Final Report for Phase II of the Comprehensive Study to Understand Longitudinal ERW Seam Failures

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Executive Summary

On November 1, 2007 a liquid propane pipeline operated by Dixie Pipeline Company ruptured near Carmichael, Mississippi, which several pipeline industry experts collaboratively indicated the origin was likely a defect in the longitudinal Electric Resistance Welded (ERW) seam, with the ensuing fracture running along that joint into portions of the adjacent pipes. These experts also noted that a seam-integrity assessment did not prevent the failure, as this failure came 2 years after an in-line inspection (ILI) with a sophisticated crack-detection tool; and 23 years after a hydrostatic test to a hoop stress level greater than 1.25 times the maximum operating hoop stress level. Following the National Transportation Safety Board's (NTSB) public report, the NTSB issued Recommendation P-09-1, which called upon the Department of Transportation Pipeline and Hazardous Material Safety Administration (DOT-PHMSA) to conduct a comprehensive study to identify actions that can be used by operators to eliminate catastrophic longitudinal seam failures in pipe, and indicated the required scope. This led to the PHMSA-issued research announcement (RA) that targeted Recommendation P-09-1 in the form of Broad Agency Announcement (BAA) Solicitation DTPH56-11-RA-000001. That Solicitation sought a Comprehensive Understanding of Longitudinal ERW Seam Failures.

In response to that Solicitation, Battelle, as the prime contractor, proposed a two-phase project to work to develop the understanding sought by the research announcement in resolving Recommendation P-09-1.

The Phase I final report along with numerous interim reports for both Phase I and Phase II can be found at the following website: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390.

This report focuses on the results obtained during the work completed under Phase II. Summary of results and recommendations from the five task reports will be presented. This information is broken into the following areas:

- Improve Hydrotesting Protocols for ERW/FW Seams (Phase II - Task 1)
- Enhance Defect Detection and Sizing via Inspection (Phase II - Task 2)
- Defect Characterization: Types, Sizes, & Shapes (Phase II - Task 3)
- Develop and Refine Predictive Models and Quantify Growth Mechanisms (Phase II - Task 4)
- Develop Management Tools: Manual, Software, Protocols, and Training (Phase II - Task 5)
- Public Outreach

While detailed conclusions are provided in each section, the major conclusions from each of the areas are summarized in the following list.

- Spike Pressure of 100% to 110% SMYS is sufficient to fail flaw sizes commensurate with the pipe grade (SMYS) and expected ERW toughness (Charpy)
- There is no benefit of reduced hydrotest failures, via the simulations, by reducing the simulated spike time from 30 minutes to 10 minutes.
- X80 tends to be more sensitive to the pressure during the simulated hydrostatic test than X42. With low Charpy energy, the hydrostatic test considerations of 100% SMYS and 110% SMYS provide failures with lower crack dimensions as compared to the X42. *This is due to the absolute stress driving the failure rather than the relative stress to SMYS. (i.e. 110% of 80 ksi is 88 ksi which is 8 ksi over the X80 SMYS while 110 % of 42 ksi is 46.2 ksi which is only 4.2 ksi over the X42 SMYS)*
- X80 tends to be more sensitive to the growth rate in the simulated fatigue analyses. As compared to X42, for a given profile (as % SMYS), the X80 tends to have accelerated crack growth due to a larger absolute stress intensity range. *This is due to the absolute stress driving the failure rather than the relative stress to SMYS.*

- Electromagnetic acoustic transducer (EMAT) technologies performed to their reported crack detection specification[1] even with challenging seam flaws in uneven trim and/or connected to underlying laminations. This specification was met despite each tool missing one crack, which not only existed in uneven trim but also hovered just above the service provider's minimum size threshold.

    - EMAT depth calls were found to be typically within +/- 25% if the seam crack was detected *and* shallower than 70% nominal wall thickness (NWT). Near through wall features (90%+ NWT) were typically sized 15 to 40% shallower than reality. However, in these scenarios crack depths of 50% NWT or deeper were still reported by EMAT for these severe cracks.

    - EMAT depth call accuracy appeared independent of crack length as features became longer. Note that all cracks in this study were shorter than 6 inches.

- As for identifying a seam crack's precise location (i.e. denoting if a crack is in a ERW weld bondline, heat affected zone, or body), gathering that particular insight from inline inspection (ILI) is not developed at this time. Current EMAT ILI resolution restricts this specific identification ability, with limited sensor size and frequency being the major driving factor.

- While it is generally accepted that magnetic flux leakage (MFL) technology is not well suited for detection and sizing of all cracks types, MFL still has a suitable role in crack inspection; when paired with EMAT, it commonly is used as a screening tool for identifying the long seam and pipe fabrication processes and also aides in discriminating crack-like anomalies from seam variations such as excess trim. MFL can also be used independently for "crack-like" anomalies that are sufficiently open and have a metal loss volume, which is not uncommon for certain hook cracks, for example. Transverse MFL is meant for long, narrow, axially oriented metal loss or these crack-like anomalies with volume.

    - In general, MFL undersized the long-seam anomalies in this study. In the case of near-through wall cracks, MFL severely undersized them, reporting 30% nominal wall thickness (NWT) depths when in reality they exist at 90%+. Therefore, additional conservatism may be required for dig criteria and fatigue analysis when using this method.

    - As for identifying a seam crack's precise location (in bondline, HAZ, or body), gathering that particular insight from ILI is not developed at

[1] Depending on the EMAT tool, the minimum crack length for 90% POD confidence varied from 1-inch to 1.97-inches. Minimum depth varied from 0.04-inch to 20% of wall thickness.

this time. Current EMAT ILI resolution restricts this specific identification ability, with limited sensor size and frequency being the major driving factor.

- Investigation revealed that magnetic particle inspection (MPI) and shear wave can be unreliable, as it twice falsely reported near-through-wall features where no crack existed. Trim tool markings and human error are suspected source of error in these incidents.

    - It is strongly recommended that MPI and shear wave ultrasonic (UT) approach not be used alone to locate and then size significant longitudinal seam cracks. That is, if shear wave reports near through-wall features, it may be advisable to verify with another technology in the event that the call is a false positive similar to those witnessed here.

    - It is recommended to take caution when sizing seam anomalies with complex alignment (e.g. uneven trim or flash, ID/OD misalignment) only with single beam shear wave. This was the reported cause of error on a critical false positive (i.e. a crack was reported as nearly through wall deep reported but later deemed non-existent in reality) observed in this limited subset of cracks.

- Investigation of full matrix capture inspection performance versus actual fracture sizes of anomalies showed encouraging improvements from the two generations employed under this study. The 2016 version tested correctly identified the majority of crack and lamination geometries (e.g. denoting cold weld versus hook crack versus lamination). This was the best defect characterization of tools employed in this study. Although minor, those misinterpreted geometries were falsely calling hook cracks and stringers as cold welds.

- As for anomaly sizing, full matrix capture was the most accurate of technologies employed. It sized 14 of the 16 simple flaws (i.e., not overlapped with a lamination) lengths within +/- 0.5”. However, the remaining two were fairly large outliers as they were under sized by an average of 1.7inches in length. Of these outliers, one was a stringer (#13) and the other a hook crack (#15). With respect to depth sizing, 13 of 16 simple flaws were sized within +/-16%. The remaining three flaws were oversized in depth by approximately 30% to 55% and were either stringers or hook cracks. Even with these outliers, the overall sizing accuracy was viewed as generally reliable.

- Full Matrix Capture (i.e. the IWEX system) can characterize crack type, which could then be used to infer most likely crack location. That is, a true cold weld will be located along the bondline. Hook cracks are generally contained in the HAZ, although they can extend to the bondline and pipe body. How far they extend into the pipe body depends on the extent of the inclusion or lamination that curved up to form the hook crack.

- The two deepest cracks collected were hydrostatically tested until they began to leak. However, they re-sealed upon de-pressurization. Subsequent metallography indicated that post-weld repairs were completed at these cold welds and executed without post-weld heat treatment (PWHT). Without PWHT, weld residual stress remains in the part, which is typically neglected in failure assessment software for buried oil and gas pipelines (i.e. ERW longitudinal welds typically undergo PWHT at the mill). Therefore, with no PWHT and a weld repair at the cracks' locations, these two experimental burst tests are not appropriate validation cases for PipeAssess PI™ and other failure pressure prediction models.

- Overall, nearly two dozen crack geometries were modeled with finite element methods and their Stress Intensity Factor (SIF) solutions joined among themselves and smoothly transitioned to construct a full solution set.

- Each SIF set went through a manual screening for outliers. They were corrected with guidance from SIF values in the proximity or in some cases API 579's SIF solution set. In this process, corrections were also verified to not disrupt the monotonically increasing or decreasing K slope behavior, whichever was the case.

- The stress intensity factor results were based on more than 2000 finite element solutions that examined various crack geometries (length, depth, internal, external), various corrosion geometries, (pit geometry, symmetric and asymmetric general corrosion), and various weld cap heights. In spite of the richness of the data set, there are still limitations (which are considered conservative with respect to failure pressure) which are enumerated as:

    - The multiple crack solution uses single crack SIFs and the BS 7910 Fitness-for-Service coalescence interaction rules,

    - The hook crack solutions are built from the API579 Fitness-for-Service radially-oriented embedded flaw solution and fracture mechanics considerations,

    - Hook cracks are considered linear approximations rather than actual curved of the hook-cracks,

- Models were validated to data such as;

    - Net-section collapse and fracture-based tearing models were validated to historical full-scale test results.

  - Stress-induced creep models were validated based on historical laboratory test data.
  - Analytical fatigue models were validated based on both laboratory and full-scale tests

- Variability and accuracy of inputs into the failure calculations significantly effects the outputs, thus
  - Safety factors on output should be commensurate with the pedigree of the data used to generate the results
  - The best data availability should be used in the calculations (i.e. the local properties in the location of the crack; bond line, heat-affected zone, pipe body…etc.)
  - If data are not available, conservative assumptions for inputs should be made to ensure conservative calculations
- An integrity management software solution was developed for ERW Axial Seam weld analysis. A version of the software was delivered to the DOT PHMSA as "a Government Use Version". Appendix A of the interim report for Phase II, Task 5 contains the User's Manual.
- In the investigator's opinion, as shown in Figure 1,
  - PipeAssess PI™ results are less conservatively bias than the other models
  - PipeAssess PI™ results more accurately represent the mean value of the experimental data
  - PipeAssess PI™ results show similar variability between prediction and actual failure pressure to other methods (Legacy and API)
  - the similarity in the variability in the output, for all the models shown, comes from the uncertainty in the input parameters

Contents

Commonly Used Acronyms within Phase II

ABI	Automated Ball Indentation
API	American Petroleum Institute
ASTM	American Society of Testing and Materials
BAA	Broad Agency Announcement
CCP	Center Cracked Panel
C-MFL	Circumferential Magnetic Flux Leakage
COD	Crack Opening Displacement
CVN	Charpy V-Notch Toughness
CW	Cold Weld
DOT	Department of Transportation
EMAT	Electromagnetic Acoustic Transducer
ERW	Electric Resistance Welded
FMC	Full Matrix Capture
FW	Flash Welded
HAZ	Heat Affected Zone
HC	Hook Crack
HC/UFI	Hook Crack or Upturned-Fiber Imperfection
HF	High Frequency
ID	Inner Diameter
ID	Inner Diameter
ILI	Inline Inspection
ITDM	In-the-Ditch Method(s)
IWEX	Inverse Wave Field Extrapolation
J-R	Curve of J_{mat} versus Δa
KAI	Kiefner and Associates, Inc.
LF	Low Frequency
MAOP	Maximum Allowable Operating Pressure
MDS	Multiple Dataset Platform (i.e. a TDW ILI product)
MFL	Magnetic Flux Leakage
MOP	Maximum Operating Pressure
MPI	Magnetic Penetrant Inspection
MT	Magnetic Penetrant Inspection (Certification Acronym)
MWM	Meandering Winding Magnetometer

N/A	No Correlated Anomaly Reported
NACE	National Association of Corrosion Engineers
NDE	Non-Destructive Evaluation
NPS	Nominal Pipe Size
NTSB	National Transportation Safety Board
NWT	Nominal Wall Thickness
OD	Outer Diameter
OD	Outer Diameter
OES	Optical Emission Spectrometer
PAUT	Phased Array Ultrasonic
PCB	Polychlorinated Biphenyls
PHMSA	Pipeline and Hazardous Material Safety Administration
PipeAssess PI™	Battelle's Cracking Assessment for Pipeline Software
PMI	Positive Material Identification
POD	Probability of Detection
POI	Probability of Identification
R&D	Research and Development
RA	Research Announcement
RoCD^2	Rosen's Crack Detection and Coating Disbondment (i.e. a Rosen ILI product)
R-ratio	Stress Ratio of minimum stress divided by maximum stress
SEN	Single Edge Notch
SIF	Stress Intensity Factor
S-MFL	Spiral Magnetic Flux Leakage
SMYS	Specified Minimum Yield Stress
SSWC	Selective Seam Weld Corrosion
SWA	Seam Weld Anomaly
TDW	T.D.Williamson, Inc.
TFM	Total Focusing Method
TOFD	Time of Fight Diffraction
TW	Through-Wall
UT	Ultrasonic
UTS	Ultimate Tensile Strength
WT	Wall Thickness
YS	Yield Strength

Introduction

Work under Phase I followed a scope identified from National Transportation Safety Board (NTSB) Recommendation P-09-1 that developed understanding of longitudinal Electric Resistance Welded (ERW) seam failures by: 1) generating a database that quantified the industry and Government experience in regard to hydrotest and in-service failures, 2) completing a full-scale project that empirically quantified ERW seam failure behavior and resistance, and 3) developing technology to assess susceptibility to selective seam corrosion. Phase II [1] builds on that understanding by establishing the viability of pipeline monitoring technology that relies on hydrotesting, in-line non-destructive inspection, and in-the-ditch nondestructive inspection along with the development of the engineering tools to translate condition into metrics of defect severity and re-inspection interval specific to ERW seam defects. Viability in all aspects were assessed and demonstrated through use of full-scale burst tests that address the range of defects characteristics via the database developed in the initial phase of this of project. Management tools were developed for use by pipeline operators as part of their integrity management plan to help assure that their ERW pipelines are safe.

This report will recapitulate the conclusions and recommendations of the five task areas in Phase II, as well as, discuss the public outreach information conducted as part of this study.

Improve Hydrotesting Protocols for ERW/FW Seams

Overview

The details of this task (Phase II, Task 1) can be found in the report along with its attachments and appendices located at the following website: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390.

This task analyzed various crack geometries under various loading conditions, including hydrostatic testing and fatigue, to investigate hydrostatic testing protocols. Based on the results of these analyses, compare and contrast scenarios were defined to elucidate the recommendations provided. Three major crack types were investigated to ensure the recommended protocol met spirit of the competing outcomes: cold weld, hook, and selective seam weld corrosion with cracking. The selection of hydrotest test pressure (spike and hold), along with the corresponding hold times, is neither obvious nor simple. The values that were considered the "best" must satisfy conflicting desired outcomes. On one hand, the desire was to remove all flaws which are near critical or which will become critical over some operational time (i.e. operational pressure and fatigue). The counter desire was to limit the flaw growth during hydrotesting so that existing flaws will not become critical over the same operational time [2,3]. Numerous papers at the 2016 ASME IPC conference were focused on hydrostatic testing or pressure over-loads to retard crack growth. These papers are listed as reference [4-11].

The operational assumption for the overall strategy was that the pipeline operator had just inspected the pipe using ILI, In-The-Ditch methods (ITDM), or both. Based on the knowledge of the flaws located in the line, the operator would then attempt a hydrostatic test, either as part of a general procedure or as part of the procedure for the replacement of a segment of pipe found to have a critical flaw. The overall objective of this assessment was to determine an optimized procedure which would expose near-critical flaws during the hydrotest, while minimizing the growth of pre-existing flaws. To determine hypothetical survivability between inspections and/or hydrotests (i.e. ensure pre-existing flaws do not become critical), hypothetical fatigue scenarios [12] over a period of five years were conducted after the simulated hydrostatic test. At the end of the fatigue scenario, a comparison of the failure pressure using the hypothetical crack size after flaw growth to the Maximum Allowable Operating Pressure (MAOP) (i.e. 72% of the Specified Minimum Yield Strength (SMYS)) was conducted. If the failure pressure was greater than MAOP, the crack was characterized as "survived", otherwise, it was characterized as "failed after fatigue". If the crack fails during the original hydrotest, the crack was characterized as "failed during hydrotest" [3].

Conclusions and Recommendations

Based on the results of this study conducted in Phase II, Task 1 and the information in Reference [3] , the following conclusions are established from the study conducted:

- Certain crack sizes were judged to be invalid for modeling analyses a-priori due to their inability to survive at 72% SYMS. This assumption affects the fatigue analyses due to the fact the analyses is only focused on crack sizes that would not failure during operations, rather than hypothetical cracks that would grow in fatigue, but would not survive the 72% SMYS pressure.

- Spike Pressure of 100% to 110% SMYS is sufficient to fail flaw sizes commensurate with the pipe grade (SMYS) and expected ERW toughness (Charpy)

  - Small to intermediate flaws (i.e. below the ILI detection limit) are predicted to fail when Charpy impact energy values are less than 4 ft-lb (i.e. low toughness weld bondlines)

  - Large flaws are predicted to fail when Charpy impact energy values are as high as 15 ft-lbs. For example, for X80, a 35% through-wall flaw that is 2-inches long would fail a hydrostatic test of 110% SMYS for the spile pressure, with 90% SMYS for the hold pressure.

  Via modeling simulations, there is no apparent benefit of reducing the simulated spike time from 30 minutes to 10 minutes. If failure occurs, it tends to occur early in the spike test and if any crack growth occurs during the first 30 minutes, it is small enough not to effect the results in fatigue. Practical considerations in the field need to be considered before limiting the spike test to 10-minutes such as pressure stabilization throughout the test segment.

- Crack geometry plays an important role in consideration of hydrostatic testing. While a given size hook crack may be benign to pressures up to 72% SMYS, once the crack becomes surface breaking, the driving force for a given pressure could be an order of magnitude greater.

- The definition of a "very aggressive" fatigue profile is ambiguous in the context of these analyses. While the "very aggressive" fatigue spectrum is well defined in

Reference [12], the use of this spectrum coupled with the threshold stress intensity model [13], the effective R-ratio model [14], and the crack tip overload model [15] seems to reduce the aggressiveness of the spectra.

- With the model[2] application of fatigue cycles being applied post-hydrotest for 5 years:
    - Model predictions indicate that a Spike Pressure of 100% to 110% SMYS creates a sufficient plastic zone size to retard fatigue growth for most crack-like defects. (Spike pressure data was not generated for pressures less than 100% SMYS; however, the hold pressures for leak check were conducted at 90% SMYS – 1.25*72% SMYS.)
    - With the very-aggressive hypothetical fatigue spectrum, crack growth occurred, and fatigue failures were predicted for only very short, deep cracks within the 5 years of simulated analyses time.
- X80 tends to be more sensitive to the pressure during the simulated hydrostatic test than X42. With low Charpy energy, the hydrostatic test considerations of 100% SMYS and 110% SMYS provide failures with lower crack dimensions as compared to the X42. *This is due to the absolute stress driving the failure rather than the relative stress to SMYS. (i.e. 110% of 80 ksi is 88 ksi which is 8 ksi over the X80 SMYS while 110 % of 42 ksi is 46.2 ksi which is only 4.2 ksi over the X42 SMYS)*
- X80 tends to be more sensitive to the growth rate in the simulated fatigue analyses. As compared to X42, for a given profile (as % SMYS), the X80 tends to have accelerated crack growth due to a larger absolute stress intensity range. *This is due to the absolute stress driving the failure rather than the relative stress to SMYS.*

[2] Using PipeAssess PI™

- For a hook crack of the same depth as a cold weld crack with assumed equal Charpy impact energy value, the hook crack has a lower stress intensity factor, thus is expected to survive a more aggressive hydrotest than a similar cold weld crack.

- For a SSWC crack of the same depth as a cold weld crack, with assumed equal Charpy impact energy values, the SSWC crack has a higher stress intensity factor, thus is prone to failure at a less aggressive hydrotest than a similar cold weld crack.

While the conclusions provided are beneficial, additional considerations should be undertaken and understood when completing hydrostatic tests. The study was conducted assuming a MOP or MAOP of 72% SMYS, but for pipelines being operated at an MAOP much less than 72% SMYS, additional factors should be considered beyond the guidance provided here (i.e. valve and tap locations where pressure ratings are lowered).
Other considerations should include:

- Practical considerations should be undertaken to understand the realistic time to conduct a spike test as well as account for thermal expansion (i.e. the need to add or bleed water) in field applications.

- To ensure adequate leak detection, leak checks should be conducted (i.e. after spike test) at 90% of SYMS for up to 24 hours.

- Variation in terrain should be considered when designing the hydrotest, as should the length of the test section. Changes in elevation may require more frequent and shorter test sections.

- As part of this study, active corrosion growth (i.e. pitting, stress corrosion cracking, or selective seam-weld corrosion), was not considered as part of this analysis for the post-hydrotest investigation.

While the research outlined in this report was intended to be a comprehensive study to understand longitudinal ERW seam failure, consideration of future work on the hydrotest protocols beyond the work completed as part of Phase II, Task 1 may be warranted. The work conducted herein relied on data that had been developed for specific material grades. While most grades have been studied, and time dependent Ramberg-Osgood parameters have been identified, there are still gaps in the data. One of these gaps is the lack of stress-induced creep data within the industry for Grade B, Grade X60, and Grade X65 pipe. Another one of these gaps is in the interaction between cracking and other anomalies such as corrosion pits and / or dents.

Enhance Defect Detection and Sizing via Inspection

Overview

The details of this task (Phase II, Task 2) can be found in an interim report and its attachments and appendices located at the following website:
https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390.

This task is an extension of the 2013 Phase I, Task 2 task, in which the executive summary is reported in reference [16] as the long seam anomalies collected at that time lacked variety (i.e., vast majority were cold welds or mill anomalies), and they were later found to lack the necessary severity as all but one burst test failed above SMYS. This limited variety and lack of failure below SMYS stagnated the progress of the project's assessment model development, evaluation of inspection technologies, and experimental verification. Therefore, a second collection of field anomalies was initiated in late 2013 and was more successful as a variety of seam weld anomalies (i.e., cold weld, hook cracks, stress corrosion cracking, laminations) were acquired, some with significant size. These anomalies are the focus of this task report and subject of ILI, ITDM, and destructive inspection.

Testing and validating ILI and ITDM inspection tools provide unique challenges, which were recognized and mitigated early in the task. First, the inspection methods under test were also the means of identifying anomalies for validation. Therefore, if a crack was present but was not reported by any inspection technique, its existence and therefore the false negative reporting went undocumented. This limitation was recognized and mitigated in the test plan; many different inspection techniques were tested and the program primarily focused on the larger indications collected. It was therefore assumed that a consequential crack-like anomaly in the seam was seen by at least one of the five inspection technologies employed. The second challenge revolved around the objective to collect representative seam anomalies from the field. The dilemma was the sequence of events: one cannot ensure the anomaly population is representative until the pipe collection period is closed and testing complete, at which point it is typically too late to search for additional anomalies if deemed necessary. This was a natural limitation of the Phase I work and was improved upon in this Phase II effort. After due diligence, a broad range of crack types and depths ranging all the way to 99% through-wall cold welds to the onset of stress corrosion cracking were successfully collected. In total over 2,500 feet of pipe was acquired, and the pipe contained nearly 90 crack-like anomalies 25% deep or greater. Of those features nineteen (19) anomaly sets were then selected for validation. Two of the anomalies were discovered to be false positives, which is when a crack detected with a non-destructive technique is subsequently found not to exist. Shear wave originally reported these two flaws' depths as near through wall, but the remaining inspection technologies were in overwhelming consensus that no seam crack existed in these locations. This included both EMAT and MFL ILI as well as PAUT, TOFD, and IWEX. These false positives left seventeen (17) anomalies to undergo full destructive evaluation via a pressure test and/or standard metallography. This validation subset included both cold welds and hook cracks as well as isolated features and those within close proximity to one another and/or directly adjoined to a lamination. While all features were obtained from pipe which was once in-service, two of the cold welds were found to be particularly uncommon; they appeared to be mill repairs of leaking cold welds detected by the mill hydrotest, which is no longer acceptable post the 1940s war era.

Regardless, this task successfully acquired a broad range of seam anomalies that were representative of the field in varying sizes and geometries.

One of the key benefits of this research was providing inspection technologies and service providers the opportunity to improve their analytical analyses and/or hardware if desired. This was done by providing each technology multiple rounds to inspect and also access to truth data via destructive testing, which is rarely available in the field. Knowledge gained and immediate improvements were quickly observed in this program. For example, one ITDM technology showcased noticeable improvements among their different inspection rounds, and one ILI technology was able to re-review their data and locate three anomalies not previously reported. It is expected that the inspection service providers will use these results for further advancement of their technology, each of which is anticipated to be proprietary.

As technologies are continually evolving, this report should be considered a snapshot in time of their performance. The inspections themselves and their reporting took place between 2014 and early 2016. Also note the assessment of available technologies was not exhaustive in this program, as many more ILI and ITDM technologies are available than were tested. Furthermore, analysis of the data provided by ILI and ITDM technologies is a manual process; the differences in interpretation of results (i.e. Human Factors) were not part of this study.

Conclusions and Recommendations

Locating sizable seam cracks pulled from field LF-ERW pipe for R&D proved to be a challenge, but after several years of collecting pipe, nearly 90 seam cracks deeper than 25% NWT were acquired. They represent a broad spectrum of crack geometries including cold welds, hook cracks, stress corrosion cracking, and laminations. The largest number of the flaws existed in 16-inch nominal diameter pipe and those that were the most severe flaws were installed into a 300-ft long simulated pipeline for multiple ILI assessments. A total of five different ITDM technologies and two different ILI technologies were employed. ITDM were supplied by ApplusRTD and JENTEK, which included MPI with shear wave sizing, PAUT, TOFD, MWM Array, and Full Matrix Capture Ultrasonic Imaging. ILI technologies were supplied by ROSEN and TDW and included EMAT and MFL with flux lines that cross the seam weld. FMC technology was supplied by ApplusRTD with IWEX.

Among all the ITDM technologies tested, the primary focus was on IWEX, a Full Matrix Capture method. In most cases MPI, PAUT, TOFD, and IWEX sizing were reported together by the NDE service provider. That is, *one* crack size and location were reported despite using multiple NDE techniques. IWEX sizing was considered the most accurate by the provider and thereby was depended on for any ITDM discrepancies. This aligned with the task's objective to quickly characterize hundreds of cracks within the best of NDE ability before down-selecting cracks for ILI and destructive characterization. A limitation of this approach, however, was that it was not possible to evaluate performance differences between MPI with shear wave sizing, PAUT, and TOFD ITDMs. Overall, this did not dampen the ability to understand the current state of leading ILI and ITDM designed for crack-like anomalies.

Nineteen cracks were identified as ILI validation candidates and underwent metallography and fractography for confirmation of actual crack size and type. Although this anomaly subset is not large enough for statistically derived conclusions, valuable trends and observations can be drawn. They are as follows for each inspection technique:

Electromagnetic Acoustic Transducer (EMAT) Inline Inspection (ILI) for Longitudinal Seam Cracks

- EMAT technologies performed to their reported crack detection specification[3] even with challenging seam flaws in uneven trim and/or connected to underlying laminations. This specification was met despite each tool missing one crack, which not only existed in uneven trim but also hovered just above the service provider's minimum size threshold.

[3] Depending on the EMAT tool, the minimum crack length for 90% POD confidence varied from 1-inch to 1.97-inches. Minimum depth varied from 0.04-inch to 20% of wall thickness.

- In general, seam crack-like anomalies tend to be called slightly longer and shallower than reality by EMAT. 17 of 21 EMAT calls were overstated +0.4” to +4.7”. The remaining four seam calls were undersized in length:
    - Anomaly #9: an EMAT reported no crack while actual length 2.6 inches
    - Anomaly #10: an EMAT reported 1.7 inches while actually 1.8 inches long
    - Anomaly #15: an EMAT reported 1.7 inches while actually 3.7 inches long
    - Anomaly #15: a different EMAT tool reported 3.4 inches length while actually 3.7 inches
- EMAT depth calls were found to be typically within +/- 25% if the seam crack was detected *and* shallower than 70% NWT. Near through wall features (90%+ NWT) were typically sized 15 to 40% shallower than reality. In these scenarios notable depth (50% or more) was still reported by EMAT for these severe cracks.
- EMAT depth call accuracy appeared independent of crack length as features approached 4 inches long.
- EMAT length call accuracy generally increased as features became deeper and approached through-wall.
- As for identifying a seam crack’s precise location (in bondline, HAZ, or body), gathering that particular insight from ILI is not developed at this time. Current EMAT ILI resolution restricts this specific identification ability, with limited sensor size and frequency being the major driving factor.
- If complex trim (e.g. irregular, uneven, cut-ins) or ID/OD seam alignment is present or suspect, it is recommended to closely work with the ILI provider(s) as they may have prior, similar case studies as the pipeline in question to provide adjusted POD and sizing tolerances.

Magnetic Flux Leakage (MFL) Inline Inspection (ILI) for Longitudinal Seam Cracks

- While it is generally accepted that MFL technology is not well suited for detection and sizing of all cracks types, MFL still has a suitable role in crack inspection; when paired with EMAT, it commonly is used as a screening tool for identifying the long seam and pipe fabrication processes and also aides in discriminating crack-like anomalies from seam variations such as excess trim. MFL can also be used independently for “crack-like” anomalies that are sufficiently open and have a metal loss volume, which is not uncommon for certain hook cracks, for example. Transverse MFL is meant for long, narrow, axially oriented metal loss or these crack-like anomalies with volume.

- In general, MFL undersized the long-seam anomalies in this study. In the case of near-through wall cracks, MFL severely undersized them, reporting 30% NWT depths when in reality they exist at 90%+. Therefore, additional conservatism may be required for dig criteria and fatigue analysis when using this method.
- As for identifying a seam crack’s precise location (in bondline, HAZ, or body), gathering that particular insight from ILI is not developed at this time. Current EMAT ILI resolution restricts this specific identification ability, with limited sensor size and frequency being the major driving factor.

Magnetic Particle Inspection (MPI) and Ultrasonic (UT) In-the-Ditch Methods for Longitudinal Seam Cracks

- Investigation revealed that MPI and UT shear wave can be unreliable, as it twice falsely reported near-through-wall features where no crack existed. Trim tool markings and human error are suspected source of error in these incidents.
- It is strongly recommended that MPI and shear wave UT approach not be used alone to screen for longitudinal seam cracks.
- It is recommended to take caution when sizing seam anomalies with complex alignment (e.g. uneven trim or flash, ID/OD misalignment) only with single beam shear wave. This was the reported cause of error on a critical false positive (i.e. a crack was reported as nearly through wall deep reported but later deemed non-existent in reality) observed in this limited subset of cracks.

Full Matrix Capture (FMC) as Represented by IWEX for Longitudinal Seam Cracks

- Investigation of full matrix capture results showed encouraging improvements from the two generations employed under this study. The 2016 version tested correctly identified the majority of flaw geometries. This was the best defect characterization of tools employed in this study. Although minor, those misinterpreted geometries were falsely calling hook cracks and stringers as cold welds.

- As for anomaly sizing, full matrix capture was the most accurate of technologies employed. It sized 14 of the 16 simple flaws (i.e., not overlapped with a lamination) lengths within +/- 0.5”. However, the remaining two were fairly large outliers as they were under sized by an average of 1.7inches in length. Of these outliers one was a stringer (#13) and the other a hook crack (#15). With respect to depth sizing, 13 of 16 simple flaws were sized within +/-16%. The remaining three flaws were oversized by approximately 30% to 55% and were either stringers or hook cracks. Even with these outliers, the overall sizing accuracy was viewed as generally reliable.
- Full Matrix Capture (FMC) (i.e. IWEX) *depth* call accuracy increased as anomalies became longer and approached 4 inches long.
- Full Matrix Capture (i.e. IWEX) *length* calls tended to be undersized for features approximately 50% through-wall or shallower. The opposite trend was observed for deeper anomalies where FMC tended to overstate length.
- Full Matrix Capture (i.e. IWEX) can characterize crack type, which could then be used to infer most likely crack location. That is, a true cold weld will be located along the bondline. Hook cracks are generally contained in the HAZ, although they can extend to the bondline and pipe body. How far they extend into the pipe body depends on the extent of the inclusion or lamination that curved up to form the hook crack.

Hydrostatic Tests for Model Validation of Longitudinal Seam Cracks

- The two deepest cracks collected (#1 and #2) were hydrostatically tested to failure. Their re-sealing behavior upon de-pressurization and subsequent metallography indicated that post-weld repairs were completed at these cold welds and executed without post-weld heat treatment. Therefore, these experimental burst tests are not appropriate validation cases for PipeAssess PI™ and other failure pressure prediction models.

While results of each inspection method are compared herein, it is reasonable to expect ITDM to be capable of higher accuracy and precision than ILI. ILI is optimal for inspecting extended distances first and locating discrete sites for further, pinpointed evaluation via ITDM afterwards. ITDM and ILI are complementary inspection techniques in this manner.

Overall, ITDM and ILI technologies are evolving and maturing. For ITDM, IWEX exemplified considerable improvements with the two generations tested one year apart within this program. For ILI, considerable improvements were observed with the addition of EMAT tools for crack detection in pipe with diameters 16 inches and less as compared to MFL and liquid coupled UT ILI being the only tools available at the beginning of this program. Technology improvements are evident by comparing multiple generations of ILI on the same crack and also through ILI assessment reports over time. For instance, the 2013 Kiefner ILI track record report [17] showed that while these tools can find anomalies, some will be missed and sizing is not particularly accurate. Therefore, the probability of finding the few crack-like anomalies that would fail a hydrotest in an operating pipeline was low with 2013 ILI systems. This is becoming different with today’s technologies. Now, with commercial EMAT ILI tools available and field-experience growing, operators are beginning to have the ability to identify cracks that could potentially fail a hydrotest. EMAT technology can also detect smaller anomalies that would go undetected in a hydrotest and the sizing capability appears to be sufficient to dismiss these smaller anomalies from further investigation.

Defect Characterization: Types, Sizes, & Shapes

Overview

The details of information discussed in the section can be found in the Phase II, Task 3 report and its attachments and appendices located at the following website: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390.

This task characterized defect size and shape by defect type, defining a consistent basis to quantify these key inputs to the predictions of defect severity, and the timeline for operator response and re-inspection. The key parameter was the crack stress intensity factor (SIF) for typical ERW crack geometries. Because errors in depth can, in some cases, cause predictions of failure behavior to error by a factor of ten or more, this activity addresses the necessary accuracy for these parameters relative to their practical significance, from both an analytical and measurement perspective. Analytically, this activity addressed the fact that size and shape, as typically seen in the field, have been poorly represented by the library of stress intensity factors previously available in predictive models, by using finite element analysis to bridge this gap. Basically, new stress intensity factor solutions have been developed for pipe/defect geometries likely to be found in Flash Weld (FW) and Electric Resistance Weld (ERW) pipe, using advanced finite element analysis techniques (Phase II, Task 3 Report). This activity bridges the measurement gap relative to the how ILI and In-the-Ditch Methods (ITDM) must quantify and report size and shape to be useful in defect sensitivity analysis, identifying what sizing accuracy is needed, and the conditions under which adjacent axial planar defects interact.

The objective of this activity was to bridge technology gaps in defect characterization in regard to types, sizes, shapes, and analytical idealizations relevant to the FW and ERW processes by generating a catalogue of new stress intensity factor solutions for crack shapes and sizes likely to be encountered in FW and ERW pipe. This activity increases pipeline safety by critical improvements to the tools necessary to implement both ILI and hydrotesting, and demonstrating their viability. Realizing that autogenously generated upset-welds formed by FW, Low Frequency (LF) ERW and High Frequency (HF) ERW processes all share the same dependence on heat and pressure to create a forged bond line and lead to similar types of features, this activity will bridge the technology gaps in terms of two groups of effectively planar defects – located either in the bond line, the upset, or the Heat Affected Zone (HAZ). Activities have considered drivers for failure of each defect type, relative to how the weld-process, the steel, and the service conditions affect that failure. For purposes of improved predictive modeling, each defect type was characterized relative to its axial through-wall (TW) appearance as flat and planar (as for cold welds and simple hook cracks and selective seam weld corrosion (SSWC)) versus non-planar and complex (as occurs for other hook cracks and SSWC). SSWC can be further quantified relative to its transverse cross-section that reduces the net-section – either symmetrically or asymmetrically. Finally, this activity idealized each defect type relative to its local properties, and modes of failure, such that predictive models can be established along with improved/new test methods/practices. It was anticipated that a range of idealized geometries needed to capture reality from the simple through quite complex shapes observed.

Conclusions and Recommendations

Overall, nearly two dozen crack geometries were modeled with finite element methods and their stress intensity factor (SIF) solutions joined among themselves and smoothly transitioned to construct a full solution set. Joining occurred in two locations:

- First, finite and infinitely long cold weld solutions were merged to cover a wide range of crack lengths to ensure a continuous solution set as a given anomaly grows.
- Second, appropriate SSWC solutions were joined such that a general corrosion pit with no crack could smoothly evolve into the same pit but with a crack extending at the base of the pit. Smooth transitions were ensured at these interfaces as well as throughout the provided SIF data itself.

In some instances, the finite element method provided outliers that did not agree with the aggregate data set as cited in the conclusions section of Reference [18]. This was most common in the very shallow or near-through wall crack geometries, and it was theorized to be an artifact of the extended finite element method (XFEM) or chosen finite element mesh geometry. As a result, each SIF set went through a manual screening for these outliers. They were corrected with guidance from SIF values in the proximity or in some cases API 579's SIF solution set [19]. In this process, corrections were also verified to not disrupt the monotonically increasing or decreasing K slope behavior, whichever was the case.

The hook crack geometry was problematic for generating K solutions in that the possible geometries were extremely varied. Either an enormous number of finite element analyses must be run to provide a usefully large K solution space or else a simplified approach must be adopted to be able to make the problem tractable. The latter approach was adopted by utilizing existing API579 K solutions and applying well known fracture mechanics principles to approximate the expected behavior. From experience, it was known that embedded hook cracks have failure pressures well above comparable depth surface cracks. The embedded K solution methodology implemented was consistent with this field experience.

The stress intensity factor results were based on more than 2000 finite element solutions that examined various crack geometries (length, depth, internal, external), various corrosion geometries, (pit geometry, symmetric and asymmetric general corrosion), and various weld cap heights. Along with the finite element solutions, the following considerations were made in the development of the over-all fracture mechanics analyses:

- The multiple crack solution uses single crack SIFs and the BS 7910 Fitness-for-Service coalescence interaction rules,

- The hook crack solutions are built from the API579 Fitness-for-Service radially-oriented embedded flaw solution and fracture mechanics considerations,

- Hook cracks are linear approximations rather than accounting for the actual curvature of the hook-crack (i.e. no ILI or ITDM can provide the precise shape of a hook-crack),

- Hook cracks do not consider various amounts of trim on the upset, and
- The analysis space is limited for any of the solutions that were developed during this task.

Developing SIFs for the unanalyzed cases listed above using additional finite element analyses would take significant resources to generate meaningful and useful results. Considering the multiple crack case, the possibilities for crack depths, number of interacting cracks, and spacing between flaws is limitless. Likewise, for hook cracks, the possible geometries that may be encountered in practice are unbounded. The key to limiting the number of finite element analyses (and resources) needed to improve the current SIFs would be to pick cases that would provide additional validity for the currently implemented SIF solutions and define the degree of conservatism in the present models, because it is unlikely that a large enough set of finite element analyses can be run to make a sufficiently generalized solution solely from FEA results.

Develop and Refine Predictive Models and Quantify Growth Mechanisms

Overview

The details of this task (Phase II, Task 4) can be found in an interim report and its attachments and appendices located at the following website: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390.

Loss of pressure bearing capacity in transmission pipelines can occur due to several mechanisms. Time-independent failure can occur by plastic collapse, also known as net-section collapse, or it can occur by fracture, which can be brittle or ductile. Likewise, time-dependent failure can occur by stress-induced creep or it can occur by fatigue. Comprehensive assessment of pipeline integrity, which includes the effects of sustained static loading, hydrotesting, and cyclic pressure loading, requires consideration of all these loading types for safe operation.

ILI inspections can identify and size defects, but size by itself does not define defect tolerance or limiting pressure capacity. For this, models driven by ILI crack size and relevant pipeline steel material properties are needed. For this task, the various analytical models incorporated in the integrity management tool (Phase II, Task 5 – PipeAssess PI™) were developed. Additionally, this task was used to complete verification and validation studies of PipeAssess PI™ with the various time-independent and time-dependent models utilized.

Conclusions and Recommendations

The following conclusions and recommendations are provided based on the results obtained via validation.

- Analytical models were used based on historical literature. [2-3]

- New stress-intensity solutions, based on fracture mechanics theory, were developed using FEA in Phase II, Task 3 and implemented in the software for Task 5. Task 4 focused on validating the implementation of the models.

- Net-section collapse and fracture-based tearing models were validated to historical full-scale test results.

- Stress-induced creep models were validated based on historical data.

- Analytical fatigue models were validated based on both laboratory and full-scale tests

- Variability and accuracy of inputs into the failure calculations significantly effects the outputs, thus

  - Safety factors on output should be commensurate with the pedigree of the data used to generate the results
  - The best data availability should be used in the calculations (i.e. the local properties in the location of the crack; bond line, heat-affected zone, pipe body…etc.)
  - If data are not available, conservative assumptions should be made to ensure conservative calculations

- Hook crack analyses are challenging
  - Embedded hook cracks should be analyzed with methodology as described in Reference [13] embedded flaws
  - Surface-breaking hook crack should be analyzed using the infinitely long surface crack with the appropriate Charpy energy

- In the investigator's opinion, as shown in Figure 1,
  - PipeAssess PI™ results are less conservatively bias than the other models
  - PipeAssess PI™ results more accurately represent the mean value of the experimental data
  - PipeAssess PI™ results show similar variability between prediction and actual failure pressure to other methods (Legacy and API)
  - the similarity in the variability in the output, for all the models shown, comes from the uncertainty in the input parameters

Develop Management Tools: Manual, Software, Protocols, and Training

Overview

The details of this task (Phase II, Task 5) can be found in an interim report and its attachments and appendices located at the following website: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390.

This task was used to integrate the work completed under this project into a software package known as PipeAssess PI™. An overview of the software was provided along with the User's Manual as an appendix to the interim report. The software as "a Government Use Version" was delivered to the DOT. A version of the software (PipeAssess PI™) is being licensed by Battelle to commercial clients. Details of the current version as well as code updates, via Battelle-invested independent research dollars, can be found at this link: Battelle PipeAssess PI™[4]

The software can be used to analyze various axial crack-like geometries in cylindrical pressurized cylinders. There are two fundamental modes of operation: failure pressures and growth. In addition, there are three fundamental crack geometries: cold weld crack, hook cracks, and selective seam weld cracks. Details of the crack geometries can be found in Reference [20]. The fundamental purpose for the software is to determine the failure pressure of an incipient crack (i.e. found during inspection) or to determine if an incipient crack will fail prior to the next inspection interval either due to hydrostatic testing or fatigue cycling.

Three primary failure modes; fracture, plastic collapse, and tensile overload, are detailed in Reference [21]. For the fracture failure mode, stress intensity factors were developed as part of Phase II, Task 3 of this project, which included specific schemes for analyzing hook crack failure and propagation. The techniques used for fatigue crack growth rate analyses can be found in References [13] and [21].

Two items of note were that the validation of the software to database results was reported in Phase II, Task 4 and the summary graph shown in Figure 1. Secondly,

[4] https://www.battelle.org/commercial-offerings/oil-gas/pipeline-integrity/battelle-pipeassess-pi-axial-crack-software

PipeAssess PI™ was used to complete a brief study on the effects of Charpy energy and crack size on calculated failure pressure. These results are reported in Appendix A.

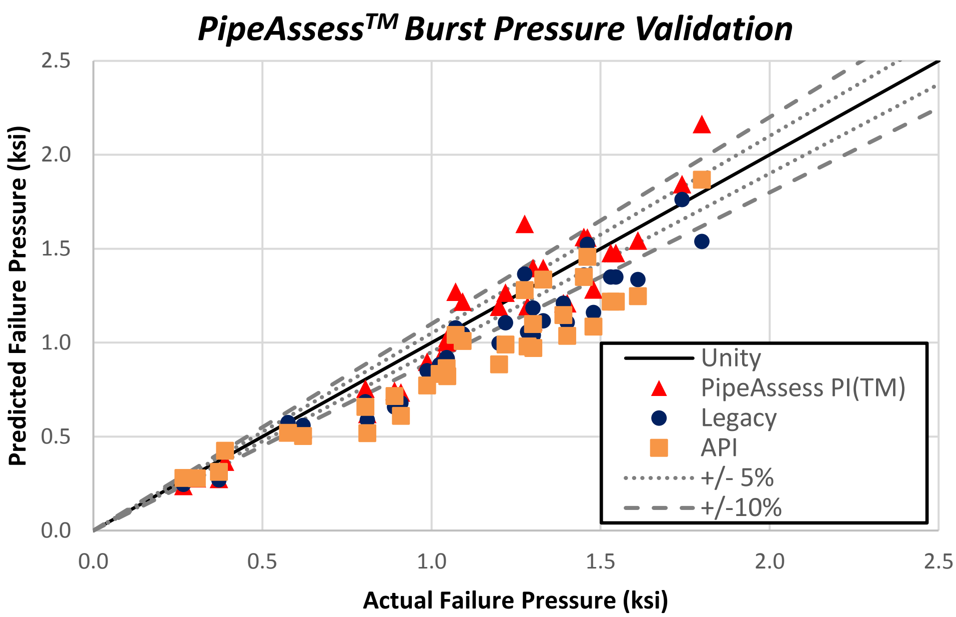


Figure 1: Validation of PipeAssess PI™

Conclusions and Recommendations

The results of Phase II, Task 5 were

- An integrity management software solution was developed for ERW Axial Seam weld analysis.
- A version of the software was delivered to the DOT PHMSA as "a Government Use Version". Appendix A of the interim report for Phase II, Task 5 contains the User's Manual.
- Interim report for Phase II, Task 5 contains the presentation given at the 2016 R&D Forum in Cleveland, Ohio.
- Phase II, Tasks 1 through 4 developed, verified, and validated the models used in the software.

Public Outreach

As part of this contract, Battelle and DOT PHMSA ensured that the information contained within these reports, including scientific results along with software demonstrations, were provided to the public in suitable forums. The following information lists, in-part, the information and format of the dissemination of information:

Technical Papers and Presentations

Young, B., et al. (2017). "Validation of Fatigue Models for ERW Seam Weld Cracking," ASME 2017 Pressure Vessels and Piping Conference. Waikoloa, Hawaii, ASME. **PVP2017**.

Olson, R., et al. (2017). "An Overview of Time Dependent Crack Growth Models Used for ERW Seam Weld Analyses," ASME 2017 Pressure Vessels and Piping Conference. Waikoloa, Hawaii, ASME. **PVP2017**.

O'Brian, J., et al. (2017). "Stress Intensity Factor Solutions for Crack-Like Anomalies in ERW Seam Welded Pipe," ASME 2017 Pressure Vessels and Piping Conference. Waikoloa, Hawaii, ASME. **PVP2017**.

O'Brian, J., et al. (2017). "The Impact of Crack Profiles on Pipeline Integrity: Advancing Assessments with New ILI Capabilities" Clarion Pipeline Pigging & Integrity Management (PPIM) Conference. Houston, Texas, PPIM. **PPIM2017**.

O'Brian, J., et al. (2017). "Comprehensive NDE Technology Assessment for LF-ERW Seam Anomalies." Clarion Pipeline & Integrity Management (PPIM) Conference. Houston, Texas, PPIM. **PPIM2017**.

Young, B. and J. O'Brian (2016). "The Comprehensive Study to Understand Longitudinal ERW Seam Failures Project with an Overview of Battelle's PipeAssess™ Software," Department of Transportation (DOT) Pipeline Hazardous Materials Safety Administration Research & Development (PHMSA) Forum. Cleveland, Ohio. **PHMSA R&D Forum.**

Young, B., et al. (2016). "Review of Phase II for the Comprehensive Study to Understand Longitudinal ERW Seam Failures," International Pipeline Conference (IPC). Calgary, Canada. **IPC2016**.

Olson, R., et al. (2016). "Findings from an Investigation of Hydrotest Protocols," International Pipeline Conference (IPC). Calgary, Canada. **IPC2016**.

Young, B., et al. (2014). "Overview of a Comprehensive Study to Understand Longitudinal ERW Seam Failures," International Pipeline Conference (IPC). Calgary, Canada. **IPC2014**.

Beavers, J. A., et al. (2014). "Development of Selective Seam Weld Corrosion Test Method," International Pipeline Conference (IPC), Calgary, CN, ASME. **IPC2014.**

Kiefner, J. F., et al. (2014). "Track Record of In-Line Inspection as a Means of ERW Seam Assessment in Response to NTSB Recommendation P-09-1, Arising from the Carmichael, MS Rupture," International Pipeline Conference (IPC), Calgary, Canada, ASME. **IPC2014.**

Kiefner, J. F., et al. (2014). "Types of Defects That Affect ERW Seam Integrity in Response to NTSB Recommendation P-09-1, Arising from the Carmichael, MS Rupture," International Pipeline Conference (IPC), Calgary, Canada, ASME. **IPC2014.**

Quickel, G. T., et al. (2014). "Small-Scale Testing to Characterize ERW Seam Properties in Response to NTSB Recommendation P-09-1, Arising from the Carmichael, MS Rupture," International Pipeline Conference (IPC), Calgary, Canada, ASME. **IPC2014.**

Trade Journals Technical Papers

O'Brian, J., et al. (2017). Assessing the Criticality of Seam Weld Cracks. **PPSA Newsletter**. June 2017.

Young, B., et al. (2017). A Case for Cutting Costs. **World Pipeline**. July 2017

O'Brian, J., et al. (2017). Impact of Crack Profiles on Pipeline Integrity: Advancing Assessment with New ILI Capabilities - Part 1. **Pipelines International**. June: 20-22, 2017.

O'Brian, J., et al. (2017). Impact of Crack Profiles on Pipeline Integrity: Advancing Assessment with New ILI Capabilities - Part 2. **Pipelines International**. Pending July 2017.

Miscellaneous Public Discussion

Nestleroth, J. B. and C. Macrory-Dalton (2017). Crack Management Workshop, Kiefner and Associates Inc. **KAI Training.**

O'Brian, J. and B. Young (2016). Special Topic Presentation: DOT PHMSA's Comprehensive ERW SEAM Project (Phase II, Task 5) Crack Management using Battelle's PipeAssess^{TM} Software Flyer, Battelle Memorial Institute.

O'Brian, J. (2016). Informal Overview of DOT's ERW Study Program at PRCI Research Exchange (RX). San Diego, CA. **PRCI RX**.

Young, B. (2014). Industry Discussion with PRCI at DOT Public Meeting and Workshop Chicago, Illinois

Other Information

Battelle Releases

- O'Brian, J. and B. Young (2016). Special Topic Presentation: DOT PHMSA's Comprehensive ERW SEAM Project (Phase II, Task 5) Crack Management using Battelle's PipeAssess^{TM} Software Flyer, Battelle Memorial Institute.

- "Battelle's PipeAssess PI™ Software Reduces Costs for Oil and Gas Pipeline Businesses" Business Wire, Released on 3/15/17 http://www.businesswire.com/news/home/20170315005810/en/Battelle%E2%80%99s-PipeAssess-PI%E2%84%A2-Software-Reduces-Costs-Oil

- YouTube Video: https://www.youtube.com/watch?v=tbBXAfozFIs

- Website for PipeAssess PI™: https://www.battelle.org/commercial-offerings/oil-gas/pipeline-integrity/battelle-pipeassess-pi-axial-crack-software

Video Tutorials

- How to Run a Burst Test - released by 3/31/17 https://battelle.box.com/s/f93h7c9r0isq0rng8k6m3czelgbn4tke

- Probabilistic Analysis – Release date Summer '17

- Fatigue Analysis - Release date Summer '17

Webinars

- Battelle: 30-minute tutorial webinars with demonstration to users (March '17 – TBD); these are client scheduled and anticipate running well into 2018

- Pipeline and Gas Journal (June 2018)

https://pgjonline.com/pipeline-integrity-reduce-costs-for-testing-and-failure-and-meet-dot-requirements/

Works Cited

[1] B. A. Young, S. Nanney and J. M. O'Brian, "Review of Phase II for the Comprehensive Study to Understand Longitudinal ERW Seam Failures," in *ASME-IPC 2016*, Calgary, 2016.

[2] B. N. Leis, F. W. Brust and P. M. Scott, "NG-18 Report No. 193: Development and Validation of a Ductile Flaw Growth Analysis for Gas Transmission Line Pipe," American Gas Association, 1991.

[3] B. N. Leis and F. W. Brust, "NG-18 Report No. 194: Hydrotest Strategies for Gas Transmission Pipelines Based on Ductile-Flaw-Growth Considerations," American Gas Association, 1992.

[4] R. J. Olson, B. A. Young and B. Leis, "Findings from an Investigation of Hydrotest Protocols," in *ASME IPC 2016*, Calgary, 2016.

[5] T. Anderson and G. Throwald, "A Fintie Element Procedure to Model the Effect of Hydrostatic Testing on Subsequent Fatigue Crack Growth," in *ASME IPC 2016*, Calgary, 2016.

[6] N. Al-Otaibi, H. Al-Muslim, W. Harper, T. Bubenik and W. A. Al-Usaimi, "Assessing the Benefits of Hydrotests for Pipelines with SCC History Post-Detection ILI Runs," in *ASME IPC 2016*, Calgary, 2016.

[7] M. Hilger, B. Mittelstadt and M. V. P. Piazza, "Pipeline Oporator Perspective in Use of Hydrostatic Testing as an Integrity Management Tool," in *ASME IPC 2016*, Calgary, 2016.

[8] D. Warman, N. Grusdowich, H. Kleeman, S. Boardman and U. Duruike, "De Facto Hydrostatic Test Pressures - A Study in Double Stroking," in *ASME IPC 2016*, Calgary, 2016.

[9] J. Rau and M. Kirkwood, "Hydrotesting and In-Line Inspection; Now and in the Future," in *ASME IPC 2016*, Calgary, 2016.

[10] S. Keane, M. Rosenfeld and L. Heise, "Hydrostatic Pressure Testing as Part of an Integrity Magagement Program: A Case Study," in *ASME IPC 2016*, Calgary, 2016.

[11] Hryciuk, P.M., Carzoglio, E., Minellono, J., et al., "The Use of Hydrotesting and EMAT Inline Inspection Technology for the Integrity Managment of Stress Corrosion Cracking (SCC) in Gas Pipelines," in *ASME IPC 2016*, Calgary, 2016.

[12] Micheal Baker Jr., Inc., "TTO Number 5, Intergrity Managment Program Delivery Order DTRS56-020D070036, Low Frequency ERW and Lap Welded Longitudinal Seam Evaluation; Final Report - Rev 3.," Department of Transportation, Research and Special Programs Administration, Office of Pipeline safety, 2014.

[13] B. Young, J. O'Brian and R. Olson, "Validation of Fatigue Models for ERW Seam Weld Cracking", in ASME PVP-2017, Waikola, 2017

[14] D. Lombardo and J. Paul, "Aircraft Structures Technical Memorandom 492," 1988. [Online]. Available: www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA199552.

[15] J. Willenborg, R. Engle and H. and Wood, "A Crack Growth Retardation Model Ising an Effective Stress Approach," Air Force Flight Dynamics Laboratory, Wright Patterson Air Force Base, Ohio, 1971.

[16] B. N. Leis, B. A. Young and e. al., "Final Summary Report and Recommendations for the Comprehensive Study to Understand Longitudinal ERW Seam Failures -- Phase One," < http://primis.phmsa.dot.gov/matrix/FilGet.rdm?fil=8501&s=EC16005513FE40EE867254CFB69090FD&c=1 >, DTPH56-11-T-000003, 2013.

[17] J. F. Kiefner, K. M. Kolovich and et. al., "Subtask 1.3: Track Record of In-Line Inspection as a Means of ERW Seam Integrity Assessment"," < http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390 >, DTPH56-11-T-000003L, 2013.

[18] D.-J. Shim and et al., "Application of Extended Finite Element Method (XFEM) to Stress Intensity Factor Calculations," Proceedings of the ASME 2015 Pressure Vessels & Piping Conference, Massachusetts, 2015.

[19] The American Society of Mechanical Engineers and the American Petroleum Insititute, "API 579-1/ASME FFS-1, Second Edition," 2007.

[20] B. Young, J. O'Brian and R. Olson, "Defect Characterization: Types, Sizes, Shapes, and Idealizations," Battelle Memorial Institute, Columbus, 2017.

[21] B. A. Young, R. J. Olson and J. M. O'Brain, "Phase 2, Task 4 Report: Analysis Models," Battelle Memorial Institute, 2017. [Online]. Available: http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390.

Appendix A

Results from an Example PipeAssess PI™ Analysis

Sensitivity Analysis:

Failure Pressure vs Pipe Grade, Charpy Impact Energy & Crack Size

Battelle's PipeAssess PI™ processed hundreds of cases to illustrate the impact of pipe grade, charpy impact energy, and crack size has on a cold weld's failure pressure. This appendix provides a summary of the results of the study. Five different API 5L pipe grades (X42, X52, X60, X70, X80), three different full-size Charpy impact energies (4 ft-lbs, 10 ft-lbs, 15 ft-lbs), and six different crack depths varying from 30% to 80% through-wall, each with four different crack aspect ratios to determine crack length (i.e. 2c/a = 4, 10, 15, 20) were evaluated. All inputs are summarized in Tables 1 through 3.

Input Parameters

Geometric and material property inputs are summarized in Table 1. Historical databases were used to dictate representative material properties for each grade. Pipe geometric characteristics were held constant with an outer diameter of 24-inches, a wall thickness of 0.280-inch, and anomaly type representative of a cold weld. PipeAssess has several cold weld models; the selected model of choice is documented in Table 2 and utilizes the latest stress intensity factor solution circa 2016. The anomaly's dimensions was as shown in Table 3.

Table 1: Material Properties Input

Outer Diameter (in)	24	24	24	24	24
Wall Thickness (in)	0.281	0.281	0.281	0.281	0.281
Grade	**X42**	**X52**	**X60**	**X70**	**X80**
SMYS (ksi)	42	52	60	70	80
E (ksi)	29,000	29,000	29,000	29,000	29,000
YS (ksi)[1]	46.2	57.2	66	77	88
UTS (ksi)[2]	70	80	84	95	96
72% P_{SMYS} (psi)	708	877	1,012	1,180	1,349

Note 1: Historical Reports indicate the typical YS is approximately 1.1xSMYS

Note 2: Historical Database Averages

Note 3: X42 and X80 values also reported in Table 2 of reference[1]

[1] Bruce Young and Rick Olson, "Interim Report for Phase II - Task 1 of the Comprehensive Study to Understand Longitudinal ERW Seam Failures: Hydrostatic Testing Protocols", DOT Contract No. DTPH56-11-T-000003, 2017.

Table 2: Anomaly Type Characterization Input

Anomaly Type	Cold Weld
Anomaly Profile	Elliptical
Anomaly Location	Surface Breaking from the Outer Diameter
PipeAssess Anomaly Category	CW_E_OD_PTWC_S_3D

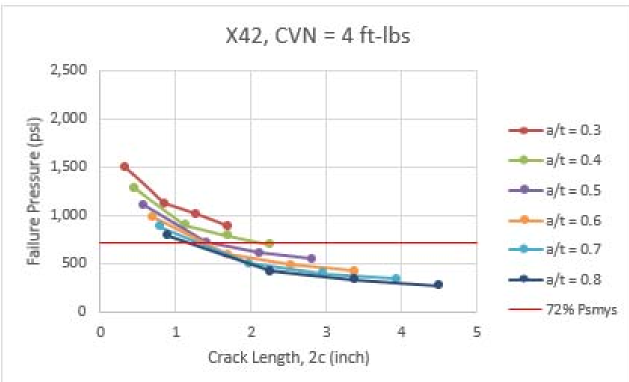
Table 3: Anomaly Sizing Input

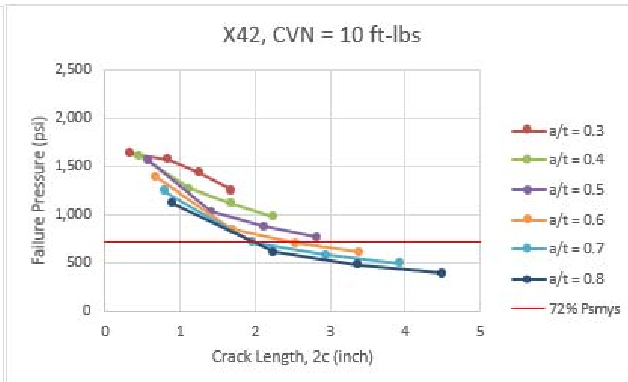
Crack Depth-to-Wall Thickness (a/t)	Crack Length-to-Depth Aspect Ratio (2c/a)
0.3	4, 10, 15, 20
0.4	4, 10, 15, 20
0.5	4, 10, 15, 20
0.6	4, 10, 15, 20
0.7	4, 10, 15, 20
0.8	4, 10, 15, 20

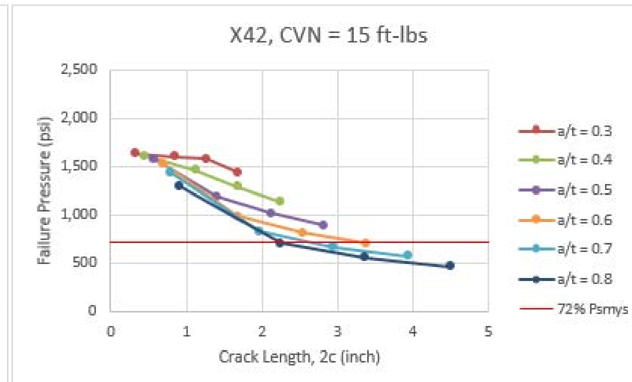
Acronyms

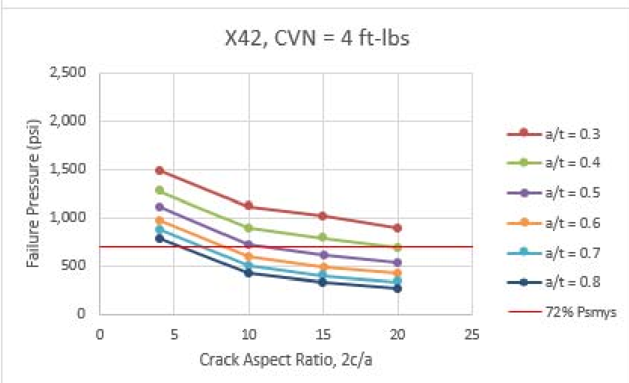
a/t	Crack Depth,a -to- Wall Thickness,t
CVN	Charpy V-Notch Impact Energy
DOT	Department of Transportation
E	Young’s Modulus
ERW	Electric Resistance Weld
P_{SMYS}	Pressure at SMYS
SMYS	Specified Minimum Yield Strength
UTS	Ultimate Yield Strength
YS	Yield Strength
2c	Crack Length
2c/a	Crack Length, 2c -to- Crack Depth, a

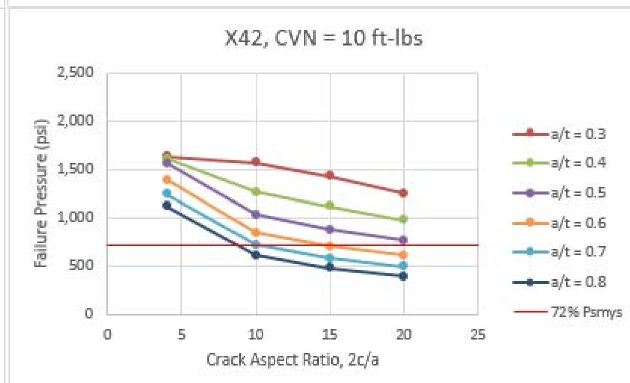
X42 Output Failure Pressures

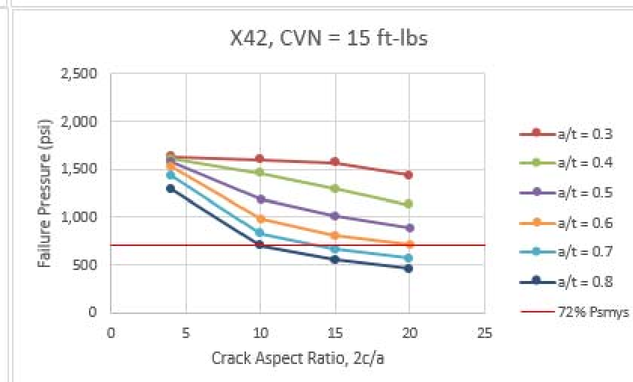




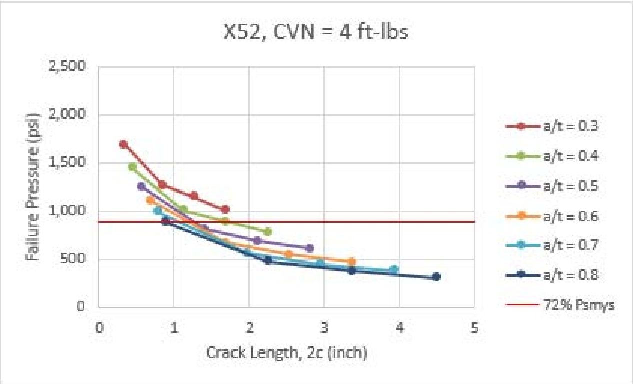


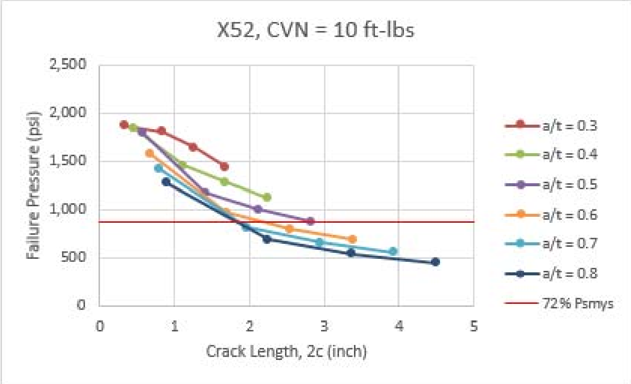


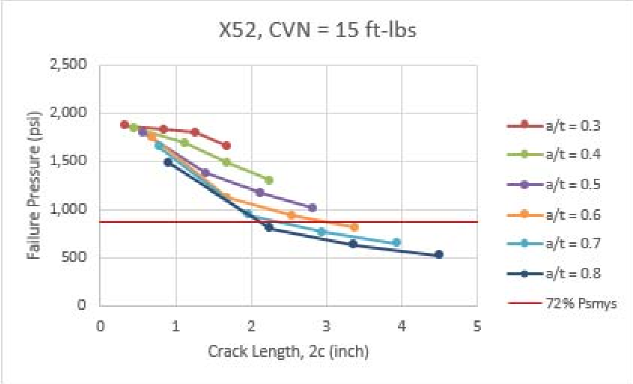


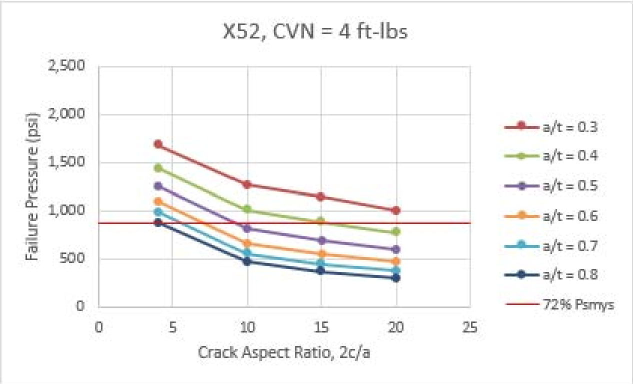


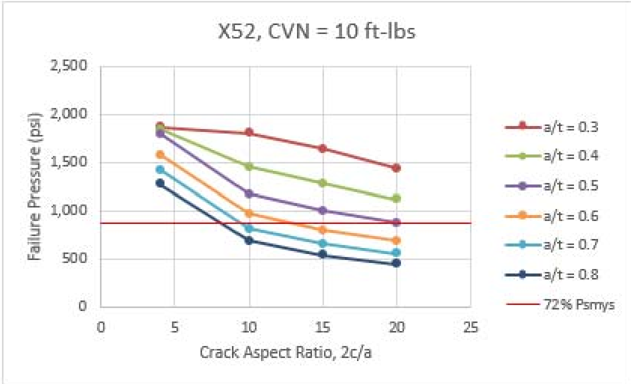
X52 Output Failure Pressures

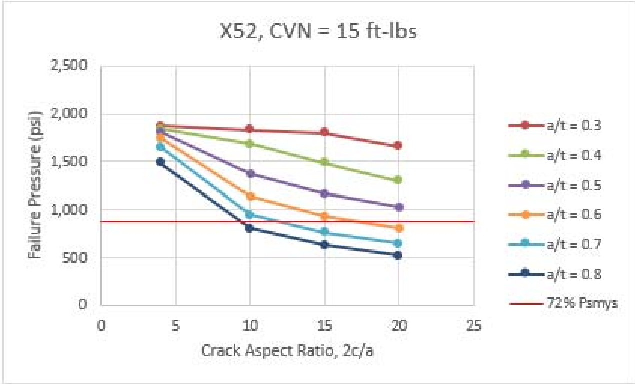




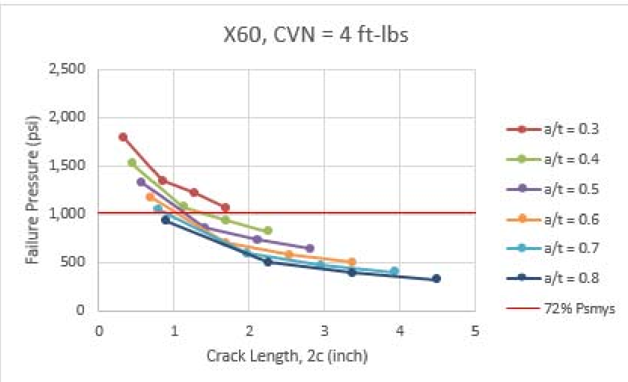


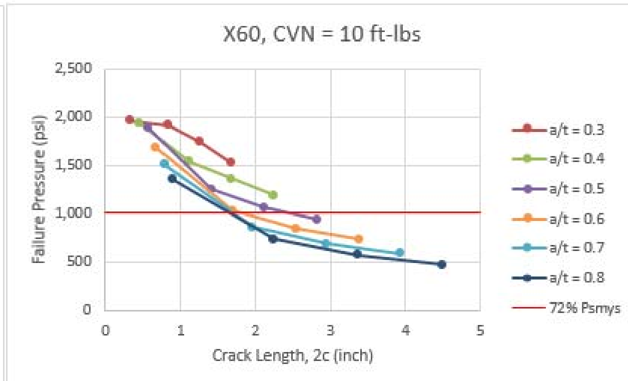


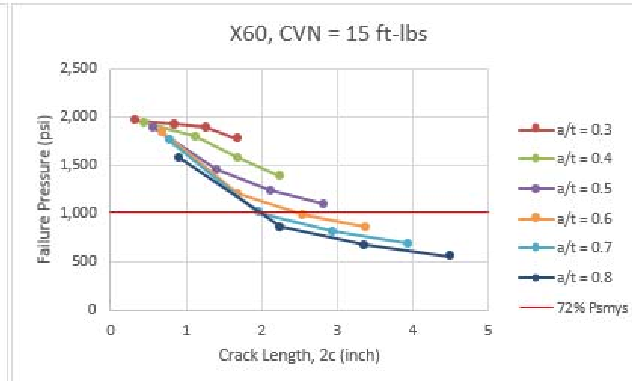


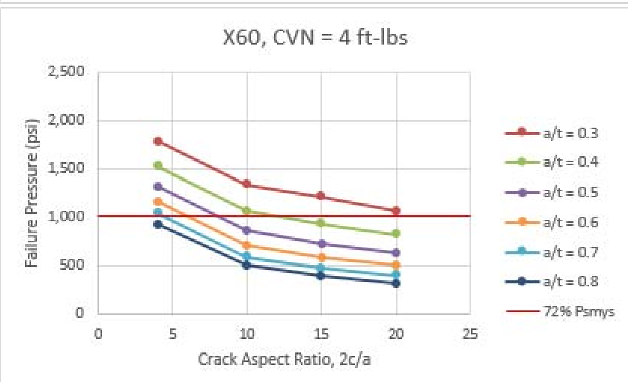


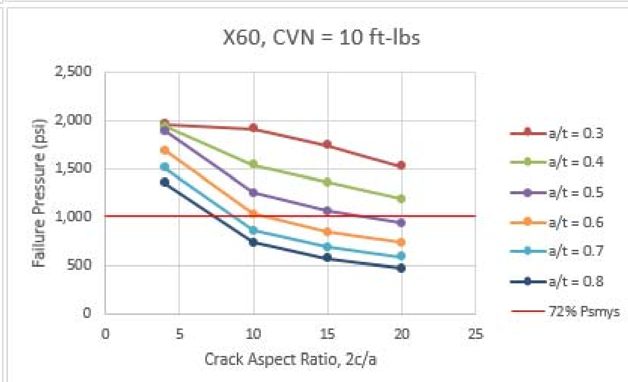
X60 Output Failure Pressures

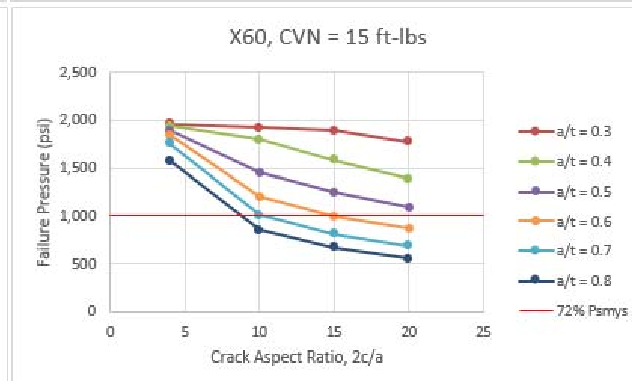




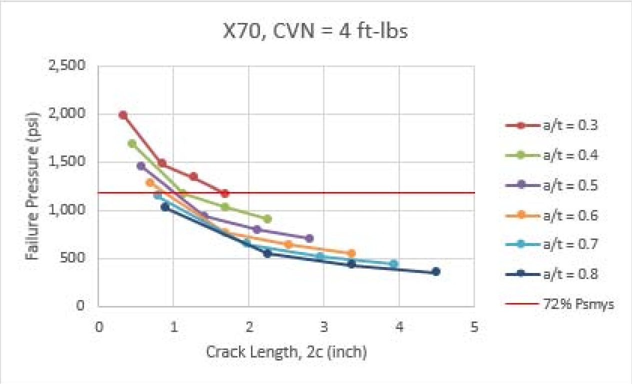


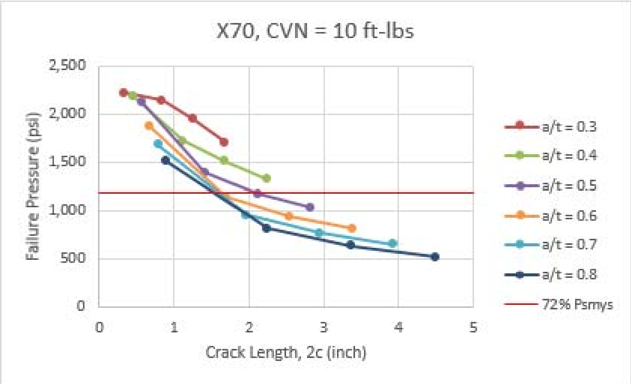


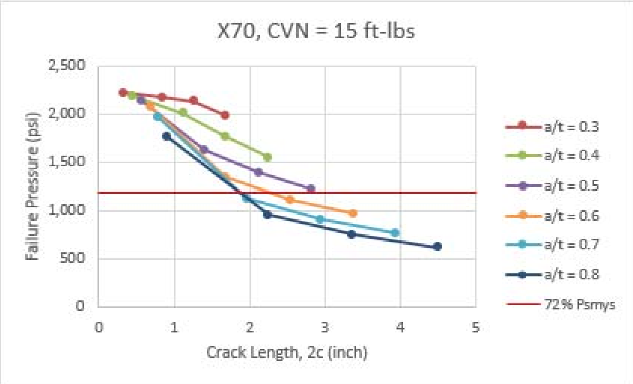


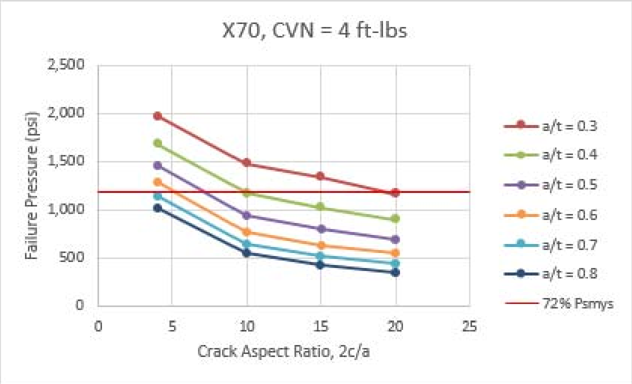


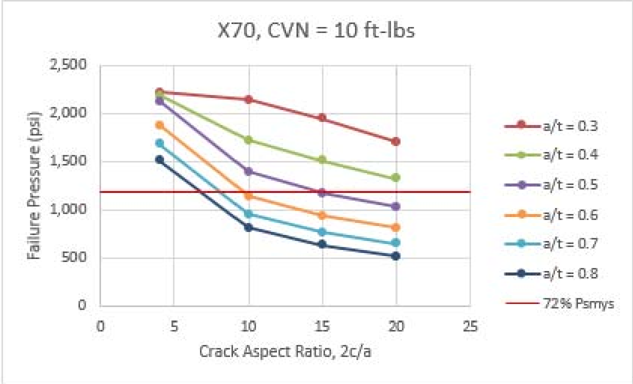
X70 Output Failure Pressures

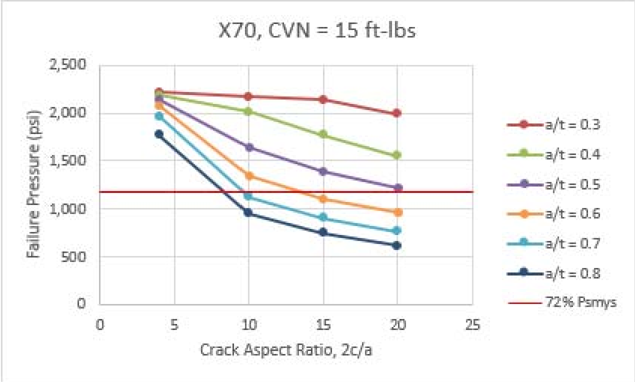












X80 Output Failure Pressures