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Validating Non-Destructive Tools for Surface to Bulk Correlations of Yield Strength, Toughness, and Chemistry

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Project Manager / Administrative Contact
Matt Manning
Gas Technology Institute
847.971.1214
mmanning@gti.energy

Principal Investigator / Technical Contact
Daniel Ersoy
Element Resources, LLC
847.343.9755
dersoy@elementresourcesllc.com

Authors
Daniel Ersoy (Element Resources)
Brian Miller (GTI)
Marta Guerrero Merino (GTI)
Dr. Yongming Liu, Qiongfang Zhang, Jie Chen, Nan Xu (ASU, Ch. 6)

GTI
1700 S. Mount Prospect Rd.
Des Plaines, Illinois 60018
www.gti.energy

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PART I: SUMMARY, TECHNICAL APPROACH, AND DATA ORGANIZATION

Part I contains:

- Chapter 1: Executive Summary
- Chapter 2: Technical Approach and Data Organization

Chapter 1: Executive Summary

1.1 Project Objective

The deliverables of this project will facilitate the use of non-destructive surface testing: micro-indentation, micro-machining, in situ chemistry, and replicate microscopy analysis as accurate, efficient, and cost-effective tools for material property confirmation.

This work will provide benefits to pipeline safety, energy continuity, and integrity assessment programs since the developed techniques and models and validated testing technology will not require a line to be taken out of service or destructively cut out samples from the in-service pipeline.

The results of this project will also be applicable to DOT/PHMSA regulations that require operators to backfill their material property records for grandfathered pipeline segments and/or those that do not have adequate material records.

1.2 Acknowledgements

Sponsors

The project team greatly thanks the two sponsors of this effort:

U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration, under project #729, agreement 693JK31810003.

Public project web page at: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=729

Operations Technology Development, under project OTD 4.14.c.2

Further information available at: https://www.otd-co.org.

Technical Advisory Panel (TAP)

- DOT/PHMSA, OTD
- GTI, Element Resources, and ASU
- Gas Pipeline Participants
    - Ameren
    - Peoples Gas
    - North Shore Gas
    - National Fuel
    - Southwest Gas
    - Intermountain Gas
    - Dominion
    - National Grid

Project Team

- **U.S. DOT / PHMSA**: Joseph Pishnery (AOR) and Robert Smith (Prgm Mgr.)
- **OTD**: Mike Adamo
- **Element Resources**: Daniel Ersoy
- **Gas Technology Institute**: Brian Miller and Marta Guerrero-Merino
- **Arizona State University**: Dr. Yongming Liu, Jie Chen, Qionfang Zhang, Sonam Dahire, and Nan Xu

1.3 Report Structure

The report represents a significant body of work over 3 years+. Therefore, the report is broken up into five "Parts" which each house Chapters related to the Part.

The five Parts are:

- Part I: Summary, Technical Approach, and Data Organization
- Part II: Surface / Bulk Testing Comparisons
- Part III: Modeling
- Part IV: Project Conclusions and Recommendations
- Part V: Appendices, References, and Attachments

1.4 Concise Report Chapter Summaries

This section provides a high level and concise summary of each of the five Parts and related eight Chapters. The remainder of the report provides further details for each section and the attachments which number 1,000 pages provide much more detail and supporting information.

Part I: Summary, Technical Approach, and Data Organization

Chapter 1: Executive Summary

Provides concise summary of the project: objective, team, and chapter content.

Chapter 2: Technical Approach and Data Organization

The test results from thousands of lab and field material tests done on actual pipeline samples have been used to develop models that account for pipe material thermo-mechanical process variations and through-wall variability of material, mechanical, and chemical properties.

A Technical Advisory Panel (TAP) was formed with the sponsors, the technical team, and eight pipeline operators. The TAP was used to solicit input on scope of work details, operational considerations, and deliverable design.

A separate "training set" of twenty pipelines was made available to GTI, Element Resources, and ASU to allow initial model testing and prove-out prior to the seventy primary samples that were used to fully characterize pipeline properties and the correlation of surface to bulk properties, as well as develop predictive models of bulk properties based solely on surface obtained pipeline data.

A set of seventy pipeline samples (termed Pipe Library) that were in service from the natural gas industry were selected for the project testing and modeling. A great deal of care and effort was put forth to select a reasonable number that provided the adequate breadth of variety as typically encountered by the industry in the field.

The Pipe Library detailed breakdown in the report is termed the design of experiments (DOE). The ranges for the key pipeline attributes are:

- Installation years from 1930 to 2004 with over 60% pre-code pipelines
- Diameters from 4 to 30 inches
- Grades from A to X52
- All steel types: rimmed/capped, semi-killed, and fully killed
- All key long seam types: ERW, SAW, Seamless, and Spiral
- Wall thickness over wide range: 0.156 to 0.460 inches
- Chemistry grade variety, e.g.: 1008, 1010, 1015, 1016, 1021, 1022, 1023, 1025, 1026, 1030, 1522, 1525, and vanadium and niobium High Strength Low Allow (HSLA) grades
- ASTM Grain Size (log scale) range spanning: 7.0 to 13.0

A structured, column database was developed with 203 variables (fields) to collect and organize all project test data from the lab and field-based testing. A separate, similar but smaller database, was designed to collect and organize a supplemental toughness testing program. These databases house nearly 15,000 data entries from lab and field-based testing and are provided as Appendix A and Appendix B external Excel files in column database orientations.

Part II: Surface / Bulk Testing Comparisons

Chapter 3: Material Yield and Tensile Strength, Grain Size, and Chemistry

This chapter describes the trends and comparisons between surface and bulk pipe properties. Methodologies are listed in Chapter 2 and the associated and very detailed Attachments to this report. Readers are directed to these sections for more information related to methods and procedures.

The chapter is broken down into four main sections, one each focused on: yield strength, ultimate tensile strength, chemistry, and grain size. Chemistry is also very important to determine steel type.

The testing uncovered a range of variation across the pipe wall thickness. The data used in this Chapter is provided in Appendix A.

For the normalized/annealed *seamless* pipelines, the properties were mostly uniform or isotropic across the pipe wall, meaning that the nondestructive evaluation technologies done on the pipe outer wall surface are representative of the rest of the wall and therefore the bulk properties needed for characterization.

For *non-seamless* pipes (that have long seam welds) there can be significant anisotropic properties of *yield strength* and *chemistry* (specifically carbon segregation) between the surface obtained values and an average across the wall and/or bulk chemistry and full-wall mechanical testing results.

The reasons for this difference between the surface and bulk properties is discussed in detail in this chapter, but in summary the major categorical factors are: (a) cold work and forming stress from pipe manufacturing (without post production normalizing/annealing as in seamless pipe), (b) chemical segregation from primary steel production (e.g., rimmed/capped centerline carbon segregation), (c) HSLA steel grain refinement especially near the outer surfaces of the pipe wall, and (d) other thermomechanical factors.

The surface NDE test results from two technologies (Frontics AIS and MMT HSD) for yield strength and ultimate tensile strength were compared to the full-wall lab test results.

The observed trends likely indicate that the MMT HSD "surface scratch-type" technique (see Attachments) interrogates mostly the outer layers of the pipe wall while the Frontics AIS "indentation-type" technique (see Attachments) may in effect test deeper into the pipe wall.

Seamless pipe is normalized/annealed and is therefore very homogenous across its thickness. Welded pipe on the other hand is produced from hot rolled plate or strip that usually exhibits through-thickness variations in microstructure. These differences in grain size or in pearlite interlamellar distance are produced by localized through-thickness differences in temperature as the plate is rolled and then cooled on the run-out table. In addition, forming the pipe through the U-bend, O-bend, and Expansion (UOE) process followed by welding often produces significant residual stresses and cold work that tends to make the outer layers of the pipe "stronger" from a yield testing standpoint. Finally, the cold expansion step (and potential mill hydrotest) may or may not have been performed which introduces another element of uncertainty in properties prediction.

The same can be said for HSLA steels that due to the chemistry and grain refiners added, and thermomechanical processing, may lead to a finer (smaller diameter) grain size structure on the outer walls of the pipe thickness. This could also increase the yield strength near the surface due to the well-known Hall-Petch phenomenon that finer grain sizes contribute to higher yield strengths. While the properties of all steels are affected by thermomechanical processing factors, HSLA or micro-alloyed steels are produced in way so as to maximize the strengthening mechanisms available through controlled rolling and accelerated cooling.

Taken as a whole, and on average, welded and/or HSLA pipes and steels lead to a pipe stronger on the outside layers than the inside layers. From the data, this appears to be a likely reason why the MMT surface yield strengths (prior to any modeling) are higher for these situations than the full-wall lab tensile tests.

Both NDE techniques exhibited little difference between the lab and their NDE surface-derived tensile strengths. This is consistent with the reality that the factors that produce a gradient of yield strength across a pipe wall do not affect the ultimate tensile strength the same way. The yield strength is very sensitive to any changes that reduce or increase the ability for atomic slip planes and dislocations to move through the material matrix, whereas tensile strength is actual breaking of these bonds outright.

Chapter 4: Material Toughness (Supplemental Section)

A subset of 30 of the 70 pipeline samples from the DOE had extensive Charpy V-notch (CVN) toughness testing completed on them. The data for these is provided in Appendix B.

This chapter analyzes the results of the testing which included CVN absorbed energy, lateral expansion, and percent shear over various temperatures. Enough temperatures were performed to establish the CVN upper shelf energy level.

Frontics also tested these 30 pipeline samples in the form of coupons for K_{IC} fracture toughness. Those results are presented in Attachment #4 but are not compared directly to the CVN values since the testing direction and mode are different.

In general, the CVN energy went down when temperature was reduced and phosphorous and sulfur levels increased for non-HSLA steels.

The research team feels that this Chapter will provide an excellent foundation for future research and development as new field-ready and non-destructive toughness test methods are developed.

Part III: Modeling

Chapter 5: Causally Based Regression

This chapter contains the regression and model fits (when provided) from the nondestructive technology and the causal models from the analysis developed during this project, as well as historical models from the literature.

The causality of each model is a function of the choices of independent variables and how they are interacted or not. The choices for the structure of the causal models were based on the range of API steels tested and expected in the field, i.e., the DOE. These include lower to moderate carbon steels with ferritic and/or pearlitic phase structures. The inclusion of the key alloy elements used to strengthen the steels through solid solution and precipitation strengthening were accounted for as well.

Many historic models recorded in the literature were tested but it became evident that although these models did have some merit, that the lack of ubiquitous computing power from the decades that they were developed potentially resulted in a limited number of terms for the least square regressions and exclusion of some key, higher order terms. With the availability of very powerful personal computers and equally important the associated statistical analysis packages, there were no restrictions on the causal model terms and forms selected for modeling in this project.

The best causal models for the Frontics and MMT NDE technologies were developed for yield strength and outperformed all the other models from historical research or those that were developed at the time by the technology provider in some cases.

The modeling of the ultimate tensile strength was a much simpler formula from a causal basis. It is highly dependent on manganese and carbon content. There are only minimal differences between all of the models for ultimate tensile strength for both the custom and the historic models in the literature.

In summary, the project was highly successful with the model development. The causal model developed and combined with the Frontics AIS output for yield strength was able to achieve a predicted vs. actual regression fit with a 95% confidence for predicting yield strength across the entire pipe sample DOE. The MMT technology showed non-conservative bias in all models for yield strength, especially near or above 50 ksi actual (full-wall) yield strength for the aforementioned reasons. The ultimate tensile strength causal models achieved the same 95% confidence level for both NDE technologies across the full pipe DOE range.

Chapter 6: Data Analytics Modeling: OLS, BMA, BNM, GPM, and MBGPM

Several classical and novel data analytics methods are demonstrated, compared, and validated using the collected experimental datasets. They are: ordinary least-square regression (OLS), Bayesian Model Averaging (BMA), Bayesian Network Model (BNM), Gaussian Process Model (GPM), and Manifold-Based Gaussian Process Model (MBGPM). The results showed that the Bayesian averaging and updating principle is able to show the best prediction performance with large uncertainties from measurements. It also shows that the Frontics measurements have less prediction error in the investigated data analytics methods which is consistent with the causal-based OLS modeling of Chapter 5. The models developed in this chapter are included as R-language source code in Appendix D.

Part IV: Project Conclusions and Recommendations

Chapter 7: Conclusions

1. The project successfully measured and categorized the mechanical, chemical, and physical differences across a broad range of pipe sample walls through methodical full-wall and bulk testing as compared to surface-collected physical, mechanical, and chemical NDE testing.

2. Differences in yield strength between the surface derived values and bulk, full-wall were analyzed via a sensitivity study and explained through the changes in surface yield strength due to primary steel production processes, seam type and pipe forming process, and steel chemistry. All these factors/variables can be determined from surface testing.

3. Based on the extensive testing and analysis an ambitious set of modeling tasks were completed include causal-based OLS and data analytics-based modeling. Successful models for yield strength and ultimate tensile strength were developed to predict bulk properties from purely surface obtained information for yield strength and tensile strength.

4. The optimum causal models combined with the Frontics AIS technology surface data achieved a 95% confidence in yield strength predictions by overlapping the full-wall yield strength from lab tests across the entire pipe sample DOE. The optimal models for the MMT HSD exhibited bias in the yield strength for certain pipe configurations related to non-isotropic properties across the pipe wall. The models reduced the bias of the MMT results, but could not completely adjust for it particularly at higher yield strengths.

5. Both NDE technologies optimal models, coupled with the surface data, achieved 95% confidence in ultimate tensile strength predictions by overlapping the full-wall ultimate tensile strength from lab testing across the entire pipe sample DOE.

6. Chemistry values were correlated successfully for 15 key elements, and the only significant variation of chemical properties across the pipe wall was noted from surface to bulk values for carbon and sulfur. A set of chemical element kernel distributions were developed to estimate the magnitude of these differences across the pipe wall based on steel type and other factors.

7. A supplemental body of detailed toughness testing was completed on over 40% of the pipe samples in the DOE and collected and analyzed as a supplemental task of the project. This work will provide invaluable to future NDE technology development aimed at estimating pipe toughness through surface nondestructive testing.

Chapter 8: Recommendations

1. The relations, models, and distributions developed under this project can be used to predict full-wall yield and ultimate strengths from surface-based NDE technology such as Frontics AIS and MMT HSD for *seamless* pipes.
2. The Frontics AIS technology also was successful at a 95% confidence for predicting *yield* strength across the entire pipe sample DOE on *non-seamless* pipes, i.e., pipes with long seam welds like ERW, SAW, etc.
3. Further research is warranted/advised into the promising MMT HSD technology to help reduce bias in the full-wall yield strength predictions based on surface readings for non-seamless pipe that have variation of yield strength across the pipe thickness cross section. The current models provided by the manufacturer and developed under this project could not remove the bias in these measurements, particularly for higher yield strengths.
4. The relations, models, and distributions developed under this project can be used to predict full-wall *ultimate tensile* strengths from surface-based NDE technology such as Frontics AIS and MMT HSD. Using the causal-based models developed, both technologies achieved a 95% confidence for predicting tensile strength across the entire pipe sample DOE, seamless or non-seamless.

Part V: Appendices, References, and Attachments

Appendices

- **Appendix A**: External File - Project Master Data Table for 70 Pipeline Samples in Excel (778KB). APPENDIX_A_MASTER_DATA_TABLE_V01.xlsx
- **Appendix B**: External File - Charpy Toughness and Related Data 30 Pipeline Samples in Excel (195 KB). APPENDIX_B_CHARPY_DATA_TABLE_V01.xlsx
- **Appendix C**: Contained in this report - Causal-Based Regression Output Tables.
- **Appendix D**: External File - R-Code for Regressions in Chapter 6 in a ZIP file (53 KB). APPENDIX_D_CH6_R-CODE.zip

References

- Final report citations are expanded in this section. Contained in this report.

Attachments

- **Attachment #1** - Frontics: Measurement of Yield strength, Tensile strength and Fracture toughness of API 5L pipe using Instrumented Indentation Testing (328 pages pdf). FARE-190603-1 Part I.pdf
- **Attachment #2** - Frontics: Measurement of Yield strength, Tensile strength and Fracture toughness of API 5L pipe using Instrumented Indentation Testing - Part II (298 pages). FARE-190603-1 Part II.pdf
- **Attachment #3** - Frontics: Measurement of Yield strength, Tensile strength and Fracture toughness of API 5L pipe using Instrumented Indentation Testing - Additional Sample (8 pages). FARE-190723-1 Part I Appendix 2.pdf
- **Attachment #4** - Frontics: Measurement of Yield strength, Tensile strength and Fracture toughness of API 5L pipe samples using Instrumented Indentation Testing - Coupon testing (108 pages). FARE-201122A.pdf
- **Attachment #5** - MMT: Procedure Bundle (47 pages). 2020MMTProcedureBundle_2021.03.01.pdf
- **Attachment #6** - MMT: Final report for nondestructive HSD Testing for 70 cutout samples (267 pages). 2021.02.10-MMTFinalNDEReportForGTI19006.pdf