Use of Full-Scale Testing as a Means for Improving Burst Pressure Predictions of Crack-Like Features

Atul Ganpatye[1], Chris Alexander[1], Tony Rizk[2], and Rodney Clayton[2]
[1]ADV Integrity, Inc., [2]Boardwalk Pipeline Partners

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Abstract

A study was conducted using full-scale burst testing to evaluate methods for increasing the accuracy of predicted failure pressures of crack-like features using current crack assessment tools. It is widely recognized that the calculation methods currently employed by the pipeline industry to estimate failure pressures of pipes having crack-like features are conservative. Differences between burst test pressures and predicted values can be as high as 50%. Results demonstrated via full-scale testing using 12 pipe samples the differences exist between actual and predicted failure pressures of crack-like features using 26-inch x 0.281-inch, Grade X52 A.O. Smith pipe material. Cracks were generated in the base pipe having depths ranging from 20.9% to 69.0% of the pipe's nominal wall thickness. On average, the results with analytical assessment methods using lower bound material properties are "off" between 20% and 40%.

Improvements in the assessment methods were achieved using more accurate material properties data that included integrating actual material properties such as the yield strength of the pipe material in the fracture models. As expected, the use of lower shelf Charpy values and the Specified Minimum Yield Strength results in extremely low predicted failure pressures. The results of this study demonstrated that by employing the improved assessment methods the number of features that would have required excavation based on a 1.25 MAOP threshold and repair in this study dropped from 87.5% (7 of 8 tested samples would require excavation and repair) to only defects having depths greater than 60% (1 of 8, or 12.5%) if actual material properties from full-scale testing were used. In reality the benefits for an actual pipeline would be even greater as many of the in-service crack-like features are relatively shallow (e.g., less than 40%) and current assessment methods would require excavation and repair.

Introduction and Background

Pipeline operators are required to address threats associated with pipelines having crack-like features. Improvements in current in-line inspection technologies are increasing the number of features on which operators are required to make integrity assessment decisions. Although improvements in inspection technologies are appreciated, a failure to proportionally improve assessment methods is resulting in unwarranted excavations and repairs, which is not the best use of the pipeline industry's available resources for safely operating pipelines.

To make today's assessment methods more effective and efficient a new and improved approach is required. However, there are a limited number of options available to the pipeline industry considering limitations and uncertainties associated with current inspection technologies and material characterization options. Listed below are several options available to the pipeline community for improving our confidence in managing crack-like flaws, along with a brief commentary on each.

Inspection: Improve confidence in the dimensional measurements of crack-like features by improving the capabilities of in-line (ILI) and in-the-ditch inspection technologies. Although today's ILI technologies are vastly improved over what was available a decade ago, challenges exist in terms of the accuracy that can be achieved. Due to complexities associated with technology development, seeking to make improvements in inspection technologies should not be expected to deliver immediate results for the pipeline industry. In parallel to advancing sizing accuracy of ILI

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technologies, significant improvements in predicting burst pressures associated with crack-like features can be achieved. This will most likely happen by interpreting fracture resistance-based on full-scale testing that will be demonstrated and presented in this paper.

Calculation Methods: The fracture models associated with current calculation methods are based on three factors: stress state, material properties (i.e., toughness and yield strength), and crack and pipe geometries. It appears that the calculation methods being employed today are sound, but improvements can be made in terms of making minor adjustments to allow easier incorporation of actual material properties and refining the approaches for better prediction of plastic-collapse dominated failure. Therefore, seeking to modify equations associated with current calculation methods is not recommended and unlikely to yield significant advances in our ability to predict failure pressures of cracks.

Material Properties: Of the options available to the pipeline industry for improving burst pressure predictions with the least amount of effort, increasing current understanding associated with material fracture toughness is particularly noteworthy. The current assessment methods use fracture toughness values based on specimens that present higher strain constraint (as compared to what's more applicable for thin wall pipes) and result in predicting lower failure pressures than actually exist[1]. Shown in Figure 1 is a graph plotting measured toughness as a function of crack-tip constraint. As shown, the highest level of restraint and lowest measured toughness is the compact tension (CT) sample. The CT sample is the primary means used by the pipeline industry for quantifying fracture toughness. In contrast, the full-scale burst test presents the least amount of restraint and allows the most accurate representation of toughness for an actual pipeline. Full-scale testing is the best available and most direct option for accurately characterizing fracture toughness properties in an internally pressurized pipeline.

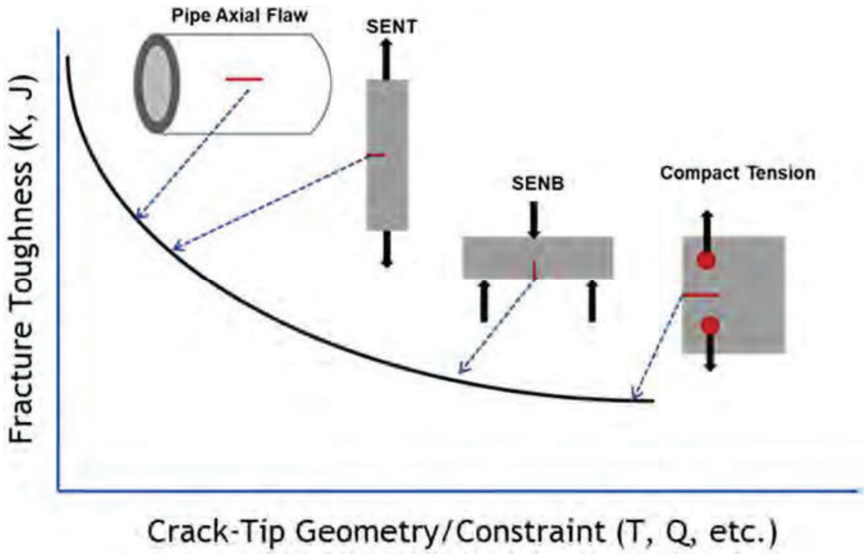

Figure 1. Measured toughness as a function of crack-tip constraint

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[1] Coupon-level fracture toughness testing samples do not fully characterize a pipe's stress state, resulting in an over-constraint condition. See Figure 1 for details.

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A primary motivation for Boardwalk and other pipeline operators in developing improved methods for estimating failure pressures associated with crack-like features are the limitations imposed by current regulations that require operators to use toughness values based on lower bound Charpy energy levels. According to §192.712 *Analysis of predicted failure pressure* [specifically (e)(i)(c)] the following material toughness limitations are imposed on operators in that they must use one of the following for material toughness values.

> (A) Charpy v-notch toughness values from comparable pipe with known properties of the same vintage and from the same steel and pipe manufacturer;
>
> (B) A conservative Charpy v-notch toughness value to determine the toughness based upon the ongoing material properties verification process specified in § 192.607;
>
> (C) If the pipeline segment does not have a history of reportable incidents caused by cracking or crack-like defects, maximum Charpy v-notch toughness values of **13.0 ft-lbs.** for body cracks and **4.0 ft-lbs.** for cold weld, lack of fusion, and selective seam weld corrosion defects;
>
> (D) If the pipeline segment has a history of reportable incidents caused by cracking or crack-like defects, maximum Charpy v-notch toughness values of **5.0 ft-lbs.** for body cracks and **1.0 ft-lbs.** for cold weld, lack of fusion, and selective seam weld corrosion;
>
> or
>
> (E) Other appropriate values that an operator demonstrates can provide conservative Charpy v-notch toughness values of crack-related conditions of the pipeline segment. Operators using an assumed Charpy v-notch toughness value must notify PHMSA in advance in accordance with § 192.18 and include in the notification the bases for demonstrating that the Charpy v-notch toughness values proposed are appropriate and conservative for use in analysis of crack-related conditions.

Of particular interest in the above text are the highlighted sections that impose limitations of 13 ft-lbs. for body cracks and 4 ft-lbs. for seam features for pipelines that do not have a history of reportable incidences. For pipelines with reportable incidences, these Charpy values are reduced to 5 ft-lbs. and 1 ft-lbs., respectively. Additionally, per § 192.712(e)(2)(ii)(A) if an operator does not know the pipe's material strength, they must assume Grade A pipe (30,000 psi). This yield strength places severe limitations on the predicted pressure carrying capacity of a pipeline. The combined conservatisms associated with minimum material strength and toughness values will significantly increase the number of excavations and repairs facing U.S. pipeline operators.

Typically, traditional crack management programs employ steps similar to those listed below.

- **Inspection Results:** Identify crack-like feature geometry based on inspections.
- **Analytical Models:** Estimate stress intensity (K_I) and reference stress for the feature – feature size/geometry influence.
- **Sub-scale Testing:** Use fracture toughness (K_{mat}), yield stress and ultimate stress – material properties influence.
- **Failure Pressure Predictions:** Calculate fracture ratio and collapse ratio, and plot on a Failure Assessment Diagram (FAD), as shown in Figure 2.

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As stated previously, the pipeline industry's current approach to managing cracks requires excessive levels of conservatism because of uncertainties associated with crack geometry and material properties. What ADV has proposed to Boardwalk is an improved methodology that removes uncertainties with pipe materials using full-scale test data instead of relying purely on sub-scale fracture mechanics test results. This is illustrated graphically in Figure 3. The uncertainties associated with predicting failure pressures are addressed by replacing sub-scale testing that uses uniaxial testing as the means for quantifying material properties with full-scale testing that directly measures behavior of the pipe subject to internal pressure loading.

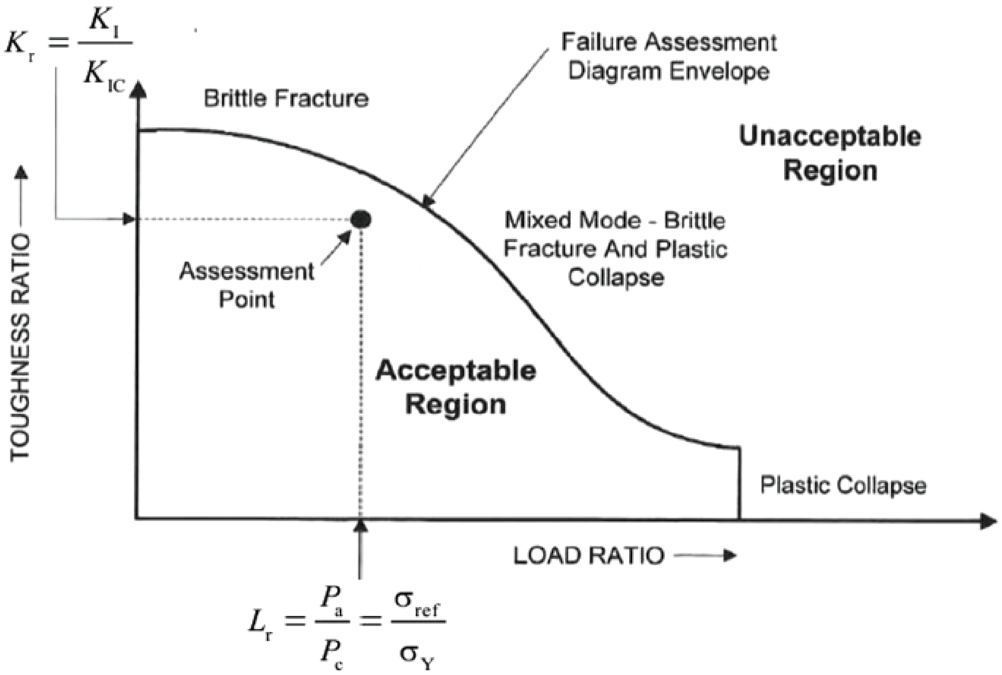
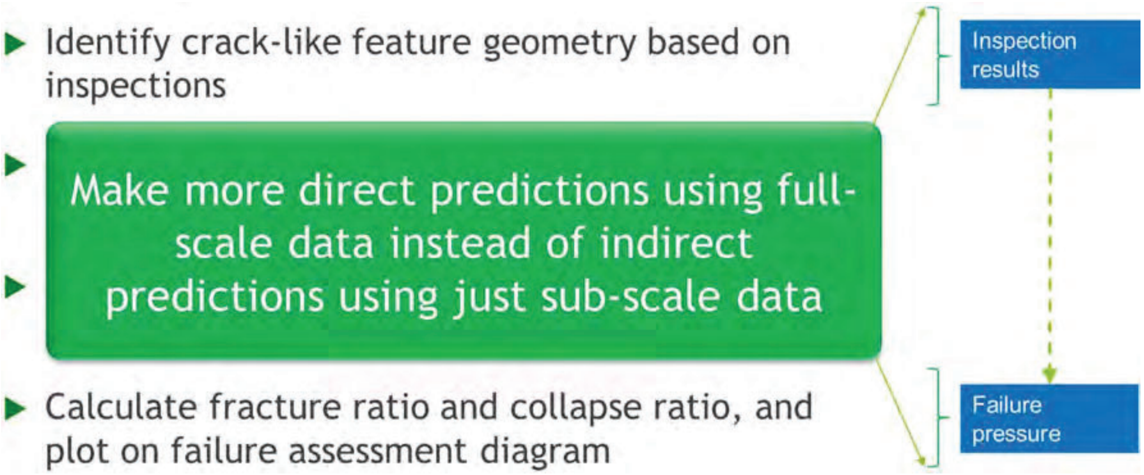


Figure 2. Exemplar Failure Assessment Diagram

K_r = Toughness Ratio | K_I = Stress Intensity | K_{IC} = Fracture Toughness
L_r = Load Ratio | P_a = Applied Load | P_c = Plastic Collapse Load | σ_{ref} = Applied (reference) Stress | σ_Y = Yield Strength of Materia



- Identify crack-like feature geometry based on inspections

Make more direct predictions using full-scale data instead of indirect predictions using just sub-scale data

- Calculate fracture ratio and collapse ratio, and plot on failure assessment diagram

Inspection results

Failure pressure

Figure 3. Novel approach for an improved crack management program

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A New Approach for Quantifying Failure Pressures

The primary aim of this paper is to present an alternative approach for quantifying the failure pressures of pipes having crack-like features. This involves demonstrating a more accurate method for predicting burst pressures of pipes having crack-like features using material properties derived from full-scale test results. Listed below are the generalized steps involved in the proposed approach for a pipeline operator.

1. Obtain sufficient quantity of pipe material to permit material testing and full-scale sample fabrication.
2. Material testing should be conducted using sub-scale samples to obtain chemistry, tensile properties (i.e., YS, UTS, and elongation), Charpy, and fracture toughness (K_{mat}). Material characterization is an important part of the documentation process and the accumulation of material data, combined with full-scale results, is the key to managing the conservatism associated with the current regulations.
3. Select a range of crack geometries that represent features that will be in the pipeline system, bounded by depth and length (e.g., 20% to 65% of the pipe's nominal wall thickness).
4. Fabricate full-scale pipe samples by welding end caps to sections of pipe no less than five pipe diameters in length. The number of samples should be between 9 and 12.
5. Install EDM notches to the prescribed geometries. A notch length on the order of 3 inches is recommended, as shown in Figure 4.
6. A loading method should be applied prior to burst testing to ensure microcracking exists at the base of the notches. A cross-sectional image of an EDM notch with microcracking at its base is shown in Figure 5. Crack growth is monitored using a clip gage[2] as shown in Figure 6.
7. After the sample has been fabricated and fitted with the appropriate defect, it should be destructively tested. For gas pipelines the primary failure mode of concern is burst pressure; however, of the available test matrix some samples (e.g., 3 samples) should be pressure cycled to failure to establish a representative fatigue life. For liquid operators pressure cycle fatigue is a primary concern and crack growth as a function of cycle number should be monitored during full-scale testing.
8. After all testing has been completed the resulting failure pressures should be evaluated as functions of crack length and depth. The analysis associated with this effort will be addressed in greater detail in the **Application of Results to Pipeline Operation** section of this paper.

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[2] The clip gage is a mechanical device that is useful for inferring "radially inward" crack growth based on opening of the "mouth" of the EDM notch. Research is required to advance our ability to accurately measure actual crack growth; however, at the present time this technology represents state-of-the-art for full-scale testing.

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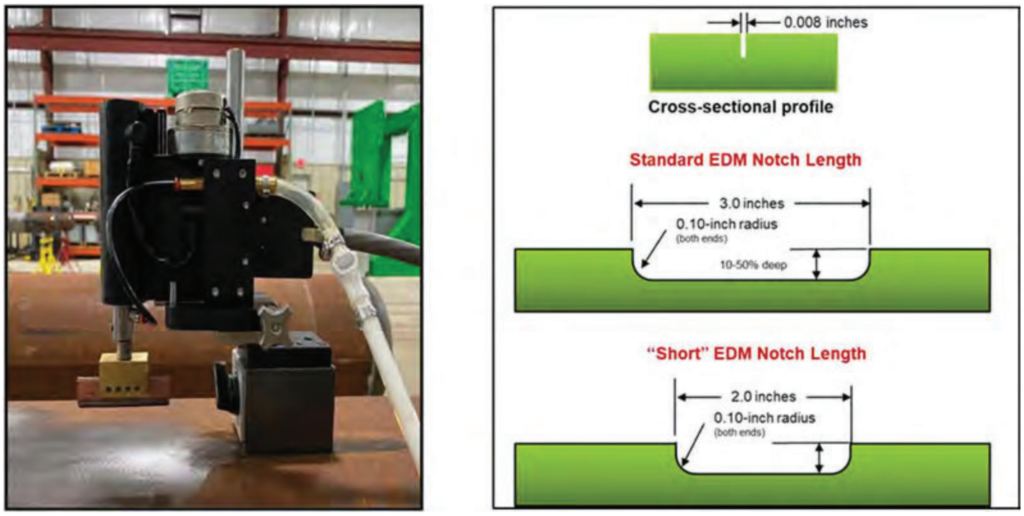

Figure 4. Machine used to install EDM notch and a typical geometry schematic

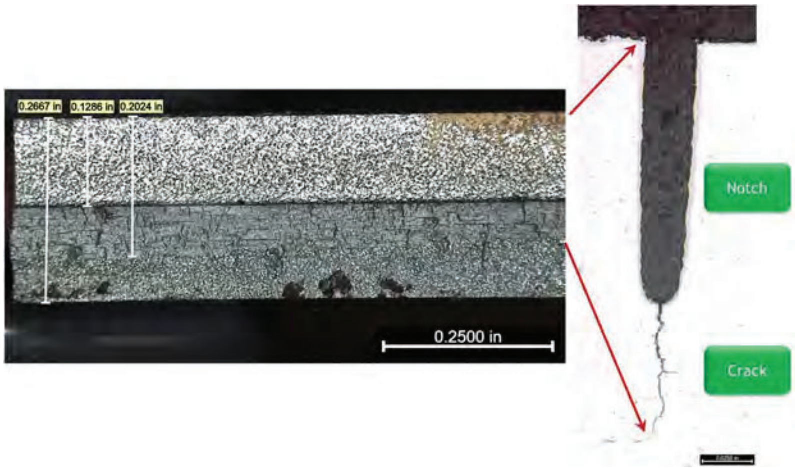

Figure 5. Microcracking observed at the base of an EDM notch (meridional and cross-section views)

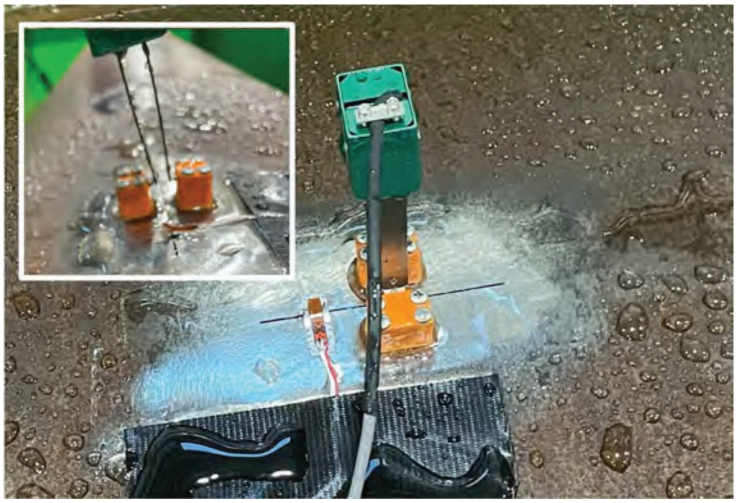

Figure 6. Clip gage used to monitor crack growth of an EDM notch

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Test Methods

A full-scale test program was conducted using Boardwalk's 26-inch x 0.281-inch, Grade X52 pipe. The intent was to evaluate a range of crack depths and determine their impact on the pressure-carrying capacity of the pipe material. The steps involved in this process included fabricating pipe samples, installing EDM notches and pre-cycling to generate microcracking at the base of the notches, loading the sample either via cyclic pressure or burst testing, and post-test inspection.

The sections that follow provide details on the process used to generate cracks in the pipe, the test matrix, and the steps involved in testing.

Generation of Cracks

The ability to generate crack-like features is essential for a testing program such as the one completed for Boardwalk. Current inspection technologies do not have the resolution to detect the sharpness of a crack or even its width; however, theoretically a blunt notch and crack tip should behave differently. From a testing and numerical modeling standpoint it is always best (most conservative) to assume that a sharp crack tip exists. Figure 7 is a plot showing data used by ADV to confirm crack growth at the base of the notch (CMOD: crack mouth opening displacement). The resulting crack geometry is shown in the Figure 8 macrographs that highlights the region of the EDM starter notch, pre-cycled crack growth region, and the final fracture.

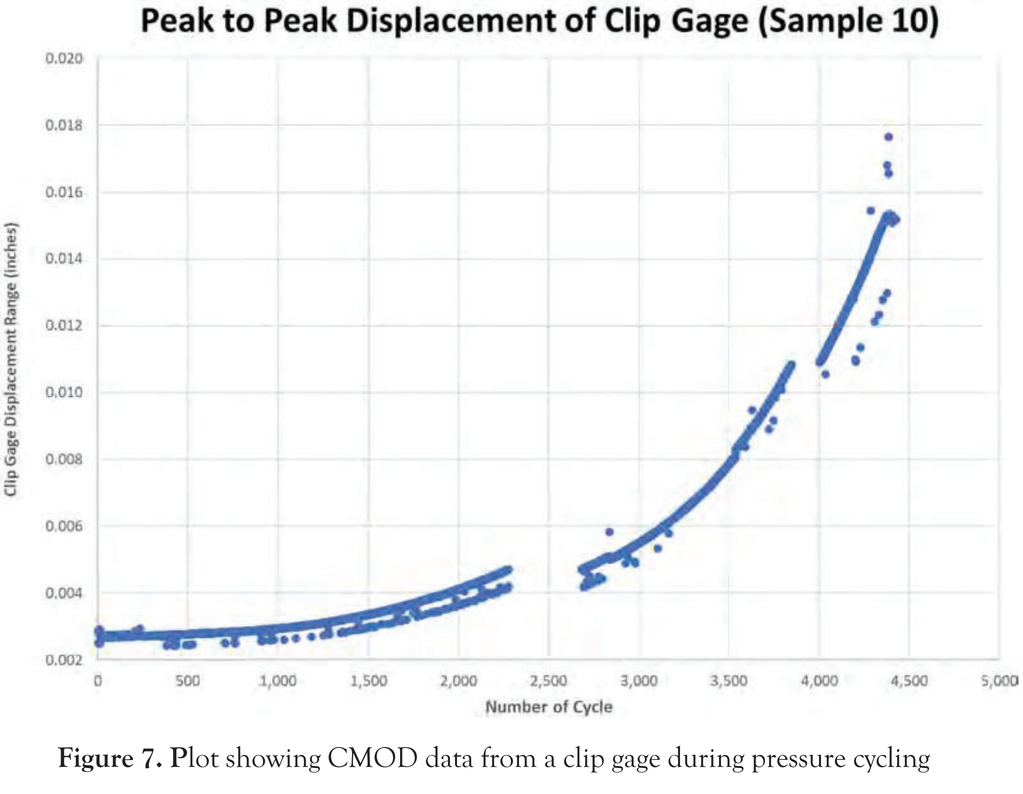

Figure 7. Plot showing CMOD data from a clip gage during pressure cycling

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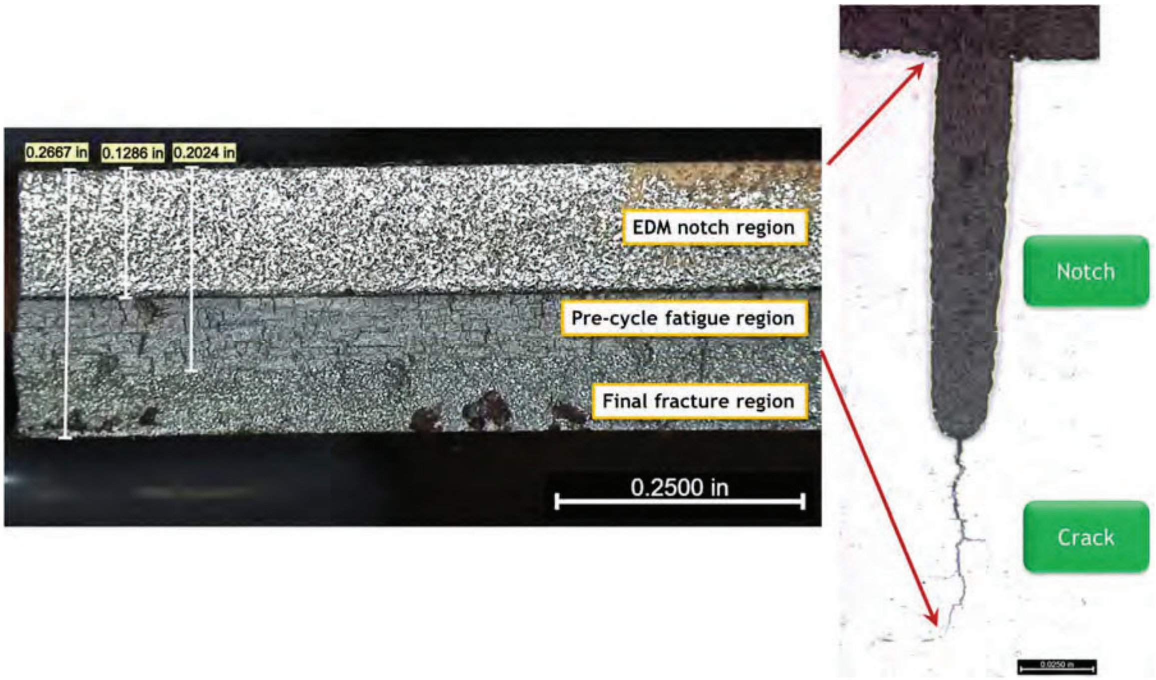

Figure 8. Photo macrographs showing the meridional and cross-sectional views

Test Matrix

Prior to testing, ADV and Boardwalk selected a range of target crack depths that would evaluate a range of feature depths that might be encountered in an actual pipeline. Table 1 lists the complete test matrix that includes variations in crack geometry, notch configuration (i.e., notch only or notch with pre-cycling), and loading type (i.e., burst only, burst plus pre-cycling, or fatigue). Because of the potential scatter inherent with fatigue data, Sample 10 was re-tested with the same notch configuration. As noted in this table, 75% of the samples are focused on burst testing because as a gas pipeline operator Boardwalk's pipeline systems will experience minimal pressure cycling.

A total of 12 samples were tested in this program. Provided below are the steps involved in testing these samples.

1. Pipe was obtained from Boardwalk (26-inch x 0.281-inch, Grade X52, manufactured by A.O. Smith).
2. The pipe material was cut into 13-ft lengths and elliptical end caps were welded to the ends of each pipe sample.
3. The samples were labeled and EDM notches were installed to the prescribed depths.
4. The following pressure regimes were applied for the respective pipe samples.
    a. Samples 1 through 3 were burst tested (notch only samples).
    b. Samples 4 through 9 were pre-cycled to generate cracks at the base of the EDM notches and then burst tested. After burst testing the actual post-cycle crack depths were used in plotting burst pressures as a function of crack depth. Burst pressures were recorded.
    c. Samples 10A, 10AR, and 11B were pressure cycled to failure. The number of cycles to failure were recorded.

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Table 1. Pipe sample test matrix

Sample Number	Notch and Crack Geometry (1, 2)	Loading Type		
		Burst Only	Fatigue + Burst (10,000 cycles + burst) (3)	Fatigue Only
1A-B	20% deep | notch only	✓		
2B-B	50% deep | notch only	✓		
3C-B	75% deep | notch only	✓		
4A-BF	20% deep | notch + pre-crack		✓ (3)	
5B-BF	50% deep | notch + pre-crack		✓	
6C-BF (4)	75% deep | notch + pre-crack		✓ (3)	
7A-F	20% deep | notch + pre-crack		✓	
8B-F	35% deep | notch + pre-crack		✓ (5)	
9C-F	50% deep | notch + pre-crack		✓	
10A-F	20% deep | notch + cycling			✓
10AR-F (repeat)	20% deep | notch + cycling			✓
11B-F	35% deep | notch + cycling			✓

NOTES:

(1) Notch depths expressed as a percentage of the pipe's nominal wall thickness (26-inch x 0.281-inch).

(2) All notch lengths were 3.0 inches.

(3) Samples subjected to fatigue testing were pressure cycled. The "Fatigue + Burst" samples were cycled to at most approximately 10,000 cycles before burst testing.

(4) The notch depth for Sample 6 was measured to be 85.3% of the actual wall thickness and failed after the application of 20 cycles, so the EDM notch depths in subsequent samples were 50% or less.

(5) Sample 8 with 35% deep notch was cycled from approximately 100 psig to 550 psig (9% to 49% SMYS)

(6) Sample 9 with 50% deep notch was cycled from approximately 100 psig to 400 psig (9% to 35% SMYS)

Test Results

This section of the paper presents test results for the 12 pipe samples. Included is a presentation of results, as well as a high-level analysis of the data and general observations.

Tabulated Data

Provided in Table 2 is a complete list of all test data, including burst pressures, number of pre-cycles, and number of fatigue cycles to failure. Included in this table are the final crack depths measured after testing was complete. The measured post-test values are not exact as there was some level of wall thickness reduction due to necking of the steel during burst testing; however, the presented data were used to analyze the test results. The final crack depth is important for establishing data trends associated with failure pressure as a function of crack depth. The following section of this paper plots the data presented in Table 2 and provides commentary on observed trends.

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Table 2. Pipe sample test matrix with burst and fatigue results

Sample Number	Notch and Crack Geometry (1, 2)	Loading Type		
		Final Crack Depth (3)	Fatigue Cycles (4)	Burst Pressure (psig)
1A-B	20% deep notch	20.9%	N/A	1,504
2B-B	50% deep notch	45.3%	N/A	1,257
3C-B	75% deep notch	69.0%	N/A	1,153
4A-BF	20% deep notch + pre-crack	40.7%	9,198	1,348
5B-BF	50% deep notch + pre-crack	62.7%	262	1,202
6C-BF (5)	75% deep notch + pre-crack	85.0%	20	797
7A-F	20% deep notch + pre-crack	40.7%	10,809	1,396
8B-F	35% deep notch + pre-crack	53.1%	5,946	1,265
9C-F	50% deep notch + pre-crack	65.4%	10,000	1,238
10A-F	20% deep notch + cycling	Thru-wall	1,533	N/A
10AR-F	20% deep notch + cycling	Thru-wall	4,427	N/A
11B-F	35% deep notch + cycling	Thru-wall	7,129	N/A

NOTES:

(1) Notch depths expressed as a percentage of the pipes nominal wall thickness (26-inch x 0.281-inch).

(2) All crack lengths were 3.0 inches.

(3) The final crack depths were measured after burst testing was completed.

(4) Samples subjected to fatigue testing were cycled from 100 psig to 809 psig (9% to 72% SMYS, except for Samples 8 and 9 as noted in Table 1). The “Fatigue + Burst” samples were cycled to at most approximately 10,000 cycles before burst testing.

(5) The notch depth for Sample 6 was measured to be 85.3% of the actual wall thickness and failed after the application of 20 cycles, so the EDM notch depths in subsequent samples were less than 75%.

(6) Provided in Appendix B are post-test macrographs of each sample that were used to confirm the final crack geometries.

Plotted Data and Observed Trends

Provided in this section of the paper is a plot of the data presented in Table 2. Plotted in Figure 9 are burst pressures as functions of notch and crack depths. The notch and crack depths are based on the final post-burst measured values. Also included in this plot is the data point for Sample 6, although it is considered an outlier because the notch depth was inadvertently installed at 85% and the resulting failure was more representative of a high strain, low cycle fatigue data point than an actual burst tests.

Also included in Figure 9 are lines representing 72% and 100% SMYS. It is noted that except Sample 6, all failures exceed the 100% SMYS line, which is also 39% greater than the MAOP line at 72% SMYS. Although extensive analysis of the data plotted in Figure 9 will be conducted, the observation that all failure data points reside above the 100% SMYS line is important information for Boardwalk as a pipeline operator, especially considering three of the features had depths greater than 60% including one that was 69% of the pipe’s wall thickness.

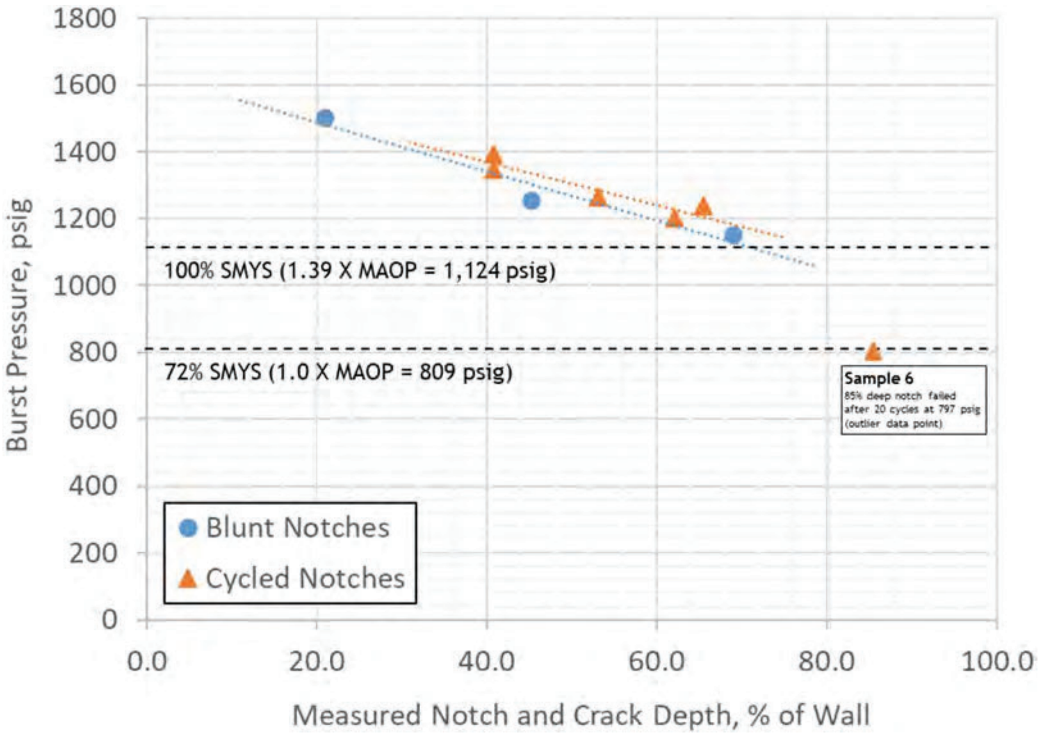

Figure 9. Burst pressures as a function of notch and crack depths

Application of Results to Pipeline Operations

The testing analysis methods employed in this study are generally applicable for all pipe materials, but the specific applicability of these results are for Boardwalk's 26-inch x 0.281-inch, Grade X52 A.O. Smith pipe specifically tested in this program. Figure 10 has been prepared to illustrate how the results in this program can be used to provide guidance for which crack-like flaws require excavation and repair. Once a "burst pressure failure curve" (i.e., API 579, MAT-8, actual, etc.) has been established correlating burst pressure as a function of crack depth, the pipeline operator has a choice in defining the threat level[3] they are willing to accept. The threat level is based on the safety factor associated with failure pressure relative to operating pressure. This section of the paper provides a comparison of the experimental burst test results to failure pressure estimates based on the following fracture models.

- API 579 using minimum yield strength (SMYS)
- API 579 using actual yield strength
- API 579 using actual Lrmax (maximum load ratio, modified using actual yield stress and ultimate strength)
- API 579 using lower shelf Charpy V-notch (CVN) values
- MAT-8 based on converted fracture toughness from CVN data (K_c based)
- API 579 based on effective fracture toughness interpreted from full-scale test results

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[3] The term "threat" is used here rather than "risk." Risk is defined as the product of likelihood of occurrence (i.e., threat) and consequence of failure. Consequence is outside the context of this body of work (and is very operator-specific), but threat management is directly related to defect assessment that is at the very center of this study.

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Guidance from the PHMSA Gas Rule (RIN 2137-AF39)

In RIN 2137-AF39 PHMSA provides guidance on safety factors relative to predicted failure pressures and MAOP. Copied below is text from 254-page "Mega" Rule, *Pipeline Safety: Safety of Gas Transmission Pipelines: Repair Criteria, Integrity Management Improvements, Cathodic Protection, Management of Change, and Other Related Amendments* (pages 108-110). Of particular interest are the safety factors that corresponds to 1,10, 1.25 and 1.39 times MAOP, which correspond to 79%, 90%, and 100% SMYS, respectively. **Bold text** below has been added by ADV to highlight these points in the PHMSA text.

> In this final rule, PHMSA did not adopt the proposed definitions of "significant seam cracking" and "significant stress corrosion cracking." With the revisions to the cracking repair criteria, these definitions weren't necessary. Similarly, with the deletion of the proposed repair criteria using those specific definitions, the recommendation for deleting the phrase "any indication of" from those criteria, became moot. Further, PHMSA's revisions to the cracking repair criteria also made the recommendation for PHMSA to combine the proposed SCC criteria and the seam cracking criteria moot.
>
> PHMSA believes that the repair criteria it proposed in the NPRM for cracks are consistent with research findings and provides an adequate safety margin while accounting for the severity of the defects through the analysis of the predicted failure pressure.[4] PHMSA believes the repair criteria for cracks that were suggested by some of the commenters would not provide an adequate safety margin due to factors including the accuracy of tool results, varying pipe toughness, and pressure cycling. This was discussed at length by the GPAC, who ultimately recommended that anomalies be classified as immediate conditions where the crack depth plus corrosion is greater than 50 percent of pipe wall thickness, compared to certain commenters who suggested that cracks with a depth of up to 70 percent pipe wall thickness be classified as immediate conditions.
>
> While the GPAC did not have an explicit recommendation for scheduled (i.e., non-immediate) crack repair criteria, they recommended that PHMSA consider a repair schedule for cracks that is less conservative than what was proposed in the NPRM. Their recommended schedule is: 1.39 times MAOP for Class 1 and 2 locations and 1.5 times MAOP for Class 3 and 4 locations. PHMSA considered this recommendation and determined that the condition should cover Class 1 locations and Class 2 locations containing Class 1 pipe that has been uprated in accordance with § 192.611, where the predicted failure pressure is 1.39 times MAOP. For all other Class 2 locations and higher class locations, the predicted failure pressure would be 1.5 times MAOP. Section 192.611 allows Class 1 pipe to remain in a Class 2 location if it has had a subpart J pressure test, for 8 hours, at 1.25 times MAOP. Also, it allows pipe with a design factor of 0.72, with the reciprocal of 1 divided by 0.72 being equal to 1.39, which is the predicted failure pressure. **Therefore, PHMSA elected to apply a predicted failure pressure ratio of 1.39 times MAOP to both Class 1 pipe and uprated Class 2 pipe.**

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[4] See ASME, "STP-PT-0011:Integrity Management of Stress Corrosion Cracking in Gas Pipeline High Consequence Areas" (2008). See also Young, B.A., et al., "Comprehensive Study to Understand Longitudinal ERW Seam Failures" (2017). Both papers call for anomaly evaluation; the knowledge of certain properties, including the length and depth of the crack, and pipe properties like wall thickness, grade, and toughness; and a proposed safety factor based on the time until the next assessment period. The papers also require that the depth of a crack not be greater than the depth of the assessment tool's tolerance. See § 192.712(e).

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> For immediate conditions, the GPAC asked PHMSA to consider if a less conservative repair criterion of 1.1 times MAOP (after tool tolerance had been applied) would be appropriate. PHMSA considered this suggestion but notes that, after allowing for pressure excursions above MAOP due to over pressure protection device settings, the actual safety margin of such an approach would be between 0 and 6 percent. **PHMSA has determined that this safety margin for immediate crack conditions is inadequate and, for this final rule, has retained the requirement that operators must immediately repair crack anomalies with a predicted failure pressure that is less than 1.25 times MAOP.**
>
> PHMSA took technical guidance information from several sources into account regarding significant SCC and significant seam weld corrosion when creating the repair criteria for these anomalies, including ASME ST-PT-011 ("Integrity Management of Stress Corrosion Cracking in Gas Pipeline High Consequence Areas").[5]

Interpretation of Results Relative to RIN-2 Ruling

In Figure 10 three safety factor lines have been drawn: 100% SMYS, 90% SMYS, and 79% SMYS. A 72% SMYS line is drawn for reference purposes only. The selection of a safety factor is important as it considers uncertainties in material behavior and crack sizing. According to the PHMSA ruling, an immediate response is required for predicted failure pressures for cracks that are less than 1.25 times MAOP (or 90% SMYS).

> PHMSA has determined that this safety margin for immediate crack conditions is inadequate and, for this final rule, has retained the requirement that operators must immediately repair crack anomalies with a predicted failure pressure that is less than **1.25 times MAOP**.

In the context of the presentation in this paper, these predicted failure points below the safety factor line are considered "unacceptable" and would require an immediate response on the part of an operator. The selected fracture model ultimately determines the number of excavations that will be required by an operator. Of all combinations presented in Figure 10, the most restrictive results are associated with the API 579 SMYS, CVN Lower Shelf and the 100% SMYS (1.39 MAOP) safety threshold line. Anything below the horizontal line is considered unacceptable (or requiring repair) and anything above is considered acceptable. In this case, 7 or the 8 data points would be considered unacceptable, or 87.5%.

Table 3 was compiled using the data plotted in Figure 10. This table illustrates the impact that both fracture model and the safety margin threshold can have on what crack depths are considered unacceptable from an integrity standpoint. If one considers the 100% SMYS threshold line and the API 579 fracture model with lower bound material values, 87.5% of the eight (8) crack-like features considered in this study will require excavation. In contrast, if the API 579 fracture model is used with fracture toughness based on full-scale burst test results only 12.5% (1 of 8) of the features would require excavation. These are noted in the table below as **BOLD RED**.

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[5] ASME, "STP-PT-011: Integrity Management of Stress Corrosion Cracking in Gas Pipeline High Consequence Areas" (2008).

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Table 3. Estimated number of excavations based on fracture model and safety threshold

Safety Threshold Line	Fracture Model	Acceptable Data Points	Unacceptable Data Points	Required Excavations
100% SMYS Threshold (1.39 MAOP)	API 579 (SMYS, CVN lower shelf)	1	7	87.5%
	MAT-8 (K_c based)	1	7	87.5%
	API 579 (actual properties)	6	2	25.0%
	API 579 (K_{mat} based on burst tests)	7	1	12.5%
	Full-scale burst test results	8	0	0%
90% SMYS Threshold (1.25 MAOP)	API 579 (SMYS, CVN lower shelf)	1	7	87.5%
	MAT-8 (K_c based)	3	5	62.5%
	API 579 (actual properties)	7	1	12.5%
	API 579 (K_{mat} based on burst tests)	8	0	0%
	Full-scale burst test results	8	0	0%

Figure 10. Predicted burst pressures as functions crack depth

Another useful format for presenting the analytical and experimental results is shown in Table 4. Included in this table are calculations associated with six different fracture model / material data combinations plus the full-scale burst test results. A total of eight data points are listed for each combination. Also included in this table are two threshold values against which the failure pressures are compared including 100% SMYS (1.39 MAOP) and 90% SMYS (1.25 MAOP). These data points are the same values plotted in Figure 10. To provide context all values less than the specified threshold pressure value are shown as **RED**, while all values greater than the specified threshold pressure value are shown as **GREEN**.

One can conclude that the benefits associated with fracture toughness values extracted from full-scale testing are worth the additional effort when considering the reduction in required excavations. This scenario is achieved because Boardwalk can now quantify the true performance capabilities of its pipe material.

Table 4. Failure pressures as functions of fracture model and crack depth

Sample ID	Final Crack Depth (% wall)	Burst Test Pressure (psig)	API 579 SMYS (psig)	API 579 Actual (psig)	API 579 Actual Lr_{max} (psig)	API 579 SMYS, CVN Lower Shelf (psig)	MAT8 (Kc-based) (psig)	Adjusted K_{mat} from Burst Tests (psig)
THRESHOLD: 100% SMYS (1.39 MAOP = 1,124 psig)								
1A-B	20.9	1,504	1,220	1,460	1,561	1,222	1,208	1,461
4A-BF	40.7	1,348	1,150	1,277	1,277	986	1,019	1,370
7A-BF	40.7	1,396	1,150	1,277	1,277	986	1,019	1,370
2B-B	45.2	1,257	1,054	1,167	1,167	882	966	1,318
8B-BF	53.1	1,265	1,026	1,136	1,136	852	949	1,300
5B-BF	62.0	1,202	1,054	1,167	1,167	882	966	1,318
9C-BF	65.4	1,238	927	1,023	1,023	752	874	1,187
3C-B	69.0	1,153	848	934	934	678	736	1,088
THRESHOLD: 90% SMYS (1.25 MAOP = 1,011 psig)								
1A-B	20.9	1,504	1,220	1,460	1,561	1,222	1,208	1,461
4A-BF	40.7	1,348	1,150	1,277	1,277	986	1,019	1,370
7A-BF	40.7	1,396	1,150	1,277	1,277	986	1,019	1,370
2B-B	45.2	1,257	1,054	1,167	1,167	882	966	1,318
8B-BF	53.1	1,265	1,026	1,136	1,136	852	949	1,300
5B-BF	62.0	1,202	1,054	1,167	1,167	882	966	1,318
9C-BF	65.4	1,238	927	1,023	1,023	752	874	1,187
3C-B	69.0	1,153	848	934	934	678	736	1,088

A final method for presenting the comparison of results is illustrated in Figure 11, showing differences between predicted and actual failure pressures from full-scale testing. Average differences for each of the calculation method were calculated and are included in the list below.

- API 579 using SMYS | **Difference of 18.8%** (maximum difference of 41.2%)
- API 579 using actual yield strength | Difference of 9.2%
- API 579 using actual Lrmax | Difference of 8.3%
- API 579 using lower bound CVN values | **Difference of 30.6%**
- MAT-8 based on fracture toughness from CVN data | Difference of 25.5%
- API 579 based on fracture toughness from full-scale test | **Difference of -0.6%**

As discussed previously, the largest differences exist when the minimum specified material properties are used (i.e., SMYS and lower bound CVNs), but the most accurate assessment method is achieved when using fracture toughness based on full-scale test results. These findings support the importance in having accurate material properties when estimating the failure pressures of pipes with crack-like features. Even the use of actual yield strength and Charpy values have a profound impact on better managing the conservatism of the fracture models.

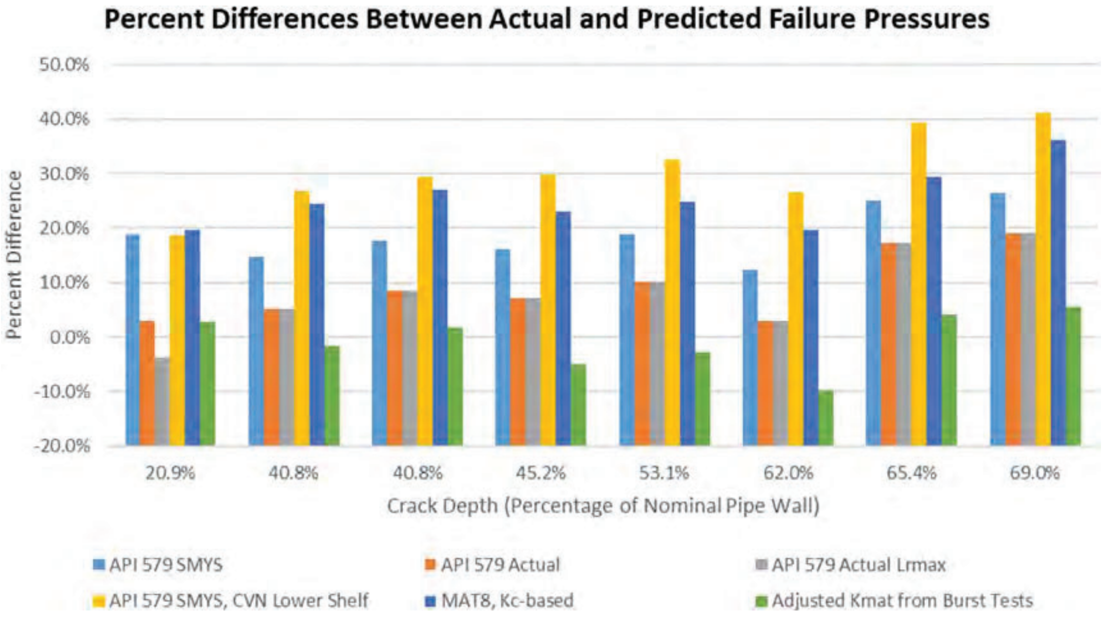

Figure 11. Graph comparing predicted and actual failure pressures

Conclusions

Provided below are concluding remarks related to how the current body of work has advanced our understanding of fracture mechanics and validated an approach that can significantly refine future crack assessment studies.

- Estimated burst pressures are sensitive to material property input data. The use of SMYS and lower shelf Charpy values results in low predicted failure pressures. Although conservative, a large number of excavations and repairs will be required.
- The use of actual material properties, as opposed to assumed minimum values, increases estimated failure pressures, and better represents actual failure pressures.
- The most accurate fracture models use fracture toughness derived from full-scale testing. The benefits for Boardwalk are two-fold. First, less uncertainty exists in predicting actual failure pressures. Secondly, the number of excavations and repairs required of Boardwalk will be reduced significantly (i.e., up to 75/% based on test results in this study).

This body of work has the potential to change pipeline operator's capacity to manage crack-like features safely and effectively and also influence regulations and the pipeline industry's crack management programs. Regulators should also be exposed to the concepts presented in this study so that future regulations and guidance can be provided that are consistent with the approaches presented in this comprehensive full-scale assessment program.

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