer fittings broke and should be avoided when freeze-tolerance is desired. Further testing and analysis is needed to better understand the length dependence of freeze bursting and effects of piping aging, and field testing should proceed cautiously.

1. INTRODUCTION

Reducing costs and increasing reliability of solar water heaters (SWH) is believed necessary for a substantial SWH market to exist in the U.S. (1). One strategy is through expanded use of passive SWH (PSWH). PSWH include integral-collector-storage and thermosiphon, as shown in Fig. 1. PSWH eliminate the pumps, controller, sensors, and power needs of active systems. New types of polymer-based PSWH with ~50% cost reduction are nearing market entry (1). However, the market for PSWH has been limited by the risk of freeze-induced bursting of the supply and return lines (2). These pipes carry pressurized potable water through unconditioned attic space to the thermal storage on or under the roof, as in Fig. 1. Because of excellent high temperature resistance, copper pipes are almost always used. However, copper pipes can freeze and burst in the attic, a catastrophe with costs that can be much larger than the SWH's savings over its lifetime and contributing to erosion of SWH's reputation generally. Therefore, the market has rightfully been restricted to areas with near-zero freeze probability, as indicated on the left side of Fig. 2 (2). As a result, lower-cost, more-reliable PSWH are at present considered unsuited for almost all the continental U.S., where hard freezes occur at least occasionally. The goal of this work is to establish that practical pipe freeze protection may be provided by combining a sufficiently-reliable primary freeze protection (PFP) method with a fail-safe, freeze-tolerant piping, enabling northward extension of the PSWH market.

A primary freeze protection (PFP) mechanism keeps the piping unblocked; when the supply/return piping is frozen, the homeowner must bypass the PSWH to regain hot water. PFP failure must be very rare (e.g., << 1 per 100 system-lifetimes) for this approach to be acceptable to the market. PFP recently investigated include: 1) natural convection loops (NCL) of room air in ducts surrounding the pipes (3,4); 2) NCL in the supply/return pipes themselves (fed by tank heat or room air heat) (5,6); and 3) freeze protection valves (FPV's) on the return line as in Fig. 4 (7). FPV seem to be the least expensive option and do not consume site thermal energy, but they do reject to drain the water used to warm the piping. Water consumption from FPV is relatively small until hard-freeze climates are reached (7). The right-hand side of Fig. 1 indicates areas with consumption less than 1000-gallon/year consumed (less than household average monthly consumption), a potentially large market extension. However, any primary means of freeze protection can fail usually in multiple ways, and ***there*** ***must*** ***be a fail-safe back-up for the primary means of freeze protection***.

Some polymeric piping is freeze-tolerant: the pipe is elastic and expands upon freezing without harm. Polybutylene pipe was shown to be freeze-tolerant in (8), freezing over 700 cycles before the first burst. However, that pipe was removed from the market ~ 1990. Cross-linked polyethylene (PEX) is presently the dominant polymer potable water piping material used in the U.S. Some PEX suppliers' and manufacturers' literature states that their pipe is freeze tolerant; however, substantive supporting data or analyses were not available. A literature search on PEX freeze tolerance provided no substantive information on PEX freeze tolerance. The objective of this study is to indicate by analysis and by test whether PEX piping systems are freeze tolerant. A mechanical analysis based upon material properties is followed by experimental freeze-thaw cycling results on four brands of PEX pipes and their recommended connectors.

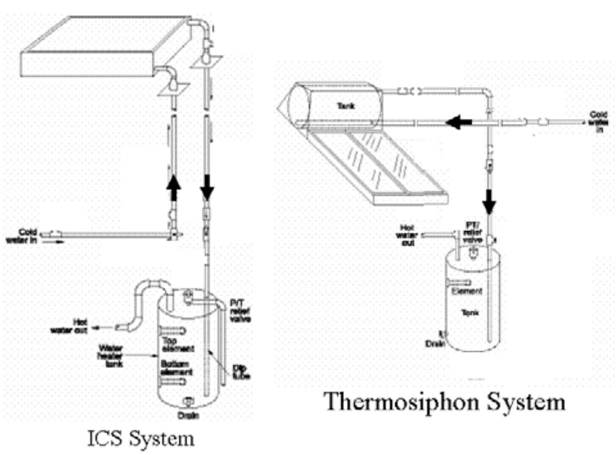

Fig. 1. Schematic two passive SWH. The balance-of-system is very simple, reducing hardware cost and system failures.

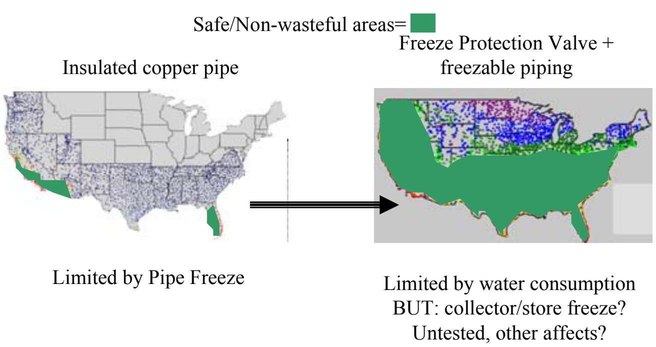

Fig. 2. ***On the left:*** Freeze probability map for 3/4" copper pipe with 1" insulation, with zero-freeze-probability areas in green. PSWH with insulated metallic pipes should be installed only in the green areas. ***On the right:*** Water consumption map for FPV, with the areas consuming less than 1000 gal/year in green.

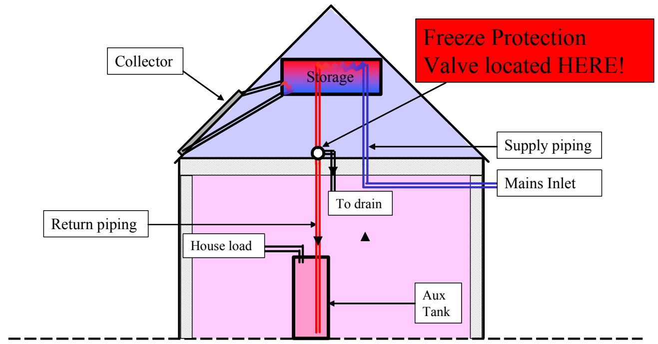

Fig. 3. An indirect thermosiphon system with un-pressurized storage is shown, with a freeze protection valve mounted at the ceiling-line just before the return pipe enters conditioned space.

The ultimate goal of this and related work is to extend PSWH markets using a PFP method with freeze-tolerant PEX piping as the fail-safe backup in case the primary method fails. However, this goal presents many difficulties, this small study raises several questions, and caution is appropriate. Failure rates for possible PFP methods are not well-known, yet these rates must be very low for market acceptance of this approach. Another important caution stems from the fact that *polymeric piping weakens and is subject to burst at higher temperature*. PEX supply/return tubing has not been allowed by rating organizations because burst-causing high temperatures (e.g. 150 $^{\circ}$C) can occur when fluid starts circulating through stagnating SWH. Hence, *high system temperatures must be completely and reliably avoided* before polymeric piping can be safely considered.

2. MECHANICAL ANALYSIS

An analysis based upon measured mechanical properties of PEX pipe is useful to establish a materials basis for piping freeze tolerance. The analysis is based upon the concept of a "quasi-linear region" where strain is ~linear with stress and the material returns without deformation to the initial geometry when the stress is removed (4). Despite lack of a "strictly linear" region in polymers, strain in the quasi-linear region does not induce measurable permanent deformation. If strain remains in this region under freezing, it is plausible that the pipe would be able to withstand repeated freeze-thaw cycles without bursting. For this analysis, we assume that the blockages are established before any freezing occurs in the pipe (a conservative assumption) and that insulation and freezing are uniform (as in normal piping runs). Mechanical data were taken on two pipe types, a silane PEX and an irradiated PEX. Tensile measurements were taken with a standard tensile test apparatus (Instron Model 1122 with 5500R load frame) using ASTM D 638-9B procedures

(9). A temperature-controlled chamber surrounding the instrument jaws allowed property measurement as a function of temperature, including near 0 °C (uses liquid nitrogen). Results are shown in Fig. 4 for one tested pipe at 0 °C. At strain below ~4%, the deformation appears ~linear, although curvature is evident from the outset. Permanent deformation is clearly evident beyond 10% strain, where the material begins "flowing," and is also most likely occurring above 6%. It is possible that some deformation might occur below the 4% point. The pipe would still be able to take some number (hopefully large) of freeze cycles before the accumulation of the small deformations would cause sufficient wall-thinning to fail. Behavior in the silane PEX is very repeatable over 5 samples. Irradiated PEX showed similar behavior, but sample variability was much higher (4). This was also the only PEX pipe that burst in lengths between fitting greater than 7".

Freezing and pressure-buildup in pipes are relatively complex (10). As pipes freeze, an annulus of ice attaches on the pipe inner surface and freezes inward toward the pipe axis. However, there is no pressure buildup until two separated "ice blockages" occur because until that occurs water is pushed back into the mains or forward into the downstream house piping system (which has significant expansion capability). Subsequent to blockages, further freezing causes pressure to build up. Pathological cases of nonuniform freezing with a "piston action" can be created by tapering insulation to force the freeze between the blockages to occur nonuniformly from the blockages in, forcing water inward and creating potentially *very* high pressures and/or strains; such "pathological insulation" was done here as an example of what not to do.

When a blocked pipe freezes, pressure builds up and the pipe expands in both the circumferential (hoop) and the axial direction. Elementary mechanical analyses of a thin-walled, closed cylinder in the linear domain where stress (σ) is proportional to strain (ε) shows that these variables are related as

$$\sigma_{axial} = \tfrac{1}{2}\sigma_{hoop} \Rightarrow \varepsilon_{axial}=\tfrac{1}{2}\varepsilon_{hoop} \Rightarrow (L_{ice}-L_{water})/L_{water}=\tfrac{1}{2}(r_{ice}-r_{water})/r_{water} \quad (1)$$

The volume ratio of the ice to the water can be expressed as

$$V_{ice}/V_{water} = \rho_{water}/\rho_{ice} = (r_{ice}/r_{water})^2 * (L_{ice}/L_{water}) \quad (2)$$

with ρ_w/ρ_i =1.091. Substituting L_{ice}/L_{water} from (1) into (2) yields

$$(r_{ice}/r_{water})^3 + (r_{ice}/r_{water})^2 - 2\rho_{water}/\rho_{ice} = 0 \quad (3)$$

which results in (r_{ice}/r_{water}) = 1.035. Thus, ε_{hoop} =3.5%, and ε_{axial} = 1.75. The calculated hoop strains compared very well with data on 10 pipe sections, where hoop strain averaged 3.48% (4). These strains appear to be in the quasi-linear region, indicating that the pipe could probably be freeze-thaw cycled a number of times. However, note that this strain is uncomfortably close to where the curvature rapidly increases and where significant permanent deformation might start occurring. Thus, any concentrations of stress due to nonuniformities of freezing should be avoided. Although uniform freezing appears safe, nonuniform freezing can induce higher strain and permanent deformation. This speculation appears to be supported by observed freeze-bursts in shorter piping lengths, which promote nonuniform freezing.

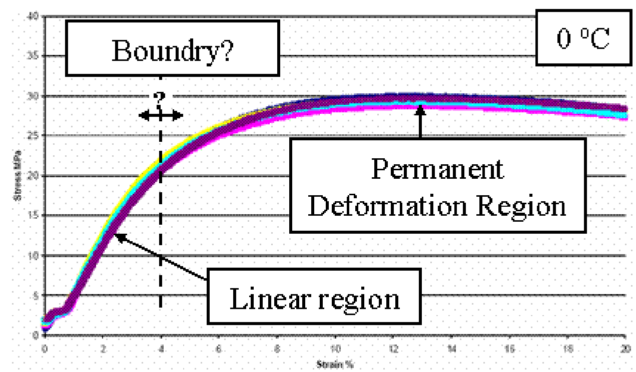

Fig 4. Stress versus strain for 5 samples of silane PEX. A quasi-linear region without significant permanent deformation exists below ~3-4% strain. The boundary is hard to establish. Slippage during the initial cool-down to 0 °C is evident at initial strain.

3. <u>FREEEZE-CYCLING EXPERIMENT</u>

A freeze-cycling experiment was set up using a computer-controlled freezer with internal heaters and fans, and a temperature-controlled circulator, as shown in Fig. 5. Four brands of PEX piping were used, as shown in Table 1 and Fig. 6. All commonly-used cross-linking methods are included, including chemical (peroxide and silane) and physical (irradiation) methods. In addition, a multi-layer PEX-Aluminum-PEX pipe (PAX) was tested Both 1/2" and 3/4" diameters were used, along with recommended fittings (tees, elbows, and connectors, and reducers). Piping ran between inlet and outlet manifolds in the freezer with 36 ports. For each pipe type and diameter there were three straight runs (one uniformly insulated) and one "U-bend" run with vertical runs. Tables 1 and 2 give the number of pipes (by length) and fittings installed of each type, with the details of mounting in (4). In addition, pathological cases with insulation tapered from ends to the middle were installed to exemplify a configuration to be avoided. These cases consisted of a pipe of length 4' to 16'with un-insulated brass connectors at the ends (to establish two freeze blockages early in the freeze cycle), and with insulation increasing toward the middle, forcing a piston action as freeze progressed toward the middle of the pipe.

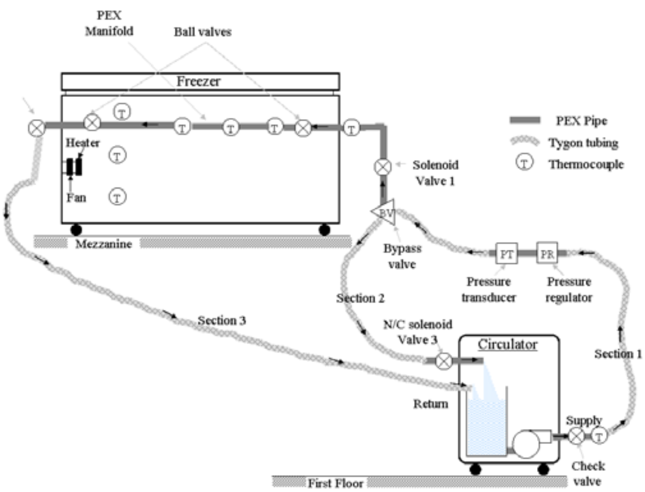

Fig. 5. Schematic diagram of pipe freeze experiment. The circulator keeps pressurized water in the piping while limiting water inventory. Fans maintain temperature uniformity, and a heater thaws the pipes out.

Fig. 6. Four types of PEX piping tested (top), along with some of the fittings tested (bottom).

At the beginning of a cycle, the pipes are warm and the freezer is turned on. Temperatures decay to ~0 °C, staying at that temperature until the latent energy is exhausted and the pipe is fully frozen. The temperature of the ice plug then decays toward freezer air temperature (~-40 °C). When all pipes are totally frozen, the freezer is turned off, and the heater is turned on to thaw the pipes. After thawing, the heaters are turned off, and warm water (~40 °C) circulates for 1/2 hour through the pipes (to stress the pipes and fittings via thermal expansion) before starting the next cycle. The sensor under the middle of the heaviest tapered insulation piece controlled the staging of the cycles. All pipes were assumed frozen when this sensor indicated -15 °C, and were considered thawed when it indicated +30 °C. Cycles take 8-16 hours (depending on insulation). Fig. 7 shows an example cycle.

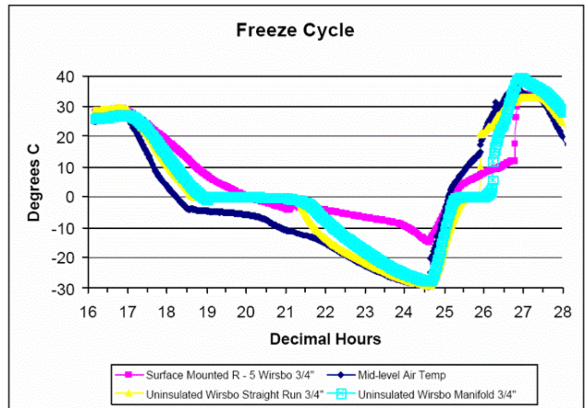

Fig. 7. Typical freeze cycle. The slowest-decaying temperature (top line at hrs. 19, 24) is beneath 2” of insulation, freezes/thaws last, and controls the cycle.

4. FREEZE-TEST RESULTS

As of paper submission, there were 450 completed freeze-thaw cycles on the piping systems in the freezer. We plan to continue cycling until 1000 cycles are reached. Results are shown in Tables 1 and 2 for pipes and fittings, respectively. In general, the bulk of the pipes and fitting were able to withstand the freeze cycles, with exceptions discussed below.

TABLE 1: PIPES: #INSTALLED/#BURST

Brand Name/Type	l < 1”	1”< l < 5”	l > 7”
hePEXplus/silane PEX	120/0	17/9	23/0
QestPex®/peroxide PEX	0/0	6/1	17/0
Durapex/Irradiated PEX	0/0	9/0	19/3
Kitec XPA/PEX-AL-PEX	Not freeze-tolerant		

4.1 Pipes and Fittings that Broke

PAX pipes and fittings both broke within 10 cycles, often less, demonstrating that Kitec pipes and fitting are not freeze-tolerant. PAX is apparently not suitable for use with water where there can be freezing events, and is not discussed further.

We also found that any of the pipes with “pathologically-tapered” insulation installed over them would eventually break. Surprisingly, it took 20-50 cycles to break the pipes, depending on the length of the pipe and the details of the insulation layering. Although no sane person would install pipe this way, it is a simple, clear demonstration of the perils of nonuniform freezing and piston action.

TABLE 2: CONNECTORS: #INSTALLED/#BROKEN

Name/Material	Fittings
ProPex®/PolySulphone[1]	20/2
ProPex/Brass[1]	25/0
Sioux Chief®/Copper[2]	101/0
Kitec Compression/Brass	Not freeze-tolerant

1) ProPex fitting are used only with the silane PEX. Sioux Chief fittings can also be used with this pipe.
2) This fitting is recommended with silane PEX and irradiated PEX.

Surprisingly, pipes of length 3-4" tended to burst, if there were brass or metal connectors on each end of the short section. There were nine such bursts with the silane PEX, one case with the peroxide PEX, and no cases of this with irradiated PEX. In no case did any of the pipes burst when polysulphone connectors were used, rather than metallic. For the silane PEX, the average cycles to break was size-dependent, taking ~35 cycles for 1/2" pieces and ~95 cycles for 3/4" pieces. One would expect that with the metal connectors (as opposed to the polymer connectors) freezing will occur *first* at the connector location, creating piping blockages at these locations. It can be inferred that a piston action follows that is strong enough to burst the pipe in 30-100 cycles, if it is about 3.8" long. Samples of the burst short pipes are shown in Fig. 8. Note that the pipes show a small bulge near the location of the burst, consistent with permanent strain before break. There is a reasonable explanation for why shorter or longer pipes did not burst, although future work must verify the hypotheses: 1) *very short pipes*: for very short segments (e.g., <2") with brass connectors, the pipe is so short that after blockage is established there is not much water left to freeze "inward to the middle", ameliorating pressure buildup; 2) *long pipes*: the piston action apparently did not extend far enough down the pipe to cause abnormally high strains to build up, with most freezing subsequent to blockage occurring relatively uniformly.

Three long pieces of the irradiated PEX broke. This seems somewhat anomalous, given that no other long pipes failed and that the stress-strain data indicates that uniformly-freezing long pipes should not burst until many cycles, if at all. It may be that nonuniform mechanical properties were an issue with this pipe type, based upon: a) the observation that the six irradiation PEX samples tested mechanically showed ~20% scatter in results; and b) the fact that irradiation-based cross-linking has been associated in the literature with nonuniform properties (4).

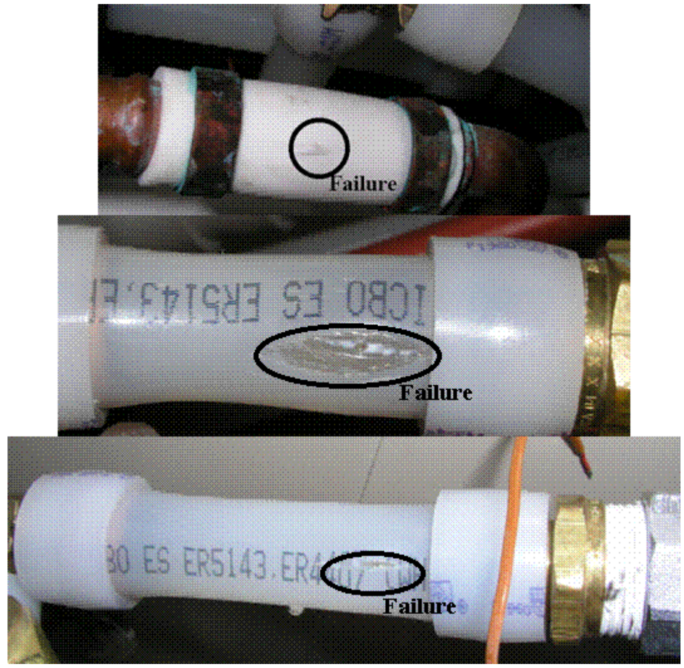

Fig. 8. Pipe burst failures in pipes with lengths about 3.8".

All of the brass compression fittings broke within 10 cycles, and are not suitable for use where freezing can occur. Although the polysulphone ProPex fittings seemed to help avoid rapid buildup of blockages, there were several of these plastic fittings that broke. It would seem prudent to not use these fittings if the piping system is designed to be freeze-tolerant.

4.2 Pipes and Fittings that Didn't Burst

Longer lengths of pipes (with exception of the irradiated PEX as noted above) all have survived freezing of over 450 cycles without burst. Three quarters of these pipes were not insulated, and the remaining 1/4 were uniformly insulated. This result indicates that the two chemically-cross-linked piping brands are freeze tolerant if they are installed in sections longer than some minimum (perhaps 7"), and if they are uniformly insulated. The design must avoid nonuniform freezing, which can lead to large stress concentrations with subsequent permanent deformation and eventual burst under freeze.

None of the 126 metal fittings in the freezer has broken. Water beneath the metal fittings could be expected to freeze faster than water beneath the polymer pipe wall, which has ~1/1000th of the conductivity of the metal. Having frozen first, the metal fittings would avoid directly seeing the affects of direct piston action. Both brands of metallic fittings seem suitable at this stage, as none of these fittings has broken.

5. CONCLUSIONS AND FUTURE WORK

The market for PSWH can be extended northward if a freeze-tolerant piping system can be identified to serve as a fail-safe back to a reasonably reliable primary freeze protection method. Stress-strain data indicate that PEX piping systems may be freeze-tolerant, as strains from freezing are in the quasi-linear region. However, there is ambiguity in defining the region, and strain from freeze puts the material uncomfortably close to the nonlinear region where permanent deformation is evident. Tests of available PEX piping systems were performed inside a freezer. Kitec and its connectors are not freeze tolerant. Tests showed that short pipe sections of order 3-5" in length with metal connectors on both ends tended to burst, and must be avoided. Tests also showed that longer sections (> 7") of the two chemically-crosslinked brands are freeze-tolerant. For an irradiation cross-linked material, three longer sections broke, and that pipe should not be considered freeze tolerant. The polysulphone connectors prevented early formation of blockages, but several broke and should not be used in a freeze-tolerant piping system. None of the two brands of metallic connectors have broken. There is good indication that the two available PEX piping systems may be freeze-tolerant if installed in long sections with uniform insulation and with metallic connectors.

Future work depends on available funding. Pipe freezing is a long-standing, serious problem with high damages possible with burst piping. A novel solution as proposed here requires more thorough investigation and gradual accumulation of field experience before widespread adoption. For initial installations, it would be wise to include additional safeguards (such as a thin-film shroud around piping with outlet to drain) until favorable field experience is accumulated. Pipe properties may change with exposure to chemicals and heat over time that could decrease the linear region significantly and could affect freeze tolerance. In addition, the length dependence of freeze-induced bursting needs to be investigated with finer resolution than used here.

6. NOMENCLATURE

Symbols

L	Pipe length
r	Pipe radius
V	Volume of pipe as cylinder
ε	Strain, $\Delta l/l_o$
σ	Stress
ρ	density

Subscripts

axial	Direction parallel to the pipe axis
hoop	Direction around the circumference of the pipe
ice	Ice
water	Water

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