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June 19, 2012

Sumeet Singh
Pacific Gas and Electric
2700 Ygnacio Valley, Suite 100
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Subject: Assessment of ABI Testing for PG&E Piping
Project No. 1100980.000

Dear Mr. Singh:

As part of PG&E's efforts to perform due diligence validation of the Maximum Allowable Operating Pressure (MAOP) of its pipeline system, Exponent Failure Analysis Associates (Exponent) was requested to assess the ability of the Automated Ball Indentation (ABI) test method to determine or confirm the yield strength and grade of Pacific Gas and Electric (PG&E) natural gas pipelines when complete information is not available. Since a single ABI vendor, Advanced Technology Corporation (ATC), did the majority of ABI testing conducted on PG&E pipelines, this assessment primarily details those results. In summary it was determined that:

- The ABI method can be used to provide predictions that correlate to API 5L yield strength of in-service PG&E pipe of varying diameter and grade, within specific risk-based confidence bounds, and is suitable to supplement PG&E's methodology to predict pipeline yield strength when complete information is not available. The chosen confidence bound must be considered in the context of a larger system pipeline risk assessment.
- ABI-based yield strength predictions of approximately 55 ksi (55,000 pounds/in^2) correlate with an API 5L yield strength roughly equal to 24 ksi with 97.5% confidence (24 ksi is the 49CFR192.107(2) value for non-tensile tested pipe). Thus, any ABI-based predictions less than approximately 55 ksi will correspond to API yield strengths less than the 24 ksi CFR minimum when appropriate confidence intervals are applied.
- ABI method employed by Advanced Technology Corporation (ATC) cannot be used to independently determine API 5L 0.5% (total extension) yield strength. The ABI method cannot replace or serve as a substitute for the API 5L tension test requirement for grading pipe.
- As PG&E continues to expand the API 5L yield strength and ABI testing database for in-service pipeline, this assessment can be revised to reflect more complete data.

- Lastly, Exponent recommends that any fracture toughness values obtained from ABI data not be relied upon for safety or integrity-based assessments.

Background of ABI Method

Stress-Strain Microprobe® (SSM) testing utilizing the ABI technique was patented by Mr. Fahmy Haggag of Advanced Technology Corporation (ATC) in 1989 [1], apparently based in part on microprobe/hardness testing work that had been conducted previously [2]. ATC indicates they have commercially marketed an ABI tool since 1991, and a portable, in-situ tester capable of testing pipelines since 1999 [3]. In 1999, Rodney E. Slater, then the US Secretary of Transportation, indicated in a letter to Tennessee Congressman Zach Wamp that: "Dr. Haggag's report has been reviewed and the technology appears to be fundamentally sound for application in the pipeline industry" [3], although no indication was given as to the extent of the technical review.

The ABI test leaves small, spherical indents on the outer surface of the pipe, and can be considered to be practically non-destructive. ATC indicates "Thousands of ABI tests have been conducted on ferritic steel samples, including grades from B to X100 of pipeline steels, at various test temperatures. Also, numerous ABI tests have been conducted in the field at ambient temperatures on pipelines in the United States, Europe, Africa, and Asia" [4]. The Korean company "Frontics" has marketed and GE Inspection Services (GEIS) has licensed a similar tool.

The ABI process involves the progressive indention of a tungsten-carbide ball into the test media (pipeline). The spherical indenter geometry allows for increasing strain with continued indentation depth. During progressive indentation, intermediate partial unloading steps are conducted until full test-penetration is completed. Upon completion, the recorded incremental load versus indention depth data is converted to plastic true stress and strain using empirical relations with elasticity and plasticity theories, and assuming interchangeability between compressive and tensile material properties. It should also be noted that the ABI process is a surface measurement technique (with typical penetration of 0.005 inches), and is sensitive to surface residual stresses. The inventor has demonstrated an approximate 4% lower measured yield strength relative to the inner surface [5].

ATC has published several studies that compare tensile properties of pipeline steel determined from both ABI and traditional tensile testing [1, 3-11]. The ABI tests are generally conducted on the flat grip portion of the tensile samples themselves. ATC indicated that comparison of ABI-predicted tensile properties with those obtained by traditional tensile testing showed close agreement. In work sponsored by the Pipeline Research Council International (PRCI) [3], the largest difference between ABI and traditional tensile-tested pipeline-steel yield strength (from Grade B to API X65) was a 10.2% over-prediction for Grade B material. Smaller differences, generally 6% or less, were observed for the other grades. Testing conducted for the United

States Department of Transportation (US DOT) on specimens taken from ANR and Columbia Gas pipelines demonstrated similar accuracy [6].

Yield Strength Determination by ABI

The methodology for Stress-Strain Microprobe® (SSM) testing utilizing the ABI technique is detailed in a test method originally drafted as a proposed American Society for Testing and Materials (ASTM) standard [12]. Presumably, the method employed by Frontics and GEIS is similar. In practice, a spherical indenter is forced into the surface of a metallic sample or a structural component. Periodic partial unloading during the test is used to determine the elastic strain and to account for the compliance of the test system. The total (elastic and plastic) indentation diameter, d_t, resulting from the loading and unloading cycles is fit by linear regression to the empirical relationship:

$$P/d_t^2 \cdot \; A \; d_t/D^{\;m\cdot\;2}$$

where P is load, m is the Meyer's coefficient (assumed to be a material property), D is indenter ball diameter, and A is a test parameter determined from the linear regression. The test parameter A is then used to calculate the yield strength as:

$$\cdot_y \cdot \; \cdot_m A \cdot \; B$$

where $\cdot_m$ is the material yield slope and B is the yield-strength offset. The values of the material yield slope ($\cdot_m$) and the yield strength offset constant (B) are presumed to depend on the type of metal (elastic and plastic deformation behavior) and the indenter diameter. These empirically determined values have been reported to be in close agreement with the 0.2% offset yield strength determined from uniaxial tension tests [3]. Note that API 5L yield strength requirements for a given pipe grade are defined as the stress at 0.5% total extension strain [13].

Unlike conventional tension testing that samples the entire bulk of the wall, such as the procedure defined under API 5L, the ABI method infers material behavior from the compressive deformation of a localized surface region of small depth (typically less than 0.005 inches). Therefore, the ABI method is potentially sensitive to localized surface effects that may not represent the bulk of the pipe through wall. Examples of these possible effects include surface residual stresses, surface morphology and surface preparation effects, and through-thickness microstructural variability (i.e. carbon segregation in rimmed steel, acicular ferrite, decreasing pearlite interlamellar spacing, and variations in grain size).

The potential factors affecting ABI in-situ field measurement results fall into two categories: destructively and nondestructively assessed. As the main purported use of the ABI method is to provide for nondestructive assessment of in-service gas pipelines, any influencing factors that require destructive confirmation (such as through-thickness variations in grain size or carbon segregation) are impractical to consider for reducing ABI field test result variability. To account for the potential presence of all such destructively assessable effects in actual field measurements, all ABI results for this assessment have been evaluated as reported and produced by the vendor. Although the ABI method is potentially sensitive to a variety of localized surface effects, this assessment study was designed to evaluate the field use of the ABI method and therefore captures all such effects.

The effect of superposed mechanical stress, such as that resulting from a pressurized pipeline, was examined by conducting multiple ABI tests on a capped and pressurized pipe (Figure 1). The pipe (16” OD, 0.375” thick, API 5L Grade A, API 5L 0.5% EUL yield strength = 51.7 ksi) was measured by the ABI method unpressurized, then ABI measurements were taken as the pressure was incrementally increased. A final ABI measurement was taken once the pipe was again depressurized. The results are shown in Figure 1. A linear decrease in ABI-predicted yield stress was observed with increasing pipe pressure, with a decrease of approximately 5 ksi at 2000 psi (equivalent to 80% SMYS). The effects of pressure on in-service pipelines can be nondestructively determined, and may be evaluated in the future to reduce the observed ABI to API 5L correlation variability.

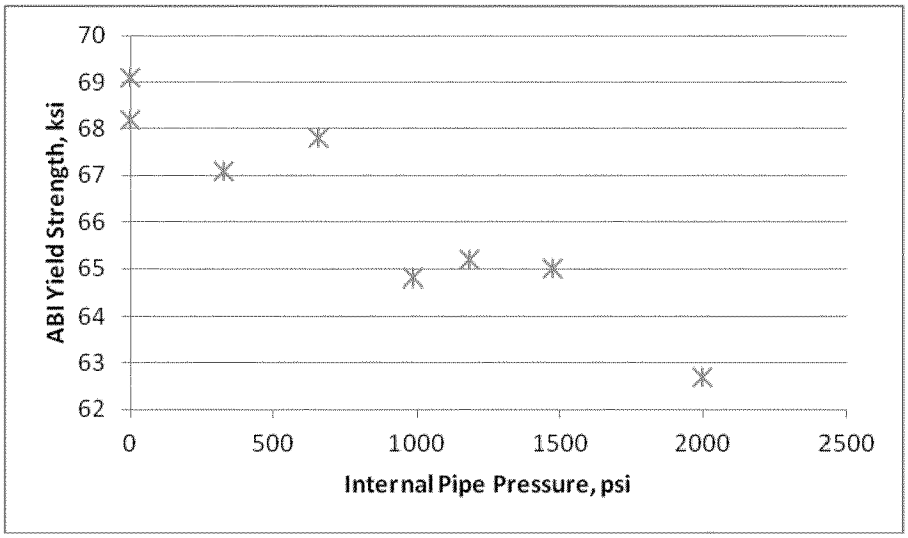

Figure 1. Effect of internal pipe pressure on ABI results.

Fracture Toughness Determination

ATC indicates that initiation fracture toughness (not tearing behavior) can be determined by integrating the indention deformation energy to a critical depth. This approach relies on the assumption that the compressive stress field ahead of the indenter behaves in a similar manner as the tensile stress field ahead of a crack. The "Haggag Toughness Method" (HTM) [3] is then utilized to determine either a critical fracture stress or strain, and the resulting initiation fracture-toughness. ATC then applies a "Master Curve" approach (pioneered by the US nuclear industry to statistically predict fracture toughness of reactor pressure vessel steels as a function of temperature) to establish statistics-based confidence intervals for toughness as a function of temperature. ATC has indicated close agreement with standard fracture toughness specimens tested per ASTM Standards E1820 and E1921. It should be noted that ABI fracture toughness values are obtained without any cracking or fracture of the tested material.

ATC compared ABI results with K_{JC} data from 37 test specimens from several pipeline grades provided by BP [3]. ATC indicated that the ABI results were within 12% of the average values for all steel samples. Further, the ABI results showed lower standard deviations than toughness data obtained by traditional fracture toughness testing. This result may indicate that ABI testing may not capture all the inherent variability associated with steel fracture and the associated wide confidence bands in fracture toughness behavior. Use of ABI toughness data with lower scatter would result in tighter confidence bands that could result in erroneously non-conservative assumptions regarding lower fracture toughness bounds.

Implicit in the ATC and HTM approaches is the assumption that the multi-axial (primarily compressive) stress fields and plastic constraint beneath the indenter tip are similar to the primarily tensile stress fields and constraints at a crack tip. Given the potential microstructural/mechanical inhomogeneities present in many pipeline steels (such as inclusion stringers or various embrittlement mechanisms, particularly in older pipes) this assumption may not be appropriate in all cases.

Applicability to Field Testing

As stated earlier, ATC has indicated that ABI tests have been conducted on in-situ pipelines in America, Africa, Europe, and Asia [4]. Review of ATC's technical reports indicates a few instances of documented testing conducted on actual pipes, including a kerosene pipe in Egypt [8, 11] and a six-inch pipe section supplied by Columbia Gas [6]. While ATC indicates significant experience testing in-situ on four continents, data from only a few actual in-situ tests appear to have been published. Thus, Exponent recommended that an initial ABI validation study be conducted on multiple grades of PG&E pipeline.

ABI Assessment Methodology

The designation of pipe strength levels of gas pipeline in the United States is described by a series of "grades", defined by API 5L [13]. One criterion for specifying a given grade of processed and manufactured gas pipeline involves cutting a sample ring from a section of the pipe, flattening so that a strap sample is produced, and then tensile testing the sample. API 5L specifies a minimum tensile yield strength result for a given grade. The grade does not define precise mechanical properties of the pipeline steel; rather it is a certification that mechanical properties exceed a certain minimum yield strength. The ABI method is therefore compared to the API 5L yield strength in this assessment, and not the specified grade of the pipe.

The general ABI test assessment procedure recommended by Exponent was as follows:

1. Conduct ABI indentation testing on selected PG&E pipeline sections as described in the ATC test method "Automated Ball Indentation (ABI) Testing of Metallic Materials and Structures to Determine Tensile Properties and Stress-Strain Curves" [14], and also following the applicable guidelines from ASTM E110 [15].
2. Representative pipeline sections have been chosen from those available in PG&E storage to best encompass the entire range of anticipated yield strength and pipeline size as guided by PG&E Gas Standard A-11 [16], as well as information provided by PG&E as to the content of their pipeline system. The test matrix, provided in Table 1, currently does not include pipe material of lower grade than Grade B (lower grades were not available for testing at the time). Thus, this procedure does not assess the correlation between ABI results and yield strength for pipe outside the range tested.
3. A minimum of four ABI indentations will be conducted on each pipeline segment to assess test operator and procedure repeatability.
4. The ABI test system calibration is to be verified as indicated by the vendor's test method and the applicable sections of ASTM E2309 [17]
5. Best practices as previously determined [12, 18] regarding in-situ test procedures should be followed, namely: a) pipeline test surface preparation finished to a minimum of 63 RMS (final polish using 600 grit paper), b) 0.762 mm or larger indenter, and c) Magnetic attachment, G-clamp, or ratchet lashing attachment of the ABI microprobe. However, any practices determined by vendor to be superior can be used.
6. Conduct API tensile tests of tensile specimens ("straps") removed from pipeline segments previously tested by the ABI in-situ test. Tensile tests are to be conducted as indicated by ASTM E08 [19], using extensometers and reporting the stress-strain behavior. The orientation and location of test pieces for the reference API tensile pipe body testing are as indicated by API Specification 5L, section 10.2.3.2 [13] and ASTM A370 [20]. No seam welds are to be included. A minimum of three tensile tests will be conducted on each pipeline segment.
7. Determine the calculated ABI yield strengths utilizing existing or best practice yield slope and yield-offset parameters as specified by the ABI test vendor.
8. Conduct a correlation comparison between ABI yield strength calculations and the API 5L tensile yield strength results.

Table 1. Test matrix based upon available pipe in Stockton yard.

Outer Diameter	Specified Minimum Yield Stress (SMYS) (ksi)				
	35	42	52	60	All
1.05	0	0	0	0	0
3.5	3" Grade B, SMLS	0	0	0	1
4.5	0	4" X42 ERW	0	0	1
6.625	0	0	0	0	0
8.625	8" Grade B SMLS	0	0	0	1
10.75	0	10" B/42 SMLS	0	0	1
12.75	0	0	12" X52 ERW	0	1
16	0	0	16" X52 ERW	0	1
18	18" Grade B SMLS	0	18" X52 ERW	0	2
20	0	0	0	20" X60/65 DSAW	1
24	0	22" X42 DSAW	0	0	1
26	0	0	0	26" 60/65 DSAW	1
30	0	0	0	0	0
34	0	0	0	0	0
36	0	0	0	36" X60 DSAW	1
All	**3**	**3**	**3**	**3**	**12**

Prior to the completion of the testing specified in Table 1, ABI testing was conducted as an addition to the ongoing PG&E effort to comply with the June 9, 2011 CPUC decision requiring all California gas transmission operators to develop a plan to pressure test or replace all gas transmission pipelines that do not have complete records of a prior strength test conducted to modern standards. Eleven ABI and accompanying API 5L tests that were part of various field inspections as part of PG&E's Hydro-Test Project were added to the ABI assessment. PG&E is continuing to expand the API 5L tension and ABI testing database for in-service pipeline, and this assessment will be revised as more data becomes available.

Correlation to API 5L

ABI test results for yield strength were taken as the average of five measurements at a given location, as reported by the vendor. An example of ABI data provided to PG&E is shown in Appendix A. API 5L 0.5% elongation on load (EUL) yield strength results were taken as the average of three tension tests. An independent laboratory, blinded to any ABI test results, conducted the API 5L yield strength tests. A second independent laboratory, as shown in Appendix B, repeated the initial API 5L tests. The results of the ABI and API 5L yield strength comparison and the linear regression correlation are shown in Figure 2 and Figure 3. The fitted regression slope estimate was 0.81 with a 90% confidence interval of 0.52 to 1.11. The regression offset estimate was 17.78 with a 90% confidence interval of -0.70 to 36.25. The API 5L yield strength results were found to explain 53% of the variations in ABI yield strength tests. Given the resulting correlation, the ABI test method cannot be used independently to determine API 5L 0.5% (total extension) yield strength.

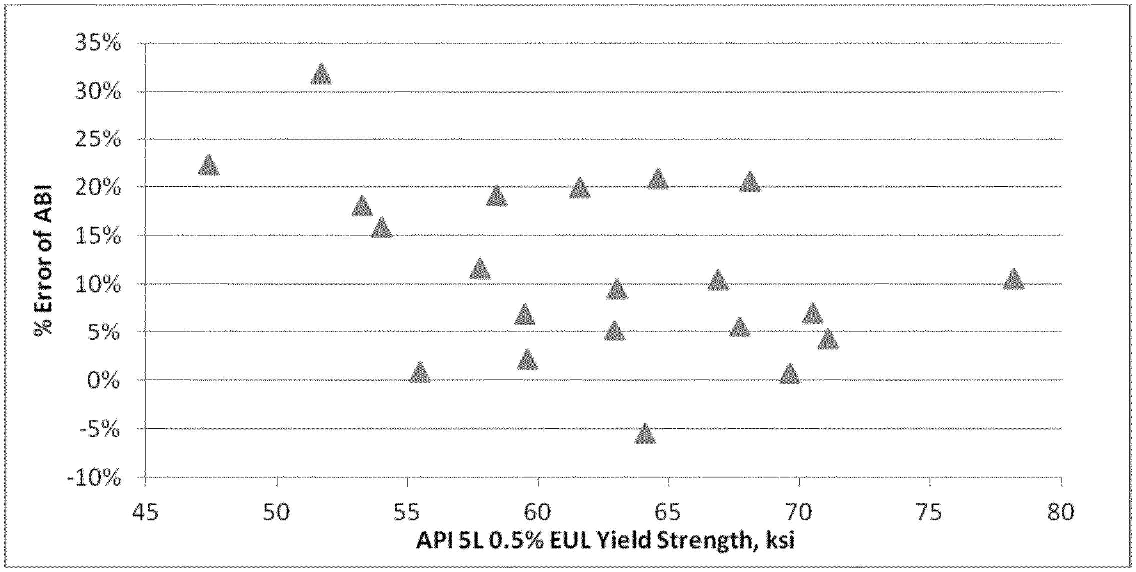

Figure 2. Error of experimental ABI results compared with API 5L results.

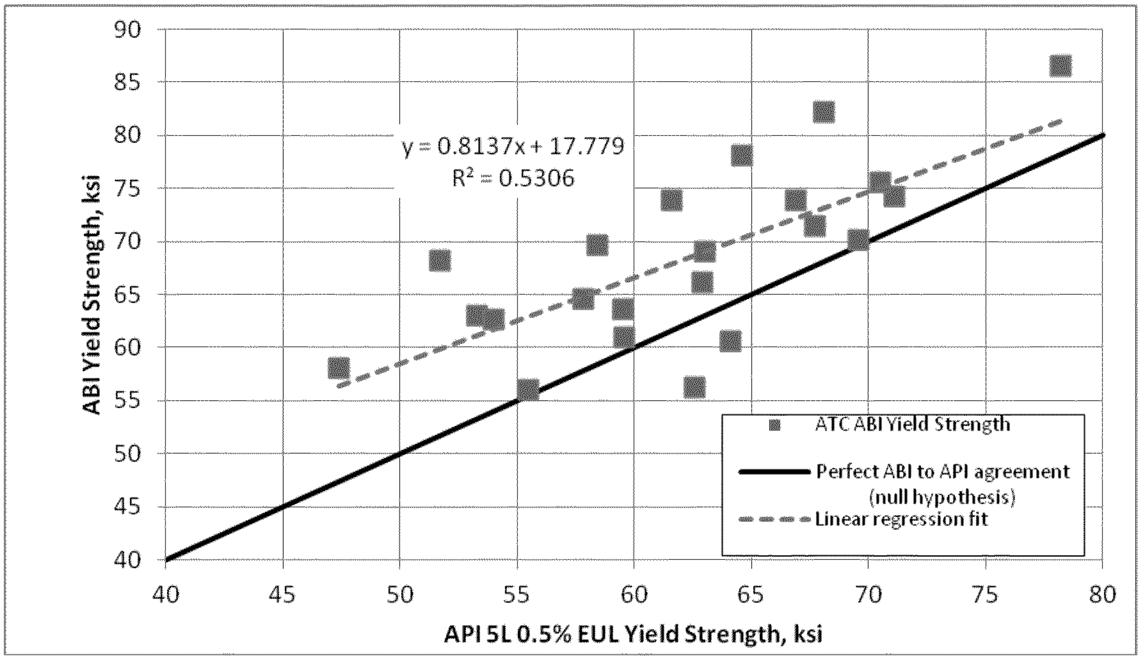

Figure 3. ABI yield results compared with API 5L yield tests. Solid line represents perfect agreement.

The ABI assessment was designed to test the entire range of specified minimum yield stress (SMYS) of the pipeline within PG&E's systems; however, this assessment involved segments with higher SMYS, on average, based on the pipe samples that were readily available. It should also be noted that the majority of ABI experimental yield strength predictions reviewed to date are within the approximate range of 58 to 70 ksi. The higher ABI test results relative to the composition of the PG&E population may partially result from using pipe grade to characterize the population. Pipe grade is typically lower than the actual expected API yield strength. PG&E is continuing to conduct API 5L tension testing of in-service pipeline with emphasis on lower grade pipe, and this assessment can be subsequently revised.

Prediction of API 5L Yield Strength from ABI Tests

In order to assess the potential of the ABI method as a field verification or predictive tool, an inverse regression analysis was conducted. This provides an estimate for an API 5L yield strength result given a new ABI experimental value, and provides prediction bounds based on information from the original regression model. The approach permits the prediction of API 5L yield strength for in-service PG&E pipe of varying diameter and grade, within specific confidence bounds. The results of the inverse regression analysis are given in Figure 4.

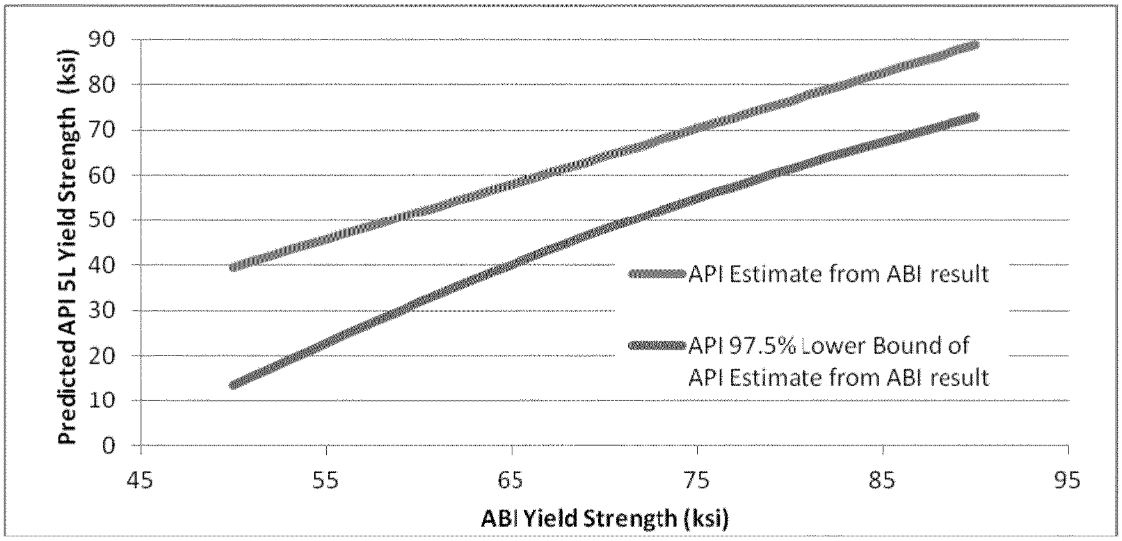

Figure 4. Results of inverse regression with prediction of API 5L yield from ABI results and lower 97.5% confidence bound.

Use of ABI for SMYS Confirmation

If used as a method to assist in confirming the SMYS determined using documentation or PG&E's Procedure for Resolution of Unknown Pipeline Features[1] (based on historical material procurement standards and practices) at a specific location, an ABI yield strength test result must exceed the lower bound for the chosen confidence level, as shown by Figure 4. For example, to confirm a SMYS result of 42 ksi to a 97.5% confidence level[2] would require an experimental ABI test result exceeding 66 ksi, as illustrated in Figure 5. ABI test results of less than approximately 55 ksi do not predict API 5L yield strengths exceeding 24 ksi with 97.5% confidence, and provide no useful validation, since 24 ksi is the 49CFR192.107(2) minimum SMYS value used for non-tensile tested pipe.

Table 2 shows the ABI test result minimum acceptance criteria. An example of the ABI confirmation procedure is given in Appendix C, and is employed for several examples of PG&E pipeline segments in Table 3.

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[1] This procedure is in the process of being issued as a PG&E Utility Procedure.

[2] This study utilizes a confidence level of 95% (i.e. ±2.5% and identically a lower bound of 97.5%). The 95% confidence level is used more frequently in statistical practice than any other level [21]. Although there are no requirements for particular industries, for example automotive industries typically use 90% confidence bounds, the nuclear industries uses 95-99%, and many other industries utilize 95%.

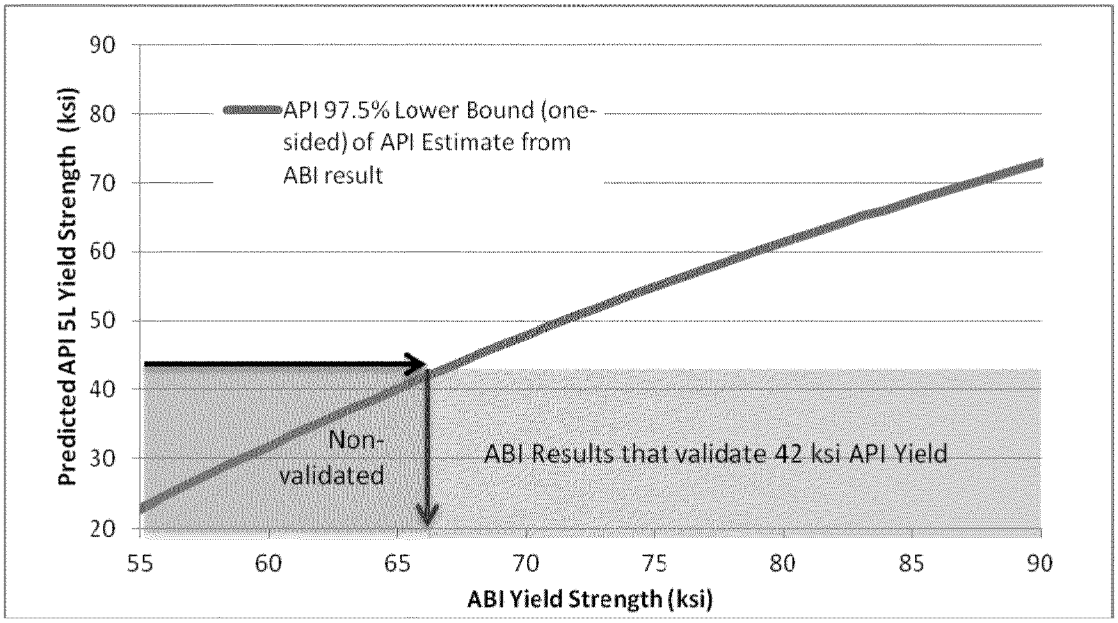

Figure 5. Example of validation of 42 ksi yield strength using the 97.5% confidence ABI results.

Table 2. ABI experimental confirmation criteria

PG&E Procedure[3] Values (4" nominal pipe size or greater)	Minimum ABI test Result for confirmation to 97.5% Confidence
65	83
60	79
52	73
48	70
46	69
42	66
35	62
33	61
30	59
28	58

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[3] *Possible outcomes from PG&E's Procedure for Resolution of Unknown Pipeline Features*

Table 3 shows the SMYS determined using documentation such as material requisition, bill of materials, purchase orders or other relevant records or PG&E's Procedure for Resolution of Unknown Pipeline Features where documentation was not available, the acceptance criteria (from Table 2), the ABI experimental results, and the API 5L yield strength test results. Based on the experimental API 5L test results and consistent with the API 5L requirement that the 0.5% EUL yield strength exceed the pipe rating, PG&E's Procedure for Resolution of Unknown Pipeline Features is shown to be a conservative method for identifying the SMYS in these examples. Of the examples shown in Table 3, only two lacked sufficient information not included in a relevant document and therefore required further investigation, such as using a technique like ABI. Both are confirmed using the ABI to a 97.5% confidence level. Of the nine examples where the pipe SMYS is known with confirming documentation, only one is also confirmed by the ABI method to 97.5% confidence. In that example (Line 132, Mile Point 8.54, Grade B), the API 5L yield strength of 68 ksi is significantly higher than the rated SYMS of 35 ksi. It is noted that all values determined from PG&E's Procedure for Resolution of Unknown Pipeline Features were confirmed by API 5L yield strength test results.

The hypothetical situations where insufficient documentation exists to confirm pipe SYMS to high confidence and where the ABI method would presumably be utilized are demonstrated in Table 4. Here it is assumed that only the pipe outer diameter is available for use in PG&E's Procedure for Resolution of Unknown Pipeline Features. In these situations, 64% of the values from PG&E's Procedure would be supported by the ABI method. Due to the variability in the ABI data set and the use of the 97.5% confidence level, cases of lower SYMS values may default to the 49CFR192.107(2) minimum SMYS of 24 ksi. PG&E would benefit from continued development of the ABI data set used to confirm and minimize the variability of the method.

Table 3. Comparison of values based on PG&E's existing records, ABI confirmation criteria, and ABI experimental results for hydro-test pipe segments

	Line 105N Mile Point 11.86	Line 300A Mile Point 122.67	Line 300A Mile Point 127.93	Line 300B Mile Point 127.47	Line 153 Mile Point 13.62	Line 300A Mile Point 353.85	Line 300B Mile Point 354.3115	Line 300A Mile Point 490.48	Line 132 Mile Point 8.54	Line 300B Mile Point 0.23	Line 105A Mile Point 39.1
PG&E Procedure Value (using all known information of record)	52[4]	52[4]	52[4]	52[4]	60[4]	46[5]	48[4]	52[4]	35[4]	52[4]	35[5]
Minimum ABI test result for validation of PG&E Procedure Value (97.5% confidence)	73	73	73	73	79	69	70	73	62	73	62
ABI Yield Test Result	56	56	66	61	74	74	61	72	82	65	64
Confirmation by ABI (97.5% confidence)	No	No	No	No	No	Yes	No	No	Yes	No	Yes
API 5L Yield Result	56	63	63	60	67	62	64	68	68	58	60

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[4] For this case, documentation such as material requisition, bill of materials, purchase orders or other relevant records were available to confirm pipe SMYS. No PG&E Procedure Value was needed.

[5] For this case, documentation was not available to confirm pipe SMYS. The PG&E Procedure Value was used.

Table 4. Comparison of PG&E Procedure values assuming only OD known, ABI confirmation criteria, and ABI experimental results and for hydro-test pipe segments

	Line 105N Mile Point 11.86	Line 300A Mile Point 122.67	Line 300A Mile Point 127.93	Line 300B Mile Point 127.47	Line 153 Mile Point 13.62	Line 300A Mile Point 353.85	Line 300B Mile Point 354.3115	Line 300A Mile Point 490.48	Line 132 Mile Point 8.54	Line 300B Mile Point 0.23	Line 105A Mile Point 39.1
PG&E Procedure Value (assuming only pipe OD known)	30	35	35	35	35	35	35	35	30	35	35
Minimum ABI test result for validation of PG&E Procedure Value (97.5% confidence)	59	62	62	62	62	62	62	62	59	62	62
ABI Yield Test Result	56	56	66	61	74	74	61	72	82	65	64
Confirmation by ABI (97.5% confidence)	No	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes

Conclusions

- The ATC ABI test methodology can be used to provide predictions that correlate to API 5L yield strength of in-service PG&E pipe, within specific confidence bounds, and is suitable to supplement PG&E's methodology to predict pipeline yield strength when complete information is not available. The chosen confidence bound must be considered in the context of a larger system pipeline risk assessment.
- ABI-predicted yield strength results of less than approximately 55 ksi cannot be used to predict API 5L yield strengths exceeding 24 ksi with 97.5% confidence. (24 ksi is the 49CFR192.107(2) value for non-tensile tested pipe.)
- ABI method employed by Advanced Technology Corporation (ATC) cannot be used to independently determine API 5L 0.5% (total extension) yield strength. The ABI method cannot replace or serve as a substitute for the API 5L tension test requirement for grading pipe.
- PG&E is continuing to expand the API 5L tension and ABI testing database for in-service pipeline, and this assessment can be revised as more data becomes available.
- Exponent does not currently recommend relying on ABI-generated fracture toughness values for safety or integrity-based pipeline analyses.

Please don't hesitate to contact me with any questions or comments.

Sincerely,

Redacted

Managing Engineer
Mechanical Engineering Center

Limitations

The scope of services performed during this investigation may not adequately address the needs of other users of this report, and any re-use of this report or its findings, conclusions, or recommendations presented herein are at the sole risk of the user. The opinions and comments formulated during this assessment are based on information available at the time of the investigation. No guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.

The findings presented herein are made to a reasonable degree of engineering certainty. We have made every effort to accurately and completely investigate all areas of concern identified during our investigation. If new data becomes available or there are perceived omissions or misstatements in this report regarding any aspect of those conditions, we ask that they be brought to our attention as soon as possible so that we have the opportunity to fully address them.

As the gas transmission and distribution utility, PG&E has ultimate responsibility for the compliance and safety of their systems. Exponent will assist in researching and interpreting the relevant standards and regulations, testing, analyzing and evaluating methodologies and procedures, and giving engineering consultation when appropriate. Exponent cannot assume ultimate responsibility for the work product of the contributions of the collaborating firms, the final results of the testing, or the business decisions made by PG&E.

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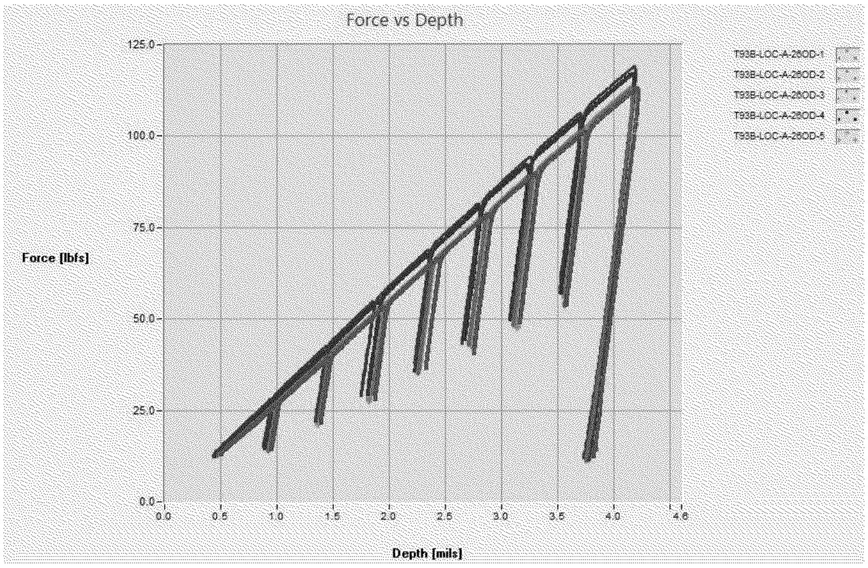
21. Statistical Intervals A Guide for Practitioners, Hahn G.J. and Meeker, W.Q., John Wiley & Sons, 1991.

Appendix A: ABI Test Results from Vendor



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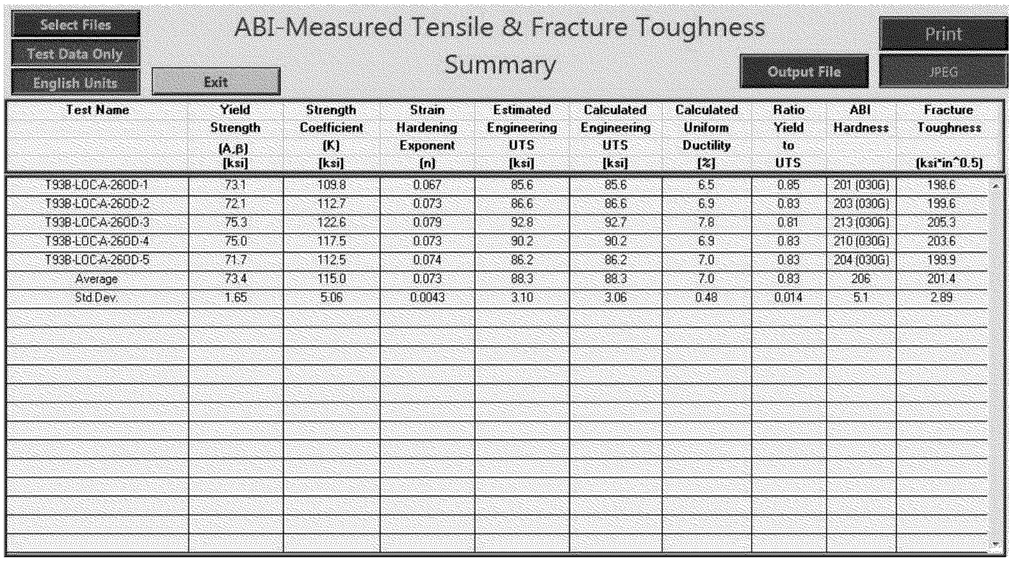
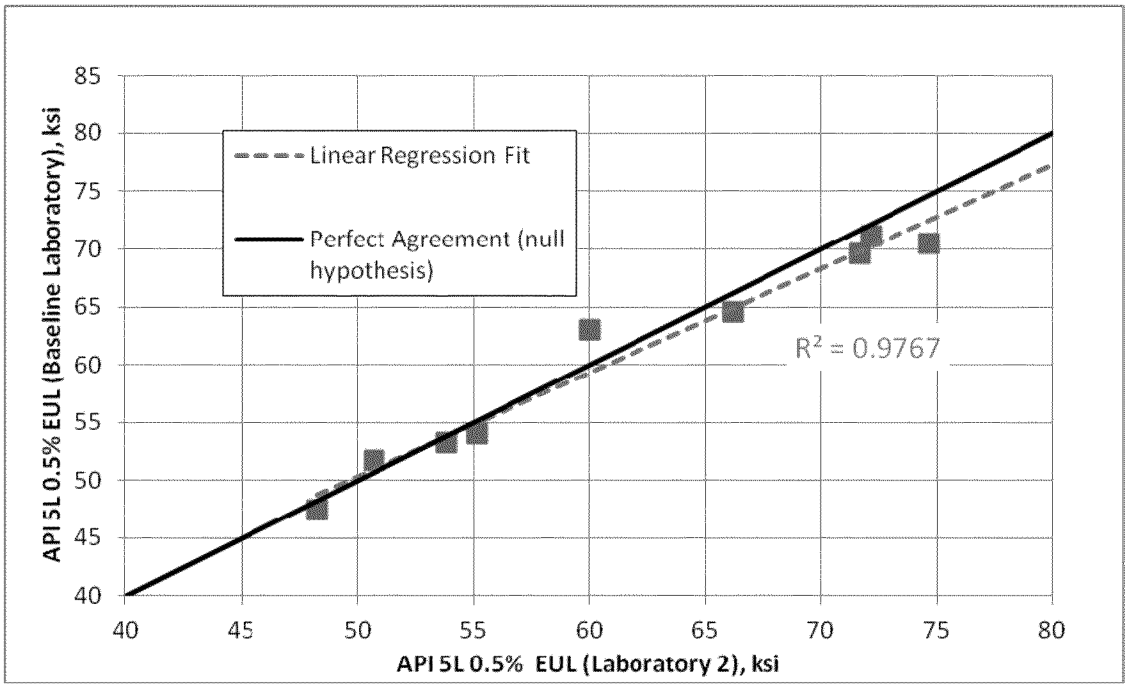


ABI-Measured Tensile & Fracture Toughness Summary

Test Name	Yield Strength (A,β) [ksi]	Strength Coefficient (K) [ksi]	Strain Hardening Exponent (n)	Estimated Engineering UTS [ksi]	Calculated Engineering UTS [ksi]	Calculated Uniform Ductility [%]	Ratio Yield to UTS	ABI Hardness	Fracture Toughness [ksi*in^0.5]
T93B-LOC-A-260D-1	73.1	109.8	0.067	85.6	85.6	6.5	0.85	201 (030G)	198.6
T93B-LOC-A-260D-2	72.1	112.7	0.073	86.6	86.6	6.9	0.83	203 (030G)	199.6
T93B-LOC-A-260D-3	75.3	122.6	0.079	92.8	92.7	7.8	0.81	213 (030G)	205.3
T93B-LOC-A-260D-4	75.0	117.5	0.073	90.2	90.2	6.9	0.83	210 (030G)	203.6
T93B-LOC-A-260D-5	71.7	112.5	0.074	86.2	86.2	7.0	0.83	204 (030G)	199.9
Average	73.4	115.0	0.073	88.3	88.3	7.0	0.83	206	201.4
Std.Dev.	1.65	5.06	0.0043	3.10	3.06	0.48	0.014	5.1	2.89

Appendix B: Comparison of API 5L 0.5% EUL Yield Results from Two Independent Laboratories



Appendix C: Example of ABI Confirmation Procedure

Example Case: Line 132, Mile Point 8.54

Step 1. Determine SMYS using PG&E's Procedure for Resolution of Unknown Pipeline Features. (i.e. SMYS = 35 ksi)

Step 2. Determine the minimum ABI confirmation value for the SMYS rating from the table below. (i.e. to confirm a SMYS of 35 ksi, the minimum ABI result must be 62 ksi)

ABI experimental confirmation criteria

PG&E Procedure Values (4" nominal pipe size or greater)	Minimum ABI test Result for confirmation to 97.5% Confidence
65	83
60	79
52	73
48	70
46	69
42	66
35	62
33	61
30	59
28	58

Step 3. Conduct ABI measurement. (i.e. ABI test result = 82 ksi)

Step 4. Compare ABI test result to minimum ABI confirmation value. If the experimental ABI exceeds the confirmation value, the PG&E Procedure SYMS value is confirmed by the ABI method. (i.e. 82 > 62, so the SMYS of 35 ksi is confirmed by the ABI test at 97.5% confidence)