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INTENTIONAL DESTRUCTIVE TESTING: A MEANS FOR ESTABLISHING MECHANICAL INTEGRITY IN PLANTS, FACILITIES, AND PIPELINES

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ABSTRACT

Operators of plants, facilities, and pipelines have at their disposal multiple resources for evaluating the integrity of identified features and anomalies. With advances in inspection technology, industry is being called upon to evaluate an ever-increasing number of features. When a feature is identified as a threat and severe enough to warrant repair or replacement, operators are faced with sometimes significant costs.

In this paper the authors provide guidance on the benefits associated with full-scale testing for evaluating mechanical integrity, referred to Intentional Destructive Testing (IDT). Unlike many analysis techniques that require the development and implementation of assumed operating and boundary conditions, well-designed IDT programs are able to replicate in situ conditions to provide operators with a clear understanding regarding the behavior of anomalies and their response to simulated operating conditions. Case studies are included to demonstrate the merits of the IDT approach. In using IDT, operators have improved confidence in predicting the behavior of identified features to ensure that maintenance resources are properly allocated for either continuing operation or repairing anomalies.

NOMENCLATURE

FEA	Finite element analysis
IDT	Intentional destructive testing
ILI	In-line inspection tool
IMP	Integrity Management Program
MAOP	Maximum Allowable Operating Pressure
SMYS	Specified Minimum Yield Strength

INTRODUCTION

At the core of integrity management is the need to ensure the safe operation of pipeline systems. There are obviously numerous means for addressing the needs associated with this central requirement, several of which include studying historical trends and failure patterns, numerical modeling, and full-scale testing. From a statistical standpoint, as the age of a given pipeline increases the likelihood for deterioration of the system also increases. As a result, the importance of understanding the present and future behavior of an aging pipeline becomes even more critical.

In recent days the authors have observed an increased interest in pipeline operators requesting that full-scale testing be performed to predict future performance of pipeline materials and existing anomalies such as dents in welds, wrinkle bends, crack-like flaws in seam welds, pipe fittings such as wyes, elbows, and branch connections, and vintage girth welds. The central driver behind this trend is that operators need to assess the integrity of their pipeline system in a manner than cannot be achieved using an analysis-only (i.e. numerical modeling) approach. The consequence of failure for transmission pipelines is too high to risk the potential for errors and possible lack of conservatism associated with unknowns in a numerical model. In a similar manner, analyses methods that are overly-conservative will generate unnecessary remediation activities. This is likely to create other problems such as over-digging and not focusing on the major problems in a pipeline.

A well-organized and executed testing program can provide significant insights into the performance of a pipeline, both present and future. As part of this effort, readers are encouraged to consider the following benefits in pursuing testing as a means for evaluating mechanical integrity.

- It is possible to organize a testing program that represents future service conditions for a pipeline. As an example, one can apply pressure cycles to a given sample to represent 20 years of future service prior to performing a burst test on a known flaw. In this manner, the testing organization is able to provide the operator with a snapshot of how their pipe material might perform at some future date.
- Most analyses required some consideration of a range of input variables, typically involving material properties and behavior. Because of the potential for variability at the input level, one must bound analysis problems to ensure that both the upper and lower bound responses have been captured. This invariably leads to reduced confidence in results. If one is to integrate selected tests into a study of this type, the overall uncertainty of the analysis work is reduced and greater confidence in predicting the behavior of the pipe is achieved when using numerical models.
- Testing can also be used to validate numerical models and improve confidence in analysis results. Typically, several well-designed tests can accompany a wide range of numerical models.

The purpose of this paper is to provide guidance for the pipeline industry in how testing, primarily full-scale destructive testing, can enhance and improve integrity management efforts. The organization of this paper includes discussions on testing methods, types of testing, case studies based on prior work, integrating analysis and testing results, and lastly a discussion on guidance in using testing as part of an engineering-based integrity management program.

TYPES AND METHODS OF TESTING

In order to discuss the value in testing it is obviously important to consider types of testing and how they are used to evaluate pipeline performance. The sections that follow include discussions on the following types of tests:

- Burst tests
- Cyclic pressure testing
- Bend testing
- Simulated damage creation

Discussions include how the tests are performed (i.e. testing methods) and what is learned in performing each test. On occasion different tests are combined to better represent actual service conditions. An example is to subject a pipeline test sample to cyclic pressures for a specified number of cycles (e.g. number of cycles representing a 20 year service life) prior to performing a burst test. This in effect provides a snapshot of the future burst capacity of the pipeline corresponding to the designated future service period.

Burst Tests

As the name implies, burst tests involve taking a test sample all the way to failure due to pressure overload. The benefit in doing so is to determine the ultimate pressure capacity of a given piece of pipe. Of equal importance is to determine the reduction in strength associated with given defects such as a crack-like flaw in a seam weld or a plain dent with corrosion.

Prior to going to failure, it is often beneficial to perform pressure holds at levels corresponding to the operating pressure of the pipeline as well as the pressure associated with the SMYS. Strain gages are also useful for providing strain in anomalies such as corrosion or a dent.

Pressure Cycle Fatigue Testing

Over the years the authors have performed hundreds of pressure cycle tests. Often the purpose in testing has been to destructively test a sample via fatigue having known defects or flaws. Another trend that has been frequent as of late is the use of pressure cycling to introduce cumulative damage prior to actually performing a burst test. This is a useful and powerful technique for providing an operator with an understanding about how a pipeline might perform at some future date. This “pre-burst” pressure cycle fatigue steps includes the following steps.

1. Estimate the number of pressure cycles expected in a given period of time (e.g. 20 years) as well as the associated pressure ranges.
2. Use a rainflow counting technique to determine a single equivalent pressure range (details provided in discussion below) using actual pressure data from a compressor or pump station. Both cycle counting (e.g., rain-flow) and a damage rule (e.g., Miner’s Rule) are required to define a single equivalent pressure range.
3. If the testing is not intended to be destructive, but rather representative of future pressure service, determine the appropriate number of cycles to apply to the sample. Several options exist
    a. Number of cycles based on actual expected conditions.
    b. To account for the standard deviations in fatigue test results, multiply the expected number of actual cycles by a factor. Typical factors range from 10 to 20, where latter is the basis for the fatigue design curves in Section VIII, Division 2 of the ASME Boiler & Pressure Code. The safety factors on cycle number are typically associated with high-strain low cycle conditions, whereas the safety factor on stress amplitude refers to the high-cycle regime.
4. Apply the selected cyclic pressure conditions to the test pipe. It is possible to accelerate the rate of testing using a larger pressure range (i.e. reduce time required to complete tests). Miner’s Rule can then be used to correlate the applied number of cycles to account for different pressure ranges. As a point of reference, using a 4th order relationship between stress and cycles to failure, a single cycle at ΔP=100% MAOP is equivalent to 16 cycles at ΔP=50% MAOP.

A rainflow counting technique is useful for developing a single pressure range based on actual pressure history. Figure 1 provides data from a prior study where the operator provided historical pressure data for a one year period. These data were used as input into a rainflow counting package to generate the histogram shown in Figure 2. From the collected pressure range bins and associated frequencies, a single equivalent pressure range was determined using Miner’s Rule for ΔP=1,140 psi (7.9 MPa). Figure 2 shows results associated with the development of the histogram and the single equivalent pressure range. The random nature of the actual pressure data can be converted into a single equivalent pressure range that can then be applied to the pipe sample during testing. Consider the table provided in Figure 2 a 4th order relationship is assumed between stress and cycles as expressed in the following relation based on Miner’s Rule.

$$\mathrm{N}_{\Delta P} = N_{1140}\left[\frac{1140\,psi}{\Delta P}\right]^4 \qquad (1)$$

In this equation N is the number of respective cycles and ΔP is the applied pressure range in units of psi. For each pressure range captured from the rainflow counting exercise (and shown in the histogram in Figure 2) a new equivalent cycle number is generated for the 1,140 psi (7.9 MPa) pressure range. As noted in this table provided in Figure 2, the sum of all resulting cycles generates a single equivalent pressure cycle. Therefore, from the random pressure data presented in Figure 1, a single equivalent cycle number of 69 is generated assuming an alternating pressure of 1,140 psi (7.9 MPa) as presented in the table in Figure 2.

Bend Testing

Bending is always part of offshore pipeline work, whether it is at the installation level or subsea accounting for responses to operating loads such as thermal buckling; however, bending can also be an issue for onshore pipelines when considering the effects of terrain, land movement, earthquakes, and mudslides. In addition to introducing bending loads, tests can simultaneously introduce the effects of internal pressure and axial tension or compression.

Because of safety concerns, bending tests often do not involve testing to rupture. Rather, bending loads are applied until a plastic collapse condition is reached and the limit state load is defined (i.e. the point where the pipe can take no more appreciable loading). Strain gages are typically used in bend testing to provide feedback on the level of strain introduced into the test sample and to identify the plastic collapse load. A case study is presented that provides results for a bend test used to quantify the level of reinforcement provided to defective girth welds reinforced with composite materials.

Simulated Damage Creation

Although a fair portion of work performed by the authors and their firm have involved testing actual defective pipe materials removed from the field, efforts are also required to simulate damage using laboratory means. Besides the obvious inclusion of applying excessive loads during tests (i.e. pressure, tension, and bending) to introduce failure, the defects most often simulated during testing include corrosion, plain dents, and mechanical damage.

Figure 3 shows the set-up for testing done to generate mechanical damage in 12.75-inch (324 mm) diameter pipe material. To inflict damage a gouge was generated by forcing a back-hoe tooth into the sample that was simultaneously pulled, during which pressure was maintained in the sample at 70% SMYS. Figure 4 shows the geometry for the three back-hoe teeth as well as a photograph of one of the simulated defects.

Whenever simulated data is created, it is important to ensure that the damage imparted to the pipe is representative of actual conditions as much as reasonably possible. This might require the use of numerical modeling using either finite element analysis (FEA) or fracture mechanics. An example is using FEA prior to indenting a test sample to determine the geometry of an indenter needed to achieve a certain dent profile.

CASE STUDIES

The best means for demonstrating the effectiveness of IDT as a means for assessing mechanical integrity is providing several case studies. The case studies included in this paper provided details on studies actually conducted for pipeline operators. An important consideration for the information presented herein is that several of these case studies were used to convey to government regulators the soundness of the pipeline in question. In effect these tests became part of integrity management program packages that assisted operators in defending their proposed courses of action.

The presentations that follow for each of the case studies contain the following elements:

1. Purpose of test
2. Type of test
3. Implications of results.

Destructive Testing Vintage Pipe with Crack-like Features

As part of their integrity management program (IMP), an operator of a 16-inch diameter propane pipeline identified the presence of seam features during a magnetic flux leakage in-line inspection run. Using a combination of fatigue and burst testing, the pressure capacity of pipe material removed from service was determined using three samples. Prior to burst testing, the test samples were pressure cycled 3,100 times at a pressure range of 45 percent SMYS. Considering a moderately aggressive pressure spectrum, this corresponds to approximately 20 years of service for this particular pipeline system.

Of the three burst tests that were performed, the minimum burst pressure that occurred was 2,129 psi, which corresponds to 148 percent of the yield pressure and translates to a hoop stress of 68,128 psi. Figure 5 is a photograph showing the hydrostatic test rupture in Sample #1; note the location of the longitudinal seam weld that occurred outside the failure. Table 1 lists the test pressure results for all three burst samples.

Post-failure metallurgical evaluation showed that no failures occurred in the weld seam and that none of the seam weld features contributed to the pressure failures. Additionally, there was no evidence that corrosion or fatigue contributed to the rupture origins or that failures occurred due to deficiencies in material properties.

The implications for the operator of this propane pipeline associated with the results of this study provided a framework for making future decisions on the operation of this line. Additionally, the consistent test results provided greater confidence in the proposed continued operation of the line. Even though seam weld features were identified by ILI, the test results showed that the magnitudes of burst pressure were acceptable for the continued operation of the pipeline. Furthermore, the pre-burst cycling effort provided the operator with a "snapshot" of what future performance could be expected.

Reinforcement of Vintage Girth Welds

Girth welds are an essential part of every transmission pipeline. With much of the current pipeline system in the United States having been installed prior to 1970, concerns exist with some pipeline companies regarding the integrity of vintage girth welds. While it is true that the failure rate in the United States attributed to vintage girth welds (based on information reported to the authorities) has not been widespread, operators recognize that they cannot be complacent as their infrastructure ages and that they should continue to search for alternatives to conventional repair and replacement options that will continue to ensure integrity.

For this reason, a study was conducted to evaluate the use of composite materials in reinforcing girth welds. Co-participants in this study included five composite repair manufacturers that currently market products and systems for reinforcing pipelines with anomalies and defects. These manufacturers made financial contributions, donated materials, and provided personnel who completed repair installations on their respective test samples.

The program involved the reinforcement of 12.75-inch x 0.188-inch, Grade X42 pipe samples with defective girth welds that did not include a root pass (i.e., simulated lack of penetration weld defects) as shown in Figure 6. Each manufacturer was responsible for repairing three pipe samples that included one tension-to-failure sample, one tension-to-failure sample with a reduced bonding area, and a bending-to-failure sample. Additionally, two unreinforced pipe samples with defective girth welds were tested (i.e., tension-to-failure and bending-to-failure samples) to provide a baseline data set to which results for the reinforced samples could be compared.

Prior to the destructive tension and bending tests, all reinforced samples were subjected to 18,000 pressure cycles ranging from 445 psi to 890 psi (36% SMYS to 72% SMYS). This condition approximates a 20-year service life for gas pipelines, assuming an aggressive pressure condition with 889 cycles per year at a stress range of 36% SMYS. For each test to failure, an internal pressure of 445 psi (36% SMYS) was held constant during testing.

During bend testing, all five of the composite reinforced systems performed well in the sense that the initial level of distortion in the pipe occurred outside of the reinforcement. These results demonstrate that the stiffness of the reinforced sections are not only greater than the base pipe, but of sufficient magnitude to ensure that wrinkles form outside a composite-reinforced section when subjected to bending loads. Figure 7 includes photographs of the unreinforced bend sample, including a cross-section of the weld after failure. The sample shown in this figure was subjected to increasing bending loads until a failure occurred.

When considering the performance of the composite reinforcing systems, there were some differences in the results for the tension-to-failure samples. The unreinforced tension sample failed at a tension load of 293 kips. Considering the reinforced tension samples with full bonding areas, the reinforced samples had tension-to-failure loads ranging from 433 to 481 kips. The repair using Product C was able to achieve a maximum tension load of 522 kips with failure occurring in the base pipe near a welded bosset outside the repair, as shown in Figure 8. A plot of tensile load versus deflection for all five of the tested systems is shown in Figure 9. The results presented in this plot only include loads applied by the load frame; whereas the tension values presented above include the presence of pressure end loads.

The results of this program demonstrated that, when properly designed and installed, composite materials reduce hoop and axial strains in girth welds and increase the limit-state capacities under combinations of pressure, tension, and bending loads. Thus, these systems provide pipeline operators with a reinforcing method to improve the reliability and integrity of pipelines having defective girth welds.

Burst Testing of Long Radius Elbow

Questions were posed regarding the integrity of elbows purchased for use in a proposed jet fuel hydrant system. The system was expected to operate at a steady state pressure of 150 psi with maximum surge pressures of 50 psi (i.e. maximum expected pressure of 200 psi). A burst test was performed on a 16-in x 0.375-in, Grade WPB 90° long radius elbow. As shown in Figure 10, locations for seven strains gages were selected to maximize the number of measurements in the elbow, but also monitor strain in the attached piping. Figure 11 is a photograph the installed strain gage on the intrados of the bend.

The burst test included 5 minute pressure holds at 72% SMYS (1,181 psi) and 100% SMYS (1,640 psi). Strain gage readings were taken at a rate of 1 scan per second continuously during the duration of the test. After the two pressure holds, the test assembly was pressurized to failure where a maximum pressure of 3,094 psi was achieved. The failure in the test assembly did not occur in the long radius elbow, but took place in one of the attached pipe segments as shown in Figure 12. It appeared, based on strain gage readings, that the pipe material likely had a lower yield than the material used in the elbow.

The following observations were made in reviewing the strain gage results:

- The hoop strain readings at Locations #3 and #6 had the lowest recorded strains and were the last to demonstrate yielding. This is consistent with the mechanics for long radius elbows where hoop stresses at the extrados are 75% of the nominal hoop stress, whereas stresses in the intrados are 125% of the nominal value (assuming the same wall thickness for all regions).
- The strain readings for the intrados gages (Locations #1 and #4) are consistent in that they track together. It is also noted that above 2,500 psi internal pressure, the strains in the intrados are less than those measured along the elbow's neutral axis (Locations #2 and #5) and the base pipe (Location #7); a fact noted due to the thicker intrados (i.e. the average thickness at the intrados was 11 percent more than the nominal elbow wall thickness of 0.375 inches).

Considering that a maximum pressure of 3,094 psi was reached in the test assembly, a safety factor of 15.5 exists on burst when assuming a maximum operating pressure of 200 psi. This program, although relatively simple to execute, was effective in confirming the integrity of the elbows in question and providing the operator confidence that the quality of the purchased elbows was sufficient for their intended service.

ENGINEERING BASED INTEGRTY MANAGEMENT

The prior discussion provides a good example of how analysis and testing can be integrated to provide improved confidence in analysis results. The greatest contribution when considering numerical modeling techniques is the development of *grading tools* for quantitatively assessing pipeline damage. At the present time there are several areas of interest for pipeline operators where the development of these types of tools will be of significant benefit. Figure 13 is a flow chart that shows the central elements involved in developing an Engineering-Based Integrity Management Program (EB-IMP). As noted, analysis and testing methods work hand-in-hand to facilitate the development of tools that can be used by operators to evaluate the level of criticality associated with a particular defect or anomaly.

Based on discussion with pipeline operators, there are several areas of concern that pose threats to the integrity of pipeline systems. A grading tool could be developed for each of the following defect types in association with an EB-IMP.

- Plain dents
- Dent in girth and seam welds
- Rock dents
- Vintage girth welds
- Seam welds (with detected crack-like flaws)
- Wrinkle bends
- Effects of composite materials in increasing the burst capacity and fatigue strength of any of the above

To ensure the validity of any tool that is developed, both analysis and testing are required. At the outset of any project whose intent is to develop a grading tool, it is essential that planning be conducted to maximize information gained from collected results. Of particular note is the fact that significant savings can be realized in conducting select tests to validate specific numerical models as opposed to conducting an extensive array of full-scale tests. Proper planning increases the likelihood that a useful grading tool will be developed.

CONCLUSIONS

This paper has provided details on how IDT full-scale testing methods can be used by pipeline operators to gain understanding about how pipelines respond to loading conditions that can lead to failure. By understanding how pipelines fail, operators are better-positioned to identify/understand which defects are of most concern and what margins of safety actually exist in operating a pipeline. While numerical modeling is useful for understanding the general response of pipe materials, it is unwise to solely rely on guidance based on analytical findings when the opportunity for full-scale testing is an option. As has been demonstrated herein, when tests are properly coordinated and planned, they can be used to validate numerical models and improve the overall confidence in grading tools.

In addition to validating numerical models, testing provides a powerful resource for assisting operators in predicting the future performance of pipelines. The most appropriate example based on information presented in this paper includes conducting full-scale burst tests on pipe samples that have been previously pressure cycled to simulate future service conditions.

It is hoped that the information in this paper will encourage and foster additional discussions among those in the pipeline industry. Because of the critical role that pipelines have in terms of the world-wide energy infrastructure, significant benefits are derived in conducting tests as part of an engineering-based integrity management program.

REFERENCES

1. Alexander, C. R. and Worth, C., *Assessing the Use of Composite Materials in Repairing Mechanical Damage In Transmission Pipelines*, Proceedings of the 6th International Pipeline Conference, Paper No. IPC2006-10482, Calgary, Alberta, Canada, September 2006.
2. Alexander, C. R. and Francini., *State of the Art Assessment of Composite Systems Used to Repair Transmission Pipelines*, Proceedings of the 6th International Pipeline Conference, Paper No. IPC2006-10484, Calgary, Alberta, Canada, September 2006.
3. Alexander, C. R., *Evaluating the Use of Composite Materials in Reinforcing Offshore Risers Using Full-scale Testing Methods*, Proceedings of the ASME International Offshore Pipeline Forum, Paper No. IOPF2007-104, Houston, Texas, USA, October 2007.
4. Alexander, C., and Jorritsma, E., *A Systematic Approach for Evaluating Dent Severity in a Liquid Transmission Pipeline System,* Proceedings of IPC2010 (Paper No. IPC2010-31538), 8th International Pipeline Conference, September 27 – October 1, 2010, Calgary, Alberta, Canada.
5. Dotson, R.L., Ginten, M., Alexander, C.R., Bedoya, J.J., and Schroeer, K., *Combining High Resolution In-Line Geometry Tools and Finite Element Analysis to Improve Dent Assessments*, PPIM-ILI2-16, Pipeline Pigging & Integrity Management Conference, Houston, Texas, February 10-13, 2014.

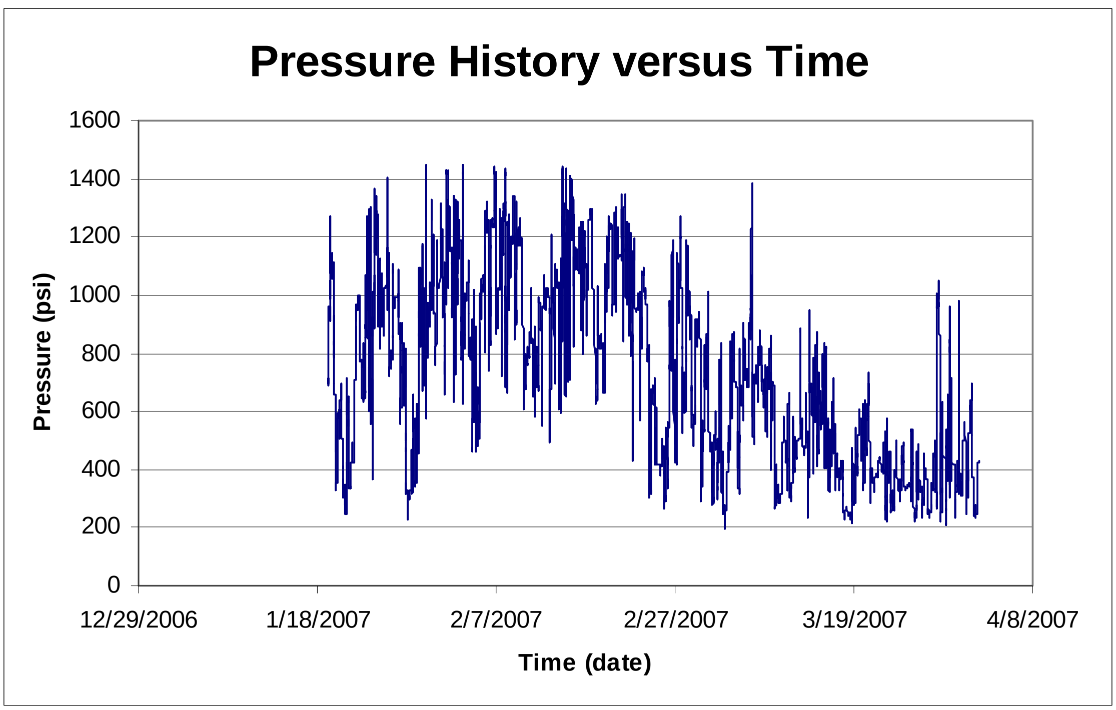
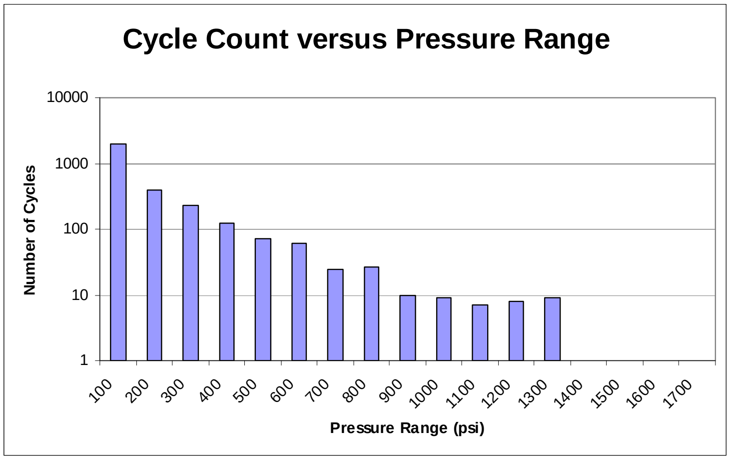


Figure 1 – Pressure history from actual liquid pipeline



Pressure Range Bin (psi)	Frequency	1140 psi Pressure Equivalent	Equivalent Cycle Number
100	2010	0.000	0
200	398	0.001	0
300	230	0.005	1
400	125	0.015	2
500	73	0.037	3
600	60	0.077	5
700	24	0.142	3
800	27	0.243	7
900	10	0.388	4
1000	9	0.592	5
1100	7	0.867	6
1200	8	1.228	10
1300	9	1.691	15
1400	1	2.275	2
1500	1	2.997	3
1600	0	3.880	0
1700	0	4.945	0
More	0	TOTAL	66
		Annual TOTAL	69

Figure 2 – Development of the histogram and single equivalent pressure range
(The average pressure range for this particular pipeline was identified as 1,140 psi)

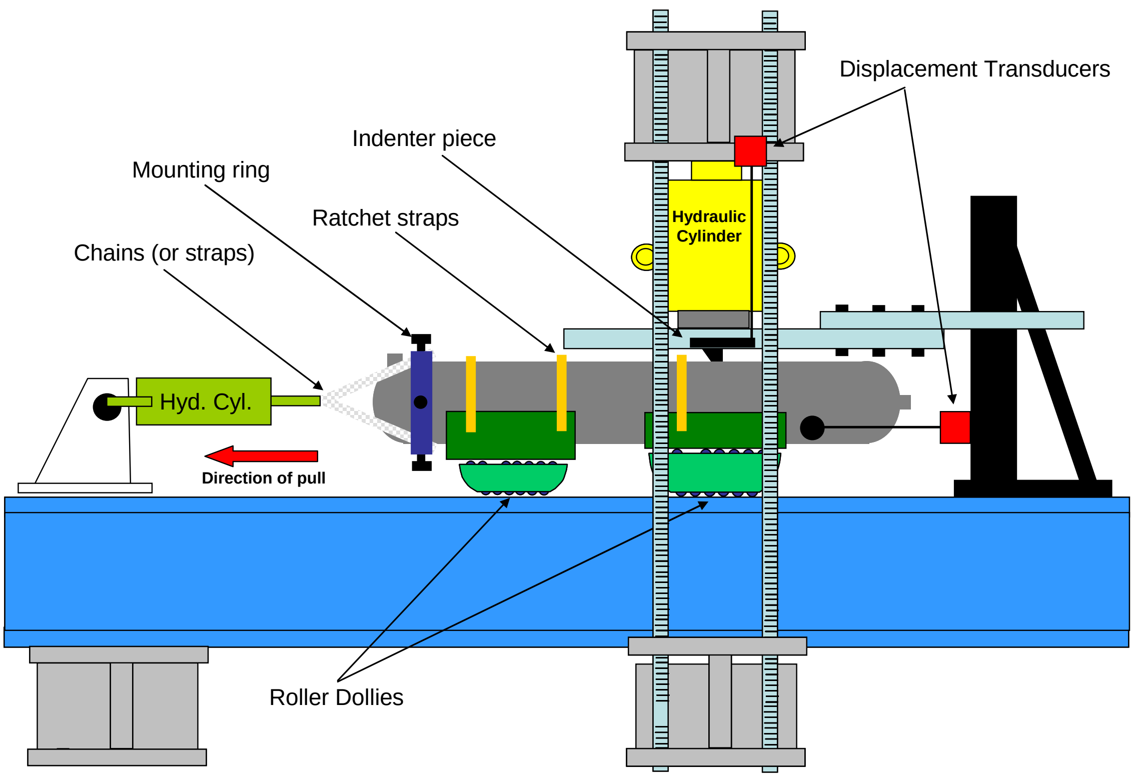


Figure 3 – Schematic of set-up used to generate mechanical damage in pipe samples

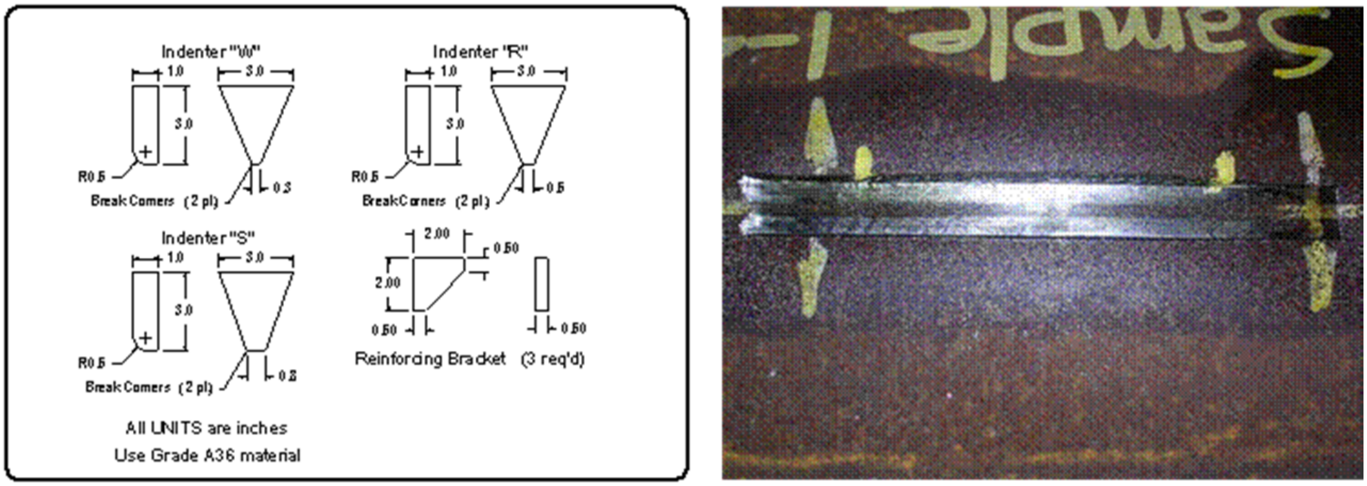


Figure 4 – Geometry of indenter teeth and resulting damage
(Drawings at left show indenter geometries and photo at right shows the resulting damage inflicted to the pipe)

Figure 5 - Hydrostatic test rupture in Sample #1
The location of the longitudinal seam weld is also shown.

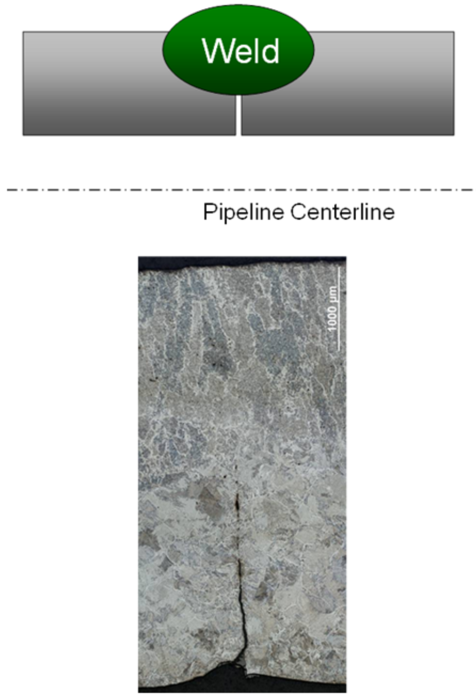


Figure 6 – Cross-section of simulated vintage girth weld with lack of penetration

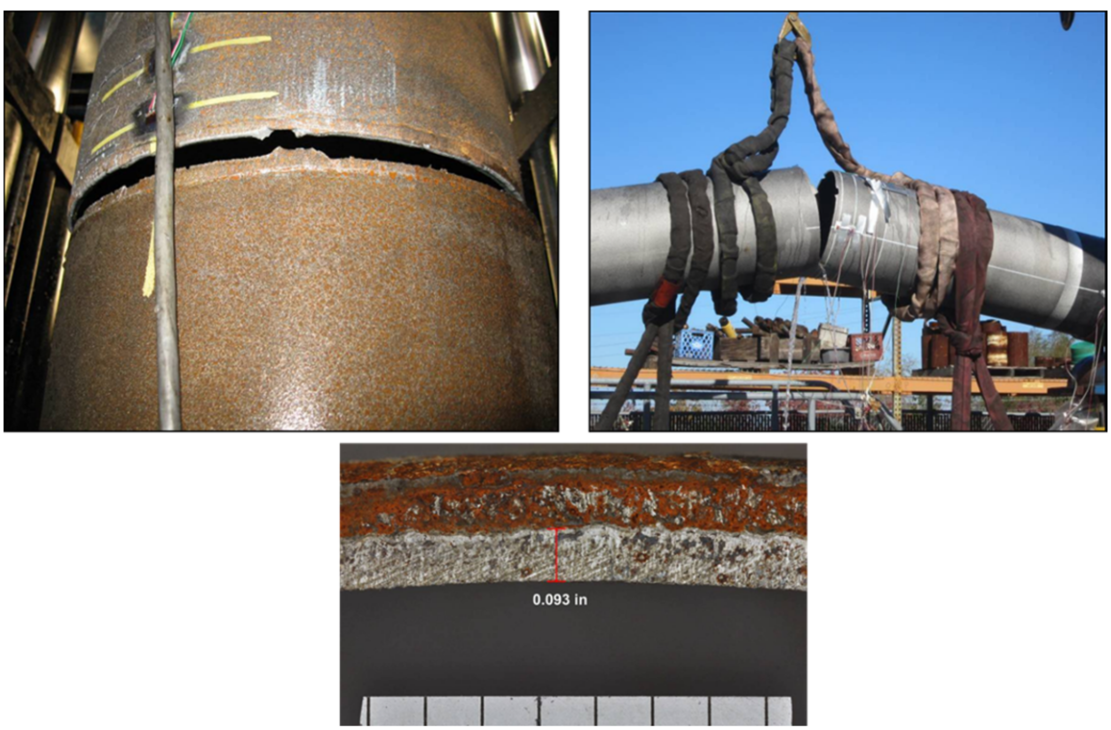


Figure 7 – Bend test results for unreinforced test sample

Sample prior to testing in tension

Failure in tension sample

Figure 8 – Photograph of failure in Product C test sample

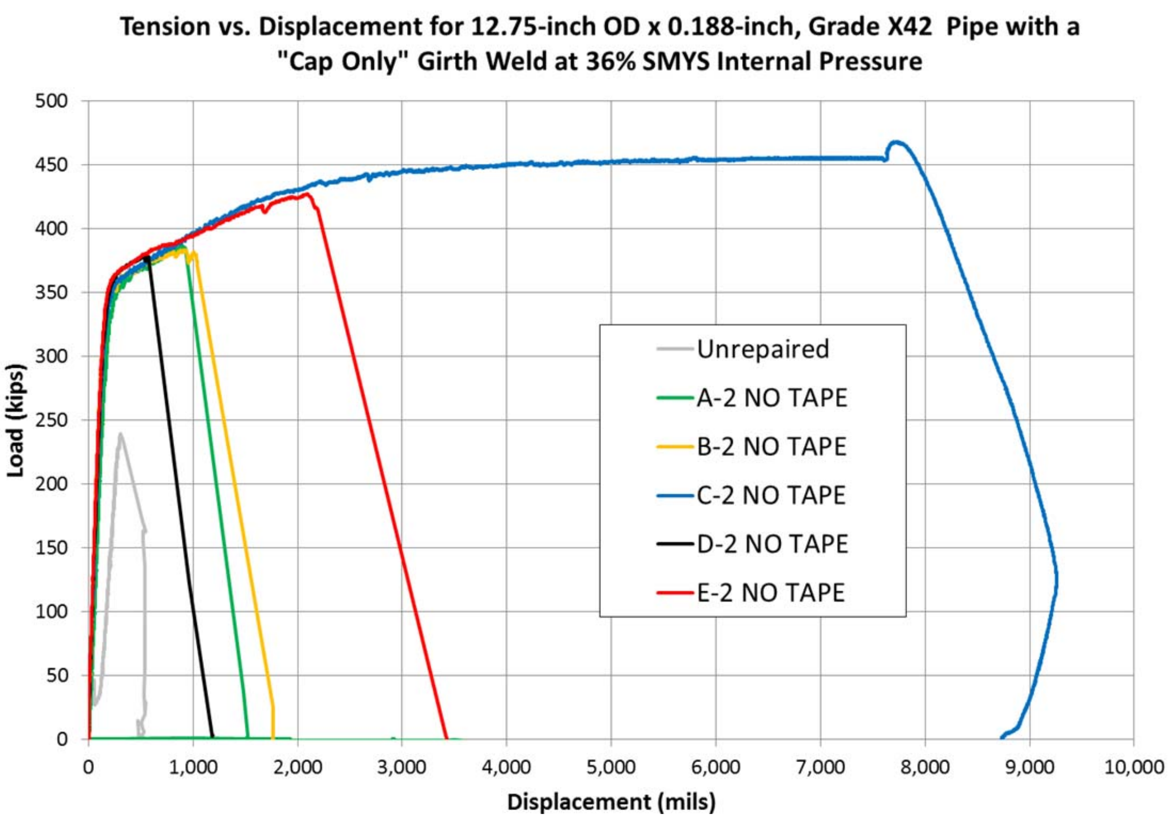


Figure 9 – Load versus deflection for vintage girth weld samples
(Results presented above <u>do not include</u> pressure end loads; actual failure loads are greater)

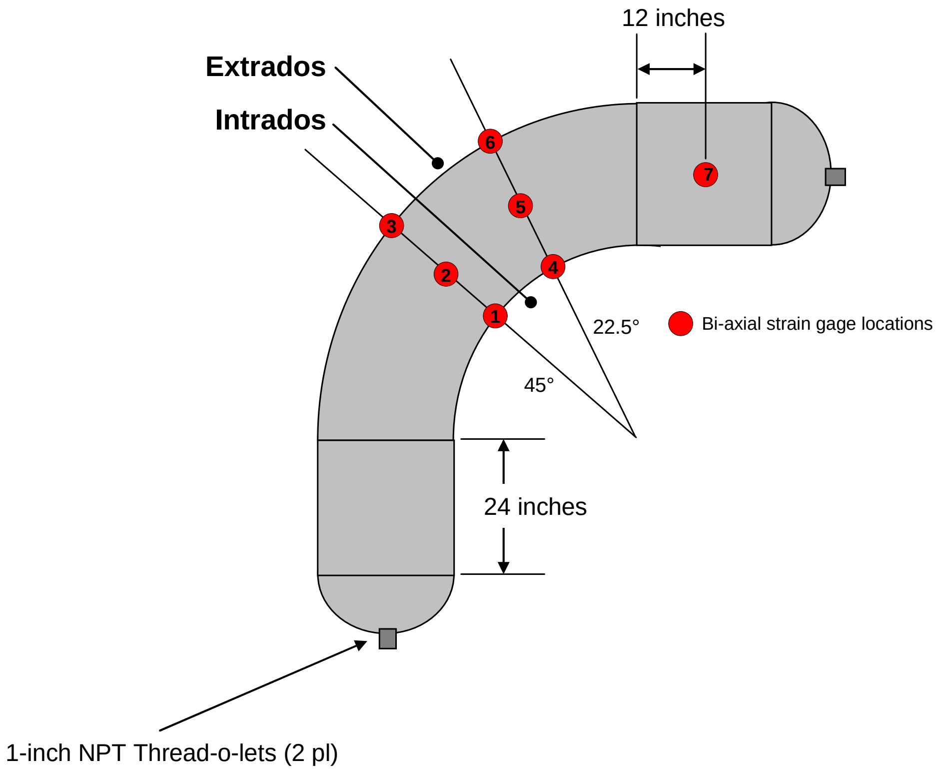


Figure 10 – Strain gage locations on welded elbow assembly

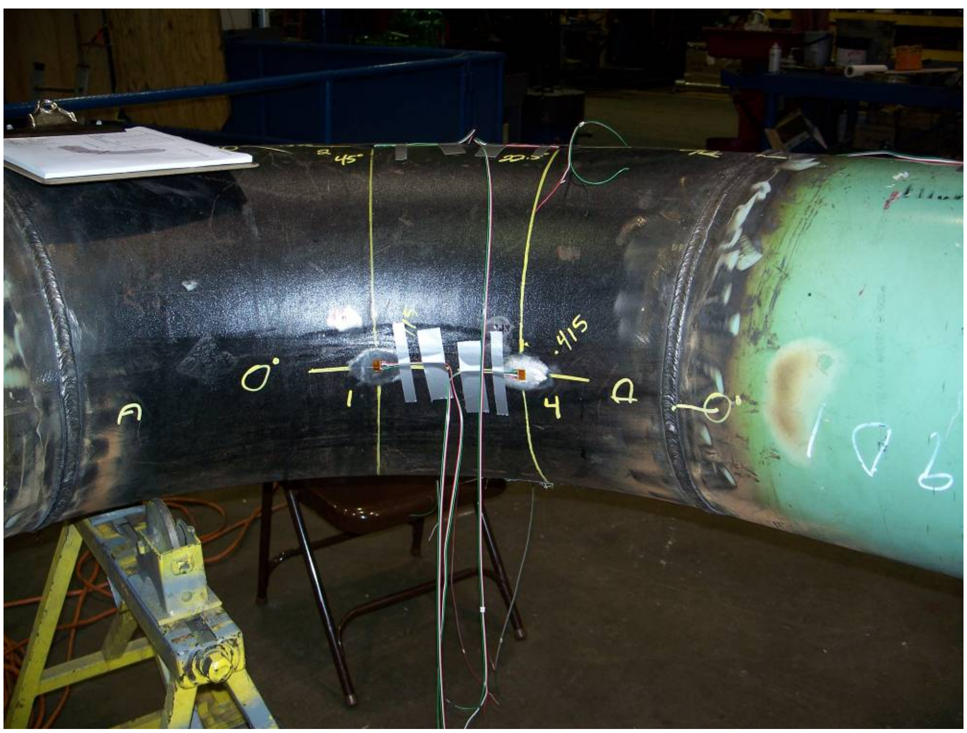


Figure 11 – Photograph of strain gages being installed on the elbow test assembly

Figure 12 – Photograph of the elbow after burst testing

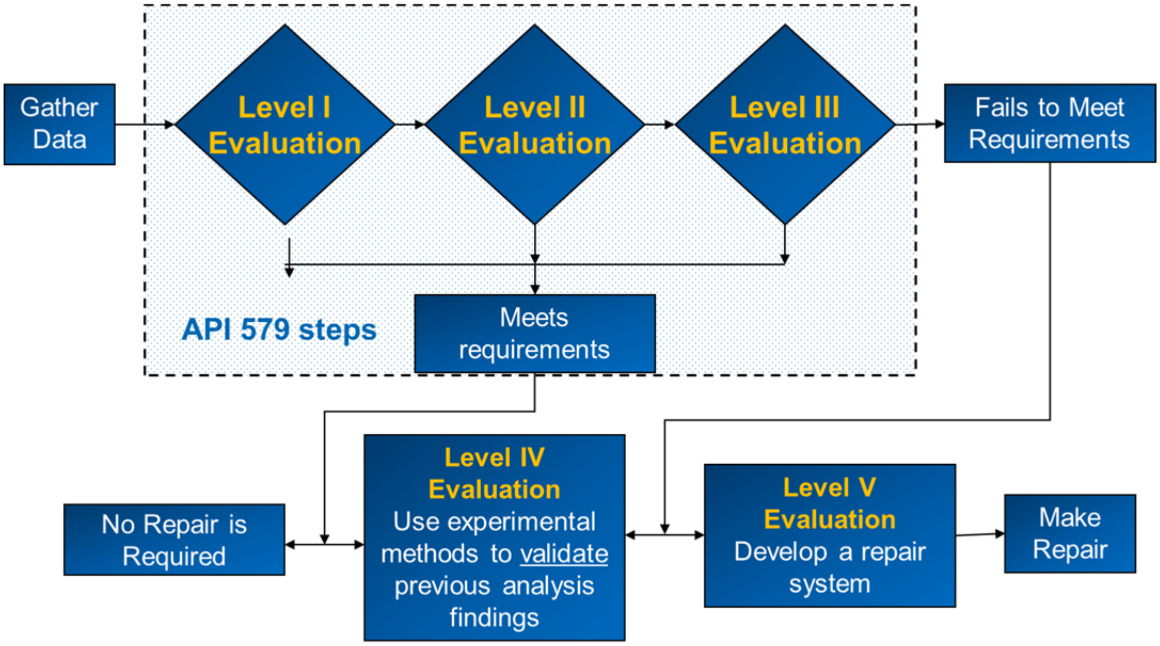


Figure 13 – Flow chart for the Five Step Engineering-Based Integrity Management Program

Table 1 – Test pressure results for the three burst samples

Sample	Maximum Pressure	Percent SMYS (P_{max} / P_{yield})	Failure Stress ($P_{max}R/t$)
Sample #1	2,164 psi	150.4%	69,248 psi
Sample #2	2,379 psi	165.4%	76,128 psi
Sample #3	2,129 psi	148.1%	68,128 psi