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DTPH5615T00009 Development of Comprehensive Pressure Test Design Guidelines - Task 5: Pressure Test Execution Guidelines

Cara Macrory-Dalton, P.E.

September 7, 2018

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on

DTPH5615T00009 Development of Comprehensive Pressure Test Design Guidelines - Task 5: Pressure Test Execution Guidelines

to

U.S. Department of Transportation
Pipeline and Hazardous Materials Safety Administration

September 7, 2018

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DTPH5615T00009 Development of Comprehensive Pressure Test Design Guidelines - Task 5: Pressure Test Execution Guidelines

Cara Macrory-Dalton, P.E.

INTRODUCTION

This report discusses Task 5 of a PHMSA-sponsored research project intended to provide guidance on aspects of pipeline pressure testing. The scope of Task 5 is to document the developed guidelines related to the execution phase of pressure tests. 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 5 report intends to provide the industry with clear guidance related to pressure test execution. The key design aspects of pressure test execution covered by this document include the following:

- equipment
- data collection and record keeping
- stabilization and pressuring sequences
- pressure-volume plots
- hold times
- leak detection
- weather effects (including freezing temperatures)
- test acceptance
- failure prediction methods
- pressure reversals
- alternative/contingency test plans
- de-pressuring and drying

Work related to providing guidance for pressure evaluation (Task 6) and other topics, including safety (Task 7) is ongoing. Developed guidelines for Tasks 6 and 7 will be provided in separate reports.

BACKGROUND

The objective of the Development of Comprehensive Pressure Test Design Guidelines Project (DTPH5615T00009, Prj# 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 1 was a kickoff meeting held on October 16, 2015. 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 specific to pressure test execution related topics are summarized in Table 1. The table shows which pressure test execution related topics are currently covered in each of the above listed documents. A topic is considered covered (denoted with a "yes" in Table 1) if relative 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. The key concepts related to pressure test execution identified for clarification by Task 2 are:

- hold times,
- acceptable pressure loss, and
- understanding and handling pressure reversals.

Table 1. Test Execution 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 111 0	INGAA Report	TTO No. 6
Test Duration (hold time)	Yes	Yes	Yes	Refers to ASME B31.8	Yes	Refers to regulatory require-ments	Yes	Refers to Title 49 CFR Part 192	No
Test Pressure Monitoring Equipment and Techniques	No	No	Yes	No	No	No	Yes	Yes	No
Pressure Reversals	No	No	No	No	No	Yes	Yes	No	Yes
Accepting a Test	No	No	No	No	No	No	Yes	Yes	No
Vintage Pipe Considerations	Refers to ASME B31.8S	Yes	No	Yes	No	Yes	No	No	Yes
Test Equipment	No	No	Yes	No	No	No	Yes	Yes	No
Record Requirements and Retention	Yes	Yes	Yes	No	Yes	Yes	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 would benefit from consistent procedures for the following topics related to pressure test execution:

- instrumentation (type, quantity and placement)
- temperature stabilization
- pressuring sequences
- spike testing hold time
- pressure reversals
- test acceptance criteria and test approval authorization
- documentation requirements, and
- water disposal

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".

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. Pressure testing with product (or a standup test), may be used in some instances as the test medium, however guidance related specifically to standup pressure testing will be provided in a later task of this project (Task 7).

PRESSURE TEST EXECUTION GUIDELINES

Equipment and Instruments

The use of electronic (digital) or mechanical instruments is equally acceptable, provided the equipment meets accuracy and certification requirements. Deadweight testers, temperature and pressure recorders, gauges, flow meters and all other measurement or recording instruments should be calibrated and certified for accuracy within the manufacturer recommended time interval (typically every 6 to 12 months) by an independent test lab.

The following is a list of recommended equipment that should be placed, installed or available for use prior to the execution of a pressure test:

- Fill pump -
    - Equipped with a properly sized flow meter
    - Capable of filling the test segment with water at a controlled rate to prevent the inclusion of air in the test section and sufficient discharge pressure for the hydrostatic head
    - Outfitted with a filter to prevent pumping foreign materials into the pipeline (100 mesh screen is ideal, however less fine mesh may be adequate depending on the water source and pump specifications)

  - Set in a secondary containment
- Pressurization pump -
  - A properly sized, variable speed positive-displacement pump capable of increasing pressure at a controlled rate of 10 psig/minute and a pressure capability above the maximum test pressure (120% of the maximum target pressure is sufficient)
  - Equipped with a stroke counter; either a solenoid-type stroke counter or meter to measure the amount of test fluid added during pressurization
  - Set in a secondary containment
- Test headers, launchers and receivers -
  - Capable of launching or receiving a minimum of two pigs or spheres and with connections for fill assembly, pressure relief, and required instrumentation
  - With a safe working pressure greater than the maximum planned test pressure (a design pressure of 150% of the anticipated test pressure is preferred)
  - Heavy-wall pups welded to each end and girth welds inspected by radiography; all welded connections to test headers should be inspected by nondestructive examination (NDE).
  - Inspected for defects or damage prior to each project
- Check valve for pressurization line to prevent whipping in the event of a failure of the pressurization pump or piping between the pump and the test header
- Air compressor capable of overcoming static head pressures during dewatering and with sufficient capacity to propel pigs at constant velocities during cleaning and drying
- Pigs or spheres -
  - Cleaning pigs
  - Bi-directional filling and dewatering steel mandrels, foam disks, pigs or spheres
  - Worn pig cups or cracked spheres should not be used
  - Outfit with tracking equipment
- Test site -
  - An enclosed, lighted, heated/air conditioned shelter of sufficient size to house the pressure recorders, deadweights and test personnel at the test monitoring site of each test section during the cleaning, fill, pressurization, testing, water disposal and drying operations
  - Lighting for all areas where night work may take place
- Communication equipment
- Splash plates and/or energy diffusers for dewatering lines (if applicable)
- Test fluid sampling equipment (if applicable)
- Water tank trucks (if applicable)
- Portable water tanks and/or frac tanks (if applicable)
- Portable nitrogen trucks (if applicable)

- Temporary piping, fittings, valves, flanges, gaskets, bolts and all other test apparatus, as may be required
- Temporary water lines for fill and/or disposal
- Failure response equipment, as may be required
  - Replacement pipe, fittings, valves, flanges, and gaskets
  - Recovery and containment equipment (such as, vacuum truck, absorbent pads, spill boom and drip pans)
  - Isolation equipment (such as freeze plug or stopple installation equipment)
  - Excavation equipment

The following is a list of recommended instruments that should be installed or available for use prior to the execution of a pressure test:

- Traditional brass deadweights
  - Precision of 1 psig, or less
- Electronic self-checking pressure recording and plotting units with a pressure transducer installed on the test header (in lieu of traditional deadweights)
  - Precision of 0.25 psig, or less
- Two pressure gauges (preferably mechanical) with load-cycle stability and shock resistance, one to be installed on each end of the test segment to ensure pressure continuity throughout the test segment
- Pressure recorder covering a 24-hour range, possessing a 10-inch minimum diameter chart size and a minimum range of 0 to 3,000 psig (larger range may be required depending on pressure test design)
- Automatic yield plot equipment
- Traditional dual-pen temperature chart recorders, covering a 24-hour range, possessing a 10-inch minimum diameter chart size and a minimum range of 0 to 150 F
- Electronic temperature data loggers capable of printing (in lieu of traditional chart recorders)
- Mechanical or digital temperature probes or sensors, such as a thermistors, thermocouples or resistance temperature detectors (RTDs). A minimum of two for above grade tests and four for below grade tests (see Considerations for Temperature Probes for additional guidance of number and placement of probes):
  - Ambient Temperature - one probe, placed above ground in the shade and out of direct sunlight at the test site
  - Exposed Pipe Temperature - one probe, placed approximately at the 6:00 clock position on the exposed pipe, insulated and protected from sunlight
  - Buried Pipe Temperature - a minimum of one probe, attached to the buried pipeline approximately 100 feet or more away from the injection site

- Ground Temperature - one probe, buried approximately 100 feet away from the injection site at the average depth of coverage for the pipeline in close proximity to the Buried Pipe Temperature probe

Further, API 1110 section 4.3 provides a list of equipment and instruments necessary to execute a pressure test[i]. The API 1110 recommended equipment list is similar to that above, however additionally includes safety and failure response equipment.

Considerations for Temperature Probes

The recommendations in this section of the report are applicable for buried pipeline segments. Temperature data should be collected from multiple locations for sufficient test acceptance and a comprehensive record. Digital instruments capable of reporting in increments of 0.01 F with an accuracy of 0.10 F should provide reliable data for test acceptance purposes. A minimum of three buried pipe temperature probes are should be installed per test segment. More than three buried pipe temperature probes may need to be considered for test segments that are expected to have complex temperature profiles, such as those that cross rivers, are in close proximity to heated oil pipelines, have variable depth of coverage, or are greater than 30 miles in length. Less than three buried temperature probes may be adequate for shorter test segments (approximately less than five miles); however, installing at least two buried temperature probes provides a back-up in the event of equipment failure.

Temperature probes can be temporarily or permanently installed. Reference the manufacturer instructions for proper installation. General installation guidelines are:

- Attach to bare pipe and repair coating
- Attach probes to the side of the pipeline at approximately the 3:00 or 9:00 clock position
- Insulate around the probe and pipe
- Test that probes are functioning properly
- Backfill prior to test execution
    - use caution to not damage the probe and cable leads
    - compact the backfill soil
    - allow time for the soil temperature to return to levels near the bulk soil (two days is sufficient), and
    - once the backfill is complete, test that probes are functioning properly again

The buried probes are intended to represent the average temperature behavior for the test and one should be placed every five to ten miles. They should be placed at accessible locations but not in close proximity to exposed pipe or the test fluid injection site.

Fill or injection fluid temperature and bulk soil temperature recordings can be useful for test acceptance purposes. Consider installing additional temperature probes to capture these data.

Also, for segments with a notable amount of exposed pipe (approximately 1% or more of the total test length) consider installing an above grade pipe temperature probe. Insulate and shade exposed pipe. Finally, the ambient temperature probe is typically located near the test trailer and deadweight location, an additional ambient probe located at the opposite end of the segment may be useful for segments longer than 30 miles.

Confidence that a pressure change is related to a temperature change can be improved by preparing a chart of recorded temperature change versus pressure change. A decrease in test pressure should be accompanied by a decrease in test fluid temperature and vice-versa. The chart in Figure 1 below shows several test sections where this relationship is apparent (the curves are oriented from lower left to upper right), and also several where there is no clear relationship between recorded pressure and recorded temperature. The pressure readings are thought to be accurate, but the temperature data suggests that the temperature probes may not have been ideally situated.

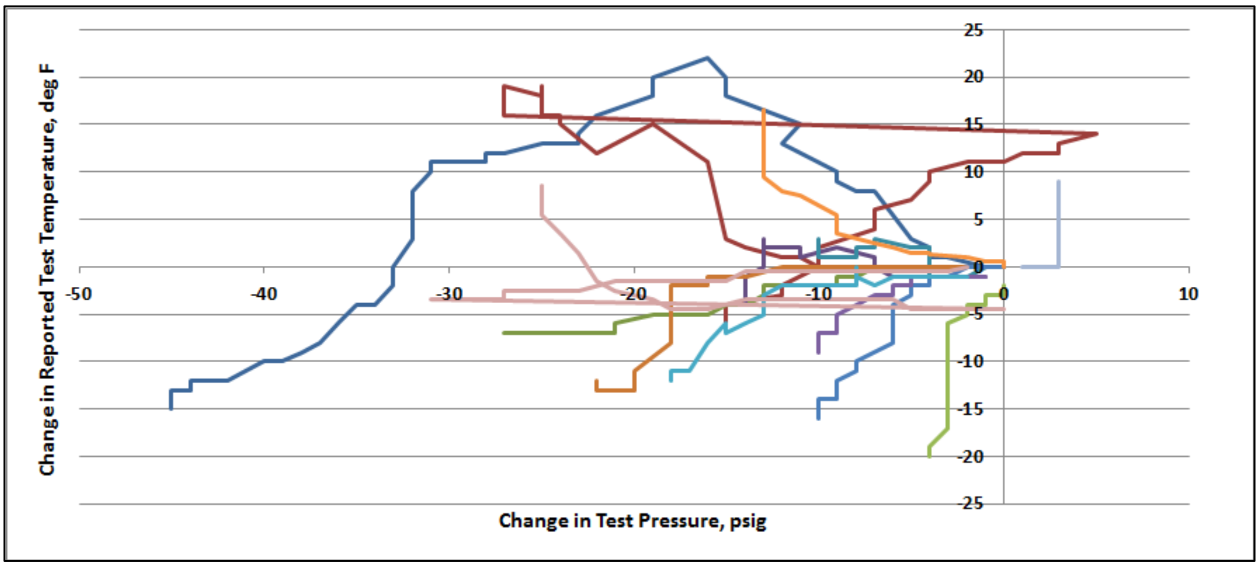

Figure 1. Some Pressure and Temperature Readings during Hydrostatic Testing

Record Keeping

Minimum requirements for pressure testing records are outlined in 49 CFR 192.517 for gas operated pipelines and 49 CFR 195.310 for liquid operated pipelines. The CFR requirements are copied here for reference.

49 CFR 192.517 Records

(a) Each operator shall make, and retain for the useful life of the pipeline, a record of each test performed under §§192.505 and 192.507. The record must contain at least the following information:

(1) The operator's name, the name of the operator's employee responsible for making the test, and the name of any test company used.

(2) Test medium used.

(3) Test pressure.

(4) Test duration.

(5) Pressure recording charts, or other record of pressure readings.

(6) Elevation variations, whenever significant for the particular test.

(7) Leaks and failures noted and their disposition.

(b) Each operator must maintain a record of each test required by §§192.509, 192.511, and 192.513 for at least 5 years.

49 CFR 195.310 Records.

(a) A record must be made of each pressure test required by this subpart, and the record of the latest test must be retained as long as the facility tested is in use.

(b) The record required by paragraph (a) of this section must include:

(1) The pressure recording charts;

(2) Test instrument calibration data;

(3) The name of the operator, the name of the person responsible for making the test, and the name of the test company used, if any;

(4) The date and time of the test;

(5) The minimum test pressure;

(6) The test medium;

(7) A description of the facility tested and the test apparatus;

(8) An explanation of any pressure discontinuities, including test failures, that appear on the pressure recording charts;

(9) Where elevation differences in the section under test exceed 100 feet (30 meters), a profile of the pipeline that shows the elevation and test sites over the entire length of the test section; and

(10) Temperature of the test medium or pipe during the test period.

The data collection and record keeping recommendations provided in this guidance document meet or exceed the minimum requirements of the current federal regulations listed above.

It is recommended that complete records are maintained for failed pressure tests and successful pressure tests. Documentation of failed pressure test attempts (those caused by a leak, rupture, inadequate stabilization, or improper fill and pressurization) can provide useful information for subsequent testing and future test planning. It is imperative that records related to failed pressure tests are prominently labeled as not the final test attempt and reference the date and record of the successful pressure test.

Complete records of pressure tests are invaluable for future reference, usually in circumstances unforeseen at the time of the test such as: confirming regulatory compliance, addressing integrity management matters, supporting changes in operation or location class, supporting root cause investigation of incidents, or supporting sale of an asset. Codes and standards specify that records are to be maintained indefinitely, or for the useful life of the pipeline.

General

The following data related to pressure testing should be collected and records maintained permanently:

- fill log with total volume indicated,
- pressurization log,
- yield plot (if applicable),
- test log with tabulated data collected at approximately 15-minute increments (or less as needed), includes:
  - date and time,
  - recorded pressure,
  - temperature (ambient, ground, exposed pipe and buried pipe),
  - weather conditions,
  - visual inspection,
  - volume added or removed, and
  - general observations or comments,
- pressure test summary report,
- pressure recording charts or printouts,

- temperature recording charts or printouts,
- instrument calibration certifications,
- schematic of tested segment, piping or assembly,
- pipeline elevation profile,
- test plan (see the Task 4 report on pressure test planning guidelines),
- PE test acceptance letter (if applicable),
- MTRs (if applicable, replacement or new construction),
- pictures,
- failure reports (if applicable), and
- authorization signatures

Pressure testing is an expensive undertaking. The preparation and preservation of complete documentation of a pressure test adds negligible cost, but can save significant effort or cost many years later.

Test Report

Pressure test reports should include the following information:

- test report cover sheet with:
    - project name
    - pipeline segment or assembly name
    - operator name
    - test and report dates, and
    - company specific coding that assists with record identification (if applicable)
- summary with:
    - narrative description of the project and specific test
    - purpose of the test
    - personnel and contractors involved and those present indicated
    - outline of test procedure
    - isolation methods, and
    - results of test
- test segment name (or number) and description
- start date and time of "on" test with initial pressure
- end date and time of "off" test with final pressure
- test boundary locations (begin and end) station numbers and elevations
- pipe attributes and components included in the test (outside diameter, wall thickness, grade, vintage, manufacturer, seam type, ANSI flange class rating, etc.)
- test segment length
- length of exposed pipe
- average depth of cover (if applicable)

- maximum and minimum elevations with station locations
- maximum and minimum allowable test pressures
- test fluid with additives listed (if applicable)
- source of test fluid
- pressure pump location, station number and elevation
- deadweight tester
    - serial number
    - calibration date
    - location, station number and elevation
- pressure and temperature recorders
    - serial numbers
    - calibration dates
    - locations and station numbers
- date and time of each stage
    - fill
    - stabilization
    - pressurization (including leak checks)
    - yield plot (if applicable)
    - spike test (if applicable)
    - strength test
    - leak test, and
    - depressurization
- explanation of any pressure discontinuities, including test failures or intentional test fluid removal (bleeds) or injections
- description of the weather
- sketch or schematic of the test segment or assembly
- pipeline elevation profile, and
- test plan profile (see the Task 4 report on pressure test planning guidelines for an example)

Charts

Pressure and temperature charts should include the following information:

- recorder serial number
- data description (such as ambient temperature, pressure, etc.)
- test segment
- date and time the chart was put on and taken off
- date and time the test started and ended
- location of equipment

- test segment description (such as line size and length)
- deadweight pressure at start and end of test
- test fluid
- signatures (test contractor and operator representative/inspector)
- pressure test service contractor’s project description stamp (or sticker)
- indicate any discrepancies or noteworthy occurrences on the chart with a comment, such as:
    - changed out chart
    - start pressuring
    - start/end of plot
    - start/end spike test
    - start hold test
    - bleed fluid
    - added fluid
    - gained/loss pressure
    - chart bumped
    - end hold test, and
    - start/end of depressurization

Photodocumentation

Photographic documentation is not a typical requirement, but can be a positive demonstration of non-fraudulent records, as well as, provide additional information for pressure test acceptance and subsequent test planning. Examples of pictures to capture and maintain are:

- deadweight and pressure recorder with serial numbers visible
- ambient temperature recorder with serial numbers visible
- above ground pipe temperature recorder(s) with serial numbers visible
- buried pipe temperature recorder(s) with serial numbers visible
- ground temperature recorder(s) with serial numbers visible
- temperature probe installations
- gauges
- test manifold mounted to pipeline
- launcher and receiver locations
- frac tank, equipment and test trailer layout
- cleaning and de-pressure pigs launched and received
- dew point meter reading and last swab when drying (if applicable), and
- failures

Failure Report

The purpose of a pressure test is to prove the strength of the pipe and in-line components. A pressure test is potentially destructive, and a test failure is always possible. Test failures of new pipe are rare but do still occur. Test failures of older vintage pipelines may not be unexpected, particularly when testing to historic high absolute pressure or test pressure ratios in an attempt to increase reassessment intervals. Test failures can have important commercial or integrity management implications and should be thoroughly documented and analyzed.

The intent of this section is to provide guidelines for failure documentation with data available during the pressure test execution phase. Additional guidelines related to laboratory analysis of failures caused by pressure testing will be provided in the Task 6 report on pressure test evaluation.

A failure report should document the following:

- location of the failure by state, county, section, township, range, tract number, and station number
- deadweight pressure at time failure was detected
- calculated pressure at location of the failure correcting for elevation
- date and time the failure was detected, method used, and test attempt number
- date and time the failure was located, and method used
- date and time the failure was repaired and description of the repair (such as entire joint replacement, repair sleeve, etc.)
- apparent location of the failure origin (such as longitudinal seam weld, circumferential girth weld, field bend, etc.) and clock position
- apparent cause, pending confirmation by detailed metallurgical examination and testing,
- photographs of failure site pre-excavation, post excavation and apparent failure origin,
- mode of failure (leak or rupture)
- pipe attributes (outside diameter, wall thickness, grade, vintage, manufacturer, seam type, etc.)
- estimated volume of fluid loss
- extent of damage to surface structures or surrounding property

Stabilization and Pressurization Sequences

Stabilization is critical to the success of all pressure tests. A stable test segment allows for sound, defensible test acceptance and improved confidence in leak determination. An unstable test segment undergoes notable fluctuations in pressure, possibly due to changes in temperature, pressure surge (or fluid hammer), and/or dissolution of air into the test fluid. Unsteady pressure during a test can introduce uncertainty as to the test's validity, sometimes well after the pipeline has entered service. The compressible and thermal properties of gases allow for better stability compared to testing with liquid. The recommendations within the section are most applicable to buried pipeline hydrostatic tests with water; aside from some general points on stabilization periods, pressurization rates and leak checking that apply to testing in all fluids.

All pressure tests should allow for an adequate stabilization period. The amount of time required for test segment stabilization is dependent on actual test conditions. It has been observed that stabilization may require 12 to 72 hours, however 24 hours is typically adequate. The length of the stabilization period is considered satisfactory once the buried pipe temperature is congruent with, or converging to the bulk soil temperature. The convergence time will tend to increase when the test water is significantly warmer or colder than the soil temperature at pipeline depth, and also may be greater with large diameter pipe. Therefore, it is recommended that test procedures allow for an adjustable stabilization time, rather than defining a pre-determined time limit for stabilization.

Stabilization can be improved by implementing a fill and pressurization procedure that limits the potential for entrapped air and large fill water-to-soil temperature differentials. Considerations for a fill procedure include:

- Insulate and backfill with the same soil type (if applicable) at the locations of temperature probes.
- Minimize the length of, insulate and shade exposed pipe.
- Use a below grade water source where available.
- Fill from a low point elevation.
- Use a properly sized pump capable of the pressures required to overcome friction, elevation and to propel fill pigs through the entire line segment being filled.
- Prevent air entering the fill pump by ensuring the suction basket is well submerged and there are no penetrating whirlpools. If digging the sump pump is not allowed, commercial devices are available designed to pump water from shallow sources.
- Ensure sufficient backpressure to prevent the fill pig running downhill ahead of water causing cavitation and resultant air pocket. A backpressure of approximately 50 psig greater than the static head is sufficient.
- Fill at rate that will minimize the velocity of the pigs to approximately 3 mph or less.
- Utilize several pigs in the fill train to promote the capture of any air between pigs.
- Install taps at high elevations and bleed off air or gas.

The extended stabilization period can begin once the initial water fill is complete. Alternatively, the extended stabilization period can be included as part of a multi-staged pressurization process, and is presented in the recommended procedure below. Pressurization guidelines are as follow.

- Prior to connecting the pressurization (squeeze) pump:
  - check all flange fittings for leaks and, if found, depressurize to zero or isolate before tightening flanges or repairing,
  - measure pressure at each end of the test segment and confirm hydraulic head matches those used for hydrostatic test calculations, and
  - set new pressure and temperature charts and check that instruments are functioning properly.
- Connect squeeze pump and between sequences pressurize continuously at a controlled rate that prevents pressure surges:
  - A pressurization rate can be determined by surge analysis specific to the test segment parameters, otherwise 20 psig/min is considered acceptable for this sequencing stage.
  - At approximately 50% of the target test pressure, again check all flange fittings for leaks and hold 15 to 30 minutes. If leaks are found depressurize to zero or isolate before tightening flanges or repairing, and repeat pressurization routine.
  - Pressurize at a rate of 10 psig/min to 20 psig/min to approximately 80% of the target test pressure and again check all flange fittings for leaks and hold 15 to 30 minutes. If leaks are found depressurize to zero or isolate before tightening flanges or repairing, and repeat pressurization routine.
- Initiate the extended stabilization period (overnight, line pack hold) at approximately 50% to 80% of the target test pressure. Additional safety pre-cautions may be required and will be discussed in the Task 7 report on other pressure test considerations.
- Once the stabilization period is satisfied and the pressure is at the lessor of 80% of the target test pressure or 90% of specified minimum yield strength (SMYS), begin the final pressurization at a rate of 10 psig/min or less and commence the pressure-volume yield plot (if applicable).
- Terminate the pressurization once the target test pressure is achieved, not to exceed the yield point (if applicable), as determined by the double-stroke method or by the 0.2% offset method.

Note that for gas pipelines an observed minor leak at a flange does not invalidate the strength test if the pressure can be maintained throughout the test and not decrease below the minimum bound pressure. The leak must be repaired after the test and prior to returning the pipeline to service. While this is an acceptable practice under current industry standards and regulation, it is the opinion of the author that the guidelines for leak detection and repair presented herein are followed equally for gas pipelines as for liquid pipelines.

Pressure-Volume Plots

Pressure-volume data should be plotted during the final stage of pressurization to limit pipe yielding when either the target test pressure anywhere along the test segment is expected to exceed 90% of SMYS, or pipe properties are unknown. The slope of the pressure-volume (P-V) plot should not decline to less than half the elastic slope. In the paper, "The Benefits and Limitations of Hydrostatic Testing" by J.F. Kiefner and W.A. Maxey[ii] the following statements on pressure-volume plots are made:

> "Shown in [Figure 2] is a pressure-versus-pump-stroke plot of an actual hydrostatic test. The plot is created by recording the number of pump strokes of a positive displacement pump as each 10 psig increase of pressure is attained. Prior to beginning the plot, it is prudent to hold the test section at a constant pressure to assure that there are no leaks. After it is established that there is no leak, the plot should be started at a pressure level no higher than 90 percent of SMYS for the low elevation point in the test section in order to establish the "elastic" slope of the plot. By projecting the elastic slope lines across the plot as shown, one can then record pump strokes and compare the evolving plot to those slopes. If and when the actual plot begins to deviate from the elastic slope, either some pipe is beginning to yield or a leak has developed. The pressurization can be continued in any event until the "double-the-strokes" point is reached. This is the point at which it takes twice as many strokes to increase the pressure 10 psig as it did in the elastic range."

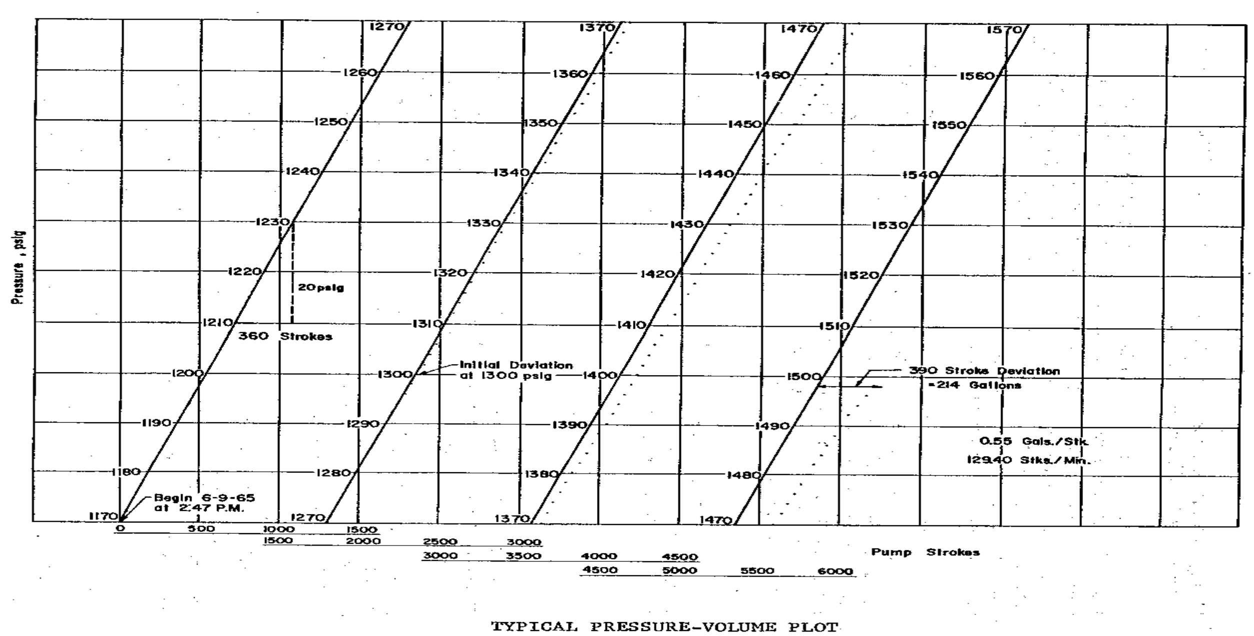

Figure 2. Pressure-versus-Pump-Stroke Plot

Positive displacement pumps deliver a constant volume of water with each stroke, thus counting pump strokes is a standard way of keeping track of the volume of fluid added during pressurization. The amount of volume added can also be estimated with flow meters. In the elastic range one can determine the slope of the pressure-volume (or pump-stroke) plot. By projecting forward the elastic slope as pressure is increased, one can detect a deviation in slope if any plastic strain begins to occur. The test can be terminated at a pre-determined slope decrease to minimize the amount of expanded pipe. P-V plots are characterized by one of the following slope trends:

- Remains straight, indicating no air entrapment and no yielding.
- Curves upward indicating trapped air dissolving in the test water.
- Curves downward indicating yielding.

A decrease to half the original slope (or "double-the-strokes") is thought to be a reasonable point to terminate a test with a minimal amount of expansion. Yielding can be very isolated, to a single low-strength or thin-wall joint of pipe, although yielding in large numbers of pipe joints have also occurred. Additionally, pertaining to the effect of biaxial stress (which was discussed in the Task 4 report for this project), Warman, et al. conclude[iii], "…considerably higher hydrostatic test pressures than normally used can be applied without significant yielding of even the weakest joint set to be located at the low point. [Analysis] also demonstrates that the doublestroke method is a conservative means to stop a yield plot prior to significant yielding in any joints occurring especially at lower [yield strength-to-tensile strength] ratios."

Note that a leak may be signified by a deviation in slope also. To be sure the deviation is not caused by a leak, stop adding fluid, and let the pressure decay 10 psig. Then re-pressurize to the previous maximum level and stop again to allow the pressure to decay 10 psig. If the deviation is due to a leak, the decay should occur repeatedly at the same rate. If the deviation is due to yielding, the decay rate should decrease to essentially zero within a few cycles.

Additional concepts on P-V, yield plots are provided in Appendix A.

Hold Times

Minimum requirements for pressure testing are outlined in 192 Subpart J for gas pipelines and 195 Subpart E for liquid pipelines. Subparts J and E cover hold time and safety factors for the determination of MAOP and MOP, respectively. These tests are commonly designated as conventional tests or hold tests.

Federal regulation 195 Subpart E[iv] pressure testing requirements stipulate a strength test be maintained at a minimum of 1.25 times the MOP for four hours; and, in the case of a pipeline that is not visually inspected for leakage during the test (such as a buried or partially buried pipeline segment), for at least an additional four continuous hours at a minimum of 1.10 times the MOP. Unless stated otherwise, Federal regulation 192 Subpart J[v] pressure testing requirements stipulate a pressure test be maintained for at least eight continuous hours for MAOP certification.

The duration of a pressure test is not critical to the effectiveness of an assessment in terms of proving the pipe strength or integrity management. This statement is based on fracture mechanics principles and experience and is supported by industry research[vi]. There is little to no benefit in holding a spike test longer than necessary to verify the pressure being measured is stable. This depends on the conditions of the test but a timeframe of three minutes is ideal[vii]. The benefit of longer hold times is for the detection of leaks, not to improve the integrity of the pipeline. A leak test performed at a pressure that is less than the maximum strength test pressure level can be effective and is less damaging. An adaptation of works performed by Kiefner, Maxey, and Eiber and a detailed discussion on the significance of hold time and its impact on flaw extension is provided in Appendix B.

Spike tests should be implemented immediately prior to the conventional hold tests. The recommended duration for a spike test is long enough to assure the pipeline has experienced a continuous pressure at or above the target level, to obtain a clear record of the achieved pressure, and to cause defects that are near critical to fail. The duration should be brief enough to prevent additional crack growth in defects that are subcritical since the purpose of the spike test is to prevent unnecessary damage due to long hold periods near the failure pressure of a flaw that otherwise would not fail. There is evidence from fracture mechanics tests that damage near the failure threshold begins to occur after a dwell time as short as 0.05 hours. NG-18 Report No. 111 and the Baker TTO-6 report each emphasizes that the value of the spike test is in the test pressure ratio, not the duration of the spike. However, opinions and recommendations for the spike duration vary. This report recommends that the hold period for a spike test should be three to five minutes and should not exceed 10 minutes in recognition of the purpose of the spike test and the fracture mechanics data, but other guidance documents recommend a minimum of 10 minutes up to 30 minutes and many practitioners perceive a sense of assurance with a longer duration. The basis for the short spike duration recommendation is basic fracture tests showing that damage in the form of flaw extension occurs beyond hold times near the immediate-failure stress after 0.05 hours, and avoiding such damage is the fundamental point of the spike test format. This recommendation is in conjunction with the spike test pressure and conventional hold test pressure value recommendations from the pressure test planning guidelines.

For pipeline sections that are 100% visually inspected for the duration of the test, it is recommended to not exceed the minimum conventional hold period stipulated by regulation.

Again, the benefit of extensive hold time is for leak identification and if relying on visual inspection for leak detection the tests should be held for the shortest duration allowed.

For pipeline sections that are buried, the recommended period for the conventional hold test may exceed the minimum federal requirement. This recommendation is inherent to the conventional hold test's purpose to either identify or prove the absence of leaks. As will be discussed in later sections of this report, test acceptance and leak detection methods may require extending the conventional hold test beyond the minimum time requirement. Maximum durations could be eight hours to 24 hours. A test longer than 24 hours should only be carried out if concurrent with other leak detection efforts.

Leak Detection

This section outlines approaches for determining the presence of a leak by means of pressure testing, as well as, methods to locate leak sites once a leak suspected.

Volume Balance and Trend Analysis

A method for leak detection for buried pipeline segments is to study the relationship of volume, pressure and temperature.

The presence of a leak is more readily determined on smaller volume test segments where even small leak rates can result in a notable pressure decrease. One must be critical of any drop in pressure, but particularly for larger volume segments where a leak may only cause a small drop in pressure. Leaks tend to produce a steady rate of pressure loss. One method of discerning a leak from stabilization is to monitor the rate of pressure loss for a period of time, re-pressurize to the same initial pressure, and monitor the rate of pressure loss for the same amount of time and compare. Depending on the amount of pressure loss experienced, or the presence of outside variables that can be difficult to account for (such as temperature or weather effects), this re-pressurization and monitor routine may need to be repeated more than once. If a leak is present the rate of pressure loss should be about the same for each re-pressurization and, if not, the rate should slow with each re-pressurization.

Pneumatic tests are not as sensitive to pressure changes with temperature changes, and are considered relatively more stable. However, considering the most commonly executed pneumatic tests are to low pressures (such as 100 psig), pneumatic tests are not as sensitive to the detection of small leaks.

For hydrostatic tests, depending on the test segment elevation gradient, source of water, isolation configuration, and fill and pressurization procedures a test can undergo continued stabilization within the first hours of the assessment resulting in a loss of pressure. Typically the most significant amount of pressure loss caused by such stabilization occurs within the first

15 to 90 minutes of an assessment and is either caused by the dissolution of entrapped air, temperature fluctuations from the added water during pressurization ('squeeze' water), water filling a valve cavity, or a combination of all three. For a test experiencing pressure loss where the cause is suspected to be stabilization, the rate of pressure loss should decrease overtime (often logarithmically or asymptotically) and the trend of pressure changes and temperature changes should converge. Similarly, for suspected stabilization, rate of pressure loss should decrease with time and the trend of expected change in volume (ΔV) and actual ΔV should eventually converge. It may be necessary to extend the hydrostatic test hold time beyond the initial planned limits in order to witness and record evidence of the expected-pressure-change-to-actual-pressure-change convergence.

The change in temperature (ΔT) should trend with the change in pressure (ΔP) consistently for the duration of the assessment (although there may be a lag in pressure changes which is acceptable if the test is held for a long enough duration to capture the lag, typically no more than one hour behind the temperature). For instance, if the test segment temperature is not stable, and increases for part of the assessment then decreases for part of the assessment, likewise the pressure should increase then decrease (for a period of time roughly equivalent to the amount of time corresponding to the respective temperature changes). Following the same temperature scenario, if the pressure steadily decreases, or even remains constant during the period of temperature increases then decreases with decreasing temperatures, the test may not be acceptable. Basically if the temperature is adequately representing the test segment temperature, one cannot be selective when justifying pressure behavior.

Comparing the expected change in volume (due to temperature changes) to the actual change in volume (determined by recorded change in pressure) should be performed using volume balance calculations suitable to the test fluid. The ideal gas law is appropriate for use for pneumatic tests. There are proprietary volume balance calculators on the market for hydrostatic tests. However, published resources for acceptable volume balance formulas include Chapter 5 of the Pipeline Rules of Thumb Handbook[viii], Appendix C of AS/NZS 2885.5:2012[ix], and the Pipeline Planning and Construction Manual[x]. Each method assumes idealized conditions that should be well understood before using. These assumptions generally apply:

- The test fluid is pure.
- There is no entrapped air in the test segment (not applicable to AS/NZS 2885.5:2012).
- The test segment is either fully restrained or fully unrestrained.
- The pipe material properties are accurate.
- The temperature measurements are accurate and represent the entire test segment.
- The pressure measurements are accurate.
- The pipe geometry and initial volume capacity estimates are accurate.

The effect of temperature changes on test pressure is dependent on test volume (pipe diameter, wall thickness and segment length) and thermal properties of the test fluid and pipe (coefficient of thermal expansion, bulk modulus, and compressibility factor). Thermal properties vary with temperature. For instance, the higher the water temperature the more sensitive the pressure is to changes in temperature (or larger expected $\Delta P/\Delta T$)[1]. Also, the smaller volume tests have a larger expected $\Delta P/\Delta T$ relationship compared to larger volume tests. For hydrostatic tests with water, typical $\Delta P/\Delta T$ values can range from 15 psig/deg F to 40 psig/deg F. This potential for relatively large pressure changes caused by relatively small temperature changes highlights the importance of accurate temperature and pressure data collection during pressure testing (see Equipment and Instrument section for recommendations). It is apparent that a modest temperature increase could mask the presence of a small leak by offsetting its pressure drop. Calculations should account for known volume deviations due to intentional depressurizations or re-pressurizations by adding or subtracting volume, respectively, from the total balance calculation.

For a comprehensive study of a pressure test, compare the expected ΔV due to ΔT to the actual ΔV determined by recorded ΔP under multiple scenarios including:

- hourly increments over the duration of the test,
- at trend shifts in the data,
- between the initial and final hour, and
- the final one to two hours.

The difference between the expected ΔV to the assumed actual ΔV (accounting for any known volume additions or subtractions) is considered the unaccounted for change in volume. From the initial and final hour of a conventional hold test, Kiefner's observation is that an unaccounted for change of 0.01% of the initial test volume or less typically corresponds to a leak-free assessment. However, this criterion alone should not be used for overall test acceptance therefore reference the Test Acceptance section of this report for further guidance.

Test Fluid Removal and Injections

All test fluid removals (bleeds) and injections made during the test must be justified and clearly documented. Excessively large or repeated injections may be an indication of a leak and excessive bleeds may mask the presence of a leak. The total volume removed or added should be measured and documented. Only bleed to avoid exceeding the maximum bound test pressure and over-pressuring the test segment. Only inject additional fluid to prevent the test pressure from decreasing below the minimum bound test pressure. The cause of the pressure

[1] At temperatures greater than 45 deg. F and less than 100 deg. F., a common range for hydrostatic pressure testing.

loss should be well understood or plausible, such as pressure loss supported by temperature loss or pressure loss attributed to stabilization (where the rate of loss is nonlinear or slowing down). Make an effort to limit injections and bleeds to the first half of the test (ideally the first hour) as stabilization significantly impacts volume balance calculations.

Visual Inspection

For above ground tests where visual inspection is the primary method for leak detection, it is recommended to apply a mixture of liquid soap and water to all flanges and appurtenances. While under pressure, if a leak is present, the soapy mixture should produce bubbles (commonly referred to as a 'bubble test').

If the test fluid is water, small drips ('seepers' or 'weeps') can evaporate and may go undetected, particularly if the test segment is in direct sunlight. A best practice is to avoid testing during the heat of the day and to provide shade if not testing in a controlled environment such as a shop.

Location Methods

Once a rupture occurs, or a leak is suspected, there is a variety of methods to employ to locate the failure site. Often a combination of more than one method is required to identify a leak and immediate (or even eventual) success is not guaranteed with any one method. Further segment isolation in combination with patrol is typically the most successful approach for finding small leaks.

Engineering Analysis

Some postulations can be made as to where the likelihood of failure is higher. A few starting points to narrow the search for a failure site include:

- locations where ILI detected features have an estimated failure pressure less than the test pressure
- locations where ILI detected features remain unrepaired (particularly longitudinal features)
- locations of buried appurtenances
- locations where repair methods and/or workmanship quality are unknown
- low point elevations,
- locations where the pipeline crosses streams or other bodies of water
- areas near excavation work or new development

Utilizing known information about the head pressure on either side of a rupture site (assuming pressure is monitored on both ends of a test segment), the elevation of the pipeline segment and Bernoulli's equation[2], one can estimate the elevation at the rupture site and refine the possible locations.

Isolation

If a pipeline has a history of small leaks, or a primary threat of defects that are known to fail as small leaks, shorter test segments should be planned in order to reduce the amount of volume per test segment. The smaller the test volume the greater the pressure drop will be if a leak does occur making it easier to verify the existence of a leak. An intermediate valve between the upstream and downstream boundaries that can be closed in the event further segmentation is needed to locate a leak is ideal. Other isolation methods include installing weld caps, stopples, and freeze plugs at intermediate locations along a test segment. Once an intermediate location is isolated, pressurize either side to the same pressure and monitor for pressure decreases. Only one of the two subsections should indicate a pressure decrease; if the two subsections have roughly equal volume, the rate of pressure loss should double. A few iterations of targeted isolation may be necessary before the leak site is found.

For freeze plugs, 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 anomaly detected in the pipe. There are additional hazards related to freeze plugs that will be addressed in the Task 7 report on other considerations.

Patrol and Dyes

Patrolling (aerial or line walking) should be immediately implemented when searching for a failure site. Water accumulated in an unexpected location near or over the pipeline may indicate the location of a leak. Success in locating a failure site based on the presence of water is dependent on the depth of cover and the level of soil saturation. If the soil is well drained, it may take a considerable amount of water to surface. It may be impossible to recognize a leak where water is normally present. The idea behind dyes is it is simply easier to visually identify colors than clear fluid; however, dyed water still must surface in order to be located. Dyes prove most useful when the soil is completely saturated, either from heavy rains or marshy terrain, making it nearly impossible to discern test water from naturally occurring sources otherwise. If utilizing dyes, consider any environmental restrictions that may exist in the area or disposal constraints.

[2] See Equation 1 of the Kiefner Final Report No. 16-224, "DTPH5615T00009 Development of Comprehensive Pressure Test Design Guidelines - Task 4: Pressure Test Planning Guidelines".

Odorants and Tracers

Odorants, tracer chemicals or gases (such as nitrogen with mercaptan) are added to the test fluid and detected above grade with either sampling equipment or 'sniffing' dogs. While the use of odorants is a proven detection method, uncontrollable environmental factors can make their success unpredictable. For instance wind can either disperse the odorant all together, or indicate an incorrect location.

Helium can be an effective solution in locating leaks because the small, light molecule readily migrates to the surface[xi]. However, this is not a frequently implemented method since the test segment must be dewatered and re-pressurized with an air-helium mixture.

Most tracer chemicals, some being mildly radioactive, are not normally found in nature so the detection of even trace quantities indicate test fluid escaping from the pipe. However the location where the tracer chemical is detected may not coincide well with the location of the leak, due to the effects of wind, soil stratigraphy, or movement of water below ground. Field procedures must minimize spurious detection, confirm positive readings, and aid in pinpointing the leak source.

Acoustics and Sonar

Geophones, or other acoustic devices, and sonar can detect leaks. The technology is only functional for a limited range therefore is better suited for short distance applications, possibly in conjunction with a selection of probable locations determined by engineering analysis.

Weather Effects

Weather conditions and ambient temperatures can have an impact on pressure testing. There are certainly additional safety considerations and logistical concerns related to extreme weather conditions; however the focus of this section will be the impact of weather on the pressure and temperature of a pressure test, which directly impacts test acceptance. Other weather concerns will be addressed in the Task 7 report on other pressure test considerations.

Small volume tests (about 1,000 bbls or less) or those having a significant amount of exposed pipe (approximately 1% or more of the total test length) are more susceptible to pressure changes due to ambient conditions. Excessive heat and direct sun exposure can increase the test segment temperature and, in turn, increase the test pressure. Under certain test conditions such an increase in pressure may require a test bleed to avoid exceeding the maximum test bound and over-pressuring the test segment.

The onset of rain can reduce the temperature particularly if the bulk soil is saturated. Another concern with rain is that moisture on instrument connections can cause false readings or instrument failure, so precautions should be made to keep instrument connections dry.

For hydrostatic testing with water, avoid testing in freezing temperatures. Water can freeze inside testing equipment such as hoses, leads, headers, etc. and, in extreme conditions, even the pipeline segment. Frozen equipment, especially small tubes and hoses, will cause errors in pressure readings which could lead to over-pressuring the pipeline or collecting a false record of the test pressure. There are known situations where the sensor line to the deadweight gage became frozen, leading to overpressuring the pipeline to the point of failure. While testing in freezing weather is not recommended, in the event it is necessary certain precautions can be implemented:

- Insulate all equipment and above grade components and pipe.
- Use additives, such as antifreeze, or preheat test water as it is introduced into the pipeline.
- Install heat trace near equipment and on above grade pipe.
- Install a second pressure recorder.

The use of antifreeze may pose an environmental concern in the event of a test leak or failure. An example of a winter testing procedure where it is necessary to heat the test water is provided in Appendix D.

Test Acceptance

Any situation in which the test pressure or test temperature appears to change without a corresponding and consistent change in the other value could indicate could indicate either an irregularity in the recorded data, or a possible leak. The test engineer should carefully evaluate why the test pressure or test temperature is changing. A plausible explanation should exist for all pressure and temperature behavior. The only test scenario that can be assumed as leak free is when both the pressure and temperature do not change, and even then one must be certain that the data recorded is accurate.

If ambient conditions are affecting a test, one should be able to observe that effect for the duration of the test. For instance, pressure should be observed increasing with increasing ambient temperature if it is observed that pressure decreases with decreasing ambient temperature. Note that a complete test procedure should not rely solely on ambient temperature readings, which can vary significantly from pipe temperature.

Volume balance calculations should be fundamental to any test acceptance process. The initial temperature, pressure and volume information and the final temperature, pressure and volume information can be used to calculate an overall unaccounted for percent volume change. The recommended criterion for test acceptance is an overall unaccounted for change of 0.05% of the initial test volume or less[3]. Additionally, the trend of data for the entire assessment should be considered in order to support, or to refute, the acceptance result. It is also recommended that at least a portion (roughly one to two hours) of the conventional hold test maintains a stable pressure, even if fluctuations are supported by temperature trends. That may require extending the hold period.

Authorization of an acceptable test should be clearly documented and communicated to key personnel and project stakeholders. Industry best practice is that the authorizing individual(s) be trained on relative company procedures and have some amount of experience monitoring the execution of pressure tests. Individuals with the authority to determine if a pressure test is acceptable vary and may include one or more of the following:

- a trained, degreed engineer
- professional engineer (PE)
- test director or project manager
- pipeline integrity engineer
- pipeline inspector
- pressure test services contractor

Requirements of traceable, verifiable, and complete (T/V/C) records are addressed by PHMSA in the advisory bulletin ADB-2012-06[xii], including the statement, "Complete records are those in which the record is finalized as evidenced by a signature, date or other appropriate marking." Individuals responsible for authorizing the acceptance of a pressure test should sign pressure test acceptance documentation to meet the requirements of T/V/C.

Failures

When the failure or leak occurs, it must be repaired prior to the repressurization and subsequent retest attempt. It is permissible to make a temporary repair in order to facilitate completion of the test. However, ruptured pipe must be replaced. If the replacement pipe is not part of the retest, it must be pretested before the line can reenter service. The failed pipe should be set aside for further examination and testing in order to understand the cause. If new pipe failed during a commissioning hydrostatic test, the reason for the failure may be needed to support a commercial claim, and to determine the likelihood of other pipe from the same heat or production shift being similarly affected. If older pipe failed during an integrity revalidation test, the reason for the failure may be needed to evaluate whether the condition could be present elsewhere in the pipeline.

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[3] While Kiefner's observation is that an unaccounted for change of 0.01% of the initial test volume, or less, typically corresponds to a leak-free assessment, it is also recognized that for the purpose of implementing an acceptance criterion some consideration should be given to measurement error and the potential for inaccuracy of the idealized calculation estimations.

This section provides guidelines related to the necessary information to collect and study if failures begin to occur. There are some techniques described for preventing excessive failures in certain vintage lines with potential sensitivity to high test stress levels, as well as considerations for contingency test planning.

Data Collection

Collect and record all data listed in the Record Keeping, Failure Records section of this report. Additionally, for the purpose of executing laboratory analysis or an investigation of the failure:

- Coordinate the failure investigation as soon as possible.
- Preserve the assumed leak origin or fracture surface.
- Limit exposure to soil and water because they can corrode fracture surfaces.
- Notations to be made using permanent ink or paint markers the pipe or component removed include:
    - description (pipeline name, test segment and failure number, date),
    - location,
    - distance from reference girth weld,
    - o'clock position, and
    - flow direction.

Minimizing Failures

There are limited instances that allow pressure testing using media other than water. However, in general, hydrostatic testing is conducted with water as a means to determine a pipeline's fitness for service in a controlled, safe manner. If a failure is going to occur on a pipeline it is better for it to occur with the least amount of impact to public safety and the environment. While the bottom line may be better to fail with water than while in service, a test plan should outline parameters to prevent an excessive amount of test failures. Determining what is "excessive" can be a challenge and will vary depending on the pipeline system. The following guidelines are intended to reduce the amount of unnecessary failures while still achieving the integrity benefits of the intended test plan.

Typical Cause of Multiple Test Failures

The first step in preventing excessive test failures is to understand the typical source of multiple test failures. Test failures are more likely to occur when an existing pipeline is tested to a hoop stress level in excess of those in prior tests of the pipeline or the pipe manufacturer's pressure test in the pipe mill. A major cause of such failures is seam manufacturing defects. Older-vintage pipe materials may or may not be a pipeline integrity threat, but the potential for them to contain more manufacturing defects than pipe materials made since 1970 and to have properties inferior to the more recent pipe materials is significant. Therefore, when an existing pipeline containing older-vintage materials is retested, test failures may arise in conjunction with material defects.

Older-vintage pipe is generally regarded as line pipe manufactured at a time when little or no attempt was made to enhance ductile toughness, when the quality and properties of longitudinal seams often were inferior to those of the parent pipe material, and no requirement was imposed on the manufacturer for nondestructive inspection of either the seams or the pipe body. In particular, pipe materials manufactured using seam-fabricating processes such as single-submerged-arc welding, low-frequency ERW, furnace lap-welding, or furnace butt-welding are considered to be particularly more likely to cause hydrostatic test failures than modern materials.

Predictive Models for Defect Failure from ILI Results

There are several predictive models available to calculate the failure pressure of surface flaws based on length and depth, including B31G, Modified B31G, RSTRENG, Modified Ln-Sec[xiii], PAFFC[xiv], CorLas™ [xv], PipeAssess PI™, and API 579 Level II[xvi]. If data from ILI tools are available, predicted failure pressures of any remaining graded flaw should be determined and compared to the target test pressure. If the predicted failure pressure is less than the intended hydrostatic test pressure then the remediation of the flaw prior to the hydrostatic test could be considered.

Estimating the Number of Failures during Testing

As failures begin to occur during testing it is possible to forecast the number of failures to be expected in conjunction with a target pressure by studying the distribution of failure pressures. A procedure for estimating the number of failures was presented by J.F. Kiefner, K.M. Kolovich, and S. Kariyawasam in, "A Study of Cases of Hydrostatic Tests Where Multiple Test Failures Have Occurred". The study demonstrated that data from the first few failures of a test can be extrapolated to predict the total number of failures at a given target test pressure. Highlights from that study are presented below.

If failures begin to occur before the target test pressure is attained, a spreadsheet can be populated with the following information:

- test section number
- test failure number
- failure pressure at the deadweight location, psig
- site failure pressure at the failure location, psig
- site failure pressure at the failure location, %SMYS

To estimate the ultimate number of failures, the site failure pressures should be listed in ascending order and numbered 1 through *n* for *n* failures up through the most recent test break. The ordered list of site failure pressures of a few initial failures can be used to generate a plot of cumulative test failures versus failure pressure as was done for the example case shown in Figure 3.

Figure 3 is created by plotting the number of failures from 1 to n versus the ordered site failure pressures. In the example case, 23 breaks occurred in the testing of the first six test sections. The data are fit with a trendline and the trendline equation and R^2 ratio can be displayed as shown. The R^2 value coefficient indicates the goodness of the fit. A value of 1 is a perfect fit so values close to 1 indicate a good fit. The trendline function in a spreadsheet is likely to offer several types of curve-fits. It is recommended that an exponential fit be used, but occasionally some other fit such as a linear fit may result in the best fit. If the R^2 ratio ranges from 0.7 to 1.0, it probably can be considered an acceptable fit. The estimate of the ultimate number of failures is then carried out by extrapolation. In the example case the site failure pressures were extrapolated 65 psig above the highest actual failure pressure at the time the extrapolation was made (23 failures in the example case). This results in a prediction that somewhere near 100 failures would be expected if the test were to be continued until the test pressure level reached 1,265 psig. Using the equation for the trendline given in Figure 3, 94 failures are predicted for a target pressure of 1,265 psig.

The 94 breaks that are predicted apply to the first six test sections. In other words, it means that that 94 breaks per X miles (the total length of the first six test sections) are expected. To estimate the number that should be anticipated throughout the rest of the test sections, one would have to know the lengths of the all sections and multiply that length by 94/X. The test section lengths are not known for this case, but for illustrative purposes, assume that the lengths of the test sections were equal. If such were the case, the ultimate number of breaks predicted would be 94 times the ratio of 16 (total number of test sections) to 6 (number of test sections used to predict the total number of breaks for a target pressure of 1,265 psig or 251 breaks. In fact only 94 test breaks occurred.

The exponential extrapolation based on 23 failures suggests that 251 failures would have been expected if all 23 miles of pipe were to have been exposed to a pressure level to cause failures at 1,265 psig. The estimation of the expected number of test breaks when a segment is tested to a given pressure level by means of the type of extrapolation shown in the Figure 3 trendline can be expected to provide an upper bound. If the predicted number is unacceptably high, the target test pressure can be lowered resulting in either a reduced HTP/MOP ratio or a reduced MOP.

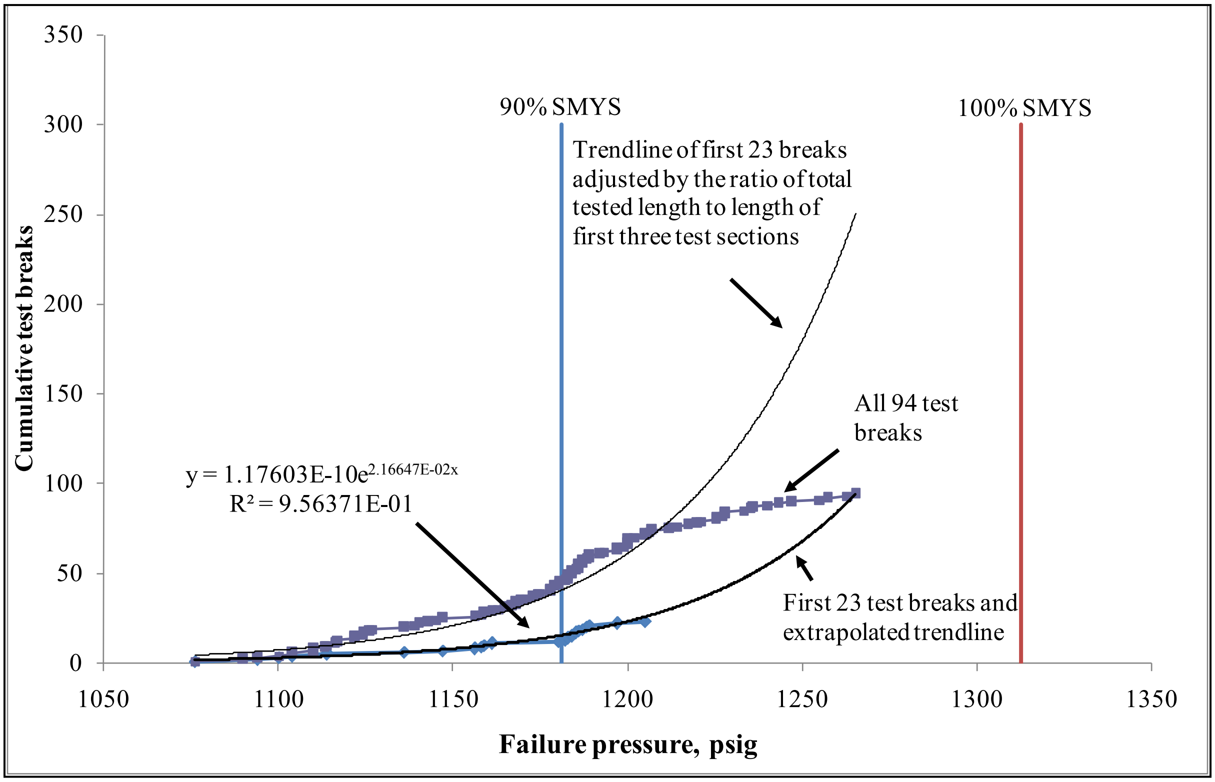

Figure 3. Predicting the Ultimate Number of Failures, Example Case

It is important to note that no test that is terminated by a rupture should be considered the final test. This is the circumstance that tends to lead to a pressure reversal. The final "accepted" test pressure should be one wherein the pressure is lowered gradually, i.e., a leak, or where the pressure is successfully held and then lowered slowly.

Numerous test failures occurred in the example case providing a sufficient amount of data for analysis. This is not always the case during a testing program, so before a decision to stop testing at the original target test pressure based on this method a statistically convincing amount of failures should occur first. The R^2 ratio should provide some indication of the statistical significance of the estimation. If only two or three failures per test section occurred, there is probably no reason to reduce the target test pressure.

Pressure Reversals

A defect that fails at a pressure level lower than the highest pressure previously exposed to during a hydrostatic test signifies the occurrence of a pressure reversal. Pressure reversals can be caused by growth during pressurization and subsequent damage to the defect during depressurization due to plastic strain. The pressure reversal size (P_r) can be expressed as a percentage:

$$P_r = \frac{100(P_t - P_f)}{P_t}$$

Equation 1

where

P_t is the highest level of pressure reached at the test site on any prior pressurization during the current test cycle (psig)
P_f is the failure pressure at the test site (psig)

If test failures begin to occur and testing is continued, the possibility of encountering pressure reversals arises. If several pressure reversals occur, it may be possible to estimate the likelihood of a pressure reversal of a given size. Study of actual hydrostatic test cases has shown that an inverse relationship exists between pressure reversal size and the probability of occurrence of the reversal, and the risk of a failure at the operating pressure from a pressure reversal is usually negligible[xvii].

Kiefner, et al. developed an improved method for estimating the probability of a pressure reversal of a given size in, "A Study of Cases of Hydrostatic Tests Where Multiple Test Failures Have Occurred". The method is summarized below.

If pressure reversals begin to occur before the target test pressure is attained, a spreadsheet can be populated with the following information:

- test section number
- test failure number
- failure pressure at the deadweight location, psig
- site failure pressure at the failure location, psig
- site failure pressure at the failure location, %SMYS
- pressure reversal size, psig
- pressure reversal size, %

The pressure reversals should be listed in ascending order by size. Analyses of a number of cases show that the cumulative rankings of pressure reversals for each given test in ascending order tend to fit exponential distributions quite well. This is shown for the example case reversals in Figure 4.

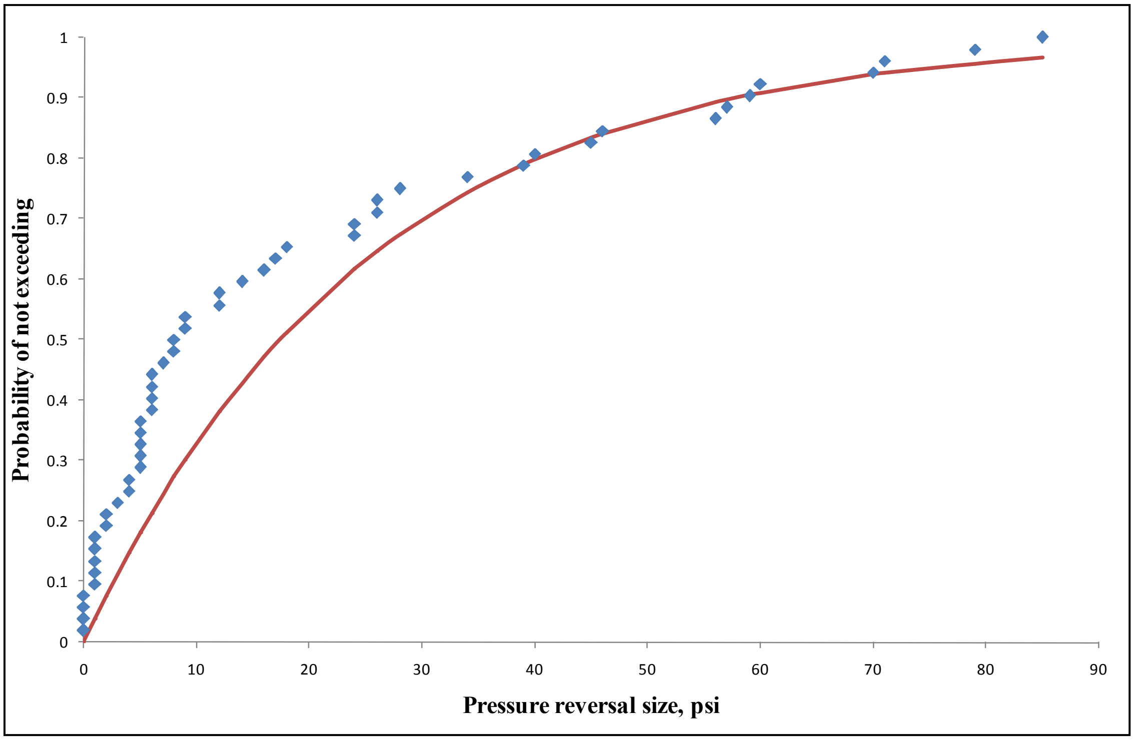

Figure 4. Cumulative Probability of Pressure Reversal Not Exceeding a Given Size, Example Case

Any given data point in Figure 4 represents a pressure reversal, the size of which determines its location on the x-axis. The y-axis position of the given pressure reversal depends on its place in the ascending order of reversals by size. Each reversal is numbered in the list in ascending order. The number of the reversal is then divided by *n* to give it a place in the cumulative distribution from 1 to *n*. The smallest reversal is plotted as (size of Reversal 1, 1/n). The next largest is plotted as (size of Reversal 2, 2/n), etc. until the largest reversal is plotted as (size of Largest Reversal, n/n=1). Plotted in the manner shown in Figure 4, the points of the example case exhibit the characteristics of the exponential distribution defined as:

$$P_{ne} = 1 - e^{-\lambda x}$$ **Equation 2**

where

P_{ne}	is the probability that the pressure reversal will not exceed size "x"
x	is a size of pressure reversal, P_t-P_f (psig)
λ	is the mean and standard deviation of the exponential distribution
λ	is chosen to accommodate the best fit to the actual distribution of pressure reversal sizes

For the example case data it was found that the data fit Equation 2 with λ = 0.0400 $psig^{-1}$ with a "goodness-of-fit" coefficient (R^2) of 0.95. The probability of occurrence of a pressure reversal of a given size, P_x, is:

$$P_x = 1 - P_{ne} = e^{-\lambda x}$$

Equation 3

In practical terms P_x is the probability that each time the pipeline is pressurized from zero to the target test pressure, a defect failure will occur at *x* psig less than the target test pressure. In the example case where the target pressure was 1,181 psig and λ is 0.0400 $psig^{-1}$, the probability of a 5% pressure reversal (x = 59 psig) is 0.094. The inverse of this number is approximately 10.64. So, each time the pipeline is pressurized from zero there is 1 chance in every 10 pressurization events that a seam defect will cause a failure at 1,122 psig. Since the example case pipeline was actually operated at an MOP of 750 psig, a 431 psig pressure reversal would be required to entirely erode the margin of safety of a test to 1,181 psig. Equation 3 indicates that the chance of that happening is 1 in every 30 million pressurization events.

Contingency Plans

A contingency plan is any pre-defined alternative to the original pressure test plan that is implemented after some criteria are met during the execution of the original test plan. Adjustment to the test plan could include changing the target test pressure, test segmentation, or both. The criteria are typically based on a threshold for number of failures, size of pressure reversals, or downtime. Contingency plans are generally reserved for spike testing projects involving vintage pipelines for which the potential for multiple failures is greater.

The greatest impact on delay and cost will be the number of test ruptures and leaks experienced. While a target test pressure can be set with the intent of maximizing the test-pressure-to-operating-pressure ratio, the occurrence of numerous failures could bring about a need for lowering the target test pressure.

Prior to testing, alternatives to the original target test pressure should be explored. Determine the potential impact on pipeline integrity, re-inspection interval and M(A)OP and define a minimum threshold of acceptance for each. A maximum threshold for failure and test duration should be established as well.

Consider the following for use in the development of a contingency plan. For a given test, assume there are three potential outcomes of the first pressurization of a test segment:

1. The original target test pressure will be attained, and the required amount of hold time at that pressure will elapse with no occurrence of a rupture or detectable leak.

2. The original target test pressure will be attained, but a rupture or detectable leak will occur before the required amount of hold time has elapsed.
3. A rupture or detectable leak will occur before the original target test pressure is reached.

In the event of outcome No. 1 occurring, it is reasonable to assume that the necessary leak test can be carried out at a reduced level of pressure. Small leaks, if detected and found, must be located and a repair made before the test can be reattempted to the original target test pressure. The repair may be temporary in order to complete the testing promptly. In contrast, in the event outcome No. 2 or No. 3 occurring, the leak or rupture must be located and a repair made before the test can be reattempted. The repair may be temporary in order to complete the testing promptly.

Future cycles of pressurization will have one of the same three outcomes. If outcomes No. 2 or No. 3 recur, the failures should be studied for evidence of pressure reversals. If pressure reversals are occurring, the probability of a reversal large enough to cause failure at the intended M(A)OP should be determined (see Pressure Reversals section).

Figure 5 is a flow chart designed to assist in determining when and to what extent the target test pressure should be lowered in an attempt to avoid additional ruptures from occurring during testing of an existing pipeline segment. This process is valid for the analysis of test failures caused by defects in the longitudinal seam weld (see Typical Cause of Multiple Test Failures section). It is also only intended for spike testing based on the maximum bound test pressure recommendations made in the Task 4 report. The variables utilized in the flow chart are described below.

- **HTP:** Minimum bound hydrostatic test pressure (psig) for the conventional hold, or federal regulation strength test
- **STP:** Spike test pressure (psig)
- **P_{f_1}:** Failure pressure (psig) at the test site of the first test failure
- **P_{f_x} or P_{f_x-1}:** Failure pressure (psig) at the test site of failures subsequent to P_{f_1}. The subscripts "x" and "x-1" represent the failure number (e.g. if it is the third test failure the line has experienced then "x" = 3 and "x – 1" = 3 – 1 = 2).
- **P_{target}:** Target pressure (psig) the test plan is attempting to achieve
- **P_t:** Highest level of pressure (psig) reached at the test site on any prior pressurization during the current test cycle. For the first test failure, P_t is equal to P_{f_1}.
- **P_{r_1}:** Pressure reversal size (%) of the first pressure reversal (See Equation 1)
- **P_{r_i}:** Pressure reversal size (%). If P_{f_x} is less than P_t, then this signifies the occurrence of a pressure reversal, and the reversal size must be calculated (See Equation 1). The subscript "i" represents the reversal number (e.g. if it is the second reversal the line has experienced then "i" = 2).

- **P_{r_max}:** Pressure reversal size (%) of the largest pressure reversal to occur on any prior pressurization during the current test cycle. For the first pressure reversal, P_{r_max} is equal to P_{r_1}.
- **P_{r_limit}:** Pressure reversal maximum size limit (%). The reversal size that would diminish the entire margin between the STP and the HTP. Complete erosion of this margin may require the M(A)OP to be lowered. It can be calculated as, $P_{r\_limit} = 1 - (HTP/STP)$, and should be rounded down to the nearest percent.
- **Failure count:** The total number of test failures that have occurred on the test segment during the current test cycle.
- **Threshold:** The number of tolerable failures the test project can withstand before the target test pressure must be lowered due to cost restraints, schedule restraints, or both. This threshold can be set infinitely high if cost and schedule are not limiting factors.
- **F_R:** Pressure reduction factor (%). The percent of the target test pressure the contingency test pressure should be set at in an attempt to avoid additional pressure reversals from occurring. This factor is calculated as shown below.
    - $F_R = 1 - [\text{Average}(P_{r\_1}, P_{r\_2},\ldots, P_{r\_x}) / 100]$
        - $\text{Average}(P_{r\_1}, P_{r\_2},\ldots, P_{r\_x}) = (P_{r\_1}, P_{r\_2},\ldots, P_{r\_x}) / x$

Examples demonstrating how to apply the contingency test plan flow chart are provided in Appendix C.

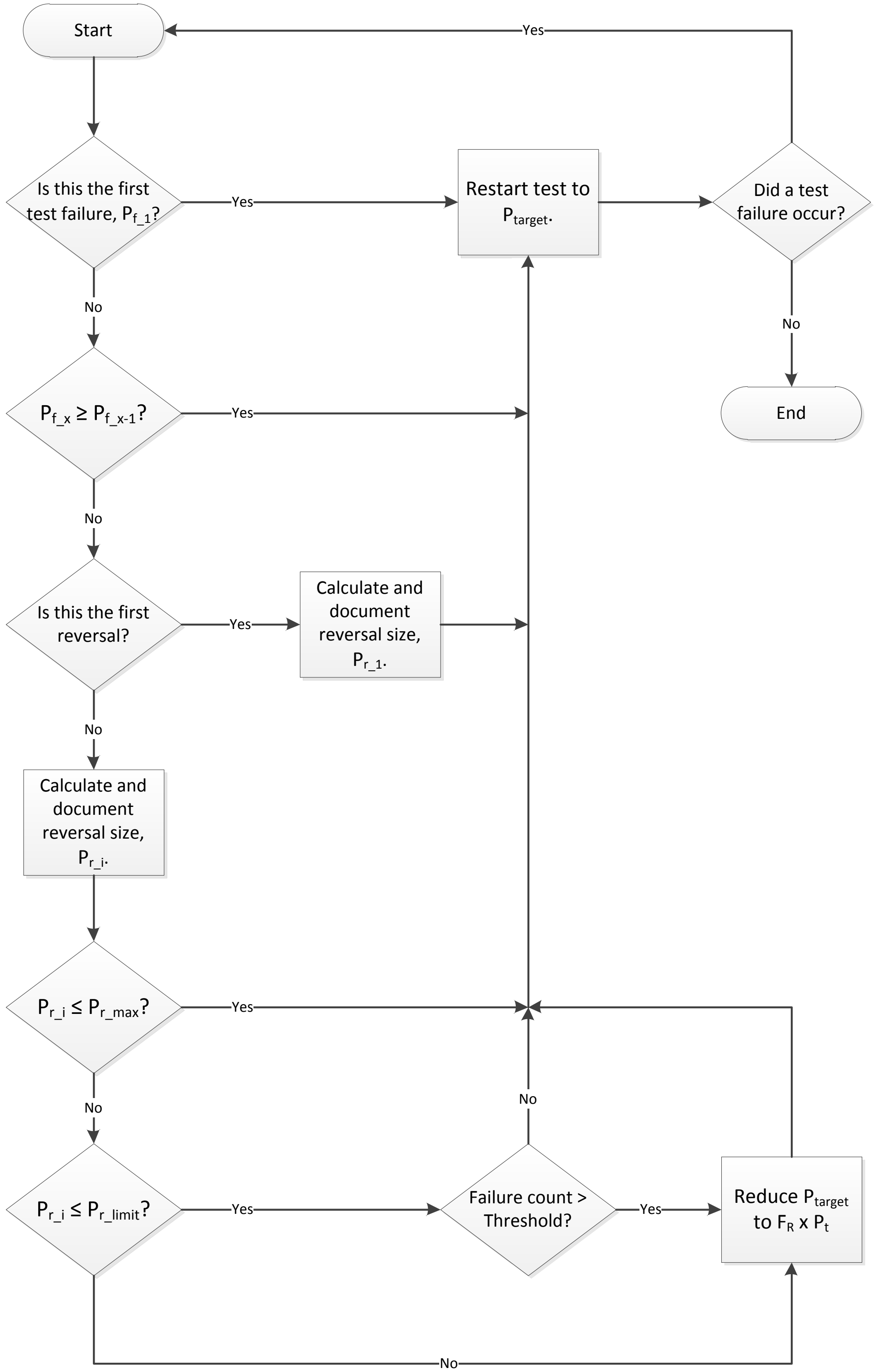

Figure 5. Contingency Test Plan Flow Chart

Depressurization, Dewatering and Drying

There are safety considerations for depressurization that will be discussed in the Task 7 report on other pressure test considerations. They essentially relate to potential energy, properly rated equipment and establishing an effective anchoring system. Also, environmental considerations related to water disposal will be addressed in the Task 7 report on other pressure test considerations.

Depressurization should be controlled, and 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.

The extent of drying required after a test varies depending on the pipeline service. Drying methods include one displacement pig run (to displace free water), drying with chemicals, pigging with dehydrated air, and nitrogen pigging to as low as a -80 deg. F dew point. Generally, CO_2 pipelines require the lowest dew point and heated nitrogen is used for drying, whereas crude oil pipelines may only require a single pig displacement.

Additionally, API 1110 section 5.9 provides general guidelines on depressurization, displacement and the disposal of test fluids[xviii]. Chapter 6 of the Pipeline Rules of Thumb Handbook[xix] provides guidelines related to dewatering and drying.

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[v] TITLE 49—Transportation, Subtitle B – Other Regulations Relating to Transportation, Chapter 1 – Pipeline and Hazardous Materials Safety Administration, Department of Transportation, Subchapter D – Pipeline Safety, Part 192 – Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards.

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APPENDIX A –BASIC CONCEPTS OF YIELD PLOTTING

Basic Concepts of Yield Plotting

For the purposes of these pressure test execution guidelines, a pressure-volume plot or pressure-stroke plot are synonymous with the term yield plot and are analogous to an average stress-strain curve for the pipeline. When the pressure is plotted against the volume of fluid added after filling, the initial data plotted will form a straight line representing the "elastic" region of the deformation process. AB of Figure A-1 represents the elastic region. While in the elastic region, removing the pressure results in the plot returning along the same slope (or straight line AB) and no permanent deformation of the pipe will occur. As the yield plot continues, the plotted data will begin to curve downwards away from the straight line extrapolation of the elastic region. The point where the deviation from straight line proportionality first occurs, called the elastic limit, is identified on Figure A-1 as B and corresponds to the pressure at which part of the test section begin to yield (or permanently deform). The curve portion BD of the plot represents the "plastic" region of the deformation process. Removing the pressure while in the plastic region will result in the plot returning along a line DE parallel but offset from the line plotted while pressurizing in the elastic region, and permanent deformation will have occurred. If a second yield plot were to be made starting with the same initial pressure at the start of pressurization, the line plotted during the second pressurization would be identical to a line plotted during the first depressurizing from within the plastic region and not deviate from this straight line until point D is reached (i.e., the plot would follow ED).

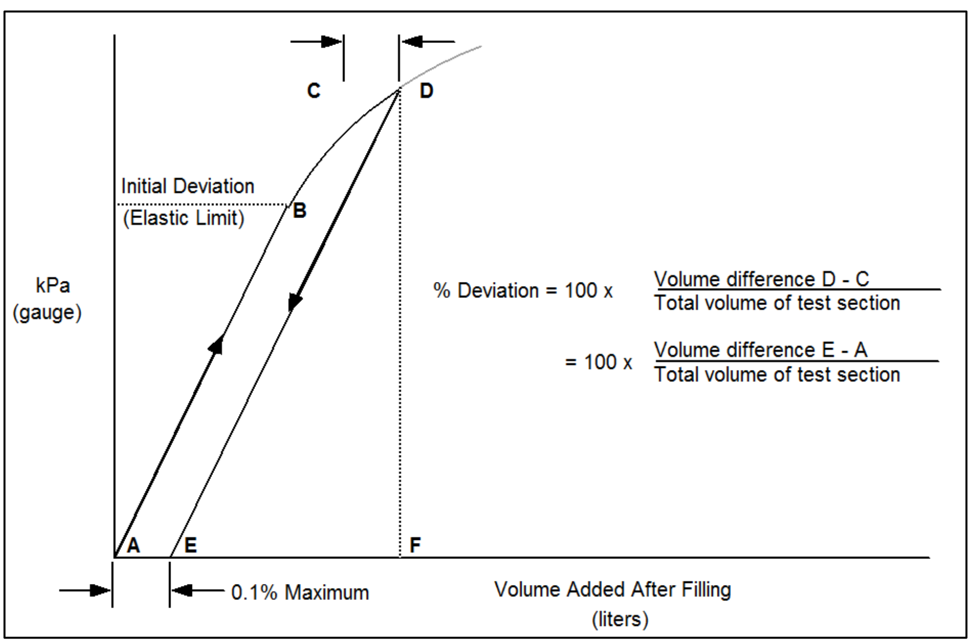

Figure A-1. Yield Plot Theory Sketch

The effect of entrapped air within a test section on a yield plot is shown in Figure A-2. The compression of the entrapped air during pressurizing will result in a false slope of the straight line extrapolation. As the air is compressed further it will begin to behave as an incompressible liquid, and the slope of the plotted line will correct itself (increase) to that of the true pressure-volume relationship. Although yielding will occur as in the true pressure-volume relation, the point of initial deviation may not be detectable on the plot, and the total deviation will be distorted.

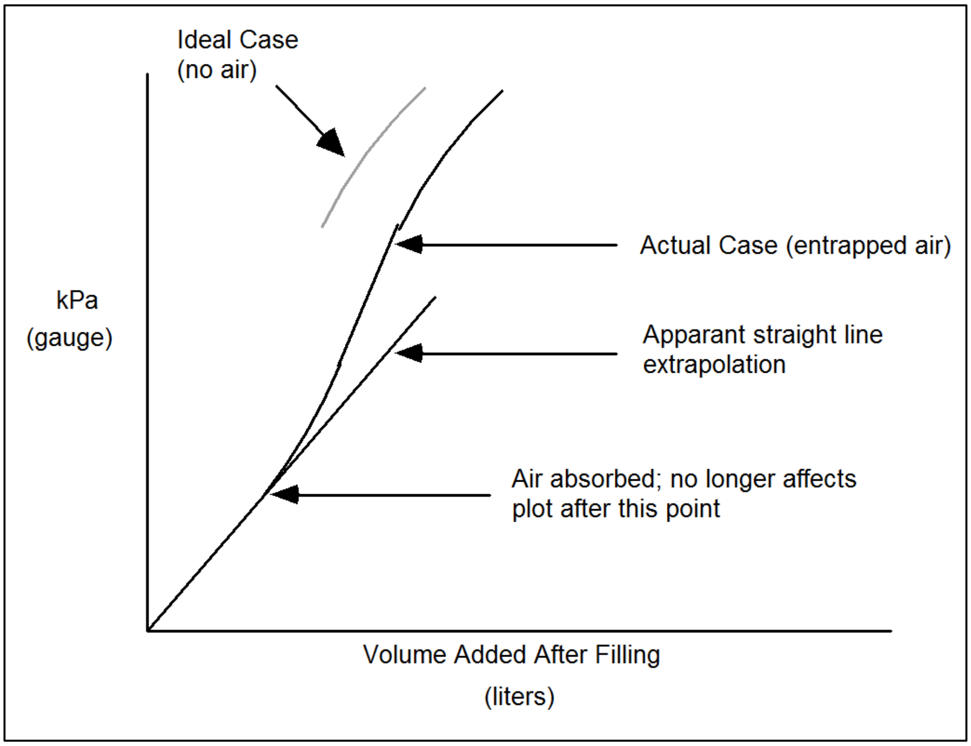

Figure A-2. Effect of Entrapped Air

APPENDIX B – EFFECT OF HOLD TIME ON PIPE INTEGRITY

Benefit of Hold Time is for Leak Detection

The need for a considerable hold time is for finding leaks on a pipeline. Some defects may exist that are small enough that they will not lead to an immediate drop in hydrostatic pressure, but will lead to a small amount of fluid leaking through the defect that will cause a gradual drop in test pressure. It is often difficult to distinguish the difference between variations in pressure caused by thermal fluctuations of the fluid in the pipeline from gradual loss in test pressure due to small leaks. Because of the large volume of test fluid that can exist in a pipeline, it is advantageous to hold the pressure for a long enough period of time to achieve thermal equilibrium such that thermal effects no longer mask pressure loss due to small leaks. This is the reasoning behind the 8 hour hold time required by federal regulations discussed previously in this document.

Holding for the purpose of detecting leaks does not have to be done at the maximum test pressure to be effective. However, it should be done at an applied pressure level above the operating pressure in order to improve the detection of leaks that are only open at high pressure near or above M(A)OP. Shorter hold times are adequate where the piping is above ground, because small leaks such as may occur at flanged connections can be identified visually.

Effect of Hold Time on Pipeline Integrity

In order to understand the significance of hold time with respect to pipeline integrity one needs to understand the regions of crack growth. Under an increasing stress level, or at a sustained stress level very close to the failure point, crack growth proceeds in a stable manner until the crack grows large enough that it becomes unstable and proceeds to failure. These concepts are outlined in a 1980 report sponsored by the Pipeline Research Committee of the American Gas Association NG-18 committee titled: *A Study of the Causes of Failures of Defects that Have Survived a Prior Hydrostatic Test*, by Kiefner, Maxey, and Eiber.

The vast majority of steel pipelines operate at temperatures above its material's fracture initiation transition temperature. At temperatures above this transition temperature steel behaves in a ductile manner. The authors of the study referenced above describe ductile behavior in terms of irreversible strain or "creep-like behavior" in the presence of a crack-like defect. In creep-like behavior defects exhibit physical extension at stress levels below their failure stress levels. The defect extension phenomenon results when the ultimate strain capacity of the material in the vicinity of the defect is exhausted. The ductile failure phenomenon is time-dependent, where the crack growth continues albeit slowly. Depending on how close the applied stress is to the failure stress of the defect, this creep-like behavior may continue until a sudden unstable extension of the defect occurs or it may decrease and cease altogether as described schematically in Figure B-1.

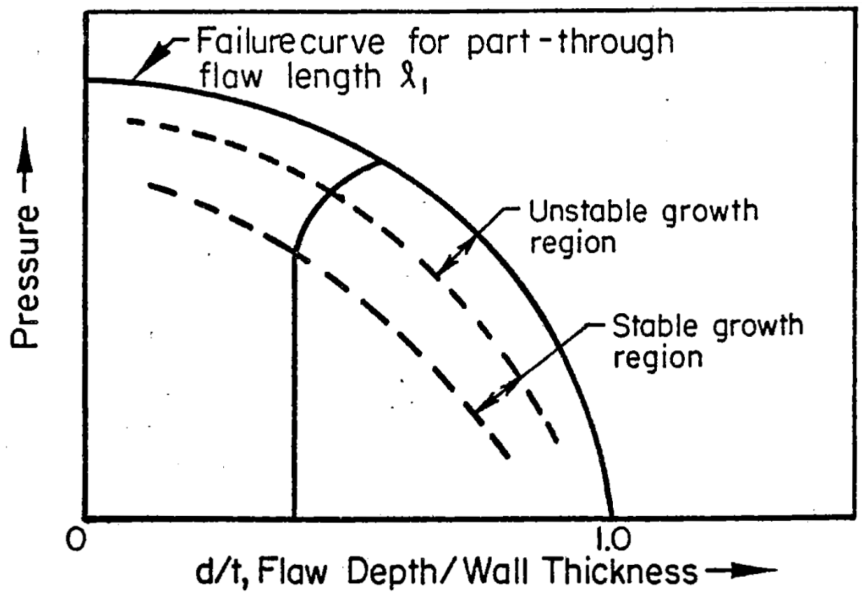

Figure B-1. Idealized Behavior of Part-though Flaws during Loading to Failure

As a defect in a pipe is loaded it begins to change depth after a minimum pressure level is reached. This is shown in Figure B-1 where the vertical line of the graph starts to curve to the right. With further increase in pressure, the crack continues to elongate until a critical pressure level is reached, at which time the defect will fail. The initial portion of the loading cycle, where growth is so small it is difficult to measure, essentially can be considered a region of no growth, and is termed the stable growth region in Figure B-1. If the loading of the defect in this region were stopped and held constant, the defect would continue to grow slowly for some period of time and then stabilize. However, if the defect is loaded to a higher stress level into the unstable growth region as shown in Figure B-1 and if the loading stops in this region, the defect will continue to grow until failure occurs even without a further increase in load. The strain versus time pattern in these two regions is show in Figure B-2.

The regions where stable or unstable crack growth can occur under static stress are often encountered during the hold time of a pressure test. Unstable crack growth will eventually lead to failure if the load is held long enough, whereas stable crack growth will stop.

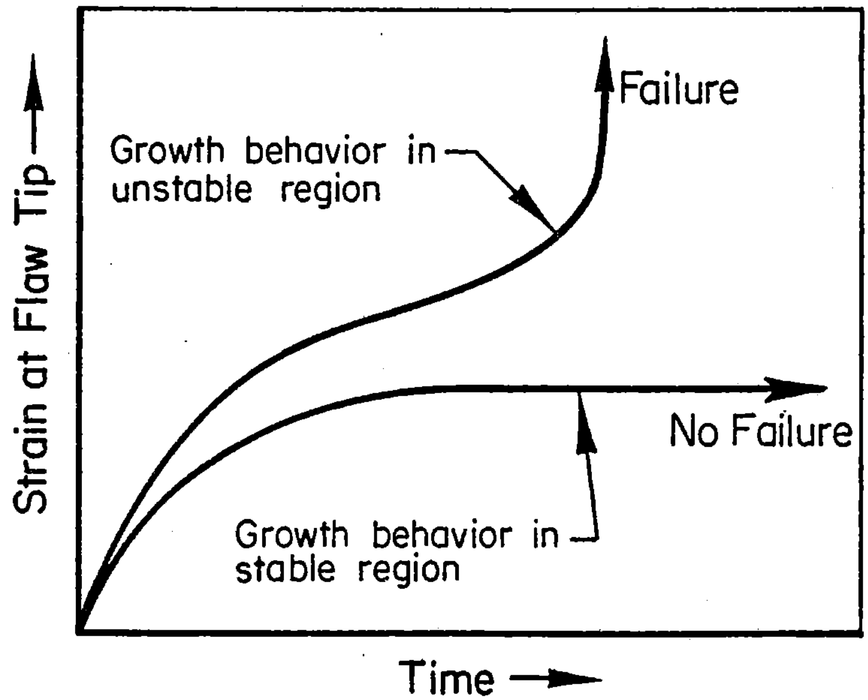

Figure B-2. Idealized Behavior of Flaws Loaded and Held in the Stable and Unstable Growth Regions

To understand the effect of longer hold times, Figure B-3 shows four hypothetical cracks undergoing unstable growth. Each of the four defects is slightly less severe than the first. In a test to a given target test pressure all are severe enough that they will enter the unstable crack growth region and grow to failure at the target test pressure if the pressure is held long enough. The curves represent the crack-opening displacement over time during the test for each crack, and failure is indicated by the curve turning upward so the crack opening becomes infinite. As hypothesized here, the times to failure are about 10 minutes, 2½ hours, 5 days, and 1 month for Defects 1, 2, 3, and 4 respectively. Because the presence of a flaw is unknown until a defect fails, nothing can be known about the status of the four defects until they fail. Let us assume that crack size is related to crack opening displacement, and no matter when the test is terminated, its status can be judged by the crack-opening displacement at that time, and that smaller openings are measures of a better outcome in terms of lesser flaw extension.

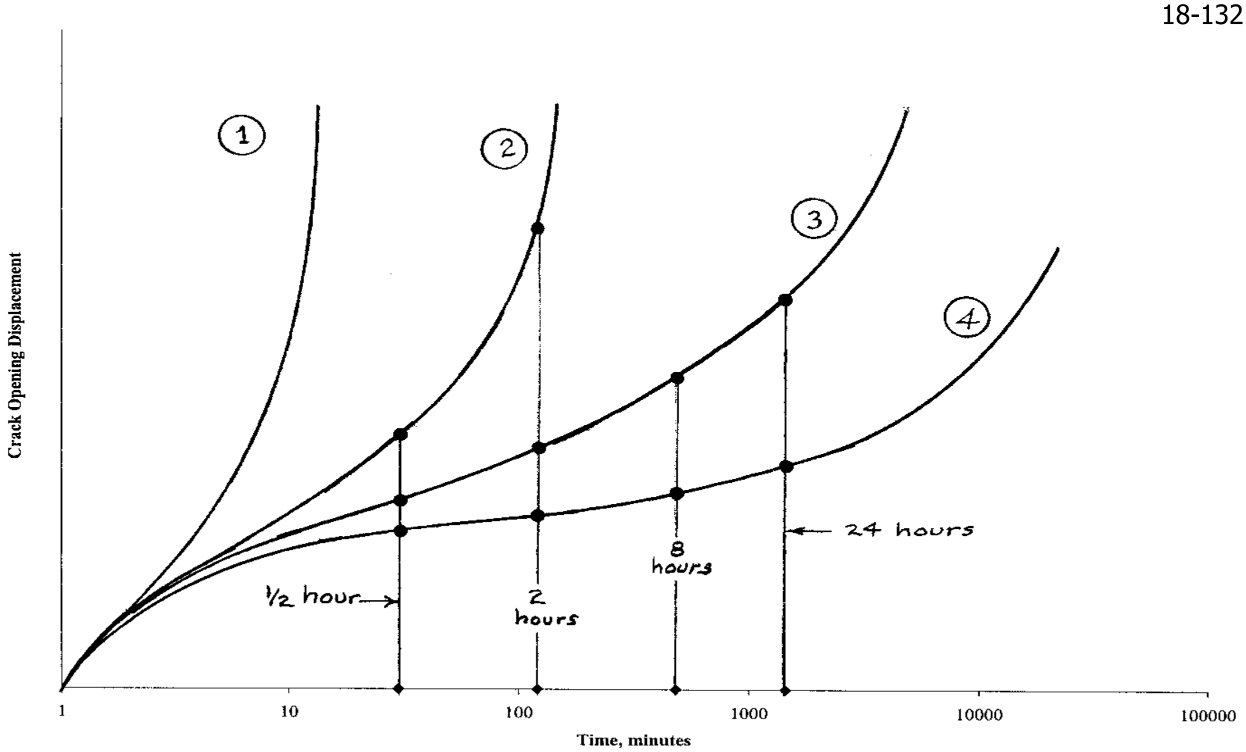

Figure B-3. Four Hypothetical Defects undergoing Unstable Crack Growth during a Hold Test

So considering hydrostatic test hold times of ½, 2, 8, or 24 hours and the postulated potential realistic cracks, which hold time is the best? Note that the most severe defect, Defect 1, is going to fail in 10 minutes irrespective of which time is chosen.

The example is hypothetical and is not meant to portray every potential outcome in every hydrostatic test, but it does illustrate that longer test times may not be beneficial and it is impossible to choose the best hold time because the pipeline operator has no way of knowing what defects, if any, exist or how close they are to failure if they do not fail during the test. Consequently, an operator cannot choose the best hold time for the purpose of demonstrating pipeline integrity. **The value of a particular hold time cannot be ascertained in terms of pipeline integrity because the consequences of holding cannot be measured. This means that, for purposes of establishing pipe integrity, any specified duration of the maximum test pressure is arbitrary.**

Kiefner, Maxey, and Eiber summarize the significance of hold time in their 1980 PRC report:

The effect of hold time at maximum test pressure is to cause defects to grow and perhaps cause those defects to fail that would otherwise have required higher pressures to fail in a straight-away pressurization. Holding at the maximum test pressure level causes defects that *grow substantially to fail and also causes a portion of the remaining family of defects to extend. Thus one of the following circumstances results from hold time:*

1. *At the end of an arbitrary hold period in which no failures have occurred, a portion of the remaining defects have grown but no additional failures have occurred. Thus, the hold period was of no value since it has caused only the growth of defects and no additional failures.*
2. *At the end of an arbitrary hold period in which one or more failures have occurred, the cycles of pressure needed to reestablish the hold following each failure have caused any remaining defects to grow and increases the probability of a subsequent failure.*
3. *At the end of a hold period terminated by a test failure, there is just as likely to be a defect on the verge of failure as there would have been if the test had been terminated with a shorter hold time.*

Support for short spike test durations can be found in basic fracture tests data from Tiffany and Masters, as cited in NG-18 Report No. 111. Figure B-4(a) and Figure B-4(b) show the effect of sustained hold time below the point of failure in critical crack-tip stress-intensity of fracture specimens, normalized to the immediate-failure crack-tip stress-intensity[4]. The normalized crack-tip stress-intensity is seen to decrease with increased hold time near the failure load. The time-dependent critical load dropped approximately 5% after 0.1 hr and approximately 10% loss after 1.0 hr. Moreover, a 1-hour hold had as severe an effect as a hold for several hours. These results were interpreted to indicate an accumulation of damage at the crack tip with hold time, most likely in the form of tearing or crack extension, and are the basis for this report's recommendation to minimize hold time ideally to not more than 0.05 hour (3 minutes).

[4] Tiffany, C.F. and Masters, J.N., "Applied Fracture Mechanics", Symposium on Fracture Toughness Testing and Its Applications, ASTM STP 381, 1965.

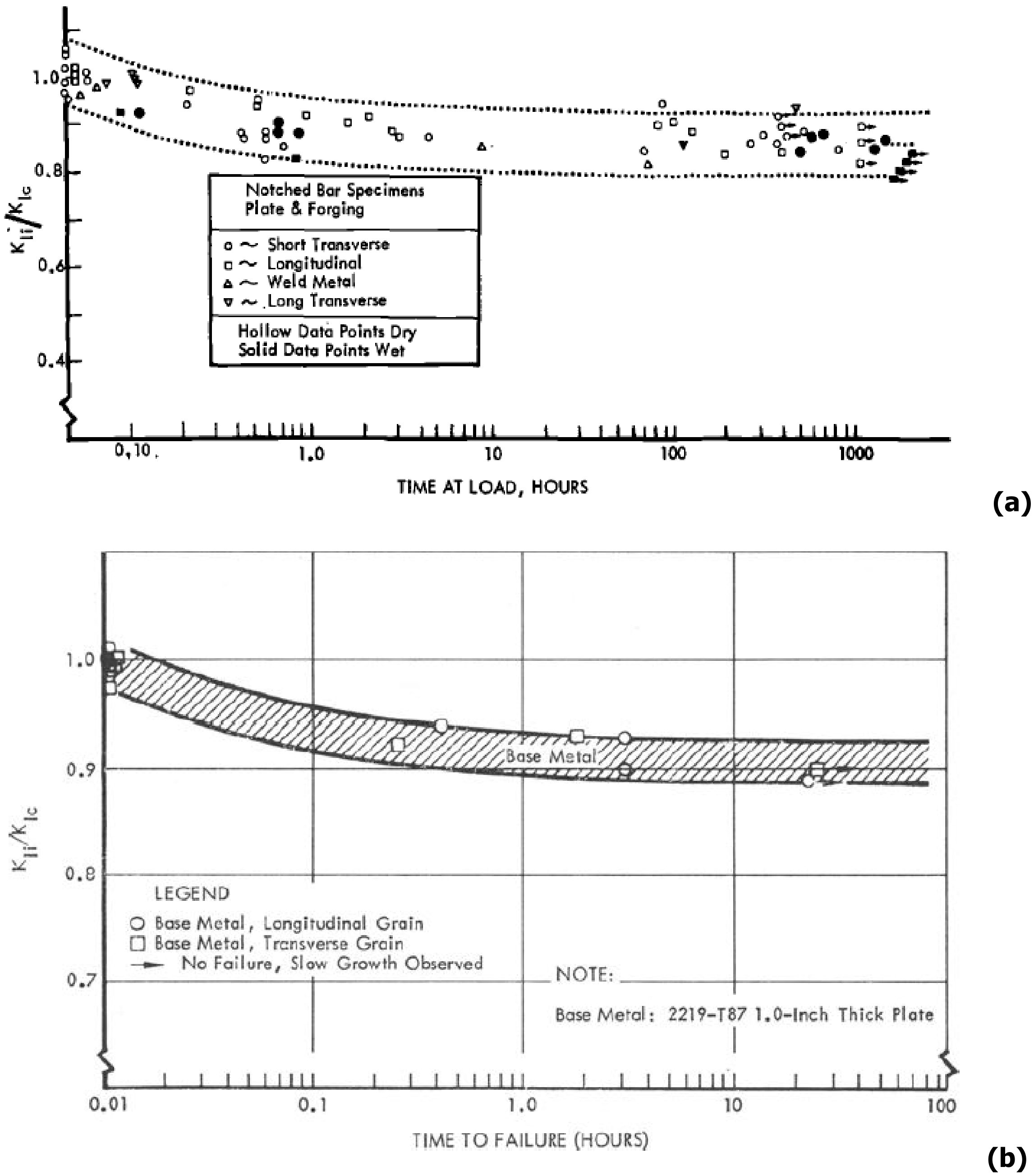

Figure B-4. Effect of Hold Time on Critical Crack-Tip Stress-Intensity (from Tiffany & Masters)

APPENDIX C – CONTINGENCY TEST PLAN FLOW CHART EXAMPLES

The following examples illustrate the concept of a contingency test plan. The examples concern a pipeline which has been taken out of service due to a recent in-service failure. The pipeline is to be hydrostatically tested to prove its integrity and to assess the line for leaks. The liquid products pipeline transports crude oil 10 miles from a terminal storage facility to a nearby refinery. The line was constructed in 1948 and consists of 20-inch OD, 0.312-inch WT, API 5LX grade X42 LF-ERW line pipe. The MOP of the line is 943 psig (72% SMYS).

The hydrostatic test plan calls for the line to be divided into two test segments (TS). TS1 and TS2 are four miles and six miles in length, respectively. The testing of each TS will commence with a spike test to 1,310 psig (100% SMYS). The duration of the spike test will be five to ten minutes after which the pressure will be reduced to 1,179 psig (1.25 x MOP), the level required to satisfy Subpart E minimum test requirements stipulated by the regulations. Pressure will be held at this level for eight hours. Due to schedule and cost restraints, a total of nine failures (sum total for both test segments) is the threshold limit that can be tolerated before the target pressure should be lowered in an attempt to avoid further test failures.

Example 1 (TS 1) and Example 2 (TS 2) below demonstrate how the proposed contingency test plan flow chart can be implemented to aid the operator in making test decisions in the event that multiple test failures and/or pressure reversals begin to occur as well as when and to what extent a target hydrostatic test pressure should be reduced in an attempt to avoid additional failures.

Variable values are defined and/or updated for each test attempt described in Examples 1 and 2. The color next to the text describing each test attempt corresponds with the line color on the accompanying flow chart to guide the reader through the example and demonstrate how the flow chart is used. The flow chart variable definitions, discussed previously, are repeated below for ease of reference.

- **HTP:** Minimum bound hydrostatic test pressure (psig) for the conventional hold, or federal regulation strength test.
- **STP:** Spike test pressure (psig).
- **P_{f_1}:** Failure pressure (psig) at the test site of the first test failure.
- **P_{f_x} or P_{f_x-1}:** Failure pressure (psig) at the test site of failures subsequent to P_{f_1}. The subscripts "x" and "x-1" represent the failure number (e.g. if it is the third test failure the line has experienced then "x" = 3 and "x – 1" = 3 – 1 = 2).
- **P_{target}:** Target pressure (psig) the test plan is attempting to achieve.
- **P_t:** Highest level of pressure (psig) reached at the test site on any prior pressurization during the current test cycle. For the first test failure, P_t is equal to P_{f_1}.
- **P_{r_1}:** Pressure reversal size (%) of the first pressure reversal (See Equation 1).

- **P_{r_i}:** Pressure reversal size (%). If P_{f_x} is less than P_t, then this signifies the occurrence of a pressure reversal, and the reversal size must be calculated (See Equation 1). The subscript "i" represents the reversal number (e.g. if it is the second reversal the line has experienced then "i" = 2).
- **P_{r_max}:** Pressure reversal size (%) of the largest pressure reversal to occur on any prior pressurization during the current test cycle. For the first pressure reversal, P_{r_max} is equal to P_{r_1}.
- **P_{r_limit}:** Pressure reversal maximum size limit (%). The reversal size that would diminish the entire margin between the STP and the HTP. Complete erosion of this margin may require the M(A)OP to be lowered. It can be calculated as, $P_{r\_limit} = 1 - (HTP/STP)$, and should be rounded down to the nearest percent.
- **Failure count:** The total number of test failures that have occurred on the test segment during the current test cycle.
- **Threshold:** The number of tolerable failures the test project can withstand before the target test pressure must be lowered due to cost restraints, schedule restraints, or both. This threshold can be set infinitely high if cost and schedule are not limiting factors.
- **F_R:** Pressure reduction factor (%). The percent of the target test pressure the contingency test pressure should be set at in an attempt to avoid additional pressure reversals from occurring. This factor is calculated as shown below.
  - $F_R = 1 - [\text{Average}(P_{r\_1}, P_{r\_2}, \ldots, P_{r\_x}) / 100]$
    - $\text{Average}(P_{r\_1}, P_{r\_2}, \ldots, P_{r\_x}) = (P_{r\_1}, P_{r\_2}, \ldots, P_{r\_x}) / x$

Example 1: TS1

1. Begin pressuring up to target pressure, P_{target}, of 1,310 psig, but ruptures at 1,283 psig. **Failed test.**
    a. P_{f_1} = 1,283 psig
    b. P_t = 1,283 psig

2. Make repairs. Begin pressuring up to 1,310 psig, but ruptures at 1,310 psig. **Failed test.**
    a. P_{f_2} = 1,310 psig
    b. P_t = 1,283 psig

3. Make repairs. Begin pressuring up to 1,310 psig, but ruptures at 1,284 psig (2% reversal). **Failed test.**
    a. P_{f_3} = 1,284 psig
    b. P_t = 1,310 psig
    c. $P_{r\_1} = 100 * (P_t - P_{f\_3}) / P_t = 100 * (1{,}310 - 1{,}284) / 1{,}310 = 2\%$

4. Make repairs. Begin pressuring up to 1,310 psig, but ruptures at 1,271 psig (3% reversal). **Failed test.**
    a. P_{f_4} = 1,271 psig
    b. P_t = 1,310 psig
    c. $P_{r\_2} = 100 * (P_t - P_{f\_4}) / P_t = 100 * (1{,}310 - 1{,}271) / 1{,}310 = 3\%$
    d. P_{r_max} = 2%
    e. P_{r_limit} = 1 – (HTP / STP) = 1 – (1,179 / 1,310) = 10%
    f. Failure count = 4
    g. Threshold = 9

5. Make repairs. Begin pressuring up to 1,310 psig, but ruptures at 1,297 psig (1% reversal). **Failed test.**
    a. P_{f_5} = 1,297 psig
    b. P_t = 1,310 psig
    c. $P_{r\_3} = 100 * (P_t - P_{f\_5}) / P_t = 100 * (1{,}310 - 1{,}297) / 1{,}310 = 1\%$
    d. P_{r_max} = 3%

6. Make repairs. Pressure up to 1,310 psig and hold 5 minutes. No failures. **Successful spike phase of test. Reduce pressure to the required hold level to meet requirements per applicable regulations and standards.**

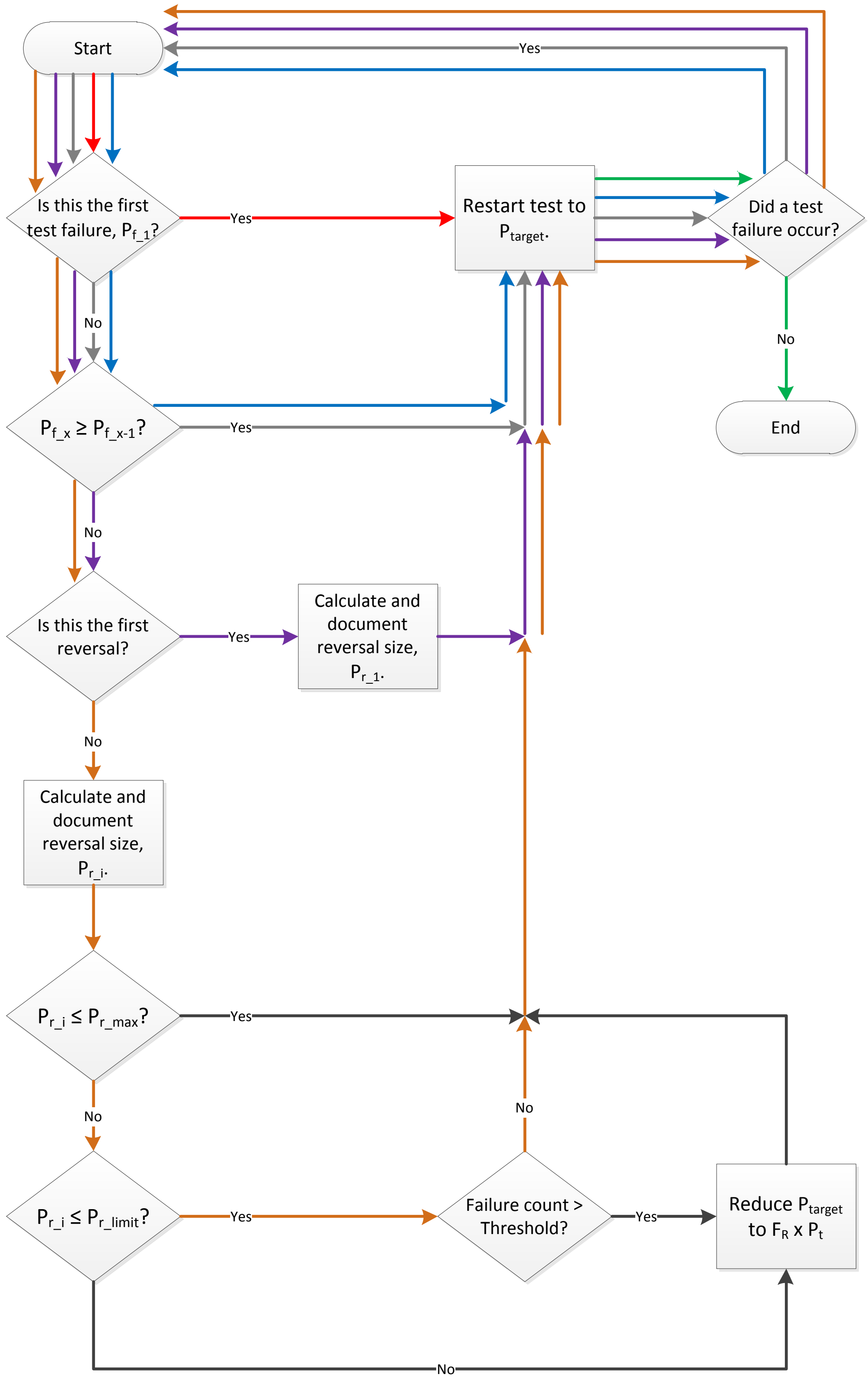

Figure C-1. Contingency Test Plan Flow Chart for Example 1

Example 2: TS 2

1. Begin pressuring up to target pressure, P_{target}, of 1,310 psig, but ruptures at 1,214 psig. **Failed test.**
    a. P_{f_1} = 1,214 psig
    b. P_t = 1,214 psig

2. Make repairs. Begin pressuring up to 1,310 psig, but ruptures at 1,190 psig (2% reversal). **Failed test.**
    a. P_{f_2} = 1,190 psig
    b. P_t = 1,214 psig
    c. $P_{r\_1} = 100 * (P_t - P_{f\_2}) / P_t = 100 * (1{,}214 - 1{,}190) / 1{,}214 = 2\%$

3. Make repairs. Begin pressuring up to 1,310 psig, but ruptures at 1,263 psig. **Failed test.**
    a. P_{f_3} = 1,263 psig
    b. P_t = 1,263 psig

4. Make repairs. Begin pressuring up to 1,310 psig, but ruptures at 1,257 psig (0.5% reversal). **Failed test.**
    a. P_{f_4} = 1,257 psig
    b. P_t = 1,263 psig
    c. $P_{r\_2} = 100 * (P_t - P_{f\_4}) / P_t = 100 * (1{,}263 - 1{,}257) / 1{,}263 = 0.5\%$
    d. P_{r_max} = 2%

5. Make repairs. Begin pressuring up to 1,310 psig, but ruptures at 1,200 psig (5% reversal). **Failed test.**
    a. P_{f_5} = 1,200 psig
    b. P_t = 1,263 psig
    c. $P_{r\_3} = 100 * (P_t - P_{f\_5}) / P_t = 100 * (1{,}263 - 1{,}200) / 1{,}263 = 5\%$
    d. P_{r_max} = 2%
    e. P_{r_limit} = 1 – (HTP / STP) = 1 – (1,179 / 1,310) = 10%
    f. Failure count = 10 (5 failures from TS1 + 5 failures currently from TS2)
    g. Threshold = 9
    h. Failure threshold exceeded. Reduce P_{target} to contingency test pressure.
        i. F_R = 1- [Average(P_{r_1}, P_{r_2}, P_{r_3}) / 100] = 1 – [2.5 / 100] = 0.975
            1. Average(P_{r_1}, P_{r_2}, P_{r_3}) = (2 + 0.5 + 5) / 3 = 2.5%
        ii. Reduced $P_{target} = F_R * P_t$ = 0.975 * 1,263 = 1,231 psig

6. Make repairs. Pressure up to 1,231 psig and hold 5 minutes. No failures. **Successful spike phase of test. Reduce pressure to the required hold level to meet requirements per applicable regulations and standards.**

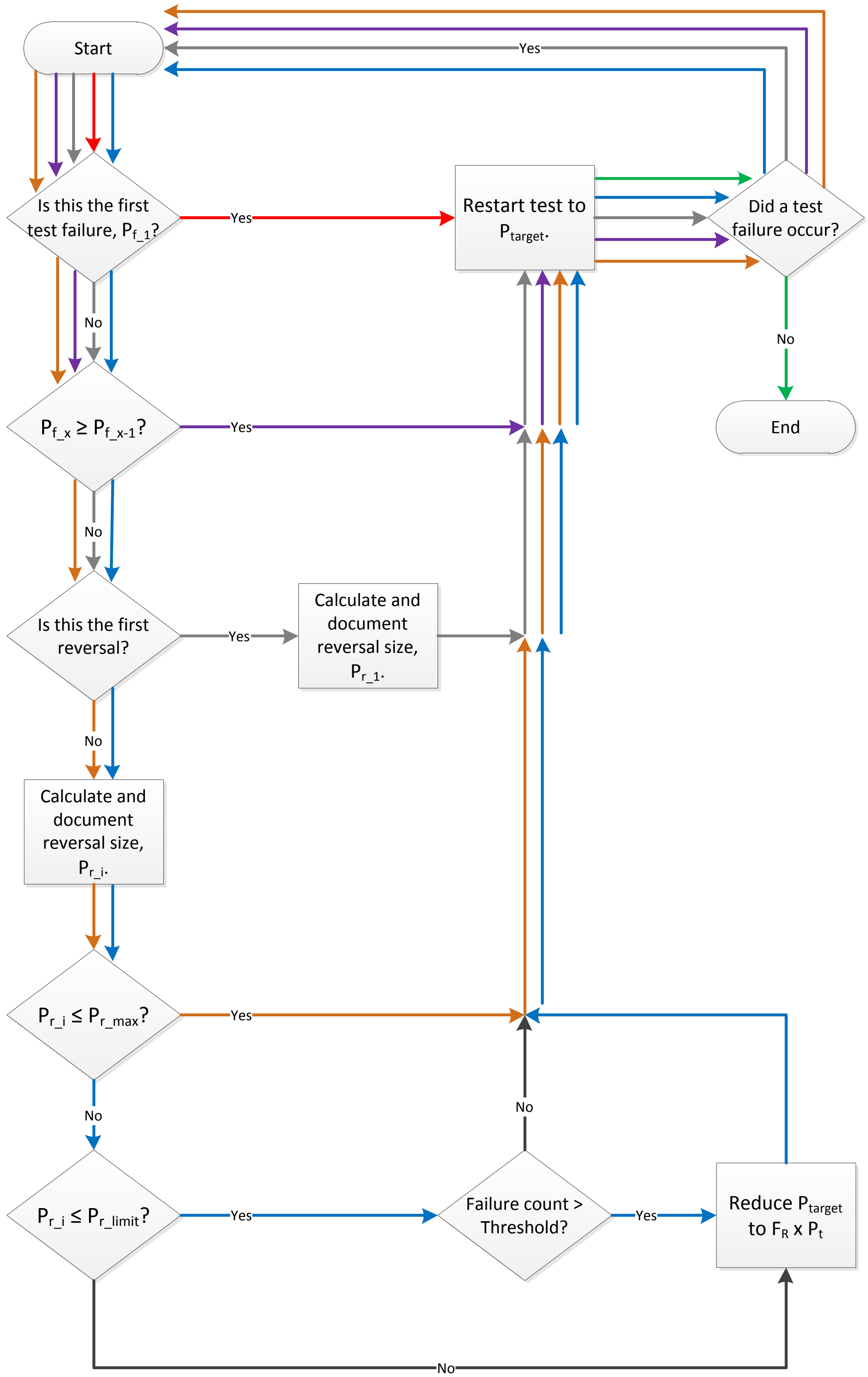

Figure C-2. Contingency Test Plan Flow Chart for Example 2

APPENDIX D – WINTER TESTING PROCEDURE EXAMPLES

Primary Winter Testing Procedure - Example

The following sub sections outline the additional requirements and changes for winter testing. Winter testing procedures are required for new construction when the pipe is installed in a frozen ditch. These procedures are not required for hydrostatic tests conducted for integrity purposes unless ground around the pipe is likely to freeze prior to completion of the test.

Winter Mainline Testing Procedure

Winter mainline testing is defined as testing where low ground and ambient temperatures require the fill water to be heated. The enclosing and heating of open lengths of pipe should not be considered winter mainline testing.

A temperature recorder should be installed by means of a thermowell to monitor the temperature of water added to the test section. The temperature of the water extracted from the test section during warm water passage should be monitored. Pipe and ground temperatures should be monitored at several points along the test section.

Test heads and other piping which have not been backfilled should be adequately sheltered and heated. The heat sources should not be in direct contact with piping.

In ambient conditions below 0°C (32°F), hydraulic instrumentation lines must be filled carefully with antifreeze to purge out any air and water, hence preventing the line from freezing off. Installation of the instrument line should be as per Figure D-1 and D-2 sketches. If the pressure begins to fluctuate, freezing is indicated and the lines must be cleared. Ensure that valves on the test head remain in the open position, otherwise if the heat supply fails, water isolated between the closed valve and blind flange will freeze and burst the valve body.

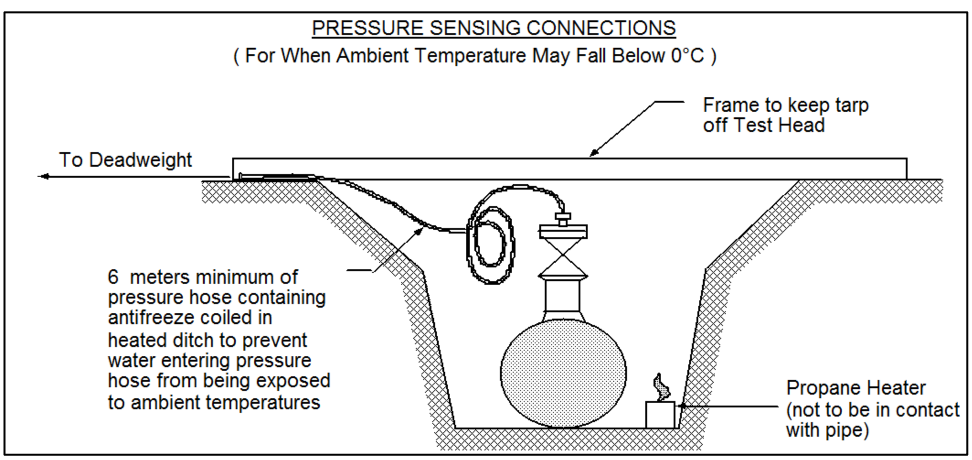

Figure D-1. Winter Testing - Pressure Sensing Connections

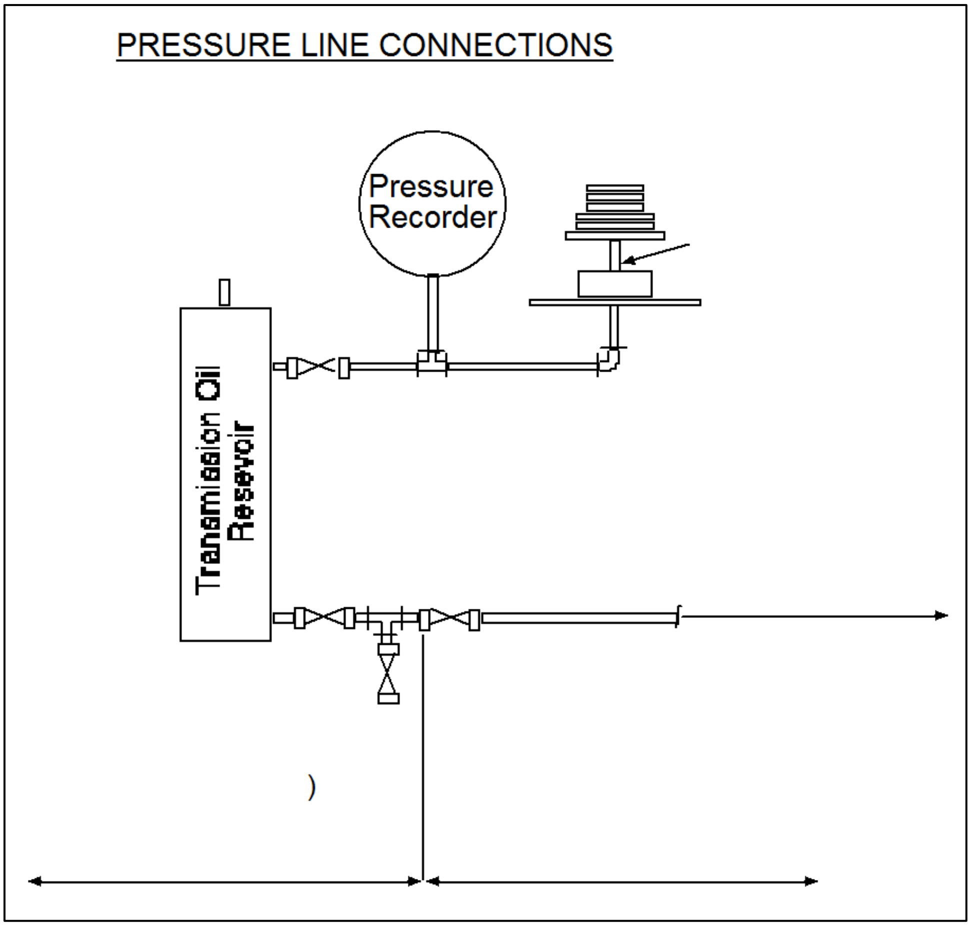

Figure D-2. Winter Testing - Pressure Line Connections

Filling with Water - Winter Mainline

To prevent water from freezing in the pipeline during winter mainline testing, it is necessary that warm water be passed through the test section. This warm water passage is required to melt the frozen ground surrounding the pipe, thus providing a heat sink. Following warm water passage, the size of the melted area surrounding the pipe will begin to decrease.

Water should be passed through the section to a site previously identified as acceptable to the Company, landowner, and regulatory authorities. During water passage an energy absorbing diffuser should be installed on the discharge line to prevent erosion, bottom scour or damage to vegetation.

Two methods of warm water passage used to obtain the desired water, pipe and ground temperature are illustrated in Figures D-3 and D-4.

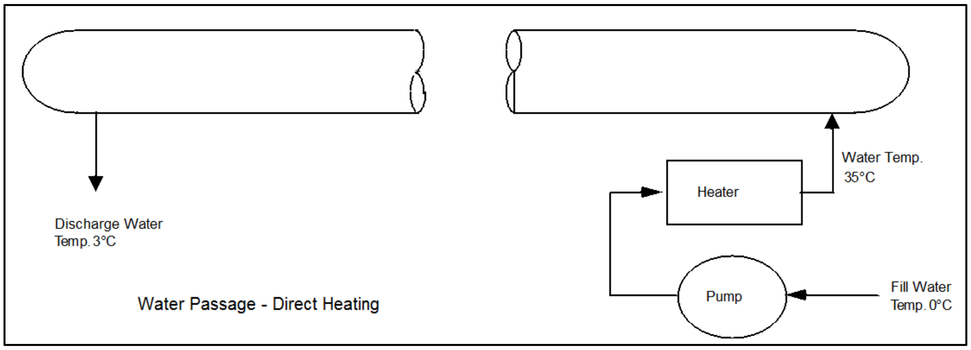

Figure D-3. Water Passage - Winter Testing

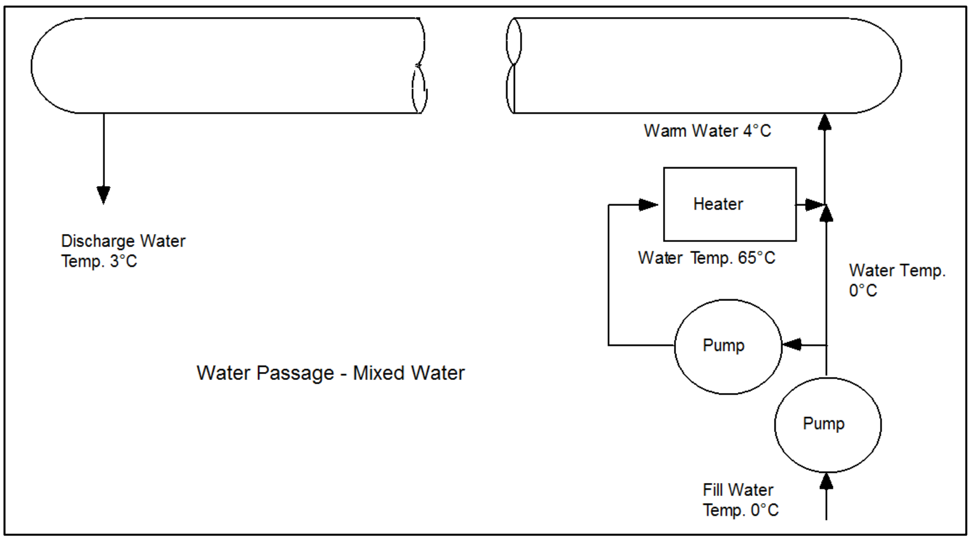

Figure D-4. Water Passage - Winter Testing

The capacity of the heater must be sufficient to provide warm water (temperature greater than 10°C) to the test head at a fill rate of approximately 7,000 L/Minute. The heater should have a capacity of between 14 and 20 million BTU's output.

The initial 10% of the fill water consisting of a blend of warm and cold water must be pumped into the mainline at a temperature of 35°C or greater. Thereafter, the fill water blend is to be added to the mainline at a minimum temperature of 4°C as illustrated in Figure D-4.

Water should be passed through the test section until a discharge temperature greater than 3°C has been achieved for a minimum of two hours following discharge of the initial 10% volume.

Temperature Stabilization - Winter Mainline

Temperature stabilization is not required for winter testing operations. During filling operations, the test water is heated to an adequate stabilized temperature, hence eliminating the need to stabilize.

Dewatering - Winter Mainline

Provisions should be made so that dewatering of the pipeline may be conducted readily to prevent freezing of the water. Such dewatering may be necessary as in the case of delays due to equipment failure or line rupture under test.

Drying - Winter Mainline

A minimum of two drying runs should be made immediately following the dewatering operation.

Secondary Winter Testing Procedure - Example

Winter secondary testing is defined as where ambient temperatures require secondary tests to be conducted in a heated enclosure.

Auxiliary Heating - Winter Secondary

Test heads and all exposed piping should be fully enclosed in a heated framed structure, such that the piping is uniformly heated. The structure should be constructed in such a manner as to facilitate visual inspection.

The heat should be supplied starting the day prior to filling the section and the heat sources should not be in direct contact with the piping.

Dewatering Winter Secondary Tests

All water should be removed immediately following completion of the test.