Statistical Analysis of Oil and Gas Pipelines to Predict Pipe Grade using Power BI

William V. Harper[1], Thomas A. Bubenik[1], Tara P. McMahan[1], Benjamin R. Hanna[1], Steven J. Polasik[1], Adriana Nenciu[2], Stacy G. Hickey[1], David J. Stucki[2]

[1]DNV USA, Inc., 5777 Frantz Road, Dublin, OH 43017
[2]Otterbein University, 1 S. Grove St., Westerville, OH 43081

Abstract
Oil and gas transmission pipelines are comprised of steel segments (joints) with lengths of about 40 feet. A key property of a joint is specified grade (minimum material and mechanical properties). For some pipes, the grade is no longer known. The Pipeline and Hazardous Materials Safety Administration (PHMSA) has tightened regulations leading to the need to estimate joint grade from destructive and non-destructive testing. PHMSA developed the revisions to address the recommendations made by the National Transportation Safety Board (NTSB). The NTSB highlighted the importance of using accurate material properties to determine the integrity of pipelines.

GradeIt is a Power BI app that provides a statistical grade estimation for joints based on measured values of yield strength. The fidelity of the grade estimation relies on the number of data points, as there may be multiple yield strength measurements for each joint. GradeIt uses statistical methods to estimate grade as well as a user-defined level of conservatism. GradeIt introduces new metrics to quantify the quality of the overall population grade relative to the assumption of differing pipe grades.

Key Words: Oil, Gas, Pipeline, Pipe Grade, PHMSA

1. Introduction

Transmission pipelines that carry oil and gas consist of steel joints with a typical length of around 40 feet. A key classification of a joint is its grade. For numerous reasons, a pipeline operator may not know the grade of some pipe. The Pipeline and Hazardous Materials Safety Administration (PHMSA) has tightened the regulations in the United States leading to the need to better estimate the joint grade. GradeIt is a Power BI app that provides a statistical grade estimation for joints and the yield strengths used in the process.

In 2019 PHMSA published a Final Rule that revised regulations with the overarching goal of improving the safety of onshore gas transmission pipelines (84 FR 52180, 2019 and related 49 CFR § 192.607(b), § 192.607(e), 2019). PHMSA developed the revisions to address, among multiple considerations, the recommendations made by the National Transportation Safety Board (NTSB) following their investigation into the 2010 gas pipeline incident in San Bruno, CA (National Transportation Safety Board, 2011). The NTSB investigation highlighted the importance of accurate pipeline characteristics within engineering assessments used to ensure the integrity of onshore pipelines. Inaccurate documentation can ultimately lead to inadequate decisions and reduced public safety. Within the revised regulations, PHMSA is specifically requiring pipeline operators to have records documenting physical pipeline characteristics and attributes that are "traceable, verifiable, and complete" (49 CFR 192.607(b), 2019).

To demonstrate that their records are "traceable, verifiable, and complete" pipeline operators can perform non-destructive testing methods if those methods account for measurement inaccuracy and uncertainty. Pipeline operators are required to use an approach designed to achieve at least a 95% confidence level that material properties used in the operation and maintenance of the pipeline are valid (49 CFR 192.607(e), 2019).

Assessing reasonable grades for unknown pipe is a challenging, time consuming, and expensive undertaking. Only a small portion of a pipeline segment whose grade is not known is sampled. It is from this sample that the operator must prepare their case for the grade of the full segment population. GradeIt is a support tool to aid in the quantification of the available data and help the operating company find a recommendation that has statistical justification.

Any statistical method would have highly variable yield strength measurements within its analysis. As such, the definite answer to what pipe grade should be used by a pipeline operator is subjective and must be assessed internally within the operator's organization. GradeIt consolidates the relevant yield strength and joint data, providing a variety of decision support mechanisms to aid the operator in reporting an appropriate pipeline grade.

GradeIt compares the measured yield strength values of pipe segments with what has been measured and used in the industry for each grade. Statistical means and standard deviations are analyzed to provide the most likely pipe grades, as well as possible alternative pipe grades due to statistical overlap. This publication primarily focuses on the subset of GradeIt output specifically geared toward providing an answer to what is/are reasonable grade(s) given the available data. Some other GradeIt pages are also detailed that provide backing information or allow the client to assess the impact of both data and assumptions.

2. GradeIt Key Outputs

Currently there are over a dozen Power BI pages within GradeIt that provide insight into the collected data. The user may select any pipeline segment for their organization or combine segments as desired. This section focuses on the most useful pages in aiding the user to estimate the grade of a given population. In general, the pipeline operator will use a single grade for a specific pipeline segment. If there are differing populations within the segment, then separate joint grades should be used by the client. GradeIt can help identify those joints that do not fit the pattern of the rest of the segment. For a given population, this entails combining (and might also include sub setting) the joint and yield strength results shown in the following pages into one proposed grade. It is a challenging task and one that should involve statistical analysis, expert opinion, and potentially the degree of conservatism that the operator desires.

GradeIt references to Power BI items are distinguished in the following manner:

- GradeIt Power BI pages: these will use the same font as used in Power BI as well as being bold and in quotes, e.g., **"Joint Summary"**.
- Visuals (table, matrix, plot) on a GradeIt page: these are shown in italics and surrounded with quotes, e.g., *"Joint, Yield Strength"*.

- References to other items on a Power BI page: these items such as a column name are given with surrounding quotes, e.g. “Closest Grade”.

Key Power BI GradeIt pages will be discussed in more detail than other pages. These key pages are as follows, where segment is used to represent the full population of joints for given line(s) currently being analyzed. Segment sample data are the yield and joint information from the segment population of interest.

- **“Joint Summary”**: grade estimate for each joint and metrics summarizing the segment sample data, including probability-based grade estimates for the full population
- **“API 1176”**: grades compatible with a desired 95% confidence level
- **“Match %, < nominal”**: percentage of each grade prediction matching expectation; percentage of yield strength less than nominal strength of each grade

2.1 “Joint Summary”

One of the most useful Power BI pages is **“Joint Summary”** that provides a foundation for much of GradeIt. Each row in the *“Grades Estimation”* matrix seen in Figure 1 represents a single joint of pipe. Each joint has a unique identification as the pipeline operator may combine different pipeline segments to identify a common grade. Joint grade estimation is based on yield strength measurements, which are shown in units of ksi (1000 psi). In Figure 1, the yield strength sample size n, mean, and standard deviation (“SDJoint”) are followed by grade probabilities when the sample size n is greater than 1.

The probabilities in *“Grades Estimation”* use joint strength values based on American Pipeline Institute recommended practice API 1176 (API 1176, 2016). There are nine commonly cited pipeline grades (A, B, X42, …, X70) that are in order of increasing strength. These have been augmented with two additional grades representing joints that are below grade A (<A) and above grade X70 (Z80). Yield strength measurements have high variability and these supplemental grades are useful in the identification of bad input data or poor yield measurements.

For each grade on a given joint, a normal distribution using the sample mean, standard deviation, and sample size is compared to the lower bound of a given grade bin based on API 1176. The result is the probability that the joint grade is at least the grade specified in the column heading, e.g., “X42”. For example, the red underlined 0.99 from *“Grades Estimation”* in the first row is the probability that this joint is Grade X42 or higher.

It is suggested that the client use the estimated grade in the shaded blue column called “Closest Grade” as a starting point. “Closest Grade” is the highest grade that has a probability of at least 0.50. To obtain a probability of at least 0.50, the yield sample mean on the joint must be in the bin for that API 1176 grade range or a higher grade.

For a pipeline operator, it is often more important to know the grade of the larger population of a pipeline segment rather than that of an individual joint. Only a subset of the line segment will have yield measurements that must then be extended to the entire population of interest. The bottom “Total” row of *“Grades Estimation”* shows that the “Closest Grade” for the entire batch of joints analyzed is grade X46; however, some operators may desire to be more conservative.

The light green *"PXX, Color (0.50 matches Closest Grade)"* slicer at the bottom right of **"Joint Summary"** allows the user to control two aspects of the analysis. First, the value selected (PXX) controls the conditional formatting of the probabilities, i.e., only probabilities of at least this value will have the light green background. Secondly, and more importantly, this value determines the predicted grade as listed in the "PXX Grade" column. As can be seen in **"Joint Summary"**, migrating from the blue column "Closest Grade" corresponding to PXX = 0.50 to the light green "PXX Grade" column using PXX = 0.80 has lowered some predicted grades. To satisfy a PXX = 0.80, the probability of being at least a given grade must now be 0.80 or higher. This option permits operators to have flexibility in how they estimate their line grade. For operators that are interested in appraising grade on potentially border-line joints, PXX may be set to values < 0.50 to see if the predicted grade is increased.

The "Total" line in *"Grades Estimation"* provides the overall grade estimate for all joints evaluated. For this example, X46 is both the "Closest Grade" and "PXX Grade". This, among other aspects of GradeIt, aids in the determination of a reasonable grade for the population of interest. The "Total" line results are based on the joints and yield strength values that are visible in Power BI. The *"Joint, Yield Strength"* slicer on the right of **"Joint Summary"** (also found in other selected pages) determines which of the joints and/or yield strengths are visible and summarized accordingly in the current GradeIt output. Most slicers have been synchronized across potentially impacted Power BI pages. A change in a multi-page slicer impacts the analyses across all pages. Such modeling efforts permit an in-depth assessment of multiple concerns, including the study of potential outliers.

Below the "Total" line on the left is a 95% two-tailed confidence interval for the population mean of the line segment(s) based on the visible (selected) values in the *"Joint, Yield Strength"* slicer. This 95% confidence interval for the population mean is derived from all visible data used in the analysis. Any data dropped via the *"Joint, Yield Strength"* slicer is not used in the development of any analysis in GradeIt, including this population mean confidence interval. This interval may be thought of as covering reasonable values for the population mean.

Grade Estimation

UniqueJointCol	n	Mean	SDJoint	<A	A	B	X42	X46	X52	X56	X60	X65	X70	Z80	Closest Grade	Consist	Joint Cons?	PXX Grade
X46_11 --(DNV line 10)	3	53.22	1.96	1.00	1.00	1.00	0.99	0.60	0.00	0.00	0.00	0.00	0.00	0.00	X46	0.99	1	X42
X46_12 --(DNV line 10)	5	52.44	3.71	1.00	1.00	1.00	0.89	0.38	0.01	0.00	0.00	0.00	0.00	0.00	X42	0.64	1	X42
X46_13 --(DNV line 10)	3	53.92	3.43	1.00	1.00	1.00	0.96	0.69	0.10	0.00	0.00	0.00	0.00	0.00	X46	0.74	1	X42
X46_14 --(DNV line 10)	2	51.53	7.14	1.00	1.00	0.92	0.59	0.39	0.16	0.03	0.00	0.00	0.00	0.00	X42	0.61	1	B
X46_15 --(DNV line 10)	4	51.45	2.88	1.00	1.00	1.00	0.77	0.15	0.00	0.00	0.00	0.00	0.00	0.00	X42	0.37	1	B
X46_16 --(DNV line 10)	1	52.00	0.00												X42	0.78	1	X42
X46_17 --(DNV line 10)	2	58.77	3.27	1.00	1.00	1.00	1.00	0.99	0.84	0.17	0.00	0.00	0.00	0.00	X52	0.25	1	X52
X46_18 --(DNV line 10)	1	55.99	0.00												X46	0.55	1	X46
X46_19 --(DNV line 10)	3	54.42	4.83	1.00	1.00	1.00	0.93	0.70	0.23	0.01	0.00	0.00	0.00	0.00	X46	0.58	1	X42
X46_20 --(DNV line 10)	6	52.86	2.85	1.00	1.00	1.00	0.98	0.47	0.00	0.00	0.00	0.00	0.00	0.00	X42	0.82	1	X42
X46_21 --(DNV line 10)	3	54.33	1.40	1.00	1.00	1.00	1.00	0.96	0.00	0.00	0.00	0.00	0.00	0.00	X46	0.61	1	X46
X46_22 --(DNV line 10)	4	51.81	3.55	1.00	1.00	1.00	0.79	0.26	0.00	0.00	0.00	0.00	0.00	0.00	X42	0.47	1	B
X46_23 --(DNV line 10)	3	51.37	2.29	1.00	1.00	1.00	0.77	0.12	0.00	0.00	0.00	0.00	0.00	0.00	X42	0.44	1	B
X46_24 --(DNV line 10)	5	50.92	2.22	1.00	1.00	1.00	0.70	0.02	0.00	0.00	0.00	0.00	0.00	0.00	X42	0.20	1	B
X46_25 --(DNV line 10)	3	53.75	6.64	1.00	1.00	0.99	0.81	0.58	0.24	0.03	0.00	0.00	0.00	0.00	X46	0.79	1	X42
X46_26 --(DNV line 10)	6	54.13	3.13	1.00	1.00	1.00	1.00	0.82	0.03	0.00	0.00	0.00	0.00	0.00	X46	0.52	1	X46
X46_27 --(DNV line 10)	3	51.90	3.51	1.00	1.00	1.00	0.77	0.30	0.01	0.00	0.00	0.00	0.00	0.00	X42	0.57	1	B
X46_28 --(DNV line 10)	3	53.48	2.92	1.00	1.00	1.00	0.97	0.62	0.04	0.00	0.00	0.00	0.00	0.00	X46	0.89	1	X42
X46_29 --(DNV line 10)	6	53.72	2.51	1.00	1.00	1.00	1.00	0.77	0.00	0.00	0.00	0.00	0.00	0.00	X46	0.71	1	X42
X46_30 --(DNV line 10)	6	52.59	3.33	1.00	1.00	1.00	0.95	0.40	0.00	0.00	0.00	0.00	0.00	0.00	X42	0.68	1	X42
X46_31 --(DNV line 10)	5	53.77	0.88	1.00	1.00	1.00	1.00	0.98	0.00	0.00	0.00	0.00	0.00	0.00	X46	0.71	1	X46
X46_32 --(DNV line 10)	1	53.57	0.00												X46	0.93	1	X46
X46_33 --(DNV line 10)	1	52.04	0.00												X42	0.79	1	X42
Total	**169**	**53.19**	**3.30**	**1.00**	**1.00**	**1.00**	**1.00**	**0.82**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**X46**	**1.00**	**1**	**X46**

Mean 95% CI Lower	Mean 95% CI Upper
52.68	**53.69**

Line Selected = Company 1 - 40 Grade X46 with SD=3_v1 --(DNV line 10)

Joint, Yield Strength
- Select all
- X46_11 --(DNV line 10)
  - 50.97
  - 54.15
  - 54.55
- X46_12 --(DNV line 10)
- X46_13 --(DNV line 10)
- X46_14 --(DNV line 10)
- X46_15 --(DNV line 10)
- X46_16 --(DNV line 10)
- X46_17 --(DNV line 10)
- X46_18 --(DNV line 10)
- X46_19 --(DNV line 10)
- X46_20 --(DNV line 10)
- X46_21 --(DNV line 10)
- X46_22 --(DNV line 10)
- X46_23 --(DNV line 10)
- X46_24 --(DNV line 10)
- X46_25 --(DNV line 10)
- X46_26 --(DNV line 10)
- X46_27 --(DNV line 10)
  - 49.40
  - 50.39

PXX, Color (0.50 matches Closest Grade)

0.80

Figure 1. **"Joint Summary"** page.

2.2 "API 1176"

The characteristics to define pipe grade are derived from yield strength data in API 1176. GradeIt has the summarized API 1176 data (Figure 2) and includes an additional two grades (<A, Z80) mentioned before. The lower bound for a grade ("Low") is used in the computation of the probabilities in the **"Joint Summary"** page. The "Strength" column from Figure 2 is used to assess which yield strengths are below nominal grade, as covered in the next section.

Portions of GradeIt are based on probability instead of confidence level. Both the "Closest Grade" and "PXX Grade" pipe grades are based on probability methods and not statistical inference confidence intervals. While these results are important, PHMSA requires a 95% confidence level on the results presented.

The 95% population mean confidence interval shown in the lower left of the **"Joint Summary"** page is repeated on the left of the **"API 1176"** page. Combining the confidence interval with the API 1176 table allows the identification of pipe grades that are compatible (overlap) with this 95% population mean confidence interval. It is seen in the column "Data meets 95% criteria?" that pipe grades X42 and X46 meet the PHMSA 95% confidence level criteria. This information, along with the two grade assessments ("Closest Grade" and "PXX Grade") in the total line of the **"Joint Summary"** and the **"Match %, < nominal"** pages described later, are key GradeIt tools used to support an assigned population grade.

Mean 95% CI Lower	Mean 95% CI Upper
52.68	53.69

API 1176, PHMSA 95% confidence level evaluation

Grade	1176 Mean	Strength	Low	High	Data meets 95% criteria?
<A	31.40	15.00	-99.00	35.70	
A	40.00	25.00	35.70	44.30	
B	48.60	35.00	44.30	50.40	
X42	52.20	42.00	50.40	52.95	Passes
X46	53.70	46.00	52.95	56.45	Passes
X52	59.20	52.00	56.45	61.00	
X56	62.80	56.00	61.00	65.75	
X60	68.70	60.00	65.75	70.35	
X65	72.00	65.00	70.35	76.20	
X70	80.40	70.00	76.20	86.25	
Z80	92.10	80.00	86.25	999.00	

Line Selected = Company 1 - 40 Grade X46 with SD=3_v1 --(DNV line 10)

Figure 2. **"API 1176"** page

2.3 "Match %, < nominal"

Expected counts depend on the grade, the selected standard deviation, and the API 1176 Low, Mean, and High strengths. The API 1176 values come from the relevant row of **"API 1176"**.

"Match %, < nominal" shows the "Match %" metric that provides the user detailed information and a clearer path toward selecting an overall grade for the entire population of interest. This is seen in the *"Match %, below nominal %"* table that summarizes the matched percentage for all grades in the column "Match %".

Grade X46 is selected in the *"Expected Grade"* slicer. This becomes the user expected grade for analysis purposes at a given step in the overall assessment. It is not necessarily what the client plans to use in its assessments, but instead allows analysis of how well the selected expected grade matches the predicted data based on the sample data from the segment.

The expected counts are given in matrix *"Expected vs Predicted Grades"* for X46. "Match %" for X46 using the observed standard deviation of 3.30 ksi and PXX set = 0.50 in the *"PXX, Color (0.50 matches Closest Grade)"* slicer) results in 76.36% that is computed by taking the sum the row minimums (which is the overlap) of the "Expected vs Predicted Grades" columns and then dividing this sum by the number of joints. It should be noted that the degree of separation between the grades B, X42, and X46, as shown in **"API 1176"**, is less than between other grades. Using a smaller standard deviation than the observed standard deviation tightens the results and may aid a final decision of what grade to recommend.

"Yield Below Nominal Strength" is the percentage of yield strength measurements in the selected data set that are less than the specified minimum yield strength (SMYS) in the API 1176 column "Strength," e.g., 42 ksi for X42. This will not change as the user selects a different grade in the *"Expected Grade"* slicer. Low values of "Yield Below Nominal Strength" of around 5% or less are recommended for selecting an appropriate grade. This data shows that 1.2% of the measurements are below SMYS for X46, but this number jumps to 39.6% for the next higher pipe grade, X52. This result, in addition to what was estimated from prior pages, lends credence that X46 appears to be a reasonable candidate for the population pipe grade based on the sample data.

The visual *"Standard Deviation assessment"* compares the overall standard deviation from the "Total" line on the **"Joint Summary"** page to both the maximum joint standard deviation and the pooled standard deviation across all joints in the sample. If statistically significant, the ratios are colored red.

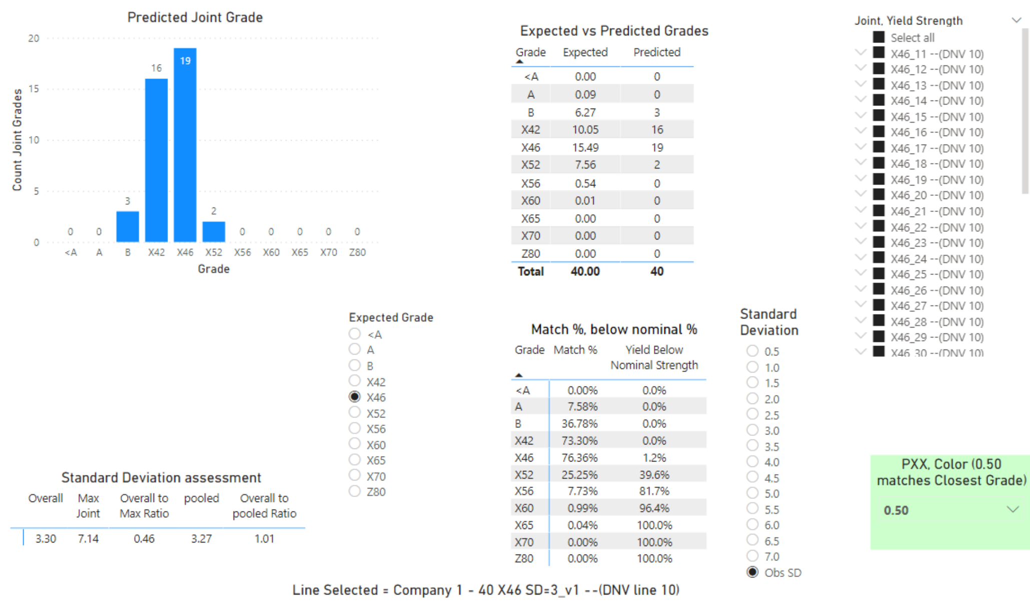


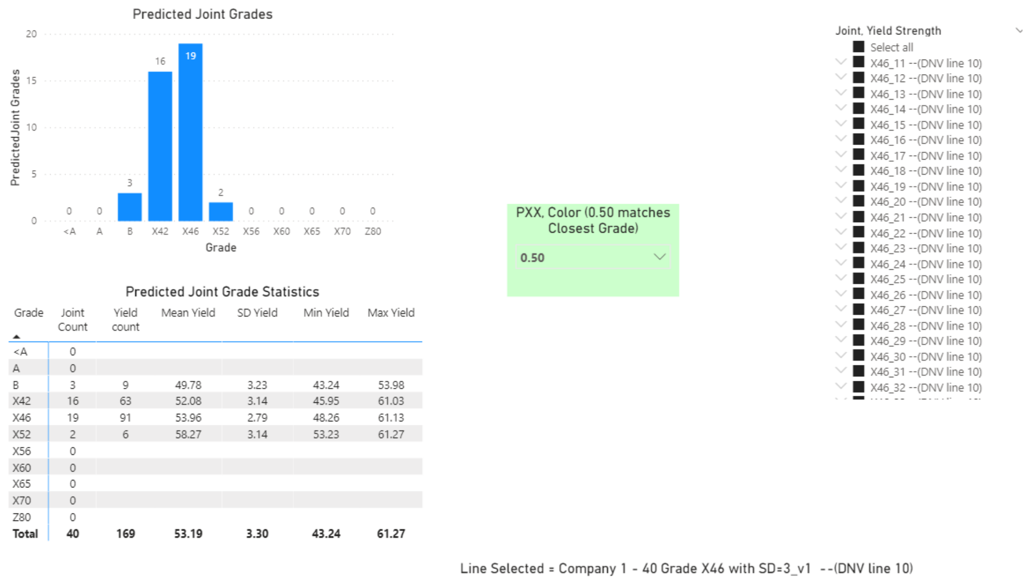
Figure 3. **"Match %, < nominal"** page

3. GradeIt Support Pages

There are numerous other Power BI pages in GradeIt that provide additional detail as well as permit experimentation and sensitivity studies. Depending on the client needs, some of these will be more important than others. A few of these pages are briefly covered in this section.

3.1 "PXX detail page"

Figure 4 from **"PXX detail page"** provides information on the predicted "PXX Grade" for the line(s) of interest and the underlying yield strength measures. This page has the *"PXX, Color (0.50 matches Closest Grade)"* slicer set to 0.50 that is the recommended value for starting an analysis. The matrix *"Predicted Joint Grade Statistics"* in the lower left provides the number of joints in each predicted grade, mirroring the column chart above it, and gives information on the underlying yield strengths.



Predicted Joint Grade Statistics

Grade	Joint Count	Yield count	Mean Yield	SD Yield	Min Yield	Max Yield
<A	0					
A	0					
B	3	9	49.78	3.23	43.24	53.98
X42	16	63	52.08	3.14	45.95	61.03
X46	19	91	53.96	2.79	48.26	61.13
X52	2	6	58.27	3.14	53.23	61.27
X56	0					
X60	0					
X65	0					
X70	0					
Z80	0					
Total	**40**	**169**	**53.19**	**3.30**	**43.24**	**61.27**

Figure 4. **"PXX detail"** page.

3.2 "Plot Joint Grade"

The **"Plot Joint Grade"** page in Figure 5 compares the PXX predicted joint grades to the expected grades in column charts and in tabular form (*"Expected vs Predicted Grades"*). This is based on user selection of *"Grade"*, *"Standard Deviation"* and the *"PXX, Color (0.50 matches Closest Grade)"* slicer choice. The *"Standard Deviation"* slicer allows the user to select from a range of values but defaults to the observed standard deviation (3.30 ksi for this segment) in the total line of the **"Joint Summary"** page. The resulting expected probabilities in the **"Expectations"** page of Figure 12 are based on the selected standard deviation as well as the values from API 1176. As the user reduces or increases the standard deviation used, the expected grade count column chart will tighten or broaden out, respectively.

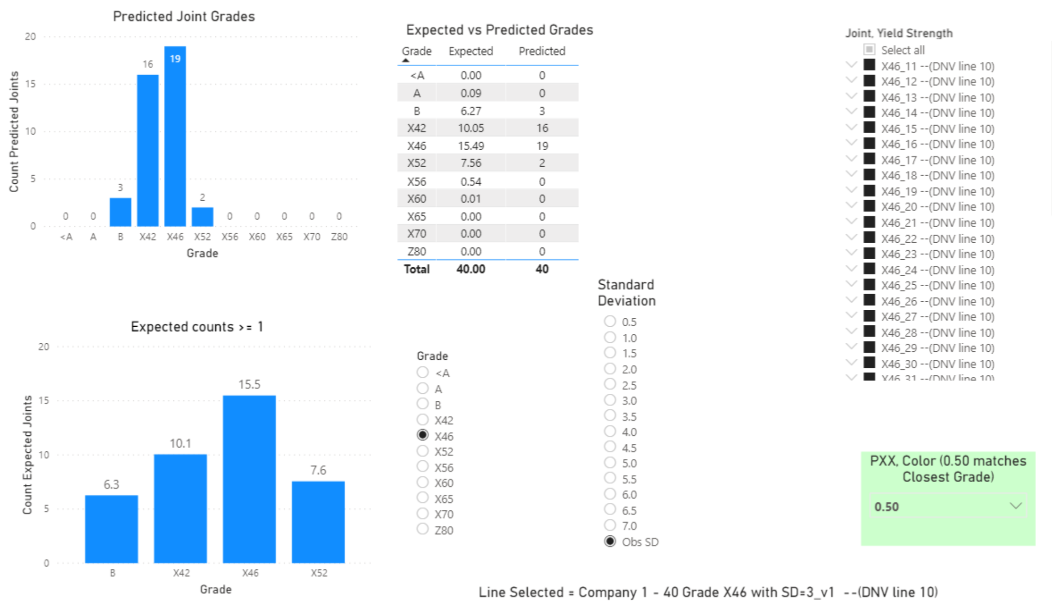


Figure 5. **"Plot Joint Grade"** page

3.3 "ref SD Joint Grade"

Figure 6 from the **"ref SD Joint Grade"** page provides an opportunity for sensitivity analysis. As with some of the earlier pages, the expected grade may be changed using the "Grade" slicer along with the assumed standard deviation for the plot in the lower left. Additionally, the *"PXX, Color (0.50 matches Closest Grade)"* slicer selection impacts the results. The standard deviation in the slicer titled *"SD #1"* is synchronized with the standard deviation slicers in other pages. In addition to that, the plot on the lower right has a separate standard deviation slicer *"SD # 2"* as well as a *"Mean Shift"* slicer. If the *"Mean Shift"* slicer is fixed at the default value of 0, then comparison between the two lower plots is a direct comparison of the impact of changing the assumed standard deviation. The *"Mean Shift"* slicer changes the comparison by allowing a shift in the API 1176 "Low" and "High" boundaries. This feature provides another sensitivity analysis approach like allowing the user to change the standard deviation used. For example, the -1.0 shown in Figure 6 drops the "Low" and "High" API 1176 boundaries (Figure 2) for the expected grade in the *"Expected counts Ref SD slicer #2"* plot by 1.0 ksi, resulting in more expected higher grades. Unlike other synchronized slicers, changes on the right side of this page with *"SD # 2"* and *"Mean Shift"* do not impact results on any other pages.

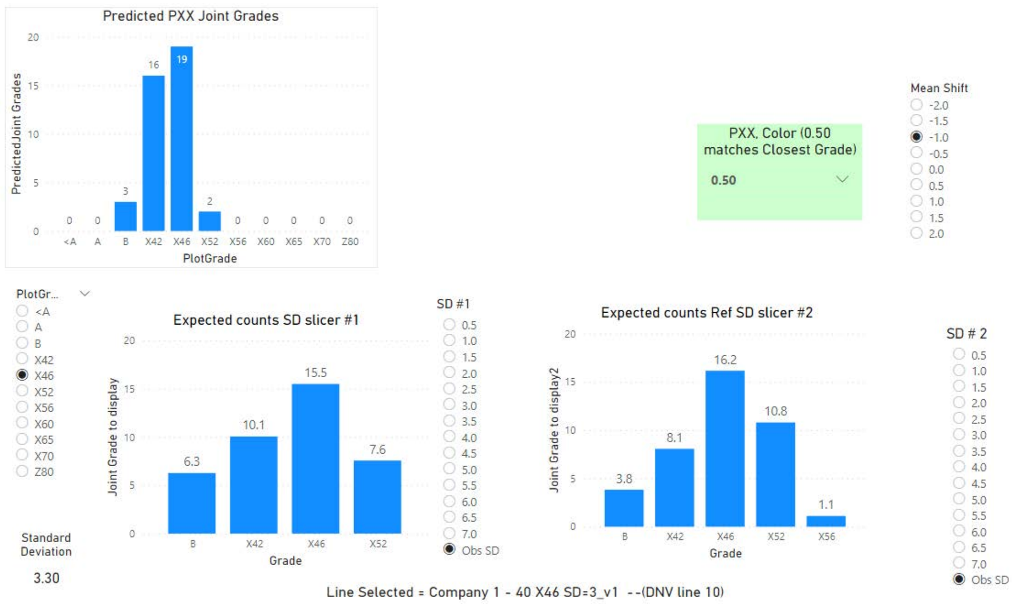
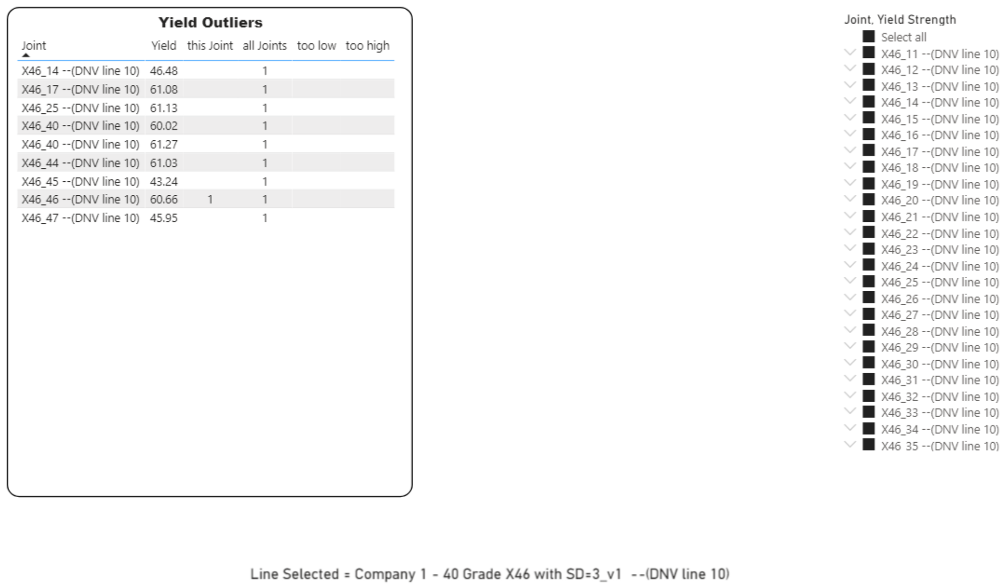


Figure 6. **"ref SD Joint Grade"** page

3.4 "Outliers"

The **"Outliers"** page shown in Figure 7 provides a dynamic assessment of unusual yield strength values. Four outlier categories are seen in the *"Yield Outliers"* matrix on the left of this page. If a given yield strength measurement is found to be a potential outlier in a category, a 1 is placed in the relevant column. The nine yield values shown in Figure 7 indicated as potential outliers in the "all Joints" column are the lowest or highest yield value of the visible sample data for the line being evaluated. If the yield measurement is extreme relative to other yield values on a given joint, then the yield is designated a potential outlier in the column "this Joint" category. For both categories, a yield value shown in this matrix is at least two standard deviations away from either the specific joint mean ("this Joint") or the mean of all the joints ("all Joints"). When there is only a single yield strength on a joint, it is not possible to declare the yield value to be a potential outlier on the joint. Yield measurements below 22 ksi fall into the "too low" column while values exceeding 110 ksi fall into the "too high" column. **"Outliers"** can be used as a quality check on the data, and the user can change the selection of data in the *"Joint, Yield Strength"* slicer as desired. The outlier assessment updates based on the data currently selected, i.e., the visible data as it is termed in Power BI.



Yield Outliers

Joint	Yield	this Joint	all Joints	too low	too high
X46_14 --(DNV line 10)	46.48		1		
X46_17 --(DNV line 10)	61.08		1		
X46_25 --(DNV line 10)	61.13		1		
X46_40 --(DNV line 10)	60.02		1		
X46_40 --(DNV line 10)	61.27		1		
X46_44 --(DNV line 10)	61.03		1		
X46_45 --(DNV line 10)	43.24		1		
X46_46 --(DNV line 10)	60.66	1	1		
X46_47 --(DNV line 10)	45.95		1		

Figure 7. **“Outliers”** page

3.5 “Plot Yield Grade” page

“Plot Yield Grade” in Figure 8 is similar to **“Plot Joint Grade”** in Figure 5, however it uses the individual yield strength measurements instead of joint-based comparisons. Because each yield is an individual value, there is more granularity than when examining results at the joint level. This has proven useful in both testing for possible outliers and trying to arrive at a reasonable grade/grades for the full population of joints that this sample represents. Visually, the top *“Yield Grade”* prediction plot is not unlike the bottom *“Expected Counts >= 1”* plot for the selected grade of X46 in the *“PlotGrade”* slicer. The *“Yield Grade”* plot uses the table from API 1176 to give a best estimate of which grade each individual measurement represents. The *“Expected Counts >= 1”* plot shows the hypothetical number of individual grade measurements one would expect given the sample size, selected grade, and standard deviation.

The user might try different options in the *“Standard Deviation”* slicer or could consider at least temporarily dropping some of the potential outliers using the *“Joint, Yield Strength”* slicer. On the far right of **“Plot Yield Grade”** is a complete list *“Individual Yield Grade”* of all the visible yield values. Each has their own predicted grade which can be used to identify potential suspect data. GradeIt provides the user as much information as possible about the data and allows an interactive search for reasonable results. The statistical underpinnings are aids in this endeavor. **“Plot Yield Grade”** results feed into the page **“Yield below nominal”** in Figure 9.

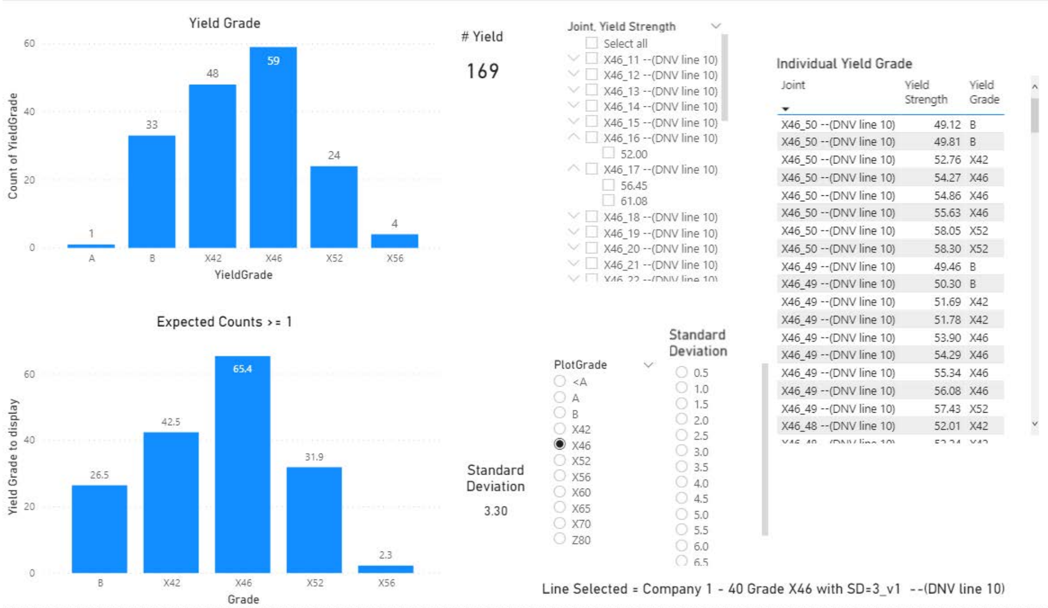


Figure 8. **"Plot Yield Grade"** page

3.6 "Yield below nominal" page

Figure 9 is the **"Yield below nominal"** page that expands the far right visual *"Individual Yield Grade"* of **"Plot Yield Grade"**. The main visual *"Yield Grade less than nominal for selected grade"* shows which individual yield measurements are below the nominal value for the selected grade on the *"Grade"* slicer at the left of this page. A value of 1 in the column "Below Nominal" indicates the yield is below nominal for the selected grade. As noted in the title line of this page, the below nominal information is summarized on the earlier page **"Match %, < nominal"** shown in Figure 3. Nominal as used here is the advertised yield strength (Strength in **"API 1176"**), i.e., the SMYS.

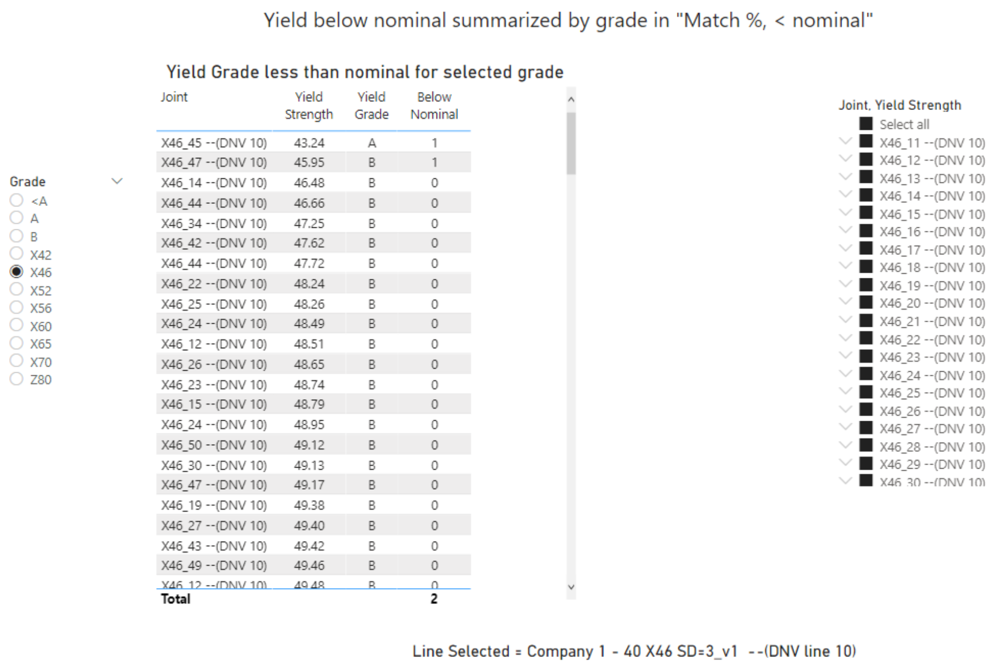
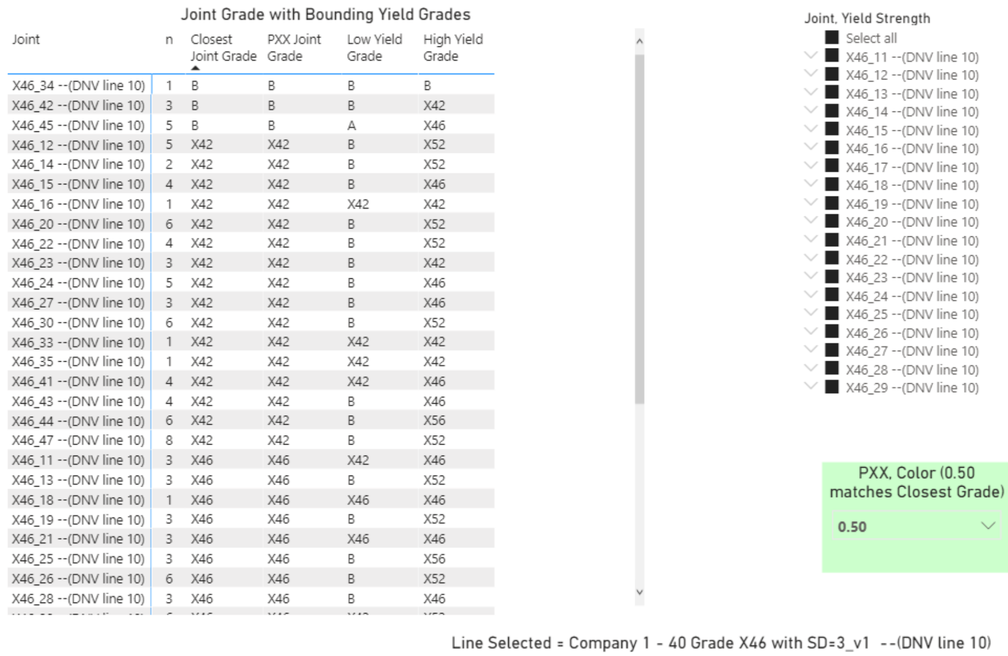


Figure 9. **"Yield below nominal"** page

3.7 "Bounding Yield Grades" and "Detailed Bounding" pages

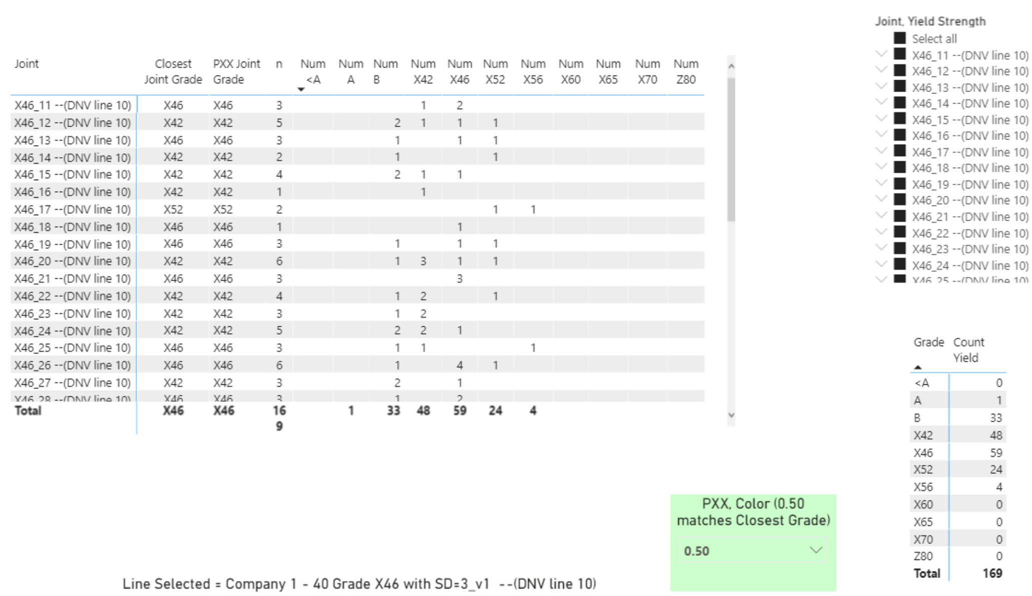
Pages **"Bounding Yield Grades"** (Figure 10) and **"Detailed Bounding"** (Figure 11) are useful in tracking what yield grades are on a given joint. **"Bounding Yield Grades"** shows for each joint the number of yield measurements, the minimum and the maximum yield grades of a joint along with the predicted joint grade. Predicted joint grade is shown in the same two forms as in the page **"Joint Summary"**, i.e., "Closest Grade" as well as "PXX Grade". **"Detailed Bounding"** shows each individual yield grade providing even more information to the user.



Joint Grade with Bounding Yield Grades

Joint	n	Closest Joint Grade	PXX Joint Grade	Low Yield Grade	High Yield Grade
X46_34 --(DNV line 10)	1	B	B	B	B
X46_42 --(DNV line 10)	3	B	B	B	X42
X46_45 --(DNV line 10)	5	B	B	A	X46
X46_12 --(DNV line 10)	5	X42	X42	B	X52
X46_14 --(DNV line 10)	2	X42	X42	B	X52
X46_15 --(DNV line 10)	4	X42	X42	B	X46
X46_16 --(DNV line 10)	1	X42	X42	X42	X42
X46_20 --(DNV line 10)	6	X42	X42	B	X52
X46_22 --(DNV line 10)	4	X42	X42	B	X52
X46_23 --(DNV line 10)	3	X42	X42	B	X42
X46_24 --(DNV line 10)	5	X42	X42	B	X46
X46_27 --(DNV line 10)	3	X42	X42	B	X46
X46_30 --(DNV line 10)	6	X42	X42	B	X52
X46_33 --(DNV line 10)	1	X42	X42	X42	X42
X46_35 --(DNV line 10)	1	X42	X42	X42	X42
X46_41 --(DNV line 10)	4	X42	X42	X42	X46
X46_43 --(DNV line 10)	4	X42	X42	B	X46
X46_44 --(DNV line 10)	6	X42	X42	B	X56
X46_47 --(DNV line 10)	8	X42	X42	B	X52
X46_11 --(DNV line 10)	3	X46	X46	X42	X46
X46_13 --(DNV line 10)	3	X46	X46	B	X52
X46_18 --(DNV line 10)	1	X46	X46	X46	X46
X46_19 --(DNV line 10)	3	X46	X46	B	X52
X46_21 --(DNV line 10)	3	X46	X46	X46	X46
X46_25 --(DNV line 10)	3	X46	X46	B	X56
X46_26 --(DNV line 10)	6	X46	X46	B	X52
X46_28 --(DNV line 10)	3	X46	X46	B	X46

Figure 10. **"Bounding Yield Grades"** page



Joint	Closest Joint Grade	PXX Joint Grade	n	Num <A	Num A	Num B	Num X42	Num X46	Num X52	Num X56	Num X60	Num X65	Num X70	Num Z80
X46_11 --(DNV line 10)	X46	X46	3				1	2						
X46_12 --(DNV line 10)	X42	X42	5			2	1	1	1					
X46_13 --(DNV line 10)	X46	X46	3			1		1	1					
X46_14 --(DNV line 10)	X42	X42	2			1			1					
X46_15 --(DNV line 10)	X42	X42	4			2	1	1						
X46_16 --(DNV line 10)	X42	X42	1				1							
X46_17 --(DNV line 10)	X52	X52	2						1	1				
X46_18 --(DNV line 10)	X46	X46	1					1						
X46_19 --(DNV line 10)	X46	X46	3			1		1	1					
X46_20 --(DNV line 10)	X42	X42	6			1	3	1	1					
X46_21 --(DNV line 10)	X46	X46	3					3						
X46_22 --(DNV line 10)	X42	X42	4			1	2		1					
X46_23 --(DNV line 10)	X42	X42	3			1	2							
X46_24 --(DNV line 10)	X42	X42	5			2	2	1						
X46_25 --(DNV line 10)	X46	X46	3			1	1			1				
X46_26 --(DNV line 10)	X46	X46	6			1		4	1					
X46_27 --(DNV line 10)	X42	X42	3			2		1						
X46_28 --(DNV line 10)	X46	X46	3			1		2						
Total	**X46**	**X46**	**169**		**1**	**33**	**48**	**59**	**24**	**4**				

Grade	Count Yield
<A	0
A	1
B	33
X42	48
X46	59
X52	24
X56	4
X60	0
X65	0
X70	0
Z80	0
Total	**169**

Figure 11. **"Detailed Bounding"** page.

3.8 "Expectations" page

Figure 12 is the **"Expectations"** page based on **"API 1176"** and the relevant standard deviation. Assuming normality, the probabilities are the likelihood of being between the "Low" and "High" columns given the API 1176 mean and the chosen standard deviation. It is recommended that the client use the default observed standard deviation in much of the analysis. Changing the "Standard Deviation" slicer on any page will change these values. A standard deviation below the observed standard deviation tightens the expected grade distribution and might aid in the study of potential outliers. Grade estimation of pipe is not easy and understanding the impact of yield strength uncertainty is key to providing the best possible grade determinations.

Assumed Standard Deviation (k) from Slicer

3.30

Grade	1176 Mean	Low	High	<A LH	A LH	B LH	X42LH	X46LH	X52LH	X56LH	X60LH	X65LH	X70LH	Z80LH
<A	31.40	-99.00	35.70	0.90	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A	40.00	35.70	44.30	0.10	0.81	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	48.60	44.30	50.40	0.00	0.10	0.61	0.28	0.16	0.00	0.00	0.00	0.00	0.00	0.00
X42	52.20	50.40	52.95	0.00	0.00	0.20	0.30	0.25	0.03	0.00	0.00	0.00	0.00	0.00
X46	53.70	52.95	56.45	0.00	0.00	0.09	0.31	0.39	0.17	0.03	0.00	0.00	0.00	0.00
X52	59.20	56.45	61.00	0.00	0.00	0.01	0.10	0.19	0.50	0.27	0.01	0.00	0.00	0.00
X56	62.80	61.00	65.75	0.00	0.00	0.00	0.00	0.01	0.27	0.52	0.18	0.03	0.00	0.00
X60	68.70	65.75	70.35	0.00	0.00	0.00	0.00	0.00	0.02	0.17	0.51	0.28	0.00	0.00
X65	72.00	70.35	76.20	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.30	0.59	0.10	0.00
X70	80.40	76.20	86.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.10	0.86	0.04
Z80	92.10	86.25	999.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.96

SD
- 0.5
- 1.0
- 1.5
- 2.0
- 2.5
- 3.0
- 3.5
- 4.0
- 4.5
- 5.0
- 5.5
- 6.0
- 6.5
- 7.0
- Obs SD (selected)

Columns such as X46LH are the conditional expected predictions given real grade (using 1176 Mean, and standard deviation selected).
Rows are the conditional real grade given the prediction.

Figure 12. **"Expectations"** page

4. Summary

In 2019 PHMSA revised regulations via its Final Rule aimed at improving the safety of onshore gas transmission pipelines by requiring operating companies to estimate pipe grade on pipelines without current satisfactory documentation. The Power BI app GradeIt is specifically designed to aid the user in this process. GradeIt consolidates relevant yield strength and joint data, providing a variety of decision support mechanisms to aid the operator in reporting an appropriate pipeline grade for a pipeline population of interest. GradeIt compares the measured yield strength values of pipe segments with what has been measured and used in the industry for each grade. Statistical means and standard deviations are analyzed to provide the most likely pipe grades, as well as possible alternative pipe grades due to statistical overlap. GradeIt blends probability, statistical inference, and sensitivity analysis to aid in a defensible grade determination.

5. References

84 FR 52180, Pipeline Safety: Safety of Gas Transmission Pipelines: MAOP Reconfirmation, Expansion of Assessment Requirements, and Other Related Amendments, (October 1, 2019)

49 CFR § 192.607(b) and § 192.607(e), Verification of Pipeline Material Properties and Attributes: Onshore steel transmission pipelines, (2019)

National Transportation Safety Board. 2011. Pacific Gas and Electric Company Natural Gas Transmission Pipeline Rupture and Fire, San Bruno, California, September 9, 2010. Pipeline Accident Report NTSB/PAR-11/01. Washington, DC.

API Recommended Practice 1176, 2016, "Assessment and Management of Cracking in Pipelines", API Publishing Services, Washington DC, www.api.org.