MEMORANDUM

Date: April 21, 2020

From: Carl Bundschuh, P.E., Randy Parks, P.E., and Konnor Bursaw, P.E. - Dewberry Engineers Inc.

Subject: p-CAT™ Pipe Wall Thickness Verification using High Resolution Eddy Current Testing

This technical memorandum (TM) presents Dewberry's findings for the validity of Hydromax USA's p-CAT™ analysis. This TM consists of the following sections.

- 1.0 – Background and Purpose
- 2.0 - Methodology
- 3.0 - Results
- 4.0 - Conclusions

The following appendices are attached to this TM.

- Appendix A – Hydromax USA p-CAT™ Report and Visual Summary
- Appendix B – JanX INCOTEST Report
- Appendix C – Soil Sample Results
- Appendix D – Pipe Photos
- Appendix E – Original 1955 Record Drawings

1.0 BACKGROUND

The City of Louisville owns a steel 16-inch diameter raw water pipeline that was installed in 1955, assumed to be 0.25-inch thick with a coal tar lining and coating. The City is replacing a small section of this pipeline to facilitate the installation of a valve vault. Because there have been issues with this pipeline in the past, the City has decided to take this opportunity to evaluate a new non-invasive pipeline assessment tool called p-CAT™. The p-CAT™ Pipeline Condition Assessment Technology used by Hydromax USA (HUSA) is a noninvasive, non-destructive pipeline condition assessment tool. The tool can be used as a screening tool to locate areas of reduced pipe wall thickness over thousands of feet of pipe. The technology was developed in Australia and has been used and validated overseas extensively, however, this is the first validation study undertaken in the United States since its introduction to the US market in 2017.

HUSA performed an assessment on 2.65 miles of the 16-inch diameter pipeline and prepared a report of their findings for the City of Louisville in 2018. Dewberry's purpose in preparing this report is to assess the validity and accuracy of the p-CAT™ assessment tool by comparing HUSA's report to the actual condition of the pipeline.

2.0 METHODOLOGY

The methodologies used to assess the p-CAT™ results required excavating the pipeline, inspecting the pipe for the presence of corrosion or pipe distress, and performing wall thickness measurements over a 40 ft segment. These results were then compared to the p-CAT™ results over the section tested.

The City of Louisville planned to install a valve vault in a section of the pipeline with the portion that HUSA p-CAT™ analysis was performed. To coincide with other construction activities being performed on the pipeline by the City of Louisville, the section of pipeline planned to be removed for the vault installation was selected to be assessed for comparison to the p-CAT™ results.

The location of this section can be seen in the figure below, adjacent to Marshall Road. Dewberry performed an external visual inspection of the pipeline and coating and took soil samples for corrosivity analysis. Dewberry performed spot pipe wall thickness readings with an Ultrasonic Thickness Gauge and oversaw the INCOTEST wall thickness measurements performed by JanX over the entire in-situ selected pipe segment. The 40-foot pipe segment was later cut into several sections, and relocated to the City of Louisville water Treatment Facility for further analysis and internal inspection.

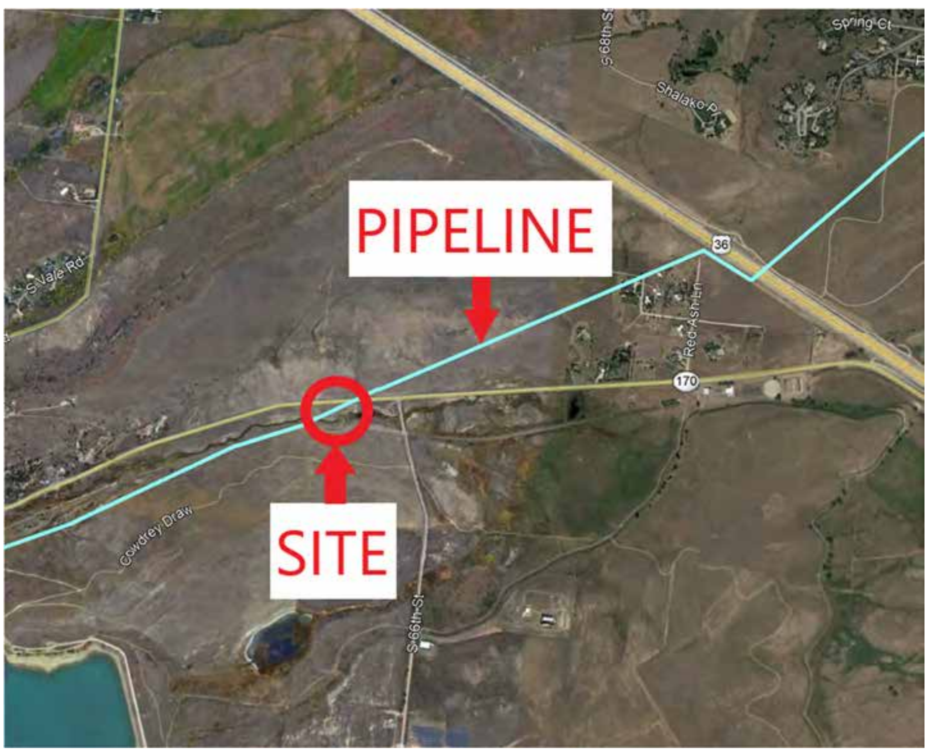

Figure 1 – Site Location

2.1 Site Observations

The 16-inch diameter raw water pipeline runs from west of Highway 93 to a water treatment facility located in Louisville, CO. At the site of the excavation, the pipeline parallels a small creek or drainage and crosses Marshall Road to the northeast. Soils adjacent to the pipe were dry, sandy-clay soils. Three soil samples were taken along the trench at the pipe elevation and a soil corrosivity analysis performed. Results of the test ranged from mildly corrosive to corrosive as found. When saturated, the soils ranged from moderately corrosive to very corrosive. The results of the soil analysis are presented in Appendix C.

Figure 2 – Excavation Site

2.2 Pipe Observations

The pipe was installed in 1955 and is constructed of individual pipe segments 40-foot long, connected to the adjacent pipes with a dresser coupling. Each 40-foot stick of pipe is comprised of four 10-foot sections of 'can' pipe (flat plates, rolled into cylinders and longitudinally welded) which are then butt-welded together to form a 40-foot stick. Each individual pipe stick has a bonding wire cad welded to the adjacent pipe. The City of Louisville notes that this pipeline is protected by discrete sacrificial anodes; however, no buried anodes were present at the excavation site and none are shown on the original drawings.

The lining and coatings are both coal tar enamel. The coating was tested by the City of Louisville for the presence of asbestos and the results indicate no asbestos binders were used. The coating was intact around the circumference, with significant variation of coating thickness. The pipe showed very little external corrosion with only very minor surface corrosion under the pipe and around the coupling.

Figure 3 – Pipe and Coupling Conditions

Figure 4 – Pipe Coating Conditions

In several locations, the coating was removed with a hammer to observe how well bonded the coating was, look for coating disbondment, and observe the presence of corrosion. The coating appeared to be well bonded to the pipe, with no visible corrosion observed in any of the locations coating was removed.

Figure 5 & 6 – Outer Coating Removal to Check Bonding (orange color is from paint)

The interior of the pipeline is coal tar enamel lined and is free from disbondment, pitting, rusting, or any signs of visible corrosion. The lining itself has no apparent spalling or cracking. The pipeline was cut into two pieces for removal and transportation from the project site to the City's Water Treatment Facility for further analysis. Sectioning the pipe in two places allowed Dewberry to observe the condition of the pipe interior at four locations. All interior pipe observation indicated an intact, well bonded lining with no visible interior corrosion.

Figure 7 – Interior of Pipeline

The lining was removed with a hammer in a few places to observe how well bonded the lining appeared, look for lining disbondment, and observe the presence of any corrosion. The lining appeared to be well bonded to the pipe, with no visible corrosion observed in any of the locations the coating was removed.

Figure 8 – Interior Coating Removal to Check Bonding

2.3 p-CAT™ – Hydromax USA

The p-CAT™ investigation works by inducing a small hydraulic pressure transient event in the pipeline. This pressure event is created by installing a spring loaded valve assembly known as the transient generator station to an existing 2-inch corporation stop location (e.g. ARV manhole). A small amount of water is released for a short period of time; the water is then quickly stopped by closing the spring loaded valve to produce a controlled pressure event of no more than 8 psi. The associated changes in pressure along the pipeline are then measured with two pressure transducers located at separate locations along the pipeline spanning up to 3,200 feet in either direction from the transient generator station. The pressure event is simulated several times for one test location with, in this project, seven different testing locations.

In a lined metallic pipe, the measured pressure transient is directly related to the remaining wall strength of the pipe. In addition wall degradation can be calculated based on the original pipe specifications. This thickness is a combination of the assumed coating thickness and remaining pipeline thickness, as both affect the pressure wave speed.

Figure 9 – Hydraulic Transient Induction Point (Transient Generator Station)

p-CAT™ evaluates long stretches of pipe between features up to a mile or more per test covering multiple miles per day. Providing sub-sectional analysis of pipe wall thicknesses over approximately 30 foot sections of pipe, where each section represents a change in the transient wave speed. . As a medium to high resolution non-invasive pipe condition assessment tool p-CAT™ has the ability to identify pipe wall degradation down to 0.0078 inches as stated by HydromaxUSA. Localized points of degradation that are less than 0.0078 inches will not be reported unless they impact the overall sub-sectional results.

2.4 Ultrasonic Thickness Gauge (UTG)

Dewberry performed spot UT (Ultrasonic Thickness) checks over multiple locations on the pipe using an ultrasonic thickness gauge (UTG). A UTG uses a single-point probe to produce ultrasonic waves on an exposed pipeline. The equipment relates the reflected waves' return speed to a pipe thickness, which also depends on the material of the pipe. A UTG must be used on bare pipe, or the coating or lining must be removed where measurements are taken because the wave speeds would vary in between the coating and steel pipe, or the wave would be refracted and affect the readings.

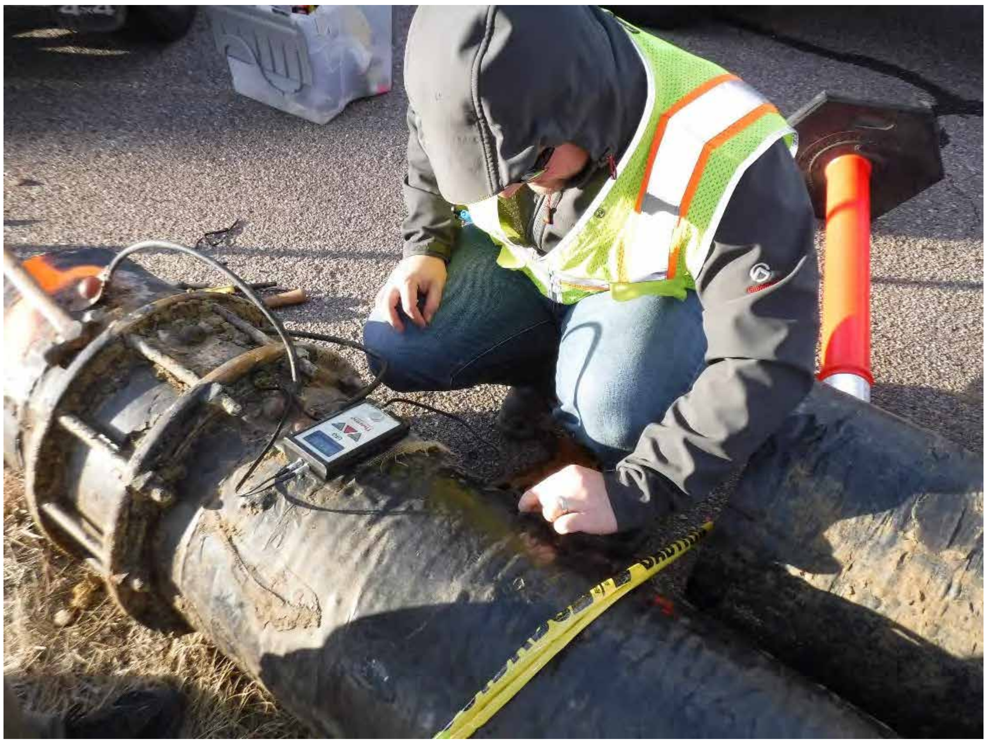

Figure 10 – UTG Equipment

2.5 Eddy Current Testing - INCOTEST (JanX)

During the development of the project approach, it was unknown if the coating contained asbestos. Dewberry selected the INCOTEST method of testing because coatings do not need to be removed in order to determine the wall thickness assessment. The INCOTEST assessment would not have required the safety precautions associated with handling asbestos laden material, or the labor involved with removal of the coating. However, material testing performed during the project determined that there was no asbestos present in the coating.

The INCOTEST (INsulated COmponent TEST) is the trademarked name given to JanX's adaption of an Eddy Current Test. The investigation works by running a radial configuration of sensors along an exposed pipeline. For this analysis, the INCOTEST was performed on the entire 40-foot section of exposed pipeline prior to removal from the site. The sensors measure an induced magnetic current that can be related to pipe thickness. Preliminary measurements are taken with a UT meter at a number of locations, and the INCOTEST machine calibrated to this wall thickness in the same location. The INCOTEST machine can then be slowly moved along the pipeline and the wall thickness measurements captured.

The individual sensors used in this test are 0.6 inches in diameter and evenly spaced at 2.532 inches around the 51.051-inch pipe circumference. The radial apparatus took readings every 0.941 inches along the entire length of the 40-foot section of pipeline. The measurements are accurate to within 5 percent of the pipeline thickness and can be performed on cross-sections ranging in thickness from 0.118 inches to 2.560 inches. The result is an array of nearly 10,000 data points of pipe thicknesses measurements at discrete locations along the pipe, depicted in the adjacent figure.

Figure 11 – INCOTEST Equipment

Unlike the p-CAT™ analysis, the INCOTEST can only be performed on limited sections of pipeline. The excavation cost and effort associated with the INCOTEST is often prohibitive in pipeline inspections. In this case, the INCOTEST was only performed on the section of pipeline removed for study.

3.0 RESULTS

3.1 p-CAT™ Results

The p-CAT™ investigation was performed on the entire 2.65 miles of pipeline on September 4th and 5th, 2018. The section of pipe which was assessed for comparison to the p-CAT™ test is located between Anomaly D and Anomaly E shown in Figure 12.

The results of the p-CAT™ test determined varying levels of pipe deterioration had occurred on the Louisville Raw Water pipeline based on the varying wave speeds produced along the length of the pipeline as shown in Figure 12.

The 1955 record drawings for the pipeline do not indicate the original wall thickness of the pipeline, and no original specifications were available. As a result, The City of Louisville Colorado initially assumed that the pipeline may be schedule 40, 20 or 10 pipe, given the pipe age and diameter. For analysis, The City of Louisville Colorado and HUSA agreed to assume the original pipe to be schedule 10 steel pipe with a wall thickness of 0.25-inch and a 0.13-inch tar lining for the wall loss assessment. The lining was assumed to have half the strength of standard cement mortar lining for correlating wave speed to wall thickness in the analysis. HUSA's baseline pipe wall section thickness and lining properties are listed in Table 1 below. These measurements were used as the theoretical original pipeline physical properties for determining the remaining estimated wall thickness in the p-CAT™ analysis. The p-CAT™ analysis can be re-simulated to provide updated results in cases where updated information regarding pipe specifications becomes available post assessment.

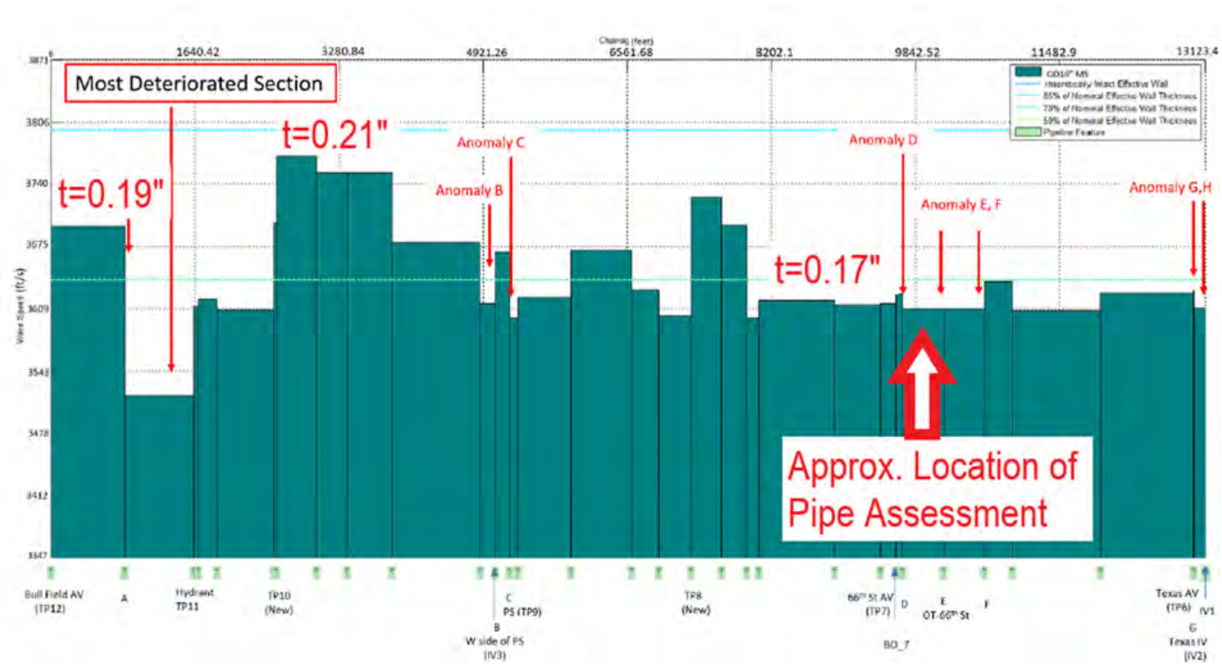

Figure 12 – Wave Speed Variation Along the Pipeline

Figure from City of Louisville p-CAT™ pipeline Condition Assessment, included as Appendix A. Figure 12 assumes external corrosion with corresponding remaining wall thicknesses in inches indicated in red (example t=X.XX").

Table 1 – p-CAT™ Assessment Pipeline Assumptions

Outside Pipe Diameter	16 inches
Assumed Original Wall Thickness	0.25 inches
Coal Tar Lining	0.13 inches
Total Equivalent Wall Thickness	0.27 inches

With a preliminary material, assumed original wall thickness, and lining selected, the estimated wall thickness at various locations along the pipeline can be determined through the wave speed at various locations along the alignment. Differences between the theoretical wall thickness and estimated wall thickness are assumed to be wall losses due to internal or external corrosion.

The corresponding thicknesses along the entire 2.65-mile pipeline ranges from 0.15 inches to 0.21 inches with the median thickness being 0.17 inches. The p-CAT™ results are presented in Table 2 below.

Table 2 – p-CAT™ Results

Overall Pipeline Thickness Range (over 2.65 miles)	0.15-0.21 inches
Pipeline Thickness at Pipe Assessment Location	0.17 inches

The p-CAT™ report identifies the thickness for the section of interest (between Anomaly D and E) of pipeline to be 0.17 inches. This corresponds to 32 percent wall loss from the assumed original wall thickness of 0.25 inches. Percent degradation is based on client-provided information on original pipe wall thickness.

3.2 Ultrasonic Thickness Measurements Results

The UTG measurements were performed to verify the INCOTEST results. These measurements were performed intermittently along the pipeline, at crown, springline and invert. The thickness measurements ranged from 0.179 inches to 0.190 inches and are accurate to within ±0.004 inches.

Figure 13 – UTG Testing

The UTG readings loosely correlate with the INCOTEST readings, varying an average of 0.008 inches. Additionally, comparing the UTG and INCOTEST results, the readings are not consistently different as the differences vary between 0.002 inches and 0.023 inches. The UTG readings do, however, confirm the pipeline thickness to be approximately in the range measured by the INCOTEST.

3.3 Eddy Current Testing - INCOTEST (JanX) Results

The INCOTEST was performed to verify the results of the p-CAT™ readings. The radial apparatus took readings every 0.941 inches along the entire length of the 40-foot section of pipeline.

The individual readings varied from 0.141 inches to 0.191 inches with recognizable patterns in thickness differences; see Table 3 for a summary of the readings. Plotting the thickness, it is evident that there are four individual pipes welded together and each pipe as a different average thickness that varies from 0.167 inches to 0.175 inches. Additionally, there appear to be seams in the pipe sections that have reduced wall thickness. These pipe thickness differences are depicted in Figure 14 on the following page with red/yellow as thinner pipe and blue as thicker pipe.

The average wall thickness for the entire 38-foot length of the JanX test is 0.171 inches (a foot on each end was removed to eliminate end effects from the eddy currents at the end of the pipeline). Narrowing the limits to shorter lengths of pipe creates variance for average wall thickness that depends on the section of pipe included in those limits. For example, analyzing a 30-foot length of pipe yields an average wall thickness from 0.171 inches to 0.173 inches, depending on the continuous 30-foot length being averaged.

Table 3 – INCOTEST Wall Thickness Readings

Minimum Thickness	0.141 inches
Maximum Thickness	0.191 inches
Average Thickness over 38 feet	0.171 inches
Average Thicknesses over 30 feet	0.171-0.173 inches

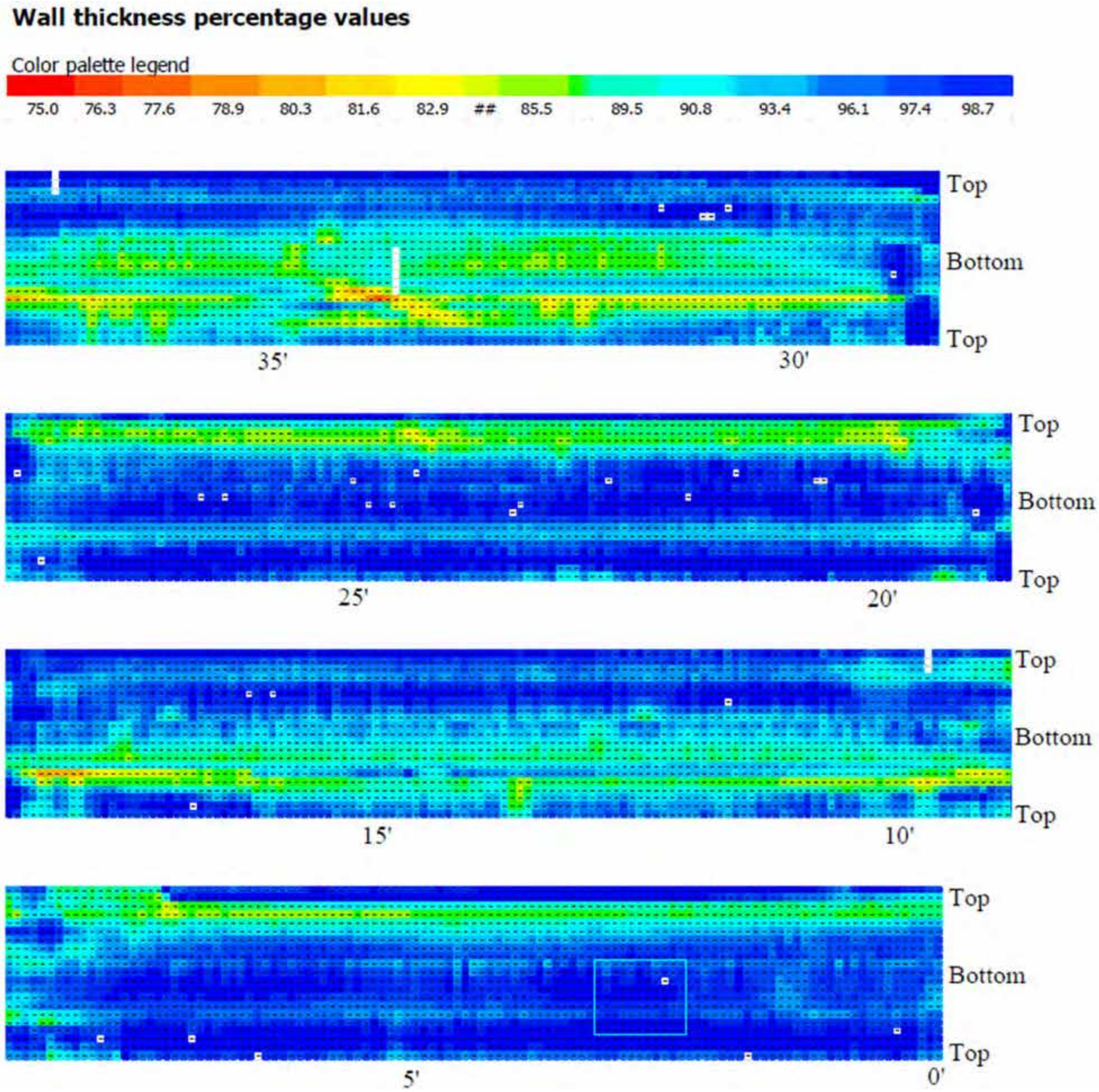

Figure 14 – Four Pipe Sections' Relative Thicknesses, Graphically Separated at the Welded Joints

4.0 CONCLUSIONS

4.1 Pipe Wall Measurement Results

The INCOTEST, spot ultrasonic thickness test measurements and the Hydromax USA p-CAT™ analysis all found the average thickness of the removed pipe to be approximately 0.17 inches, summarized in Table 4 on the next page. Hydromax USA p-CAT™ accurately measured the average wall thickness of pipe being investigated in this study at this location. Confirmation of the p-CAT™ analysis at a second location which could provide access to the pipe was attempted to further compare the results. This alternate location was an air-vacuum valve vault which p-CAT™ indicated a 0.19-inch wall thickness, however, the ground within the vault proved too difficult to expose the pipe with hand tools.

Table 4 – Thickness Reading Comparison

Testing Method	Average Thickness Reading
INCOTEST – Eddy Current Test	0.171 inches
p-CAT™	0.17 inches

4.2 Percentage of Wall Degradation Results

The results of the p-CAT™ analysis reported this section of pipe as deteriorated based on the difference of apparent pipe wall thickness along the entire reach. While the p-CAT™ measurement of wall thickness is accurate, the wall degradation calculated is inaccurate based on provided or assumed preliminary pipe class. Wall degradation is dependent on the assumed original pipe wall thickness and it's consistency along the pipe. Visual inspection of the pipeline showed that this pipe is in good condition, with intact linings and coatings. The original pipeline assumed thickness used to calculate percent of wall degradation was found to be incorrect and as a result p-CAT™ overstates the pipeline's percentage deterioration, while still accurately reporting correct wall thickness at this location. The pipeline was likely constructed with a tolerance that allowed varying thicknesses of pipe wall along its entire length, for which the p-CAT™ test can identify and adjust for changes in pipe specification/known wall thickness to properly evaluate percentage of pipe wall degradation between varying pipe sections. The p-CAT™ valuations can be re-evaluated post assessment to update and report findings based on new pipeline specifications/known wall thicknesses as they become apparent.

The pipeline is not in danger of failing with a wall thickness of 0.17 inches. Dewberry calculated the minimum required wall thickness for internal pressure for this pipeline to be 0.08 inches, based on an assumed steel allowable stress of 15ksi (assuming half stress design) and a pipeline design pressure of 150psi.

4.3 Qualifiers

Although this study validated that Hydromax USA's p-CAT™ accurately measured the pipeline thickness at our location of interest, testing only one section of pipe limits the conclusions that can be drawn from the results. Multiple sections of pipe with different thickness and types of deterioration would need to be excavated and evaluated in order to further validate the p-CAT™ report.

APPENDIX A

Hydromax p-CAT Report and Visual Summary

Louisville Raw Water line

2.65miles of OD 16-inch Tar Lined Steel Pipe
Louisville, Colorado, USA

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Contractor	Detection Services Pty Ltd, Hydromax USA and the City of Louisville CO.
Circulation list	Detection Services and Hydromax USA (HUSA) and the City of Louisville CO. (CoLC)
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Executive Summary

The following report details the p-CAT™ testing and findings of the Louisville Raw Water line in the City of Louisville, Colorado, USA conducted by Detection Services (DS) and Hydromax USA (HUSA). The condition assessment of the pipeline of interest was completed for Hydromax USA on the behalf of the City of Louisville, Colorado (CoLC).

The tests were conducted on the 4th and 5th of September 2018 by DS and HUSA. The purpose of this survey, using p-CAT™ on the selected pipelines, was to assess the existing condition of the pipeline and identify any known and unknown features and other anomalies such as blockages and air pockets.

The pipeline of interest is referred to as the Louisville Raw Water line, and was installed in 1955 from OD 16" Steel. The pipeline of interest is assumed to be 2.65 miles of 16- inch Tar lined Steel Raw water main. The section of pipeline analyzed in this report starts at a Bull Field air valve (TP12), near 1803 S Foothills Highway, and ends at an Inline valve (IV1) at the start of the PVC road crossing.

The analysis undertaken to determine the pipeline wall condition was based on the following assumptions:

- Outside diameter of 16 inch (provided by Hydromax (HUSA) and in accordance with ANSI/ASME B 36.10 and 36.19);
- Wall thickness of 0.25 inch (in accordance with ANSI/ASME B 36.10 and 36.19); and
- Tar lining of 0.13 inch (in accordance with ANSI/ASME B 36.10 and 36.19).

The following pipeline wall condition was identified during the p-CAT™ analysis:

- 73% of the total pipeline length has a remaining wall thickness of between 54 and 70%.
- 27% of the total pipeline length has a remaining wall thickness of between 70 and 80%.

It should be noted that these remaining wall thickness results are determined using assumed initial wall thicknesses and outer diameters as requested by HUSA. Should HUSA obtain further information regarding the initial wall thickness of the pipelines DS will be able to recalculate the percentage remaining wall thickness.

The following known features and anomalies where identified during the signal analysis. The recommended actions are listed below:

- Three medium priority anomalies representing:
  - The presence of an entrained and entrapped air pocket.
  - One known off-take with possible sealing problem or deterioration.
  - One potential concrete encasement or potential blockage.
- Five low priority anomalies representing:
  - Concrete encasement (additional cover) or possible blockage.
  - Known features or possible deterioration or blockages.

It is recommended to investigate the current pipeline properties and configuration, and the presence of possible entrained or entrapped gas before coming to the conclusion that sections are deteriorated. These faults can also affect the accuracy of the p-CAT™ results for both the condition assessment and the anomaly identification.

Section 5 includes a summary and recommendations from the p-CAT™ analysis results. An in-depth visual summary of the obtained results is also provided in a separate document accompanying this report.

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1 Introduction

This report gives details and findings from the non-invasive pipe condition assessment (p-CAT™) of the 16-inch Tar Lined Steel Pipe, known as the Louisville Raw Water line, as shown in Table 1.1 The purpose of this survey using p-CAT™ on the selected pipelines was to assess the existing condition of the pipeline and identify any known/unknown features and other anomalies such as blockages and air pockets.

For the following information regarding this project please refer to the Appendix:

- Appendix A: Glossary of terms
- Appendix B: Pipeline Feature Chainages
- Appendix C: Examples of Selected Pressure Traces
- Appendix D: Test Methodology and Equipment
- Appendix E: Theory of p-CAT™

Table 1.1: Project background for Louisville Raw Water line.

	Pipeline Condition Assessment
Pipe Name	Louisville Raw Water line
Client	Hydromax USA
Test Date	4th and 5th September 2018
Report Date	10th October 2018
Information Provided	Site visits, GIS access, and as-built drawings.
Section of Interest	
Location	The City of Louisville, Colorado, USA
Approx. Length	2.65 miles
Section of Interest	From TP12 (Bull Field AV) to IV1 (PVC Start)
Primary Material	16-inch Tar Lined Steel Pipe
Other Materials	NA

1.1 Non-invasive Pipe Conditional Assessment (p-CAT™)

p-CAT™ uses two main techniques for interpreting the transient pressure wave tests results:

- Sub-Section Partitioned Wave Speed Analysis™ for assessment of the level of deterioration of the pipe wall in a sub-section, and
- Signal Analysis for detection of known features and significant anomalies such as air pockets and blockages.

1.2 Pipeline Configuration

The pipe material, lengths and features of the Louisville Raw Water line and their locations are listed in Table 1.2, and shown in Figure 1.1.

Table 1.2: Louisville Raw Water line material sections (as per provided information).

Location	Approx. Length (miles)	Size (inches)	Material	Year
Between TP12 (Bull Field AV) and IV1 (PVC start)	2.65	16”	Steel	1955

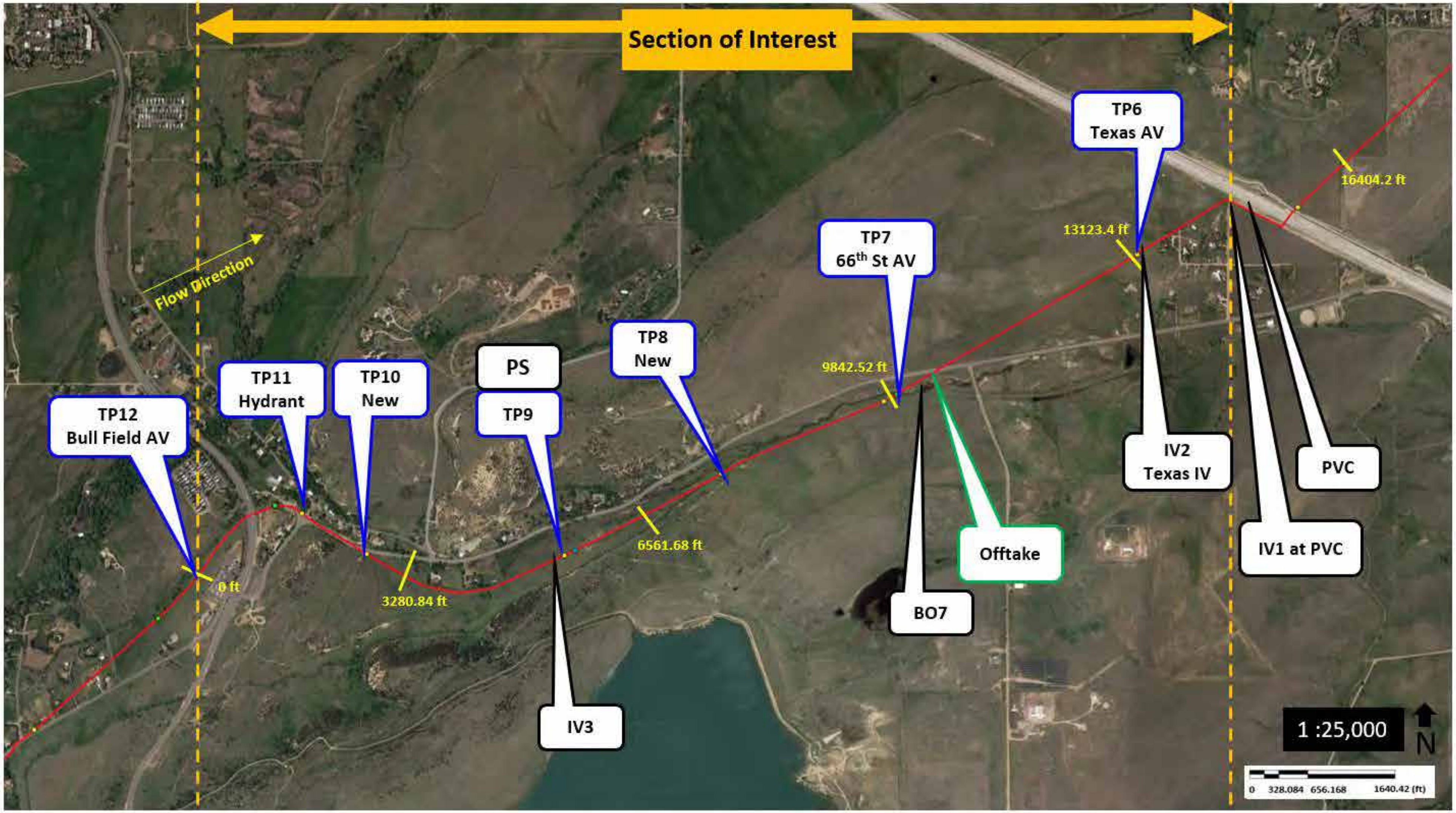


Figure 1.1: 16-inch Tar Lined Steel Pipe, the Louisville Raw Water line section of interest.

2 Tests Conducted

The tests conducted, and the test set up used for each test, are listed in Table 2.1. The locations of the generation points and measurement points are shown in schematic form in Figure 1.1.

The relevant chainages are provided in Appendix B and are used for all the conducted analysis.

Table 2.1: Field test set up.

Day	Test	Station position			Valve Settings
		Generation	Measurement		
1	1	**TP6**	TP7	TP8	IV1 Closed*
	2	**TP6**	TP7	TP8	IV2 Closed*
	3	**TP7**	TP6	TP8	
2	1	**TP8**	TP7	TP9	
	2	**TP10**	TP9	TP12	
	3	**TP11**	TP9	TP12	
	4	**TP12**	TP11	TP10	
Maximum Transient Size					8 psi
Maximum Discharge					88 gal

*Day1_Test1 and the rest of the tests were tested under different valve setting conditions. However, both had the off-take and HYD closed.

Further details on the test equipment and process can be found in Appendix D.

3 Pipeline Properties and Theoretical Wave Speeds

The original pipeline dimensions are required for the p-CAT™ analysis in order to provide an accurate estimate of the current pipe wall condition. This is carried out by comparing the theoretical intact wave speed against the wave speeds measured during testing.

3.1 Intact Theoretical Pipeline Properties

Assumed pipeline properties are taken from as-built drawings issued by the client and the standard ANSI/ASME B 36.10 and 36.19 to determine the theoretical wave speeds and pipeline conditions for deterioration calculations. These initial properties show the pipe in its intact condition and are summarized below in Table 3.1 and Table 3.2.

The method of determining this intact pipeline state is explored in Appendices D and E.

Dimensions of the pipeline were provided to DS by HUSA. The properties of the tar lined steel pipeline, which is the section of interest, are not confirmed. While HUSA intimated that the pipeline properties may be 0.25-inch steel pipe with 0.13-inch tar lining and that Schedules 40, 20 or 10 may be applicable, they have agreed that the schedule 20 or 10 should be used for this analysis. However, there was no information about the exact properties of this section of interest.

No information for the strength of the tar lining could be found with the required specifications at this time, regarding a 0.25-inch steel pipe with 0.13-inch tar lining. **For the purpose of this analysis the section of interest is assumed to be Schedule 10 with the lining assumed to have half the strength of standard cement mortar lining.** These provided measurements were used as assumed the physical properties in the p-CAT™ analysis.

Should the client obtain further information regarding the initial pipeline properties of the section of interest, DS will be able to recalculate the results and including the remaining wall thickness.

Table 3.1: Physical properties of the Louisville Raw Water line.

Assumed physical properties			16-inch Tar Lined Steel Pipe
Outside diameter	(OD)	Inch	16
Wall thickness	(e_W)[1]	Inch	0.25
Tar lining thickness	(e_C)[2]	Inch	0.13
Total equivalent wall thickness	(e_{eq})[3]	Inch	0.27

[1] The subscript W indicates the metallic wall thickness.

[2] The subscript C indicates the thickness of the tar lining.

[3] The subscript eq indicates the equivalent wall thickness of the pipe. Refer to Appendix E1 for the adopted method of calculating total equivalent wall thickness.

Table 3.2: Material properties of the Louisville Raw Water line.

Material properties			16-inch Tar Lined Steel Pipe
Young's modulus of Steel Pipe	(E_M)	M PSI	30.1
Poisson's ratio of Steel Pipe	(μ_M)		0.3
Young's modulus of Cement Mortar lining	(E_C)	M PSI	1.81
Poisson's ratio of Cement Mortar lining	(μ_C)		0.2

The Young's modulus for steel used in this analysis was chosen as a general approximation of the various Young's Modulus that are found in pipes with a large range in age and method of production.

3.2 Theoretical Deterioration from Intact Pipeline

Using the above-mentioned intact pipeline properties, the theoretical wave speeds can be determined for various equivalent wall thicknesses in the pipe. The total equivalent wall thickness is the combined thickness of the actual metallic wall thickness and the lining thickness in terms of metallic wall. For instance, 0.47 inch of cement mortar lining is equivalent to 0.055 inch of mild steel wall.

The total equivalent wall thicknesses determined by p-CAT™ considers the following modes of pipeline deterioration for metallic pipes:

- Internal corrosion, where the structural integrity of the lining is reduced through de-bonding;
- External corrosion, where the structural integrity and the bond of the lining is intact.

A visual depiction of lined metal pipeline deterioration is presented in Figure 3.1.

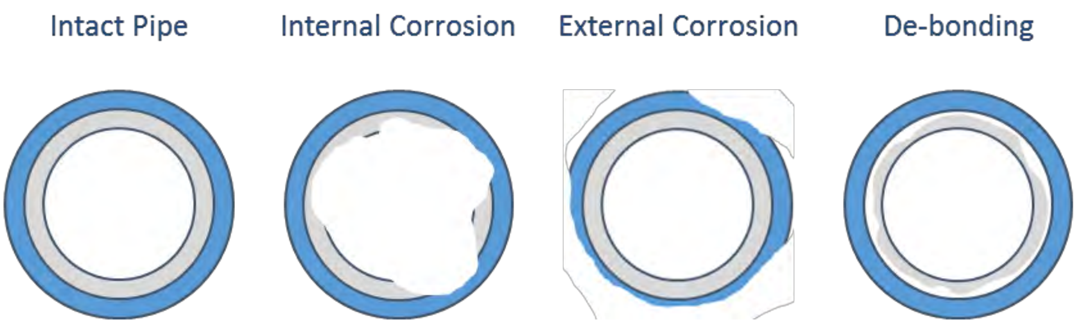


Figure 3.1: Modes of cement lined metal pipeline deterioration;
Intact cement lined metal pipeline, pipeline subjected to internal corrosion, external corrosion, and the de-bonding of the lining.

4 Results

All the information that was provided to DS and HUSA has been verified through site visits and meetings and has been collated. This information was used in the following analysis to determine the known pipeline features (e.g. isolation valves and off-takes) as well as their condition and locations, and the sections of pipeline deterioration.

4.1 Signal Analysis for the Identification of Known Features and Anomalies

Signal analysis for known feature and anomaly identification has been undertaken for the Louisville Raw Water line. The priority terminology used when referring to the anomalies identified in the signal analysis is shown in Table 4.1. Anomalies within the Louisville Raw Water line section of interest have been identified and are listed, along with their interpretation and recommendations, in Table 4.2.

Example of pressure traces, at which known features are identified by p-CAT™ signal analysis is provided in Appendix C.

Table 4.1: Known features and anomaly priority terminology.

Priority	Description	Recommended action required
Low	The detected feature corresponds to known system components based on the collected system information.	No action is required.
Medium	The detected anomaly does not correspond to any known system components.	It is suggested that the client conduct further investigation via records or site visit. A lack of known components (such as a pipe replacement section) in this location may indicate a deteriorated section or fault.
HIGH	The detected anomaly indicates a location of possible future failure; It is potentially interrupting the system serviceability and is vulnerable to bursts and leaks.	It is suggested that action be taken immediately.

For each of the sites, the Sub-Section Partitioned Wave Speed Analysis™ has also been undertaken. The result tables summarize the average deterioration of the pipe wall over determined sub-sections. Note that p-CAT™ is able to provide the total equivalent wall thickness along the length of the pipeline. However, the calculated thicknesses assume a consistent condition across the circumference of the pipe and p-CAT™ is unable to distinguish between internal or external corrosion. Hence the result tables present both deterioration scenarios of external and internal corrosion.

The following known features and anomalies, and their resulting recommended actions were identified during the signal analysis:

- Three medium priority anomalies representing:
  - The presence of an entrained and entrapped air pocket.
  - One known off-take with possible sealing problem or deterioration.
  - One potential concrete encasement or potential blockage.
- Five low priority anomalies representing:
  - Concrete encasement (additional cover) or possible blockage.
  - Known feature IV3 or possible deterioration.
  - TP9 on the By-pass or potential deterioration.
  - Known feature IV2 or potential deterioration or possible blockage.
  - Known feature IV1 on the PVC.

Table 4.2: Summary of the anomalies detected in Louisville Raw Water Pipeline.

Identifier	Approximate location	Interpretation	Priority	Recommended action
A	45ft before the western side of S Foothills Hwy.	Concrete encasement of the road crossing or a possible blockage.	low	Check the pipeline configuration records for material and diameter change. If no change, potential blockage.
B	IV3 west of Pump Station.	Known feature or possible deterioration.	low	Check the pipeline condition and valve condition.
C	TP9 in the Pump Station.	AV Tapping in the PS or possible deterioration	low	Check the pipeline condition and valve condition.
D	Eastern side of ditch, east of BO_7	Possible additional cover or blockage	**Medium**	Investigate the pipeline condition and confirm pipeline material and diameters. If no change, potential blockage.
E	Off-take 66th St	Known off-take, possible sealing problem or deterioration.	**Medium**	Examine the functionality of the valve and determine its sealing status.
F	p-CAT™ Ch.10582.3 ft, 1115.5 ft east of TP7	Possible entrained and entrapped air	**Medium**	Confirm the presence and location of the air valve. Investigate the valve sealing status and pipeline condition and remove the air pocket as it may affect the system performance. There is an increased likelihood of localized internal deterioration at this point.
G	IV2, 9 ft east of TP6	Known feature, or possible deterioration or blockage.	low	None. Known system issue.
H	IV1	Known feature.	low	None. Known system issue.

4.2 Pipeline Wall Deterioration (Sub-sectional Condition)

The following section shows the Sub-Section Partitioned Wave Speed Analysis™ results for the pipeline. Table 4.4 summarizes the deterioration of the pipe wall over determined sub-sections. Note that p-CAT™ is able to provide the total equivalent wall thickness along the length of the pipeline. However, the calculated thicknesses assume a consistent condition across the circumference of the pipe.

The varying levels of deterioration of the Louisville Raw Water line subjected to internal and external corrosion are shown in Figure 4.1 and Figure 4.2 respectively. An in-depth summary that visually presents the results of the remaining wall thicknesses is provided to Hydromax USA in a separate document accompanied with this report.

The method used to determine the deterioration is further explained in Appendix E. The priority terminology used when referring to the anomalies identified in the signal analysis is shown in Table 4.3 below.

Table 4.3: Sub-sectional terminology.

Priority	Remaining Wall
Low	85 -100%
Medium	70 -85%
HIGH	0 -70%
NA	Unable to be analyzed

The following pipeline wall condition was identified during the p-CAT™ analysis:

- 73% of the total pipeline length has a remaining wall thickness of between 54 and 70%.
- 27% of the total pipeline length has a remaining wall thickness of between 70 and 80%.

As discussed in Section 3.1, there was no original information about the exact properties of the steel pipe with tar-lining used in this particular section of interest. Also, there was no information about the strength of the tar lining that could be found at this time.

After consulting with HUSA, **Schedule 10 with a lining of half the strength of cement mortar was decided to be used as the initial pipeline properties**. These theoretical conditions were used during the p-CAT™ analysis but have resulted in high priority conditions for a majority of the pipe. If required, the p-CAT™ analysis team can change the schedule to 10s or 5s which will bring up the proportional percentages. This will not affect the results of the wave speed analysis, those results and the final wall thickness will remain the same only how they compare to a new original wall will change. Thus, If the client obtains further information regarding the initial wall thickness or the exact properties, DS will be able to recalculate the percentage remaining wall thickness.

Table 4.4: Wall deterioration results for Louisville Raw Water line.

Section Identifier	Approx. Chainage (feet)		Sub-section Location on Pipeline	Approx. Length (feet)	Assumed Pipe Material	Theoretical Wall Thickness (inch)		Remaining Effective Wall Thickness[1] (Difference between metal wall or cement mortar lining from the nominal theoretical value) (inch)						Sub-Sectional Average Wave Speed (ft/s)
								Assumed Internal Corrosion[2]			Assumed External Corrosion[3]			
	Start	End				Wall	Lining	Wall	Lining	%Remain	Wall	Lining	%Remain	
S1	0	843	TP12 to Anomaly A (western side of S Foothills Hwy).	843	MS	0.25	0.13	0.19 (-0.1)	0.00 (-0.13)	73%	0.17 (-0.1)	0.13 (0)	68%	3695.4
S2	843	1393	Anomaly A to eastern side of the driveway to 5333 Eldorado Springs Dr.	550	MS	0.25	0.13	0.15 (-0.1)	0.00 (-0.13)	59%	0.13 (-0.1)	0.13 (0)	54%	3518.1
S3	1393	1632	Eastern side of driveway to TP11.	239	MS	0.25	0.13	0.15 (-0.1)	0.00 (-0.13)	59%	0.13 (-0.1)	0.13 (0)	54%	3517.9
S4	1632	1677	TP11 to Intersection with Eldorado Springs Dr and Marshall Dr.	45	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	61%	3610.8
S5	1677	1895	Intersection with Eldorado Springs Dr and Marshall Dr to 5430 Marshall Rd.	219	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	62%	3618.7
S6	1895	2540	5430 Marshall Rd to eastern side of the road crossing at 5444 Marshall Rd.	644	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	65%	0.15 (-0.1)	0.13 (0)	61%	3607.3
S7	2540	2572	5444 Marshall Rd crossing to TP10.	32	MS	0.25	0.13	0.19 (-0.1)	0.00 (-0.13)	73%	0.17 (-0.1)	0.13 (0)	68%	3698.5
S8	2572	3024	TP10 to 452 ft east of TP10.	452	MS	0.25	0.13	0.21 (0)	0.00 (-0.13)	80%	0.19 (-0.1)	0.13 (0)	75%	3770.0
S9	3024	3368	452 ft east of TP10 to the bend (15^{o}) behind 5608 Marshall Rd.	343	MS	0.25	0.13	0.20 (0)	0.00 (-0.13)	78%	0.18 (-0.1)	0.13 (0)	73%	3752.3
S10	3368	3885	Bend 15^{o} to 1313 ft east of TP10.	518	MS	0.25	0.13	0.20 (0)	0.00 (-0.13)	78%	0.18 (-0.1)	0.13 (0)	73%	3752.4
S11	3885	4882	1313 ft east of TP10 to 2310 ft east of TP10 (344ft west of TP9).	997	MS	0.25	0.13	0.18 (-0.1)	0.00 (-0.13)	71%	0.16 (-0.1)	0.13 (0)	67%	3678.4
S12	4882	5065	2310 ft east of TP10 (344 ft west of TP9) to Anomaly B (IV3).	183	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	61%	3613.8
S13	5065	5226	Anomaly B (IV3) to Anomaly C (TP9).	161	MS	0.25	0.13	0.18 (-0.1)	0.00 (-0.13)	70%	0.16 (-0.1)	0.13 (0)	66%	3668.5
S14	5226	5322	Anomaly C (TP9) to 96 ft east of TP9 (p-CAT™ Ch.5321.7 ft).	96	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	65%	0.15 (-0.1)	0.13 (0)	60%	3599.3
S15	5322	5923	96 ft east of TP9 (p-CAT™ Ch.5321.7 ft) to 697 ft east of TP9.	601	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	62%	3620.3
S16	5923	6612	697 ft east of TP9 to 677 ft west of TP8 (1386 ft east of TP9).	689	MS	0.25	0.13	0.18 (-0.1)	0.00 (-0.13)	71%	0.16 (-0.1)	0.13 (0)	66%	3670.0
S17	6612	6920	677 ft west of TP8 to 369 ft west of TP8 (1694 ft east of TP9).	308	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	67%	0.15 (-0.1)	0.13 (0)	62%	3628.2

Table 4.4 continued

Section Identifier	Approx. Chainage (feet)		Sub-section Location on Pipeline	Approx. Length (feet)	Assumed Pipe Material	Theoretical Wall Thickness (inch)		Remaining Effective Wall Thickness[1] (Difference between metal wall or cement mortar lining from the nominal theoretical value) (inch)						Sub-Sectional Average Wave Speed (ft/s)
								Assumed Internal Corrosion[2]			Assumed External Corrosion[3]			
	Start	End				Wall	Lining	Wall	Lining	%Remain	Wall	Lining	%Remain	
S18	6920	7290	369 ft west of TP8 (1694 ft east of TP9) to TP8.	369	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	65%	0.15 (-0.1)	0.13 (0)	60%	3601.1
S19	7290	7634	TP8 to the slight bend 185ft east of the Davidson Ditch crossing (345 ft east of TP8).	345	MS	0.25	0.13	0.19 (-0.1)	0.00 (-0.13)	76%	0.17 (-0.1)	0.13 (0)	71%	3726.0
S20	7634	7921	Slight bend to 631 ft east of TP8.	286	MS	0.25	0.13	0.19 (-0.1)	0.00 (-0.13)	73%	0.17 (-0.1)	0.13 (0)	68%	3696.8
S21	7921	8058	631 ft east of TP8 to 768 ft east of TP8.	137	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	65%	0.15 (-0.1)	0.13 (0)	60%	3598.9
S22	8058	8919	768 ft east of TP8 to 1629 ft east of TP8 (527 ft west of TP7).	861	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	62%	3617.7
S23	8919	9446	1629 ft east of TP8 to TP7.	527	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	61%	3612.8
S24	9446	9621	TP7 to BO_7.	174	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	61%	3614.3
S25	9621	9691	BO_7 to Anomaly D, eastern side of ditch, east of BO_7 (244 ft east of TP7).	70	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	67%	0.15 (-0.1)	0.13 (0)	62%	3624.6
S26	9691	10165	Anomaly D to Anomaly E, 66th St Off-take.	474	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	61%	3608.6
S27	10165	10625	66th St Off-take to Anomaly F (p-CAT™ Ch.10582.3 ft, 1115.5 ft east of TP7).	460	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	61%	3608.7
S28	10625	10941	Anomaly F to 1494 ft east of TP7.	316	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	68%	0.16 (-0.1)	0.13 (0)	63%	3637.1
S29	10941	11939	1494 ft east of TP7 to 2492 ft east of TP7.	998	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	65%	0.15 (-0.1)	0.13 (0)	61%	3606.5
S30	11939	12992	2492 ft east of TP7(1053 ft west of TP6) to TP6.	1053	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	67%	0.15 (-0.1)	0.13 (0)	62%	3625.0
S31	12992	13002	TP6 to Anomaly G (IV2).	10	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	67%	0.15 (-0.1)	0.13 (0)	62%	3627.7
S32	13002	13912	Anomaly G (IV2) to western bend near Denver Boulder Turnpike, 920 ft east of TP6.	910	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	61%	3609.0
S33	13912	13968	920 ft east of TP6 to Anomaly H (IV1).	57	MS	0.25	0.13	0.20 (-0.1)	0.00 (-0.13)	77%	0.18 (-0.1)	0.13 (0)	73%	3745.1

[1] The values given are separate options representing pipe conditions with either only external corrosion or only internal corrosion. Refer to Appendix E1 for the adopted method for calculating total equivalent wall thickness. Refer Appendix A for the definitions for equivalent and effective wall thickness.

[2] Assumes that no metallic wall is deteriorated until all of the cement mortar lining has been lost (wall thickness loss is subject to internal corrosion only).

[3] Assumes that only the metallic wall is lost and the cement mortar lining remains intact (wall thickness loss is subject to external corrosion only).

[4] The percentage of remaining wall thickness is calculated from the total equivalent wall thickness.

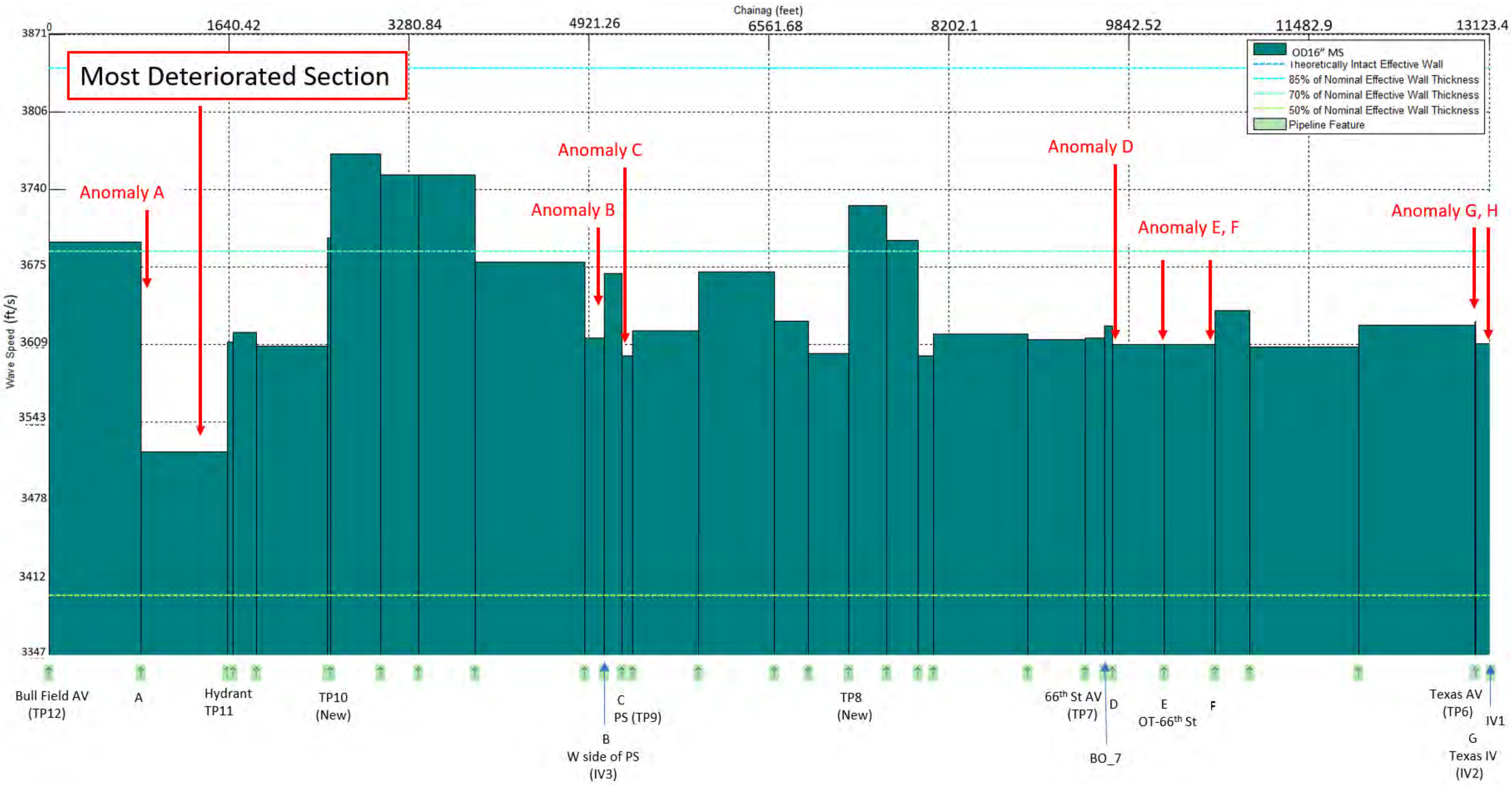


Figure 4.1: Internal pipeline wall deterioration for Louisville Raw Water line.

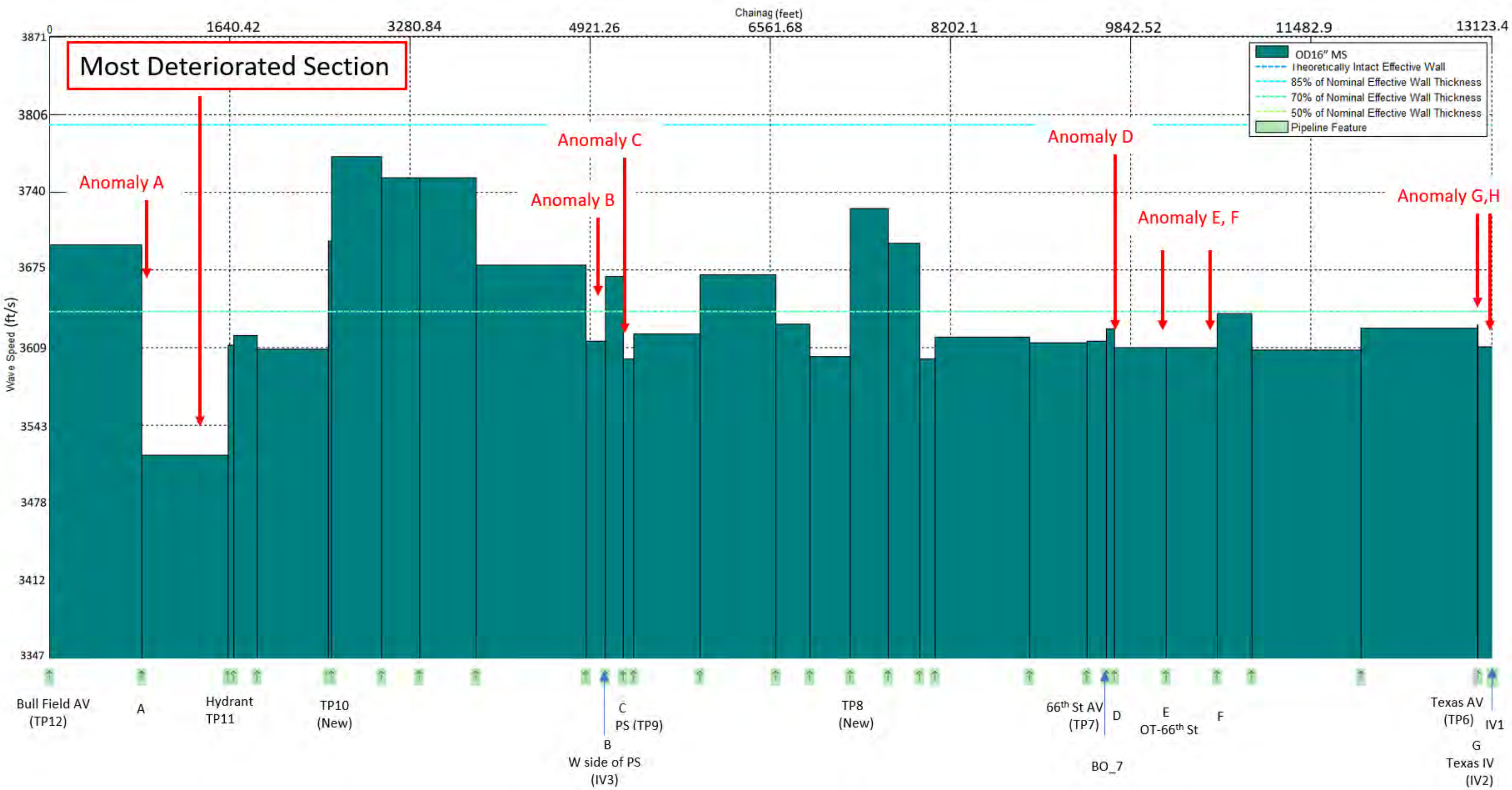


Figure 4.2: External pipeline wall deterioration for Louisville Raw Water line**.**

5 Summary and Recommendations

The following pipeline wall condition was identified during the p-CAT™ analysis:

- 73% of the total pipeline length has a remaining wall thickness of between 54 and 70%.
- 27% of the total pipeline length has a remaining wall thickness of between 70 and 80%.

It should be noted that these remaining wall thickness results are determined using assumed initial wall thicknesses and outer diameters as requested by the client.

As discussed in Section 3.1, there was no original information about the exact properties of the steel pipe with tar-lining used in this particular section of interest. Also, there was no information about the strength of the tar lining that could be found at this time.

After consulting with HUSA, Schedule 10 with a lining of half the strength of cement mortar was decided to be used as the initial pipeline properties. These theoretical conditions were used during the p-CAT™ analysis but have resulted in high priority conditions for a majority of the pipe. If required, the p-CAT™ analysis team can change the schedule to 10s or 5s which will bring up the proportional percentages. This will not affect the results of the wave speed analysis, those results and the and the final wall thickness will remain the same only how they compare to a new original wall will change. Thus, If the client obtains further information regarding the initial wall thickness or the exact properties, DS will be able to recalculate the percentage remaining wall thickness.

The following known features and anomalies where identified during the signal analysis. The recommended actions are listed below:

- Three medium priority anomalies representing:
  - The presence of an entrained and entrapped air pocket.
  - One known off-take with possible sealing problem or deterioration.
  - One potential concrete encasement or potential blockage.
- Five low priority anomalies representing:
  - Concrete encasement (additional cover) or possible blockage.
  - Known features or possible deterioration or blockages.

With regards to the 16-inch Steel Louisville Raw water main, it is recommended that HUSA investigate the current pipeline properties and configuration, and the presence of possible entrained or entrapped gas before coming to the conclusion that sections are deteriorated. These faults can also affect the accuracy of the p-CAT™ results for both the condition assessment and the anomaly identification.

The results provided in this report will assist in the assessment of the current condition of the Louisville Raw Water line. p-CAT™ has provided the remaining wall thicknesses for 33 sub-sections of different deterioration conditions over 2.65 miles of pipeline. A total of three medium priority and six low priority anomalies were also identified. This information can assist the City of Louisville, Colorado to make accurate decisions in planning and budgeting for future maintenance programs.

Appendix A: Glossary of Terms

Anomaly	-	Signal in the pipeline identified in the collected transient traces that does not correspond to a known feature on the pipeline. For example; entrapped or entrained air, blockage, pipe change.
Cement lining loss	-	Loss of lining refers to the loss of bond or structural integrity of the cement mortar lining. Cement mortar lining may still be present, however it does not contribute to the transient response of the pipeline.
Effective wall thickness	-	Average wall thickness across the cross-section of the pipeline. The effective wall thickness refers to the wall contributing to the transient response and hence structural integrity. For example, a portion of the AC wall that has experienced calcium leaching is not included in the effective wall thickness.
Equivalent wall thickness	-	The equivalent thickness is the wall thickness including the cement mortar lining in terms of the metallic wall material.
Point	-	Identified potential connection point for use as a station (measurement or generation).
Section	-	Pipeline between two stations (measurement or generation).
• **Sub-section**	-	Pipeline with similar wall condition as identified during analysis.
Station	-	Connection point used during transient testing
• **Generation**	-	Location at which the controlled transient was initiated and variation of the transient pressure was measured.
• **Measurement**	-	Location at which the variation of pressure during the transient pressure wave event was measured.
Transient	-	A transient event is a pressure wave that occurs in a pipeline whenever the flow is changed rapidly (e.g. by a rapid valve opening or closure). In this report it refers to a controlled small magnitude transient event.
Wave speed	-	The speed with which a wave front from a hydraulic transient pressure wave propagates along the pipeline.

Appendix B: Pipeline Feature Chainages

The pipeline was surveyed to locate known features and the chainages are shown in Table B.1. These values were used for all analysis.

Table B.1: Surveyed pipeline chainages for Louisville Raw Water line.

Feature	Chainage (ft)
Bull Field AV (TP12)	0
Hydrant (TP11)	1632
TP10 (New)	2572
W side of PS (IV3)	5065
PS (TP9)	5226
TP8 (New)	7290
66th St AV (TP7)	9446
OT_66th St	10165
Texas AV (TP6)	12992
Texas IV (IV2)	13002
IV at PVC start ((V1)	13968

Appendix C: Examples of Selected Pressure Traces

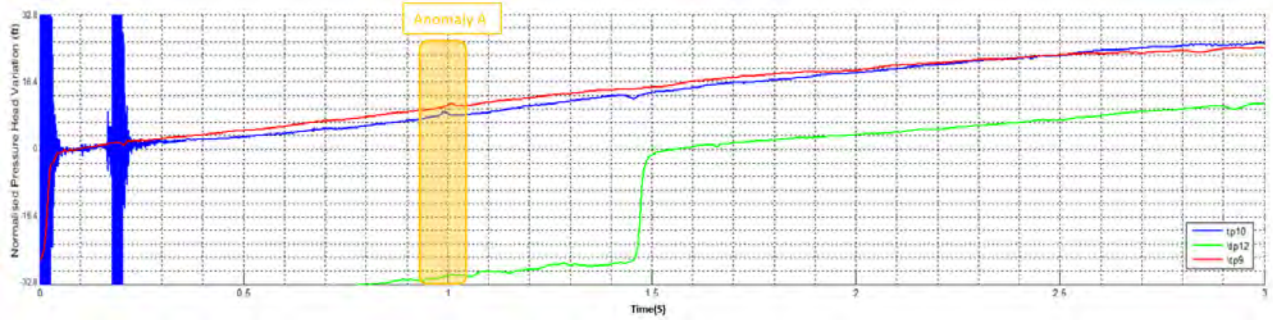


Figure C.1: Anomaly identification for transient generated at TP10.

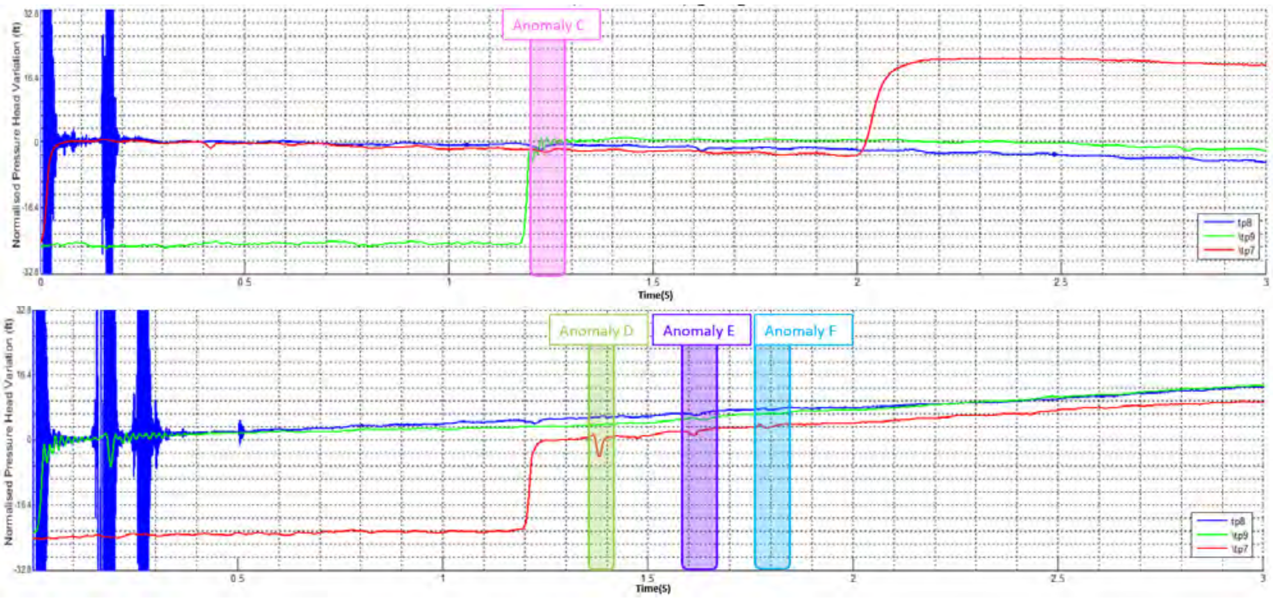


Figure C.2: Anomaly identification for transient generated at TP8.

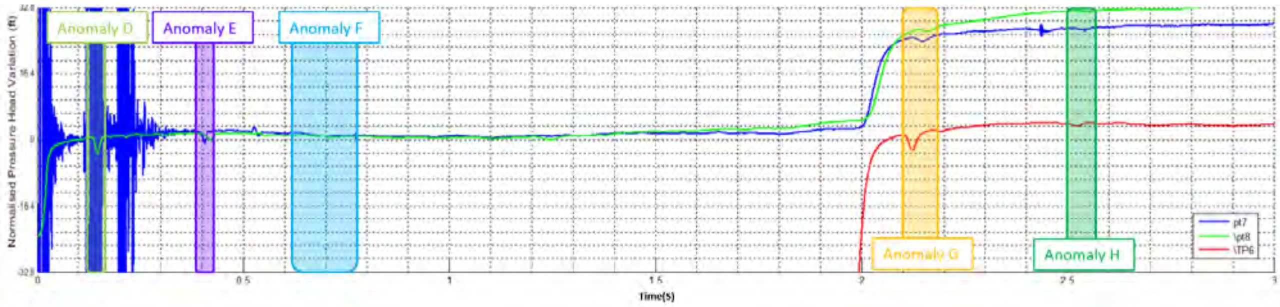


Figure C.3: Anomaly identification for transient generated at TP7.

Appendix D. Test Methodology and Equipment

D1. Non-invasive Pipe Condition Assessment (p-CAT™)

The University of Adelaide (UoA) has developed a technology that enables the simultaneous non-invasive diagnosis of pipeline condition over long distances along pipelines with minimal disruption of current services, thereby allowing decisions to be made regarding pipes which require rehabilitation. DS is putting the technology to practical use.

A controlled transient event (or small magnitude controlled hydraulic pressure event) is a pressure wave that occurs in a pipeline whenever the flow is changed rapidly (e.g. by a rapid valve opening or closure or sudden pump start or stop). The rapid change in flow is accompanied by a sharp change in pressure. The variation of pressure during the transient pressure wave event can be measured at locations along the pipes with pressure transducers. The presence of pipe wall damage due to metallic corrosion and/or cement mortar lining loss has a visible impact on the resultant transient pressure wave trace. This observation is the basis of advanced mathematical techniques that use fluid transient pressure waves for detecting the size and location of these defects.

For cement mortar lined metallic pipes, there is a relationship between changes in the thickness of metal and cement mortar lining forming a pipeline wall and the speed (or wave speed) with which a wavefront from a hydraulic transient pressure wave propagates along the pipeline. Changes in the thickness of metal and cement mortar lining give rise to reflections which can be theoretically interpreted to obtain a distribution of damage along the pipeline.

In Asbestos Cement (AC) pipelines there is a relationship between changes in the effective thickness of the cement forming a pipeline wall and the speed (or wave speed) with which a wave front from a hydraulic transient pressure wave propagates along the pipeline. Changes in the effective thickness of the cement (e.g. due to leaching of calcium) give rise to reflections which can be theoretically interpreted to obtain a distribution of damage along the pipeline. Softening of the AC pipe material would also be evident.

In CI pipelines tuberculation and graphitization may occur whereby the Iron is leached from the pipe wall by bacteria. This results in graphitized sections of the pipe wall and tuberculation of iron composites connected to the pipe wall restricting the internal diameter. The graphitized sections and tuberculation do not contribute to the structural integrity and are hence not included in the effective wall thickness.

Validation of the techniques on field pipelines by DS and UoA has shown that measured transient pressure wave traces can provide significant amounts of information about a pipe system. This is due to small reflections of propagating transient pressure waves resulting from variations in the pipeline surface. The reflections are used to predict both the location and extent of damage along the tested length of pipe and confirmed using point sampling methods.

p-CAT™ analysis uses two main techniques for interpreting the results from the transient pressure wave tests:

- Sub-Section Partitioned Wave Speed Analysis™ for assessment of the level of deterioration of the pipe wall in a sub-section, and
- Signal Analysis for detection of significant anomalies such as air pockets and blockages.

D2. Sub-Section Partitioned Wave Speed Analysis™

Changes in wall thickness are related directly to the speed of propagation of a transient pressure wave (wave speed) and these changes give rise to the observed reflections. If the wall of a pipeline has a reduction in thickness, then a transient pressure wave will propagate at a slower speed than the theoretical maximum. This wave speed variation results in a small reflection of the incident controlled transient event wave. Alternatively, if a change in pipe wall thickness occurs along the pipeline as a result of a connection between two different pipes that are similar in diameter but with different wall thicknesses, the wave speed will be different in the two sections. The p-CAT™ technique analyses the transient pressure wave traces and wave reflections to identify sub-sections of pipe between two measurement stations that have variations in wave speed. This variation could be the result of known changes in the pipe material or pipe material properties or appurtenances or changes in pipe wall condition. Details of the background theory on the Sub-Section Partitioned Wave Speed Analysis™ are provided in Appendix E.

D3. Signal Analysis

Signal analysis is a higher resolution analysis based on the same principles as the Sub-Section Partitioned Wave Speed Analysis™. It is used to identify known features in the pipeline system and significant anomalies within the system such as air pockets and blockages. It can also identify the locations of changes in pipeline material, in-line valves and off-takes. A time shift is conducted of the measured responses on either side of the location at which the transient pressure wave is generated, such that the origin of each reflection can be uniquely determined by signal analysis. The known feature or anomaly is then categorized based on its characteristics.

The resolution of transient pressure wave signal analysis depends on the accuracy and sharpness of the measured and provided data, the extent of complexity of pipeline system configuration and the accuracy in the estimation of the distance between measurement stations. In the tests, the client provided pipe information was used to determine the locations of the measuring points and to approximate the pipe lengths. The precision of the anomaly location is ±30 ft for tests due to the precision of the pipe lengths.

D4. Test Procedure

Each test was generally composed of one transient generation point (a water discharge point) and two or more pressure measurement points. The following is the procedure for equipment installation and collection of the pressure signal:

a) Installation of a hydraulic transient signal generator with a signal acquisition system on a corporation stop.
b) Installation of a signal acquisition system at the measurement points on corporation stops.
c) Carrying out tests for collecting pressure signals: water is released at the transient generation point, time is allowed for the resulting transients to settle, and then the transient generator is quickly closed to create a hydraulic transient signal. The size of outlet on the transient generator is selected to create a transient pulse of no more than 30 feet of head pressure. Transient input signals are repeated at each location 3 to 5 times.
d) Test equipment is then packed up and moved to another test location.
e) At the end of the day, the data is packaged and transferred for analysis.

One test set with one generation point and two measurement points can take one to two hours including moving, installing equipment and testing.

D5. Test Equipment

The hydraulic transient pressure wave generator and the signal acquisition system for the measurement points used in the testing is shown in Figure D.1. Pressure measurement recordings are transferred via amplifiers and 16-bit A/D converter to a personal laptop computer with a data acquisition interface based on LabVIEW software. The sampling frequency for measuring pressure data was 2 kHz (2,000 samples per second).

(a)
Hydrant type transient pressure wave generator attached to a test point

(b)
Pressure measurement equipment attached to a test point

(c)
Data acquisition (DAQ) system

Figure D.1: Field testing equipment.

Appendix E: Theory of p-CAT™

E1. Theory and Equations

This Appendix describes the background information about the Sub-Section Partitioned Wave Speed Analysis™. The physical observation that there are reflections following the initiation of a hydraulic transient pressure wave event in a pipeline is the basis for the technique. The fundamental physical mechanism giving rise to the observed reflections is recognized as changes in the thickness of pipe wall and/or cement mortar lining, which in turn alters the speed of propagation of hydraulic transient pressure waves. The relationship between the changes in the equivalent pipe wall thickness and the variation in the wave speed can be used to classify the condition of the pipeline. This relationship can be theoretically described by the following equation:

$$a = \sqrt{\frac{K/\rho}{1+(K/E)\cdot(D/e_{eq})\cdot\psi}} \qquad (1)$$

where a = speed of propagation of hydraulic transient pressure wave (wave speed), K = bulk modulus of water, ρ = density of water, E = Young's modulus of elasticity of the pipeline wall material, D = internal diameter of the pipeline, e_{eq} = wall thickness of a single material pipe or the total equivalent wall thickness of composite material pipe, and ψ = the pipeline restraint factor.

The contribution of the cement mortar lining can be included as an equivalent thickness of metallic wall using

$$e_{eq\_C} = e_C \times \frac{E_C}{E_M} \qquad (2)$$

where e_{eq_C} is the equivalent metallic wall thickness given by the cement mortar lining, e_c = the original thickness of the cement mortar lining, E_C and E_M = the Young's moduli of elasticity of cement mortar lining and metal respectively.

When the cement mortar lining spalls off the inside of a section of pipeline, changes occur in the total equivalent pipe wall thickness. The loss of cement mortar lining reduces the stiffness of the pipeline wall by an amount proportional to the thickness and modulus of elasticity of the cement. Once exposed, the pipe wall begins to corrode, leading to a reduction in the thickness of the metal wall. External pipe wall corrosion can also cause a thinning of the pipe wall.

The impedance and wave speed of a pipe section are extremely sensitive to the combined effect of the loss of cement mortar lining and corrosion of the metal wall. As a consequence, the magnitude and frequency of reflections from the transient pressure wave will increase as the wavefront moves along a section of pipeline that is deteriorated. It is important to recognize that wave speed is also sensitive to the reduction of wall thickness caused by external corrosion (i.e., pipe wall thinning should give a slower wave speed and a micro-reflection regardless of it is due to external or internal corrosion).

E2. Interpretation of Variations in Wave Speed in a Pipe Section between Two Points

Determination of the average wave speed using the time for a transient pressure wave traveling between two measurement points is a quantitative low resolution technique, whereby the average thickness of the remaining pipe wall can be estimated for the section bounded by the two measurement points. The Sub-Section Partitioned Wave Speed Analysis™ increases the resolution by incorporating the variations in wave speed in a pipe section bounded by two measurement points. When a transient pressure wave meets a segment of pipe with a change in material, pipe wall deterioration, or a concrete encasement (all result in a change in wave speed), it causes wave reflections which are shown as variations in pressure in the traces measured by transducers. In the Sub-Section Partitioned Wave Speed Analysis™, by analyzing the size and timing of these pressure variations, the wave speeds for two or more sub-sections between a pair of measurement points can be determined. Variations in pressure are translated to variations in wave speed from the average, which are then used to determine the condition of each sub-section.

E3. Example of Sub-Section Partitioned Wave Speed Analysis™

An example of the Sub-Section Partitioned Wave Speed Analysis™ is presented below in Figure E1. The testing configuration of Day5-Test2 (Gen at DAV33, M1 at D31, M2 at D34, M3 at D35 as shown in Figure E1) was selected as example data on the M6A pipeline. The section for which the sub-section partitioned wave speed analysis is carried out is between Gen at D33 and M1 at D31.

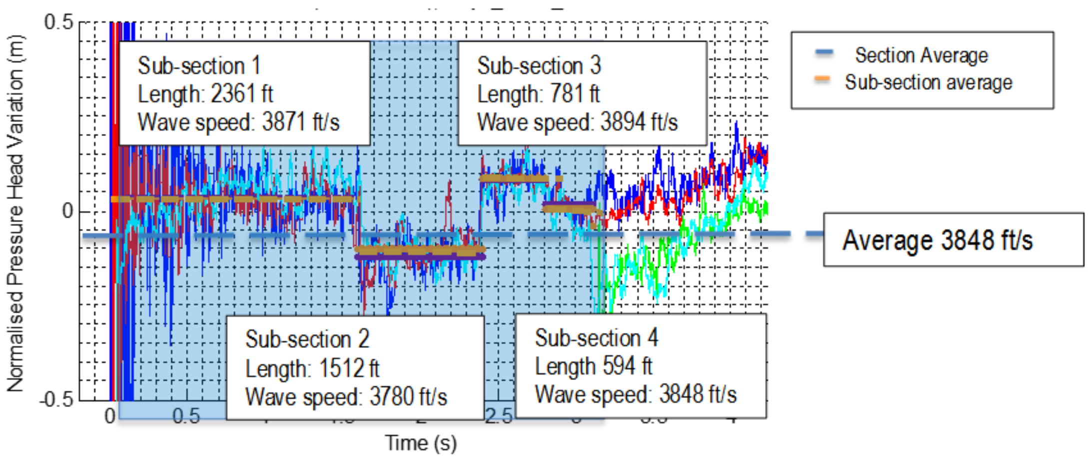


Figure E.1: Segment for estimation of wave speed variation between measurement stations.

In Figure E.1, the dashed blue line depicts the inferred wave speed (3848 ft/s) for the entire example section between D33 and D31 (shaded blue box), which was estimated by the transient pressure wave arrival time. Within this section there are sub-sections of relatively stable pressure head. These sections represent sections with distinct wave speeds and Sub-Section Partitioned Wave Speed Analysis™ was used to determine the representative wave speeds in each sub-section. Note in this example sub-section 2 represents the section near SC4 where a known MSCL replacement is located. The theoretical wave speed for 0.236-inch OD MSCL is 3717 ft/s.

Visual Summary of p-CAT™ Pipeline Condition Assessment Findings

Hydromax USA and the City of Louisville, Colorado.

10 October 2018

Louisville Raw water Pipe line

2.65 miles of OD 16-inch Tar lined steel pipeline in the City of Louisville , Colorado

Prepared by CJ PTW YK 20181010

Overview

This document is a summary of the findings from pipe condition assessment testing of the Louisville Raw water pipe line for Hydromax USA and the City of Louisville, Colorado.

The field trials were conducted on the pipeline with the purpose of assessing the pipeline condition and identifying anomalies such as blockages, air pockets and wall thickness deterioration using p-CAT^{TM}.

Tests on the mains were conducted in the field between 4th and 5th September 2018.

The pipeline section of interest was constructed in 1955 from OD 16-inch Tar lined Steel Pipe.

The section of interest begins at TP12 (Bull Field air valve) near 1803 S Foothills Hwy and to an Inline valve (IV1) at the start of the PVC road crossing.

Notes

A draft report containing the findings of the trial has been produced and provided to Hydromax USA (HUSA) and the City of Louisville, Colorado (CoLC). This document should be read in conjunction with the draft report.

The following summarises the reports findings via a series of google maps, annotated with:

- Locations of anomalies identified during analysis,
- Partitioned sub-sections identified during analysis and their pipeline condition, and
- Non-pipe assets used as measurement and transient generation points.

It must be noted at this time that the results have not yet been reviewed in detail by HUSA and CoLC.

All recommendations and priority assignments are to be considered preliminary at this time.

Summary of Analysis

The following pipeline wall condition was identified during the p-CAT™ analysis:

- 73% of the total analyzed pipeline length has a remaining wall thickness of between 54 - 70%, which is highly deteriorated.
- 27% of the total analyzed pipeline length has a remaining wall thickness of between 70 – 80%, which is also in a concerning condition.

The following known features and anomalies, and their resulting recommended actions were also identified during the signal analysis:

- Three medium priority anomalies representing:
  - One presence of an entrained and entrapped air pocket.
  - One known off-take with possible sealing problem or deterioration.
  - One potential concrete encasement or potential blockage.
- Five low priority anomalies representing:
  - Concrete encasement (additional cover) or possible blockage.
  - Known feature IV3 or possible deterioration.
  - TP9 on the By-pass or potential deterioration.
  - Known feature IV2 or potential deterioration or possible blockage.
  - Known feature IV1 on the PVC.

Table 1: Localised fault detection results

Identifier	Approximate location	Interpretation	Priority	Recommended action
A	45ft before the western side of S Foothills Hwy.	Concrete encasement of the road crossing or a possible blockage.	low	Check the pipeline configuration records for material and diameter change. If no change, potential blockage.
B	IV3 west of Pump Station.	Known feature or possible deterioration.	low	Check the pipeline condition and valve condition.
C	TP9 east of Pump Station.	AV Tapping in the PS or possible deterioration	low	Check the pipeline condition and valve condition.
D	Eastern side of ditch, east of BO_7.	Possible additional cover or blockage	**Medium**	Investigate the pipeline condition and confirm pipeline material and diameters. If no change, potential blockage.
E	Off-take 66th St	Known off-take, possible sealing problem or deterioration.	**Medium**	Examine the functionality of the valve and determine its sealing status.
F	p-CAT™ Ch.10582.3 ft, 1115.5 ft east of TP7	Possible entrained and entrapped air	**Medium**	Confirm the presence and location of the air valve. Investigate the valve sealing status and pipeline condition and remove the air pocket as it may affect the system performance. There is an increased likelihood of localized internal deterioration at this point.
G	IV2, 9 ft east of TP6	Known feature, or possible deterioration or blockage.	low	None. Known system issue.
H	IV1	Known feature.	low	None. Known system issue.

Table 2: Sub-sectional analysis results

Section Identifier	Approx. Chainage (feet) Start	Approx. Chainage (feet) End	Sub-section Location on Pipeline	Approx. Length (feet)	Assumed Pipe Material	Theoretical Wall Thickness (inch) Wall	Theoretical Wall Thickness (inch) Lining	Remaining Effective Wall Thickness[1] (Difference between metal wall or cement mortar lining from the nominal theoretical value) (inch) – Assumed Internal Corrosion[2] Wall	Assumed Internal Corrosion[2] Lining	Assumed Internal Corrosion[2] %Remain	Assumed External Corrosion[3] Wall	Assumed External Corrosion[3] Lining	Assumed External Corrosion[3] %Remain	Sub-Sectional Average Wave Speed (ft/s)
S1	0	843	TP12 to Anomaly A (western side of S Foothill Hwy).	843	MS	0.25	0.13	0.19 (-0.1)	0.00 (-0.13)	73%	0.17 (-0.1)	0.13 (0)	68%	3695.4
S2	843	1393	Anomaly A to eastern side of the driveway to 5333 Eldorado Springs Dr.	550	MS	0.25	0.13	0.15 (-0.1)	0.00 (-0.13)	59%	0.13 (-0.1)	0.13 (0)	54%	3518.1
S3	1393	1632	Eastern side of driveway to TP11.	239	MS	0.25	0.13	0.15 (-0.1)	0.00 (-0.13)	59%	0.13 (-0.1)	0.13 (0)	54%	3517.9
S4	1632	1677	TP11 to Intersection with Eldorado Springs Dr and Marshall Dr.	45	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	61%	3610.8
S5	1677	1895	Intersection with Eldorado Springs Dr and Marshall Dr to 5430 Marshall Rd.	219	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	62%	3618.7
S6	1895	2540	5430 Marshall Rd to eastern side of the road crossing at 5444 Marshall Rd.	644	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	65%	0.15 (-0.1)	0.13 (0)	61%	3607.3
S7	2540	2572	5444 Marshall Rd crossing to TP10.	32	MS	0.25	0.13	0.19 (-0.1)	0.00 (-0.13)	73%	0.17 (-0.1)	0.13 (0)	68%	3698.5
S8	2572	3024	TP10 to 452 ft east of TP10 .	452	MS	0.25	0.13	0.21 (0)	0.00 (-0.13)	80%	0.19 (-0.1)	0.13 (0)	75%	3770.0
S9	3024	3368	452 ft east of TP10 to the bend (15°) behind 5608 Marshall Rd.	343	MS	0.25	0.13	0.20 (0)	0.00 (-0.13)	78%	0.18 (-0.1)	0.13 (0)	73%	3752.3
S10	3368	3885	Bend 15° to 1313 ft east of TP10.	518	MS	0.25	0.13	0.20 (0)	0.00 (-0.13)	78%	0.18 (-0.1)	0.13 (0)	73%	3752.4
S11	3885	4882	1313 ft east of TP10 to 2310 ft east of TP10 (344ft west of TP9).	997	MS	0.25	0.13	0.18 (-0.1)	0.00 (-0.13)	71%	0.16 (-0.1)	0.13 (0)	67%	3678.4
S12	4882	5065	2310 ft east of TP10 (344ft west of TP9) to Anomaly B (IV3).	183	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	61%	3613.8
S13	5065	5226	Anomaly B (IV3) to Anomaly C (TP9).	161	MS	0.25	0.13	0.18 (-0.1)	0.00 (-0.13)	70%	0.16 (-0.1)	0.13 (0)	66%	3668.5
S14	5226	5322	Anomaly C (TP9) to 96 ft east of TP9 (p-CAT™ Ch.5321.7 ft).	96	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	65%	0.15 (-0.1)	0.13 (0)	60%	3599.3
S15	5322	5923	96 ft east of TP9 (p-CAT™ Ch.5321.7 ft) to 697 ft east of TP9.	601	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	62%	3620.3
S16	5923	6612	697 ft east of TP9 to 677 ft west of TP8 (1386 ft east of TP9).	689	MS	0.25	0.13	0.18 (-0.1)	0.00 (-0.13)	71%	0.16 (-0.1)	0.13 (0)	66%	3670.0
S17	6612	6920	677 ft west of TP8 to 369 ft west of TP8 (1694 ft east of TP9).	308	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	67%	0.15 (-0.1)	0.13 (0)	62%	3628.2

Table 2: Sub-sectional analysis results

Section Identifier	Approx. Chainage (feet) Start	Approx. Chainage (feet) End	Sub-section Location on Pipeline	Approx. Length (feet)	Assumed Pipe Material	Theoretical Wall Thickness (inch) Wall	Theoretical Wall Thickness (inch) Lining	Remaining Effective Wall Thickness[1] (Difference between metal wall or cement mortar lining from the nominal theoretical value) (inch) – Assumed Internal Corrosion[2] Wall	Assumed Internal Corrosion[2] Lining	Assumed Internal Corrosion[2] %Remain	Assumed External Corrosion[3] Wall	Assumed External Corrosion[3] Lining	Assumed External Corrosion[3] %Remain	Sub-Sectional Average Wave Speed (ft/s)
S18	6920	7290	369 ft west of TP8 (1694 ft east of TP9) to TP8.	369	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	65%	0.15 (-0.1)	0.13 (0)	60%	3601.1
S19	7290	7634	TP8 to the slight bend 185ft east of the Davidson Ditch crossing (345 ft east of TP8).	345	MS	0.25	0.13	0.19 (-0.1)	0.00 (-0.13)	76%	0.17 (-0.1)	0.13 (0)	71%	3726.0
S20	7634	7921	Slight bend to 631 ft east of TP8.	286	MS	0.25	0.13	0.19 (-0.1)	0.00 (-0.13)	73%	0.17 (-0.1)	0.13 (0)	68%	3696.8
S21	7921	8058	631 ft east of TP8 to 768 ft east of TP8.	137	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	65%	0.15 (-0.1)	0.13 (0)	60%	3598.9
S22	8058	8919	768 ft east of TP8 to 1629 ft east of TP8 (527 ft west of TP7).	861	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	62%	3617.7
S23	8919	9446	1629 ft east of TP8 (527 ft west of TP7) to TP7.	527	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	61%	3612.8
S24	9446	9621	TP7 to BO_7.	174	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	61%	3614.3
S25	9621	9691	BO_7 to Anomaly D, eastern side of ditch, east of BO_7 (244 ft east of TP7).	70	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	67%	0.15 (-0.1)	0.13 (0)	62%	3624.6
S26	9691	10165	Anomaly D to Anomaly E, 66th St Off-take.	474	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	61%	3608.6
S27	10165	10625	66th St Off-take to Anomaly F (p-CAT™ Ch.10582.3 ft, 1115.5 ft east of TP7).	460	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	61%	3608.7
S28	10625	10941	Anomaly F to 1494 ft east of TP7.	316	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	68%	0.16 (-0.1)	0.13 (0)	63%	3637.1
S29	10941	11939	1494 ft east of TP7 to 2492 ft east of TP7.	998	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	65%	0.15 (-0.1)	0.13 (0)	61%	3606.5
S30	11939	12992	2492 ft east of TP7 to TP6.	1053	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	67%	0.15 (-0.1)	0.13 (0)	62%	3625.0
S31	12992	13002	TP6 to Anomaly G (IV2).	10	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	67%	0.15 (-0.1)	0.13 (0)	62%	3627.7
S32	13002	13912	Anomaly G (IV2) to western bend near Denver Boulder Turnpike, 920 ft east of TP6.	910	MS	0.25	0.13	0.17 (-0.1)	0.00 (-0.13)	66%	0.15 (-0.1)	0.13 (0)	61%	3609.0
S33	13912	13968	920 ft east of TP6 to Anomaly H (IV1).	57	MS	0.25	0.13	0.20 (-0.1)	0.00 (-0.13)	77%	0.18 (-0.1)	0.13 (0)	73%	3745.1

Key

Identified Anomalies:

Low Priority: anomaly detected corresponds to know system component and no action is required.

Medium Priority: anomaly detected does not correspond to known feature. It is recommended to conduct further investigation via records or site visits.

HIGH Priority: anomaly detected indicates a location of possible future failure. It is recommended that action is required to be taken immediately.

Pipeline Features:

Pipeline feature not identified as an anomaly

p-CAT Test Stations:

Pipeline features used as measurement or generation stations

Feature Acronyms:

AV: Air Valve
ARV: Air Release Valve
BOV: Blow Off Valve
CNL: Can Not locate
OT: Off-take
HYD: Fire Hydrant
IV: Inline Valve
PS: Pump Station
TP: Tapping Point

Subsection Priority:

85 - 100% Remaining Wall

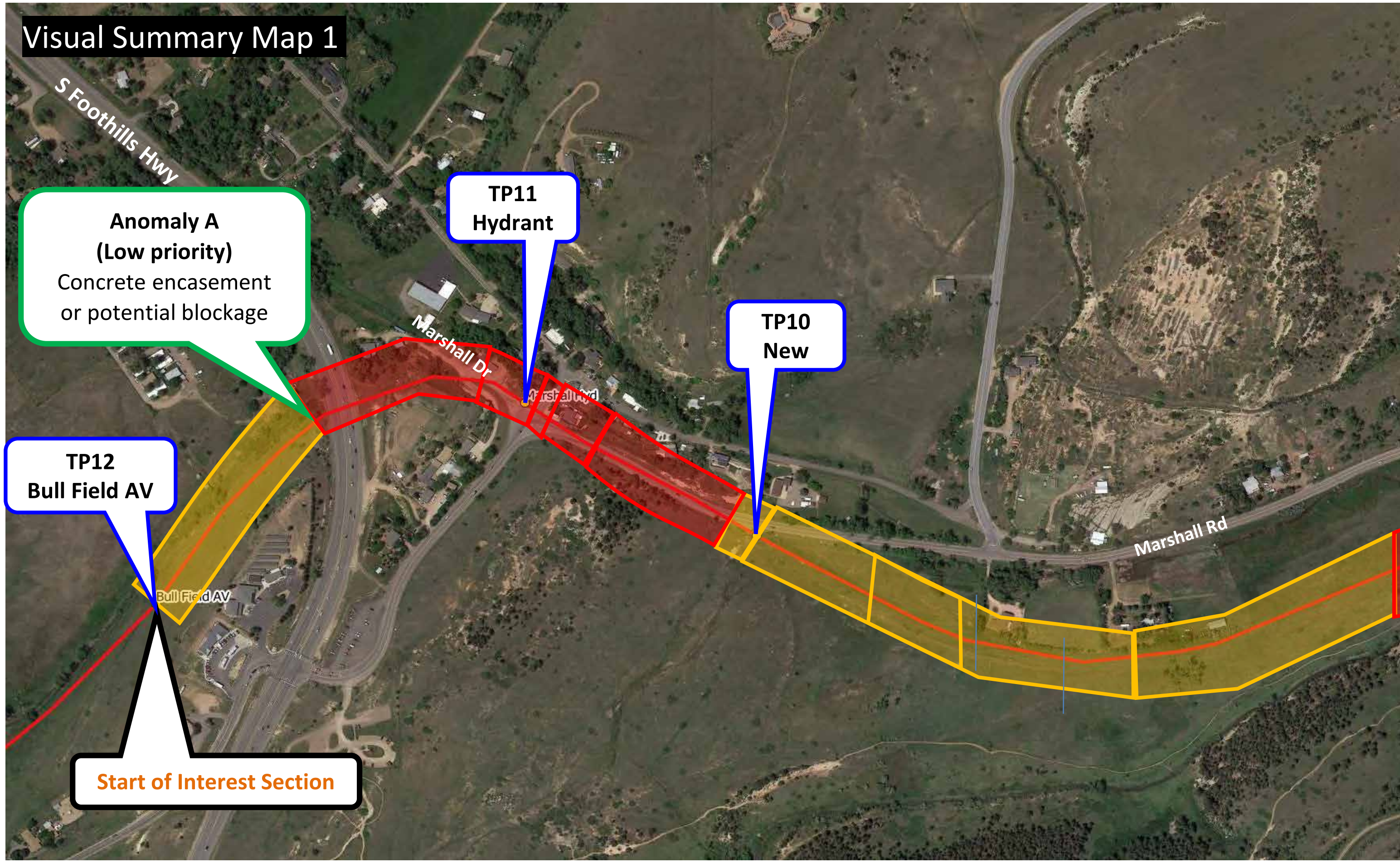
70 – 85% Remaining Wall

50 – 70% Remaining Wall

No condition assessment

Louisville Raw Water Pipeline

1 : 6000 N

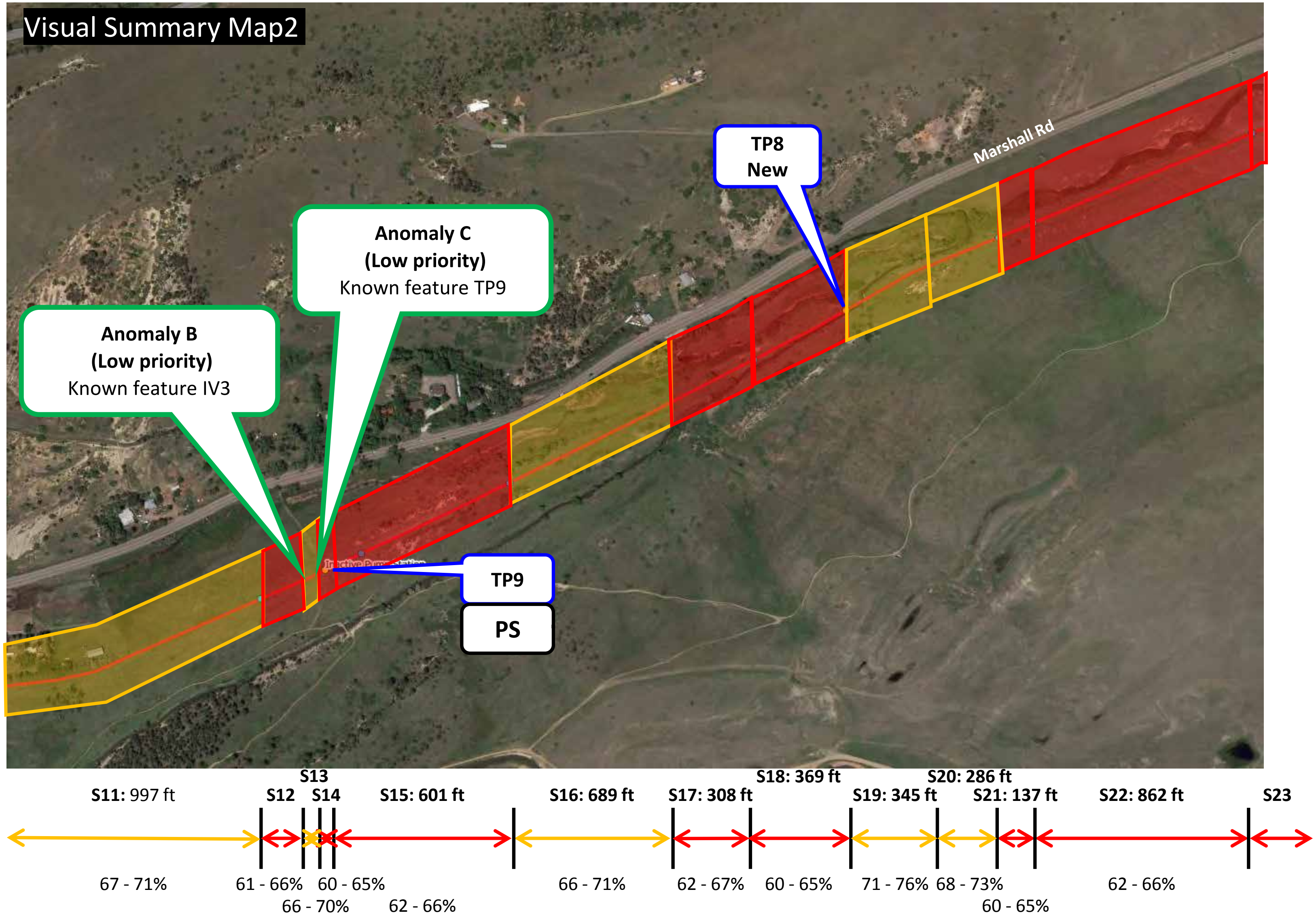


Sections	S1: 843 ft	S2: 550 ft	S3	S4	S5	S6 : 664 ft	S7	S8: 452	S9: 452	S10: 518	S11: 997 ft	S12: 183 ft
Remaining wall thickness (External – Internal)	68 - 73%	54 - 59%	54 - 59%	61 - 66%	54 - 59%	61 - 65%	68 - 73%	75 - 80%	73 - 78%	73 - 78%	67 - 71%	61 - 66%

Please refer to Table 1 for the recommended action regarding high and medium priority anomalies and Table 2 for remaining wall thicknesses

Louisville Raw Water Pipeline

1 : 6000 N

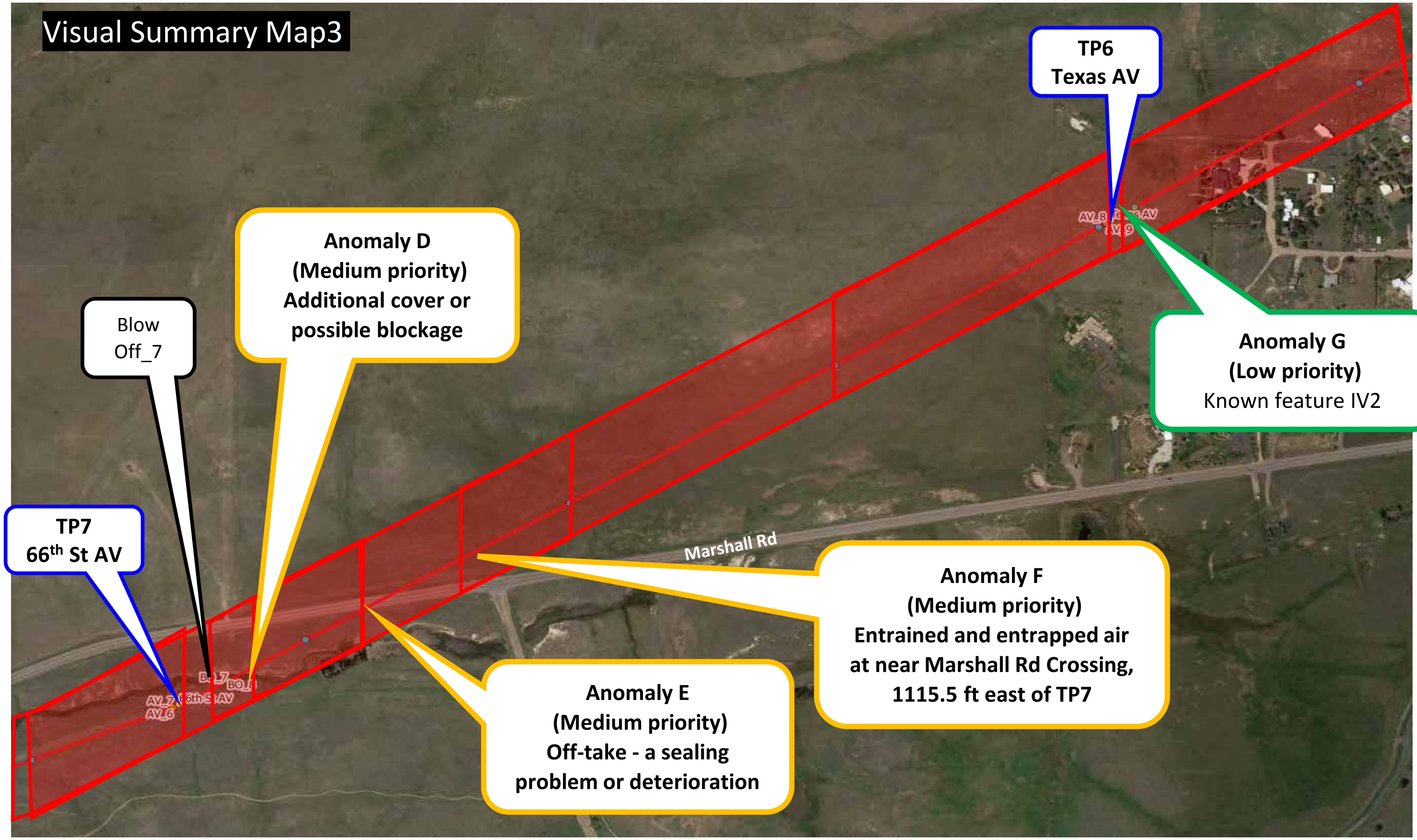


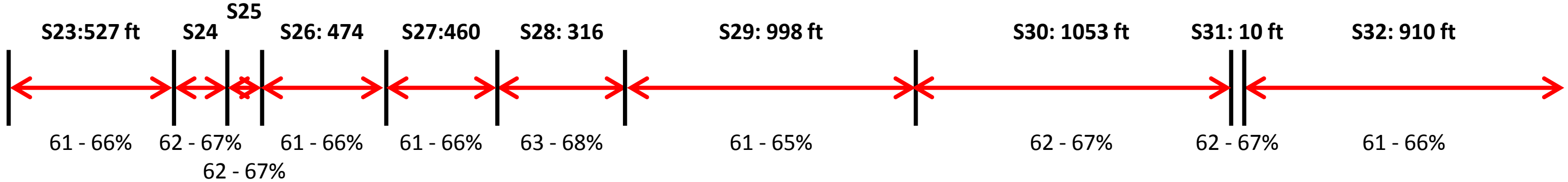
Please refer to Table 1 for the recommended action regarding high and medium priority anomalies and Table 2 for remaining wall thicknesses

Louisville Raw Water Pipeline

1 : 6000

N





Please refer to Table 1 for the recommended action regarding high and medium priority anomalies and Table 2 for remaining wall thicknesses

Louisville Raw Water Pipeline

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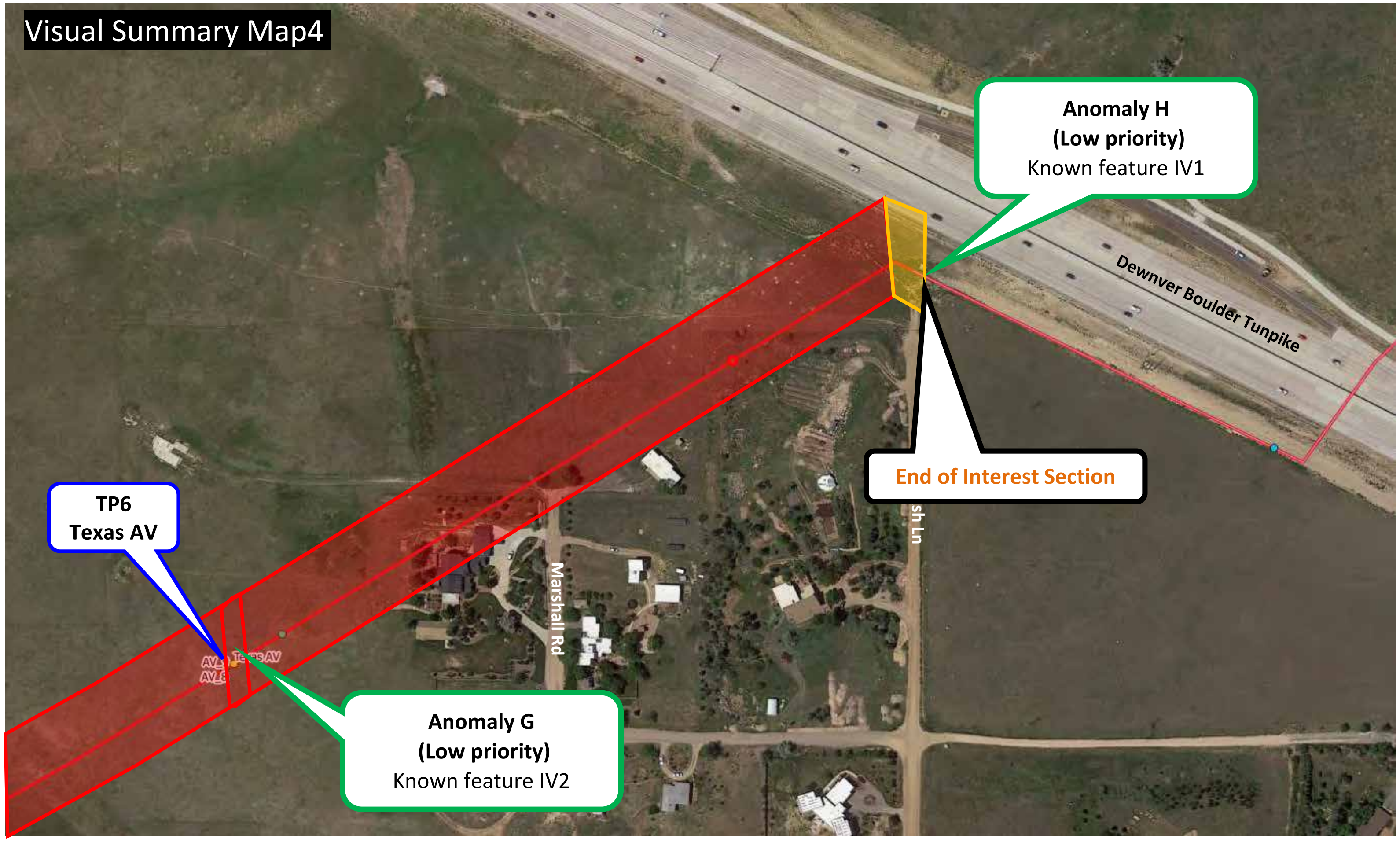
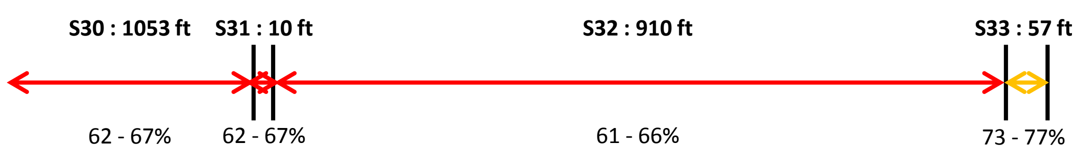




Please refer to Table 1 for the recommended action regarding high and medium priority anomalies and Table 2 for remaining wall thicknesses

APPENDIX B
JanX INCOTEST Report

Insulated Component Testing of

City of Louisville water line

Prepared for

Hydromax

By

JANX

V 2.0 – April 2019

Quality Assurance and Quality Control Statement

By my signature I attest that this report has been prepared and reviewed in accordance with the JANX Quality Assurance and Quality Control procedures:

Michael Speegle
Level II Technologist

10/31/2019

DISCLAIMER

Results are an interpretation of the inspection method, not a guarantee.

Note: All thickness readings are compared to a reference point taken at each component location and are function of the Magnetic properties of the object's base material.

NOTICE

Scan start point (A1)

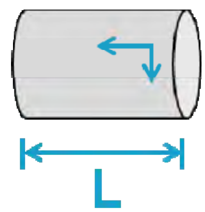
Component Inspection Report

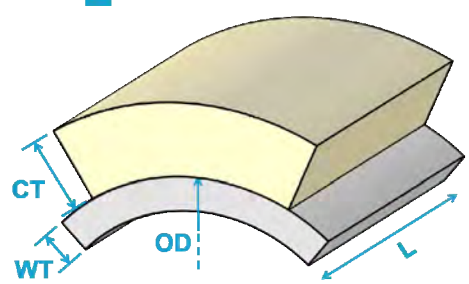
Summary

Client	Dewberry Engineers Inc.
Job Number	50118856
Site	road crossing at 170
Component Type	16" dia. pipe
Inspector	Michael Speegle

Component Details

Name	city of louisville water line
Geometry	Pipe
Material	Carbon steel
Dimensions	⌀ 16.000 in x 540.000 in
Wall Thickness	0.180 in
Coating/Insulation	0.125 in
Jacket Material	
Jacket Thickness	
Has Wiremesh/Reinforcement Bar	No





Scan Zones

Name	Mode	Status	Offset from Origin	Circ. Size	Ax. Size
1	Dynamic	Started	0.000 in, 0.000 in	51.051 in	540.000 in

Scan started at the U/S knuckle and progressed D/S and clockwise.

Scan Zone

Name	Mode	Probe	Status	Offset from Origin	Circ. Size	Ax. Size
1	Dynamic	PECA-6CH-MED-XXXX	Started	0.000 in, 0.000 in	51.051 in	540.000 in

Setup

Probe	PECA-6CH-MED-XXXX
Probe Footprint	1.881 in
Circumferential Footprint	1.911 in
Pulse Duration	24.5 ms
Max. Power	10.0 W
A-scan Start Time	1.2 ms
A-scan Duration	24.5 ms
Characteristic Decay Time	6.3 ms
Jacket Delay	0.0 ms
PEC Autoset Main Channel	Ch 3
Acquisition Rate	14.35 Hz
Line Filter Frequency	60.0 Hz
Sizing Algorithm	2.2

Channel Name	Gain (dB)
Ch 1	21
Ch 2	21
Ch 3	21
Ch 4	21
Ch 5	21
Ch 6	21

Data Quality

Saturation	0.00%
Overspeed	0.15%
Weak Signal	0.00%
Bad Fit	0.00%
Signal Distortion	0.01%

Total data points with warnings	0.16%

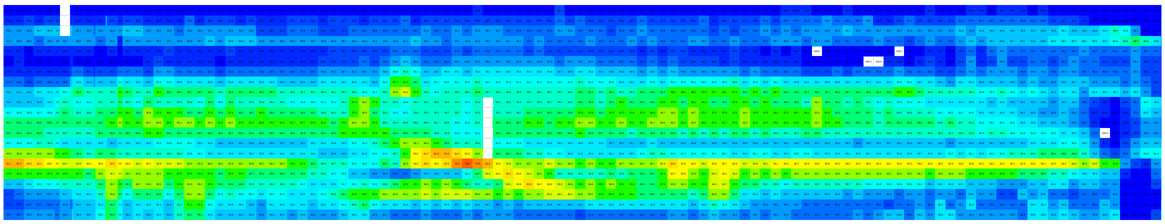
Calibration

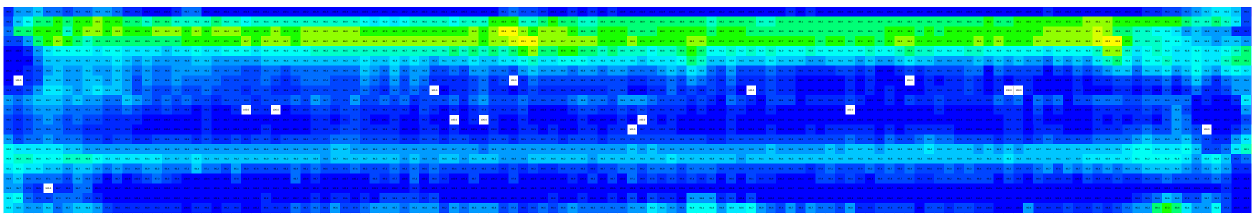
Subcomponent	Circ. 1 (in)	Ax. 1 (in)	Circ. 2 (in)	Ax	Edge smoothing fa	Description
Main	22.792	29.159	45.584	39	0 %	Existing area in scan zone

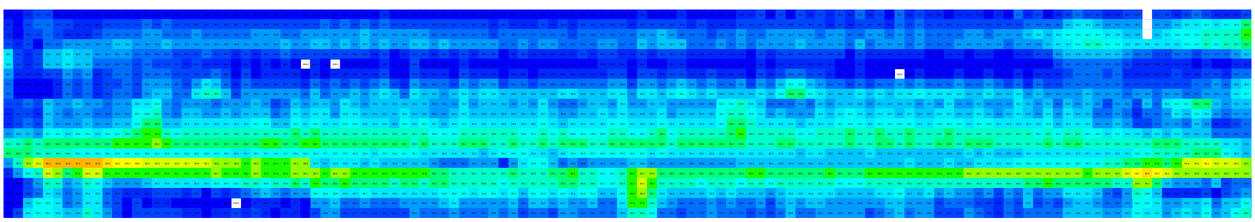
Wall thickness percentage values

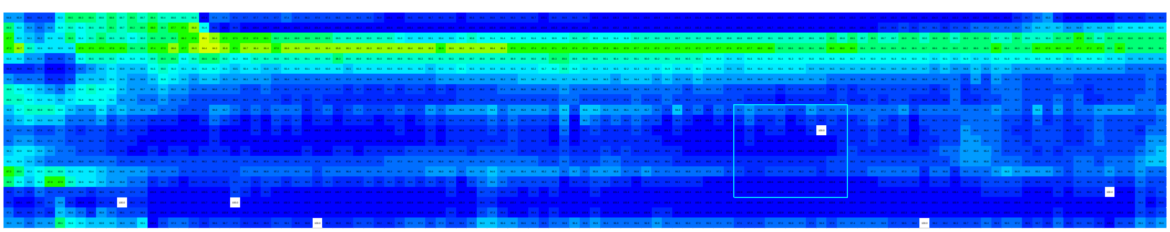
Color palette legend

75.0 76.3 77.6 78.9 80.3 81.6 82.9 ## 85.5 89.5 90.8 93.4 96.1 97.4 98.7





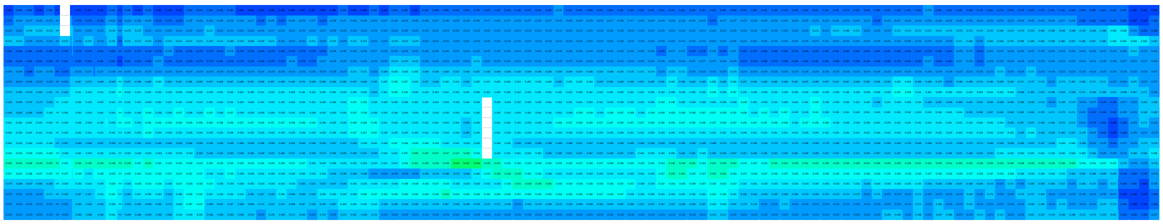


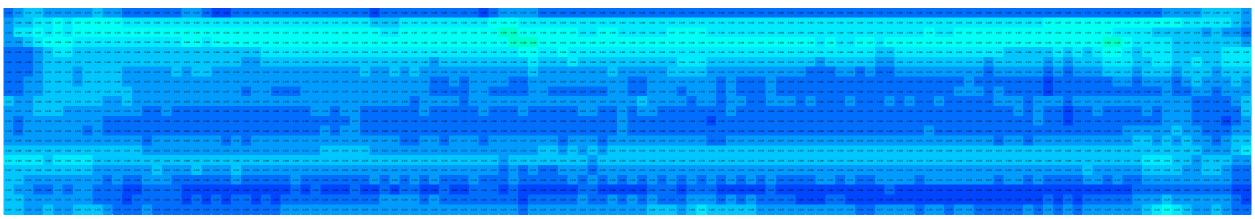


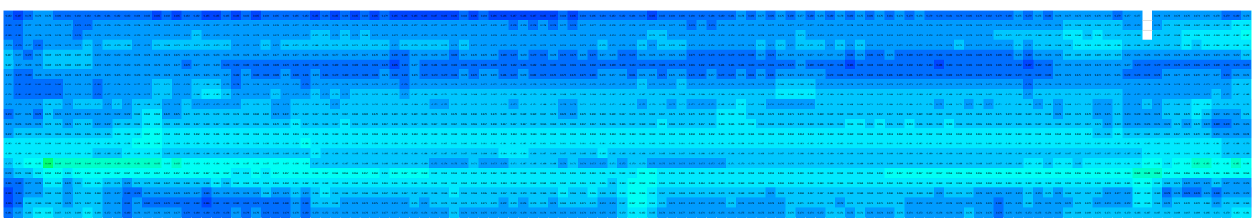
Wall thickness values

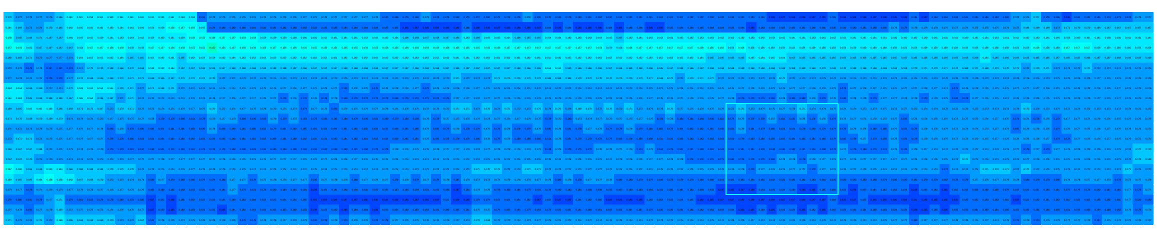
Color palette legend

0.072	0.079	0.085	0.092	0.099	0.105	0.112	##	0.125	0.145	0.152	0.165	0.178	0.185	0.191



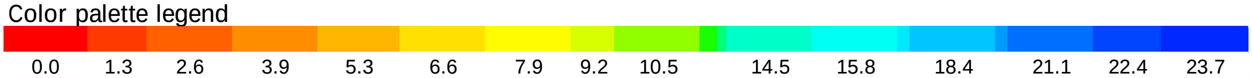


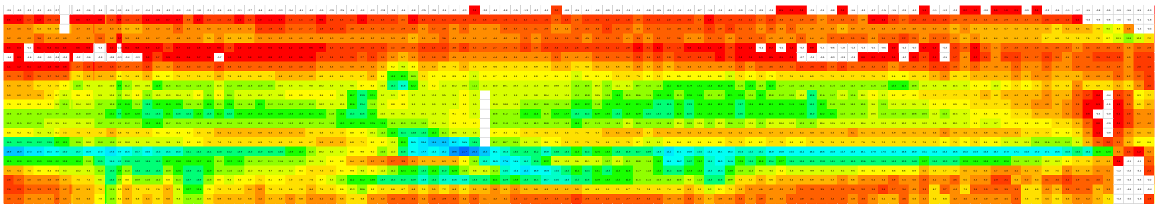


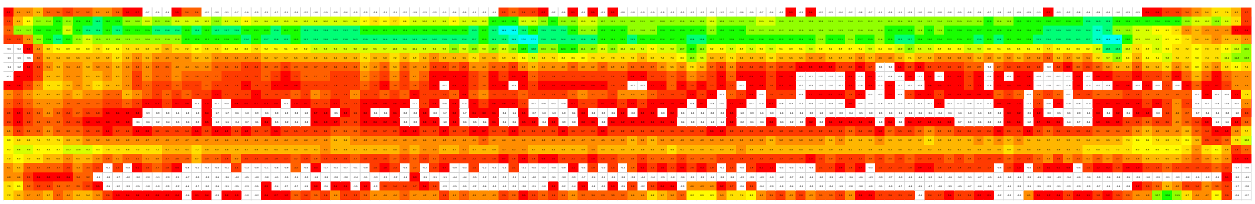


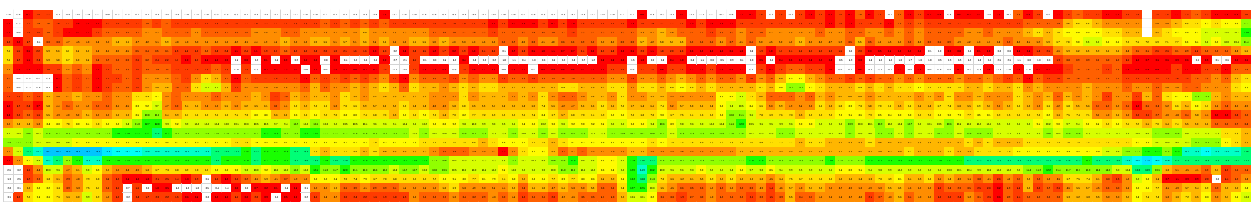
Wall loss percentage values

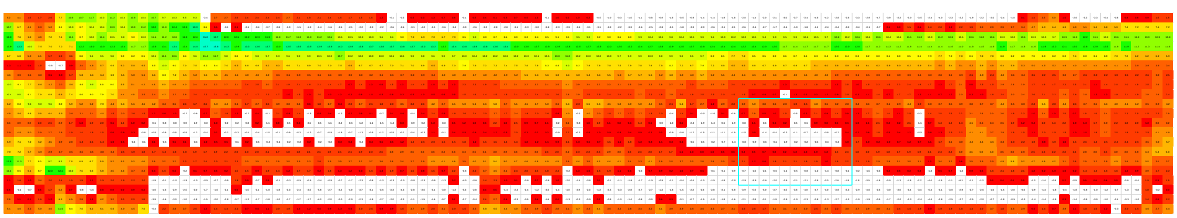
Color palette legend











APPENDIX C

Soil Sample Results

Soil Corrosivity Analysis Form

Client Name: Dewberry
Location / Area Name: See GPS Below
Soil Collection Date(s): See Below
CP Technician Name: Chris Shealy / Matt Jones

Sample ID	Date Tested	Sample GPS Location		Corrosivity Classification			Results
		Latitude	Longitude	Resistivity (Ω-cm)	Average Resistivity (Ω-cm)	pH (Units)	
1: West	10/25/2019	39.573928	-105.12780	N/A	N/A	N/A	N/A
As Found	10/25/2019	39.573928	-105.12780	4.42K 4.41K 4.41K	4.41K	5.5	Mildly Corrosive
Partially Saturated	10/25/2019	39.573928	-105.12780	1825 1822 1821	1,823	6.7	Moderately Corrosive
Saturated	10/25/2019	39.573928	-105.12780	1603 1597 1593	1,598	7.3	Moderately Corrosive
2: Central	10/25/2019	39.573933	-105.12762	N/A	N/A	N/A	N/A
As Found	10/25/2019	39.573933	-105.12762	1439 1440 1441	1,440	5.8	Moderately Corrosive
Partially Saturated	10/25/2019	39.573933	-105.12762	790 787 785	787	6.6	Corrosive
Saturated	10/25/2019	39.573933	-105.12762	672 671 670	671	7.2	Corrosive

Soil Corrosivity Analysis Form

Client Name: Dewberry
Location / Area Name: See GPS Below
Soil Collection Date(s): See Below
CP Technician Name: Chris Shealy / Matt Jones

Sample ID	Date Tested	Sample GPS Location		Corrosivity Classification			Results
		Latitude	Longitude	Resistivity (Ω-cm)	Average Resistivity (Ω-cm)	pH (Units)	
3: East	10/25/2019	39.573934	-105.12740	N/A	N/A	N/A	N/A
As Found	10/25/2019	39.573934	-105.12740	932 934 935	934	6.2	Corrosive
Partially Saturated	10/25/2019	39.573934	-105.12740	538 529 524	530	7.7	Corrosive
Saturated	10/25/2019	39.573934	-105.13	461 459 456	459	7.3	Very Corrosive

APPENDIX D

Pipe Results


.178"


TOP


4x4


TORQUE

APPENDIX E

Original 1955 Record Drawings

PLATE 1 - PLAN-PROFILE O. P. R. & R. E. STANDARD
THE FREDERICK POST CO., CHICAGO


N
HAROLD L. DE BACKER
BM# 24 SW Cor of W. Conc Wing Wall Sta 244+43
2°30'
2°00'
1°30'
BM# 25 3/4" x 3' Pipe Set in 8" Conc Footing S.W. P. Pole Sta 263+00
Abandoned RR Grade to 265+00
Abandoned RR Grade to 265+00
BM# 26 Iron Pipe Sta 265+50 EL 5577.61
8°27'
Marshall Road
Permanent Fence Gate
Permanent Fence Gates
HENRY AND FLORA CHOUSSARD
245+01.47
251+41.47
255+41
264+21.47
265+01.47
REVISED AS CONSTRUCTED 2/6/56
LW 10
WATER SUPPLY LINE FOR THE TOWN OF LOUISVILLE, COLORADO
STA. 242+00.0 TO STA. 272+00.0
PLAN AND PROFILE
HORIZ. SCALE 1" = 100' VERT. SCALE 1" = 10"
UTILITY ENGINEERING COMPANY
12345 WEST 19TH PLACE
DENVER, COLO.
BE 7-0389
DRAWN BY 7/14/55
CHECKED BY J. Russell Chamber 7/15/55
PLAN
PROFILE
ELEVATIONS
5590
5580
5570
5560
5550
5540
VPI 244+61.97 EL 5547.30
VPI 245+41.47 EL 5551.00
VPI 249+41.47 EL 5553.00
VPI 252+21.47 EL 5554.00
VPI 263+81.47 EL 5569.50
VPI 265+01.47 2" AIR and VACUUM RELEASE IN EL 5570.00
VPI 265+03.97 2" AIR and VACUUM RELEASE OUT EL 5570.00
VPI 267+03.97 4" BLOWOFF IN EL 5560.00
VPI 267+06.47 4" BLOWOFF OUT EL 5560.00
VPI 268+66.47 EL 5568.00
Natural Ground Surface
ADDITIONAL COVER
ADDITIONAL COVER
ADDITIONAL COVER
INVERT 16" PIPE
16" O.D. PIPE
242
245
STATIONS
250
255
260
265
270
PLATE PLAN PROFILE STANDARD
410-4

WATER SUPPLY LINE FOR THE
TOWN OF LOUISVILLE, COLORADO
STA 272+00.0 TO STA 303+00.0
PLAN AND PROFILE
HORIZ. SCALE 1" = 100'
VERT. SCALE 1" = 10'
UTILITY ENGINEERING COMPANY
12345 WEST 19TH PLACE
DENVER, COLO
BE 7-0389
DRAWN BY Joseph E. Krue Jr
7/14/55
CHECKED BY J Russell Chambers
7/15 55
LW 11
REVISED AS CONSTRUCTED Joseph E Krue Jr 2/6/56
LESLIE AND ALENE TAGGART
BM # 28 Top of Hub Sta. 300+49. El. 5686.
BM # 27 Spike in T Pole 40' N. Sta 273+50. El. 5586.78
HENRY AND FLORA CHOUSSARD
Marshall Road
Permanent Fence Gates
300+28.97
1°30'
PLAN
PROFILE
ELEVATIONS
STATIONS
Natural Ground Surface
INVERT 16" PIPE
ADDITIONAL COVER
16" OD PIPE
PIPE ANCHOR AT EACH JOINT, THIS AREA
VPI 272+86.47 EL 5576.00
VPI 273+86.47 EL 5580.00
VPI 275+86.47
VPI 276+26.47 EL 5589.50
VPI 285+46.47 EL 5592.00
VPI 288+66.47 EL 5600.00
VPI 289+86.47
VPI 293+86.47 EL 5614.00
VPI 300+26.47 2" AIR AND VACUUM RELEASE IN EL 5681.50
VPI 300+28.97 2" AIR AND VACUUM RELEASE OUT EL 5681.50
VPI 298+66.47 EL 5663.00
VPI 299+46.47 EL 5674.00
VPI 299+86.47 EL 5679.00
PLATE 1 - PLAN-PROFILE

WATER SUPPLY LINE FOR THE
TOWN OF LOUISVILLE, COLORADO
STA 303+00.0 TO STA 333+00.0
PLAN AND PROFILE
HORIZ SCALE 1" = 100'
VERT SCALE 1" = 10'
UTILITY ENGINEERING COMPANY
12345 WEST 19TH PLACE
DENVER, COLO.
BE 7-0389
DRAWN BY
7/14/55
CHECKED BY
7/15/55
LW 12
REVISED AS CONSTRUCTED
RUTH A SCOTT
LESLIE AND ALENE TAGGART
THRUST BLOCK
BM # 29 Top Hub Sta 313+60 El 5678.91
Buried Telephone Cable Mountain States Telephone and Telegraph Co
Denver Boulder Toll Road
EQUATION
WILLIAM E RUSSELL COAL CO
BM # 30 Spike in Fence Post
THRUST BLOCK
PLAN
PROFILE
ELEVATIONS
VPI 304+28.97 EL 5680.00
VPI 305+48.97
VPI 306+28.97
VPI 319+51.65 EL 5671.80
VPI 320+84.69 EL 5669.40
VPI 324+66.67 EL 5667.20
ADDITIONAL COVER
Natural Ground Surface
INVERT 16" PIPE
JACKED CASING UNDER ROAD. LINE PIPE IN SAND TO 1/2 DIA.
16" O.D. PIPE
5690
5680
5670
5660
5650
303
305
STATIONS
310
315
320
325
330
PLATE 1 PLAN PROFILE
410-4