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DTPH5615T00009 Development of Comprehensive Pressure Test Design Guidelines - Task 7: Other Considerations

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DTPH5615T00009 DEVELOPMENT OF COMPREHENSIVE PRESSURE TEST DESIGN GUIDELINES - TASK 7: OTHER CONSIDERATIONS

to

U.S. DEPARTMENT OF TRANSPORTATION
PIPELINE AND HAZARDOUS MATERIALS SAFETY ADMINISTRATION

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DTPH5615T00009 Development of Comprehensive Pressure Test Design Guidelines - Task 7: Other Considerations

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INTRODUCTION

The scope of this Task 7 report is to document the developed guidelines related to other considerations for pressure tests not covered by Tasks 4, 5 and 6. Kiefner and Associates, Inc. (Kiefner) developed these guidelines for best practices based on a review of currently available industry documents, interviews with pipeline operators and pressure test contractors, and Kiefner's own experience with pressure testing.

SUMMARY

This Task 7 report intends to provide the industry with recommendations related to other considerations for pressure tests not specific to the pressure test planning, execution, or evaluation. The key topics covered by this document include the following:

- risk or hazard evaluation,
- safety awareness and best practices, and
- environmental considerations

BACKGROUND

The objective of the Development of Comprehensive Pressure Test Design Guidelines Project (DTPH5615T00009, Project #645) is to develop comprehensive guidelines for the design of pipeline pressure tests that could be incorporated into industry standards and operator procedures. A goal of this project is to provide guidance on how to plan, execute, and evaluate pressure tests based on the most current knowledge and industry needs. The work takes into account the significant amount of research on pressure testing that has been carried out from the 1960s through the present by government, private, and industry organizations.

Task 2 was a review of existing industry standards, recommended practices, research papers, and other literature related to the pressure testing of liquid and natural gas pipelines. Task 2 determined the scope of the information already covered in existing guidance documents and identified deficiencies or disagreements, or both, between reviewed documents. The results of

Task 2 were reported on January 26, 2016 in Kiefner Final Report No. 16-009, "DTPH5615T00009 Development of Comprehensive Pressure Testing Guidelines – Task 2: Review of Existing Industry Standards and Recommended Practices". The following documents were reviewed:

- ASME B31.8-2014 Gas Transmission and Distribution Piping Systems
- ASME B31.8S-2014 Managing System Integrity of Gas Pipelines
- ASME B31.4-2012 Pipeline Transportation Systems for Liquids and Slurries
- API 1160-2013 Managing System Integrity for Hazardous Liquid Pipelines
- API 1110-2013 Recommended Practice for the Pressure Testing of Steel Pipelines for the Transportation of Gas, Petroleum Gas, Hazardous Liquids, Highly Volatile Liquids, or Carbon Dioxide
- INGAA Report No. 2013.03 "Technical, Operational, Practical, and Safety Considerations of Hydrostatic Pressure Testing Existing Pipelines"
- TTO Number 6 "Spike Hydrostatic Test Evaluation", July 2004

The results of the review not specific to pressure test planning, execution or evaluation related topics are summarized in Table 1. The table shows which other considerations for pressure tests are currently covered in each of the above listed documents. A topic is considered covered (denoted with a "yes" in Table 1) if relevant language is introduced in the document with some level of detail or discussion. A covered topic does not necessarily imply a prescriptive guideline is provided.

Table 1. Other Considerations Topical Comparison of Industry Documents

	Title 49 CFR Part 192	Title 49 CFR Part 195	ASME B31.8	ASME B31.8S	ASME B31.4	API 1160	API 1110	INGAA Report	TTO No. 6
Test Risk or Hazard Evaluation	Yes	No	Yes	No	No	No	Yes	Yes	No

The goal of Task 3 was to capture knowledge from liquid and gas pipeline operators and pressure testing service contractors relevant to pressure testing guidelines, as well as identify inconsistencies or gaps in pressure testing practices. Interviews with three pipeline operators and two pressure test services contractors were conducted by telephone and by written correspondence. The results of Task 3 were reported on June 30, 2016 in Kiefner Final Report No. 16-091, "DTPH5615T00009 Development of Comprehensive Pressure Test Design Guidelines - Task 3: Interview Pipeline Operators and Pressure Test Service Contractors".

Through the interviews conducted during Task 3, it can be concluded that pressure testing is a topic of broad industry interest. It was determined that the industry needs education on and consistent procedures for the following topics related to other considerations:

- risk or hazard evaluation,
- safety awareness and best practices, and
- environmental considerations.

Clarification on the key topics summarized here is necessary in order to provide the industry with one comprehensive document that provides clear guidance in the case of conflicts and dispels any misinformation or inappropriate guidance.

The goal of Task 4 was to document the developed guidelines related to the planning phase, or pre-execution phase, of pressure tests. The results of Task 4 were reported on December 30, 2016 in Kiefner Final Report No. 16-224, "DTPH5615T00009 Development of Comprehensive Pressure Test Design Guidelines - Task 4: Pressure Test Planning Guidelines".

The goal of Task 5 was to document the developed guidelines related to the execution phase of pressure tests. The results of Task 5 were reported on June 30, 2017 in Kiefner Report, "DTPH5615T00009 Development of Comprehensive Pressure Test Design Guidelines - Task 5: Pressure Test Execution Guidelines".

The goal of Task 6 was to document the developed guidelines related to the evaluation phase of pressure tests. The results of Task 6 were reported on December 18, 2017 in Kiefner Report, "DTPH5615T00009 Development of Comprehensive Pressure Test Design Guidelines - Task 6: Pressure Test Evaluation Guidelines".

This Task 7 report is the final deliverable subtask before the preparation and submittal of the draft final report (Task 8).

Note that the scope of this project is to develop guidelines related to pressure testing. Pressure testing encompasses two forms of pipeline pressurization: pneumatic which uses a compressible gas as the test medium and hydrostatic which uses a liquid as the test medium. The most common test medium for a pneumatic pressure test is nitrogen and the most common test medium for hydrostatic testing is water. Some guidelines documented by this task will distinguish between hydrostatic or pneumatic testing and the broader category of pressure testing.

OTHER CONSIDERATIONS FOR PRESSURE TEST GUIDELINES

Risk and Hazard Evaluation

Hydrostatic or pneumatic pressure testing is performed routinely and usually without incident. However, despite the routine practice, there are many sources of potential hazard. Testing with natural gas, air, or nitrogen has obvious dangers from the stored compression energy of the gas. Testing with water also presents hazards. Incidents of personal injury, fatality or property damage associated with pressure testing, including both pneumatic and hydrostatic pressure tests, have occurred. Many involve failures of test equipment or materials other than the pipe being tested.

Pressure testing is usually accomplished without test breaks occurring (although the likelihood of test breaks can vary greatly depending on circumstances), and test breaks usually are an inconsequential nuisance. Nevertheless, the authors are aware of a number of test failures occurring on liquid and gas pipelines that resulted in property damage, injury near miss, personal injuries, or fatalities as listed in Table 2. This list is illustrative but is not set forth as comprehensive or complete.

The majority of these consequential failures occurred with water because most testing is done with water due to the typically high target test stress levels. These incidents indicate that testing with water at high pressure is not without hazard. Many consequential test failures involved failure of components other than the line pipe being tested.

The information in Table 2 in most cases was known from direct involvement by the authors or other Kiefner personnel. A few were provided by Kiefner clients by request or were found in an on-line search.

All incidents listed in Table 2 involved testing of natural gas or hazardous liquid pipelines or associated facilities. Additional consequential pressure testing incidents are widely reported to have occurred in vessel or fabrication shops, piping in process or power facilities, storage tanks, plastic piping systems, and oil or gas field equipment. These events were not included in Table 2.

Certain patterns of causal factors are evident. These include:

- Personnel in close proximity to piping or equipment at the time of failure;
- Failure of components other than the pipe being tested. Prominent among these are couplings (usually of the 2-bolt type with cleats that engage grooves machined at the

end of temporary piping). The cleats may become damaged, cracked, or worn such that they are unable to sustain the thrust forces from pipe pressure;

- Pipe whip upon sudden separation of joints; and
- Jet and debris impingement from a leak or rupture.

Test failures that involve injury or death frequently occur due to a failure in either test equipment or pipeline fittings and equipment because workers are likely to be in close proximity. Ensuring that only pressure-rated, approved components that are within their service life and in good condition are being used and ensuring that no pipeline equipment is being exposed to a pressure above its rating are the easiest ways to reduce the likelihood of an incident during a test.

Some recurring preventive and mitigative measures include:

- Observe and maintain safe separation distances for all personnel;
- Restrict public exposure to beyond a suitable exclusion zone;
- Inspect and confirm fitness of all test equipment and components prior to use; and
- Restrain or anchor flexible or movable piping.

Many factors are involved in the considerations for safety measures. One hazard not specifically identified in the listing due to insufficient incident details available is associated with dewatering. Dewatering can involve using compressed air to propel polymer pigs through the line to push test water out of the line and into the next test section or into tanks for treatment and disposal. Changes in pipe elevation or direction may create variations in pig speed that prompt the compressor operator to increase pressure or the pipe alignment may create air pockets capable of building up stored energy of compression. The sudden dislodging of the pig and collapse of air pockets may produce large pressure transients and thrust forces that can fracture components or separate pipe joints, particularly at temporary connections.[i] Fatalities have occurred due to such incidents. The effect can be similar to a test break that occurs during a pneumatic test.

ASME B31.8-2016 contains several clauses that speak to the hazards of pressure testing in general, with some emphasis on pneumatic testing[ii]. Clause 841.3.1 outlines general provisions for pressure testing after construction. Pressure testing with water is recommended whenever possible (Clause 841.3.1(c)), however when a gas is used as the test medium the test pressure shall not exceed either 1.25 times the design pressure (Table 841.3.2-1), 30% of SMYS if flammable gas is used, or 40% to 75% of SMYS depending on the class location if air or nonflammable nontoxic gas is used (Table 841.3.3-1). Additionally, Clause 841.3.1(d) states: “When pipeline systems are installed in unstable soils or the mass of the test medium contributes to additional stresses in the pipeline system, the stresses and reactions due to

expansion, longitudinal pressure, and longitudinal bending shall be investigated prior to testing. This investigation shall confirm that the test pressures and loads do not produce unacceptable stresses, strains, deflections, or other conditions that could adversely impact the ability of the system to perform as required." Finally, precautions for public and employee safety are addressed by Clause 841.3.6.

Table 2. Pressure Testing Failures

Test Medium	Pipe Size	Pressure	Consequence	Description	Preventive or mitigative measures
Air fill to 100 psig, balance nitrogen	NPS 10	600 psig (approx.)	Property damage, facility damage, injury near miss	Welding on line while under test caused detonation at interface between compressed air and residual gas, resulting in loss of several hundred feet of pipe and public property damage	Prohibit welding or mechanical work on pipe while on test, restrict entry to ditch during test
Water	NPS 6	< 200 psig	Injury near miss	Coupling on fill line broke, unrestrained pipe whip narrowly missed several workers who had to take evasive action to avoid injury	Inspect test equipment before testing
Water	NPS 6 (30" OD test pipe)	< 200 psig	Property damage, facility damage	Coupling at swivel joint on test header fill riser broke, caused loss of control of test water, test site flooding, and damage to test header assembly	Inspect test equipment before testing
Water	30" OD	996 psig	Property damage	Pipe rupture water jet knocked down large tree limbs	Restrict access over the pipeline during test
Water	NPS 14	1850 psig (approx.)	Property damage	Instability of non-engineered artificial slope during the test overstressed pipe, pipe rupture water jet damaged adjacent house	Evacuate houses in close proximity to pipe during test
Water	36" OD	Unknown	Facility damage	Contractor used HDD pulling head as a test header which failed under pressure	Test heads must be designed to work safely at test pressure
Water	24" OD	320 psig (approx.)	Personal injury	Buried Dresser coupling separated during test of new pig launch facility, injured worker standing directly over coupling	Tie down unrestrained pipe, reinforce Dresser couplings, restrict access over the pipeline during test
Nitrogen	42" OD vessel and 24" OD piping	2100 psig (approx.)	Fatality and injury	Pipe whip caused when filter-separator quick-opening closure door blew off, possible overpressure due to PRV isolation and lack of test operator communication, test station set up in close proximity to tested piping	Check and secure mechanical equipment, verify PRVs are open, monitor and communicate pressure, observe personnel separation, follow safety procedures
Water	36" OD	Unknown	Facility damage	Pressure sense line froze while testing in cold weather, over-pressured pipe to rupture	Use antifreeze or heat trace pressure sense lines
Water	NPS 6 or 8	Unknown	Facility damage	Pressure sense line froze while testing in cold weather, over-pressured pipe to rupture	Use antifreeze or heat trace pressure sense lines

Test Medium	Pipe Size	Pressure	Consequence	Description	Preventive or mitigative measures
Water	NPS 14	1160 psig	Property damage, injury near miss	Pipe failure in road crossing damaged roadway and moved a parked car against a pole	Restrict access over the pipeline during test
Water	NPS 2 plug	Unknown	Personal injury	Pressure washer used to pressure up 100 ft of replacement pipe in yard, pressure unknown, threaded 2” plug separated from valve	Use proper pressure equipment and gauges, inspect condition of threaded joints, observe personnel separation
Water	NPS 6 (20” OD test pipe)	Unknown	Fatality	Coupling separation on test fill pipe caused unrestrained pipe whip	Inspect test equipment before testing, observe personnel separation
Water	30” OD	Unknown	Injury near miss	Flange fractured during test of above-ground piping moments after site workers walked past	Observe personnel separation
Water	24” OD	550 psig	Injury near miss	Spray and debris from test rupture near freeway created traffic hazard, reported vehicle damage from debris	Restrict traffic in close proximity, test during low traffic hours

The testing incidents summary in Table 2 highlights the fact that no testing medium is free from hazards. Some hazards exist irrespective of the test medium; for example, sudden separation of temporary coupled joints and resulting pipe whip. Other hazards are unique to the pressurizing medium, such as flooding with water, suffocation with nitrogen, broken glass due to ambient overpressure with any compressed gas, or fire with natural gas. If all test media were compared considering like conditions, the probability of failure would likely be the same because pressure provides the driving force, but the test fluid may influence the consequence. Different safety and pressure test execution procedures and practices are used by many operators. Therefore, the consequences of known failure incidents cannot be directly compared to find if the test medium results in worse (or higher consequence) failures if all conditions were the same. Since it is difficult to make numerical comparisons between test media due to differing conditions, no absolute determination of which is the most dangerous can be made. All testing media can be used safely, if all precautions are observed. Conversely, all testing media can present hazards if suitable precautions are not observed.

All test media hold unique hazards. Natural gas and air or inert gas tests are limited to lower maximum test pressures than tests conducted with water as the medium in 49 CFR Part 192.503. Also, 49 CFR Part 195.306 allows liquid petroleum that does not vaporize rapidly, air, carbon dioxide or inert gas as the test medium given a number of criteria are met that are more

restrictive than testing with water[1]. Testing with water can also present hazards even though the stored energy of compression is much less than that of gas. When testing with water the consequences can be injury or death to surrounding personnel, damage to nearby structures, and possible flooding or undermining the ground support for the pipeline or nearby structures. Testing with air or nitrogen holds hazards for nearby personnel and property that could be impacted by the blast wave of a sudden rupture or projected objects. When testing with nitrogen, there exists a possibility of creating an oxygen deficient area or confined space that could be a danger to workers. When testing with air inside an existing natural gas pipeline, a possibility of creating an explosive air-gas mixture exists. Table 3 details the specific hazards most closely associated with pressure test media. Maintaining appropriate separation distances during testing is also important.

Table 3. Test Media Hazards

Hazard	Category	Water	Nitrogen	Air	Natural gas
Mechanism	Fire	--	--	X	X
	Shock wave	--	X	X	X
	Projectiles	X	X	X	X
	Jetting	X	--	--	--
	Flooding	X	--	--	--
	Suffocation	--	X	--	X
Consequence	Equipment damage	X	X	X	X
	Property damage	X	X	X	X
	Fatality or injury	X	X	X	X
	Cratering	--	X	X	X

Safety Considerations

Findings from Pneumatic Pressure Test Experiments

Observations made by Kiefner during experimental burst testing and through review of recorded data have been used to generate recommendations for safe work practices to implement during pneumatic pressure testing.

The key findings of the experimental tests for above ground piping are:

- A shock wave formed when axially oriented flaws ruptured due to the speed of the steel tearing allowing gas to escape;

[1] The additional restrictions on maximum pressure test stress levels imposed for natural gas, air or inert gas tests are in place to reduce the risk of failure because failure with test media other than water can have higher safety and environmental consequences.

- For use in a model that uses air blast to determine exclusion radius, only the energy associated with the volume of pressurized gas in the length of pipe that ruptures plus one pipe diameter needs be considered;
- The measured free field pressure relates to the energy contained in the length of ruptured pipe plus one pipe diameter via a power law relationship;
- When the pipe ruptures axially, the resulting free field pressure is greater than the pressure generated by an equivalent mass of explosive in an open area, since the shock wave produced from a pipe rupture is directed into only one quadrant of the pipe circumference;
- The failure of the pipe in the circumferential direction will not cause an air shock wave to form.

Recommendations for above ground pneumatic pressure testing:

- Restraints or barricades should be used with above ground piping that is isolated from underground piping;
- Tarps or another material should be put on the ground to cover loose materials next to the pressurized piping section to prevent or lower the number of projectiles generated during a pipe rupture.
- If loose gravel or other loose media is surrounding the pipe to be tested, the use of matting could decrease the likelihood of high energy projectiles being created. While there is still a risk that the fracture could cause part of the pipe or a pipe appurtenance to be projected outward, the majority of the potential projectiles are likely from the ambient environment.
- Short segments of above ground piping could become projectiles. If a short segment of piping is isolated from piping that ties it to below ground piping or to tethers such as full encirclement pipe supports, the piping could be made into a rocket by the exiting compressed energy. **To mitigate the threats associated with this risk, short segments of above ground piping must be anchored or restrained. The above ground piping should be restrained by either high tensile cable, rope, or barriers placed immediately surrounding the piping.**
- In addition to a safety radius and other mitigative measures, hearing protection used by workers in the area of the test segment during pressurization and the first 15 minutes of the pressure test would provide additional safety. Since glass breakage is also possible outside of the human safety radius, instructing workers to stay away from the immediate areas of untempered glass within the glass breakage radius during

pressurization and the first 15 minutes of the test will lessen the likelihood of an injury in the event of an above ground pipe rupture.

The key findings of experimental burst tests of 0.75-inch to 8-inch OD piping at pressures ranging from 627 psig to 3,310 psig and conducted underneath 3 feet of compressed sand and 1-2 pound rocks are:

- Piping segments with calculated stored pressure energy less than 75,000 ft-lbs (0.05 lbs TNT equivalent energy) do not require an exclusion zone due to the lack of projectiles in experiments that reached a height of 5 ft above the ground surface.
- The sand and loose rock mixture used over the pipeline in the tests provided a worst case scenario for energy absorption. Rocks or other dense objects can be projected more than 100 feet per each 1,500,000 ft-lbs of energy (up to a limit, not yet defined by research) from the rupture location. This conclusion is only valid up to a limit and ongoing testing and research is determining the cut-off point for piping length that contributes to the energy transferred to the overburden. Existing pipe in non-desert environments is typically buried with a more cohesive ground cover that would likely allow less energy transfer between the released nitrogen and small projectiles.
- The measured distance rocks that were thrown conformed to a linear relationship with the stored energy in the pressurized gas for the range of tests completed. This conclusion is only valid up to a limit and ongoing testing and research is determining the cut-off point for piping length that contributes to the energy transferred to the overburden.
- Additional testing in the industry is warranted to determine how the pipe diameter and internal pressure affect the safety radius for long length test segments.

Public Safety

Local authorities, governmental agencies, potential emergency response personnel, and landowners along the right-of-way (ROW) should be notified as applicable prior to a pressure test. Safety caution signs should be placed at all public crossings, parks and playgrounds to prevent people walking along the ROW. Also notify the public by radio, newspaper, or mail of upcoming scheduled pressure tests. For residents near the pipeline, consider offering vouchers for meals away from their residence and accommodations at a hotel in order to remove them from the vicinity of the pipeline during pressure testing.

Pressurization, Static Pressure, and Depressurization

Personnel safety shall be considered during all phases of a pressure test. No member of the public, contractor, or company personnel should be allowed over a test section after the test pressure has exceeded the operating pressure. No trucks, cars, or excavating equipment

should be allowed over a test section after the test pressure has exceeded the operating pressure. Test equipment and personnel should be positioned to minimize potential hazards, and personnel performing the test should approach the pressured line only in the performance of their duties. Properly rated equipment and establishing an effective anchoring system are essential to safe pressurization and depressurization. Reliable communication equipment should be provided and maintained during pressure testing so that all personnel directly involved may communicate. An enclosed, lighted, heated, and/or air-conditioned shelter adequately sized to house test recording equipment and test personnel at the data collection site should be made available. Adequate lighting shall be available for testing operations performed at night.

The following safety guidelines should be followed during the pressurization, static testing, and depressurization of a pressure test:

- Test manifolds, pumps, and personnel should be positioned to minimize potential hazards. Typical positioning should include a barrier between the test equipment and test manifold and/or placement of test equipment a minimum distance of 50-feet from the test manifold.
- Personnel performing the test should execute all duties with caution and approach the pressurized line only in the performance of their required duties.
- Non-test personnel should remain out of the vicinity of the test header and test section.
- Liquid fill pressure is typically in the range of 300 to 500 psi. When coupled fill lines are used, the piping and connections should be inspected for damage, and only undamaged piping and couplings should be used. As the fill line is assembled, each joint should be examined to assure correct insertion and alignment. Alternatively, a girth-welded fill line can be constructed, but the girth welds should be inspected before the line is used.
- All temporary welds to be exposed to test pressure should be inspected by non-destructive testing (NDE).
- For pressurizing assembly:
    - Install a check valve near the test head.
    - Rigid steel pipes (2-inch pipes with high pressure swivel hammer unions – oil field standard) without bends other than the swivels should be used. Adequate support and bracing should be provided for the rigid piping used in connecting the facility to the test section to avoid whipping.
    - Alternatively, high pressure hoses held down by chains or whip checks may be used.
- To tighten leaking flanges or screwed fittings reduce pressure to zero (or static head pressure), or close the isolation valve if pressure is below the maximum working pressure of the valve and bleed off to zero.

- Depressurizing shall be executed in a proven safe manner, such as into a fill line and then into a secondary containment (such as a frac tank or tanker truck). Dewatering, especially when air is being released can be dramatic. Enforce the same rate for depressurizing as for filling, about 4000 gpm.
- Adequate support and bracing should be provided for the piping being used for depressurizing and dewatering the line.
- Depressurization should be carried out at a similar rate to the pressurization. Some dewatering procedures allow for displacement with liquid, such as crude oil or some refined products. However, if compressed air or nitrogen is used to displace water, measures must be taken to prevent air locks. When an air lock occurs either increase the displacing pressure (without over-pressuring) or vent at high elevations in front of the dewatering pig. API 1110 section 5.9 provides general guidelines on depressurization, displacement, and the disposal of test fluids[iii]. Chapter 6 of the Pipeline Rules of Thumb Handbook[iv] provides guidelines related to dewatering. All disposal or discharge lines should be restrained from movement.

Test Monitoring and Setback Distances

The Potential Impact Radius (PIR) calculated in accordance with 192.903 is adopted by some operators or testing contractors for determining a safety zone around a pneumatically-pressurized test section. The PIR is calculated as:

$$\mathbf{R = 0.69\sqrt{(P\ x\ D^2)}} \qquad \textbf{Equation 1}$$

where:

P = Absolute Test Pressure (psig)
D = Outside Diameter (in)
R = Radius of Potential Impact (ft)

The PIR concept was developed by Stephens (2000)[v] as a method for defining the length of a natural gas pipeline requiring special integrity management measures based on proximity to sites containing concentrations of people. The PIR formula was created by determining the amount of natural gas that would escape from a pipeline after rupture but before reaching an ignition source. The resulting flame jet's effects, considering heat flux directed at objects at a variable distance from the rupture site, were then computed. The PIR has been set at a heat flux intensity of 5,000 Btu/hr-ft^2, which corresponds to a value at which wooden structures would not be expected to ignite and fatalities of unsheltered persons subject to 30 seconds exposure would be a 1% probability. The radius calculated by the PIR does not have a basis that relates to the safety radius of a pipeline containing an inert gas, other than the fact that they both are dependent on pipeline diameter and pressure. An alternative method for calculating a safety radius for pneumatic testing is discussed in Appendix A. Note: PIR is

considered overly conservative for above ground air blast due to a ductile pipe failure, but possibly non-conservative for some below ground tests if considering the distance a projectile could travel that could potentially result in fatality. The PIR is not a "safe" distance for those outdoors. The separation distance for anyone in the general public should be at least double the PIR for a test with natural gas.

When testing with water, a minimum 25-foot exclusion radius is recommended around all above ground test sections. This is not based on calculations but in part by reviewing prior hydrostatic testing safety incidents that resulted in injuries or fatalities at less than 25-foot radius. The Interstate Natural Gas Association of America recommends in their document titled Pressure Testing (Hydrostatic /Pneumatic) Safety Guidelines that a 100-ft or greater exclusion zone for workers and test equipment be used around hydrostatic and pneumatic tests. No mention is made as to whether those requirements apply to only above ground test sections or all test sections. Many operators and pressure test contractors implement a minimum 50-foot exclusion radius for hydrostatic pressure tests, which is considered acceptable.

Appendix A gives safe distance calculation models for short and long length pressure tests using non-experimental data. The results are considered reasonable for short length tests, but long length tests are considered overly conservative. The models are provided for consideration. However, alternative safe distance calculation models are under development in the industry whereby empirical equations are used to describe the safety radii for above and below ground test segments during testing for potential human or structural impacts.

Inclement Weather

Pressure testing should be suspended during severe weather such as thunderstorms that have the potential to produce lightning, hail, heavy rain, or wind.

When there is potential for ambient temperatures to fall below freezing, temperatures need to be closely monitored and precautions taken to keep instrument lines and above ground valve stations or piping from freezing by the use of portable heating units or insulation blankets and tents. Recommended steps for cold weather testing are outlined below.

- Electronic transducers (electronic deadweights) can be used instead of conventional deadweights to avoid the risk of pressure sensing lines freezing. (The authors are aware of an incident of pressurizing a pipeline to failure due to sensor line freezing.)
- If conventional deadweights are employed use 50-50 glycol/water or 50-50 methanol/water in pressure sensing line. The use of oil is not recommended as any drops of water will separate and could freeze.

  - Coil 20 feet of sensing line filled with anti-freeze in a heated trench to prevent water entering the line during testing and becoming exposed to ambient air.
- Heat test headers with propane heaters if freezing is anticipated.
  - First place to freeze would be small-diameter equipment with small instrument valves where conventional deadweight instrument line or electronic pressure transducer are likely to be connected.
- Build plastic and frame structure around piping and heat with propane heaters.
- Dewater large diameter valve bodies in the fully open position with methanol and blanket with glycol.

Job Safety Policies, Permits and Checklists

The following are examples of applicable company safety policies that should be reviewed prior to and referenced during the execution of activities related to pressure tests:

- Environmental, Health & Safety Policy
- General Safety Rules and Responsibilities
- Vehicle Safety
- Electrical Safety
- Energy Isolation (Lockout/Tagout)
- Fall Protection
- Personal Protective Equipment
- Safe Work Practices and Permitting
- Housekeeping
- Manual Lifting – Back Injury Prevention
- Contractor & Visitor Orientation
- Incident Notification
- Injury/Illness - Handling & Reporting
- Motor Vehicle Collision - Handling & Reporting
- Incident Investigation
- Chains and Slings Inspections
- Excavation & Trenching
- Heavy Motorized Equipment
- Ladder Safety
- Flammable & Combustible Liquid – Handling & Storage
- Hazard Communication
- Hazardous Materials
- Hearing Conservation

The following permits or checklists may be necessary prior to or during pressure tests:

- Safe Work Permit
- Job Site Safety Analysis (JSA)
- Daily Excavation Checklist
- Equipment Operator Daily Check
- Confined Space Entry Permit
- Isolation Blind List (Lockout/Tagout)
- Line Cutting (above or underground)
- Vacuum Truck Safety Checklist

Freeze Plugs

An isolation method for hydrostatic testing is to freeze a short section of the test water by surrounding the bare pipeline with liquid nitrogen, forming a “freeze plug” whereby pressurized water on either side of the plug cannot pass. For freeze plug installation, if possible, select a joint having relatively better ductility and toughness compared to other pipe present on the segment. Prior to the installation of freeze plugs, inspect the full circumference of the pipe for flaws using NDE. Do not install freeze plugs at potential locations of elevated external loads, over girth welds, bends, dents, or any flaw detected in the pipe. Pressure shall be reduced on the pipeline to approximately 50% SMYS or less. If the pipeline has a history of failures (ruptures), the pressure on the pipeline should be lowered further before performing the work tasks. The nitrogen tank should be positioned at the excavation site to shield personnel in the event of a pipe rupture. Pipeline operators should require and review nitrogen services contractors’ safety procedures related to the installation and removal of the freeze chamber, hoses, vent pipe, temperature monitoring equipment, and manifolds. No individual, for any reason, shall enter a bell hole (or excavation site) while liquid nitrogen is flowing into the freeze chamber.

Environmental

Environmental permits (local, state or federal) may need to be obtained prior to pressure testing. A permit for test water discharge/disposal is typically required. The use of additives may be prevented, or require additional permitting or restrictions on disposal. Depending if the test section crosses or is in close proximity to an environmentally sensitive area, a study on the potential impact of a test failure to the environment may need to be conducted. Generally pipeline operators have a dedicated environmental group within its organization to consult. Additionally, local, state, and federal environmental protection agencies publish permitting forms, requirements, and frequently asked questions on publically assessable websites for reference.

APPENDIX A – SAFE DISTANCE CALCULATION MODELS FOR PNEUMATIC TESTS

Short Length Pressure Tests

One of the foremost hazards of testing with any gaseous medium is the threat of rupture resulting in a shock wave emanating from the rapidly decompressing pipe. To determine the safe distance from a pressure vessel filled with compressed air or gas, ASME PCC-2 (2011)[vi] Article 5.1 can be used as follows:

The energy in pressurized gas can be expressed as:

$$E = \left[\frac{1}{k-1}\right] \times \mathrm{P}_{at} \times \mathrm{V}\left[1 - \frac{P_a}{P_{at}}^{\frac{k-1}{k}}\right]$$ **Equation A-1**

where:

P_{at} = Pressure of Atmosphere (Pa)
P_a = Absolute Test Pressure (Pa)
k = Ratio of specific heat of test fluid, 1.4 for Nitrogen or Air
k = 1.32 for Natural Gas
E = Stored Energy (J)
V = Total volume under test pressure, m^3

The energy equivalency of the compressed gas to weight of TNT in an explosion can be expressed as:

$$TNT = \frac{E}{4{,}266{,}920}$$ **Equation A-2**

where:

TNT = Equivalent Energy mass of TNT (kg)
E = Stored Energy (J)

The Scaled Consequence factor can be found from the TNT equivalency as:

$$z = z' \times TNT^{1/3}$$ **Equation A-3**

where:

TNT = Equivalent Energy mass of TNT (kg)
z' = Scaled distance ($m/kg^{1/3}$)
z = Actual distance (m)

Table A-1 shows the effects of overpressure events.

Table A-1. Effects of Overpressure Events

z' m/(kg$^{1/3}$)	z' ft/(lb$^{1/3}$)	Physiological Effect	Structural Failure
20	50	No Effect Listed	Glass Windows
12	30	Eardrum Rupture	Concrete block panels
6	15	Lung Damage	Brick Walls
2	5	Fatal	No Effect Listed

This calculation measures the storage of energy in a compressed gas by the ratio of specific heats for that gas at atmospheric and test pressures. The compression energy to be released if a failure occurred can be scaled to the energy release from a quantity of explosive. The ensuing effects can be used to establish appropriate separation distances to minimize consequential harm.

The ASME PCC-2 equations are suitable for a vessel as the contained energy in the test would be rapidly released in the explosion, and can be conservatively applied to relatively short lengths of pipe. The ASME PCC-2 equations are not suitable for long lengths of pipe pressurized with a compressible gas, because in the event of a test rupture the entire volume does not decompress all at once. Table A-2 displays the cut-off distance between short and long length tests, with the given distances, in feet, being the maximum effective length of pipe contributing to the exclusion radius.

The mitigating effects of soil cover have not been accounted for in the calculations for a number of reasons. Among them are:

- pipeline service ruptures demonstrate that soil cover in usual depths is incapable of containing a high pressure rupture;
- where significant depths of soil cover could partially mitigate the effect of a pipe failure, the benefit may depend on soil type and moisture content that must then be verified shortly before the pressure test;
- a pipeline rupture at high pressure would likely eject material from the ground and create dangerous projectiles.

ASME PCC-2 states that a minimum 100-ft exclusion radius for personnel should be used for test sections with a stored pressure energy of less than 1 x 10^8 ft-lb; for test sections with a stored pressure energy of between 1 x 10^8 ft-lb and 2 x 10^8 ft-lb, a minimum 200-ft exclusion radius should be used.

Long Length Pressure Tests

When considering a long test section for pneumatic pressure testing, the ASME PCC-2 methodology is not applicable, as the contained energy in the test section would be released over a longer period of time due to the fact that a long pipeline does not decompress at once. The use of ASME PCC-2 Article 5.1 for a long length of pipe would result in excessively conservative calculations for the safe radius from the test section. An alternative approach that considers the effective decompression length of test pipe is described below.

The critical or effective decompression length of piping, which is the point wherein the length of the test section exceeds the contributing length of compressed gas pack to influence the maximum blast wave intensity, determines the necessary safety radius around the test section. The cut-off between short and long sections of pipe is given in Table A-2 and Figure A-1. This can be evaluated by comparing the internal decompression wave speed to the external shock wave characteristics created during the failure. This calculation has many permutations based on gas composition, pipe diameter, and size of discontinuity of pipe at the rupture location. Additionally, no specific studies to complete this calculation have been developed by industry, but using principles from ASME PCC-2 along with an equation for overpressure versus scaled distance, and decompression analyses reported in the literature[vii], an approximate length can be ascertained dependent on the pressure of the test section and internal pipe diameter. By comparing the rate at which the decompression wave inside the pipe travels with the speed of the external transient pressure at different length and time intervals from the rupture point and time, the peak quantity of decompression energy impacting the explosive radius that is deemed to be the threshold of harm can be found.

Table A-2. Cutoff Length for Short Length Inert Gas Test Safety Radius (feet)

Pressure (psig)	Nominal Diameter (in)													
	2 & less	3	4	6	8	10	12	16	20	24	30	34	36	42
100	500	700	840	1,140	1,500	1,860	2,120	2,680	3,420	4,080	5,040	5,620	5,900	6,880
200	580	900	1,140	1,620	2,120	2,700	3,220	3,940	4,980	5,940	7,280	8,260	8,720	10,080
300	720	1,080	1,380	2,100	2,700	3,360	3,960	4,980	6,100	7,340	9,120	10,220	10,760	12,420
400	900	1,300	1,640	2,460	3,160	3,920	4,620	5,780	7,200	8,560	10,580	11,880	12,540	14,440
500	980	1,440	1,820	2,760	3,560	4,420	5,240	6,480	8,040	9,620	11,900	13,340	14,040	16,200
600	1,140	1,620	2,140	3,220	4,100	5,060	6,040	7,480	9,300	11,060	13,700	15,420	16,220	18,760
700	1,340	1,940	2,480	3,700	4,840	5,940	6,980	8,760	10,820	12,900	15,940	17,900	18,840	21,720
800	1,540	2,260	2,920	4,200	5,480	6,720	8,000	9,960	12,340	14,660	18,100	20,300	21,420	24,700
900	1,760	2,500	3,260	4,780	6,120	7,600	8,960	11,180	13,860	16,420	20,260	22,740	23,920	27,620
1000	1,880	2,820	3,620	5,280	6,780	8,400	9,900	12,400	15,320	18,200	22,380	25,160	26,540	30,580
1100	2,080	3,060	3,980	5,760	7,420	9,200	10,860	13,540	16,780	19,900	24,500	27,540	28,980	33,360
1200	2,300	3,280	4,320	6,280	8,080	10,000	11,840	14,780	18,260	21,620	26,620	29,820	31,440	36,260
1300	2,500	3,600	4,680	6,860	8,820	10,820	12,800	15,920	19,640	23,340	28,660	32,220	33,920	39,080
1400	2,720	3,840	4,940	7,360	9,380	11,620	13,680	17,080	21,120	25,060	30,820	34,540	36,420	41,840
1500	2,840	4,180	5,300	7,860	10,140	12,440	14,660	18,240	22,540	26,720	32,800	36,880	38,840	44,700

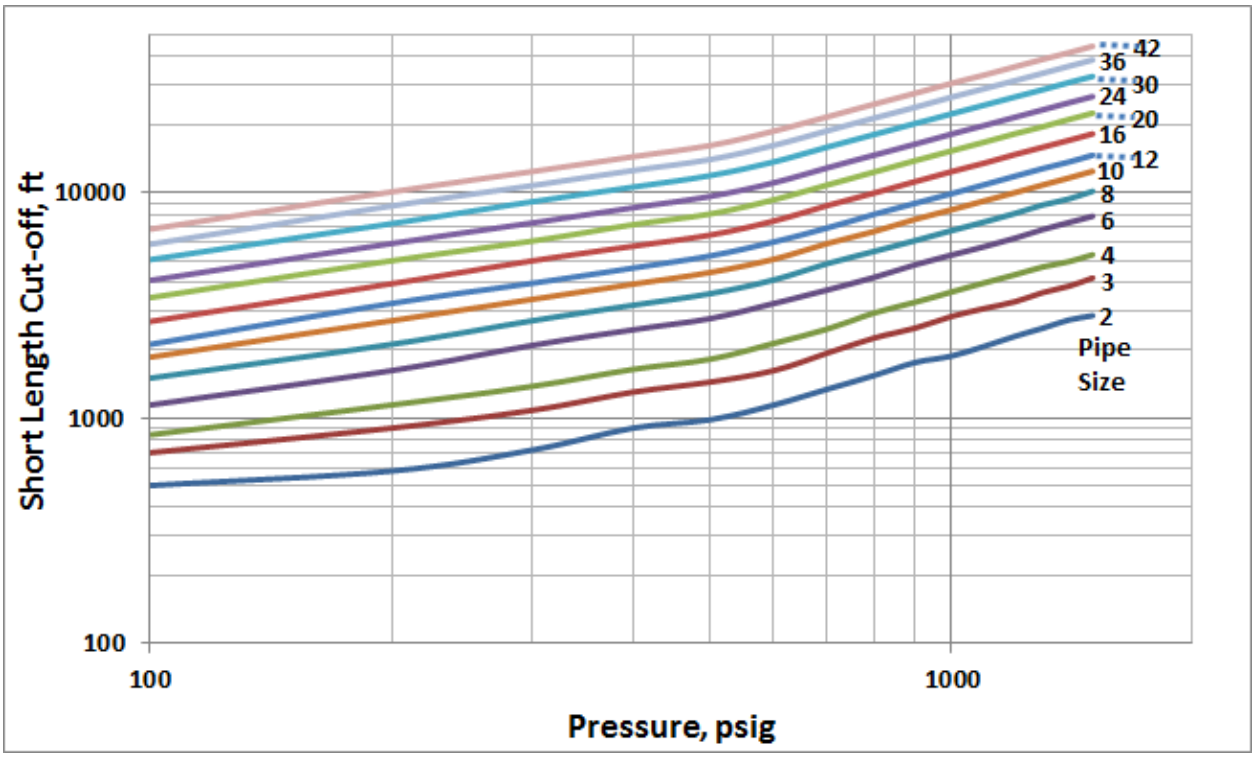

Figure A-1. Cutoff Length for Short Length Inert Gas Test Safety Radius

In the paper by Burlutskiy[ii], it was shown that the decompression wave in the pipe travels at approximately 385 meters per second. This number was calculated when considering nitrogen at 1,480 psig. However, in the absence of data to determine the decompression wave of air in a pipe, this value was used for both air and nitrogen. Additionally, factors were included to account for the maximum flow rate from pipe, assuming a guillotine type rupture. (Alternatively, this admits a longitudinal rupture with an opening at least equal to the cross-sectional area of the pipe, or larger.) These factors considered both the maximum initial flow rate as well as a flow rate decay factor as discussed by Stephens (2000)[viii]. Equations to determine the maximum flow rate are presented below:

$$Q_{in} = C_d \frac{\pi d^2}{4} p \frac{\phi}{a_0}$$ **Equation A-4**

$$\phi = \Gamma \left[\frac{2}{\Gamma+1}\right]^{\frac{\Gamma+1}{2(\Gamma-1)}}$$ **Equation A-5**

$$a_0 = \sqrt{\frac{\Gamma R T}{m}}$$ **Equation A-6**

where:

C_d = 0.62
Γ = Specific heat ratio of gas (1.4 for nitrogen or air)
R = 8,310 J/(kg-mol)/K
T = 288 K
m = Gas Molecular Weight (28 kg/mol for nitrogen gas)
d = Pipe Diameter
p = Pipeline Gauge Pressure

An equation to determine the decay factor of flow rate was deduced by curve-fitting a pressure versus time plot given by Stephens (2000). The equation used was:

$$FR = -0.125(\ln t) + 0.7355$$ **Equation A-7**

where:

FR = Mass flow rate fraction of initial flow-rate
t = Time (sec)

The overpressure of the air outside of the pipe was calculated using fitted equations provided by a study on overpressure versus scaled distance[ix]. The equations used for the overpressure calculation are:

$$Ps = 1.13E6 \times z'^{-2.01} \text{ for } z' \geq 1 \text{ and } < 10$$ **Equation A-8**

$$Ps = 1.83E6 \times z'^{-1.16} \text{ for } z' > 10 \text{ and } \leq 200$$ **Equation A-9**

where:

Ps = Overpressure (Pa)
z' = Scaled distance ($m/kg^{1/3}$)

Several simplifications were made to the model to make the results more conservative for all but the worst case scenario. The rupturing pipe was assumed to be exposed at ground level, the rupture opening area was assumed to be the full diameter of the pipeline in both directions and the entire gas compression energy of the effective length test section was assumed to be released instantaneously. In real world scenarios, particularly buried mainline testing, this worst case will never be achieved. The maximum contributing length of pipe varies based on diameter, test pressure, and the physiological effects or property damage deemed to be tolerable. ASME PCC-2 gives a table of physiological effects and property damage for various scaled consequence factors. If the threshold was set to the level corresponding to no permanent physiological effects to humans, a scaled consequence factor of 50 $ft/lb^{1/3}$ TNT equivalence would be used to calculate the maximum contributing length of compressed air or gas pack.

Figure A-2 shows the safe distance, in feet, from the pipeline at a scaled consequence factor of 50 $ft/(lb^{1/3})$ TNT equivalence on the vertical axis when using nitrogen or air. The other axes show the test pressure in psig and the nominal pipe diameter in inches. A minimum exclusion radius of 25 feet is recommended for instances in which the calculated value is less than 25 feet. Those cells are highlighted in Table A-3.

Table A-3. Long Length Test Exclusion Radius Matrix for Inert Gas (feet)

Pressure (psig)	Nominal Diameter (in)													
	2 & less	3	4	6	8	10	12	16	20	24	30	34	36	42
100	18	26	32	46	60	74	86	108	136	162	200	224	236	274
200	24	36	46	66	86	108	128	158	198	236	290	328	346	400
300	30	44	56	84	108	134	158	198	244	292	362	406	428	494
400	36	52	66	98	126	156	184	230	286	340	420	472	498	574
500	40	58	74	110	142	176	208	258	320	382	472	530	558	644
600	46	66	86	128	164	202	240	298	370	440	544	612	644	744
700	54	78	100	148	192	236	278	348	430	512	632	710	748	862
800	62	90	116	168	218	268	318	396	490	582	718	806	850	980
900	70	100	130	190	244	302	356	444	550	652	804	902	950	1,096
1000	76	112	144	210	270	334	394	492	608	722	888	998	1,052	1,212
1100	84	122	158	230	296	366	432	538	666	790	972	1,092	1,150	1,324
1200	92	132	172	250	322	398	470	586	724	858	1,056	1,184	1,248	1,438
1300	100	144	186	272	350	430	508	632	780	926	1,138	1,278	1,346	1,550
1400	108	154	198	292	374	462	544	678	838	994	1,222	1,370	1,444	1,660
1500	114	166	212	312	402	494	582	724	894	1,060	1,302	1,462	1,540	1,772

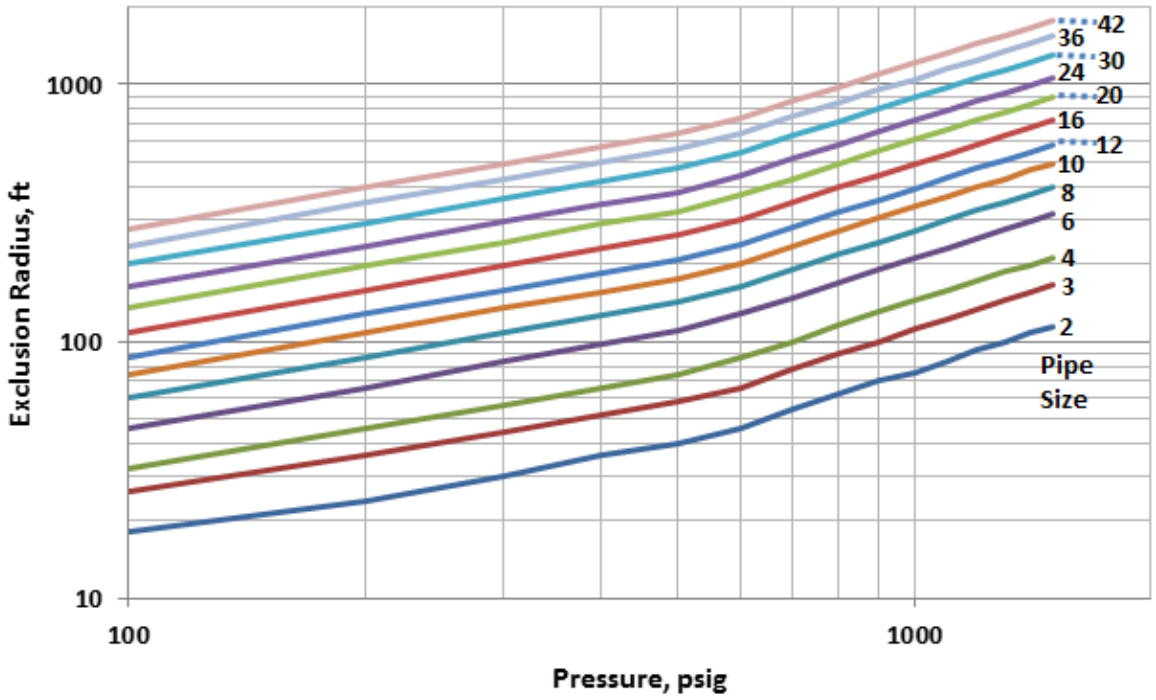

Figure A-2. Main Test Exclusion Radius Diagram when using Inert Gas

While this chart and graph can be used to determine a safe distance from a pneumatic test with air or nitrogen for workers and the public, some workers may have need to be temporarily inside this exclusion zone. As is discussed in the Risk and Hazard Evaluation section of the main body of this report, there are many different modes of failure that can occur. Hydrostatic or pneumatic pressure testing can be routine for many veteran workers and a sense of complacency can occur. By learning from previous failures and understanding the possible modes of failure, implementing additional procedural steps or checks could help to reduce the probability of failure.

Note also that in the event that a test is performed using natural gas, the PIR should be calculated. The PIR is not a "safe" distance for those outdoors. The separation distance for anyone in the general public should be at least double the PIR for a test with natural gas. The exclusion radii for tests conducted using natural gas are shown in Table A-4 and Figure A-3. The values in the table incorporate the factor of two on the calculated PIR.

Table A-4. Minimum Exclusion Radii for the General Public during Natural Gas Tests (feet)

		Nominal Diameter (in)													
		2 & less	3	4	6	8	10	12	16	20	24	30	34	36	42
Pressure (psig)	100	33	48	62	91	119	148	176	221	276	331	414	469	497	580
	200	46	68	88	129	168	210	249	312	390	468	585	664	703	820
	300	57	84	108	158	206	257	305	382	478	574	717	813	860	1,004
	400	66	97	124	183	238	297	352	442	552	662	828	938	994	1,159
	500	73	108	139	204	266	332	393	494	617	741	926	1,049	1,111	1,296
	600	80	118	152	224	292	363	431	541	676	811	1,014	1,149	1,217	1,420
	700	87	128	164	242	315	392	466	584	730	876	1,095	1,241	1,314	1,533
	800	93	137	176	259	337	420	498	625	781	937	1,171	1,327	1,405	1,639
	900	98	145	186	274	357	445	528	662	828	994	1,242	1,408	1,490	1,739
	1000	104	153	196	289	376	469	556	698	873	1,047	1,309	1,484	1,571	1,833
	1100	109	160	206	303	395	492	584	732	915	1,098	1,373	1,556	1,648	1,922
	1200	114	167	215	317	412	514	610	765	956	1,147	1,434	1,625	1,721	2,008
	1300	118	174	224	330	429	535	634	796	995	1,194	1,493	1,692	1,791	2,090
	1400	123	181	232	342	445	555	658	826	1,033	1,239	1,549	1,756	1,859	2,169
	1500	127	187	241	354	461	575	681	855	1,069	1,283	1,603	1,817	1,924	2,245

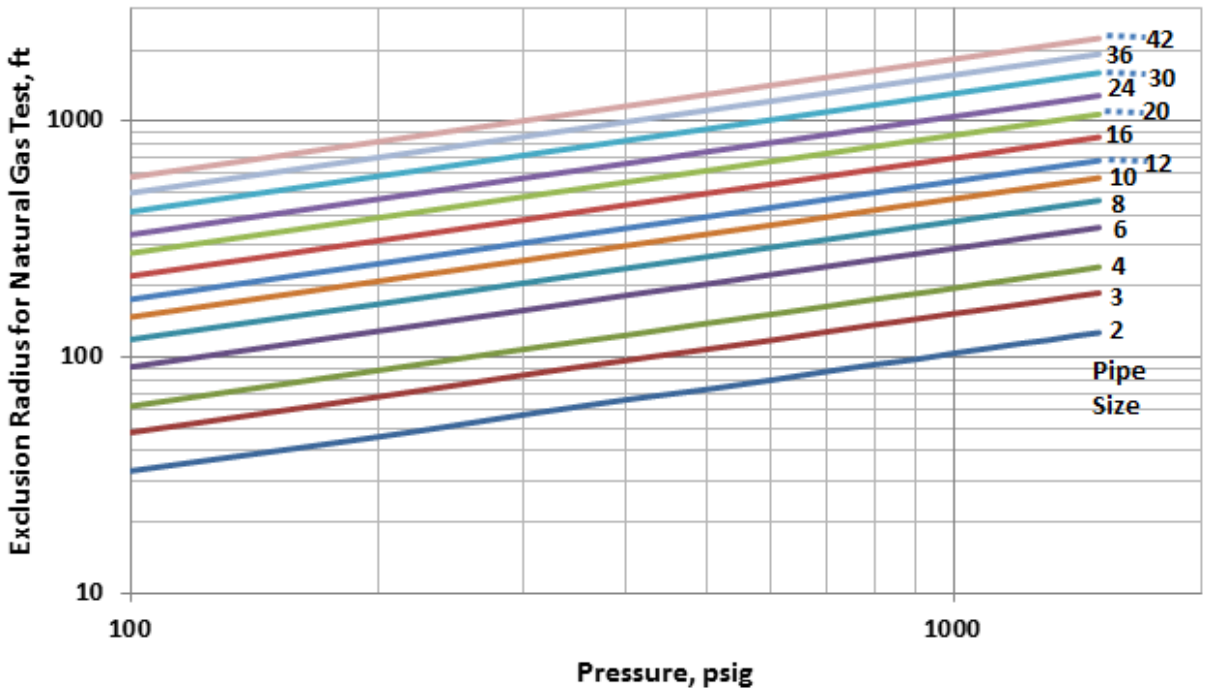

Figure A-3. Main Test Exclusion Radius Diagram when using Natural Gas

For small volume tests, the equations from ASME PCC-2 Article 5.1 can be used to determine a safe exclusion radius. K-rail (portable concrete barriers) could be used to demark exclusion zones in urban areas where extra safety precautions are desired. The farther away from the pipeline the K-rail is placed, the less protection it provides due to its low height. However, if placed too close, it might fall within a crater caused by the released air or gas, and therefore could be ineffective or cause damage. Therefore, to determine the best compromise of distance, the potential crater size was calculated using sizing equations from Gould and Tempo (1981)[x] as

$$V_{a=} V_0 \times w \times e^{\left[-5.2\times H(V_0\times w)^{-1/3}\right]}$$ **Equation A-10**

where:

V_a = expected apparent crater volume (ft^3)
V_0 = cratering efficiency of explosive for a zero height-of-burst (ft^3/ton)
W = TNT-equivalent explosive weight (tons)
H = height of burst of the explosive charge (ft)

In urban areas, glass breakage can be a potential source of injury. Certain types or dimensions of window glass could break at overpressure levels below what can cause physical harm to humans. The minimum distances at which certain types of glass would have a 50% probability

of failure were developed by Fletcher (1981)[xi], reproduced here as Figure A-4. A worst-case glass type should be assumed if the actual type of glass installed at a particular site is unknown.

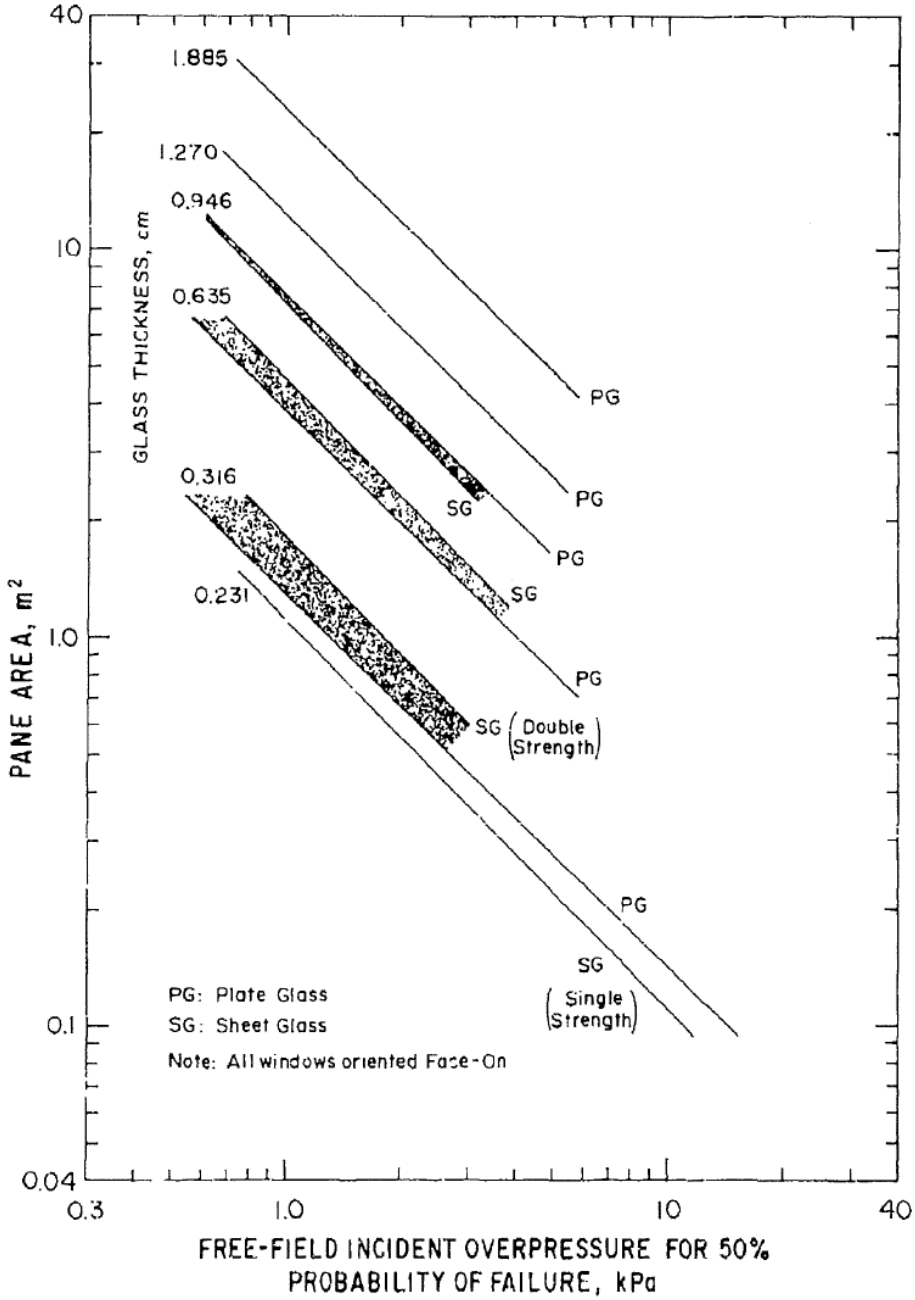

Figure A-4. Glass Pane Area versus Overpressure (from Fletcher)

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