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# OVERCOMING MATERIAL AND TEST VARIABILITY CHALLENGES IN IN-SITU MATERIAL VERIFICATION

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## ABSTRACT

*In-situ material property verification for oil and gas pipelines presents challenges and opportunities. One challenge is to limit undue increase in testing and maintenance costs which inherently occur if a generic conservative approach is used in the implementation of the new regulation requirements. This paper provides statistical data as well as case studies showing that measurements below the expected grade are not uncommon. Engineering analyses should allow for identifying outliers that present an actual risk while not overly increasing the industry-wide maintenance efforts. Here, the data from in-situ material verification at more than one thousand field excavations are fit to a normal distribution curve. Further analysis is provided for data points where an expected grade was provided as part of the field project. From 491 pipes with provided expected grade, there are several data points below the expected grade, but only three samples show a deviation of more than 8% below the minimum requirement. For samples with an expected grade of X52, the distribution from nondestructive testing is very similar to published distributions of laboratory test results, which also showed measurements slightly below the expected grade. Further analysis on pipe populations provides insight into how comparative analysis may help build confidence in verifying grade.*

Keywords: Nondestructive Evaluation (NDE), PHMSA Mega Rule, Pipe Grade, Material Verifications

## NOMENCLATURE

The following nomenclature is referenced within the text:

| | |
|---|---|
| API | American Petroleum Institute |
| ASD | Allowable stress design |
| CRTD | Committee on Research Technology Development |
| D | Nominal outside diameter |
| E | Longitudinal joint factor |
| EGR | Expected grade provided as part of the field project information |
| EGR NP | Expected grade not provided as part of the field project information |
| EUL | Elongation under load |
| F | Design factor |
| HSD | Hardness-Strength-and-Ductility-Testing |
| LRFD | Load and resistance factor design |
| MAOP | Maximum-Allowable-Operating-Pressure |
| MMT | Massachusetts Materials Technologies |
| MTR | Material Testing Record |
| NDE | Nondestructive Evaluation |
| P | Design pressure in pounds per square inch (kPa) gauge |
| $P_{SMYS}$ | Pressure required to introduce stress equal to SMYS for a given sample |
| PHMSA | Pipeline and Hazardous Materials Safety Administration |
| PSL | Product Specification Level |
| SMYS | Specified Minimum Yield Strength |
| T | Temperature derating factor |
| t | Nominal wall thickness |
| $\beta$ | Reliability index |
| $\gamma$ | Partial load safety factor |
| $\phi$ | Partial material safety factor |
| $\delta_R$ | Coefficient of variation in yield strength |
| $\delta_L$ | Coefficient of variation in load |
| $\sigma_H$ | Modified Lame Hoop Stress |
| $\sigma_y$ | Tensile yield strength |
| § | Chapter of the Code of Federal Regulation Title 49 |

## 1. INTRODUCTION

Vintage pipeline integrity is held to very high standards from many aspects including the demand for energy transmission, the public's perception of risk, the pressure from the financial community, and the compliance requirements set by the regulators. When changes take place, including through the new requirements for material verification of certain gas transmission assets, maintaining balanced expectations is a necessity.

In the United States, new regulations issued by the Pipeline and Hazardous Materials Safety Administration (PHMSA) require, in certain cases, material property verification and Maximum Operating Pressure (MAOP) re-confirmation for onshore gas transmission pipelines [1]. These regulations are also known as the Mega Rule. The implementation of the new requirements on material property verification per §192.607 is being carried out using either of the following methods or a combination of them: a collection of existing Material Testing Records (MTRs), pipe cutouts for laboratory destructive testing, or nondestructive evaluation (NDE) as part of pipe excavation programs.

As part of implementing the new gas regulation, re-confirmation of the MAOP is a major task. In certain situations, the determination of the pipe grade in generating an MTR or the confirmation of pipe grade can support the process. Per §192.105, the Specified Minimum Yield Strength (SMYS) is part of the design equation as,

$$MAOP = F \times SMYS \times \frac{2t}{D} \times E \times T \tag{1}$$

where $F$ is the design factor, $t$ is the nominal wall thickness, $D$ is the nominal outer diameter, $E$ is the longitudinal joint factor, and $T$ is a temperature derating factor. Such an engineering approach is an Allowable Stress Design (ASD), where the same $F$ is the factor of safety that accounts for both variations in loading of the pipe and variation in the material properties of the pipe. In contrast with ASD, Load and Resistance Factor Design (LRFD) used in other industries permits the dissociation of the total factor of safety of a component specific to loading and a component related to material resistance.

This paper provides recently collected field data for the material yield strength measured using NDE per §192.607. Using a large dataset of these in-field measurements, it quantifies the distributions for each expected grade (EGR). Due to material and testing variability, certain field measurements report yield strengths below SMYS. As a possible means to overcome this challenge, the paper presents an adaptation of an LRFD approach to quantify a material factor of safety which could help differentiate between a marginal deviation and a significant deviation below SMYS. The paper also presents an example of an opportunity where a pipeline operator may request a permit to increase allowable pressure or other operational requirements if the material verification of a pipeline population determines a grade higher than the EGR.

## 2. MATERIALS AND METHODS

The dataset utilized in this work was verified to be representative of a normally distributed pipeline population, focusing on data points for which both an EGR and a nondestructive strength measurement were available. Data comparative metrics as well as tools to derive statistical results and analysis were also defined.

### 2.1 Reference Database

The complete database for all measurements performed using a defined and controlled in-field NDE material verification process for the field seasons of 2020 and 2021 contained 925 data points for yield strength. Each data point was collected through the same process, utilizing standard procedures, certified field technicians, and clearly defined and verified data processing algorithms. The process used for in-situ NDE measurement of yield strength was based on frictional sliding, commonly referred to as Hardness, Strength, and Ductility (HSD) testing, in combination with microstructure grain size measurement and laboratory chemistry testing of surface metal shavings as detailed along with third-party validation in previous work [2, 3]. This NDE method is developed and validated to provide results equivalent to API 5L requirements from lab tensile tests [3]. The specific material property captured is the 0.5% Elongation Under Load (EUL) yield strength with the coupon testing orientation and procedure required by API 5L. For each pipe joint, the NDE procedure included testing of two circumferential quadrants with a minimum of 5 measurements per quadrant as required by §192.607(c)(1), and the average of all the valid test measurements was used to provide one value as the NDE 0.5% EUL yield strength for the tested pipe.

### 2.2 Definitions

According to §192.607(d)(2) of the PHMSA Mega Rule, NDE techniques should "conservatively account for measurement inaccuracy and uncertainty using reliable engineering tests and analyses". This requirement can be met using several techniques. In this work, the in-field NDE material verification process has a measurement tool tolerance of ±3.0 ksi for 0.5% EUL yield strength at an 80% confidence level, determined by comparing conventional destructive laboratory measurements and NDE results of the same material and measured using the conventional statistical confidence interval approach [4, 5].

Additionally, section §192.607(e)(1) of the regulation provides criteria for determining populations of similar pipe joints, using nominal wall thickness, grade, manufacturing process, and vintage. These guidelines were adopted for defining pipeline populations in this study. Specifically, pipes are grouped into populations if they showed similar diameter, wall thickness, and tensile grade and if their manufacturing dates did not differ by more than two years in the provided records. Other properties such as chemistry, grain size, and distribution of nondestructively measured tensile strengths were also considered when defining populations of pipe segments.

For this work, the definitions in Table 1 are used to classify whether the NDE result for testing a pipe allows determining the grade of one pipe conservatively.

It should be noted that:

- A non-conclusive result from testing of an individual pipe segment does not imply that further testing on several pipe segments in the same population could not result in a complete verification. This result demonstrates that at the stated confidence level due to NDE measurement uncertainty, no conclusive result could be obtained. Operators can either go with the conventional destructive testing to verify the EGR or continue with additional testing of pipe segments.

- Similarly, a single not verified status does not mean that the finding is not consistent with the expected grade. The not verified status can be either due to material variability across each pipe joint, due to process variations between the start and finish of steel pipe production during any given mill run, or due to a combination. In such scenarios, additional testing is warranted and, after multiple additional not verified status reports, may lead to a determination of not consistent with the expected grade.

## 2.3 Data Analysis

Each defined statistical sample has been averaged to provide a single value for yield strength. API 5L tensile grade is then determined by comparing the strength to the minimum requirements for Product Specification Level (PSL) 1 materials, with the statistical sample conforming to all grades up to what is reported.

**TABLE 1:** DEFINITIONS USED TO COMPARE NDE MEASUREMENTS WITH EXPECTED API 5L GRADES USING THE TOOL TOLERANCE

| Expected Grade Requirement Check | Criterion | Description |
|---|---|---|
| Verified | Measured - Uncertainty ≥ API 5L Grade Minimum | Measured strength exceeds the expected grade requirement at a specified confidence level. |
| Not Verified | Measured + uncertainty ≤ API 5L Grade Minimum | Measured strength is lower than expected grade at specified confidence level |
| Inconclusive | Measured - Uncertainty < API 5L Grade Minimum | Measured strength is within the uncertainty of the grade requirement at the specified confidence level |
| | Measured + Uncertainty > API 5L Grade Minimum | |

Using the NDE tool measurement uncertainty discussed in Section 2.2, the lower bound and upper bound of the confidence interval associated with the measured values can be defined as measured value minus the measurement uncertainty and measured value plus the measurement uncertainty, respectively [4]. If the lower bound measurement exceeds the minimum yield strength of the EGR, the EGR is then verified at the specified confidence level. On the other hand, if the upper bound measurement is lower than the EGR minimum yield strength at the specified confidence level, then the EGR is not verified. For scenarios where the lower bound measurement does not exceed the EGR minimum yield strength at the specified confidence level but is within the measurement uncertainty (i.e., measured – uncertainty ≤ EGR minimum yield strength and measured + uncertainty> EGR minimum yield strength), EGR verification is inconclusive. Adopting these concepts, populations of pipe segments analyzed in this study with provided EGR were categorized into verified, not verified, and inconclusive groups.

These definitions are also summarized in Table 1 and illustrated in Figure 1. In Figure 1, the measured value is represented by the red triangle and the true value, which is usually unknown, is represented by the yellow circle. At the specified confidence level, the conservative estimate (lower bound of the confidence interval) and non-conservative estimate (upper bound of the confidence interval) are shown by green and blue triangles, respectively. As demonstrated in this figure, different scenarios can take place depending on the value of measured yield strength compared with the EGR minimum requirement and the true value of the yield strength.

In case (a), the confidence interval contains the true value, and the lower bound of the confidence interval is above the EGR minimum yield strength; and therefore, EGR is verified. As illustrated in case (b), while the conservative estimate of the yield strength measurement can be above the EGR minimum requirement, and therefore, verifying the EGR, the true value can be lower than the EGR minimum requirement. This error is known as “false acceptance” or Type II error. Cases (c) and (d) present scenarios where the true value can be anywhere within the confidence interval while the EGR minimum requirement is below the upper bound of the confidence interval but above its lower bound (i.e., the difference between the EGR minimum requirement and measured yield strength is within the measurement uncertainty), leading to the EGR to be reported as inconclusive. As shown in case (e), in some rare but possible scenarios, the true value can be outside the confidence interval and above the measurement upper bound, while the entire confidence interval is below the minimum requirement of the EGR, determining it as not verified. This error is known as “false rejection” or Type I error. Using an accurate, verified, and well-calibrated tool, the probability of such errors can be substantially decreased. Lastly, case (f) represents a scenario where the true value resides within the confidence interval. However, the upper bound of the measurement interval is below the EGR minimum, and hence, the sample grade is correctly determined as not verified.

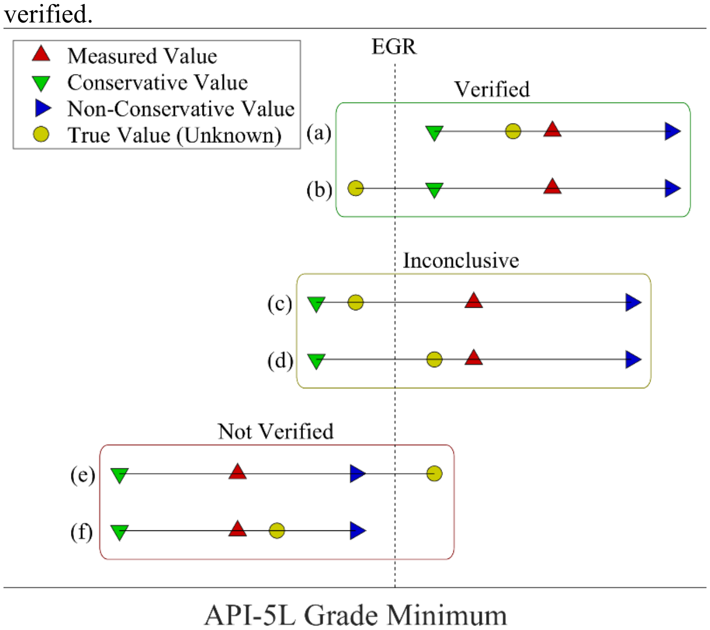


**FIGURE 1:** EXPECTED GRADE REQUIREMENT CHECK OF TESTED SAMPLES.

### 2.4 Data Interpretation Using Load and Resistance Factor Design (LRFD)

Typical engineering analysis utilizes ASD, which combines all factors into one safety factor. NDE testing, however, will measure the yield strength and other mechanical properties individually. As a result, the ASD safety factor can be split into partial safety factors corresponding to the individual measurements when evaluating pipeline assets.

For a Class 1 location (limited population in proximity), regulations limit MAOP to induce a stress value equal to or below 72% SMYS. Using LRFD partial safety factors for the load, γ, and for the material, $\phi$, could be calculated using Equation (2) and Equation (3) below, where ε is defined in Equation 4.

$$\phi = \frac{1-\varepsilon\beta\delta_R}{1-\delta_R} \quad (2)$$

$$\gamma = \frac{1+\varepsilon\beta\delta_L}{1-\delta_L} \quad (3)$$

$$\varepsilon = \frac{\sqrt{(SMYS\times\delta_R)^2+(\sigma_H\times\delta_R)^2}}{(SMYS\times\delta_R)+(\sigma_H\times\delta_R)} \quad (4)$$

For determining the partial safety factors, $\delta_R$ and $\delta_L$ correspond to the resistance and load covariance respectively, $\sigma_H$ is the hoop stress, and β is the reliability index.

Comparable safety factors to ASD methodology can be found from LRFD by combining the partial safety factors:

$$F = \frac{\gamma}{\phi} \quad (5)$$

In a prior study by the ASME Committee of Research and Technology (CRTD-86), a technical basis was provided for LRFD methods for piping [6]. CRTD-86 provides partial load safety factors and partial material safety factors for varying reliability indices used to determine the probability of failure. Table 2 lists a series of partial safety factors determined through that study. Samples analyzed in that study had comparable mechanical properties with the 925-sample dataset investigated here, with yield strength values ranging from 30 ksi to 50 ksi. Therefore, the partial safety factors provided in that report were used for comparison purposes to determine the viability of using LRFD design in the pipeline industry.

**TABLE 2:** PARTIAL LOAD SAFETY FACTOR AND PARTIAL MATERIAL SAFETY FACTOR IN CARBON STEELS FOR VARYING RELIABILITY INDICES. SOURCE CRTD-86 [6].

| β | Carbon Steel | |
|---|---|---|
| | ϕ | γ |
| 2.0 | 0.91 | 1.25 |
| 3.0 | 0.87 | 1.36 |
| 3.5 | 0.84 | 1.42 |
| 4.5 | 0.79 | 1.52 |
| 5.5 | 0.75 | 1.62 |

## 3. RESULTS AND DISCUSSION

### 3.1 Validity and Distribution of Data

Figure 2 shows the frequency distribution of NDE measured yield strength for 925 pipe samples included in this study. The distribution has a near bell-shaped curve which is a typical representation of a dataset with normal distribution. This translates into the mean, median, and mode typically having equal values. In the studied dataset, the mean and standard deviation of all pipe segments' NDE measured yield strength is 55.8 and 8.9 ksi, respectively, and 95% of the data lies between 38.0 and 73.6 ksi. The Jarque Bera test was used as a goodness-of-fit test to determine whether the sample data have skewness and kurtosis that matches a normal distribution. The test statistic was 1.1496, and the p-value of the test was 0.5628. As the p-value is much more significant than 0.05 (95% confidence level), it is reasonable to state that the skewness and kurtosis of the NDE measured yield strength dataset is not significantly different from the skewness and kurtosis of normal distribution.

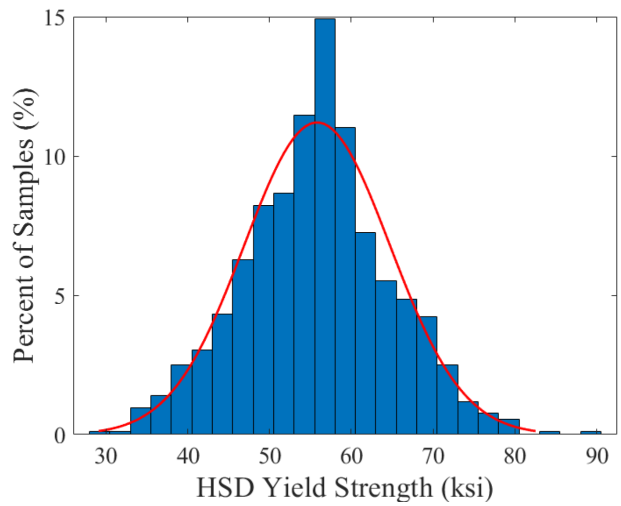


**FIGURE 2:** DISTRIBUTION OF THE NDE MEASURED 0.5% EUL YIELD STRENGTH FOR 925 PIPE SAMPLES.

Such a normal distribution of the curve implies that the tested samples were random, and a sufficiently large number of samples are available for analysis. Furthermore, as the central limit theorem holds valid, and samples tested without replacement are in small proportion, this implies that the independence requirement is still met. This means that the mean statistic of the sampling distribution is the same as the population's mean. Therefore, the dataset analyzed here could represent the aging assets of the pipelines around the U.S that are excavated for material property verification. Conclusions driven from such a dataset can be applied to thousands of miles of vintage pipelines.

Based on EGR availability for investigated populations, the dataset is divided into two categories of EGR not provided (EGR NP), and EGR provided. Figure 3 shows the API 5L grade determination distribution using the HSD NDE method across all the populations investigated. As illustrated in the figure, an EGR was provided for about 50% of the tested assets. This study focuses on the fraction of the data with provided EGR for further review and statistical analysis.

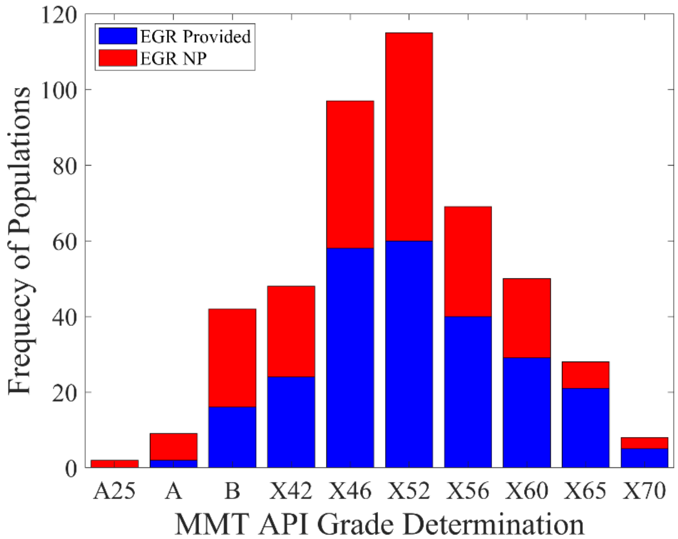


**FIGURE 3:** DISTRIBUTION OF API 5L GRADES DETERMINED FOR ALL THE SAMPLES INCLUDED IN THIS STUDY. EGR WAS NOT PROVIDED FOR APPROXIMATELY 50% OF THE PIPE SEGMENTS IN THIS DATASET.

Figure 4 is a summary of NDE results from 491 pipe segments with available EGR, provided as histograms for different expected API 5L grades showing that only 20 samples or about 4% of the tested samples were not successful in the validation of their minimum required strength values. Further analysis showed that the proportion of the pipe segments with not verified EGR increases for samples with high specified EGR. While 0% and 2% of the samples with EGR of B and X42 were not verified, respectively, 11% and 52% of the pipe joints with specified EGR of X65 and X70 could not be verified. This data shows that, in general, the conservative measurement of the yield strength exceeds the EGR minimum requirement; however, there are a limited number of pipe joints the average yield strength value does not comply with the minimum requirement of the specified grade.

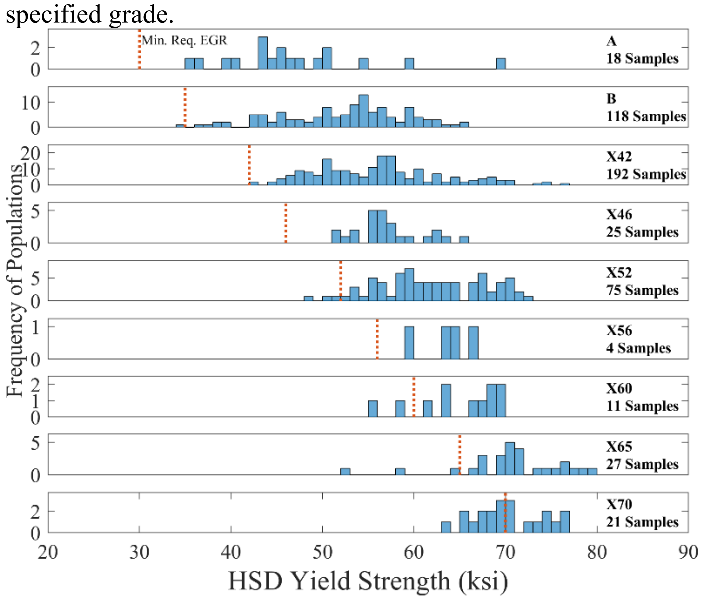


**FIGURE 4:** COMPARISON BETWEEN EGR AND HSD TESTING ON SAMPLES OBTAINED FROM VARIOUS PIPELINE SEGMENTS.

### 3.2 Distribution between Populations

Figure 5 shows four pipe populations with EGR of X52 having a similar number of pipes tested for each population. By applying a conservative shift of 3 ksi for the NDE measurement uncertainty as mentioned in Section 2.2, only populations 1 and 2 can be verified. Populations 3 and 4 include pipe segments with a conservative yield strength only slightly below the required minimum. One data point is reducing the average for population 3, leading to the total average of the population to fall below 52 ksi, labeling the population as “inconclusive”. Meanwhile, in population 4, testing more pipe segments with conservative yield strength values above the EGR resulted in the overall average of the population falling well above the expected grade requirement, which verifies the expected material properties. In these cases, approaching other sources such as chemistry or expansion of sampling could help verify inconclusive assets.

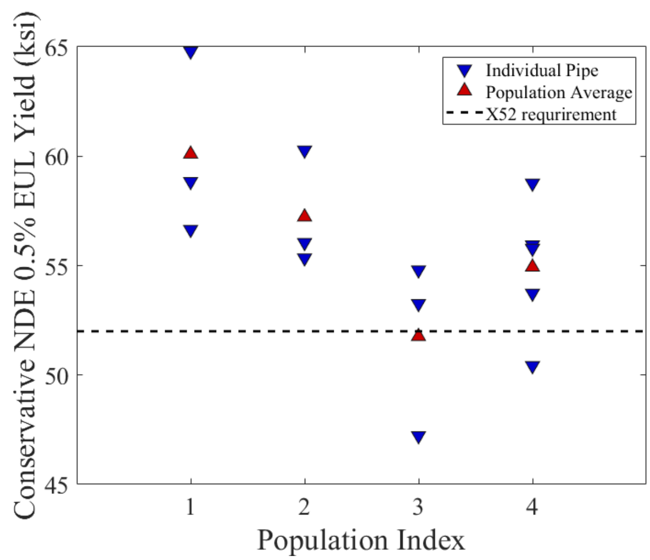


**FIGURE 5:** CONSERVATIVE NDE MEASURED YIELD VALUES OF 4 SAMPLE POPULATIONS OF PIPE SEGMENTS WITH A PROVIDED EGR OF X52. WHILE MAJORITY OF THE POPULATIONS WITH EGR OF X52 WERE SIMILAR TO POPULATIONS 1 AND 2, WITH CONSERVATIVE YIELD VALUES WELL ABOVE THE MINIMUM REQUIREMENT, SOME POPULATIONS INCLUDED PIPE SEGMENTS WHOSE YIELD VALUES SHOWED DISTRIBUTIONS SIMILAR TO THOSE OF POPULATION 3 AND 4, LEADING TO THE EGR OF THE POPULATION TO BE DETERMINED AS INCONCLUSIVE.

When looking at assets expected to be in a specific grade, there is no guarantee that all samples tested will be above the minimum required strength value. As an example, Figure 6 shows the cumulative probability of the conservative 0.5% EUL yield value distribution across all joints with an EGR of X52. It can be observed that less than 4% of the samples tested will fall below the minimum requirement of the grade expectation. This number agrees with a formerly published investigation on a destructively tested population of pipe segments [3].

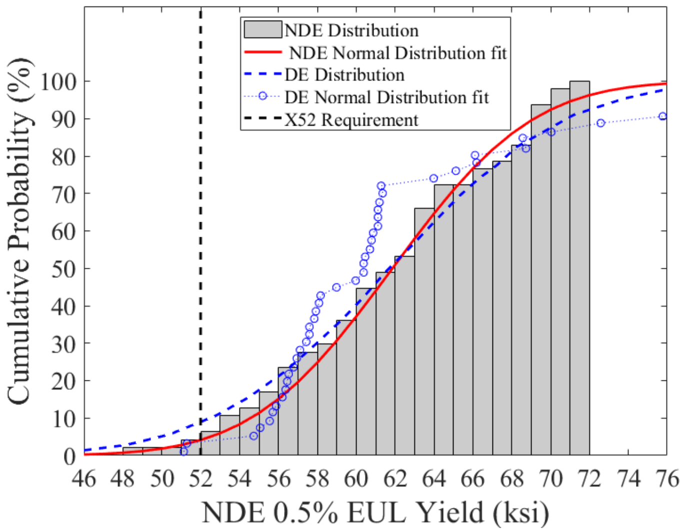


**FIGURE 6:** THE CUMULATIVE PROBABILITY OF THE NDE CONSERVATIVE 0.5% EUL YIELD VALUE DISTRIBUTION ACROSS ALL THE PIPE JOINTS WITH AN EGR OF X52. THE NDE DATA IS CONSISTENT WITH THE PREVIOUS STUDY ON POPULATION OF PIPE SEGMENTS WITH EGR OF X52 WHICH WERE DESTRUCTIVELY TESTED.

However, this does not justify that about 4% of the assets need replacement or de-rating. What needs to be justified is the significance and recurrence of the points below the requirement in a whole population or line.

Potential reasons for such distribution with yield values slightly below the minimum include material variability across each pipe joint and between the first and last product made through any given mill run. Another inherent factor is from the API 5L guidelines, which allow a lot to be re-tested when a given manufacturing lot fails the first set of laboratory strength testing.

### 3.3 Alternatives for Verifying Assets

Figure 7 provides a graphical representation of grade verification, resulting in three determinations of verified, inconclusive, and not verified, as discussed earlier.

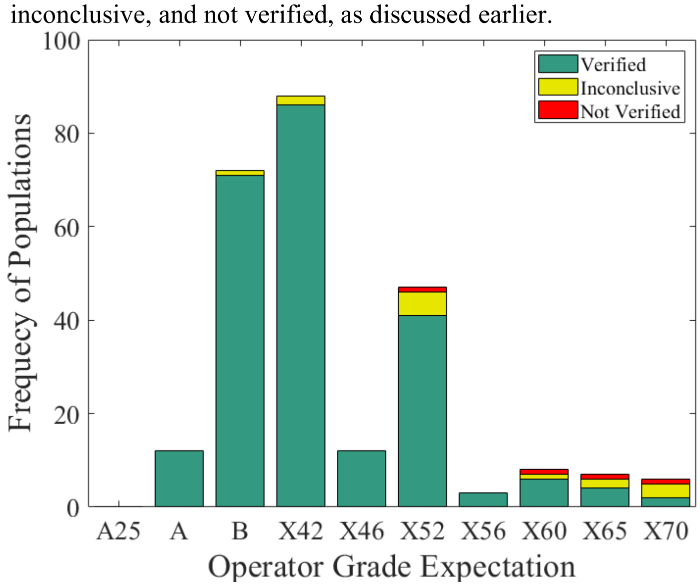


**FIGURE 7:** DISTRIBUTION OF GRADE VERIFICATION RESULTS USING NDE PROCESS FOR THE SAMPLES WITH A PROVIDED EGR.

As seen in this figure, the best scenario is that the EGR is verified and is deemed consistent with available information or existing expectations. In such a case, no further action is required from the operator in terms of material verification of the strength properties of the pipe segment. However, in case the material properties are deemed not verified with the available NDE test results, additional testing or the use of another approach may be warranted before considering the results as not consistent with the expectations. When establishing the engineering approach and analysis, a goal is to ensure that a "good" population is not rejected while a 'bad" population is not accepted. This means a population is not rejected based on one pipe test when the EGR is not verified. Furthermore, the required statistical analysis to demonstrate compliance with EGR is left for the operators as they have more information about the sampling process and thus will have their requirements for the EGR acceptance criteria.

### 3.4 Findings below SMYS

Based on the data shown in Section 3.1, approximately 4% of assets may test below SMYS. Suggested approaches to handling these below EGR assets include tolerating 1, or a few, ksi below SMYS or 10% deviation from nominal strength, which was an acceptable measurement tolerance for NDE which in drafts of §192.607.

This section provides an adaptation of an LRFD approach toward determining a deviation below SMYS that would fall within a material factor of safety and, therefore, may be classified differently than true outliers. It includes selecting several parameters that would need to be evaluated on a case-by-case basis. The probability of rupture is expressed as:

$$P(Fail) = 1 - \Phi(\beta) \tag{6}$$

A one-sided, 2.5% probability of failure corresponds to a reliability index of 2. This reliability index can be adjusted based on tolerance to risk and is used as an input to Equations 2 and 3. The reliability factor is essential for comparing calculated values to those provided in Table 2. In this scenario, $\beta = 2$ is used for analysis and comparison.

Using information provided by CRTD-86 with Equations 2 through 4 and reference tables for operating stress of 72% SMYS, the material factor of safety can be calculated as $\phi = 0.92$, and the load factor of safety can be calculated as $\gamma = 1.29$. These values are aligned with the CRTD-86 values for carbon steels when $\beta = 2$, shown in Table 2. The material safety factor of 0.92 corresponds to measured yield stress 8% below the SMYS for a given pipe.

An important consideration is the comparison of the LRFD values to ASD design factor. Conventional ASD analysis suggests that a safe pipeline operation should follow the below equation:

$$\frac{SMYS}{F} \geq \sigma_H \tag{7}$$

where $\sigma_H$ is the hoop stress. This specifies that the induced stress should not exceed SMYS divided by a design factor.

The relation of MAOP to design factor is described by:

$$\frac{P_{SMYS}}{MAOP} = F \tag{8}$$

where $P_{SMYS}$ is the pressure required to produce stresses equal to the specified SMYS value.

 

As a result, in situations where MAOP results in stress at 72% of SMYS, F = 1.39. Combining Equations 5 and 7, the following relation can be inferred:

$$\phi SMYS \geq \gamma \sigma_H \quad (9)$$

Equation 9 provides another method to understand this correlation and emphasizes the 0.92 multiplier. Actual strength 8% below SMYS can meet the ASD design factor of F =1.39, provided that the stated load factor of safety is appropriately satisfied; $\gamma = 1.29$.

Converting the partial safety factor values into a conventional ASD value can be achieved by entering $\phi$ and $\gamma$ values into Equation 5. Doing so for the values provided in this section results in an MAOP = 71.32% of $P_{SMYS,}$ or an F = 1.4, demonstrating the equality between the two methodologies.

LFRD approach to safety is not a novel concept and is used in other industries. The American Association of State Highway and Transportation Officials detailed the use of LRFD in highway bridge superstructures [7]. However, the steel coefficient of variation may vary based on manufacturing standards.

In re-evaluating the data shown in Figure 4, only three data points have more than an 8% deviation below SMYS, significantly less than the 20 NDE data points that fall below SMYS alone. Figure 8 shows this analysis for X65 samples, where two data points have more than 8% deviation below SMYS. Such analysis, adapted for the material coefficient of variation and other analysis parameters, could reduce the number of data points considered outliers by quantifying a material factor of safety previously implicit in the ASD approach.

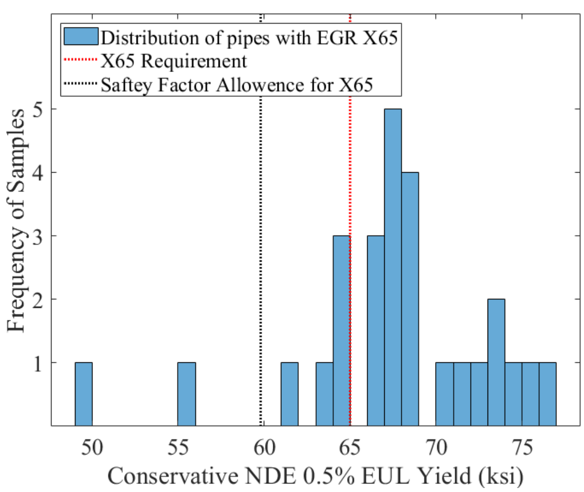


**FIGURE 8:** HISTOGRAM OF SAMPLES WITH EGR OF X65. 2 DATA POINTS ARE MORE THAN 8% BELOW EXPECTED SMYS.

### 3.5 Possibility to verify a higher-than-expected grade

In many cases, pipeline operators might find the need to request special permits for uprating an asset. For example, a pipeline might be categorized in a higher-class location due to urban expansions requiring increased safety factors (e.g., from 125% to 150%) and thus a reduction in MAOP. In such cases pipeline operator might be able to justify uprating the asset to maintain the MAOP and service rate. In this section, a justification for an increase in MAOP or maintaining the MAOP after an increase in safety factors is discussed for pipes with strength predictions significantly higher than expected grades.

In Figure 9, testing data from 14 digs is shown for a population with an EGR of X42. The measurements are consistently higher than X42, with most readings well above X42 grade. A higher grade could be assigned if this data was for a line with no available expected grade information. If the sample digs were tested using a random selection from the total pipe segment population, then based on the central limit theorem, the distribution of the sample mean approximates a normal distribution as the sample size gets larger, irrespective of the population's distribution. This implies that sample measurements will be equally distributed above and below the center of the distribution, which will be the mean value of those measurements. As demonstrated in Figure 9, at a 95% confidence level, the mean of the conservative yield values is estimated to be around 48 ksi. The distribution of the conservative values exceeds the requirement for X46, which is a higher grade than X42. One possible approach to statistically confirm a higher grade is to determine the 1st percentile data point and 10th percentile datapoint to establish EGR-specific lower bound yield strength based on normal distribution after removing any outliers [8].

The lack of clarity regarding compliance provides asset owners the opportunity to meet the regulation requirements and do so in a manner that identifies outliers without penalizing assets that can be operated safely. Using alternative sampling on a pipe population, it is possible to positively confirm a pipe grade higher than the expected grade, potentially allowing for special permit applications and addressing class changes.

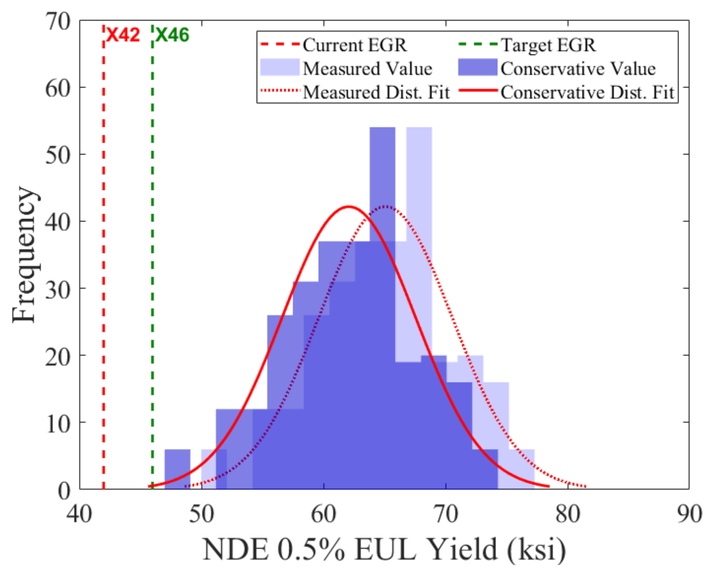


**FIGURE 9:** EXAMPLE OF A POPULATION WITH 14 PIPE JOINTS AND AN EGR OF X42.

## CONCLUSION

From the data review and analysis, it is concluded that:

- Efforts to conservatively verify the minimum yield strength required for an EGR are generally successful for pipe segments tested with the presented NDE tool. Only 4% of the total 491 samples studied here exhibited yield strength values below the minimum requirement from their EGR.

- Considering the proportion of the number of measurements made, pipes with high EGR (X54 and X70) tend to have more NDE data points below SMYS, compared to samples with lower EGR, such as B or X42.
- A number of approaches can be considered to address data points below SMYS, but within a certain level of variation, such that they would not necessarily be considered outliers.
- A material factor of safety, which is implicit in the ASD approach can be quantified.

## REFERENCES


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