Combining Nondestructive Techniques to Obtain Full Vintage Pipeline Asset Fracture Toughness

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Pipeline Pigging and Integrity Management Conference

February 6-10, 2023

Organized by
Clarion Technical Conferences

Abstract

Recent and upcoming regulatory changes have introduced requirements to analyze the predicted failure pressure and critical strain level of line pipe using flaw sizing and population-specific material properties such as material toughness. For vintage oil and gas transmission pipeline assets, even if original Material Test Records (MTRs) are available, American Petroleum Institute (API) 5L and most procurement specifications for line pipe did not include fracture toughness until the appropriate laboratory testing was added in the 1980s. In the absence of this data, operators are required to use conservative minimum values or obtain the data with options including performing cut-outs or nondestructive testing. This paper summarises public literature regarding the use of different nondestructive evaluation (NDE) techniques, and their different stages of development and implementation, for measuring fracture toughness. Of these techniques, this paper takes a deeper dive into a new NDE toughness solution using frictional sliding data for determination of the Charpy V-Notch (CVN) based transition temperature for Electro-Resistance-Welded (ERW) pipes supported by results from blind testing and example case studies.

1. Introduction

For vintage transmission pipeline assets, new material toughness data is often needed because, even if original Material Test Records (MTRs) are available, the manufacturing specifications for the line pipe did not have fracture toughness requirements until they were added in the 1980s. Given the need to obtain Traceable, Verifiable, and Complete (TVC) material data in specific assessments and for maximum allowable operating pressure (MAOP) reconfirmation, a nondestructive evaluation (NDE) approach is an attractive option. With the issuance of the Pipeline and Hazardous Materials Safety Administration (PHMSA) amendment to 49 CFR Part 192 RIN 2137-AF39 “Pipeline Safety: Safety of Gas Transmission Pipelines: Repair Criteria, Integrity Management Improvements, Cathodic Protection, Management of Change, and Other Related Amendments" in August 2022, the scope for verification of the material fracture toughness has expanded to a greater number of integrity activities as compared to the original MEGA Rule released in October 2019. In October of 2019, the requirements from §192.712 “Analysis of Predicted Failure Pressure” were referenced to be used in §192.632 “Engineering Critical Assessment for MAOP Reconfirmation" which is commonly applied when satisfying §192.624 “MAOP Reconfirmation.” With the August 2022 issuance, §192.712 has been edited to read “Analysis of Predicted Failure Pressure and Critical Strain Level.” It is now referenced by several additional sections, including the new section §192.714 on determining repair criteria. Compared to the August 2022 release, the period to implement these new requirements has been extended to begin February 2024. This extension provides an opportunity to leverage technology, engineering expertise, and practical experience to develop complete and implementable field processes that support the industry goals of safety and compliance. This paper outlines the challenges in complying with recent and upcoming regulatory requirements to support the analysis of predicted failure pressure using population-specific material toughness properties, providing an overview of existing NDE methods as well as a new solution for NDE seam toughness.

2. Challenges and Opportunities – Material Verification in the MEGA Rule

Inspection and maintenance of gas transmission pipeline assets is a regulated industry under 49 CFR Part 192. As recommended by the National Transportation Safety Board (NTSB) and mandated by congress, the ultimate goal of the recent two issuances of the gas MEGA Rule is to reduce the yearly incident rate. The industry is aligned with the new regulation with many initiatives and efforts towards the goal of “zero incidents.” As explained by others, the regulation by itself does not reach that goal [1]. The industry shall continue to collectively go above and beyond the regulation by working together, creating new technologies, and improving and implementing new processes. Although operators have the ultimate responsibility to meet the new regulatory requirements, the process requires substantial collaboration between PHMSA, pipeline operators, and third-party engineering, technology, and service vendors.

This section speaks specifically to requirements related to material verification and how, through collaboration, these requirements can be met through a careful and gradual implementation of the requirements. Many sections of the MEGA Rule related to material verification allow for flexibility and continuous improvement in their implementation. Table 1 shows three examples related to the amount of material verification testing, how to conservatively account for measurement uncertainty in NDE measurement, and how to select data to calculate the remaining failure pressure. For each of these three requirements, there are challenges to overcome and opportunities that can be captured over time.

Table 1 – Examples of Challenges and Opportunities related to Material Verification Requirements [2]

Regulatory Requirement	Challenges	Opportunities
§192.607I(2)(i) requires that for each pipe population, the operator determine material properties *"until completion of the lesser of the following: (i) One excavation per mile rounded up to the nearest whole number; or (ii) 150 excavations if the population is more than 150 miles."* [2]	For large mileage assets, this requirement cannot be fulfilled without several cycles of re-inspection every 7 years (or other time interval set by operators or regulators).	Section §192.607(e)(5) states that *"An operator may use an alternative statistical sampling approach,"* [2] providing that certain requirements are met including a 95% confidence level and that the sampling approach is submitted to PHMSA per §192.18.
§192.607(d)(2) requires that nondestructive methods *"conservatively account for measurement inaccuracy and uncertainty using reliable engineering tests and analyses"* [2]	A measurement uncertainty depends on the *"methods, tools, procedures, and techniques"* [2] validated and used to make measurements, including the individual technician executing procedures.	The industry has (1) expertise in performing "blind testing" to evaluate measurement processes against destructive test standards with statistical performance criteria and (2) Operator Qualification (OQ) gatekeeping to ensure that individual technicians follow procedures.
§192.712(d)(1) requires that, when analyzing cracks and crack-like defects, an operator must determine the predicted failure pressure and crack growth using *"technically proven fracture mechanics model appropriate to the failure mode (ductile, brittle or both), material properties (pipe and weld properties), and boundary condition used (pressure test, ILI, or other)."* [2]	Although the use of fracture mechanics model has grown in the industry over the past decades, fracture mechanics was not part of the original design requirements when most vintage assets were installed. Therefore, new testing is needed for the majority of the pipeline assets even if they have TVC pipe grade.	Nondestructive techniques are allowed by the regulation, and a number of viable techniques have been developed and validated for certain specific applications as described in Section 4 of this paper.

Excavation Quantity: Section §192.607(e)(2) states that material verification shall be conducted on a per-population basis at the rate of one excavation every mile or 150 total excavations if the population is greater than 150 miles, whichever is less [2]. A single excavation for the purpose of inspection and testing takes significant planning and time to execute and is expensive, but generally remains a low single-digit percentage of what would be the replacement cost. For large mileage assets, submitting an alternative sampling plan using a statistical basis to verify the material properties of a pipeline segment with at least a 95% confidence level is an option to consider, especially when TVC records are needed for compliance to other pipeline integrity requirements. As described in a study focused on evaluating different approaches to statistical sampling [3], while the scope of an alternative sampling plan can be pre-determined, the total number of digs required to reach the prescribed confidence level will adjust and fluctuate depending on the findings as data is collected. However, the study demonstrates scenarios where 5 to 7 tests per population may be sufficient as long as there is confidence that the asset section is a single population. Higher-grade pipes are found to require more testing than lower-grade pipes.

Accounting for Measurement Uncertainty: Section §192.607(d) states that one must *"conservatively account for measurement inaccuracy and uncertainty using reliable engineering tests and analyses"* [2] without specifying which measure of uncertainty should be used such as root mean square error (RMSE), prediction interval, or tolerance intervals. Prior work detailed in "A Statistical Approach to Material Verification of Expected Grade through Opportunistic Field Measurements" [3] used symmetric prediction intervals for comparing technologies. However, through collaboration and in more closely examining the rule and gaining additional project experience, a one-sided prediction interval or a one-sided tolerance interval have been found to be more appropriate because the rules speak to conservative evaluations, which confirms that one side of the error is what need to be accounted for. Measurements where the strength of the pipeline is overestimated should be avoided with a specified level of certainty. Table 2 shows the implication of using a symmetric interval versus a true one-sided interval in benchmarking two commercial offerings based on two different NDE methods. The data used for the comparison is the average between two published studies where side-by-side blind testing was performed. The first study was published in 2018 by the Pipeline Research Council International (PRCI) and was comprised of multiple NDE methods being blind tested on a total of 50 samples of varying vintages, grades, manufacturers, seam types, and geometries to capture a sample set representative of the total pipeline population in North America [4]. The second study was published in 2021 by Gas Technology Institute (GTI) through PHMSA and consisted of blind testing on 43 samples [5]. For these 93 datapoints, laboratory tensile testing data was performed per API 5L with the stipulated specimen orientation (longitudinal or transverse) depending on pipe diameter and manufacturing technique. The Symmetric Prediction Interval was determined using 60% 2-sided statistical prediction interval. The true one-sided prediction interval was determined using statistical tolerance interval using Hanson and Koopmans 1964 method with 80% certainty and 50% confidence.

Table 2 – Illustration of the Effect of Statistical Metrics for Comparing the Relative Performance of Two NDE Processes

Commercial Offering Methods	Symmetric Prediction Interval (ksi)	True 1-Sided Prediction Interval (ksi)
Ball Indentation	4.8	5.9
Frictional Sliding	4.4*	3.1*

* The results on the (larger internal) database are 3.0 ksi.

Over the past few years, the measurement level of accuracy for yield strength has generally been set at 80% certainty to ensure that verification can be practically implemented while still ensuring that assets with unexpected grade values are identified. With this level of certainty, the ability to detect outliers and their frequencies has been the topic of a previous recent publication [6].

Predicting Failure Pressure: Section §192.712 provides general guidelines on using material toughness for the purpose of predicting failure pressure and provides default conservative Charpy V-Notch (CVN) energy values to be used in the absence of material toughness records. Fracture toughness values were not typically included in MTRs until the 1980's which means that vintage pipeline assets typically do not have this data available for a specific set of assets. Significant challenges with collecting this data are the inherent difficulty to conduct reliable fracture toughness testing in a lab setting and the population-specific sample availability. However, a number of industry approaches are available both in the laboratory and in terms of NDE techniques to provide data for the determination of the *"failure mode (ductile, brittle or both)"* [2] and with the associated quantification of CVN toughness. The remainder of this paper will explore various methods for determining pipeline seam and body fracture toughness utilizing existing and in-development NDE solutions and will discuss methods by which the industry can compare data.

3. CVN Toughness for Pipeline

Toughness is commonly used to describe a material's ability to resist failure due to cracks or crack-like flaws. In practice, the level of specificity in referring to 'toughness' is akin to the specificity in referring to 'strength' and, therefore, further discernment is required when considering design and assessment of fitness-for-service. The MEGA Rule refers to the material capacity to be used to perform a calculation of the failure pressure as the CVN Toughness. Technically, the CVN test and the material toughness test are two different types of tests, but there are many conversion methods to express the findings from one type of test into results for the other. A CVN test measures the energy required to fracture a notched material. In contrast, a material toughness test is rooted in a stress-based fracture analysis with a more direct utility for fitness-for-service assessments of materials. A comprehensive approach to utilizing CVN for fracture toughness assessments can be found in API-579 Appendix F.4.5 [7]. Across industries, a key function of the CVN test is to compare the relative toughness of materials and determine the ductile-brittle transition temperature. To apply a CVN to fracture toughness conversion, differences in failure modes is a factor to consider.

3.1 Brittle vs Ductile Failure: Why does it matter?

Observation and study of fracture response in CVN as well as other toughness tests has shown that there are many factors that influence the ease to fracture a specimen. Among them are metrics like test temperature, loading rate, and specimen thickness [8]. Across these different scenarios, the weakest responses to an induced fracture occur when the material responds in a brittle manner. If the temperature is lower, the loading rate is faster, or the specimen is thicker, the tendency to initiate in a brittle manner increases. The exact reasoning behind this behavior is outside of the scope of this paper. However, it cannot be overemphasised that determining the conditions that could result in a brittle material response is an important factor in fracture mechanics calculations.

One of the primary use cases of CVN testing is in determining the temperature at which the behavior of a material will change from a brittle response to a ductile one due to impact loading. This critical temperature is known as the ductile to brittle transition temperature (DBTT). If the material is utilised in service at temperatures below this transition temperature, a brittle behavior can be expected, resulting in a weaker toughness characteristic. There are several methods for specifying this temperature from CVN test results. One such method commonly used for pipelines is the 85% shear area transition temperature (SATT).

When applying the SATT for use, there are additional influences on a material's toughness response in addition to just temperature. An example of these additional influences is the speed of loading, a critical parameter that should be taken into consideration. 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. Recalling that the faster a load is applied to a material, the more likely it is to elicit a brittle response, it can be understood that a SATT determined by CVN testing might prematurely predict brittle fracture from crack growth in a pipeline. As a result, in many cases it is appropriate to account for this difference by applying a 'shift' to the transition temperature determined by CVN testing. API 1176 Annex E.5 provides a method to perform this transition temperature shift as shown in Figure 1 on pipeline assets [9].

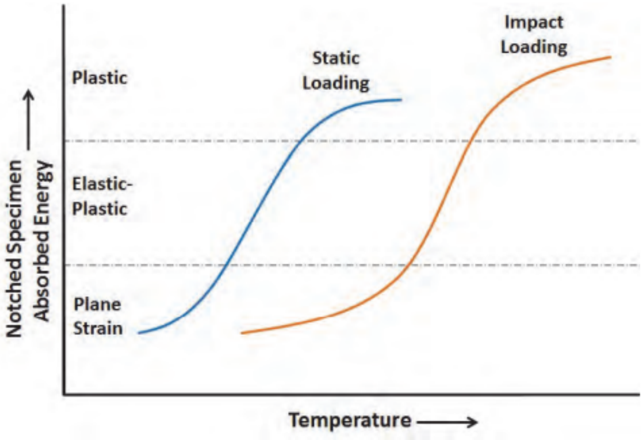

Figure 1: Transition Temperature Shift as Found in API 1176 [9]

In many pipelines, accounting for this shift can be the difference between confirming or not confirming the assumption of a ductile behavior. Not being able to confirm a ductile behavior generally requires many more repairs for detectable crack anomalies.

3.2 Considerations for Modern vs Vintage Assets

Steel and pipeline manufacturing has improved throughout the 20th century, including improvements to welding processes starting in the 1960's and converting to newer improved processes for the steel being formed throughout the 1970's-1980's [10]. With the need to consider assets across a large range of eras, manufacturers, and resulting processes, notable differences in the most effective approach to managing these populations can be expected. Essential work has already been performed to assist operators in being able to categorize their assets accordingly [10].

A key difference resulting from less strict quality control metrics in early pipeline manufacturing is the significantly worse performance of those vintages in crack assessment scenarios. Kiefner has highlighted several common sources of issues such as insufficient hydrostatic testing standards, impurities in steels, and inconsistent welding equipment performance. As it pertains to this discussion on toughness assessment, these factors lead to an increased presence of various crack-like defects as well as steel compositions which will have lower toughness or a greater risk for brittle fracture behavior than modern steel assets.

The increased toughness and quality control methods of modern steel assets permit fitness-for-service style assessments which allow for reasonable consideration of crack-arrest scenarios because of lower SATT. Under certain conditions, an SATT lower than the minimum operating temperature increases the likelihood of ductile crack propagation. However, as per API RP 1176 Annex E, "*specifying [SATT] to be below the lowest operating temperature is a modern pipeline design target*" [9]. For vintage assets, preventing fracture initiation is said to be the only practical option for mitigating the risk of failure.

3.3 Considerations of Pipe Body vs Long Seam Toughness

Many of the vintage-specific shortcomings of older pipeline materials appear in the form of defects along the longitudinal seam of the pipe. For this reason, there is an increased presence of cracks and crack-like features, which may grow to critical sizes if the material can initiate fracture in a brittle mode. The risk of seam failure of long seam varies with welding processes and welding parameters. With vintage electro-resistance-welded (ERW) processes, cold welds, hook cracks, selective seam weld corrosion, and the enlargement of seam defects by pressure-cycle induced fatigue have been determined to be the primary threats to seam integrity of ERW and Flash pipe [11]. The concentration of these threats to integrity naturally makes the toughness of the long seam a key area of interest for assessment.

For ERW seams it is known that effects related to heating of the pipe and weld area throughout the welding process, such as grain coarsening, have direct implications in lowering the toughness characteristics of the weld and heat affected zones [10]. Most often, the toughness of the weld region will be lower than that of the general pipe body. This theory has been supported through comparison of CVN results on vintage assets which show that toughness increases as one moves from the longitudinal seam to the pipe body [12]. These results have been found to be consistent with data from MMT's own database of approximately 100 pipes seen in Table 3. Although this knowledge does not remove the utility or need for pipe body toughness in all cases, it does show that an assessment of the long seam toughness may reliably determine the integrity of the highest risk area for a vintage asset.

Table 3 – Approximate CVN Toughness Comparison of Pipe Body vs Longitudinal Seam of Vintage ERW Pipeline

	Default Value per §192.712	MMT Data: Brittle (Lower Shelf CVN)	MMT Data: Ductile (Upper Shelf CVN)
Vintage ERW Long Seam	1 ft-lbs or 4 ft-lbs	1 ft-lbs to 30 ft-lbs	9 ft-lbs to 70 ft-lbs
Vintage ERW Pipe Body	5 ft-lbs or 13 ft-lbs	5 ft-lbs to 30 ft-lbs	16 ft-lbs to 80 ft-lbs

4. NDE Solutions for CVN toughness

4.1 Existing NDE Solutions for Pipeline CVN Toughness

Over the past several years NDE methods to predict CVN test results have been published. Many of these methods have demonstrated viability. There are varying levels of validation and database sizes among these methods, with most methods currently being improved with field process definitions, larger training databases, and blind testing to evaluate the accuracy and reliability in evaluating unknown samples.

As part of PRCI NDE-4C, BMT Fleet Technology composed prediction models utilizing input parameters such as hardness, chemistry composition, and metallurgical characterization to predict CVN impact energy values at select temperatures from -20°C to 40°C (-4°F to 104°F) [4]. CVN S-Curves were generated for several randomly selected materials in the publication, and it was noted that some materials will exhibit transition behavior outside the range of tested temperatures and, therefore, were not ideal for upper/lower shelf CVN or transition temperature estimates utilizing these current models. No overall performance parameters for CVN estimates of shelf energy or transition temperatures for the tested database were presented, however, performance parameters for each of the test temperatures were presented. Further developments were noted in the publication as completion of a blind trial, and refinement of the prediction model tool and spreadsheet.

As part of another PRCI project, NDE 2-9, a Nondestructive Toughness Tester (NDTT) built by Massachusetts Materials Technologies (MMT) was calibrated and evaluated for measuring fracture toughness properties. The project tested 41 vintage steel pipe joints to compare the NDTT measurement of the tensile fracture response in a superficial volume of surface material with conventional laboratory measurements of toughness on the same sample. The outcomes included the development and assessment of nondestructive prediction models for the initiation fracture toughness from compact tension (CT) testing and the upper shelf CVN impact energy [13]. Further development and additional physical modelling are underway to refine the method.

In other recent work, Reliability Safety Integrity Pipeline Solutions (RSI) and Pacific Gas and Electric (PG&E) utilized chemistry and grain size to predict upper shelf CVN and SATT. Several prediction model types utilizing various chemistry and microstructure inputs were developed using between two and four parameters. The work up to this point indicates directions for future work aimed to validate the methodology utilizing in-situ collected data as well as expanding the overall training dataset [14].

4.2 New NDE Solution for ERW CVN Transition Temperature

An NDE process for CVN toughness of ERW seams was recently developed utilizing MMT's frictional sliding-based testing method with the Hardness, Strength, and Ductility (HSD) Tester. This section presents this new process along with validation data and use case.

Multiple prediction models were developed to evaluate regions of the CVN transition curve for the ERW seam, including the impact energy at the lower shelf, upper shelf, 32°F, 55°F, and the ductile-to-brittle SATT. These nondestructive estimates were compared to curve-fits of the CVN impact energy from standardized laboratory testing. Additional models of the shear area at specified temperatures of 32°F and 55°F were also investigated through both regression and classification approaches, but the resulting performance was insufficient to pass statistical validation. Therefore, further refinement and validation was focused on an NDE determination of the SATT and upper shelf energy. 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. NDE predictions for CVN energy and transition temperature listed in the results are similarly for full-size CVN specimen. Blind trial validation performance for the full-size specimen fracture area transition temperature (FATT), as well as findings from a pilot study and analysis of an in-situ collected database are explored in the following sections.

4.2.1 Blind Validation Performance for Frictional Sliding Transition Temperature Prediction

For models which passed initial statistical validation two further trials of blind testing were conducted and their results are presented in Table 4. After the first trial, the results were utilized for further refinement and a second blind trial was completed. The conservative shift in the results table accounts for both the accuracy of the method as well as the desired confidence level of the result. A tolerance interval (TI) was utilized for the transition temperature model, while a prediction interval (PI) was utilized for the upper shelf seam toughness model. The different statistical approaches reflect the different significance of the implications for each model's use. The tolerance interval is a stricter statistical approach which was applied since confirmation of upper vs lower shelf behavior is associated with a binary 'confirm or not confirm' impact that allows use of the default upper shelf CVN value in §192.712. This is a different risk case than the more typical implication of prediction accuracy in an upper shelf CVN prediction of +/-1 to 2 ft-lbs. In practice, these metrics indicate how much should be added or subtracted to the predicted value to responsibly utilize the model. These approaches reflect those taken in similar NDE field processes for strength properties used to satisfy PHMSA specifications.

Table 4 – Blind Testing of CVN Toughness Prediction Models using Frictional Sliding Method

Model	Blind Validation Performance	
	Trial	Conservative Shift
Transition Temperature Model	Trial 1 – TI	-82°F
	Trial 2 – TI	-48°F
CVN Upper Shelf Model	Trial 1 – PI	19 ft-lbs
	Trial 2 – PI	8 ft-lbs

From the above table, the transition temperature model was implemented in a blind trial study on 15 vintage pipe materials. The results of this blind trial are presented in Figure 2 below. As shown, predictions fell within a tolerance interval of 50°F. For convenience, bounds for both 25°F and 50°F are plotted in addition to the unity line for perfect laboratory vs prediction agreement. Following successful blind trial performance, the transition temperature model was utilized in field pilot studies. Because of the status of the validation, one pipe cut-out per population was used to verify the model applicability to specific assets if the data collected was to be utilized for integrity management.

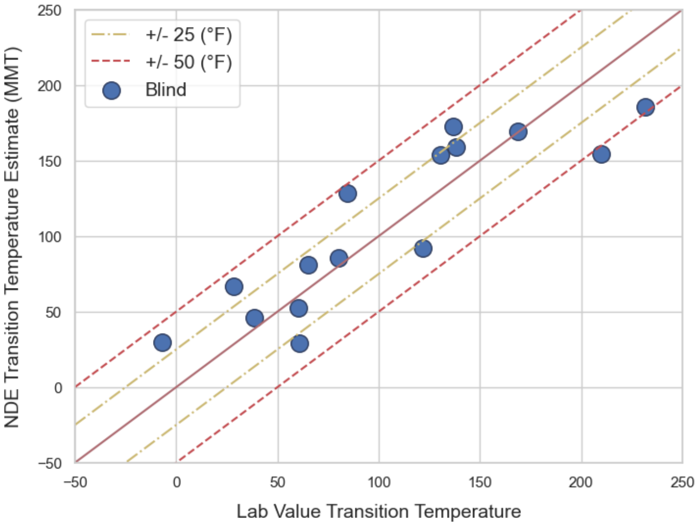

Figure 2: Unity Plot for Transition Temperature Frictional Sliding (NDE) Predicted vs Lab Value

4.2.2 Pilot Studies Using Data from Transition Temperature Model to Positively Confirm Upper Shelf Behavior

The results from a combination of additional pilot studies and from utilizing historical data collected during material verification digs with the HSD Tester on several pipeline populations are displayed in Figure 3. The 'Conservative Transition Temperature' on the y-axis is the predicted result after applying the conservative shift as indicated in Table 4. This means that a given prediction of 80 degrees would then have the tolerance interval added (i.e., 80°F+48°F = 128°F). In this way, the method conservatively accounts for any inaccuracy by assuming a higher temperature of transition to tougher ductile behavior for the predicted result. Such methods are commonly used across the industry for any material property estimation based on NDE to account for measurement uncertainty. The results for each population are presented as a box and whisker showing the median, upper and lower quartile, as well as the max and min result of each population. Interpretation of these results indicates that out of 7 populations from the field collected data, 6 would qualify for a conservative upper shelf behavior.

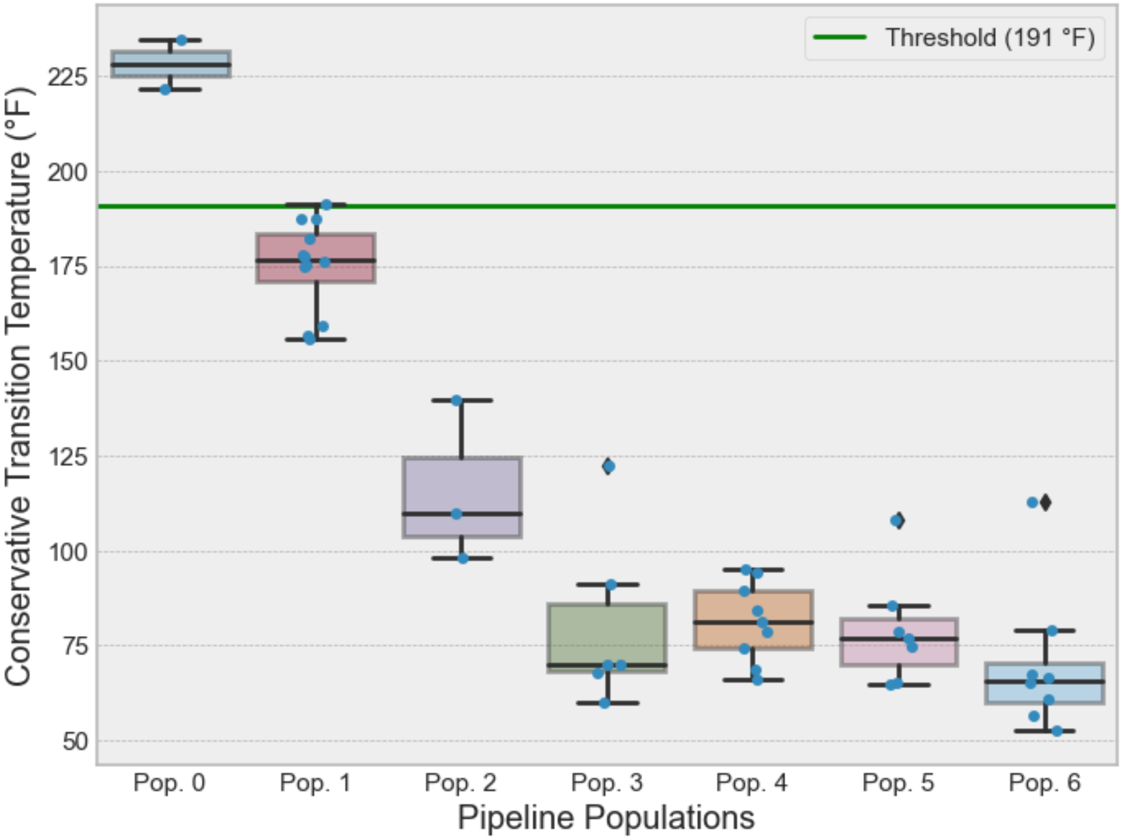

Figure 3: CVN Transition Temperature Results Grouped by Pipeline Population

In Figure 3, the green line at 191°F represents an example of upper limit temperature where the ERW seam can still be expected to behave in a ductile manner for fracture initiation even if the fracture propagation would then potentially turn brittle. This line has been set using a minimum operating temperature of 55°F and a temperature shift of 136◌̇°F using API 1176 [9] equation of:

$$\Delta T = 215 - 1.5 * (\text{Yield Strength})\ [9]$$

$$\text{Yield Strength} = 52.66\ \text{ksi}$$

Under these conditions, only one of the tested populations, Population 0, was found to have a transition temperature above the operating temperature and indicating the need to utilize brittle lower shelf CVN fracture behavior. For all other populations the determined transition temperature was below the threshold for ductile to brittle transition temperature and indicated that ductile upper shelf CVN behavior could be assumed.

4.2.3 Distribution of NDE Long Seam vs Laboratory Fracture Tests

A comparative analysis was done on the NDE tested populations to observe the distribution of all tested pipeline samples in relation to the operating temperature threshold. A kernel density estimation consisting of approximately 100 vintage ERW pipes was used to form a distribution curve according to the lab results. The overall population was observed to be skewed slightly toward the ductile to brittle transition temperature threshold. In the event that this distribution represents a bias toward materials operating close to the transition temperature regions and correspondingly being flagged more frequently for integrity and assessment digs, another ideal-normal (i.e., bell-curve) distribution about the mean was modelled. Based on these population distributions, as shown in Table 5, the likelihood of confirming upper shelf CVN and being able to use the corresponding 10 ft-lbs conservative minimum from PHMSA was 67% when using the lab data distribution as-is, and 85% when assuming an ideal normal distribution instead. This result was compared against fracture testing results on vintage ERW pipe presented at IDT Expo by Exxon, which has been recreated in Figure 4.

Table 5 – Likelihood of Qualifying Ductile Upper Shelf CVN Behavior Utilizing Current Methods

Minimum Operating Temperature 55°F		
Test Type	**Based on Actual KDE Distribution**	**Based on Ideal Normal Distribution**
MMT Long Seam CVN Transition Temperature	67%	85%

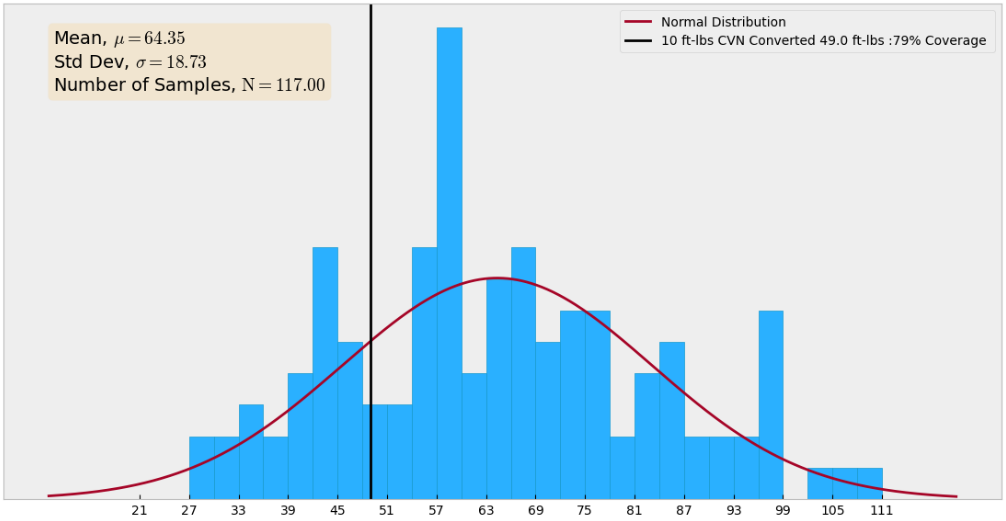

Figure 4: Distribution of K1c Results in Vintage ERW Pipeline [12]

In the above figure, the black line indicates the 10 ft-lbs CVN value corresponding to PHMSA's conservative minimum at upper shelf CVN. In order to correspond to the toughness testing data of the presented dataset, the 10 ft-lbs CVN value has been converted to K1c utilizing the Sailor-Corten correlation for static fracture toughness found in API 579 Appendix F.4.5:

$$K_{IC} = 15.5(CVN)^{0.5} \quad [7]$$

From analyzing this database of vintage ERW pipe, the likelihood of any given test meeting or exceeding the upper shelf CVN threshold is roughly 79%. This agrees with the likelihood to confirm the upper shelf CVN temperature utilizing the NDE transition temperature determination method in the pilot study.

4.2.4 Improvements Through Machine Learning

The current models are expected to improve over time through expansion of the model training database as shown in Figure 5. For the transition temperature, these model improvements will increase the likelihood of confirming an upper shelf behavior.

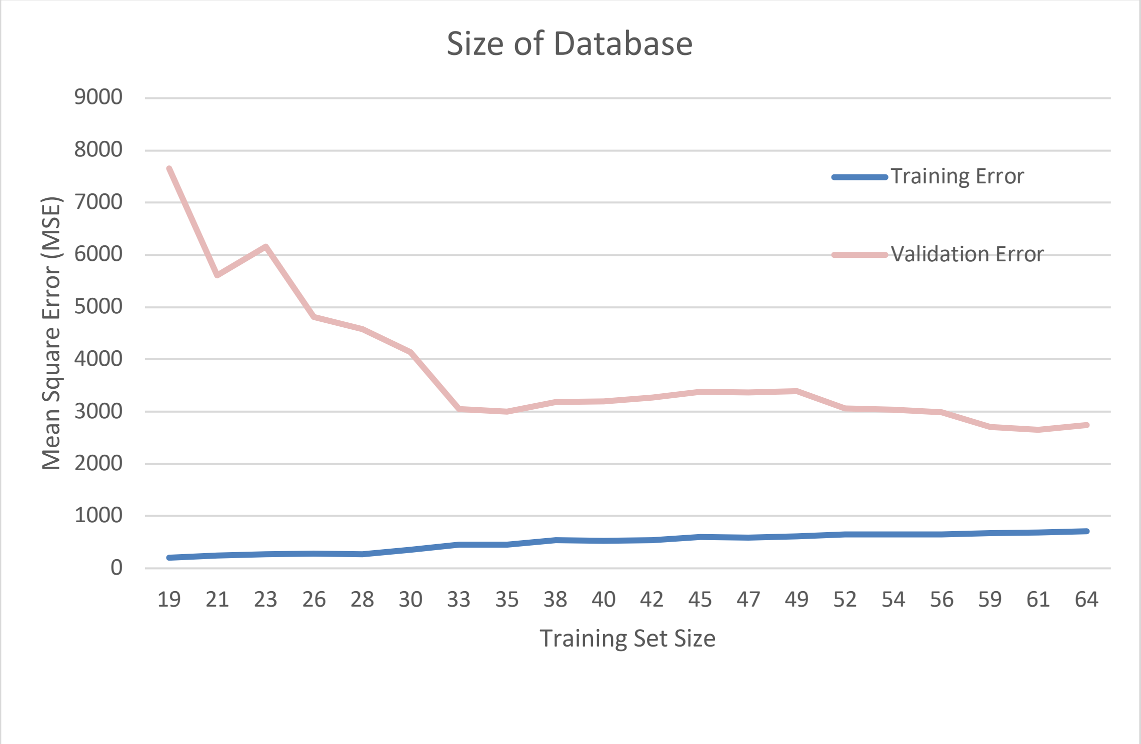

Figure 5: Model Improvements as Training Set Sizes Increase

In Figure 5, the models improve as samples are added to the training set. Note, the total number of samples is 80. When only adding the first 19 samples to the training set, the error on the training set (blue curve) is low, however the error on the validation set (red curve) is high but decreasing rapidly with each additional sample. This is normal behavior since such a small training dataset can be perfectly fit by the model at all points, but it does not have enough information to characterize the much larger validation set. The next portion of the curve is characterized by a steady drop in validation error as the training error ticks up. Given the improvement being approximately linear between 45 and 65 samples in the training set, it is expected that any further increase in the training dataset by 50% will continue to improve the RMSE and reduce the conservative shift needed for the use of NDE data as opposed to laboratory test data.

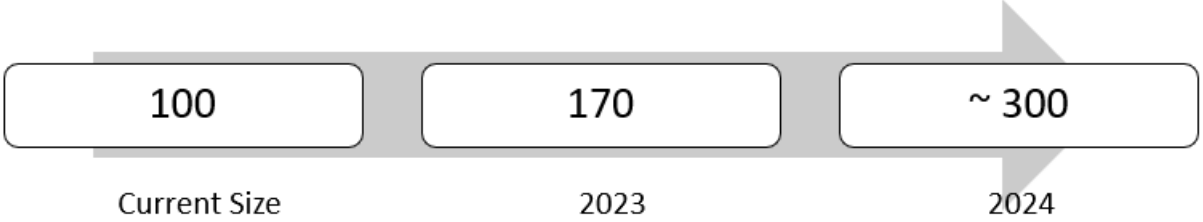

Figure 6: Expected Growth in Training Dataset through Industry Collaboration

Based upon the current size of the dataset and its observed trends, this model should reach its full potential at approximately 300 samples. This expansion can be achieved over the next 12 to 18 months through the continuation of joint industry collaboration. Noteworthy, field data collected before the final optimized models will be as valid as an input as field data collected once refined machine learning models are available. These observations apply to most NDE processes that are controlled to provide consistent and reliable raw data.

5 Conclusions

For measuring the material toughness of the pipe body, a number of NDE techniques have been developed and are at different levels of refinement and validation. For the seam toughness of vintage ERW pipes, a combination of field measurements that include hardness profiles from frictional sliding and machine learning are validated to provide the CVN transition temperature and upper shelf CVN energy. After applying a temperature shift to appropriately account for prediction of fracture initiation and conservatively accounting for measurement uncertainty, case studies show that the technique could enable the use of approximately 10 ft-lbs as the ERW seam toughness in approximately 70 to 90 % of pipe populations.

The confirmation of a 10 ft-lbs approximate lower bound for applicable CVN toughness is a significant advantage over the conservative 4 ft-lbs default value required for pipeline populations with no history of failure and which lack TVC data. Continuing efforts are underway to improve reliability of transition temperature estimates by increasing the database size of the model, which will further allow pipes to be positively confirmed with this method. However, even in its current form, the NDE technique allows a sorting of ERW asset population below or above 10 ft-lbs in similar proportion to a published distribution of laboratory conducted fracture toughness test results.

For the industry, it is important to understand that preventing fracture initiation is the only practical goal as opposed to expecting vintage steel to have toughness capable of preventing dynamic fracture propagation. The usefulness of the CVN ductile to brittle transition temperature is dependent on the methods to transfer the dynamic fracture toughness behavior into a quasi-static fracture toughness behavior such as exemplified with the calculation of a temperature shift.

Combining any NDE technique for the pipe body toughness along with ERW seam toughness from frictional sliding tests can provide a full set of data to comply with §192.712 without the use of pipe cut-outs. For other types of longitudinal welded seams, further validation work is needed to be able to assist in the determination of the repair criteria for seam anomalies. Based on the progress in the industry over the past 5 years in the area of material property determination, such challenges can be overcome through continued collaboration.

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