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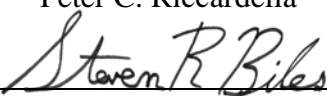

**Statistical Evaluation of Charpy
Toughness Levels for Gas
Transmission Pipelines**

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Table of Contents

<u>Section</u>	<u>Page</u>
1.0 INTRODUCTION.....	1-1
2.0 DISCUSSION	2-1
3.0 STATISTICAL ANALYSIS OF TOUGHNESS DATA FOR PIPELINE MATERIALS 3-2	
3.1 ERW Seam Welds.....	3-2
3.2 Piping Base Metal	3-5
4.0 CONCLUSIONS AND RECOMMENDATIONS.....	4-1
5.0 REFERENCES.....	5-1

List of Tables

<u>Table</u>	<u>Page</u>
Table 3-1: Evaluation of Recent Pipeline Pressure Test Failures in ERW Seam Weld Anomalies	3-4

List of Figures

<u>Figure</u>	<u>Page</u>
Figure 3-1 – Cumulative CVN Values from LEFM Analyses of Subtask 2.4 (Ref. 2) ERW Seam Weld Failure Data, classified by Anomaly Type, with Associated Weibull Distribution ...	3-3
Figure 3-2 – Complete CVN Data Set for ERW Seam Welds and Associated Weibull Fit.....	3-4
Figure 3-3 - Cumulative CVN Values for Pipe Body Data from Several Sources, and Associated Weibull Distribution	3-5
Figure 3-4– Complete CVN Data Set for Pipeline Base Metals and Associated Weibull Fit.....	3-6

1.0 INTRODUCTION

The U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration (PHMSA) recently issued a Notice of Proposed Rulemaking (NPRM) proposing extensive changes to 49 CFR Part 192 –Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards. The proposed regulation includes new requirements for Verification of Pipeline Material, Maximum Allowable Operating Pressure (MAOP) Verification, Pipeline Assessments, Integrity Management and Repairs. It also includes new detailed guidance on fracture mechanics modeling for failure stress and crack growth analysis. Material property information is required for many aspects of the proposed new regulatory requirements, especially fracture toughness for fracture mechanics-based failure stress evaluations. Fracture toughness for pipeline materials is generally characterized using Charpy V-Notch (CVN) testing, which can be correlated with more sophisticated fracture toughness parameters needed for various types of fracture mechanics analyses.

If actual material toughness is not known or not adequately documented for fracture mechanics modeling, the NPRM specifies that the operator must use a conservative Charpy energy value to determine the toughness based upon a material documentation program specified in § 192.607 of the proposed regulation; or use maximum Charpy energy values of 5.0 ft-lb for body cracks; 1.0 ft-lb for cold weld, lack of fusion, and selective seam weld corrosion defects. These default toughness levels are based on a series of Battelle reports documenting experience with pipeline materials and failures and recommendations for pipeline fracture evaluation.

The 5.0 ft-lb and 1.0 ft-lb default toughness levels are considered to be overly conservative based on extensive testing that has been performed on pipe samples plus CVN data obtained from Materials Test Reports and industry-wide data bases. The current study presents a statistical analysis of pipeline CVN toughness data, combining the same data presented in the Battelle reports with other available industry data on pipeline base metal and ERW seam weld toughness. As a result of this effort, it is concluded that 13 ft-lb for body cracks and 4.0 ft-lb for cold weld, lack of fusion, and selective seam weld corrosion defects represent more realistic, yet still adequately conservative, CVN toughness levels to use in fracture mechanics calculations when actual material toughness is not known or not adequately documented.

2.0 DISCUSSION

In the absence of a comprehensive Probabilistic Fracture Mechanics (PFM) analysis, fracture prevention of critical equipment and components is assured using conservative, deterministic analyses that combines reasonable bounding values for the required material properties with the use of safety factors and conservative bounding assumptions on applied loads, temperature conditions, crack growth rates, and potential flaw sizes that could exist in the components. For gas pipeline assessments, these safety factors and assumptions include:

- MAOP Determination – The NPRM requires that when establishing MAOP using the Engineering Critical Assessment method, the MAOP be established at the lowest predicted failure pressure for any known or postulated defects in the pipe, divided by the greater of 1.25 or the applicable safety factors listed in the regulation for various class locations (1.4 to 1.5 for Class 3 and 4 locations, depending on the date of installation). Other methods of MAOP determination in the NPRM have similar, inherent levels of conservatism.
- Applied Loading – Predicted Failure Pressure (PFP) and remaining life analyses are performed assuming continuous operation at MAOP throughout the pipe segment. Pressure distribution in the pipe is actually variable, and the location of maximum pressure is not necessarily coincident with the defect locations under evaluation.
- Metal Temperature – Similar to pressure, analyses are performed assuming continuous operation at minimum temperature at all locations. Typical pipeline operating temperatures are in the brittle to ductile transition regime, and small temperature increases can equate to a large increase in toughness. Minimum temperature locations do not necessarily coincide with the defect locations under evaluation or the maximum pressure location in the pipeline. In fact, high pressure locations downstream of compressor stations likely tend to experience higher temperatures.
- Pressure Tests – Hydrostatic pressure tests for existing steel pipe with integrity threats are conducted at pressures that implement the same class location safety factors as discussed above for MAOP determination. The use of conservatively high toughness levels to assess the maximum flaw size that could survive the test adds an additional level of conservatism. Also, any actual flaw is unlikely to be exactly the maximum flaw size that could survive the test.
- Fatigue Crack Growth Analysis – Fatigue analysis must be performed using methodology validated to give conservative predictions of flaw growth and remaining life, including conservative estimates of the Paris Law crack growth parameters and pressure-cycle spectrum. In addition, the operator must re-evaluate the remaining life of the pipeline before 50% of the remaining life calculated by this analysis has expired, effectively imposing a safety factor of 2 on the fatigue life calculation.
- Inspection – Interpretations of inspection results must conservatively account for the accuracy and reliability of the various inspection methods and tools, and any other assessment and examination results used to determine the actual sizes of cracks, metal loss, deformation and other defect dimensions by applying the most conservative limit of the tool tolerance specification. This will generally result in conservative overestimates of flaw sizes and distribution in the pipeline segment.

Coupled with all of these conservatisms, the use of extremely low, 98th and 99th percentile fracture toughness values, as proposed in the NPRM, will lead to excessive conservatism. Such excess conservatism will cause fracture mechanics analyses under proposed NPRM Section 192.624(d) to result in unrealistically low PFP and an unacceptably short remaining life in many cases. This could potentially force operators to replace pipeline segments unnecessarily, at significant expense and disruption to the general public. The 90th percentile values recommended herein will provide adequate protection against pipeline ruptures.

Furthermore, operators have a long track record of safe operation using ILI data that is reported with 90% confidence intervals. When determining validation excavation locations, following an ILI run, operators commonly add the 90% confidence bound to the reported anomaly size to account for measurement uncertainty. If operators were instead required to use 98% or 99% confidence intervals, such a method would be impractical because it would result in many more required excavations with no quantifiable improvement in pipeline safety. A similar level of conservatism should be applied to the selection of conservative default Charpy values for fracture mechanics evaluation, which is consistent with the 90th percentile values.

3.0 STATISTICAL ANALYSIS OF TOUGHNESS DATA FOR PIPELINE MATERIALS

3.1 ERW Seam Welds

Data have been compiled from various industry sources to estimate reasonable statistical bounds for CVN toughness of ERW seam welds. References 1 and 2 report data for over 100 seam weld failures that occurred in the timeframe from the late 1950s to present. Sufficient data were available to permit detailed analysis of the failures reported in Ref. 2 using both Linear Elastic Fracture Mechanics (LEFM) and Modified Ln-Secant approaches. The seam weld anomalies causing the failures were divided into four categories: Cold Weld Defects (CW), Hook Cracks (HC), Selective Seam Weld Corrosion Defects (SSWC), and Defects Enlarged by Fatigue (FE).

The analyses in Ref. 2 found that two of the defect types (CW and SSWC) tended to fail in a brittle manner due to the anomalies residing in the weld bondlines. Failure stresses for these defect types were conservatively predicted using LEFM with very low fracture toughness levels, 4 ft-lbs and 0.4 ft-lbs, equivalent Full-Size CVN energies, respectively. (CVN energies were converted to Fracture Toughness for the evaluations using a conservative correlation from the literature [Ref. 3].) The other two anomaly types (HC and FE) were found, in general, to reside in the heat affected base metal near the weld bondlines and, in general, resulted in ductile failures. Failure stresses for most of these anomalies were reasonably characterized using the Modified Ln-Secant approach with base metal CVN toughness. However, in some cases, these defect types resided in brittle material or jumped into the bondline, and were better characterized by Modified Ln-Secant using CVN of 15 ft-lbs (FE) or LEFM using CVN toughness of 4 ft-lbs (HC).

For the present study, the anomalies reported in Reference 2 were re-evaluated to estimate the value of CVN toughness that best predicted the failure stress in each case using LEFM. The

resulting CVN values were then characterized by a Weibull distribution to establish reasonable statistical bounds. The results are illustrated in Figure 3-1. It is seen from this figure that very few of the seam weld failures reported in References 1 and 2 were characterized by the extremely low CVN values discussed in Ref. 2 (0.4 and 4 ft-lbs).

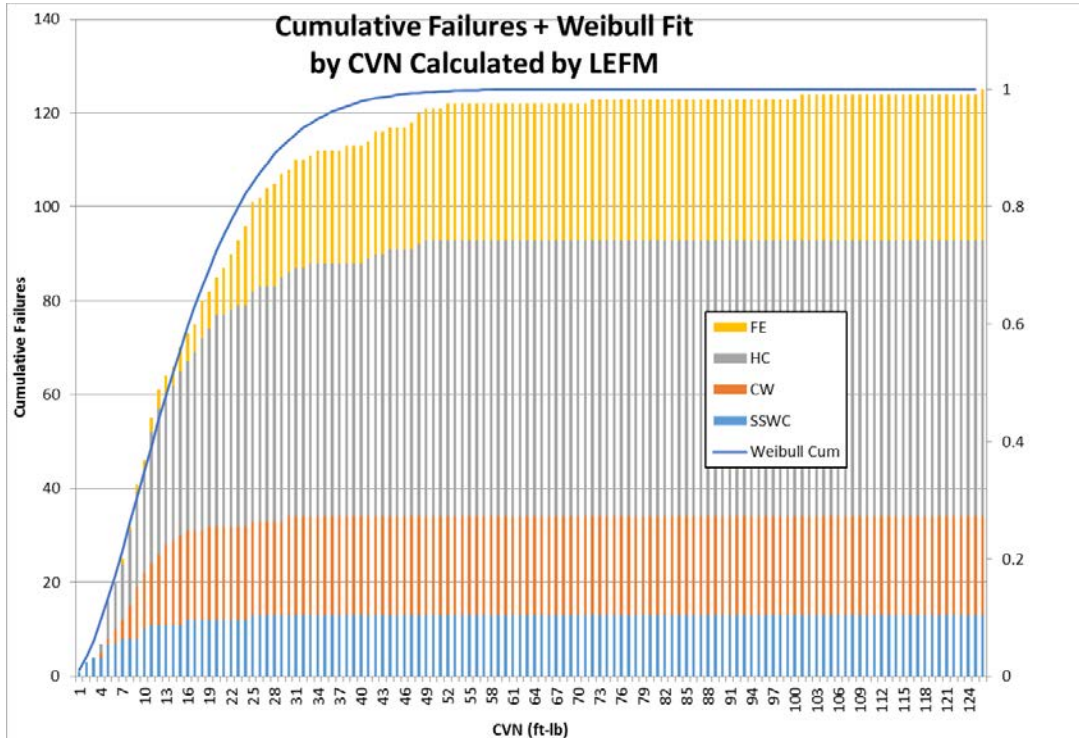


Figure 3-1 – Cumulative CVN Values from LEFM Analyses of Subtask 2.4 (Ref. 2)
ERW Seam Weld Failure Data, classified by Anomaly Type, with
Associated Weibull Distribution

Additional industry data were compiled from Material Test Reports that included CVN data on vintage ERW seam welded pipe produced by A.O. Smith and Youngstown Sheet and Tube in the 1949 through 1956 timeframe [Ref. 4]. A total of 52 additional data points were added to the Reference 1 and 2 data set. The resulting complete CVN data set (165 total) and the associated Weibull fit are illustrated in Figure 3-2. It is seen from this figure that the ERW CVN data are reasonably characterized by a Weibull distribution with a slope parameter of 1.587 and a characteristic shape parameter (corresponding to 63.2% failure rate) of 17 ft-lbs. From the Weibull distribution, 4 ft-lbs CVN represents a reasonable, 90th percentile lower bound of the data (i.e. 90 percent of ERW seam weld toughness values are expected to be larger than this value). As stated in Reference 2, “The use of lower-bound estimates or conservative models for predicting failure stress likely will result in excavations and examinations of many anomalies that are non-injurious along with those that are found to be injurious and need to be repaired”. The 4 ft-lb CVN value proposed above is a reasonable default value for CVN toughness for defect remaining life evaluations when little or no information is available to characterize actual material properties. When combined with other conservatisms inherent in fracture mechanics modeling for failure stress and crack growth analysis (as discussed in Section 3.0), use of this value will result in an acceptable level of pipeline safety in Engineering Critical Assessments.

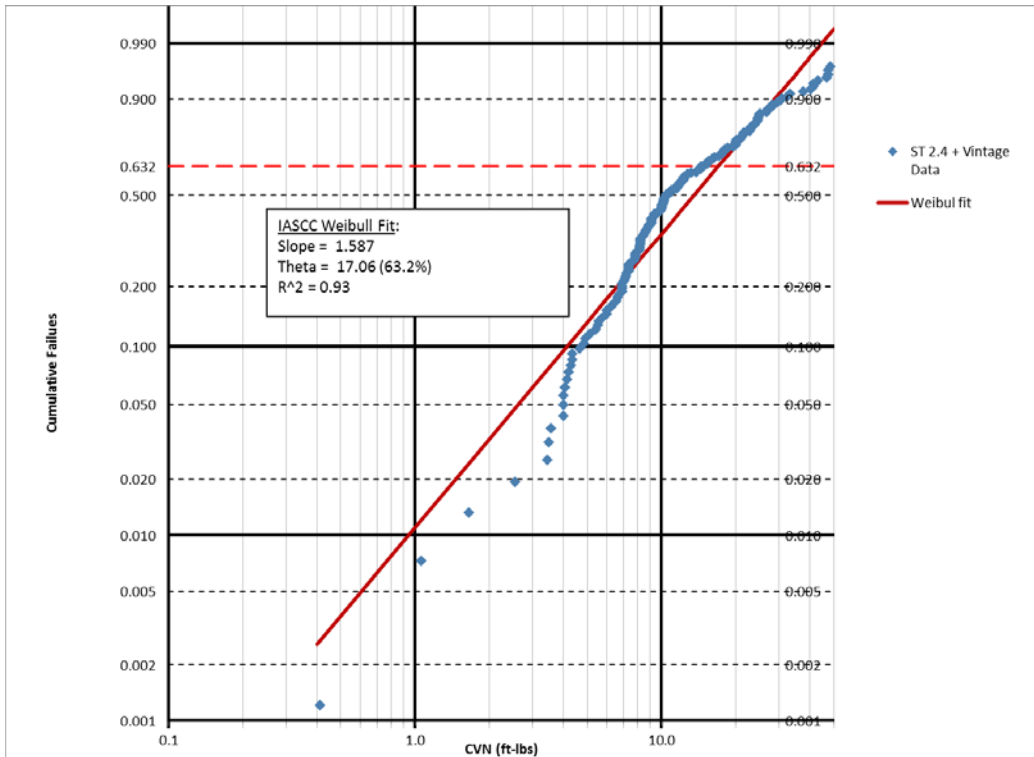


Figure 3-2 – Complete CVN Data Set for ERW Seam Welds and Associated Weibull Fit

Supporting analyses were performed of recent pressure test failures of ERW seam weld anomalies in an operating pipeline to assess the proposed 4 ft-lb lower bound. Metallurgical investigations of the failure sites were conducted to evaluate the defect lengths and depths from which the ruptures initiated, and LEFM analyses were performed to determine crack-tip stress intensity factors at the failure pressures. The results are summarized in Table 3-1. The calculated stress intensity factors were then converted to CVN levels using the Reference 3 correlation. It is seen from the table that the CVN levels corresponding to the failures were in the range of 8.9 to 11.3 ft-lbs, well above the proposed 4 ft-lb default level.

Table 3-1: Evaluation of Recent Pipeline Pressure Test Failures in ERW Seam Weld Anomalies

Rupture	OD (in)	WT (in)	Rupture Pressure (psig)	Flaw Depth a (in)	Flaw Length 2c (in)	Calculated K (ksi \sqrt{in})	Equiv CVN (ft-lb)
1	24	0.346	1781	0.38 (thru-wall)	0.25	40	10.0
2	24	0.346	1772	0.38 (thru-wall)	0.29	43	11.3
3	24	0.359	1749	0.2	0.31	42	10.9
4	24	0.352	1750	0.16	0.43	37.1	8.9

3.2 Piping Base Metal

The default pipe body toughness (5 ft-lb CVN) proposed by PHMSA in the NPRM is also overly conservative. Based on the analysis below, a more reasonable, yet still conservative default toughness of 13 ft-lb CVN is recommended.

In order to estimate a reasonable default toughness for pipe body material (away from longitudinal seam welds), pipe body toughness data were compiled from a number of sources:

- Subtask 2.4 report (Ref. 2), which included base metal CVN data in addition to weld metal failure statistics.
- Vintage Pipe Toughness Data (Ref. 4, interpolated to 50 F)
- Various Industry MTR Reports
- PRCI pipeline materials database (Ref. 5), queried for specific pipeline vintage and manufacturer for temperatures between 55 and 65 F

A total of approximately 1400 data points are included. No LEFM analysis of these data was required because the reports tabulated measured CVN data for each sample. These data are assumed to be representative of typical vintage pipe body material, although this assumption may be somewhat conservative because the query of the Ref. 5 database did not discriminate between base and weld metal, and may have included some seam weld data. The complete data set is illustrated in Figure 3-3, along with the associated Weibull fit.

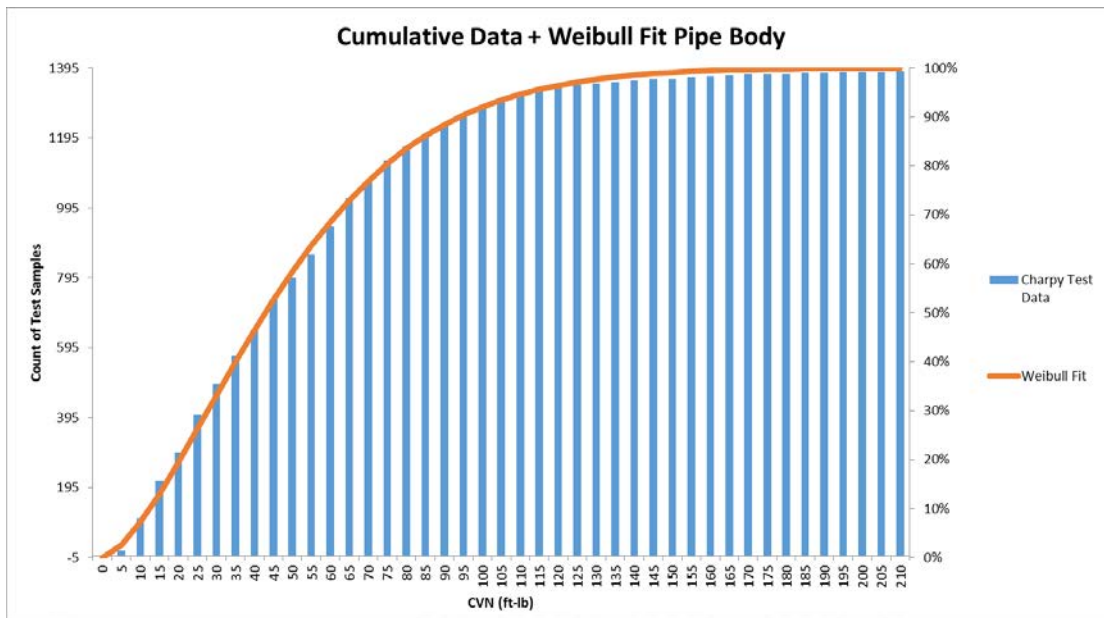


Figure 3-3 - Cumulative CVN Values for Pipe Body Data from Several Sources, and Associated Weibull Distribution

The data were characterized by a Weibull distribution to establish reasonable statistical bounds. The results are illustrated in Figure 3-4. The Weibull fit indicates that approximately 10% of pipe samples would be expected to fall below 13 ft-lb (i.e. the 90th percentile), whereas only ~2% would be expected to fall below 5 ft-lb (98th percentile). The Weibull characteristic shape parameter, corresponding to 63.2% of the data is 54 ft-lb. Pipe body cracking threats (e.g. SCC,

cracks associated with mechanical damage) would not be expected to coincide with low toughness regions of a pipeline except by chance. Thus, an analysis that assumes that the worst case hypothetical flaw coincides with the lowest 2% of toughness is a wildly conservative ‘perfect storm’ scenario. A more reasonable, but still highly conservative, analysis would assume that the worst case hypothetical flaw would coincide with the 90th percentile, or approximately 13 ft-lb CVN.

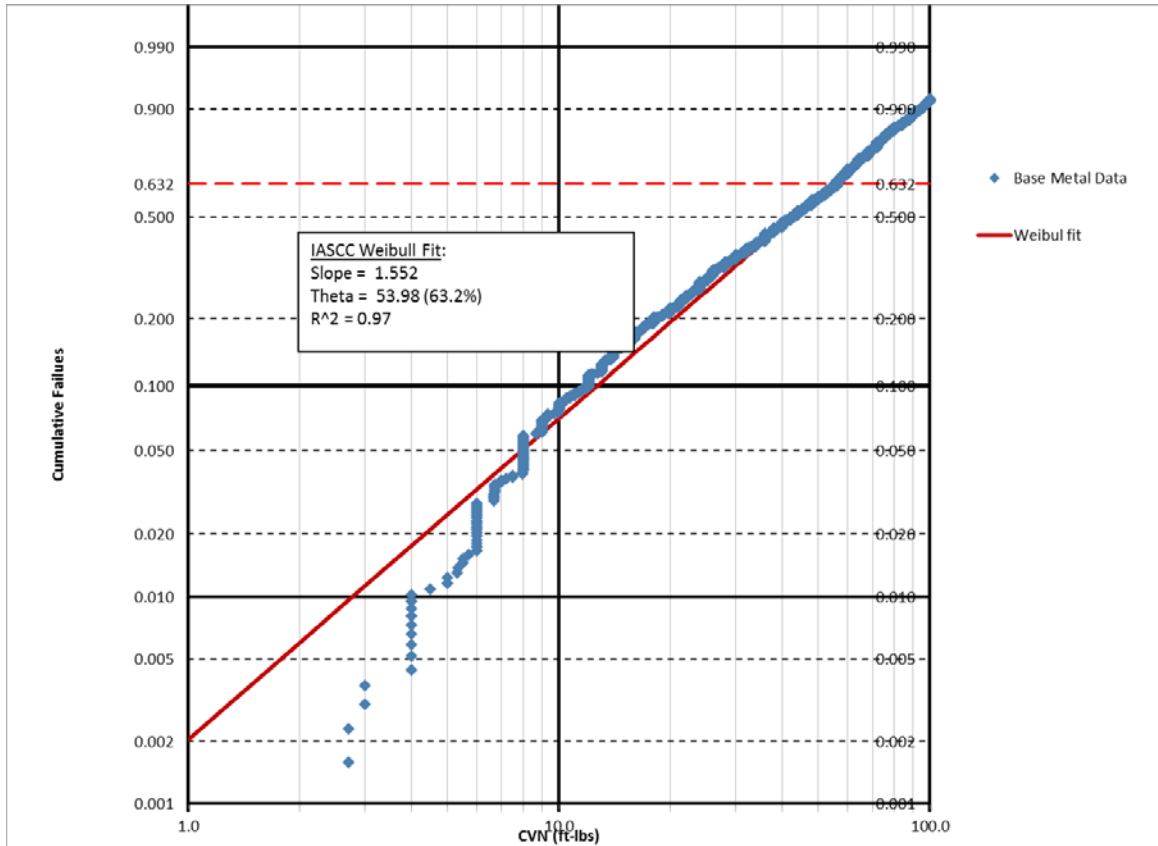


Figure 3-4– Complete CVN Data Set for Pipeline Base Metals and Associated Weibull Fit

4.0 CONCLUSIONS AND RECOMMENDATIONS

Review of the Weibull plots in Figure 3-2 and Figure 3-4 reveals that the default toughness values proposed in the NPRM of 5.0 ft-lb for body cracks and 1.0 ft-lb for seam weld defects correspond to approximately 98th and 99th percentile values, respectively. Per the conservatism identified in Section 2.0, a preliminary justification for the use of 90th percentile values is recommended. A more thorough justification would require a comprehensive probabilistic fracture mechanics (PFM) analysis which considers the range of possible flaw distributions in the pipeline, probability of detection and flaw sizing inaccuracies of NDE techniques, operating pressure and metal temperature distributions, fatigue loading spectra and crack growth behavior, as well as toughness and strength distributions for both predicted failure pressure and pressure test evaluations.

A statistical analysis has been completed of gas pipeline materials toughness data from a number of sources, including both ERW seam weld and pipe body base materials. The analysis reveals that the default toughness values proposed for fracture mechanics modeling in the NPRM, when actual material toughness is not known or not adequately documented (CVN energy values of 5.0 ft-lb for body cracks and 1.0 ft-lb for cold weld, lack of fusion, and selective seam weld corrosion defects), represent approximately 98th and 99th percentile values, based on Weibull distributions of representative data. Considering safety factors and other conservatisms that will be included in such fracture mechanics modeling, these values are overly conservative and impractical for failure pressure predictions and remaining life calculations in the presence of crack-like defects. This report recommends instead, 90th percentile values of 13.0 ft-lb for body cracks and 4.0 ft-lb for ERW seam weld cracks, which will provide adequate protection against pipeline ruptures while avoiding the costs and risks associated with remediating pipelines unnecessarily.

5.0 REFERENCES

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