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NON-DESTRUCTIVE EVALUATION OF PIPE SEAM TOUGHNESS VIA FRICTIONAL SLIDING

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ABSTRACT

Several operators have increased the number of pipe cutouts and associated laboratory toughness testing for vintage assets to fill gaps in material records the original testing certificates did not include fracture toughness, a properties that the legacy version of the manufacturing specification did not require. This paper provides a non-destructive evaluation (NDE) approach to pipe seam toughness that can reduce the need for these disruptive pipe cutouts and increase the available dataset for the pipe toughness of specific assets. The NDE approach is currently specific to electric resistance welded (ERW) pipes, but data is provided from a limited proof-of-concept for Electro Flash Welded (EFW) pipes. The current process first estimates the 85% shear transition temperature of the seam in the CVN impact energy vs. temperature curve using the machine learning (ML) model. The predicted transition temperatures are shifted based on American Petroleum Institute (API) API 1176 to account for the difference in strain rate between a CVN test (impact) and fracture initiation (quasi-static). This shifted transition temperature is then compared to the minimum operating temperature. If the operating temperature is higher than the transition temperatures, the pipe material is confirmed to be in the upper shelf region of the CVN impact energy vs. temperature curve. If upper shelf values are applicable, a distribution of CVN toughness values for like samples is used to determine a conservative toughness estimate. A secondary machine learning model can provide an actual estimate of the toughness value.

NOMENCLATURE

CVN	Charpy V-Notch
DSAW	Double Submerged Arc Weld
HF	High-frequency
FITT	Fracture initiation transition temperature
FPTT	Fracture propagation transition temperature
LF	Low frequency
OD	Outer Diameter
PWHT	Post-weld heat treatment
SAW	Submerged Arc Weld
UT	Ultrasonic Thickness
UTS	Ultimate Tensile Strength
WT	Wall Thickness
YS	Yield Strength

1. INTRODUCTION

The evolution of In-line Inspection (ILI) technologies for seam anomaly detection has rendered seam toughness a more critical factor in minimizing unnecessary excavations than before these features were detected. As ILI technologies are progressively used, they lead to the detection and sizing of more non-severe features that may not immediately threaten pipeline integrity.

Conservative values for seam toughness have generally been in the 4 to 20 ft-lbs. range. To verify these assumptions and use appropriate values for specific assets, many operators have increased the number of pipe cutouts and associated laboratory testing. If validated, non-destructive evaluation (NDE) of pipe seam toughness emerges as an appealing solution for in-service pipelines, offering the advantage of avoiding disruptive pipe cutouts.

This paper provides a methodology for using a frictional sliding method and other surface measurements to offer an NDE process to assess seam toughness properties without using a pipe cutout. The technique employs specific field procedures where data is processed through machine learning (ML) models that predict various aspects of the Charpy V-notch (CVN) transition curve, providing measurements of pipe toughness with specific measurement uncertainty for consideration in reconfirming the Maximum Operating Pressure (MAOP) using Engineering Critical Assessment (ECA) or for use as part of ILI response and the determination of fitness for service.

2. MATERIALS AND METHODS

To determine the seam toughness properties, such as transition temperature and upper shelf CVN energy, samples can be evaluated by following the in-field methodology that includes using the method of frictional sliding with a Hardness, Strength, Ductility (HSD) tester and specific analysis to determine seam toughness from frictional sliding data.

2.1. Field Procedure

The field procedure begins with appropriate documentation. Sample properties, such as OD and WT, are confirmed, while site images, sample images, and other relevant information are collected.

Once the documentation is complete, a visual inspection of the longitudinal weld is completed. If there is a visible reinforcement, the shape of this reinforcement is evaluated. If it is squared, the seam type is determined to be Flash, while a rounded reinforcement suggests a SAW or DSAW weld. If a visual inspection does not result in an identifiable reinforcement shape, the seam is likely ERW, or the sample is seamless. A circumferential thickness survey may be used to distinguish between an ERW and a seamless pipe. While ERW samples will have a relatively consistent thickness, seamless samples will often show measurable variation throughout. Figure 1 details the in-situ seam determination process.

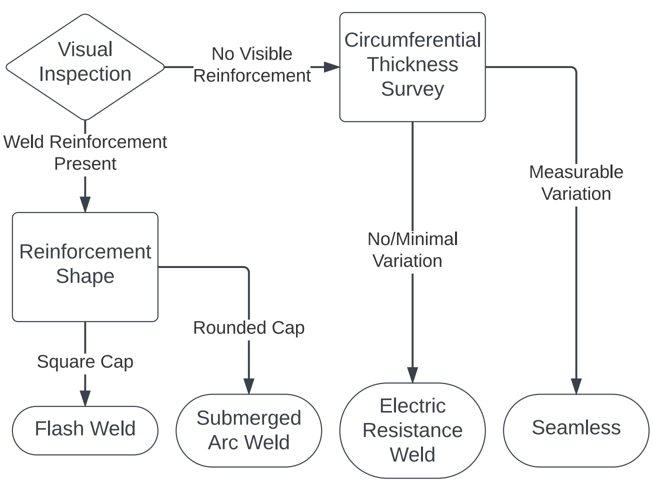


Figure 1. Flow chart depicting the in-situ identification process of various longitudinal seam types.

Two safe testing areas are determined once the seam type is identified and documented. The safety of a given test area is confirmed through processes such as visual inspection, UT lamination scan, magnetic particle inspection, radiography, or other techniques to confirm the absence of surface and subsurface flaws. To evaluate seam CVN toughness, one of the test areas must overlap the longitudinal seam. An example layout of the described test areas can be seen in Figure 2.

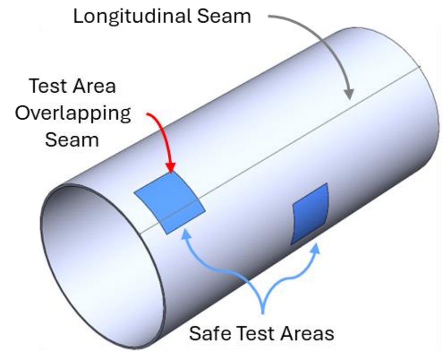


Figure 2. Potential layout of test areas on a sample.

The testing process includes capturing base metal chemical composition, microscopy images for grain analysis, and HSD frictional sliding tests, both across the seam and in the base metal.

The frictional sliding tests consist of 4 styluses, each with a unique geometry, engaging on the prepared pipe surface with a known load. The loaded styluses travel at a slow, quasi-static speed to create a residual groove profile. The material response of the profile. A representative image of the testing process across a seam is shown in Figure 3.

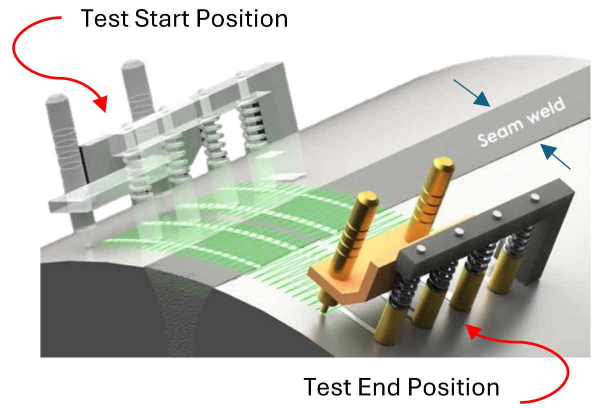


Figure 3. Representation of the HSD frictional sliding process across a longitudinal seam.

2.2. ERW Seam Classification

While the field procedure and flow chart in Figure 1 determine seam type, this process does not distinguish between ERW classifications, such as LF, HF, or HF with PWHT. These manufacturing processes result in different integrity implications for safe pipeline operation. A combination of HAZ width, sample WT, and HSD frictional sliding response data is used to create a classification model to distinguish between ERW manufacturing processes.

In prior work, a non-destructive method was proposed to identify the welding process used in electric-resistant welded (ERW) pipelines [1]. In this approach, a classification model based on a known ERW seam database predicts the seam type using NDE data, as shown in Figure 4.

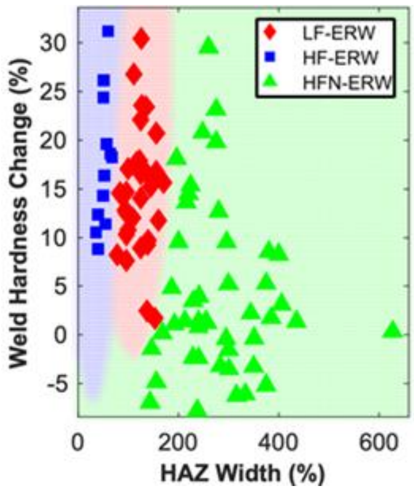


Figure 4. ERW seam-type classification tree.

This method combines hardness variations measured using HSD testing and macro-etching to measure features like heat-affected zone width and hardness changes across the weld to determine ERW seam types as low frequency (LF), high frequency (HF), and high frequency normalized (HFN) without the pipe cutouts. These measurements are then normalized for pipe size and grade, allowing for comparisons and classification of unknown samples of different sizes and grades.

In Figure 4, the colored regions on the plot show the different seam-type decision boundaries. Data points for building the model are filled in, and a black border and label identify the tested field samples. Each sample is tested twice, resulting in two data points in the above plot. The material response of an ERW-HF sample can be seen in Figure 5. The relative change in hardness between the HAZ and the base metal determines the location along the y-axis of Figure 4. A macro-etch image can be seen in Figure 6, which is used to obtain the HAZ width shown on the x-axis of Figure 4.

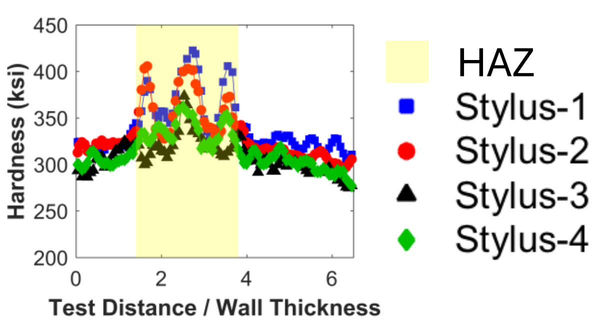


Figure 5. Example HSD frictional sliding response for an ERW-HF seam. Unique response changes can be seen across the HAZ.

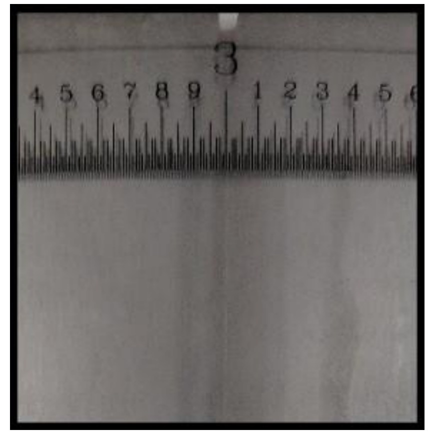


Figure 6. ERW seam macro etch.

2.3. S-Curve Parameters

Multiple prediction models using machine learning (ML) were developed to evaluate regions of the CVN transition curve for the ERW seam, including the ductile-to-brittle transition temperature (DBTT) and the impact energy at the upper shelf. These non-destructive estimates are to be compared to curve fits of the CVN impact energy defined by

$$C_v = A + B * \tanh\left(\frac{T - C}{D}\right) \quad (1)$$

where T is the CVN test temperature and A, B, C, and D are fitting coefficients define the shape of the curve. Compared to tensile strength tests of the pipe body, CVN lab tests of the ERW seam are associated with more significant uncertainties due to material variation, data interpretation, and curve-fitting implementation, which leads to higher uncertainties in the NDE models developed to predict those lab values.

All NDE predictions of the CVN impact energy are for full-size specimens, assuming a linear relationship when scaling the impact energy for sub-size specimens. The ductile-to-transition temperature is given for a full-size specimen in a drop-weight tear test (DWTT) using the relationship [2].

$$T_D = T_C + (66 * {t_w}^{0.55} * {t_c}^{-0.70} - 100) \quad (2)$$

where T_C is the CVN 85% shear-area transition temperature (SATT), t_w is the pipe wall thickness, and t_c is the CVN specimen width. The result of the applying curve fit on raw Charpy data for one pipe sample is shown in Figure 7.

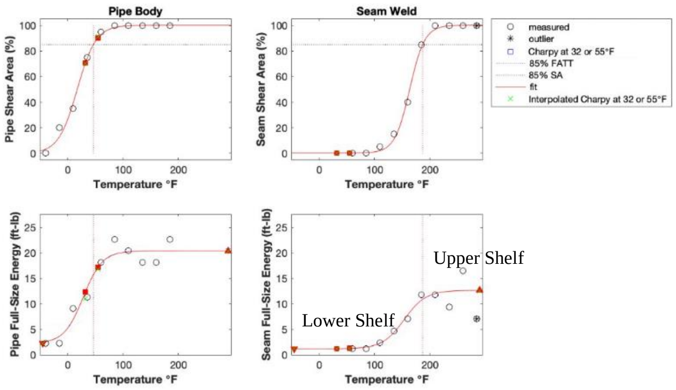


Figure 7. CVN tanh curve-fits for shear area vs. temperature and Charpy energy vs. temperature for pipe body and seam weld.

Figure 7 shows the tanh curve fits applied to raw Charpy data. The pipe sample was Charpy tested at ten different temperatures; the raw values are shown with circles. Charpy impact energy was also measured at 32°F and 55°F and is shown with squares. Seam weld toughness is not the same as pipe body toughness.

2.4. Temperature Shift

When applying the SATT for use, there are additional influences on a material's toughness response in addition to just temperature. A critical consideration is that of the speed of loading. As stated, a CVN test involves a rapid application of load through an impact and is considered a dynamic test. In contrast, the initial growth of a crack to its critical size where rapid failure occurs takes place at a quasi-static rate. American Petroleum Institute (API) Recommended Practice (RP) 1176 Annex E.5 provides a method to perform a transition temperature shift for vintage ERW pipeline assets.

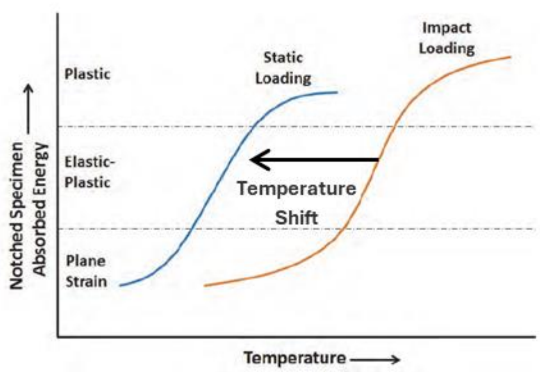


Figure 8. Transition Temperature Shift as Found in API 1176 [API 1176].

For most pipelines, accounting for this shift predicts a ductile upper shelf behavior. However, for certain ERW seams, brittle fracture initiation is possible .

The conversion from a fracture propagation transition temperature (FPTT) to a fracture initiation transition temperature (FITT) can be simply expressed as:

$$\mathrm{FITT} = \mathrm{FPTT} - \Delta\mathrm{T} \tag{3}$$

Determining the temperature shift required in Eq. 3 can be achieved through multiple routes, including API 1176 Annex (E.5). Eq. 4 shows the quasi-static temperature shift in (°F) and YS is the yield strength in (ksi).

$$\Delta\mathrm{T} = 215 - 1.5\mathrm{YS} \tag{4}$$

This equation is based on the work of John Barsom while evaluating the fracture toughness of different steels [3]. The equation is valid for YS range of 36 ksi to 140 ksi. For pipes above 140 ksi, the shift becomes 0. Based on this equation, for X-52 pipe a temperature shift of 137°F will be applied to the Fracture Toughness results obtained through CVN tests. This value is close to the temperature shift Keifner observed during experimental CVN testing of pipe samples [4].

Calculated conservative FITT can then be compared to the operating temperature for a given sample. The process of applying a temperature shift to the entire s-curve is depicted in Figure 8.

If the operating temperature exceeds the FITT, the sample is believed to be in the ductile region. In contrast, if the operating temperature is below the FITT, the sample is expected to show brittle behavior. Most samples exhibit ductile behavior at operating temperature. As such, models have been generated to determine a conservative upper-shelf estimate.

3. RESULTS AND DISCUSSION

An NDE process for CVN toughness of ERW seams estimates the regions of the CVN transition curve for the ERW seam, including the impact energy at the upper shelf and the ductile-to-brittle Shear Area Transition Temperature. These non-destructive estimates were compared to curve-fits of the CVN impact energy from standardized laboratory testing as detailed in Section 2.3. Due to the sub-size nature of CVN testing samples drawn from vintage pipe in the laboratory tested dataset, all values of the CVN impact energy are translated for full-size specimens assuming a linear relationship when scaling the impact.

3.1. Model Validation

Figure 9 illustrates the calibration and blind test results for the ductile to brittle transition temperature ML model. The number of samples used for model calibration is 46. The blind set contained 22 independent samples and was not used for training the ML Model. As shown, all blind samples were estimated to be within +/- 50°F, which was adapted as the acceptance criteria.

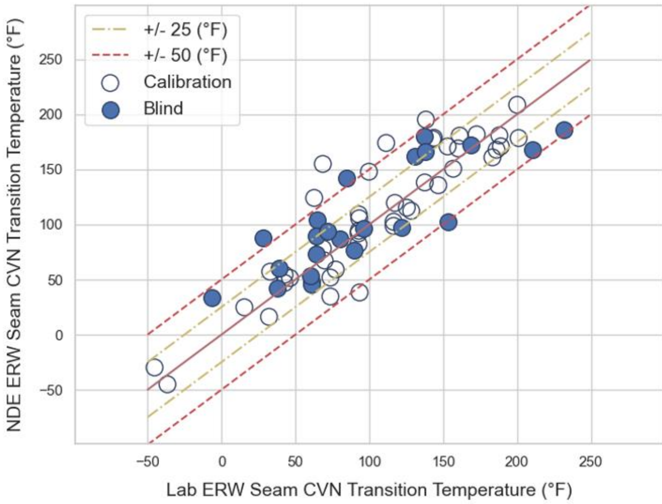


Figure 9. Transition Temperature versus Lab Transition Temperature.

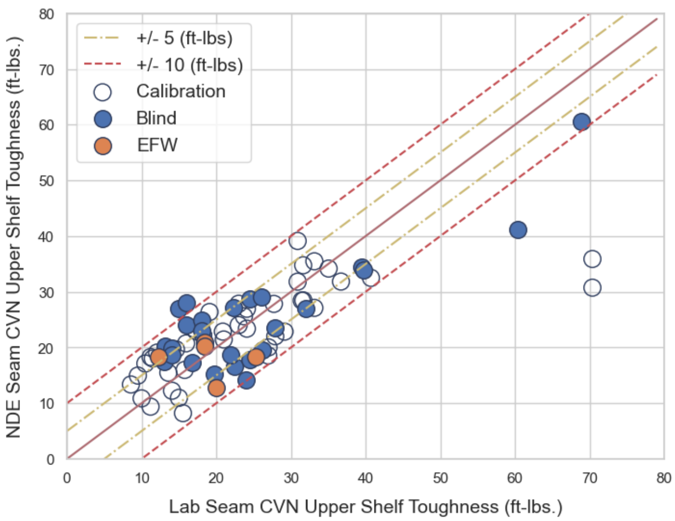


Figure 10. NDE CVN toughness versus Lab CVN toughness.

Figure 10 illustrates the calibration and blind test results for a second ML model to estimate the upper shelf seam toughness using the same pipeline samples. Like the transition temperature ML Model, the blind set contained 25 independent samples and was not used for training the ML Model. All blind samples were estimated to be within +/- 10 ft-lbs. One high-toughness pipe sample was estimated conservatively by 20 ft-lbs. due to the lower representation of such samples in the current pipe database. However, since the estimate was on the conservative side, the results were deemed acceptable.

3.2. Classification Approach for Upper Shelf

Given the measurement uncertainty associated with the determination of the upper shelf CVN model presented in section 3.1, I classification approach is proposed that leverages NDE measurements of the applicable shelf of the S-Curve for the behavior in fracture initiation at the applicable operating temperature. Once the applicable shelf of the S-Curve is determined, laboratory test result distribution is utilized to provide conservative values. As an example, Figure 11 and Figure 12 show the laboratory distribution of energy for the lower shelf and upper shelf from the sample database for LF ERW

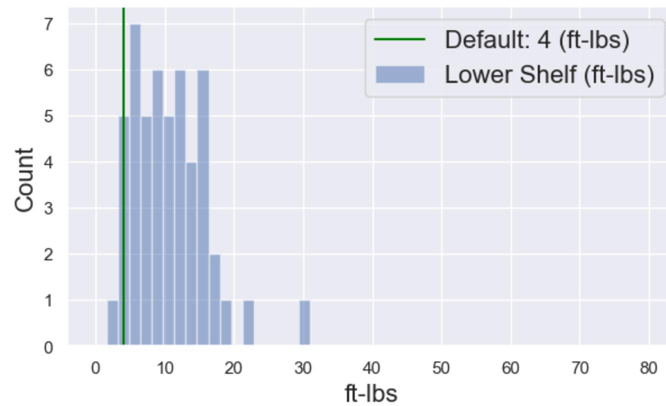


Figure 11. Histogram distribution of Seam CVN Lower Shelf Toughness for ERW samples.

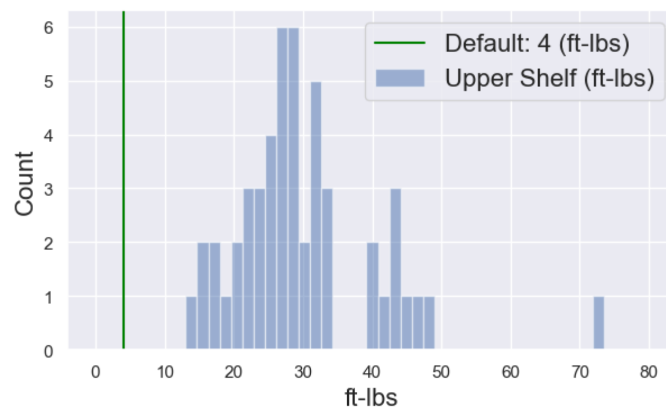
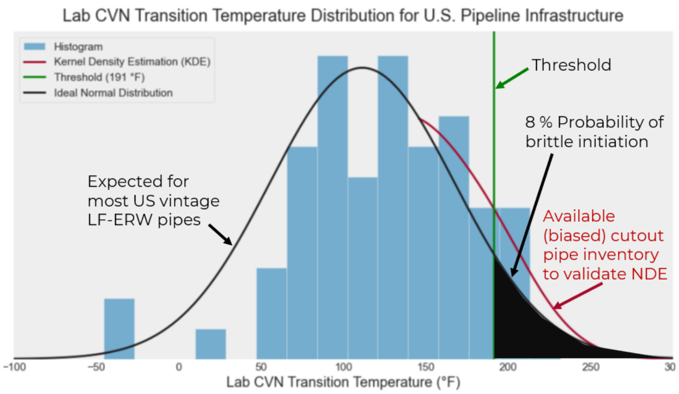


Figure 12. Histogram distribution of Seam CVN Upper Shelf Toughness for ERW samples.

If the NDE measurements allow to conservatively confirm a FITT lower the minimum operating temperature, the distribution in Figure 12 may be used justify the use of 10 ft-lbs as a conservative CVN energy for that LF ERW seam. Otherwise, default values or other source of information may be relied upon.

To estimate the likelihood of conservatively estimating 10 ft-lbs for an LF ERW seam, Figure 13 provides a histogram of laboratory transition temperature from the sample database. The distribution was corrected for bias using a Kernel Density Estimation (KDE) to account for a bias in the database for samples that originated from failures versus random samples.



Index of a propensity for a brittle fracture initiation

Figure 13. Histogram distribution of Seam CVN Transition Temperature based on 106 samples.

Once the correction is applied, an estimated 8% of the LF-ERW pipe samples randomly lab tested will have a brittle initiation based on a threshold of 191°F. The threshold was determined using the operating temperature of 55°F and a typical temperature shift of 136°F [5], [6]. By applying a conservative shift associated with obtaining the data through NDE, this distribution of transition temperature allows us to estimate at 75% the probability for a randomly selected sample to have 10 ft-lbs as a minimum conservatively estimated CVN toughness.

3.3. Case Studies

In a recent project, the assessment of electric resistance welding (ERW) seams in in-service pipelines involving four pipe joints was performed. The analysis identified all four joints as high frequency with post-weld heat treatment (HF-PWHT) seams, indicating a potentially higher fracture resistance than other ERW types. These samples are shown in the ERW classification plot in Figure 3. The transition temperature ML Model assessment values are provided in Table 1. The NDE transition temperatures were shifted to convert from Impact Fracture to Quasi-Static Fracture Initiation Temperature. As stated earlier, turning the NDE transition temperatures to the quasi-static fracture initiation temperature makes them directly comparable to the pipeline operating conditions. The histogram distribution of the converted values is provided in Figure 14.

Sample Name	Seam Type	Test #	NDE Impact Fracture (85% Shear Temperature)				Fracture Propagation to Fracture Initiation Conversion		Converted NDE 85% Shear Temperature			
			Est. (°F)	Avg. (°F)	Cons. (°F)	Avg. (°F)	Ref. YS (ksi)	API 1176 Temp. Shift (°F)	Est. (°F)	Avg. (°F)	Cons. (°F)	Avg. (°F)
Sample 1	ERW HFN	1	-22	-23.5	38	36.5	58.6	127	-149	-151	-89	-90.5
		2	-25		35				-152		-92	
Sample 2	ERW HFN	1	-3	-4.5	57	55.5	60.9	124	-127	-129	-67	-68.5
		2	-6		54				-130		-70	
Sample 3	ERW HFN	1	14	17.5	74	77.5	64	119	-105	-102	-45	-41.5
		2	21		81				-98		-38	
Sample 4	ERW HFN	1	7	10	67	70	60.8	124	-117	-114	-57	-54
		2	13		73				-111		-51	

Table 1. Field trial - NDE transition temperature results.

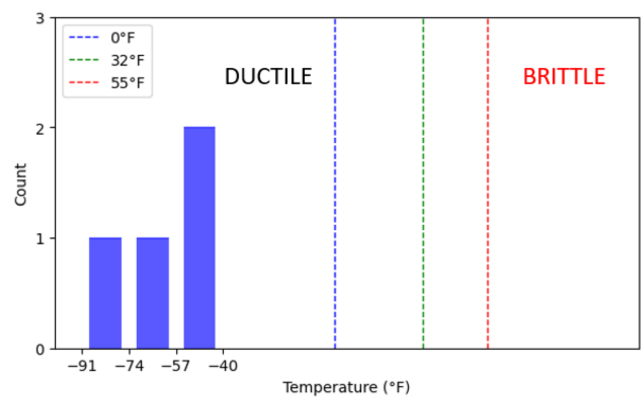


Figure 14. Histogram distribution of Quasi-Static Fracture Initiation Transition Temperature of the tested in-service pipe samples compared with the operating temperature to determine ductile versus brittle region.

As seen in Figure 14, all in-service pipe samples have converted NDE transition temperature less than the operating temperature (32°F/55°F) threshold and thus meet the criteria for the pipe joints considered on the upper shelf of the CVN transition curve region. Also, the transition temperature values were sufficiently lower than the threshold operating temperature to minimize the risk of unknown brittle fracture under normal operational conditions. Meanwhile, the range of NDE toughness values for the HFN seams was between 27-33 ft-lbs., resulting in conservative estimated values in the range of 17-22 ft-lbs. after accounting for measurement uncertainty. The results are provided in Table 2. This data from the four excavations shows that the current field process provides sufficient supporting data for taking 15 ft-lbs. toughness on this ERW HF with PWFT seamed pipeline.

Sample Name	Test #	Upper Shelf Impact Energy (ft-lbs.)	Avg.	Conservative Upper Shelf Impact Energy (ft-lbs.)	Avg.
Sample 1	1	30	32	20	22
	2	34		24	
Sample 2	1	28	28	18	18
	2	28		18	
Sample 3	1	27	26.5	17	16.5
	2	26		16	
Sample 4	1	28	28	18	18
	2	28		18	

Table 2. Field trial - NDE upper shelf impact energy results.

Duplicate HSD tests where each of the 4-styluses proceeds across the seam provide duplicate values for the transition temperature and upper shelf seam toughness. Each test involved measuring four complete hardness profiles. However, only three of those profiles were considered independent measurements for each test due to excluding a profile that failed to meet ML Model design criteria. Therefore, three independent profiles per test and two tests per pipe sample provide six independent measurements. This exceeds the minimum 5-test requirement specified in the regulation to comply with CFR 192.607. Furthermore, as seen from the tables, for the transition temperature, the repeated test showed a variation of less than +/- 5°F, while the upper shelf toughness was less than +/- 2 ft-lbs. Based on this data, duplicate testing may be sufficient.

4. CONCLUSION

A procedure where NDE data that includes hardness profiles across ERW and other material input has been successfully blind tested to determine the 85% shear transition temperature of ERW longitudinal seems with a measurement uncertainty of 60°F based on a one-sided prediction interval at 80% certainty. Initial results show the potential for expanding the process's application to vintage pipelines with EFW longitudinal seams. A case study shows that leveraging measurements from fracture mechanics testing methodologies instead of Charpy energy values would be advantageous in reducing the level of uncertainty in the material properties used for calculating the failure pressure.

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