Identification of Factors to Determine Statistically Appropriate and Conservative CVN Toughness Values for Transmission Pipelines

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Abstract

This work is motivated by the regulations in 49 CFR § 192.712(e)(2)(i)(E) that allow for use of "other appropriate values" to provide conservative Charpy V-notch (CVN) toughness estimates for crack-related conditions of pipeline segments in the absence of direct laboratory test data for the subject segment. This work extends previous efforts by investigating pipe features and characteristics (e.g., manufacture date and seam type) that can inform the statistical determination of conservative CVN estimates for a given dataset. Database sampling, documented trends in manufacturing and mechanical properties, and statistical analysis are leveraged to examine the significance of factors related to CVN measures. Results show that pipe manufacture date and seam type are two factors with correlation to CVN, which can be used for clustering and statistically evaluating a large material testing database. Furthermore, correlation and clustering analyses of a material testing database are used to evaluate the relationship of various pipe characteristics including manufacture, seam type, pipe geometry, and chemical composition to CVN toughness of gas transmission line assets.

Introduction

Recently promulgated Pipeline and Hazardous Materials Safety Administration (PHMSA) regulations related to material property verification, Maximum Allowable Operating Pressure reconfirmation, and integrity management have motivated operators and integrity management programs to address uncertainty and variability when evaluating pipeline assets. One topic of particular interest is the process for resolving unknown material properties for pipeline assets. Different options have been researched, including destructive testing, non-destructive testing, and use of statistical methods. Specifically, one material property of importance that might not be documented in an operator's system of record is Charpy V-notch (CVN) toughness. The lack of CVN material data for pipeline segments can stem from various reasons, including historical assets that never had CVN test requirements or simply record keeping gaps. Often, operators will need to apply alternative methods to determine a suitable and conservative CVN toughness value assumption for a given integrity application. Recently, selected works have presented the use of statistical methods to determine a suitable and conservative CVN toughness value. The purpose of this work is to extend these approaches by providing a statistical analysis framework with various tools and verification using literature data.

The Code of Federal Regulations (CFR) provides guidance on CVN determination in 49 CFR § 192.712(e)(2): if documented material properties are unavailable (according to § 192.607), the operator shall use conservative assumptions. The CFR provides five options for CVN estimation:

(A) CVN values from comparable pipe with known properties of the same vintage and from the same steel and pipe manufacturer;

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(B) a conservative CVN toughness value to determine the toughness based upon ongoing material properties verification process;

(C) if the pipeline segment does not have a history of reportable incidents caused by cracking or crack-like defects, maximum CVN 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 CVN 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 defects;

(E) other appropriate values that an operator demonstrates can provide conservative CVN toughness values of crack-related conditions of the pipeline segment.[1]

Previously published work has proposed, developed, and implemented statistical approaches using their own database of CVN test results to establish a CVN estimate for analysis applications. These approaches satisfy the intent for a conservative material toughness property assumption by combining the concepts of comparable pipe (presented in option A) and demonstrated statistical methods (as characterized and justified within option E).

The objective of this paper is to examine the CVN toughness statistical methods and to consider the results in the context of historical pipeline and general metallurgical expectations. This investigation aims to demonstrate the conservatism and appropriateness of a statistical approach to establish CVN toughness for a pipeline segment. Prior standards and studies have outlined methods for determining CVN and corresponding modifications to adjust for limited data, temperature conditions, upper shelf vs. lower shelf, specimen size, etc. This work assumes a high quality of testing and database record keeping and does not consider these sources of variability in the presented statistical approach. Although, operators are encouraged to potentially include such factors as part of a larger program that addresses uncertainty propagation.

This work seeks to collect the prior statistical CVN efforts, provide context based on historical and industrial expectations, and offer a case study using a material database to show how a statistical approach reflects expected trends and conservatively estimates material performance for in-service pipeline segments. Key considerations will include how the presented statistical approach compares to the PHMSA minimums and the incorporation of pipe attributes, such as seam type, manufacture date, manufacturer, and manufacturing processes, among others.

This study validates the conclusions drawn from the statistical analysis by comparing the results with established literature. This involves reviewing studies on the impact of carbon and sulfur content on CVN toughness, as well as other relevant factors. By correlating the statistical results with literature

[1] 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.

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findings, this study enhances the credibility and reliability of the approach, and ultimately, the use of the approach to determine CVN estimates for integrity assessment applications.

By providing a comprehensive analysis of the technical basis supporting the results found by statistical analysis, this paper aims to contribute to the development of more effective pipeline integrity management strategies. The findings of this study have implications for pipeline operators, regulators, and other stakeholders in the energy sector, highlighting the importance of material selection and quality control in ensuring the safety and reliability of pipeline operations.

Previous work

The minimum CVN values provided by PHMSA in 49 CFR § 192.712(e)(2)(i)(D) of 5 ft-lbs for body cracks and 1 ft-lbs for seam cracks were determined through analysis of selected pipeline failures documented in Battelle reports. From these reports, toughness values were back calculated based on known flaw size, pressure, and other pipe attributes and material properties. Work by Structural Integrity Associates, based on a dataset that included the Battelle data, has shown that the minimum CVN values provided by PHMSA correspond to the 98th and 99th percentile, for body and seam defects, respectively.[1] However, these minimum values are sufficiently low that many operators have interest in exploring other methods for determining appropriate CVN values to apply for integrity management analyses. Although the CFR allows for multiple methods for determining an appropriate CVN value (and much effort has been spent researching such methods),[2,3,4] the current work explores the use of statistical methods. Application of statistical methods should be inherently supported by PHMSA, as the minimum values themselves were the result of statistical approaches.

Previous research has investigated the application of statistical methods to understand if different analysis methods or datasets may result in more appropriate toughness values relative to the PHMSA minimums. The previously discussed Structural Integrity Associates report analyzes a similar dataset used by PHMSA but suggests that use of the 90th percentile value is sufficient and consistent with other integrity management applications. The 90th percentile yields values of 13.0 ft-lbs for body cracks and 4.0 ft-lbs for long seam flaws, values which likely resulted in the addition of 49 CFR § 192.712(e)(2)(i)(C) for pipeline segments that do not have a history of reportable incidents caused by cracking.

Other studies have leveraged large material property databases to understand the distribution of CVN values in known pipeline assets.[5,6,7,8,9] Many of these studies have attempted to identify correlations between CVN and vintage, seam type, chemical composition, and other variables. Specifically, Pacific Gas & Electric (PG&E) and its partners found that correlations could be drawn between CVN and the specific type of weld flaw, whereas the prior work reported a single number for all weld flaws.[6,7] Other work has shown correlations between CVN and pipe vintage, grade, and manufacturer.[8]

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Relative to the statistical methods applied, much of the work with large datasets has used percentiles less than the 98th and 99th percentile apparently applied by PHMSA. In particular, the 90th percentile appears to be used most frequently in the literature,[6,8] which is often cited as providing the most appropriate balance between conservativism and accuracy.

Metallurgical testing database

This study leverages data from a metallurgical testing database, which includes over 16,000 CVN samples covering vintages from the 1920s onwards. The database includes destructive metallurgical test data from cut-outs obtained from pipelines collected over the past 20+ years. It contains detailed information on pipe characteristics, chemistry, strength, and toughness, making it a valuable resource for analyzing trends and patterns in material properties over time and within certain sub-populations (e.g., seam type). The raw recorded CVN test data was augmented such that all data entries were correlated to an associated upper-shelf (US) CVN estimate and full-size specimen.[2] This "normalized" dataset allows for direct comparisons across the population.

For analysis purposes, only transverse CVN specimens from the pipe material body and seam weld were considered in the study population. Furthermore, the study population was reduced to only include data with a known manufacture year and seam type (i.e., CVN data was excluded for entries with unknown seam type). Figure 1 shows the transverse CVN specimen population breakdown distribution by seam type. The most prevalent seam types within the total population are double submerged arc weld (DSAW) and electric resistance weld (ERW). Figure 2 shows the transverse CVN specimen population breakdown distribution by pipe manufacture decade, ranging from the 1920s through the 2010s. The most prevalent manufacture decade is the 1950s. Finally, Figure 3 shows the transverse CVN specimen population breakdown distribution by manufacturer, if available. Note, the manufacturer attribute associated with a CVN data entry is limited, with not all CVN tests having a complete record. Complete data attributes and sufficient sub-populations for sampling will be discussed and considered for application purposes.

[2] CVN references throughout the report are assumed upper-shelf values.

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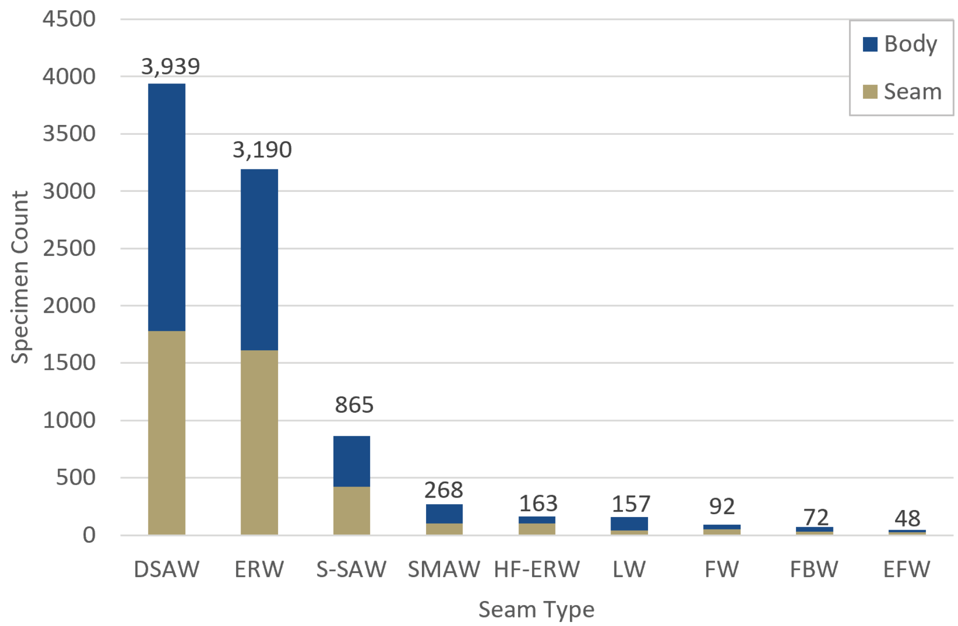

Figure 1. Transverse CVN specimen population breakdown distribution according to seam type from the metallurgical testing database.[3]

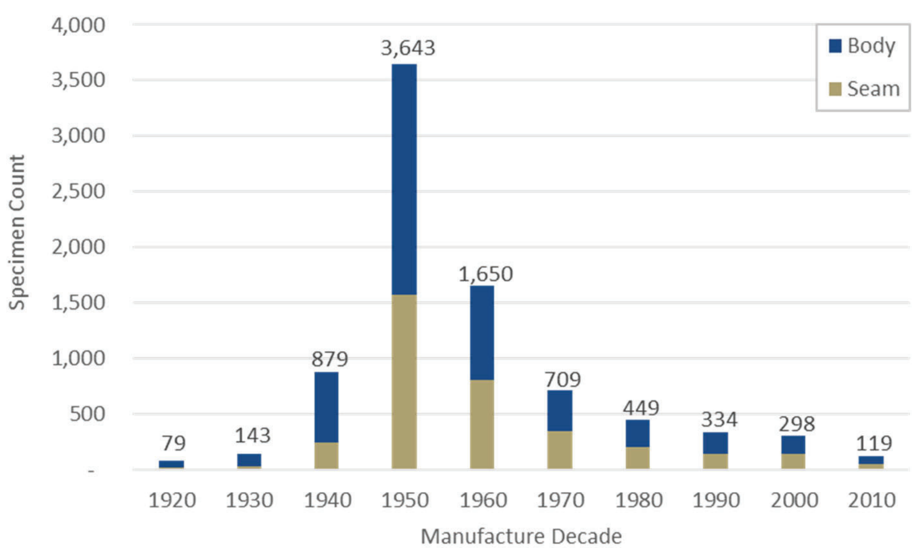

Figure 2. Transverse CVN specimen population breakdown distribution according to manufacture decade from the metallurgical testing database.

[3] Seam type abbreviations: Double Submerged Arc Welding (DSAW), Electric Resistance Welding (ERW), Single-Sided Arc Welding (S-SAW), Shielded Metal Arc Welding (SMAW), High-Frequency Electric Resistance Welding (HF-ERW), Lap Welding (LW), Electric Flash Welding (FW), Furnace Butt Welding (FBW), Electric Fusion Welding (EFW).

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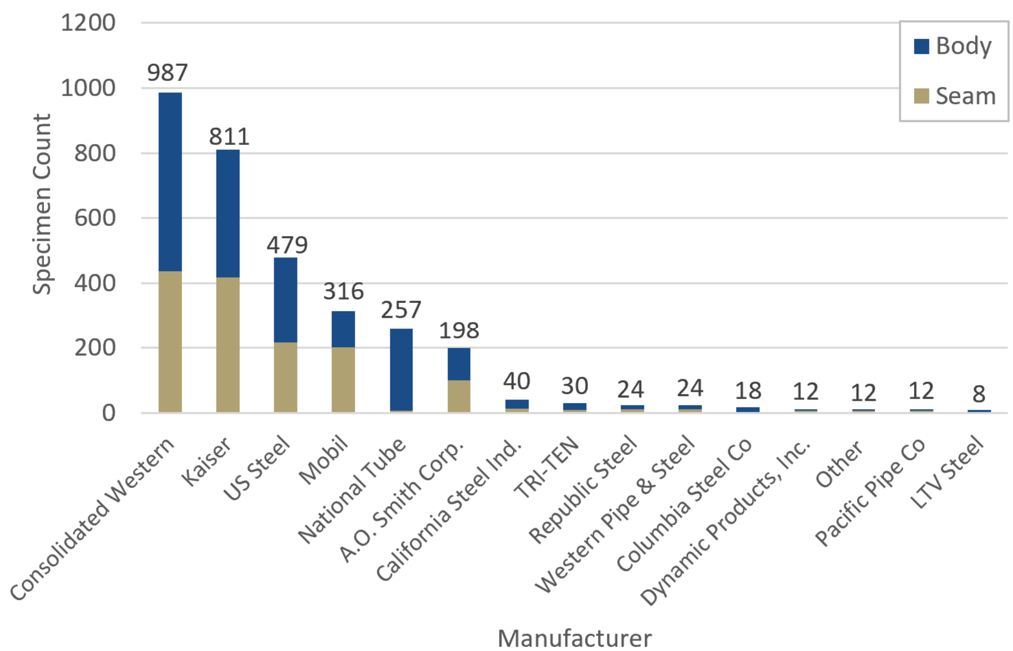

Figure 3. Transverse CVN specimen population breakdown distribution according to manufacturer from the metallurgical testing database.

To characterize general trends within the population, the average CVN for various sub-populations was determined. Figure 4 and Figure 5 show the total body and seam CVN frequency distributions, respectively, with inset plots showing the average CVN versus manufacture decade. These plots show a general trend that CVN increases alongside manufacture decade. Additionally, the body CVN data generally has a tighter distribution than the long seam CVN data. Note, the seam distribution includes all seam types, which is likely the source of the wider distribution.

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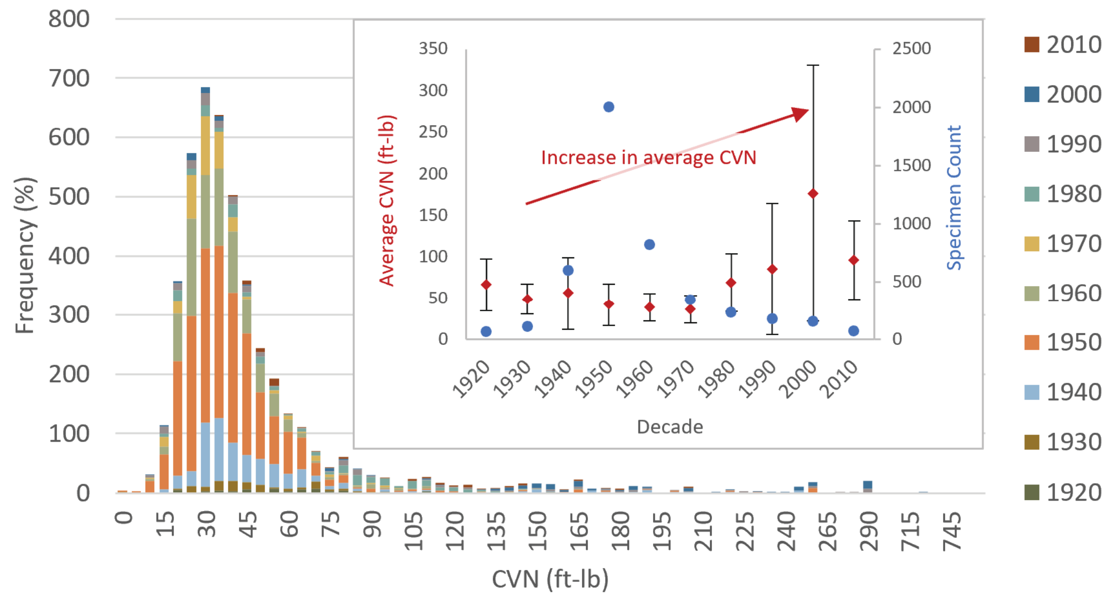

Figure 4. The distribution of pipe-body CVN as a function of manufacture decade from the metallurgical testing database.

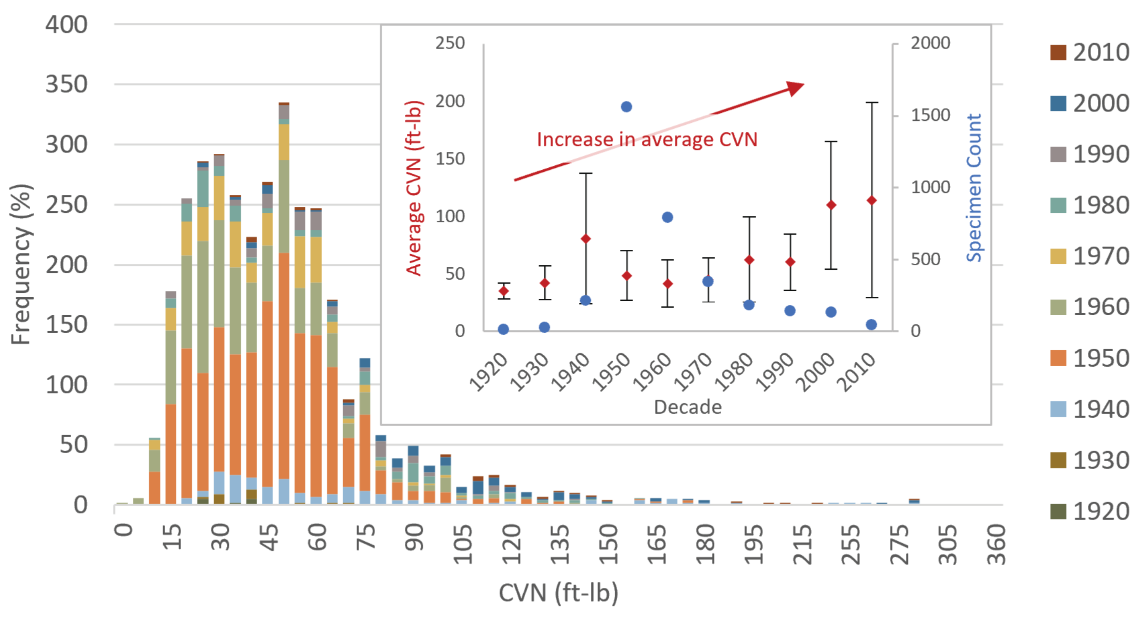

Figure 5. The distribution of long seam CVN as a function of manufacture decade from the metallurgical testing database.

As an example, the CVN data for body and seam DSAW pipe segments are examined to further document the observed trends. Figure 6 shows the average CVN values versus manufacture decade for body and seam DSAW pipeline segments. Figure 7 shows a comparison between the DSAW body

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data and historical references. This comparison generally shows that, until the 1960s, DSAW pipe bodies manufactured in earlier decades have relatively higher CVN values. As discussed in a subsequent section, this result is consistent with expected variations in typical material composition in the evaluated timeframe. Carbon-Manganese steels, which typify steels available through the 1960s, show a trade-off between strength and ductility, i.e., increasing specified minimum yield strength (SMYS) in these steels (shown in the inset) correlates with a decrease in ductility. Furthermore, the DSAW pipe body data distribution is compared to a parallel industry study based on structural steel, demonstrating a similar expected variation within the tested population (peak frequencies and shape), as shown in Figure 8. Finally, Figure 9 shows the average body and seam CVN values grouped by manufacturer. On average, the seam CVN is higher than the body CVN for most manufacturers.

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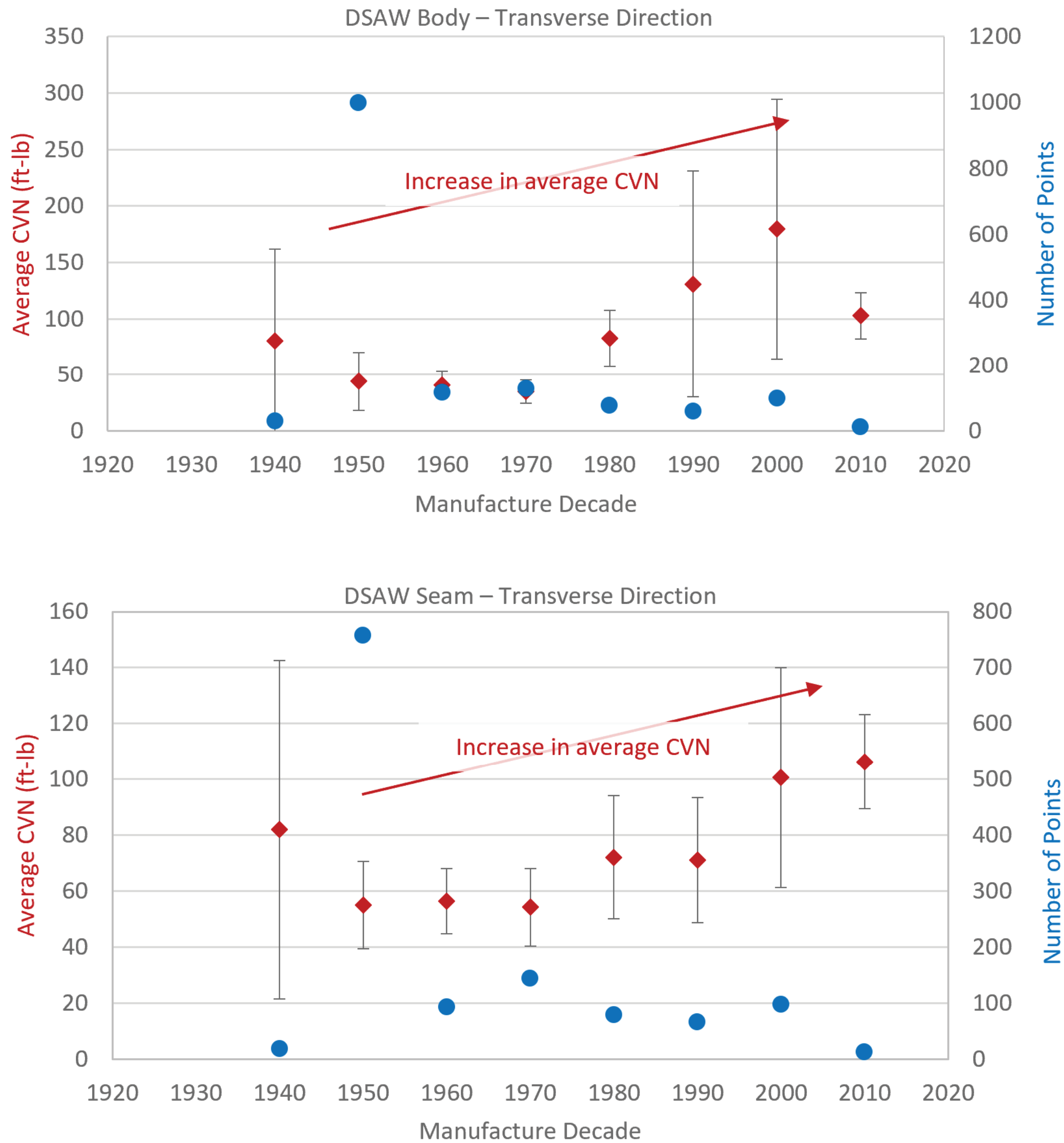

Figure 6. Average CVN values versus manufacture decade for DSAW pipeline; (above) body and (below) long seam.

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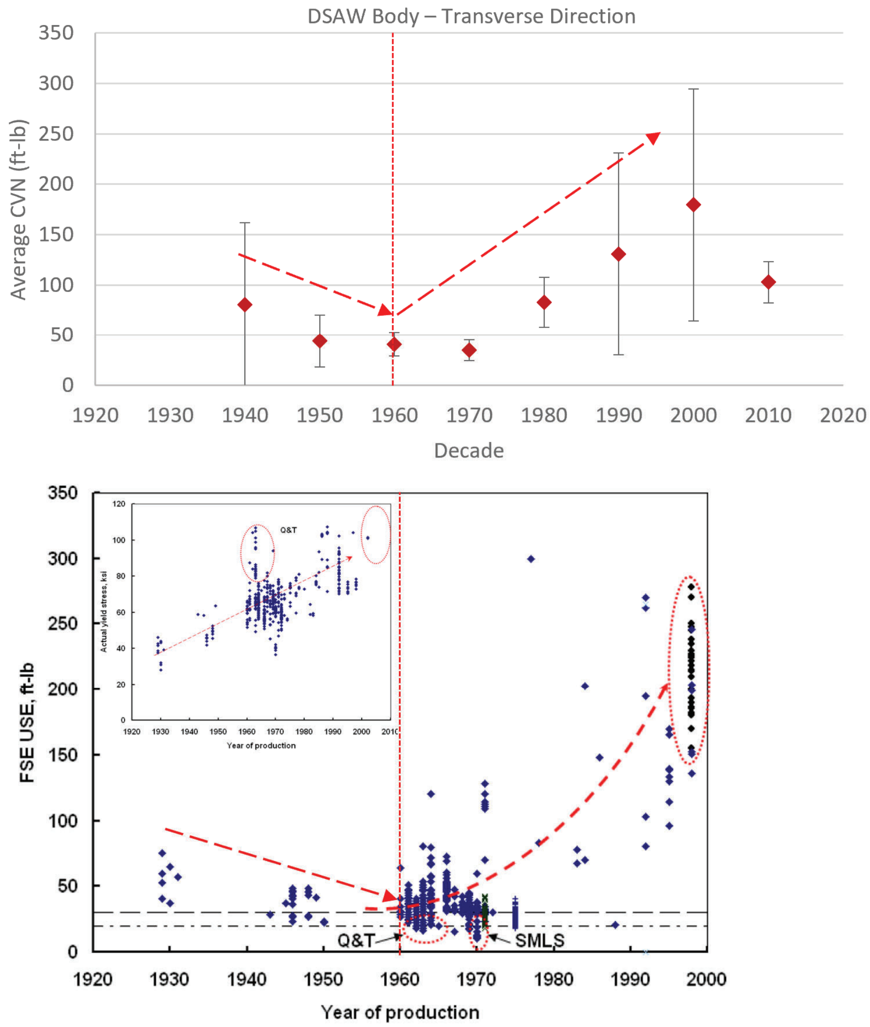

Figure 7. Average CVN values versus manufacture decade for DSAW pipeline (above) compared to historical references (below).[10]

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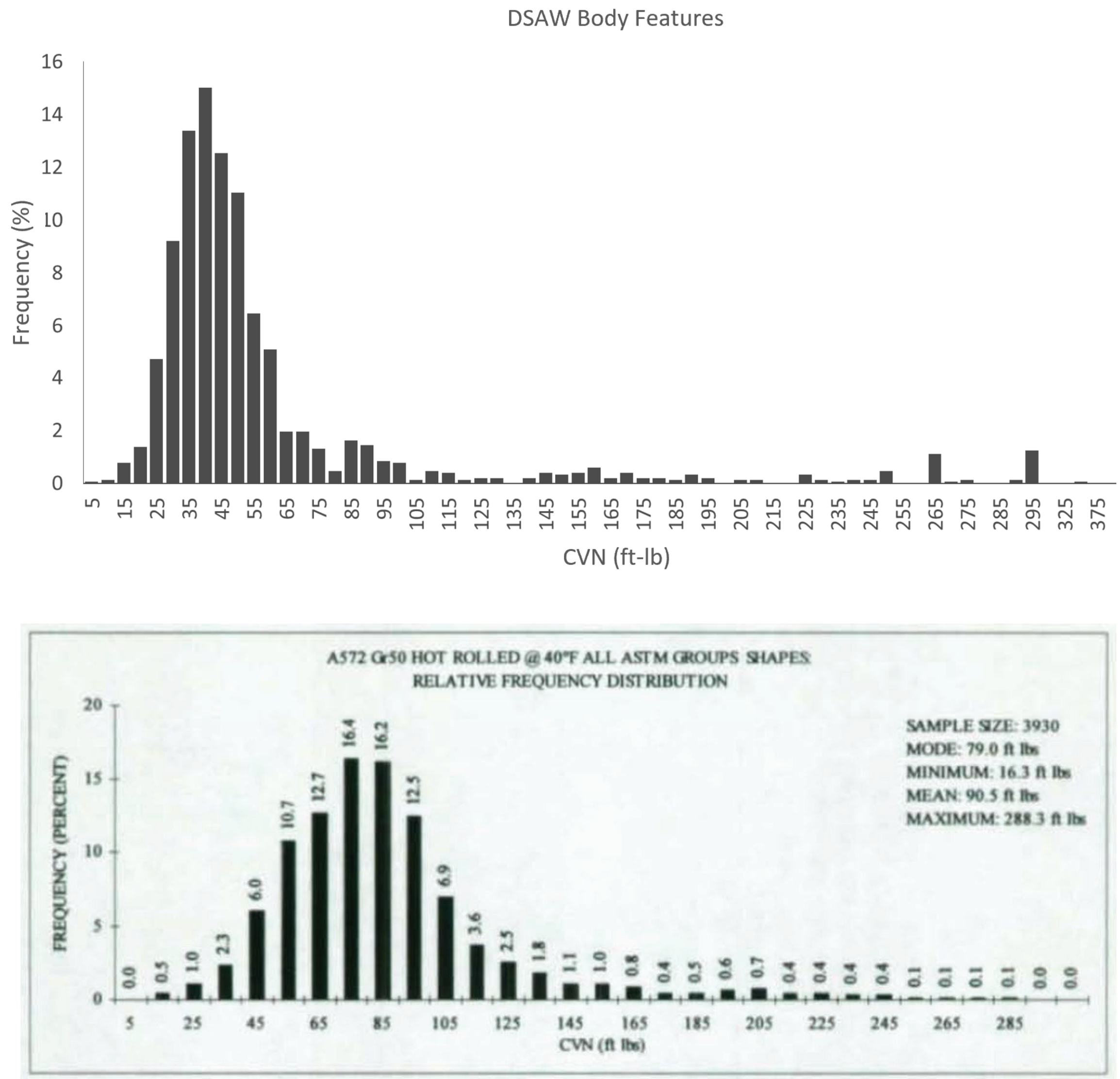

Figure 8. Distribution of CVN values for DSAW body features observed in the metallurgical testing database with known manufacture date (above) versus industry literature on structural steel (below).[11] The two distributions share similar peak frequencies and shape (nominal CVN values are not relevant for comparison).

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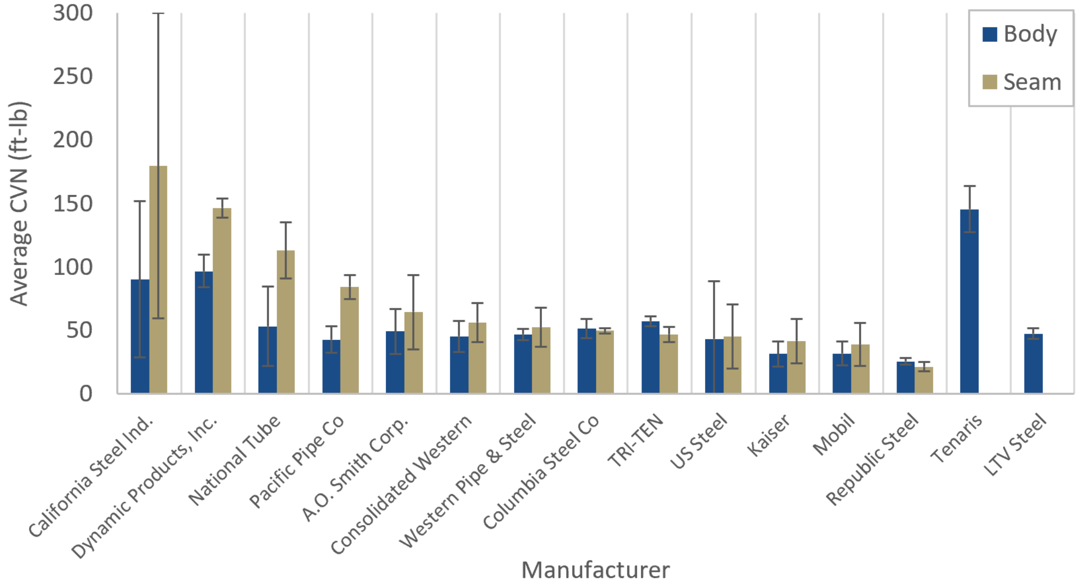

Figure 9. Average CVN for body and seam locations by manufacturer from the metallurgical testing database.

There are several key observations within the average CVN data population based on the presented groupings. First, there is an increasing trend in CVN toughness with more recent manufacture dates. This trend also captures the dip in CVN toughness shown prior to 1970 stemming from known sub-optimal manufacturing processes.[12] Second, the distribution within a specific body population (e.g., DSAW pipeline) shows a similar CVN distribution shape compared to another structural steel application. Third, within the current data population, manufacturer data is sparse, but could still be considered for sub-population sampling applications.

Statistical approaches

As discussed in the previous section, the CVN population for this study considered transverse specimens with a known seam type and manufacture date. Not all data had a complete set of attributes for all pipeline characteristics of interest (e.g., manufacturer). Each CVN data sample's characteristics, including installation and manufacture year, outer diameter (OD), wall thickness (WT), grade, seam type, and specimen location (i.e., body versus seam) were considered.

Correlation analysis

A correlation analysis was performed to understand the relationship between traditional pipe parameters, such as manufacture year, WT, OD, and SMYS with CVN. An additional analysis was performed to examine correlations between CVN with chemical elements, such as carbon and sulfur.

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Pearson correlation values above 0.30 were considered to be moderate due to the large variability in the data and the ultimate goal of trying to identify possible factors associated with CVN that can be used to verify the representative quality of the CVN data population.

Figure 10 shows the correlation between traditional pipe parameters with CVN for the pipe body. The correlation is moderate for manufacture year (correlation coefficient r = 0.34) but relatively lower for WT and SMYS.

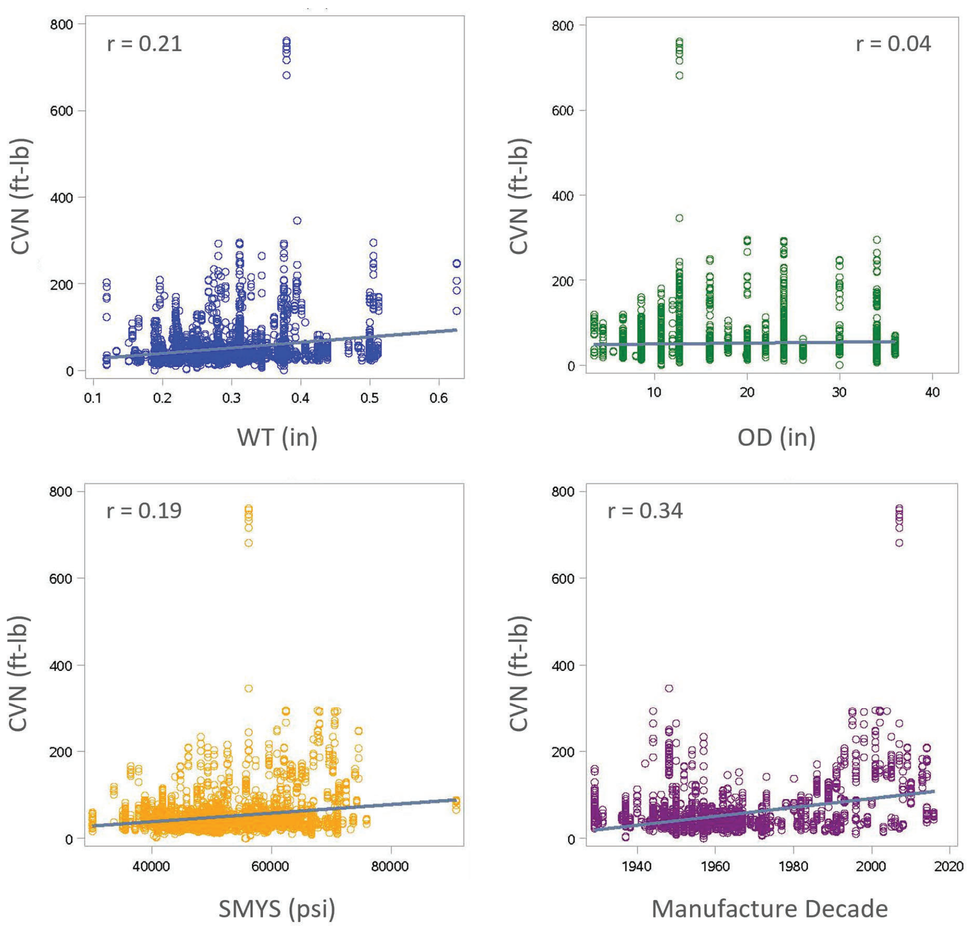

Figure 10. CVN correlation with WT (top left), OD (top right), SMYS (bottom left) and manufacture year (bottom right) with correlation values of 0.21, 0.04, 0.19, and 0.34, respectively.

As shown above, traditional pipe parameters, i.e., OD, WT, and SMYS, have low correlation with CVN toughness. Although some geometry factors can produce size effects, CVN toughness is inherently a material property and is independent of geometry, and therefore these results are not unexpected. While some relationship between SMYS and CVN is observed, the correlation is relatively weak, and is potentially a byproduct of the fact that more recent pipe generally has higher SMYS values than older / vintage pipe. The correlation analysis also shows a moderate relationship

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between manufacture year and CVN toughness, consistent with historical manufacturing process expectations. For example, Figure 11 shows a chart of manufacturing processes over time. This correlation analysis indicates that pipe manufacture date is a critical factor to consider when sampling.

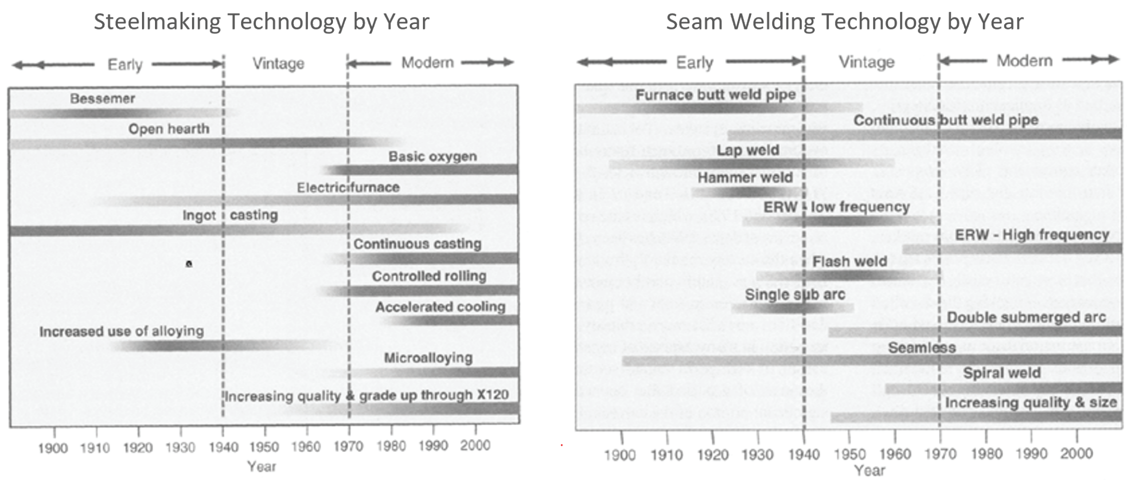

Figure 11. Historical steelmaking and seam welding over time showing the Early, Vintage, and Modern eras.[13]

The data shown above generally indicate an increase in average CVN values in recent decades, reflecting improvements in steelmaking and welding technologies (Figure 11). Figure 7 shows a decreasing average CVN until a minimum around 1960, followed by an increase thereafter. Not only is this same trend reflected in literature sources (Figure 7, bottom), but it also follows expected behavior considering the traditional trade-off between strength and ductility in Carbon-Manganese steels. As strength levels increase, ductility generally decreases for a given steel grade and processing condition. However, in the 1960-1970 timeframe, it is generally accepted that steel cleanliness improved, and processing (both steel making and welding) techniques improved dramatically.[12] These effects offset the otherwise expected decrease in ductility and toughness with increasing strength levels.

Figure 12 shows the correlation between chemical elements and CVN toughness. The results show that CVN tends to decrease with increasing carbon ($r = -0.51$) and sulfur ($r = -0.43$) content, consistent with literature findings.[14,15] Pipe body CVN values tended to increase with manganese ($r = 0.37$), niobium ($r = 0.37$), and titanium ($r = 0.36$).

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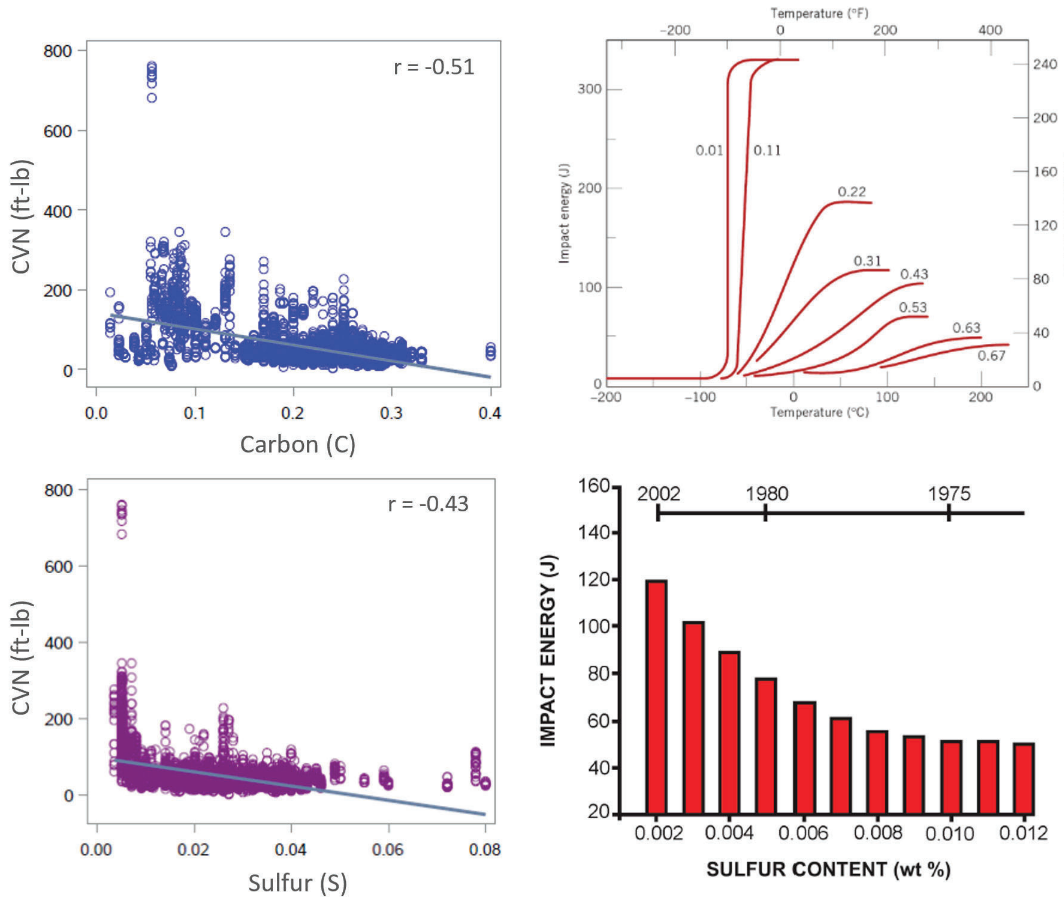

Figure 12. (Left) CVN correlations by carbon (r = -0.51) and sulfur (r = -0.43) from the metallurgical testing database; (Right) Literature characterization: effect of carbon content on CVN vs temperature of steel (top right)[14] and effect of sulfur content on CVN of line pipe (bottom right).[15]

As demonstrated above, the correlation analysis shows that CVN tends to decrease with increasing carbon and sulfur content, consistent with general understanding of metallurgical fundamentals. In low-carbon steels such as pipeline steels, increasing carbon generally serves to increase strength, but typically results in a decrease in ductility, or absorbed energy (i.e., CVN toughness). Sulfur is a known embrittling agent in steels, and increased levels of sulfur are known to decrease ductility and absorbed energy. During the steelmaking process, attempts are made to eliminate sulfur. Increasing carbon content generally increases strength but reduces toughness, while high sulfur content is typically associated with poor steel cleanliness and generally has lower CVN toughness. This relationship underscores the importance of controlling carbon and sulfur levels in steel production to achieve the desired balance between strength and toughness.

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Clustering analysis

The trend and correlation analysis presented above demonstrates that the CVN data population is representative of historical and industrial expectations related to CVN toughness trends. This result provides confidence that the data population is appropriate for statistical estimates. An important component of the statistical estimate is formulating a process to develop a sub-population that can be sampled to estimate CVN for a particular asset (i.e., comparable pipe). Previous work has shown, and is consistent with the clustering analysis presented herein, that comparable pipe manufacture year and seam type are the primary factors used to create the appropriate sub-population for sampling.[8] As part of this work, these factors were tested, as well as possible consideration of other factors, including manufacturer.

Clustering is an analytical data mining tool that groups similar data points together. A clustering analysis was carried out to investigate whether a more granular classification of the CVN data population factors substantially changes the CVN estimates. A clustering algorithm was implemented to identify similar groupings based on the empirical cumulative distribution of the CVN population. For the body CVN population, the highest-level grouping was manufacture decade, and further refinement included manufacturer and SMYS. For the seam CVN population, the highest-level grouping was similarly manufacture decade, and further refinement included seam type. At least 20 samples in a group were required for the clustering analysis.

In general, for the intended CVN estimates, obtaining a sufficient sub-population size for sampling is an important consideration throughout the statistical process. The clustering analysis was performed to consider if the various groupings could provide additional insights into CVN estimates for pipe with sparse information. Given the data availability limitations, including the manufacturer in the clustering analysis often resulted in a limited number of available decades with sufficient and reliable data.

Figure 13 shows the initial CVN population clustered by manufacture decade. The clustering groups data into statistically similar categories. For this baseline clustering, several groups are highlighted showing consistency with historical industrial data. While the 1920s, 1930s, and 1940s are in their own separate groups, the 1950s, 1960s, and 1970s are notably grouped together. Furthermore, the 1980s, 1990s, and 2010s are grouped together with the 2000s being an outlier. The grouping of the 1950s through 1970s is consistent with the historical "vintage" period identified in the literature (Figure 11). By clustering using manufacture decade, the evolution of pipe manufacturing processes over time is reflected in the groupings based on similar empirical cumulative CVN distributions. In Figure 14, steelmaking and pipe manufacturing methods from early, vintage, to modern eras are shown, the date ranges of which are overlaid onto CVN values.

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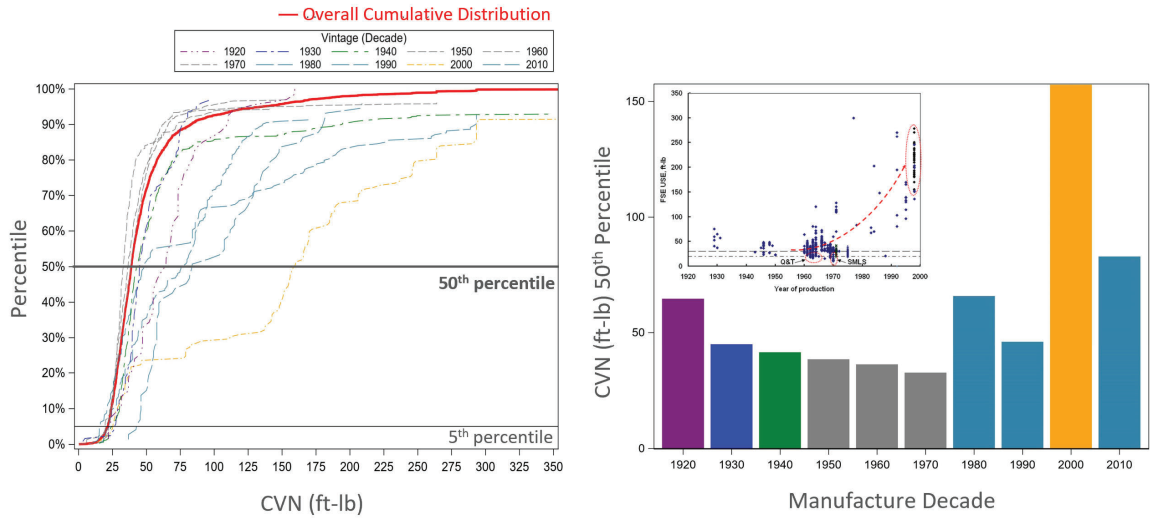

Figure 13. (Left) CVN clustering analysis by manufacture decade; (Right) Clustering results mapped onto the 50th percentile by manufacturer decade (each cluster is represented by a color).

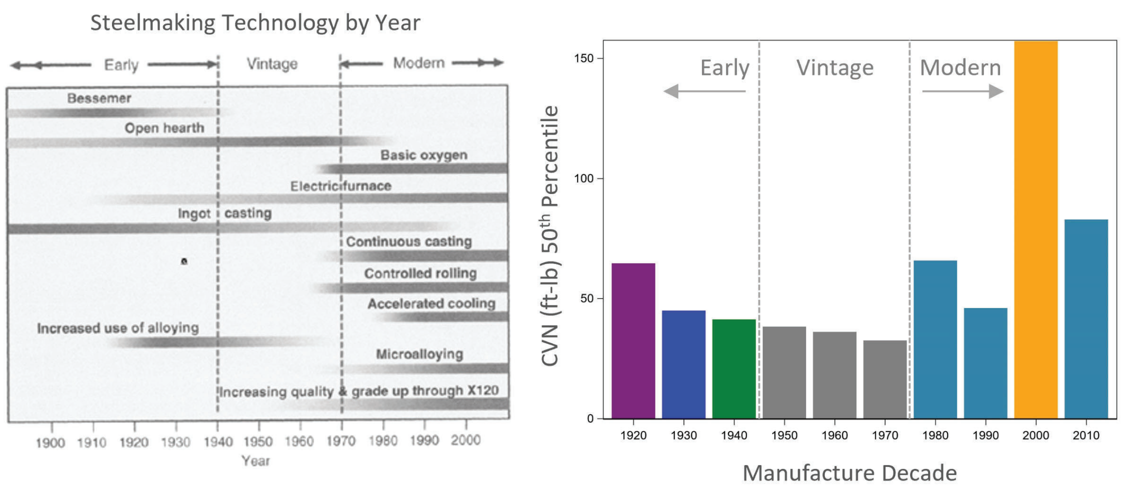

Figure 14. (Left) Pipeline steel manufacturing processes over time;[16] (Right) Cluster analysis results based on the CVN population distribution (each cluster is represented by a color).

When examining the same clustering by manufacture decade at the more conservative 5th percentile[4] instead of the median (50th percentile), the corresponding industrial trend is less pronounced and the CVN estimates are collapsed in the lower tail to a more conservative measure, as shown in Figure 15.

[4] The 5th and 10th percentiles are used for this work to indicate sampling at the conservative lower tail; this is consistent with the 95th and 90th percentiles used in other literature references and mentioned in the "Previous work" section.

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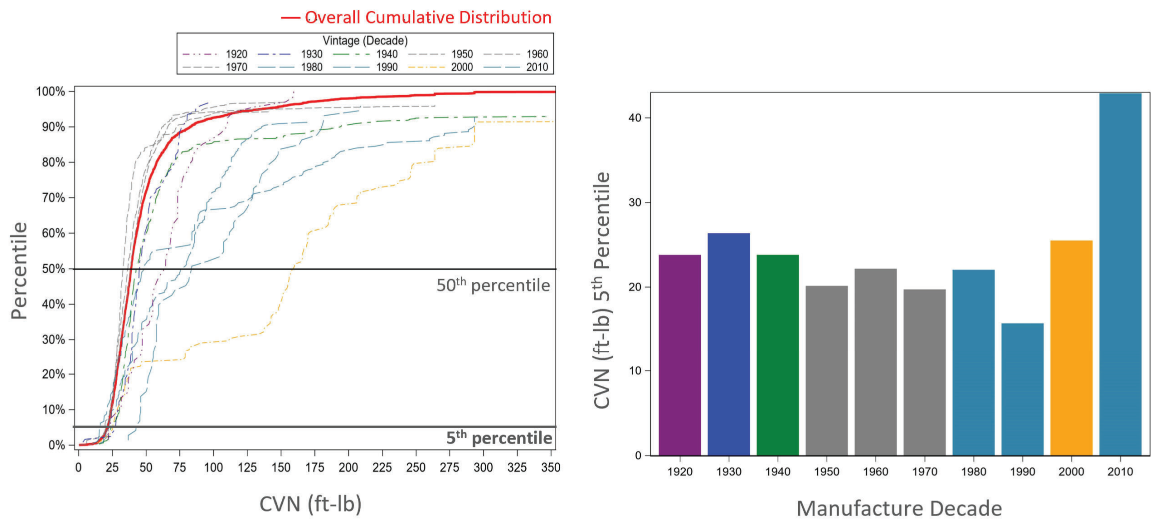

Figure 15. (Left) CVN clustering analysis by manufacture decade; (Right) Clustering results mapped onto the 5th percentile by manufacturer decade (each cluster is represented by a color).

Continuing the analysis, the manufacturer is added into the clustering factors. As mentioned, there is a limited population of CVN data with complete manufacturing data within the current dataset. For those with known manufacturer, the clustering analysis shows mixed results relative to clustering by manufacture decade only. For example, Figure 16 shows the clustering for 1950s manufacturer at the 5th percentile. Depending on the manufacturer, the sampled CVN value is above or below the overall 1950s value, but within the 95% confidence limits of the decade-only analysis. A similar result is observed for the other decades showing that including the manufacturer either leads to a higher, less conservative value, or a value very near the decade-only value. This comparison indicates that although the manufacturer would be a reasonable factor to include, if available, the effect between the decade-only factor analysis is within the margins when the conservative 5th percentile is sampled. This also demonstrates the statistical effect of selecting a lower tail conservative sample. In this case study, the lack of complete manufacturer data makes it more of a limiting factor than added value to the statistical sampling results for comparable pipe.

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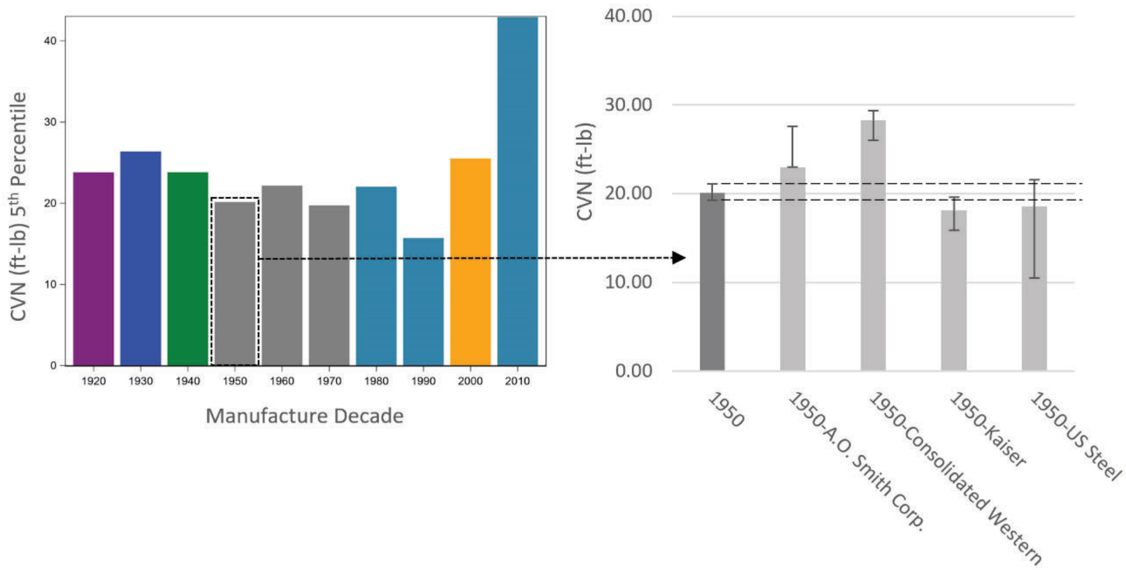

Figure 16. (Left) CVN clustering analysis by manufacture decade at the 5th percentile (each cluster is represented by a color); (Right) Breakdown of CVN by manufacturer for the 1950s decade with the distribution free 95% confidence limit error bars.

For brevity, the pipe body CVN cluster analysis for decade-manufacturer-SMYS is not presented. The analysis however, showed similar trends to the added-manufacturer results, where there was marginal variation from the decade-only analysis when sampling at the conversative 5th percentile. For the given CVN population, considering SMYS as a factor for CVN sampling was not considered to add value by making the sub-population more representative or conservative. It is recommended that cluster-type analysis be performed on CVN populations to better characterize the influence and patterns for a specific database. It is expected, depending on the data quality and completeness, that other factors could be considered to establish comparable pipe sub-populations, e.g., manufacturer, that would provide a more representative distribution of a particular asset. However, this must be balanced with maintaining a suitable population size and statistical applicability.

For completeness, but not presented herein, the pipe seam CVN cluster analysis considered manufacture decade and seam type at the 5th percentile which was deemed a robust sub-population distribution for CVN estimation. Other factors that could be considered, specific to seam CVN estimates, include for example, location within the weld (e.g., bond line or heat-affected zone (HAZ)).

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Implications for pipeline integrity applications

The analysis and discussion presented above provides the benchmarking and justification to use the current CVN database population and to implement a statistical process that can establish an appropriate and conservative CVN toughness estimate for a pipe asset.

The correlation analysis demonstrates that the CVN database population used herein is representative of historical and metallurgical expectations for CVN properties. The CVN database is consistent with manufacturing processes over time and expected steel chemical composition trends. Therefore, the database population is appropriate for analysis and determination of CVN value estimates.

Noted statistical challenges include managing sub-populations that can be used with comparable pipe that maintains the expected trends and has a sufficient population size to fit a distribution and sample reliably. These types of issues can derive from sub-population sample size, data gaps, or unexpected trend behavior. The challenge associated with sub-population sample size is addressed with the clustering analysis by investigating what factors allow for CVN sub-population to be applicable and appreciating the cost-benefit of adding factors from a conservatism and sub-population size reliability perspective.

Appropriate conservatism must be achieved with the selection of sub-populations for comparable pipe. The practical implementation presented herein considers two approaches to maintain conservatism. For this case study, in an effort to ensure sufficient population sizes, the sub-population was determined by the manufacture decade and included all prior decades. This relies on the historical trend observed within the CVN population where CVN performance generally improves over time. However, the majority of conservatism is achieved through sampling at a lower tail percentile of the sub-population distribution. As mentioned in the "Previous work" section, the lower 10^{th} percentile is considered appropriate. For the purposes of this study, the distributions were sampled at a more conservative 5^{th} percentile. Note, sampling at the lower tail 5^{th} percentile is a selection based on desired conservatism level and should be considered in the context of the application.

Furthermore, the clustering analyses, grouping, and distribution fitting provide valuable tools for identifying trends and patterns in the data, allowing for analysis methods that are agnostic to potential engineering or operational biases (e.g., perception of relatively low seam CVN toughness compared to the pipe body). The results from these analyses can then be reviewed considering engineering and metallurgical knowledge to understand if any trends may exist that would have otherwise gone unnoticed. Specifically, this study showed that clustering the data by manufacture decade and manufacturer allowed for a more refined estimate of CVN relative to the manufacture decade alone, but was not necessarily practical given data population limitations. Provided the operator has sufficient manufacturer information for their pipeline assets, they may benefit from

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performing a statistical analysis based on manufacture decade, seam type, and manufacturer. The ability to perform these statistical clustering analyses can allow for case-by-case assessments of databases and assets to determine the best approach for each unique integrity management application.

Case study

The following is a brief example demonstrating the implementation of a statistical CVN estimate based on the justification and verification efforts discussed above.

In this example, the factors considered for a comparable pipe are 1990s DSAW pipeline (manufacturer decade and seam type). The analysis considered both the pipeline body and seam CVN populations.

Once the sub-population was determined from the selected factors, several parametric distributions, such as the Log-normal, General Extreme Value, Normal, and Weibull, were used to fit the CVN values. The appropriateness of the fit can be assessed given error estimates and conservatism considerations. The 5th percentile CVN value was then sampled from the body and seam distribution to establish a conservative CVN estimate for a 1990s DSAW pipeline segment.

Figure 17 and Figure 18 show the results for the 1990s DSAW body and seam distributions, respectively. The results include a demonstration of how using comparable pipe factors that are too granular to establish the sub-population (i.e., from limited data samples) could distort the distribution making it impractical. In this case, using a 1990-1994 manufacture range (as an example of using a two-year window, such as referenced in 49 CFR § 192.607(e)) or the 1990s decade only has a limited sub-population size and a poor distribution fit. However, using the 1990s and earlier values as the sub-population has a more robust distribution, and maintains a conservative value compared to the more granular sub-populations when sampling at the 5th percentile.

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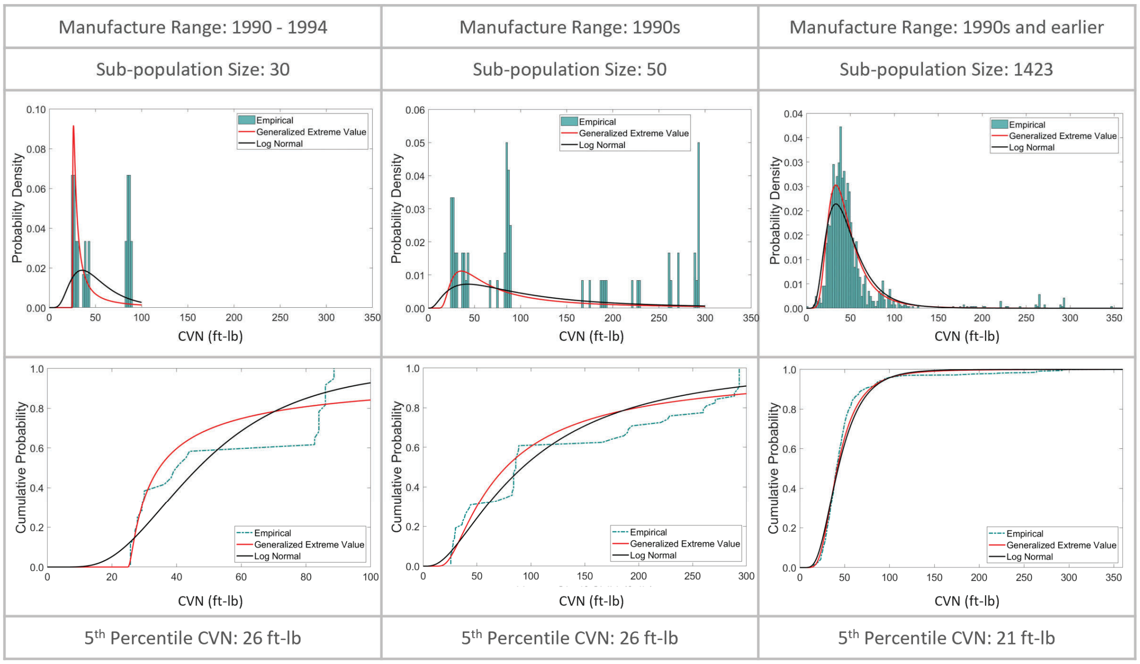

Figure 17. 1990s DSAW pipe body CVN statical estimates: (left) 1990-1994 sub-population, (middle) 1990s only sub-population, and (right) 1990s and earlier sub-population.

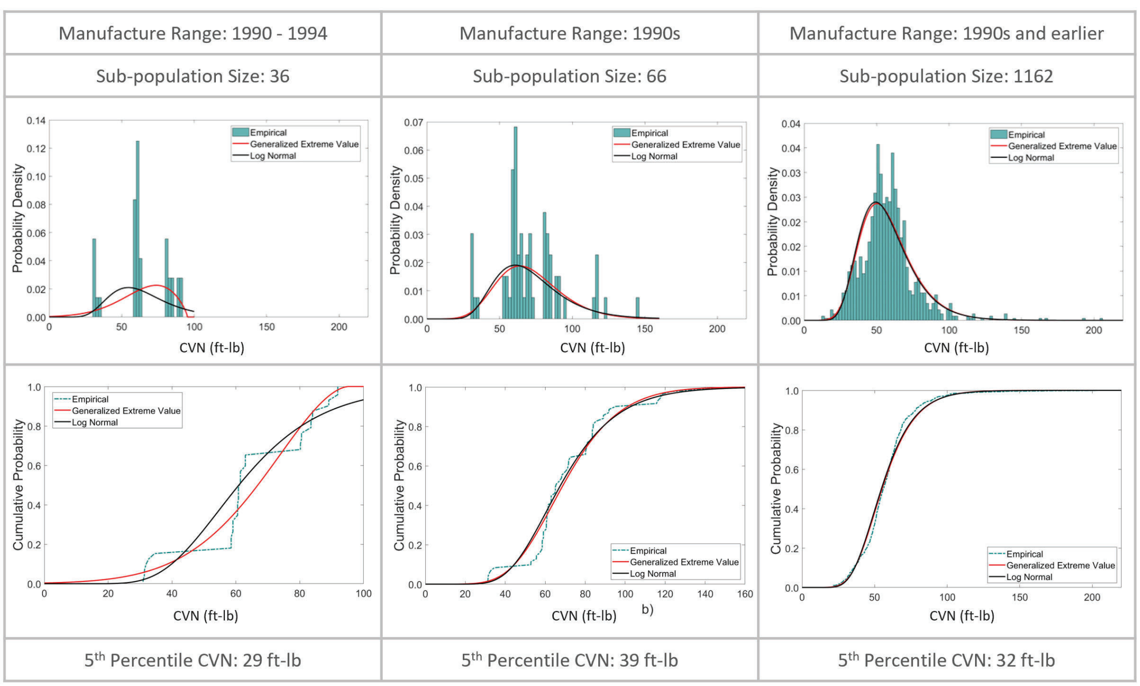

Figure 18. 1990s DSAW pipe long seam CVN statical estimates: (left) 1990-1994 sub-population, (middle) 1990s only sub-population, and (right) 1990s and earlier sub-population.

Limitations and future research

Statistically established CVN estimates must be considered in proper context. They are not replacements for known material properties determined through direct testing, but calculated expected values given a level of uncertainty and conservatism. As such, operators must appreciate the implications of the associated assumptions, their limitations, and the potential downstream effects when used within integrity management applications.

Of note with respect to the CFR, any use of an assumed toughness value other than the minimums provided by PHMSA in 49 CFR § 192.712(e)(2)(i) requires advance notification with the bases for why the assumed value is appropriate and conservative. The work presented herein is not part of a notification package or intended to serve as one. This work outlines and documents an approach to develop a CVN estimate based on statistical methods. It is recommended that processes developed in this manner be investigated independently, and verified and validated.

The presented analysis relies on data from a metallurgical testing database, which may not be representative of all pipeline materials. This is an important consideration as relying on a historical, or unrelated database that is not reflective of a particular pipeline system could create gaps in data availability and application. Additionally, the study focuses on specific factors such as carbon and sulfur content, and other elements or variables may also play a significant role in determining material properties. Future research should aim to expand the scope of the analysis to include a broader range of materials and factors, contributing to the development of more effective pipeline integrity management strategies. This could involve collecting additional data from other sources, as well as exploring the impact of other elements and manufacturing processes on CVN toughness.

Conclusions

This study analyzed a metallurgical testing database with over 16,000 CVN samples covering manufacture dates from the 1920s onwards. Trends for CVN toughness were examined and compared to trends observed in the literature. Findings confirmed prior work and were consistent with metallurgical historical knowledge and expectations. This consistency enhances the reliability of the results and supports the use of the statistical analyses for assessing pipeline material properties and potentially applying an alternative conservative value for the CVN assumptions as outlined in 49 CFR § 192.712(e)(2)(i)(E). Specifically, this work concluded:

- Inherent variability of steel CVN toughness exists, and a statistical approach to determining the most appropriate conservative value is prudent.
- There exists a strength and ductility trade off in early manufacture dates (prior to 1960) wherein increasing strength is correlated with reduced ductility and CVN.

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- After 1970, improvements in steelmaking and pipe manufacturing resulted in increased CVN with more recent manufacture dates.
- CVN data is observed to increase with decreasing carbon and sulfur content, a function of steel cleanliness and consistent with metallurgical expectations.
- Including the manufacturer in the statistical analysis may allow for additional refinement, though results may be limited based on the number of available decades with sufficient and reliable data.
- CVN data was found to have a high correlation with manufacture date and seam type, relative to other pipe characteristics.
- Although the presented analysis leverages mean CVN values for general comparison to literature and prior work, operators should consider using a conservative value (e.g., the 5^{th} or 10^{th} percentile) for integrity management applications.

This consistency with literature findings enhances the reliability of the study's results and supports the use of metallurgical testing databases for assessing pipeline material properties. The comparison to literature sources validates the conclusions drawn from the statistical analysis, providing additional credibility to the methodology. The results indicate that using the study’s metallurgical testing database provides a robust source for assessing the material properties and their implications for pipeline integrity.

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