Kiefner & Associates, Inc.
585 Scherers Court
Worthington, OH 43085
T: (614) 888-8220 • F: (614) 888-7323
www.kiefner.com

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Distribution Pipeline System Integrity Threats Related to Cold Weather

MJ Rosenfeld, PE and M Van Auker

INTRODUCTION

Cold weather can produce threats to the integrity of distribution pipeline systems. Integrity management (IM) concepts required an operator to identify integrity threats as a necessary step to prioritizing integrity assessments, and developing mitigations. This report discusses the most common integrity threats caused by cold weather and identifies the attributes of the most susceptible systems. This information should enable a gas distribution system operator to develop appropriate decision processes to address cold weather risks in the context of its distribution IM program.

SUMMARY AND CONCLUSIONS

Cold weather-related incidents have occurred in gas distribution systems, gas transmission systems, and hazardous liquid transmission systems. By far the most common cause of such incidents is frost heave, acting on buried pipe. However, a large number of less-frequent incident scenarios related to cold weather have been described in PHMSA's reportable incident database, affecting both buried and above-ground installations. All types of pipe materials found in distribution service have been affected, however piping with certain attributes appear to have higher-than-average susceptibility. These are:

- Cast iron pipe
- Pipe of unknown material type
- Steel pipe installed prior to 1950

IM principles require that the operator consider integrity threat interaction. Frost heave or snow load might be readily tolerated by some materials or a piping system in sound condition, while low-ductility materials or pipe joints made by vintage techniques may remain reliable absent certain outside forces, however, when these circumstances exist simultaneously the likelihood of a failure is significantly greater. Systems of the type listed above in locations susceptible to frost heave therefore represent potential interacting-threat situations.

Piping systems having the attributes listed above and located in areas known or suspected to be susceptible to frost heave or thaw settlement should be identified and considered for condition monitoring or mitigation activities. While frost heave was responsible for the largest number of incidents, other causes have also been identified, including snow and ice falls from rooftops, confined freezing of water trapped in components, or build-up of ice where standing water accumulates around risers or under low-mounted above-ground components.

Condition monitoring could involve a range of activities, including but not limited to:

- periodic visual site inspection during cold weather months by someone qualified to recognize evidence of frost heave or thaw settlement;
- examination of piping buried above the frost line for evidence of deflection at joints during routine excavations;
- visual inspection of sites for frozen standing water around risers or under equipment mounted low to the ground.

Mitigations could include but are not limited to:

- replace iron pipe, unknown-material pipe, and threaded steel pipe with plastic or welded steel pipe in locations known or suspected to be susceptible to frost heave;
- remediate drainage or soil conditions that promote frost heave at susceptible sites;
- correct drainage conditions that promote accumulation of standing water around risers or under low-mounted equipment;
- drain trapped moisture from equipment during routine maintenance or inspections.

ANALYSIS

Cold weather effects on pipeline systems are typically classified as time independent (i.e., randomly occurring) threats. A failure caused by a time independent threat is typically incident driven such as in the case of third party damage, versus a time dependent threat which can involve deterioration of the pipeline component over time by some mechanism such as corrosion or cracking. With exposure to cold weather, the pipeline system can be threatened by a number of circumstances that can cause excessive stress or strain to produce a failure in the pipeline components. Some of these threats include frost heave, loads on pipeline components due to snow and ice accumulation, erosion due to snow and ice melts, thermal stresses due to extreme cold temperatures, and confined expansion of freezing water within components.

Causes of Distribution System Incidents

The Pipeline Hazardous Material Safety Administration (PHMSA) has collected pipeline failure data for distribution pipeline operations in the United States. This data shows that pipeline failures due to natural forces account for approximately 5.8% and 5.9% of the failures reported in 2010 and 2011, shown in Figure 1.[1]

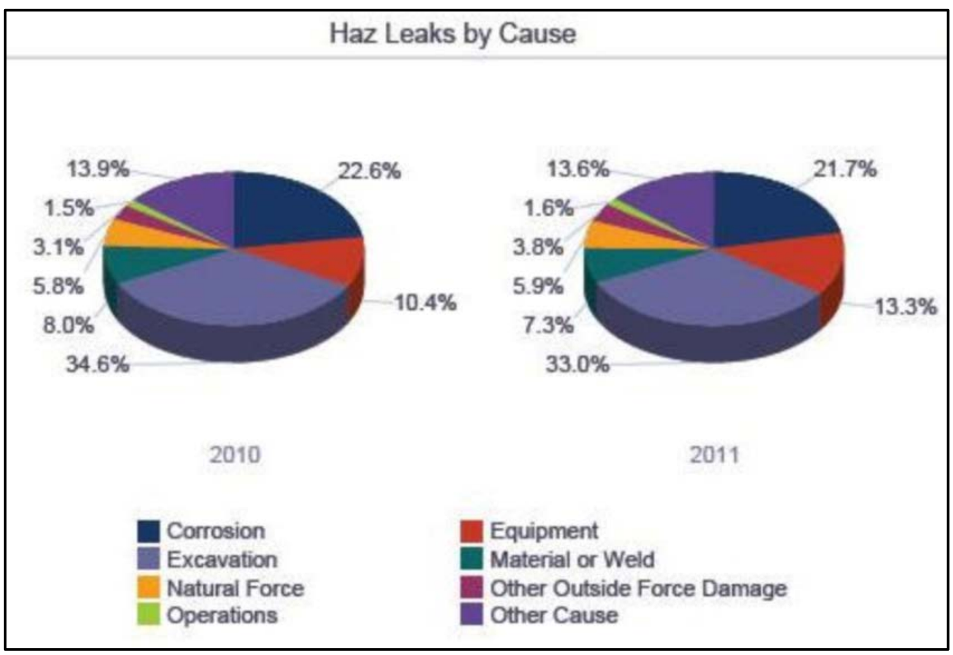

Figure 1. Hazardous Leaks on Distribution Systems by Cause

[1] www.phmsa.dot.gov

The natural force damage category includes incidents resulting from earth movement, earthquakes, landslides, subsidence, lightning, heavy rains/floods, washouts, flotation, mudslides, scouring, temperature, frost heave, frozen components, high winds, and weather events including cold weather. Closer analysis of the PHMSA data for leaks caused by natural force damage provides a better understanding of how cold weather can impact the integrity of distribution pipeline systems. The PHMSA data included 120 leak incidents on distribution systems reported to be associated with cold weather failure as a cause, Figure 2. The failure cause most frequently reported was frost heave, followed by failures due to snow accumulation and movement.

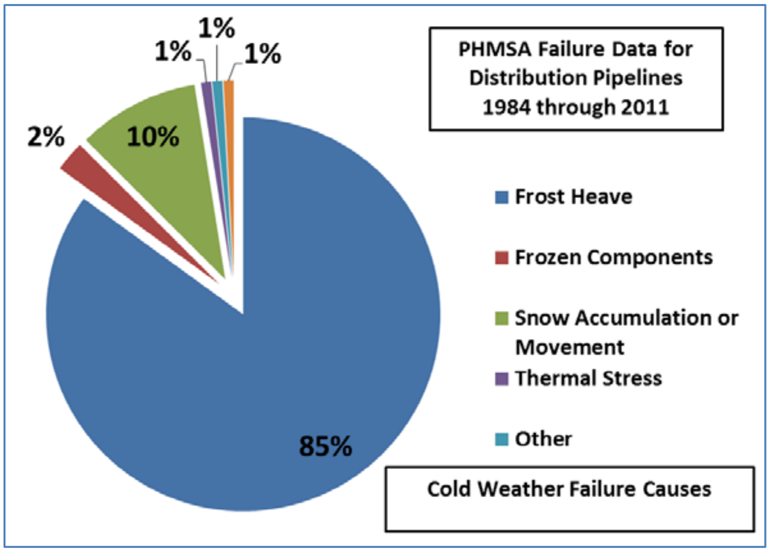

Figure 2. PHMSA Cold Weather Failure Causes

About Frost Heave

Frost heave results from ice forming beneath the surface of soil during freezing conditions in the atmosphere. The ice grows in the direction of heat loss (vertically toward the surface), starting at the freezing front or boundary below the soil surface. It requires an unfrozen water supply (usually below the frozen soil) to keep feeding the ice crystal growth. The growing ice is restrained by overlying soil, which applies a load that limits its vertical growth and promotes the formation of a lens-shaped body of ice within the soil. The growth of ice lenses continually consumes the rising water at the freezing front. The soil through which water passes to feed the formation of ice lenses must be sufficiently porous to allow capillary action, but not so porous as to break capillary continuity. Such soil is referred to as "frost heave susceptible".[2] Two common criteria for susceptibility are more than 10% of soil particles being finer than 0.075 mm, or more than 3% of particles being finer than 0.020 mm. Considering particle size alone does not account for the effects of variables such as the presence of ground water or the presence of dissolved salts or other substances which can alter the freezing state. A more comprehensive test[3] would be required in the event that precise information about susceptibility is required. Visible vertical displacement of the ground surface or effects on pavement would be consistent with the occurrence of frost heave. The resulting earth movement associated with frost heave can be significant and can impose strain on pipeline components impacted by the movement.

The primary structural integrity impact to pipeline systems as a result of frost heave is excessive longitudinal stress due to the displacement strain imposed by the earth movement. The likelihood of a failure due to frost heave may be increased when other threats exist such as circumferential stress-corrosion cracking or low-quality girth welds or threaded connections. The susceptibility of a pipeline system to damage by frost heave can be assessed by considering some key factors.

- The soil type in which the pipeline is laid. Silty and loamy types of soils would be an example of frost susceptible soil while clay or clean sand and gravel are examples of soils not susceptible to frost heave.

- The depth that a pipeline is buried. Lines buried below the frost line of a geographical area would be less susceptible to impact from frost heave since the earth movement is typically in the vertical direction and occurs above the frost line.

- Pipeline material and specification, or method of construction. The ability of a pipeline to withstand high longitudinal stress or strain may affect its likelihood for failure due to the impact of frost heave.

- The flexibility of above ground installations in frost heave susceptible areas.

The combinations of factors discussed above indicate that failure due to frost heave and other cold-weather effects represents probable interacting threat circumstances.

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[2] Andersland, O.B. and Ladanyi, B., Frozen Ground Engineering, 2nd Ed., ASCE and J. Wiley & Sons Inc., 2004.
[3] ASTM D5918, "Standard Test Methods for Frost Heave and Thaw Susceptibility of Soils", 2006.

Interacting threats are understood to occur where the probability of failure due to specific factors is significantly greater than the sum of individual probability of failure (as a proxy for "risk") from the factors occurring independently. Frost heave or snow loads, while not desirable, may be readily tolerated by ductile materials and or better-quality joints between pipes. Likewise, low-ductility materials or artifacts of vintage pipe construction technology, while not optimal, may not present a threat where normal internal pressure is the only significant load. However, certain combinations of materials in conjunction with cold weather effects may create a more acute situation than either set of circumstances do separately. This is demonstrated in the following analysis of data to identify specific attributes of piping that appear to enhance susceptibility to cold weather effects, as evidenced by high incident rates relative to the representation in the pipeline mileage fleet.

Cold Weather Failure Data

Analysis of the PHMSA reported incident data provides additional insight to the types of distribution systems that have reported failures due to cold weather effects. The data was evaluated in terms of:

- Location
- Era of installation
- Affected material
- Affected component
- Size of pipe

The results of the data analysis are discussed below. We focused on reported incident data for natural gas distribution systems, which includes mains and services. We also reviewed incident data for gas transmission systems and hazardous liquid transmission systems. With the exception of certain features unique to distribution systems (e.g. cast iron or plastic piping), the data from incidents in those systems told a similar story to the data from gas distribution systems. However an analysis of the non-distribution system data is not presented here.

The reporting interval for the data we reviewed was 1984 through 2011. During that time there were 120 incidents associated with cold weather, 95 of which were in pipe.

Location

A significant majority of the incidents affected buried pipe or components, Figure 3. This suggests that the predominant cause is related to frost heave or thaw settlement. A large proportion of those underground were also reported as under pavement.

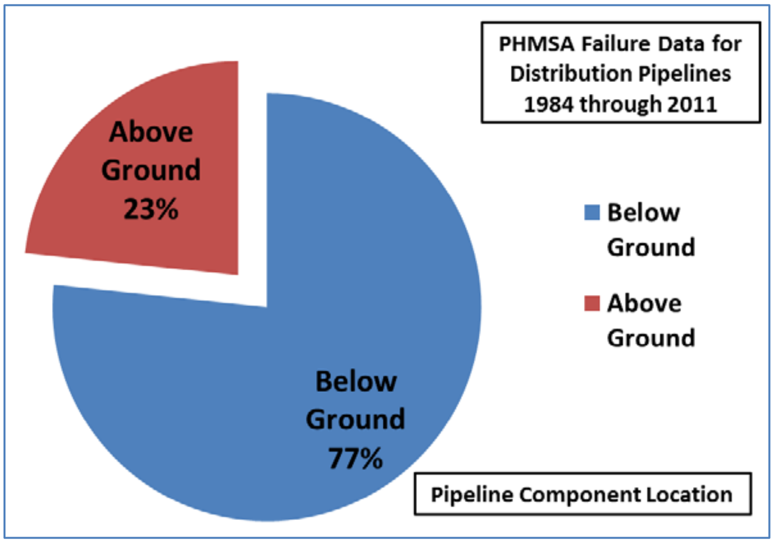

Figure 3. Cold Weather Incidents by Location

Era of Installation

The reported incidents due to cold weather were fairly evenly distributed over 20-year segments of time representing different periods of installation, from 1910 to the present, Figure 4, except that the era from 1950 to 1969 had approximately twice as many incidents as other eras.

It was thought that the larger number of incidents for 1950-1969 vintage pipe may reflect the large proportion of pipe in service installed during that time. In order to understand whether certain vintages of pipe have high or low susceptibility, the proportion of incidents attributed to specific decades of installation were compared to their representative proportions of mains miles in service nationally, listed in Table 1.

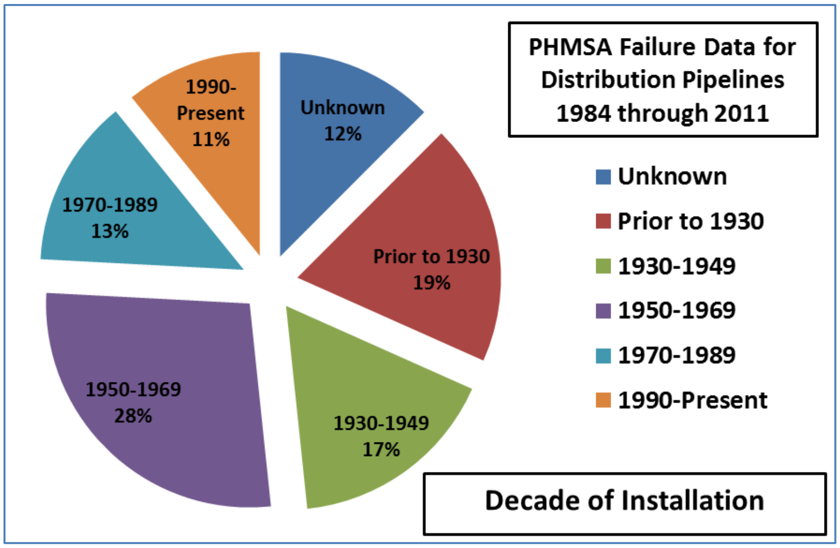

Figure 4. Cold Weather Incidents by Era of Installation

Table 1. Cold Weather Incidents and Mains Mileage by Installed Decade

Installed Decade	Incidents	% Incidents	Mains Miles	% Miles	Relative Rate
Unknown[(a)]	15	12.5%	84,736	7.0%	1.784
Pre-1940	33	27.5%	68,350	5.7%	4.866
1940 – 1949	10	8.3%	25,979	2.1%	3.880
1950 -1959	17	14.2%	107,757	8.9%	1.590
1960 – 1969	16	13.3%	196,394	16.2%	0.821
1970 – 1979	9	7.5%	131,311	10.9%	0.691
1980 – 1989	7	5.8%	155,571	12.9%	0.454
1990 – 1999	4	3.3%	232,657	19.2%	0.173
2000-Present	9	7.5%	206,731	17.1%	0.439

(a) Unknown includes both unreported and undocumented

A high susceptibility would be indicated by the ratio of the proportion of incidents normalized to the proportion of mains mileage being greater than 1.0; similarly, low susceptibility would be indicated by a ratio less than 1.0. This ratio is presented in Table 1 under the "Relative Rate" heading and is shown in Figure 5.

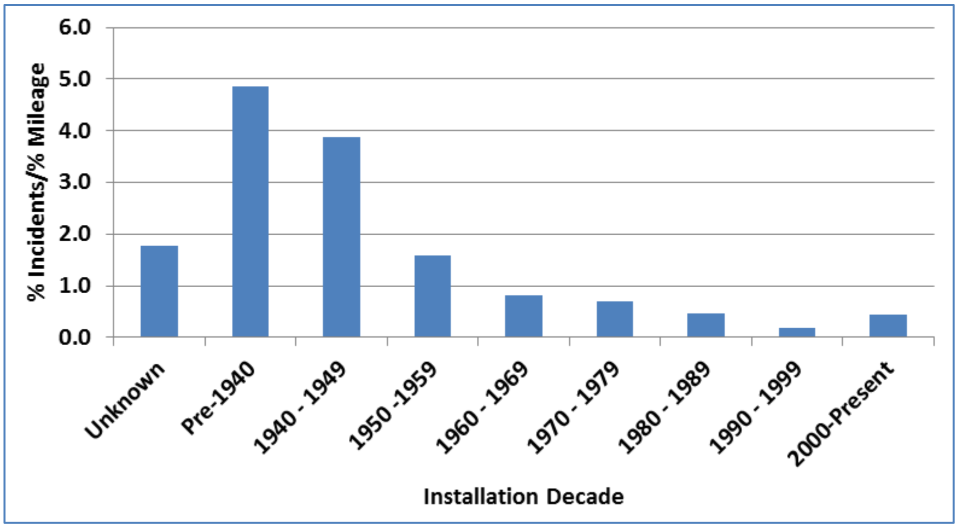

Figure 5. Normalized Susceptibility by Installed Decade

The results show that pipe installed earlier than 1950 have disproportionately high susceptibility to problems from cold weather. This is also true for pipe of unknown vintage, and pipe installed after 1950 but before 1960, but not to the extent of the pre-1950 pipe. The greater susceptibility of pre-1950 pipe is postulated to be due to two key factors. One would be the generally poor low-temperature ductility of the steels of the era which tended to have high carbon content, high sulfur content, or large-grained microstructures. The other would be the methods used to join pipe in that era, including early electric arc welds, acetylene welds, couplings, or threaded collars, all of which could have limited strength or ductility. Systems newer than 1960 exhibited comparatively lower susceptibility due to better pipe products and better quality girth welds.

Affected Materials and Components

Identified materials associated with the cold weather incidents were steel, plastic, iron, other, and unknown.[4] The systems reporting the highest number of failures were constructed of steel and cast or wrought iron, representing 40% and 42% of the incidents, respectively. Plastic and other materials represented low numbers of instances, representing 7% and 8%, respectively.

[4] "Unknown" includes the category of not reported on the F7100.1-1 annual data reporting form, which may or may not mean that the information is unknown by the operator. The material is supposed to be specified by the operator if "other" is selected.

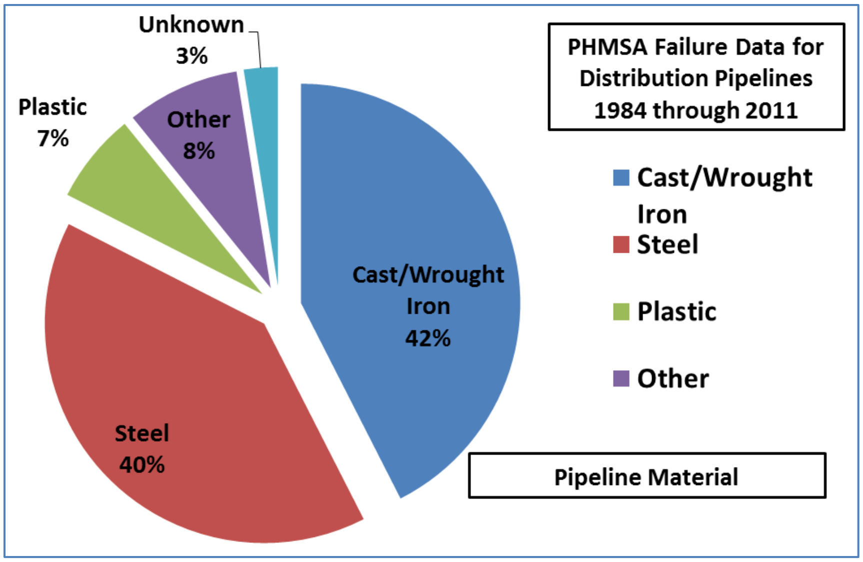

Figure 6. Cold Weather Incidents by Affected Material

However, these numbers do not appropriately describe relative susceptibility. Table 2 below lists the numbers of cold weather incidents and the number of mains miles by material type. Iron and other or unknown materials comprise very small proportions of the total mains mileage in service. The ratio of the proportion of incidents normalized to the proportion of representative miles shows extremely high susceptibility for those materials compared with steel or plastic. Steel is seen to be significantly higher than plastic, but still well below iron or the other and unknown material categories.

Table 2. Cold Weather Incidents and Mains Mileage by Material Type

Material	Incidents	% Incidents	Mains Miles	% Miles	Relative Rate
Cast/Wrought Iron	51	0.425	36,247	0.030	14.18
Steel	48	0.400	551,228	0.456	0.88
Plastic	8	0.067	620,610	0.513	0.13
Other & unknown	3	0.025	1,402	0.001	21.57

A majority of reported cold weather incidents, 58%, occurred in mains while service lines were reported in 19% of the cases, Figure 7. Meters and regulators were associated with 18% of the failures reported with most identified by causes related to snow and ice accumulation or frozen components.

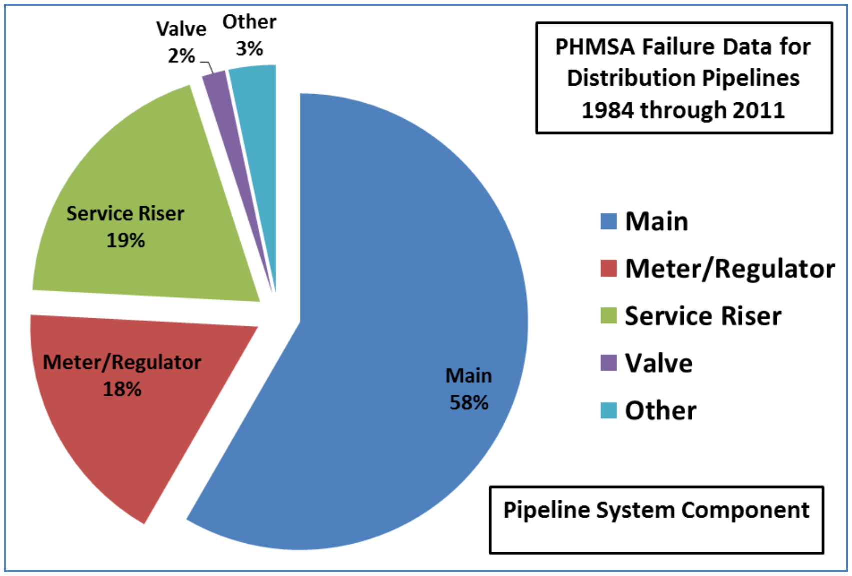

Figure 7. Cold Weather Incidents by Component

Cold Weather Incident Causes and Consequences

Cause Scenarios

A majority of the distribution systems associated with cold weather cited natural forces or outside force damage, and frequently frost heave. Other less often cited scenarios included the following, or variants thereof:

- Heavy snow or ice loads shedding off rooftops
- Damage from floating ice during flooding
- Damage from falling trees caused by ice accumulation
- Icing causing equipment or device malfunction

The PHMSA database often does not delve into the complexities of some incidents, which can only be discovered in the course of a failure investigation. Most incident reports are completed soon after an incident and before such an investigation can be completed. We are aware of a small number of incidents of near-neutral-pH stress-corrosion cracking in the threaded pipe ends of service lines, probably caused in part by frost heave or thaw settlement.[5] Only one of those incidents is identified in the PHMSA database as cold weather-related, specifically frost-heave (so the others are not

[5] A stress concentration is present at the root of the thread, acting on the axial stress induced by frost heave or settlement. A conducive environment must also be present, which might occur where a threaded joint holds moisture, oxygen in the crevice is consumed creating an anaerobic condition, and pH is in the neutral range due to lack of cathodic protection.

counted in this survey), and none are identified therein as having been affected by environmental cracking. We have also seen several incidents involving small valve bodies that fractured. These were believed to have been caused by the constrained expansion of frozen water trapped inside the valves although the direct evidence was gone (the ice was melted). We are also aware of a few incidents where the volumetric expansion of freezing water at the ground surface caused excessive reaction forces on branch connections or components. These examples illustrate the potential complexities of integrity threats associated with cold weather, or even proving that cold weather was the cause. We believe that cold weather related incidents are likely to be underreported.

Consequences

Most incidents were reported as leaks, frequently as separations of couplings or threaded joints. The isolated incidents identified as ruptures are thought to have been erroneously reported. Of the 120 distribution system incidents from 1984 through 2011, the following consequences occurred:

- 5 incidents caused 8 fatalities;
- 33 incidents caused 50 injury cases.

None of the cold weather related incidents reported for gas transmission or hazardous liquid transmission pipelines caused fatalities or injuries. This underscores the unique risk factors associated with distribution systems, namely the prevalence of gas migration paths and proximity to buildings.