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

Project Final Virtual Meeting
Thursday, January 20, 2022, 2PM to 3PM ET

Contractor: Gas Technology Institute
Presented by Principal Investigator: Daniel Ersoy, Element Resources, LLC

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GTI Project Numbers: 22428 / 22429

Presentation Topics

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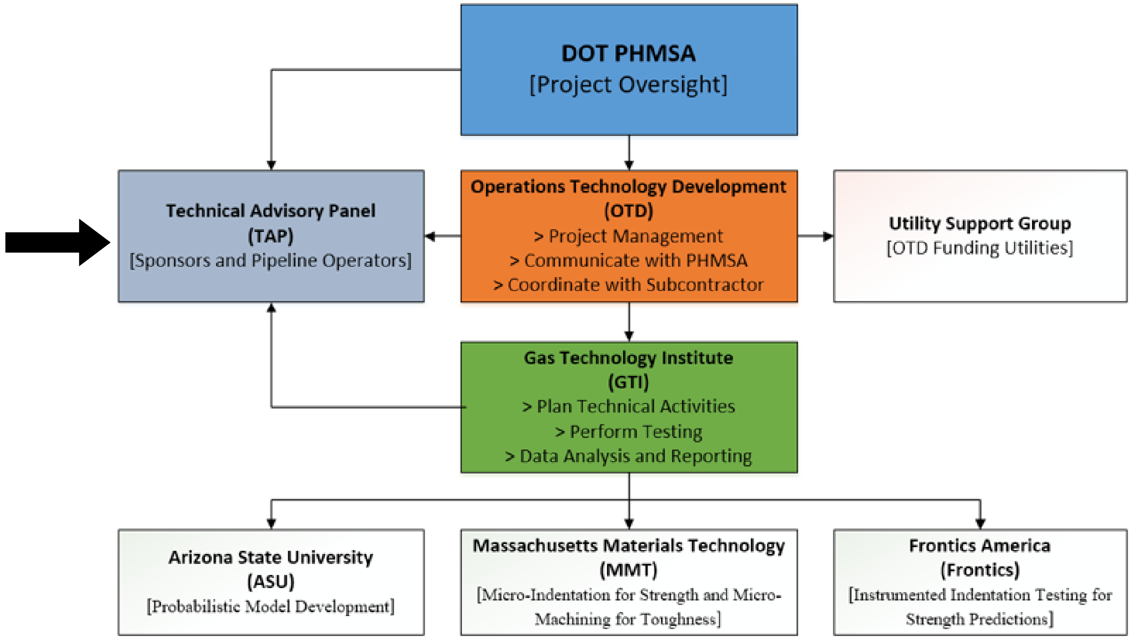
Acknowledgements

The project team greatly thanks:

- **Sponsor: U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration**, under project #729, agreement 693JK31810003.
  - The final report and this presentation can be found at the project web page: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=729
- **Sponsor: Operations Technology Development**, under project OTD 4.14.c.2.
  - Further information available at: https://www.otd-co.org
- **The prior researchers** whose work was referenced in the report. The report and method is built on a strong foundation of those who have contributed to these areas for decades. Reference material and figures used in this presentation are cited in the final report.

Sponsors and Research Team Members and Structure



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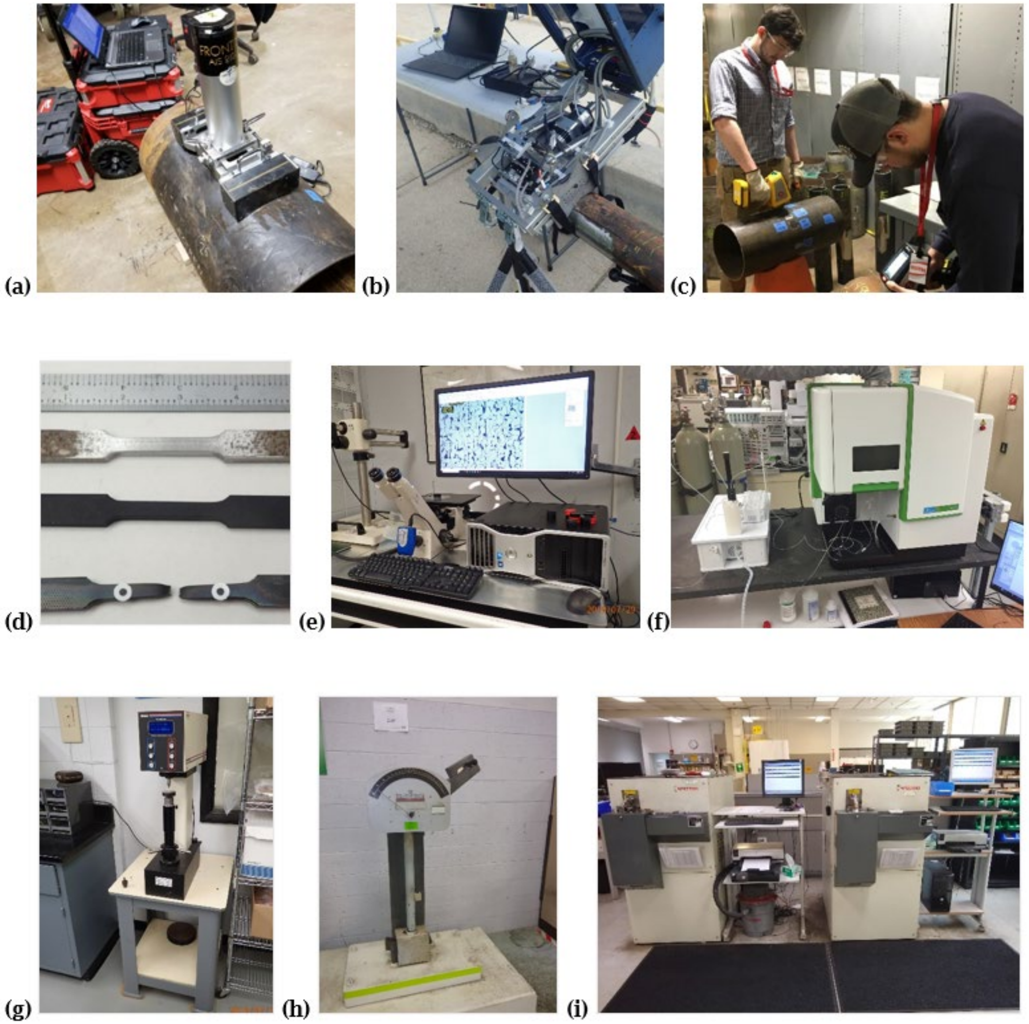
- **Technology Participants**
  - Frontics America
  - Massachusetts Materials Technology
  - SciAps
- **Project/Program Management**
  - Matt Manning, GTI
  - Kristine Wiley, GTI
  - Mike Adamo, OTD

Problem Statement that Research is Focused On

1. To 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.
2. This work will provide benefits to pipeline safety, energy continuity, and integrity assessment programs since these techniques do not require a line to be taken out of service and do not destructively cut out samples from the in-service pipeline.
3. The benefits are applicable to new DOT/PHMSA regulations that require operators to backfill their material property records for older, “grandfathered” pipeline segments.

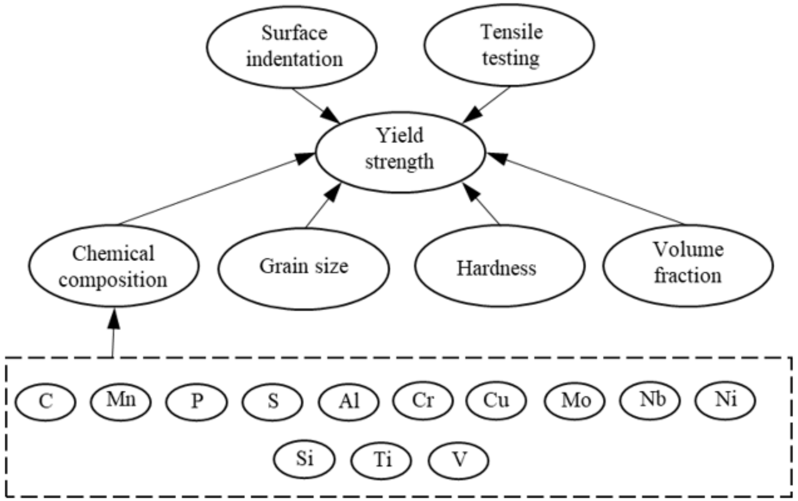
Examples of Several Testing Methods.



(a) Frontics AIS, (b) MMT HSD, (c) SciApps HH LIBS-OES, (d) Tensile Bars, (e) Grains Size Computer, (f) Lab ICP-OES Chemistry, (g) Hardness Tester, (h) Charpy Small Hammer, (i) OES Units.

Project Objectives

1. This project's focus is to test and model state-of-the-art technology from Massachusetts Materials Technologies (MMT), Frontics America (Frontics), SciAps, Arizona State University (ASU), Element Resources, and the Gas Technology Institute (GTI).
2. 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 simplified interrelation diagram between properties is shown to the right.
3. These correlations will allow surface-obtainable information from indentation and other surface testing techniques, surface chemistry analysis, and surface optical microscopy to be used for material property validation for pipelines.



Tasks Outline and Budget

1. Form Technical Advisory Panel and Scope Confirmation
2. Develop Project Database and Pipeline Sample Library
3. Develop Testing Matrix and Execute Testing
4. Data Analysis and Model Development and Optimization
5. Final Report

Total Budget with Co-funding approximately: $1,050,000 USD over ~ 36 months.

Task 1: Technical Advisory Panel (TAP) and Scope Confirmation

- 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

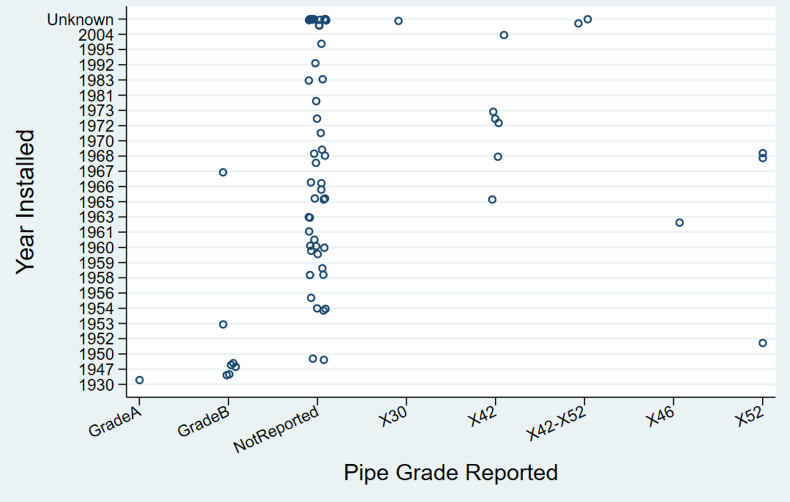
Task 2: Develop Project Database and Pipeline Sample Library

1. The sample set of seventy (**70**) pipelines has an excellent distribution of properties, and along with the additional calibration set of twenty (**20**) pipelines.
2. This set of pipes provided a diverse and realistic pipe sample set for the project, testing, and modeling.
3. A project database was developed with nearly **15,000** data entries from lab and field-based testing.

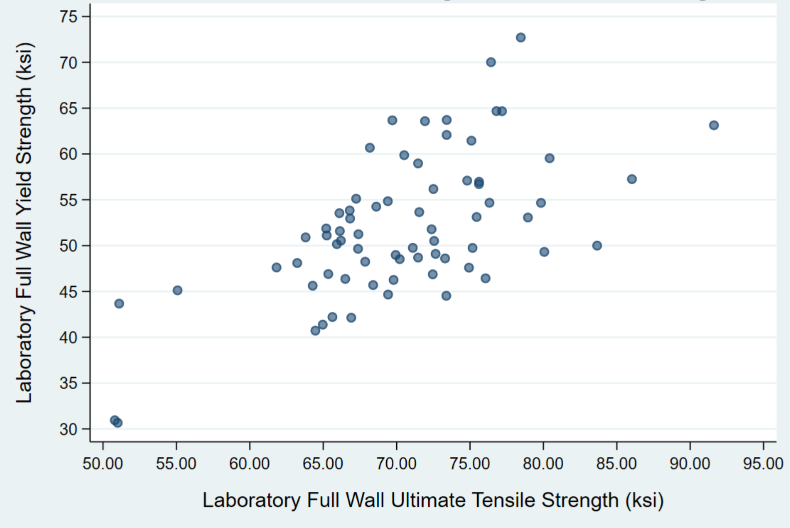
- Installations from 1930 to 2004 with over 60% pre-code pipelines
- Diameters from 4 to 30 inches
- Yield Strengths from 30 to 73 ksi; UTS from 50 to 92 ksi
- All steel types: rimmed/capped, semi-killed, and fully killed
- All key long seam types: ERW, SAW, Seamless, and Spiral
- Wall thickness over 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

Pipeline Attribute	Description of Attribute
diameter nominal	Nominal diameter of the pipe in inches
wall thickness	Wall thickness of the pipe in inches without any treatment to the sample
year installed	Specifies the installation date as provided by the utilities
grade reported	Shows the steel grade as known by the utilities
steel type	Specifies the GTI estimate of steel (rimmed, capped, killed Si, killed, Al, semi-killed)
chemistry grade	States the steel grade as per SAE-ASTM
long seam type	Long seam weld type according to inspection

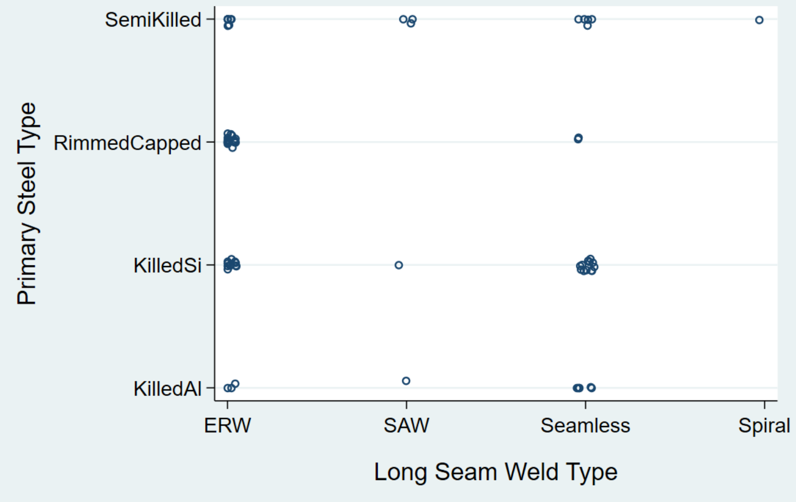
Year Installed vs. Pipe Grade Reported



Lab Full Wall Yield Strength vs. Tensile Strength

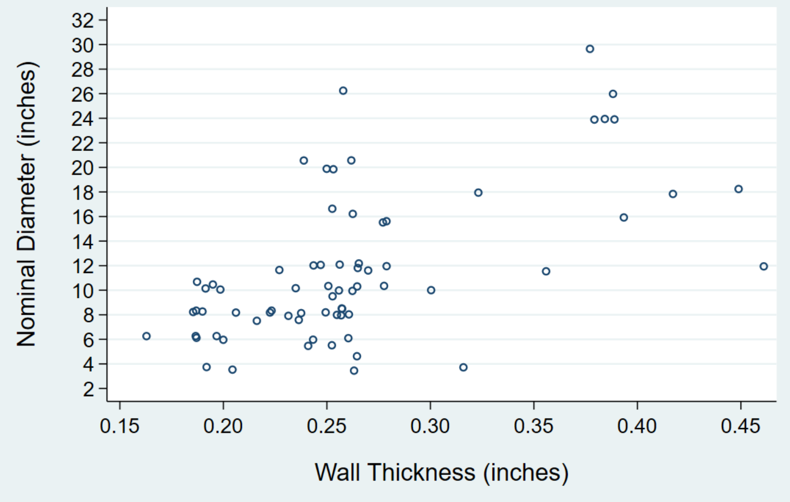


Pipe Steel Type vs. Long Seam Type

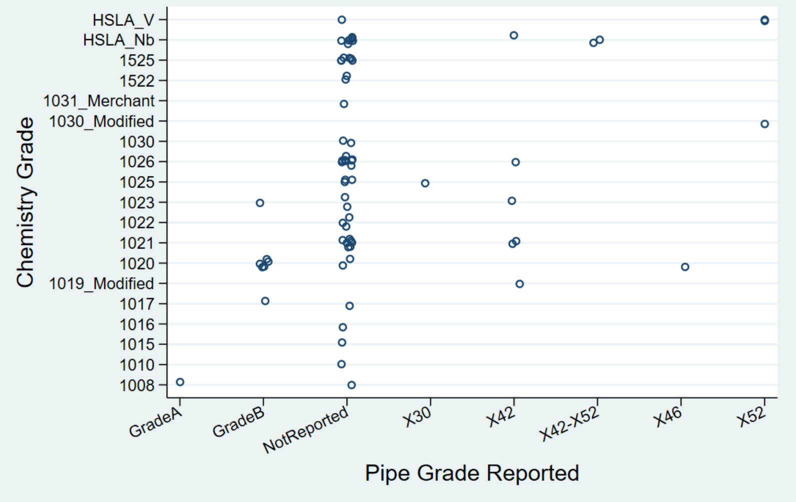


Pipe Steel Type vs. ASTM Grain Size

Pipe Diameter vs. Wall Thickness



Pipe Chemistry Grade vs. Pipe Grade Reported



Task 3: Develop Testing Matrix and Execute Testing - Field

Surface, field-based testing includes technology from MMT, Frontics, and Sci-Apps:

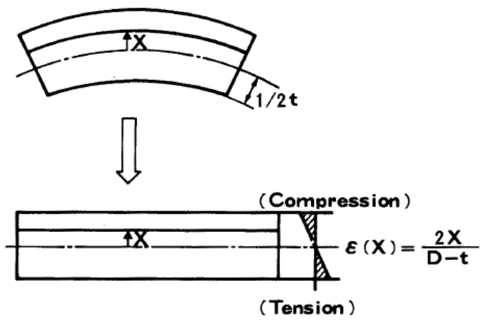
- **Yield and Tensile Strength** remote and across welds
  - MMT Hardness, Strength, and Ductility (**HSD**)
  - Frontics Advanced Indentation System (**AIS**)
- **Toughness**
  - Frontics **AIS K_{IC}** fracture toughness estimates
- **Chemistry**
  - **SciAps** field-ready, surface-based Handheld Laser Induced Breakdown Spectroscopy (HH LIBS) Optical Emission Spectroscopy (OES)
  - Surface removed **filings**
- **Microstructure and Grain Size**
  - Field-based **replicates**
  - In situ **microscopy**

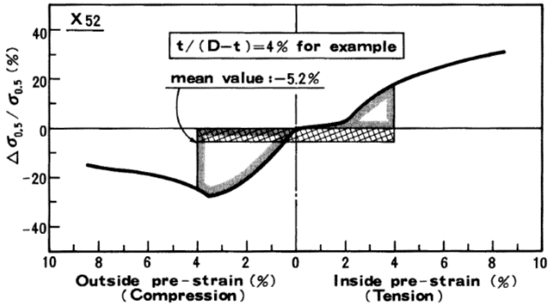
Task 3: Develop Testing Matrix and Execute Testing - Lab

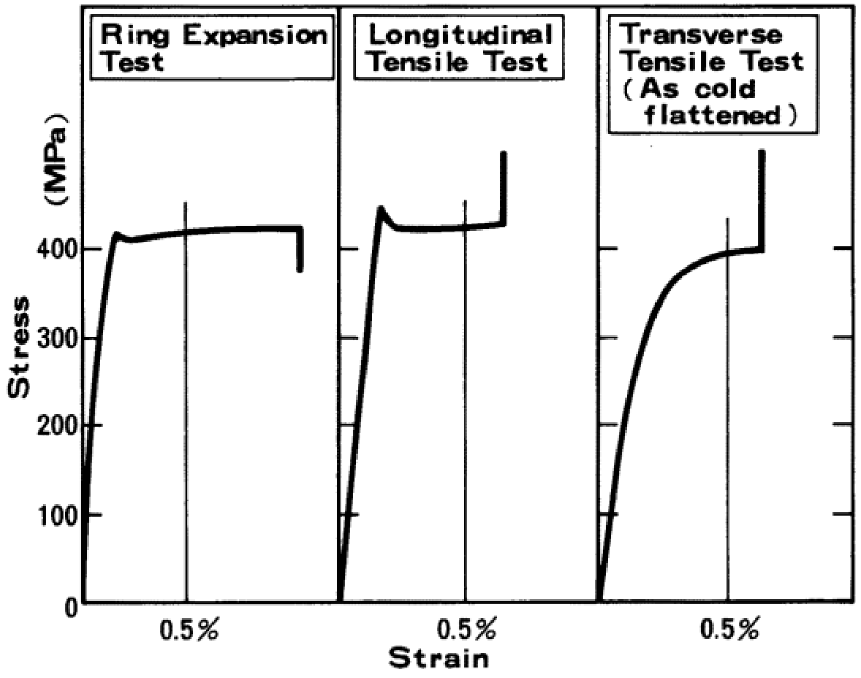
Baseline (referee) lab-based testing includes

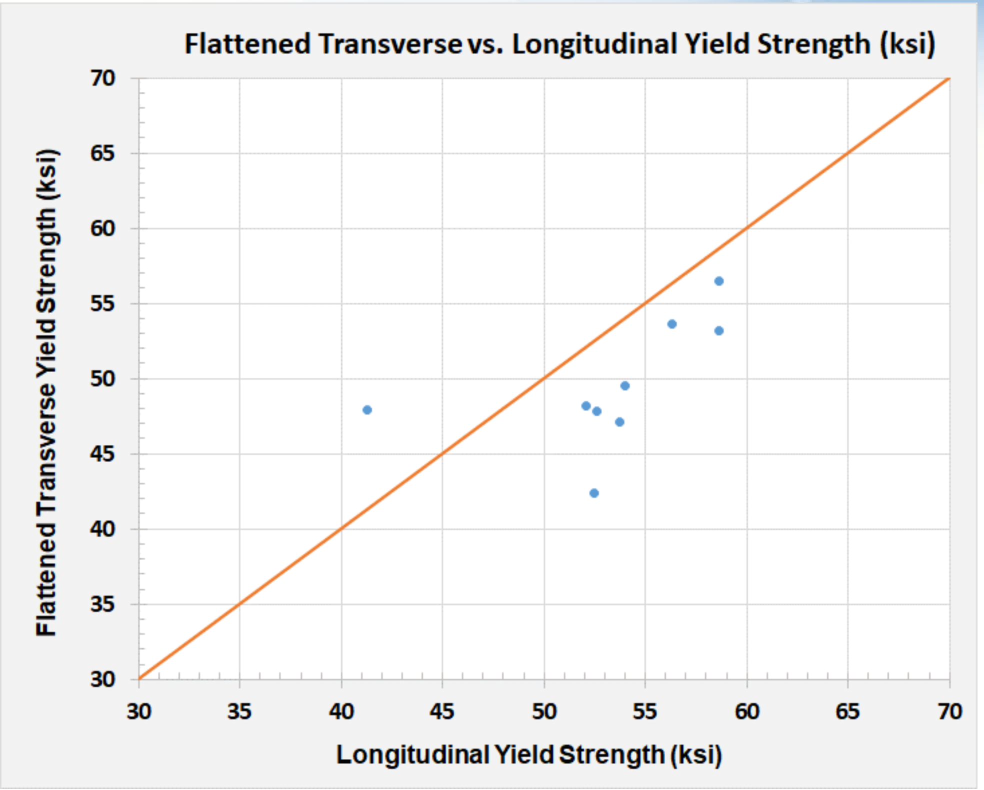
- Full wall **Tensile** tests per ASTM A370 with 1"-gauge length longitudinal specimens and an average of 3 specimens
- **Chemistry**
  - Lab Glow Discharge Spectroscopy (**GDS**) chemistry at 4 different depths. (0.005", 0.020", 3/4 thickness and mid thickness). Includes C, S, and P by GDS. 15 elements are included for baseline chemistry
  - Bulk Inductively Coupled Plasma (**ICP**) Optical Emission Spectroscopy (**OES**)
  - Bulk LECO **ASTM E1019** for C, S, and N
- **Grain size** near surface, ¼ pt, and center for both longitudinal and transverse sections, average of 6 readings; then average of near surface grain sizes (~0.005" deep) longitudinal and transverse specimens
- OD Rockwell B **Hardness** after ~ 0.005" surface grind; ID Rockwell B hardness after ~ 0.005" surface grind
- Full **Charpy** S-curve toughness curve testing and development

Task 3: Bauschinger Effect - Importance of Longitudinal Samples









Flattened Transv to Unflattened Long Pipe Samples					Yield Strength			Ultimate Tensile Strength		
Nom Diam	Wall Thk	Reported Grade	Steel Type	Chemistry Grade	YSfullL	YSflatT	FlatT_v_Long	UTSfullL	UTSflatT	FlatT_v_Long
inches	inches	text	text	text	ksi	ksi	% Diff	ksi	ksi	% Diff
12	0.340	X42	SemiKilled	1026	52.50	42.40	-19.2	67.8	68.5	1.0
10	0.209	35ksi	SemiKilled	1021	53.70	47.10	-12.3	65.0	66.3	2.0
10	0.524	X42	Rimmed	1033 MOD	58.60	53.20	-9.2	77.5	77.3	-0.3
10	0.245	NA	Rimmed	1020	52.60	47.80	-9.1	64.4	65.4	1.6
10	0.283	X42	Rimmed	1020	54.00	49.50	-8.3	63.4	63.9	0.8
12	0.353	X46	KilledSi	1020	52.10	48.20	-7.5	70.2	72.8	3.7
10	0.513	X42	Rimmed	1033 MOD	56.30	53.60	-4.8	75.9	76.4	0.7
10	0.372	X42	KilledAl	1522	58.60	56.50	-3.6	78.3	79.7	1.8
12	0.470	X42	KilledSi	1019 MOD	41.30	47.90	16.0	64.4	65.1	1.1

Task 4: Data Analysis and Model Development and Optimization

- 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.
- For the normalized/annealed seamless pipelines, the properties were mostly uniform or isotropic across the pipe wall.
- This means for seamless pipelines, that in general, 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.

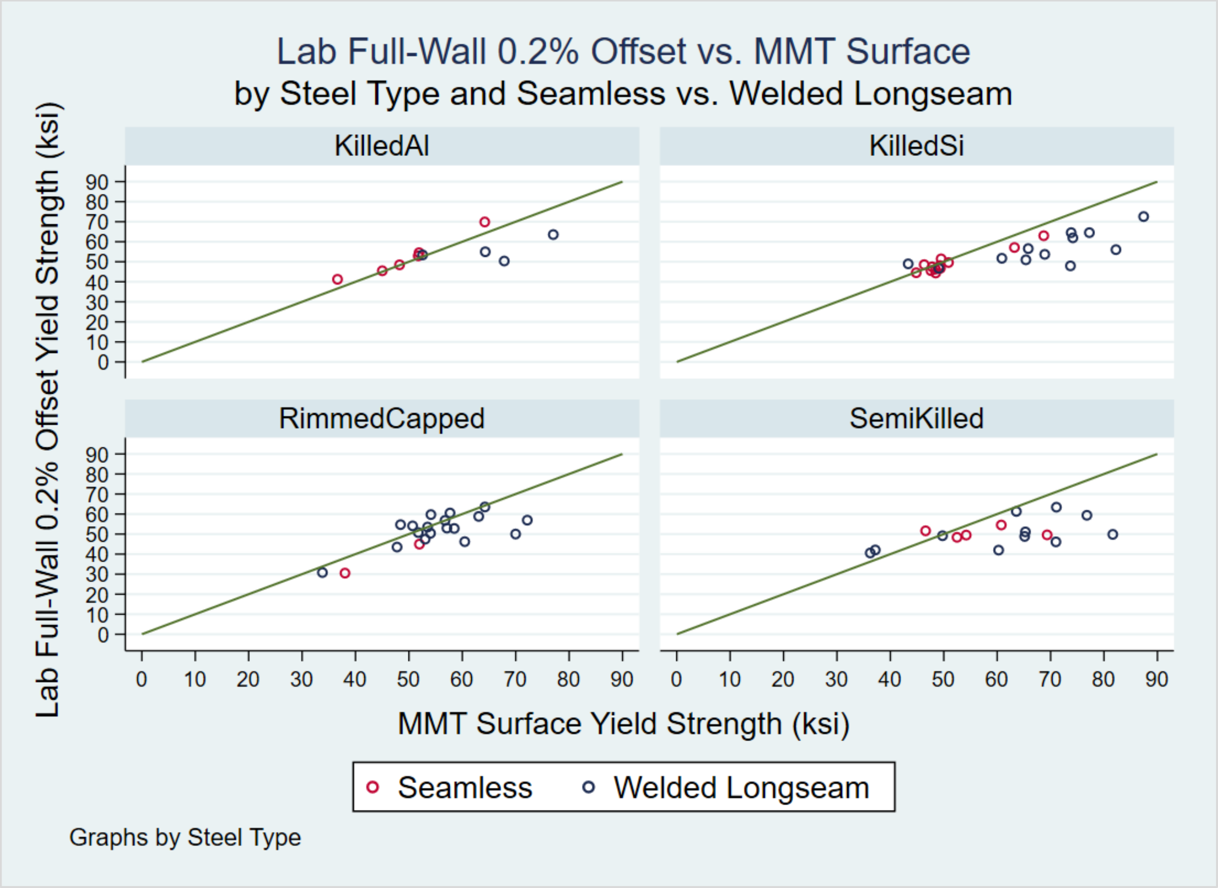
Task 4: Data Analysis and Model Development and Optimization

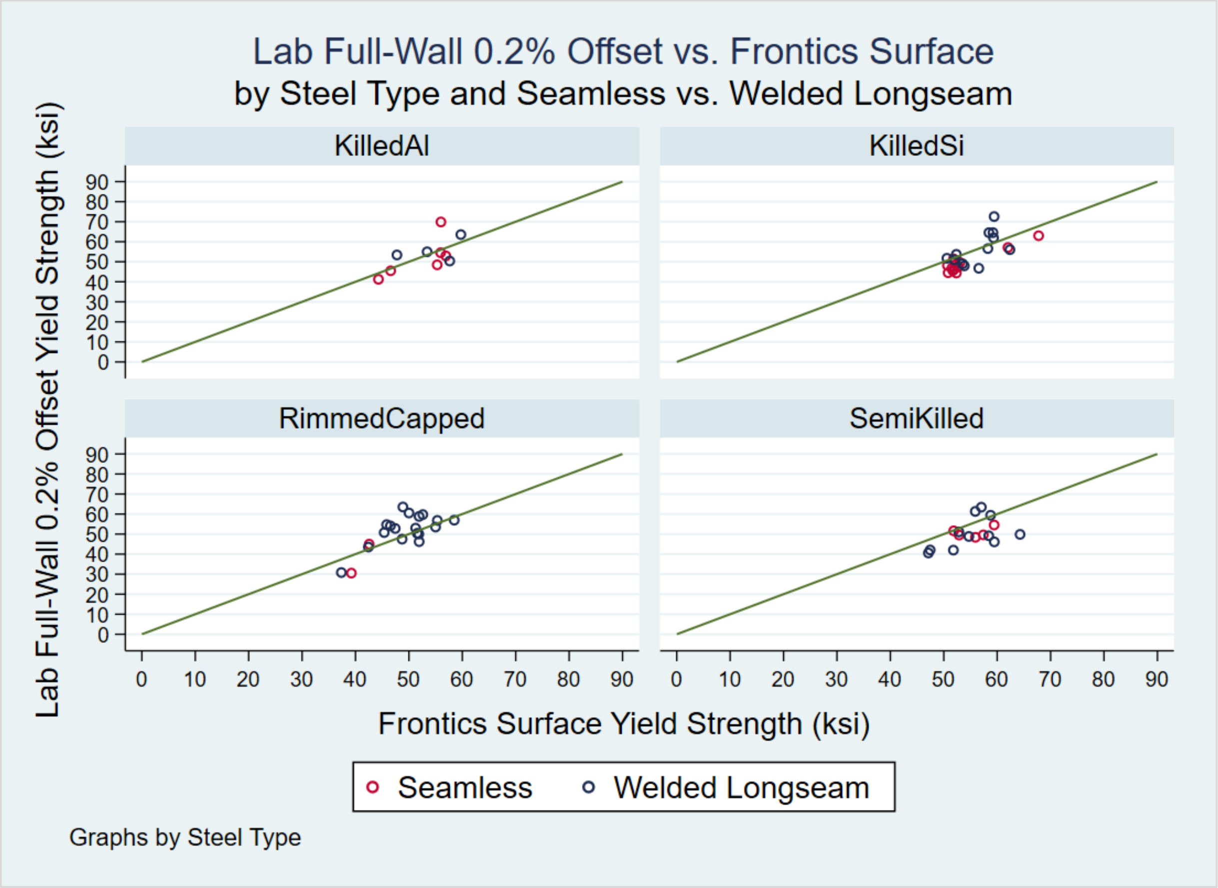
- For non-seamless pipes (that have long seam welds) there can be significant anisotropic properties of yield strength and chemistry (specifically carbon segregation) between the surface obtained values and an average across the wall and/or bulk chemistry and full-wall mechanical testing results.
- The reasons for this difference between the surface and bulk properties are discussed in detail in the final report, but in summary the major categorical factors are:
  - (a) cold work and forming stress from pipe manufacturing (without postproduction 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.

Task 4: Data Analysis and Model Development and Optimization

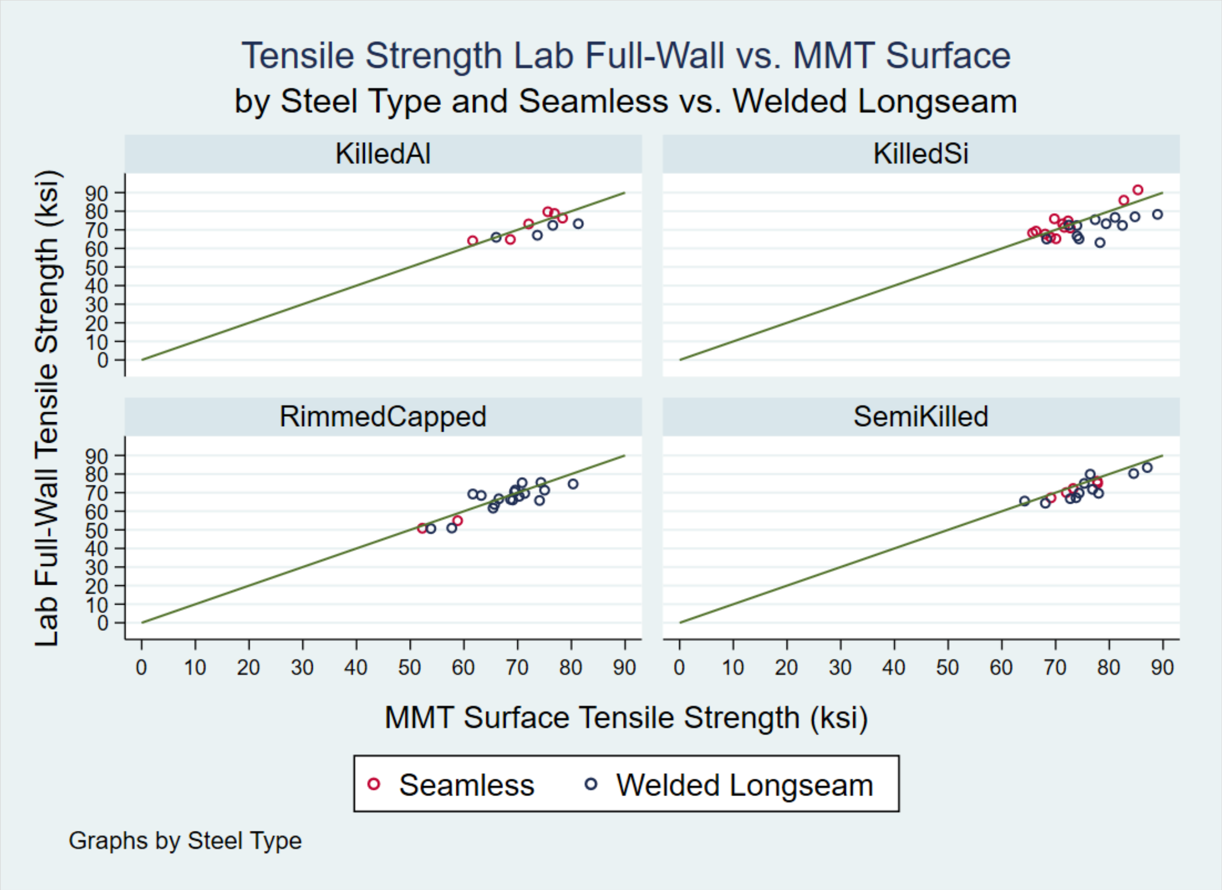
- Welded pipe is produced from a hot rolled plate or strip that usually exhibits through-thickness variations in microstructure. These differences in grain size or in pearlite interlamellar distance are produced by localized through-thickness differences in temperature as the plate is rolled and then cooled on the run-out table.
- In addition, forming the pipe through the U-bend, O-bend, and Expansion (UOE) processes 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 a way 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.

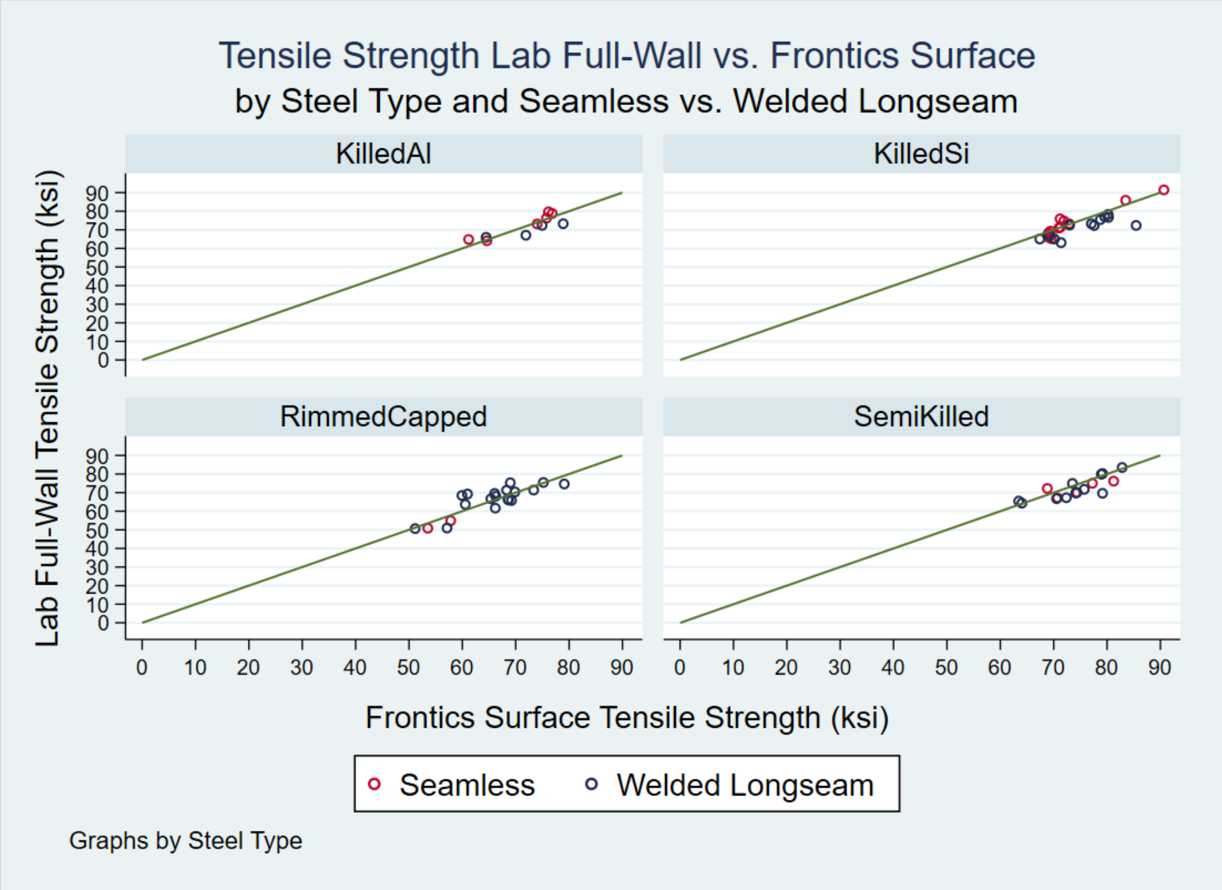
Task 4: Yield Strength by Steel Type and Seamless vs. Welded



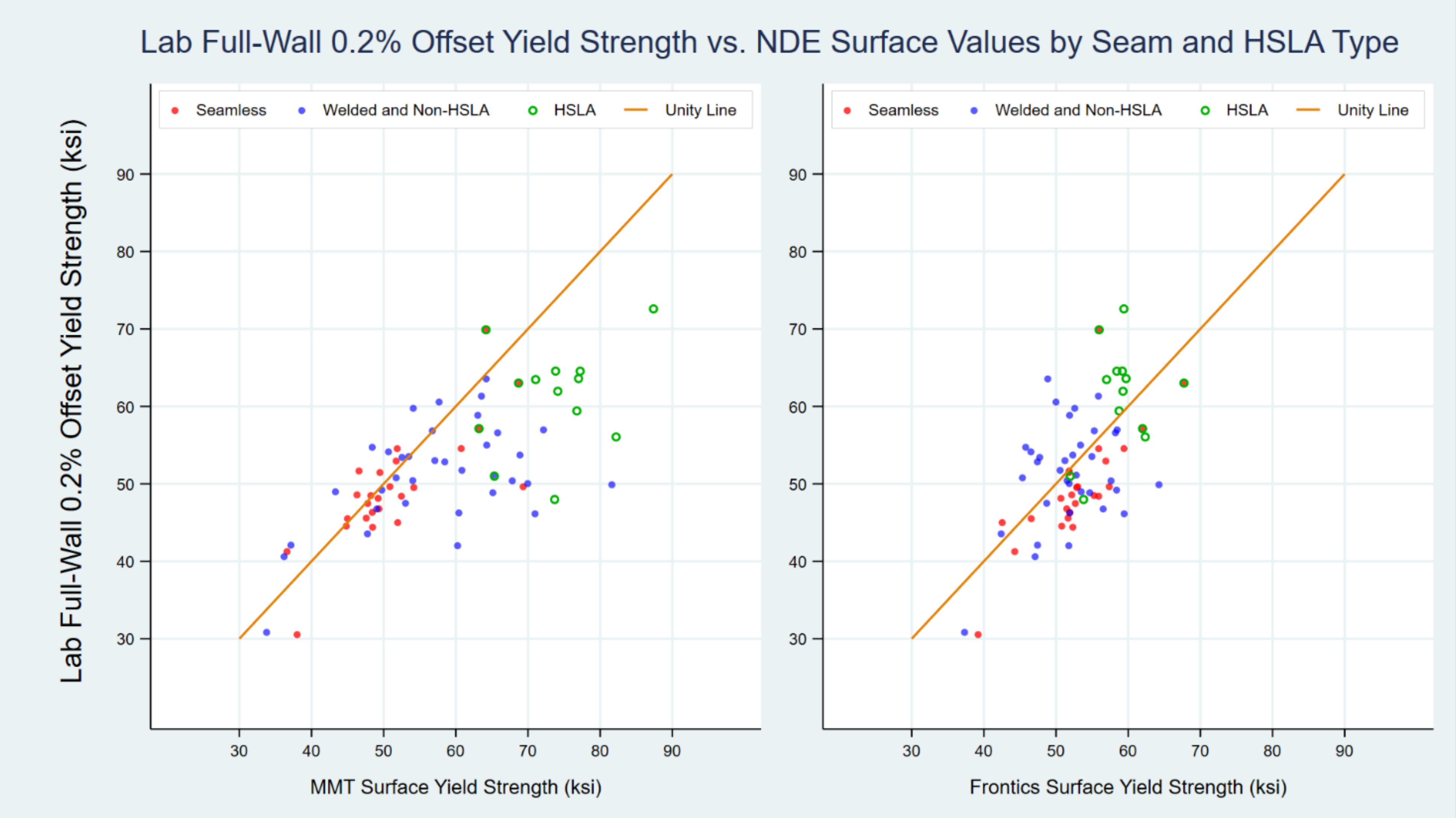


Task 4: Lab vs. NDE Surface Yield Strength by Multiple Factors

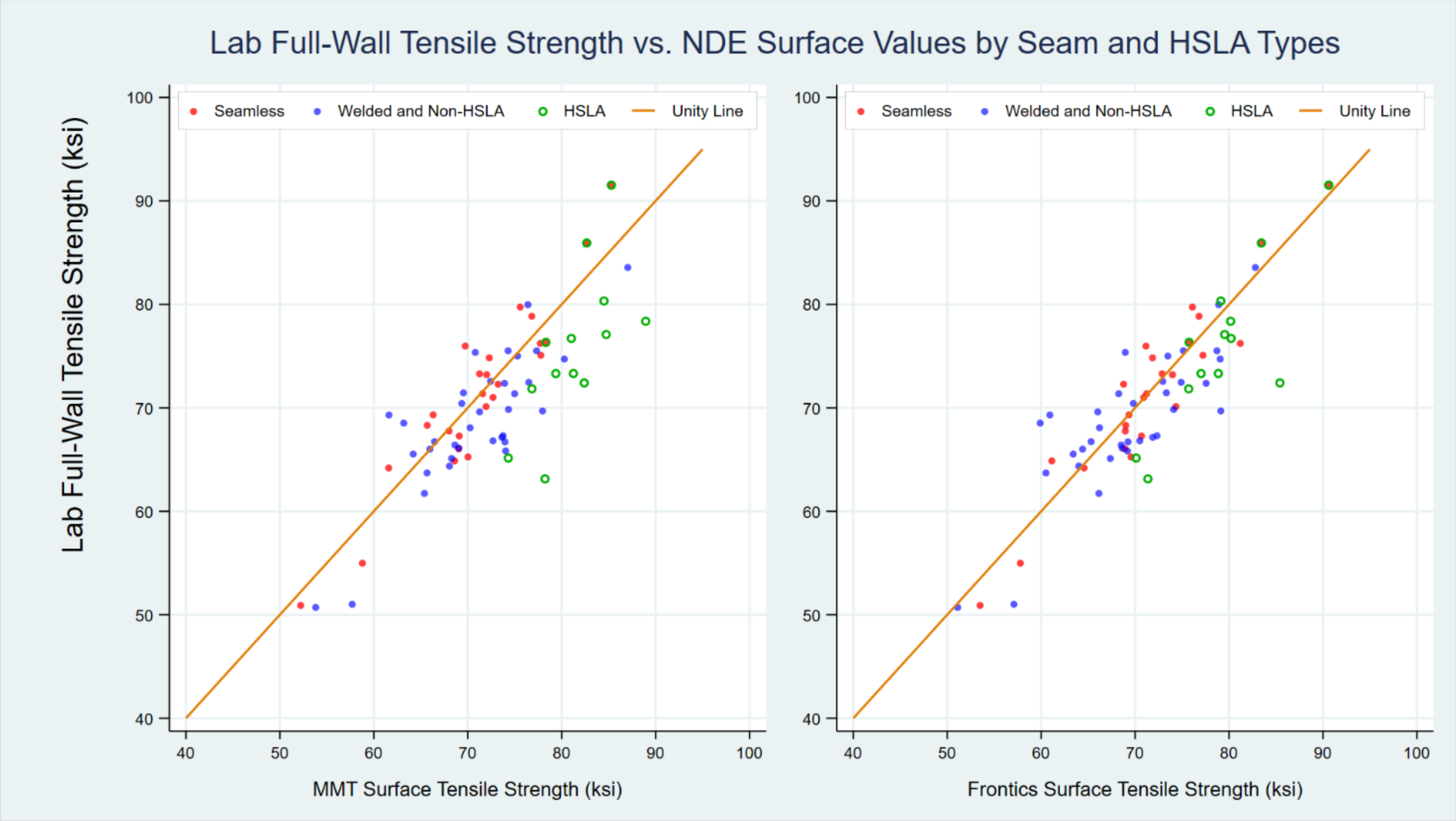




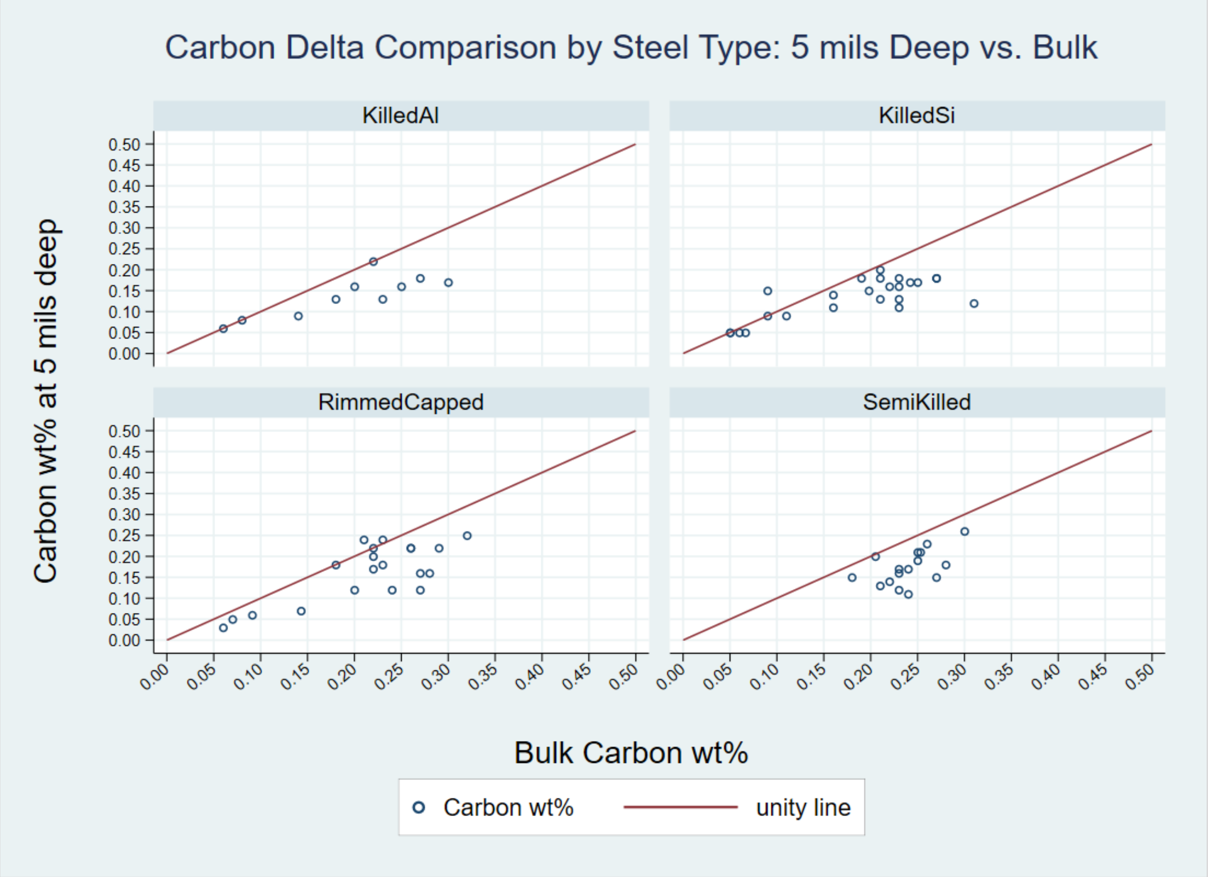
Task 4: Lab vs. NDE Surface Yield Strength by Multiple Factors

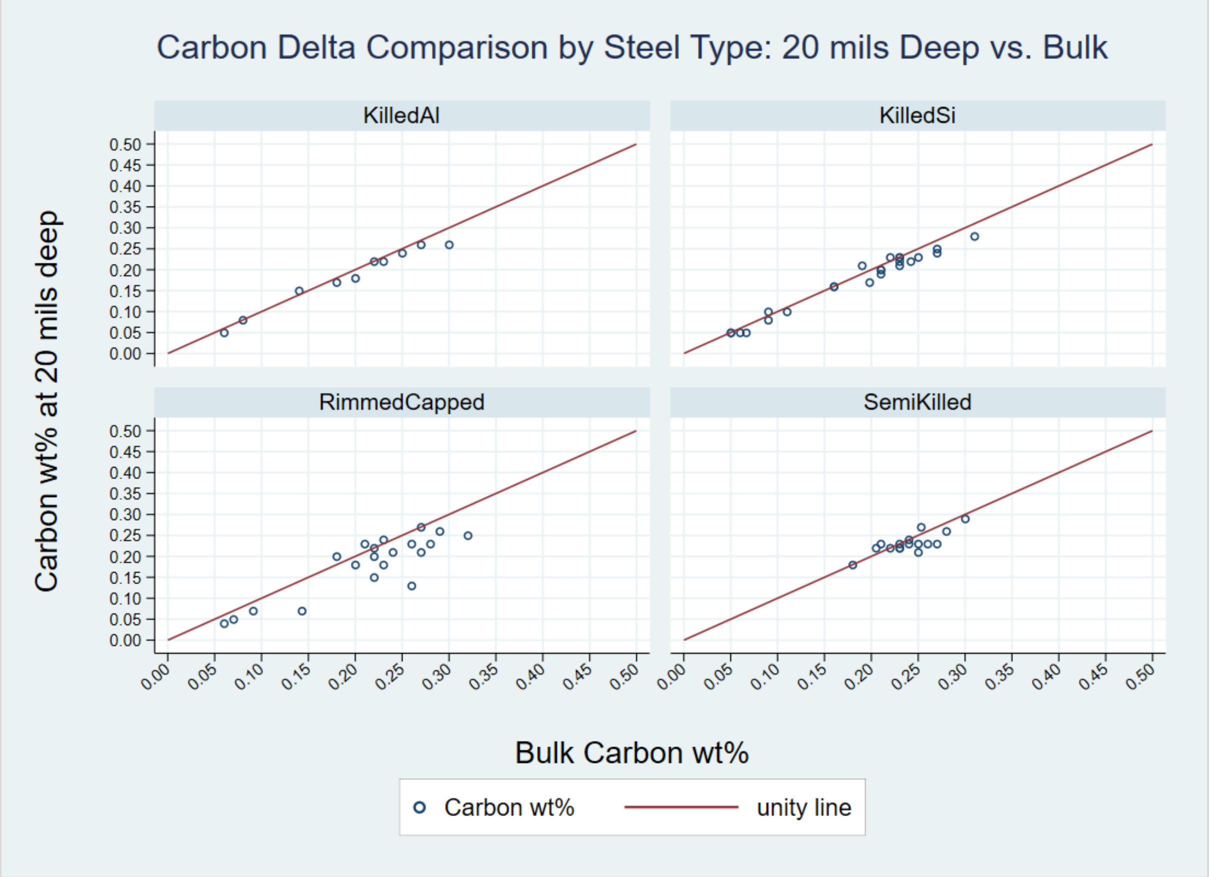


Task 4: Lab vs. NDE Surface Tensile Strength by Multiple Factors



Task 4: Carbon Percent as a Function of Depth and Steel Type





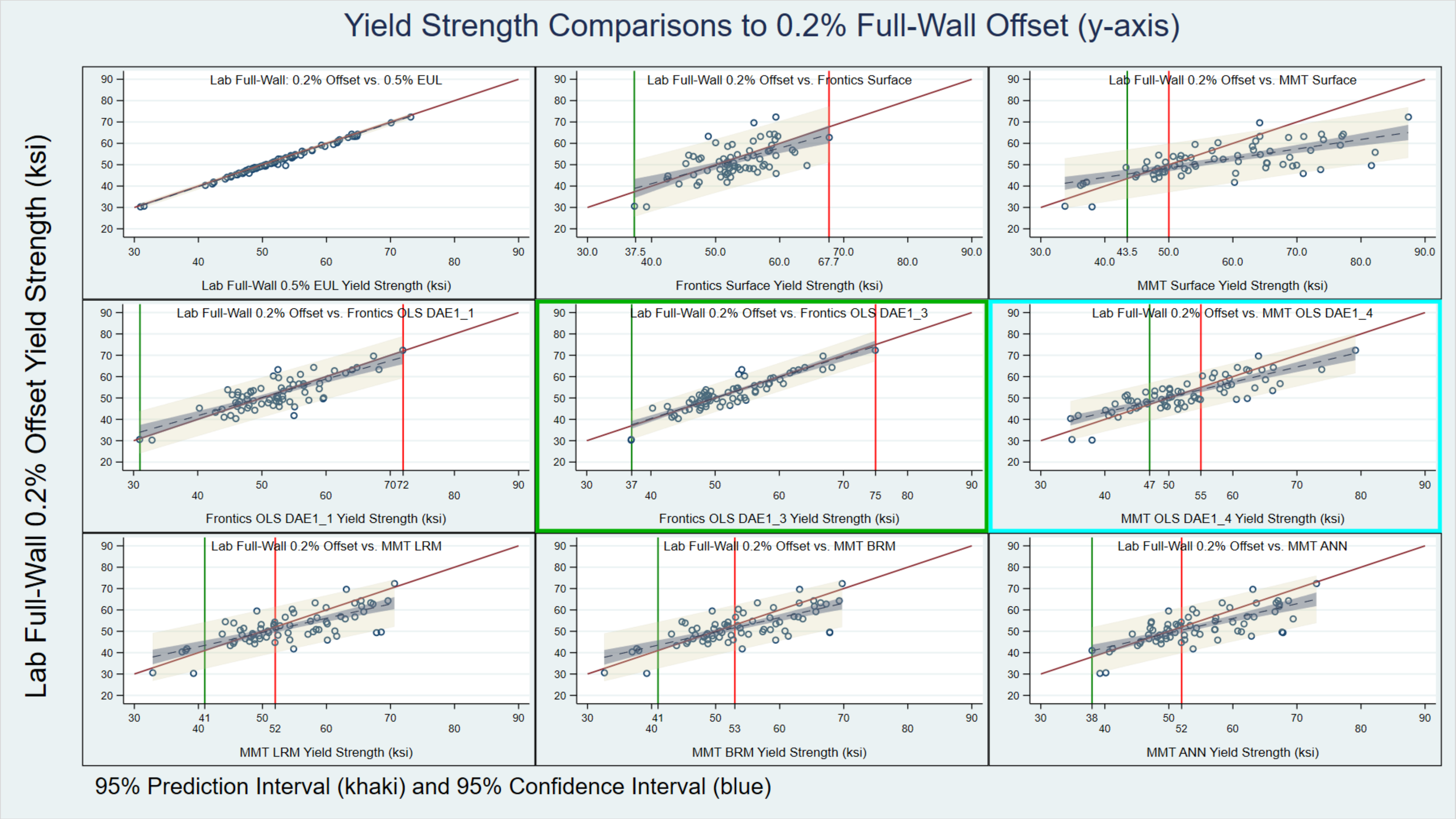
Task 4: Modeling Nomenclature

1. LRM: Linear Regression Model; surface-to-bulk
2. OLS: Ordinary Least Squares; surface-to-bulk
3. BRM: Bayesian Regression Model; surface-to-bulk
4. ANN: Artificial Neural Network; surface-to-bulk
5. OLS (DAE): Ordinary Least Squares models based on causal relationships
6. Historic: various models from the historic literature-based model fits of surface-to-bulk relations
7. Surface: raw surface yield strength values (no model applied) from NDE technology
8. 0.2% Offset: lab testing of tensile bars using the 0.2% offset method for yield strength
9. 0.5% EUL: lab testing tensile bars using the 0.5% elongation under load method for yield strength

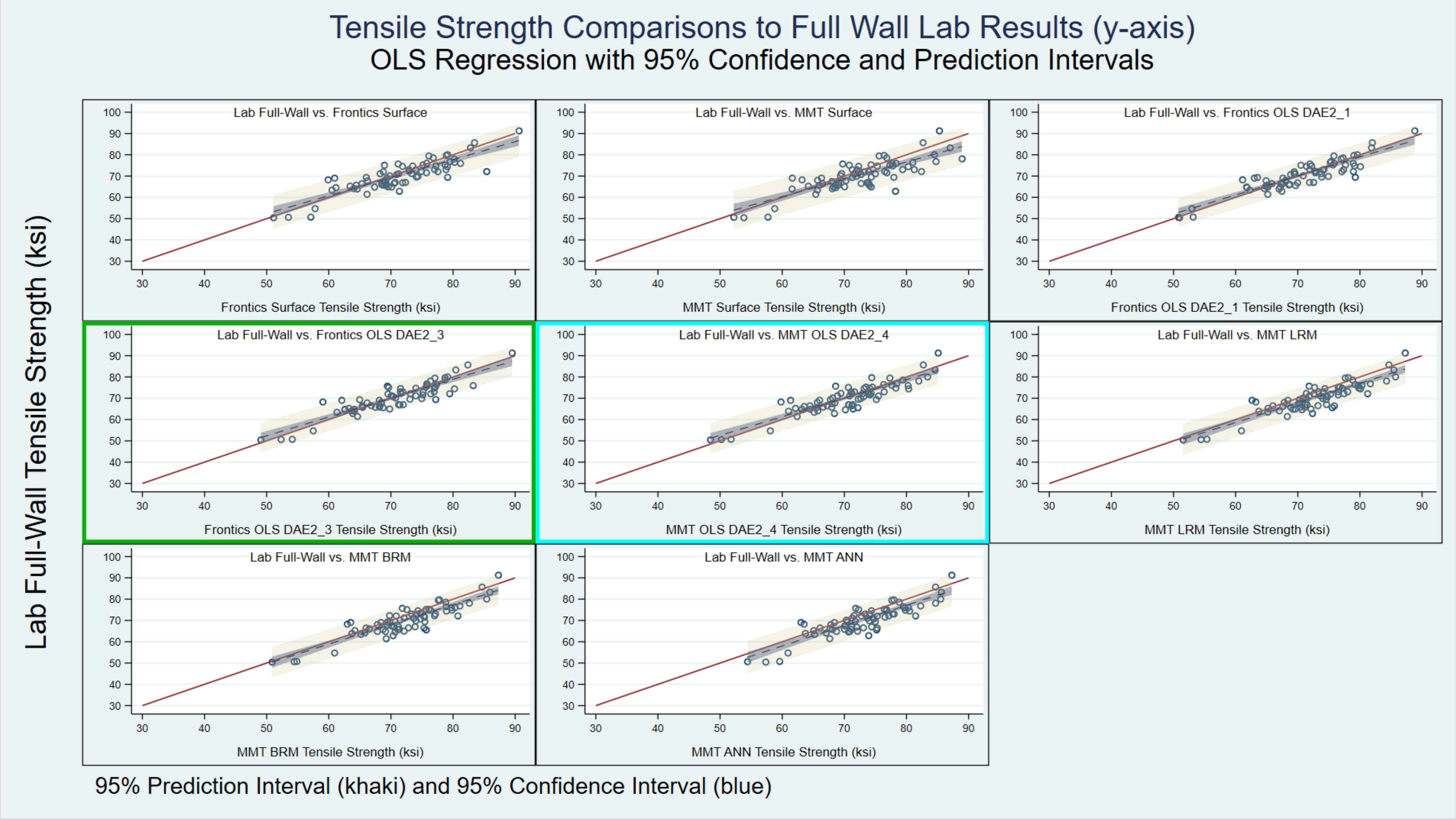
Task 4: Modeling – Causal Modeling for Yield and Tensile Strength

- Best performing causal models surface-derived independent terms listed below.
- Some of these are interrelated with other terms or themselves; see final report.
- The terms with (*) were added to the MMT causal model since they were statistically significant variables for that technology and improved the model predictions.
- Red variables are the only terms in the ultimate tensile strength causal models.
  - Steel type (categorical)
  - HSLA or not (categorical)*
  - Seamless or not (categorical)*
  - Diameter
  - Carbon
  - Manganese
  - Silicon
  - Copper
  - Phosphorous
  - Nitrogen
  - Niobium
  - Percent pearlite
  - Percent ferrite
  - Grain diameter

Task 4: Modeling - Yield Strength for Lab, Surface, and Top Models with OLS CI & PI



Task 4: Modeling - Tensile Strength for Lab, Surface, and Top Models with OLS CI & PI

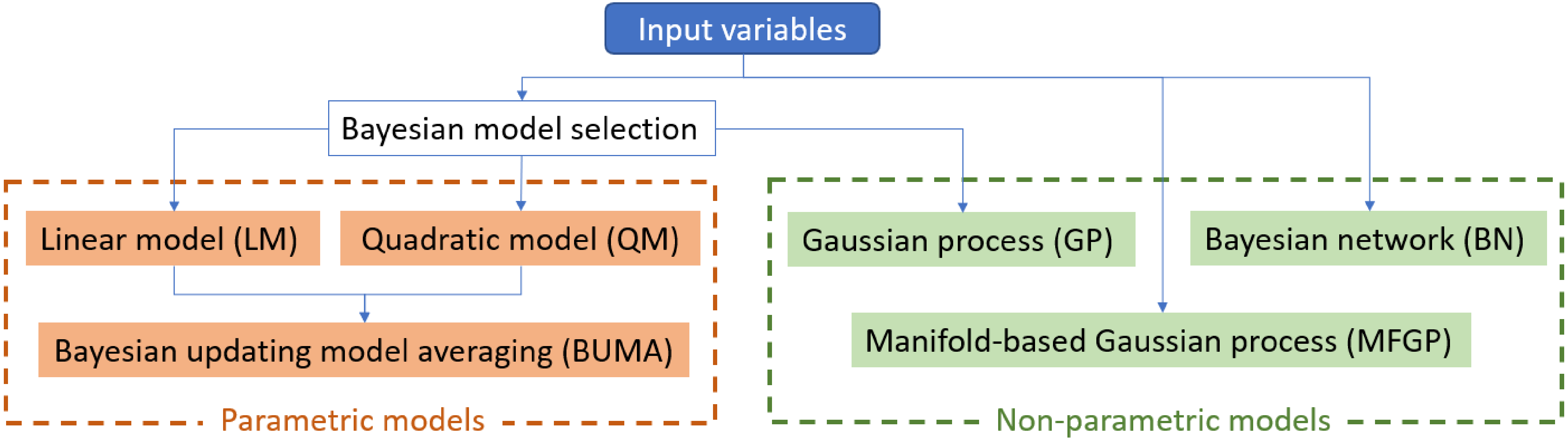


Task 4: Modeling – ASU Advanced Data Analytics Modeling Methodology

- **Problem formulation**
  - **Input variables**: surface chemical compositions, pipe overview data, hardness and grain size.
  - **Output response**: $\Delta = YS_t - YS_s$
  - **Predictive mean**: $\widehat{YS} = \hat{\Delta} + YS_s$
  - **Predictive performance**: $\text{err} = \widehat{YS} - YS_t$

YS_t is the yield strength evaluated from a 1-inch, full-wall longitudinal sample which can be seen as the benchmark of prediction

YS_s is the yield strength estimated using surface indentation techniques



Task 4: Modeling – ASU Advanced Data Analytics Modeling Results

- **Yield Strength Prediction**
  - For yield strength estimation, the quadratic model ASU_F_QM1_YS is the best with the smallest RMSE followed by the Bayesian updating averaged model ASU_F_BUMA_YS and ASU_F_QM2_YS.

Table 1. Summary of prediction performance (YS)

	AvgRMSE.Delta	AvgRMSE.YS
ASU_F_LM1_YS	4.2444	4.1732
ASU_F_LM2_YS	4.3273	4.2911
ASU_F_QM1_YS	3.8648	3.8192
ASU_F_QM2_YS	3.6333	3.5914
ASU_F_BUMA_YS	3.6463	3.6766
ASU_F_BN1_YS	4.2809	4.2802
ASU_F_BN2_YS	4.3181	4.3176
ASU_F_GP_YS	6.3216	6.3220
ASU_F_MFGP_YS	6.12	6.12

- **Ultimate Strength Prediction**
  - For ultimate strength estimation, the best model is the quadratic model ASU_F_QM1_UTS followed by ASU_F_QM2_UTS and the Bayesian updating averaged model ASU_F_BUMA_UTS.

Table 2. Summary of prediction performance (UTS)

	AvgRMSE.Delta	AvgRMSE.UTS
ASU_F_LM1_UTS	3.3592	3.3593
ASU_F_LM2_UTS	3.4261	3.4262
ASU_F_QM1_UTS	3.2585	3.2587
ASU_F_QM2_UTS	3.2760	3.2763
ASU_F_BUMA_UTS	3.2864	3.3393
ASU_F_BN1_UTS	3.3731	3.3729
ASU_F_BN2_UTS	3.3576	3.3577
ASU_F_GP_UTS	3.8250	3.8254
ASU_F_MFGP_UTS	6.6700	6.6700

Task 4: Modeling – ASU Advanced Data Analytics Modeling Summary

By using data-driven approaches, both parametric and non-parametric models are developed for yield strength and ultimate strength prediction. The performance of proposed models are evaluated by full-data regression analysis and cross-validation as well.

- **Quadratic models** (QM) with linear terms, power terms and interactive terms **overperform pure linear models** (LM).
- **Bayesian updating model averaging** (BUMA) that integrates uncertainties during the modeling process is very close to the best because of its guaranteed **robustness and reliability**. In addition, BUMA can **effectively narrow down the range of residues**.
- The performance of automated leaning Bayesian network is similar with linear model, and its predictive accuracy depends on whether the input continuous variables are normally distributed.
- The relatively poor prediction performance of Gaussian process (GP) model and manifold-based Gaussian process (MFGP) model could be caused by the randomness of delta terms and the limited data size.

Conclusions and Final Report Knowledge Transfer - Overview

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 including causal-based OLS and data analytics-based modeling. **Successful models for yield strength and ultimate tensile strength were developed to predict these bulk properties from purely surface obtained information.**
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*.

Conclusions and Final Report Knowledge Transfer - Overview

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 Design of Experiments (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 prove invaluable to future NDE technology development aimed at estimating pipe toughness through surface nondestructive testing.

Outcomes and Recommended Next Steps

1. This project provides results that will benefit current and future NDE technical service providers. The project objectively provides understanding of the variance of material properties between outer surfaces of the pipe wall and the bulk as a function of steel type, seamless, and weld types.
2. This approach maximizes the possibility of the technically sound use of nondestructive surface testing as accurate, efficient, and cost-effective tools for material property confirmation of the service pipelines.
3. The Frontics AIS technology 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.
4. For technologies that exhibit sensitivity towards non-seamless pipe, which have variation of yield strength across the pipe thickness cross section, then further research might help reduce bias in the full-wall yield strength predictions.
5. 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 those tested in this project. These technologies further achieved a 95% confidence for predicting tensile strength across the entire pipe sample DOE, seamless or non-seamless.

Project Public Page
Where Final Report and This Presentation Are Posted

https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=729

Further Questions?

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