CONDITION ASSESSMENT AND LEAK DETECTION

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ABBREVIATIONS AND DEFINITIONS

AC	Asbestos cement.
DI	Ductile Iron.
CI	Cast Iron.
GIS	Geographic Information System; a system designed to capture, store, manipulate, analyze, manage, and present all types of spatial or geographical data.
NR	No Result
POI	Point of interest; please refer to the technical glossary.
PVC	Poly-vinyl chloride; pipe wall construction consisting of poly-vinyl chloride.

1. EXECUTIVE SUMMARY

Client engaged Echologics, LLC (Echologics) to provide leak detection and condition assessment services to gain valuable evidence-based pipe condition information on their distribution water mains located in Colorado. The survey took place August 17th-19th, 2021.

1.1 SUMMARY OF KEY RESULTS

Echologics conducted the leak detection and condition assessment on 4,371 feet of water main, as per the following break down:

- 1,292 feet of 6” asbestos cement.
- 462 feet of 8” asbestos cement.
- 744 feet of 16” ductile iron.
- 1,269 feet of 12” spun cast iron.
- 604 feet of 16” spun cast iron.

Leak detection

- No leaks were discovered during the survey.

Condition Assessment

Eleven segments were assessed for remaining wall thickness, yielding the following results:

- Five segments appeared to be in poor condition with a change in effective wall thickness greater than 30 percent of the nominal thickness
- Four segments appeared to be in moderate condition with a change in effective wall thickness between 10 percent and 30 percent of the nominal thickness.
- Two segments appeared to be in good condition with a change in effective wall thickness less than 10 percent of the nominal thickness.

2. PROJECT BACKGROUND

The need for comprehensive condition assessment of our buried and aging water infrastructure is ever increasing. Most water companies and utilities across North America are struggling with budget and efficient management of the required renewal plans of their buried water assets that have reached the end of their service life. One of the primary concerns to water utility asset managers is prioritizing the limited renewal budgets to the assets that require it the most. This is where an effective condition assessment program can help. According to the Water Research Foundation, the objectives of an effective condition assessment should be to:

- Reduce the number and cost of failures, by identifying high-risk assets and enabling cost-effective, targeted, proactive remedies.
- Extend the lives of assets, by distinguishing those that are merely old from those that are truly impaired; and
- Reduce uncertainties, enabling confident answers to questions from the public and other stakeholders.

Echologics understands that these objectives hold true for CLIENT and their asset management program. Echologics completed this project to gain valuable evidence-based condition assessment information on segments of water mains in Littleton, CO.

The primary objectives were as follows:

- Determine the remaining structural condition of the water mains tested
- Along with condition assessment measurements, simultaneously investigate the system for the existence of any potential leaks

To achieve these objectives, Echologics utilized its patented ePulse® technology to assess the condition of the selected water mains. In addition to condition assessment, Echowave® leak detection was performed simultaneously with this survey. Based on the results, CLIENT will be able to make informed decisions on replacement and rehabilitation for end of service water mains. This report provides detailed information on how the above objectives have been met.

2.1 PROJECT SCOPE

The project included 4,371 feet of mains in Littleton, Colorado as shown in Figure 1 below.

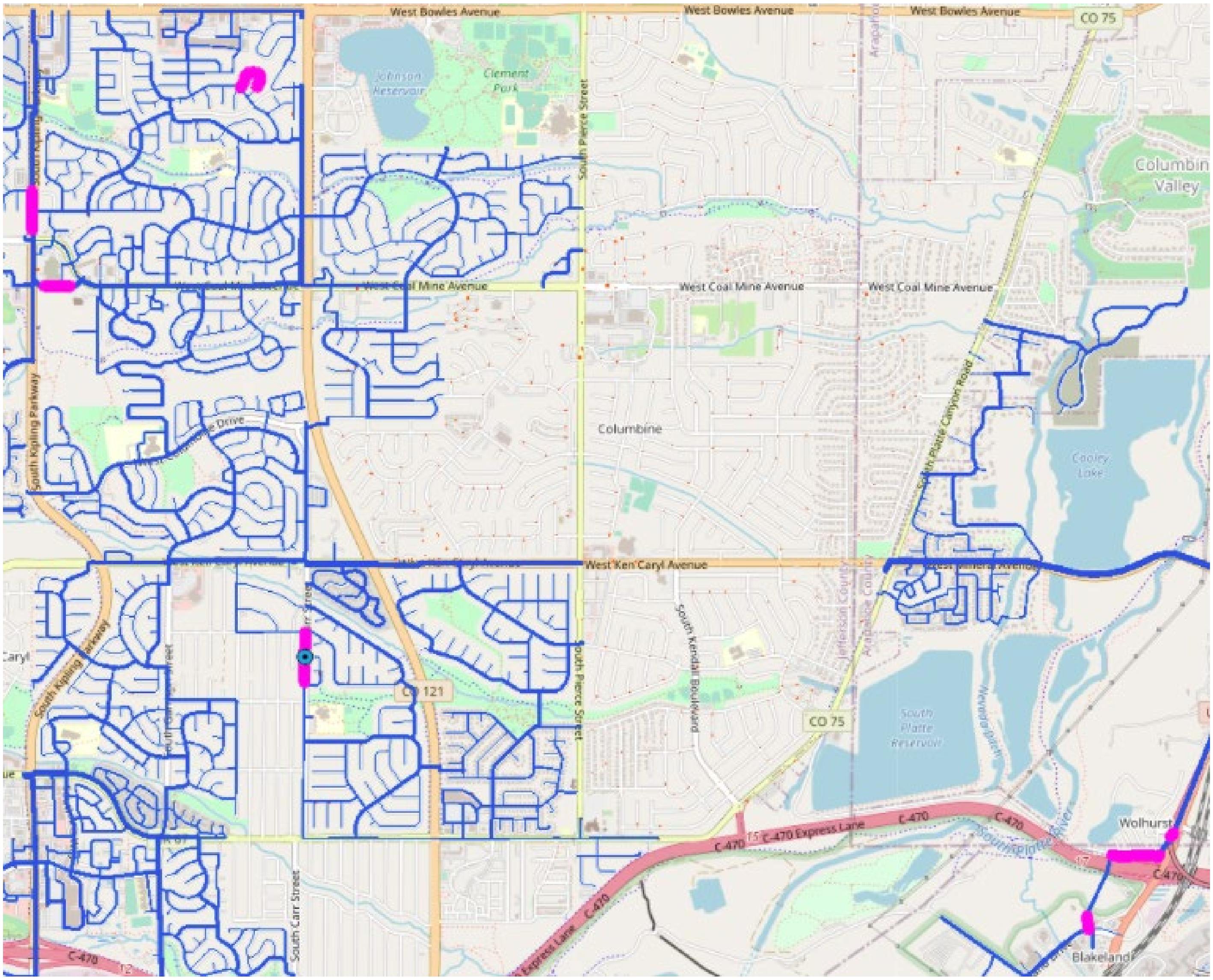

Figure 1: Project Scope

Field tests began on August 17th, 2021 and required 3 working days to complete with a team of two field staff, as well as additional utility support.

Echologics used the pipe properties shown in Table 1 for the condition assessment analysis.

Table 1: Pipe Properties

Pipe Material	Pipe Class	Approximate Install Year	Pipe Size	Mortar Thickness	Equivalent Nominal Thickness
			(in)	(inch)	(in)
Asbestos Cement	150	1970	6	N/A	0.66
Asbestos Cement	150	1970	8	N/A	0.76
Ductile Iron	50	1990	16	0.094	0.36
Spun Cast Iron	150	1961	12	0.063	0.49
Spun Cast Iron	150	1961	16	0.094	0.56

Pipe Class Nominal Thicknesses were determined by reviewing as-builds provided to Echologics. As-builds specified the Pipe Class requirements for each pipe material at the time of installation.

3. PROJECT METHODOLOGY

This section describes the methodology Echologics used to assess the water distribution mains in the project area. Echologics deployed its Echowave® Leak Detection technology to determine the presence and locations of leaks or points of interest, which are locations that indicate a potential leak and require further verification. The ePulse® technology was used to determine the current structural wall thickness of the water mains.

3.1 ECHOWAVE® LEAK DETECTION

The methodology employed is known as the cross-correlation method. With this method, a correlator listens passively for noise created by a leak. If a leak is detected, the correlator uses the time delay between sensors to determine the position of the leak.

For this leak detection survey, the following procedure was used:

1. For each location surveyed, the distance between the sensors was measured.
2. Sensors were mounted directly on valves connected to the pipe.
3. A correlation measurement was performed without introducing noise (known as a background recording), and the signal was saved to the computer so that further analysis could be performed off-site. A preliminary analysis was performed on-site to determine if any leaks were present.

No Leak Discovered

"No Leak Discovered" is classified when the audio recording doesn't display a correlation and the coherence at the two sensors is low. This is because, without a correlated noise source, there is no evidence of leakage. Where possible, leak simulations are performed to confirm the absence of leaks and to ensure equipment functionality. Refer to the Appendix C – Glossary of Technical Terms for definitions of correlation and coherence.

Point of Interest

A Point of Interest (POI) designation indicates that some, but not all, of the criteria for a positive leak detection result are met. This could mean that a strong correlation was observed, but coherence is poor, or that there is no confirmation of leak noise through other test methods such as ground sounding or secondary correlation tests.

A POI does not indicate a conclusive leak. However, if a POI is discovered, we recommend that CLIENT perform a secondary investigation to verify the presence and location of a leak.

Leak

Three pieces of conclusive evidence must be acquired for a POI to be classified as a leak. Such evidence can be established by the following methods of detection:

- Leak correlation.
- Ground sounding.
- Acoustic sounding of fittings.
- Visual observation of moving water.
- Confirmation of chlorine residuals in stagnant water.

Several criteria must be met for audio recordings to provide a definitive leak detection result. This includes, but is not limited to:

- A clean distinctive correlation peak.
- An observable coherence level.
- Similar frequency spectra in each channel.
- A minimum amount of clipping in the time signal.

In some instances, more than one correlation test can be used as evidence to conclusively identify a leak. For instance, a field specialist can perform multiple correlation tests with sensors mounted to different pipe fittings.

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3.2 EPULSE® CONDITION ASSESSMENT

A section of pipe length is bracketed by two sensor contact points on the main. The length of pipe between the sensors is referred to as a segment. A noise source is then created outside of that segment. This is typically done by tapping on a hydrant or valve. The noise source is used to determine the acoustic wave velocity in the segment of pipe. Knowing the distance between the sensors, the acoustic wave velocity (v) will be determined by v = d/t, where d is the length of pipe between the sensors, and t is the time taken for the acoustic signal to propagate between the two sensors.

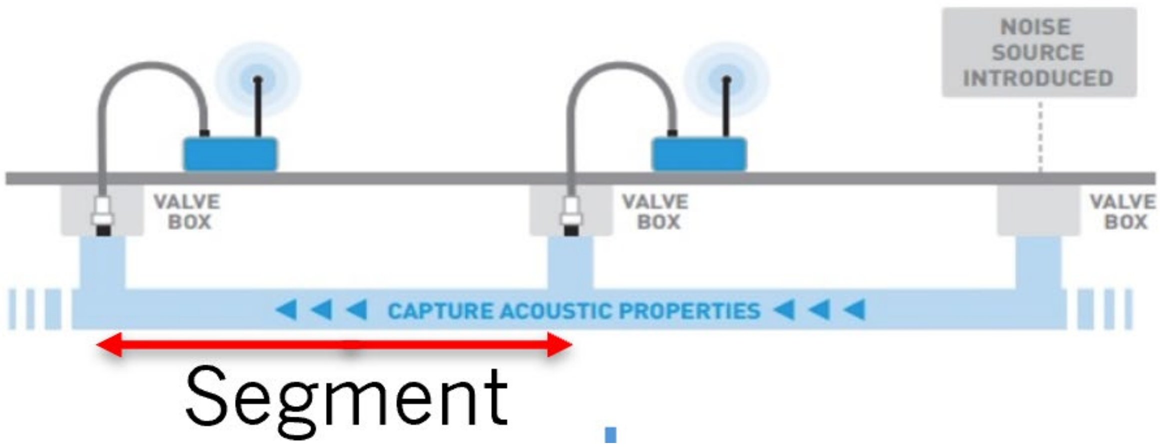

Figure 2: Typical ePulse field setup

The following procedure is followed to conduct an ePulse® data collection survey:

1. A leak detection survey is performed on the length of pipe to check for the presence of existing leaks (described in previous section).
2. A noise source is created "out-of-bracket." A variety of different noise sources can be used, including an existing leak noise, blow-off noise, pump noise, impulse noise, running a fire hydrant, tapping on a fire hydrant, or tapping directly on the pipe.
3. A new correlation measurement is performed and stored as a wave file for further analysis and confirmation off-site.

Wave Velocity Equation

The general form of the acoustic pipe integrity testing equation is shown below.

$$v = v_o \times \sqrt{\frac{1}{\left[1 + \left(\frac{D_i}{t_r}\right) \times \left(\frac{K_l}{E}\right)\right]}}$$

Equation 3-1: Wave Velocity - Thickness Model

v: measured velocity

v_{0}: propagation velocity in an infinite body of water

D_i : pipe internal diameter

K_l : bulk modulus of the liquid

E : elastic modulus of the pipe material

t_r : residual thickness of the pipe

Bulk Modulus of Water Calibration

Different water sources can produce a different bulk modulus of water. The bulk modulus essentially represents the water's inherent resistance to compression and is impacted by factors like water temperature, dissolved salts, and entrained air. Our field specialists calibrate the bulk modulus at each water company's water source. This requires performing a single test on a stretch of pipe with a known pipe condition. In practice, this generally means performing an additional test on a new section of pipe that has been installed within the past few years. ePulse® technology combines acoustic data measured in the field with information about a pipe's manufacturing to calculate its effective wall thickness (also known as mean structural hoop thickness). The pipe's material, internal diameter, and modulus of elasticity are critical variables in this calculation.

For project sites that don't have newly installed metallic pipe, a reasonable assumption is made for the Bulk Modulus of water based on previous project experience.

Remaining Wall Thickness

The percentage of effective wall thickness loss is calculated by comparing the thickness measured from acoustic testing (i.e., its effective wall thickness) to its nominal thickness. The results are also presented as a qualitative category indicating the condition of the main. Table 2 shows these qualitative condition categories. Detailed results of the condition assessment, including the change in effective wall thickness, are presented in Appendix A.

Table 2: Qualitative Categories and Color Coding

Change in Effective Thickness	Description	Color Code
Less than 10%	Good	Green
10% to 30%	Moderate	Yellow
Greater than 30%	Poor	Red

As previously stated, the ePulse® method tests the pipe's mean hoop thickness, which is different from the pipe's average thickness. A pipe's hoop stiffness is its resistance to axisymmetric expansion under the tiny pressure variations caused by sound waves. Material properties are then used to calculate the hoop thickness and stiffness.

Condition Interpretation in Asbestos Cement Mains

As asbestos cement pipes age and degrade, they do not lose physical thickness but do lose structural (or effective) thickness as the calcium leaches out of the asbestos cement matrix. This portion of the asbestos cement will become soft and will no longer bear a structural load. As a result, it will not contribute to the structural thickness.

The ePulse® method measurement is depicted in Figure 3.

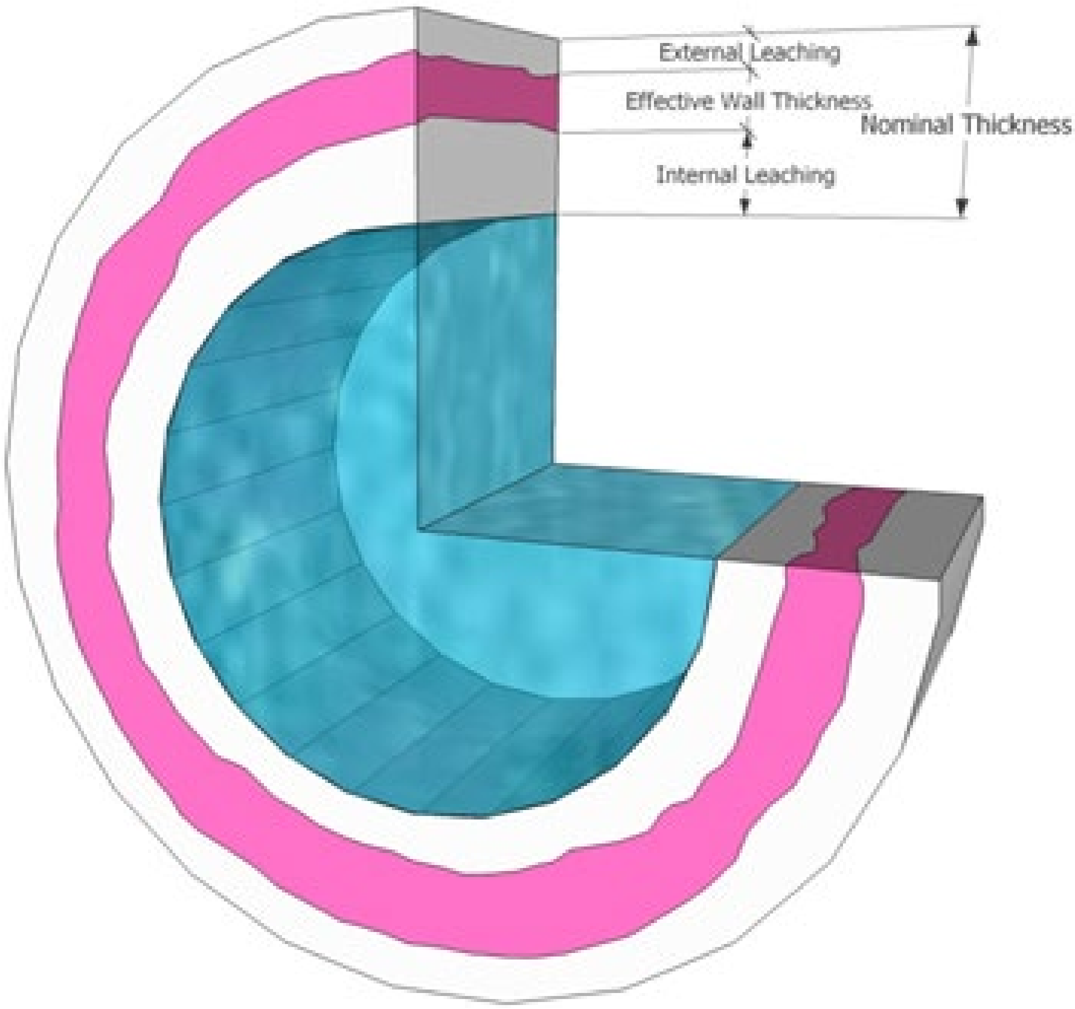

Figure 3: Effective Thickness in Asbestos Cement Pipe

Condition Interpretation in Metallic Mains

Corrosion can occur in metallic pipes either in a localized area or in a generalized manner along the main. Examples of various levels of corrosion are presented in Figure 4 below.

Most of the degradation is often caused by a combination of internal corrosion, soil aggressiveness and coating defects on the surface of the main. If no coating was present upon installation, then the degradation would be due to soil aggressiveness alone.

For cement mortar lined pipes, areas with higher losses may indicate the lining has been degraded to the point that the water column is now in contact with the metal, locally accelerating the degradation rate. This may also suggest that the soil loading conditions were such that the pipe experienced an over-deflection during its lifetime, causing damage to the interior lining.

When considering the water aggressiveness as a mechanism for corrosion, it can be assumed that the degradation is relatively uniform across the length of the main. If pipes are unlined (bare), internal degradation may be attributed to a combination of localized pitting, and the formation of tuberculation that can also be accompanied by the formation of graphitic corrosion (leaching of iron from the metal matrix).

Localized corrosion is most likely due to isolated mechanisms such as direct current corrosion, or localized aggressive soil conditions. For cement lined pipes, areas with higher losses may indicate the lining has been degraded to the point that the water column is now in contact with the metal, locally accelerating the degradation rate.

6” CI pipe with 4.2% measured loss

6” CI pipe with 47% measured loss

6” CI pipe with 10% measured loss

18” CI pipe with 18.5% measured loss

Figure 4: Examples of Different Levels of Corrosion in Metallic Pipe

4. RESULTS

4.1 LEAK DETECTION

No leaks or Points of Interests were discovered during the condition assessment survey.

4.2 EPULSE® CONDITION ASSESSMENT RESULTS

The ePulse® condition assessment results are presented in Table 3 below. Detailed results based on location are presented in Appendix A.

Table 3: ePulse® Pipe Condition Assessment Results

Segment ID	Street	Distance	Pipe Size	Pipe Material	Nominal Thickness	Effective Wall Thickness	% Change from Nominal Thickness
		(feet)	(in)		(in)	(in)	
210591A001		814.0	12	CI	0.49	0.43	-12
210591A002		202.0	12	CI	0.49	0.49	0
210591A003		102.0	16	CI	0.56	0.32	-43
210591A004		253.0	12	CI	0.49	0.37	-24
210591A005		487.0	8	AC	0.76	0.40	-47
210591A006		462.0	8	AC	0.76	0.46	-39
210591A007		502.0	16	CI	0.56	0.39	-30
210591A008		396.0	6	AC	0.66	0.45	-31
210591A009		409.0	6	AC	0.66	0.56	-15
210591A010		368.0	16	DI	0.36	0.30	-17
210591A011		376.0	16	DI	0.36	0.34	-5

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4.3 ANALYSIS OF RESULTS

Echologics assessed the pipe wall condition and checked for leaks on 4,371 feet of mains. The primary conclusions are as follows:

1. ePulse® testing indicates that:
    a. The two segments of 6” asbestos cement water main tested were found to be in moderate to poor condition with regards to remaining effective wall thickness, with 1 segment having a 15 percent change from the nominal thickness, and 1 segment having a 31 percent change from the nominal thickness. These segments were both on *South Dudley Way*.
    b. The two segments of 8” asbestos cement water main tested were found to be in poor condition with regards to remaining effective wall thickness, with both segments having greater than 30 percent change from the nominal thickness. These segments were both on *South Carr Stre*et.
    c. The three segments of 12” spun cast iron water main tested were found to be in good to moderate condition with regards to remaining effective wall thickness, with two segments having less than 10 percent change from the nominal thickness, and one segment having a 24 percent change from the nominal thickness. The segments identified in good condition were both on *Santa Fe Driv*e, and the one identified in moderate condition segment was on *Blakeland Drive.*
    d. The two segments of 16” spun cast iron water main tested were found to be in poor condition with regards to remaining effective wall thickness, with greater than 30 percent change from the nominal thickness. One segment was on *Santa Fe Drive,* and the other was on *Old Coal Mine Avenue*.
    e. The two segments of 16” ductile iron water main tested were found to be in good to moderate condition with regards to remaining effective wall thickness, with one segment having 5 percent change from the nominal thickness, and one segment having a 17 percent change from the nominal thickness. These segments were both located on *South Kipling Parkway*.
2. No leaks or Points of Interest were detected during the survey.

Echologics observed that segments with previous leak history appear to be in worse condition than segments with no previous leaks.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Echologics has successfully completed a pilot program for CLIENT on pipe wall condition and leak detection on 4,371 feet of water main in Littleton, CO. The main conclusions that can be drawn from this pilot study are as follows:

1. That ePulse testing can be easily implemented within the network without the need for excavations, external traffic control or substantial support from CLIENT water operators. The field-testing was completed without any interruption to service or disruptions to customers.
2. The ePulse acoustic field-testing obtained results for 100% of the segments tested. No segments tested returned a “No Result (NR)” status.
3. In addition to obtaining valuable structural condition assessment data, ePulse also could simultaneously survey the water mains for existing leaks – confirming no leaks were present at the time of the survey.
4. The ePulse® testing was able to isolate 1,922 feet of degraded pipe with over 30% wall thickness loss. These findings will assist CLIENT Metro’s replacement planning efforts, and has demonstrated the usefulness of ePulse® condition assessment data.

5.2 RECOMMENDATIONS AND NEXT STEPS

Based on the results of the condition assessment and leak detection for this project, Echologics offers the following overall program recommendations and next steps:

A. Discuss with Echologics' representatives' methods of incorporating ePulse® results within CLIENT Metro's asset management program. Currently, CLIENT uses break history, pipe material and age as the primary indicator of pipe condition. Echologics' experience suggests that supplementing this with measurements of structural pipe wall condition can improve the efficiency and effectiveness of capital improvement programs. Condition assessment results combined with other factors (pipe loading conditions, consequence of failure, road repair/renewal schedules, rate of decay, etc.) will improve capital asset planning and prioritization of pipe renewal efforts.

B. As only a small sample of mains were tested, CLIENT may wish to consider testing a larger sample with a wider variety of material and age.

C. The water mains identified to be in poor condition likely require immediate attention. Depending on pipe loading condition, these pipes are at higher risk of experiencing leaks and catastrophic failures and should be addressed as soon as possible.

Note that structural pipe condition is one of many factors in evaluating a pipe's suitability for service and should not be the only consideration for replacement and deferral decisions. Other important factors include pipe-loading conditions, hydraulic capacity of the pipe, road repair/renewal schedules, consequence of pipe failure, customer complaints, rate of decay, and others. With this is mind, we recommend the following actions for the three condition categories (not all categories may apply to the data collected thus far, but are provided for reference).

Good Condition Pipe – DEFER / LOW PRIORITY

According to the results of a condition assessment, the mains in this category are in good structural condition and do not need attention in the near future unless they have higher than normal loading conditions. The results suggest that the pipes in this category have a remaining effective wall thickness within 10 percent of the nominal wall thickness. Thus, we would suggest a utility continue with its standard maintenance programs for these mains.

Common industry practice is to conduct follow-up condition assessment testing in approximately ten years depending on the consequence of failure to allow for measuring the rate of change of condition with time. If these mains require rehabilitation for other reasons such as low pressure or poor water quality complaints, then cleaning and lining may be worth considering. The use and benefits of cathodic protection to slow or even stop the “aging” process of external corrosion may also be of interest.

When interpreting ePulse® results, asset owners should note the following:

1. Leaks can still occur on water mains with good pipe wall condition for reasons other than pipe wall degradation, such as pressure transients, leaks at joints, leaks on service connections, winter weather (freeze/thaw), poor installation, etc.

2. If a leak is detected on these segments, repairs should be sufficient for remediation, because the majority of the remaining pipe wall is in good structural condition.

3. The need for future assessment of these pipes should account for consequence of failure. Depending on the consequence of failure, it may be beneficial to equip these pipelines with a continuously monitoring leak detection system. For example, a non-redundant main servicing a hospital may benefit from immediate detection of leaks as soon as they develop.

Moderate Condition Pipe – MONITOR / MEDIUM PRIORITY

According to the results, the pipes in this category are in moderate condition and should be monitored depending on the pipe loading conditions. Note that pipes in this category may show a reduced capacity to withstand loading conditions, especially those approaching 30 percent loss in effective wall thickness.

Depending on the criticality of the main, we recommend monitoring these pipes. The following are some possible monitoring methods:

1. For mains without an internal lining, cleaning and lining can often extend the life of moderate condition mains. Adding cathodic protection can extend their life as well.
2. Regularly scheduled traditional leak detection surveys are a relatively inexpensive option that allow for finding leaks in a system. However, this method can be fairly labor-intensive and may not prevent catastrophic failures on high consequence pipelines.
3. A permanent leak monitoring system capable of finding most leaks on a pipeline can be beneficial. This includes small leaks before they turn into catastrophic failures.
4. A follow-up condition assessment survey is beneficial to measure the rate of decay and update the condition of the mains. A common practice is to reassess these mains in five years depending on the consequence of failure, and an analysis of the results can be used to determine the decay rates. The current decay rate may have an impact on the remaining service life of the mains. Measuring this can improve asset management.

Poor Condition Pipe – ADDRESS / HIGH PRIORITY

According to the results, pipes in this category are in poor condition and likely need urgent attention. Depending on pipe loading conditions, the pipes are at a higher risk of experiencing leaks and catastrophic failures and should be addressed as soon as possible. As noted above, other important factors should also be considered when preparing a remediation or replacement plan.

In most Cles, pipe segments that fall within this category have reached the end of their useful life. Actions such as structural lining, slip-lining, and/or full replacement should be investigated as an immediate requirement.

Each water network has its own dominant degradation mechanism and unique local considerations. We recommend that CLIENT use the results in this report along with other data and information from other services. This additional asset information may include the following:

- **Soil Corrosivity.** This comparison will help determine if external corrosion due to aggressive soil is a significant degradation mechanism. For example, if corrosive soils are discovered and the main is in poor condition, the degradation is likely related to soil conditions.
- **Water Aggressiveness.** The water's pH level, total alkalinity, and calcium hardness will reveal if the water is a mechanism for uniform degradation. For example, aggressive water would suggest that some of the degradation occurs inside; this degradation can be assumed to cause similar degradation rates for similar types of main.
- **Break History.** Collating condition assessment results and break history help identify sections of main at an increased risk of failure. These factors are not necessarily related, since pipes can have high break rates for reasons other than pipe wall degradation.
- **Consequence of Failure.** A combination of condition assessment results and a consequence of failure analysis is used to generate a risk assessment.

6. DISCLAIMER

All forms of non-destructive testing involve inherent uncertainty. Such testing depends on input parameters, and outputs can be significantly affected by variation from assumed parameters. This report includes certain suggestions and recommendations made by Echologics that are based on the following:

1. The findings included in the report.
2. The firm's experience.
3. An understanding of the client's particular requirements.

We acknowledge that the client may use this report to consider potential opportunities for pipeline repairs/replacement/rehabilitation; however, we disclaim any liability that may arise in connection with decisions based on these suggestions or recommendations or their implementation.

APPENDIX A DETAILED CONDITION ASSESSMENT RESULTS

This section provides a detailed presentation of the project scope, the data collected, and the results obtained during the project.

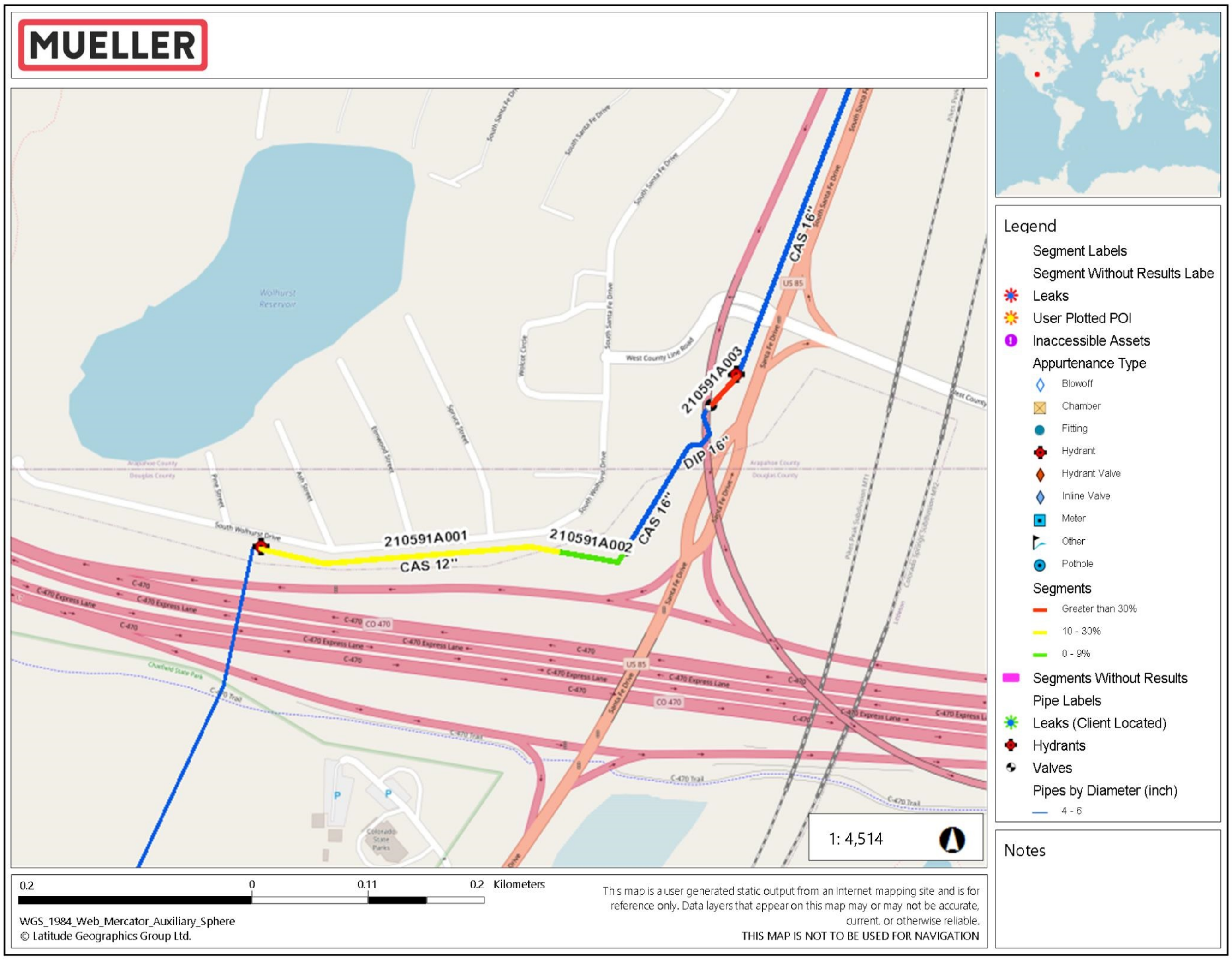

Figure A-1:

Table A-1: ePulse® Condition Assessment Results

Segment	Street	Blue Sensor	White Sensor	Length	Pipe Size	Pipe Material	Nominal Thickness	Effective Wall Thickness	% Change from Nominal Thickness
				(feet)	(in)		(in)	(in)	
210591A001		FHV10716035	Echo-4	814	12	CI	0.49	0.43	-12
210591A002		VV10724226	Echo-4	202	12	CI	0.49	0.49	0
210591A003		FHV10716036	11246457	102	16	CI	0.56	0.32	-43

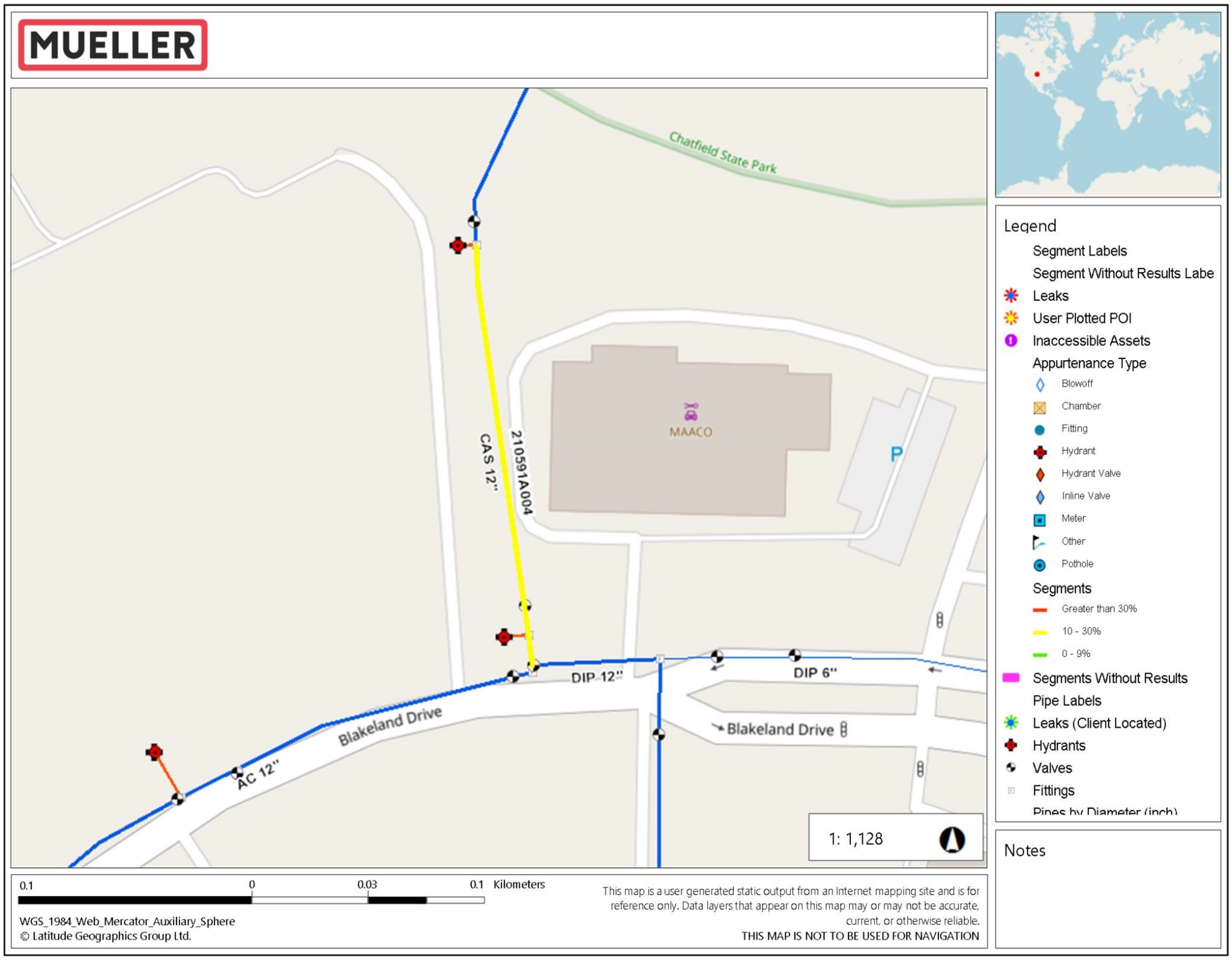

Figure A-2:

Table A-2: ePulse® Condition Assessment Results

Segment	Street	Blue Sensor	White Sensor	Length	Pipe Size	Pipe Material	Nominal Thickness	Effective Wall Thickness	% Change from Nominal Thickness
				(feet)	(in)		(in)	(in)	
210591A004		VV10724223	Echo-6	253	12	CI	0.49	0.37	-24

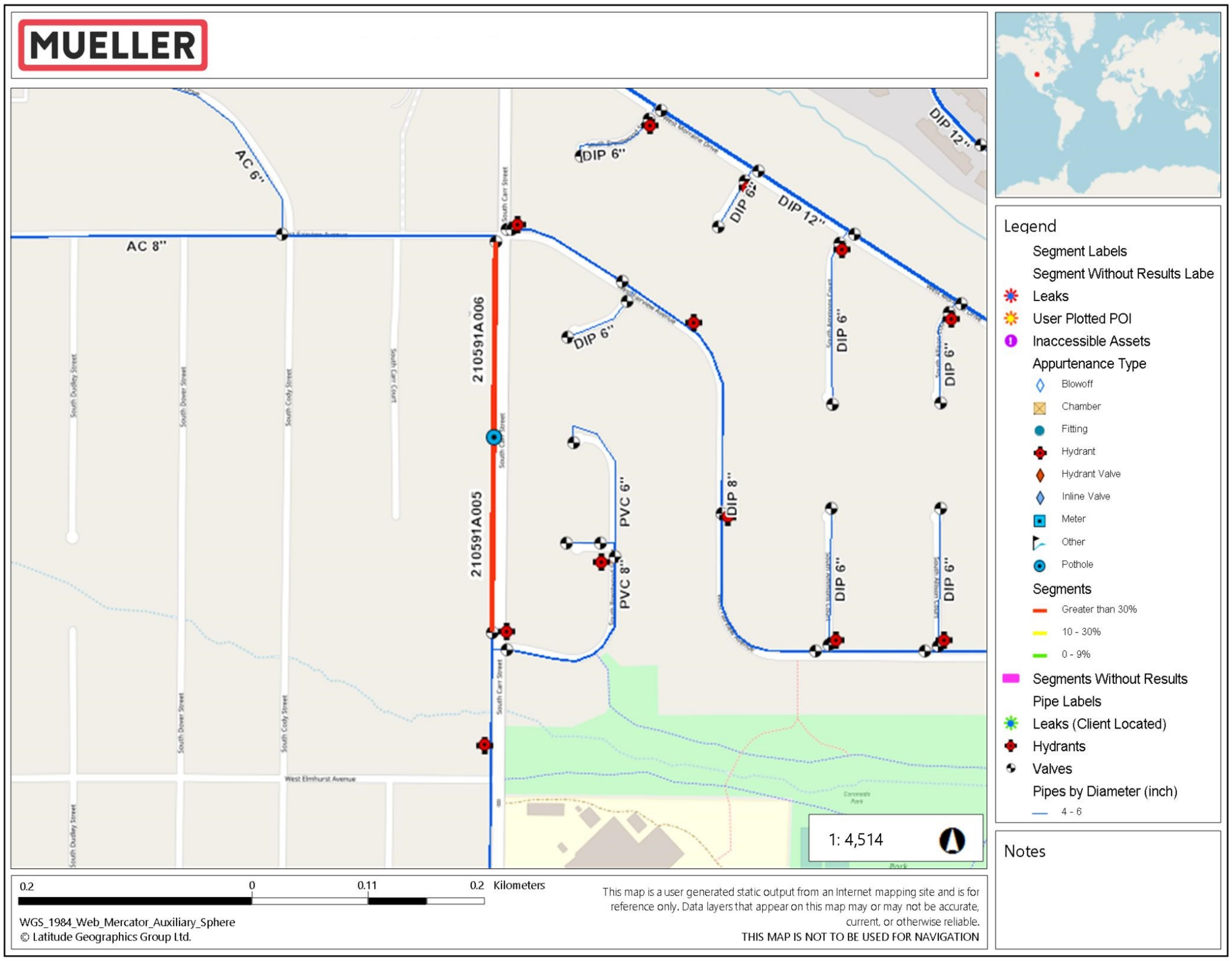

Figure A-3: **Table A.1-3: ePulse® Condition Assessment Results**

Segment	Street	Blue Sensor	White Sensor	Length	Pipe Size	Pipe Material	Nominal Thickness	Effective Wall Thickness	% Change from Nominal Thickness
				(feet)	(in)		(in)	(in)	
210591A005		PH3326-1	VV10723075	487	8	AC	0.76	0.40	-47
210591A006		PH3326-1	VV10723129	462	8	AC	0.76	0.46	-39

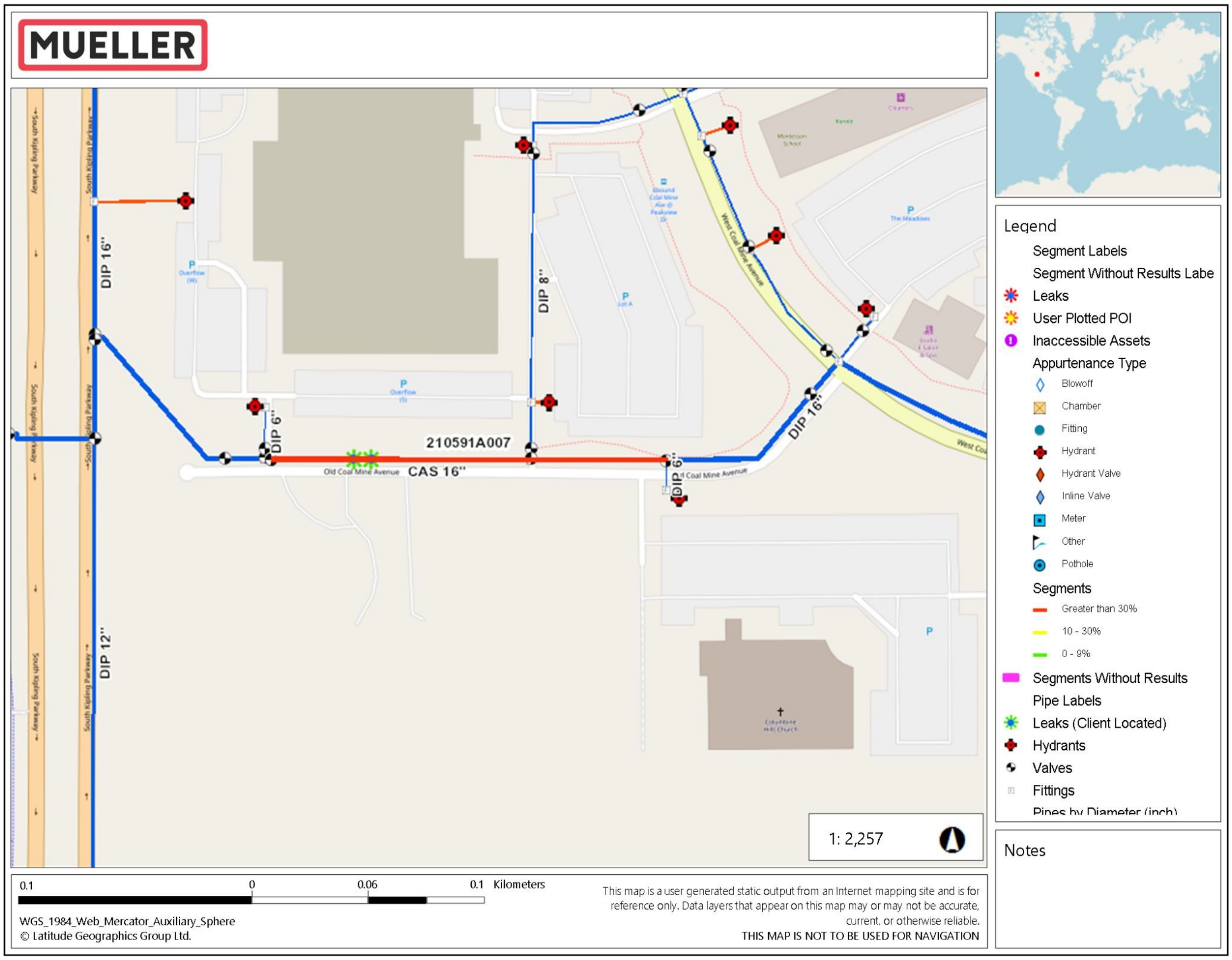

Figure A-4:

Table A-4: ePulse® Condition Assessment Results

Segment	Street	Blue Sensor	White Sensor	Length	Pipe Size	Pipe Material	Nominal Thickness	Effective Wall Thickness	% Change from Nominal Thickness
				(feet)	(in)		(in)	(in)	
210591A007		VV10725676	GIS-Vlv-5139	502	16	CI	0.56	0.39	-30

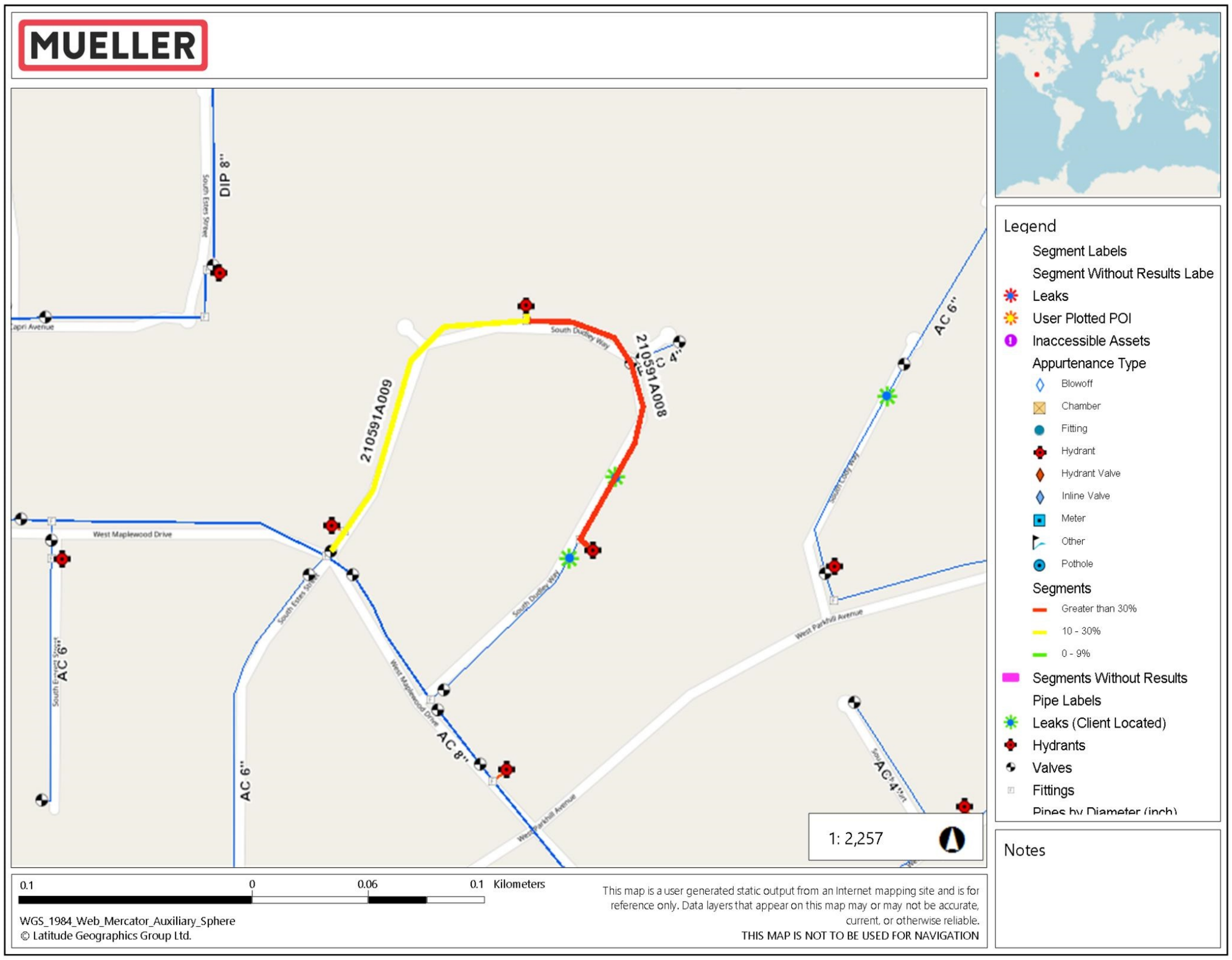

Figure A-4:

Table A-4: ePulse® Condition Assessment Results

Segment	Street	Blue Sensor	White Sensor	Length	Pipe Size	Pipe Material	Nominal Thickness	Effective Wall Thickness	% Change from Nominal Thickness
				(feet)	(in)		(in)	(in)	
210591A008		Echo-8	Echo-7	396	6	AC	0.66	0.45	-31
210591A009		VV10721759	Echo-7	409	6	AC	0.66	0.56	-15

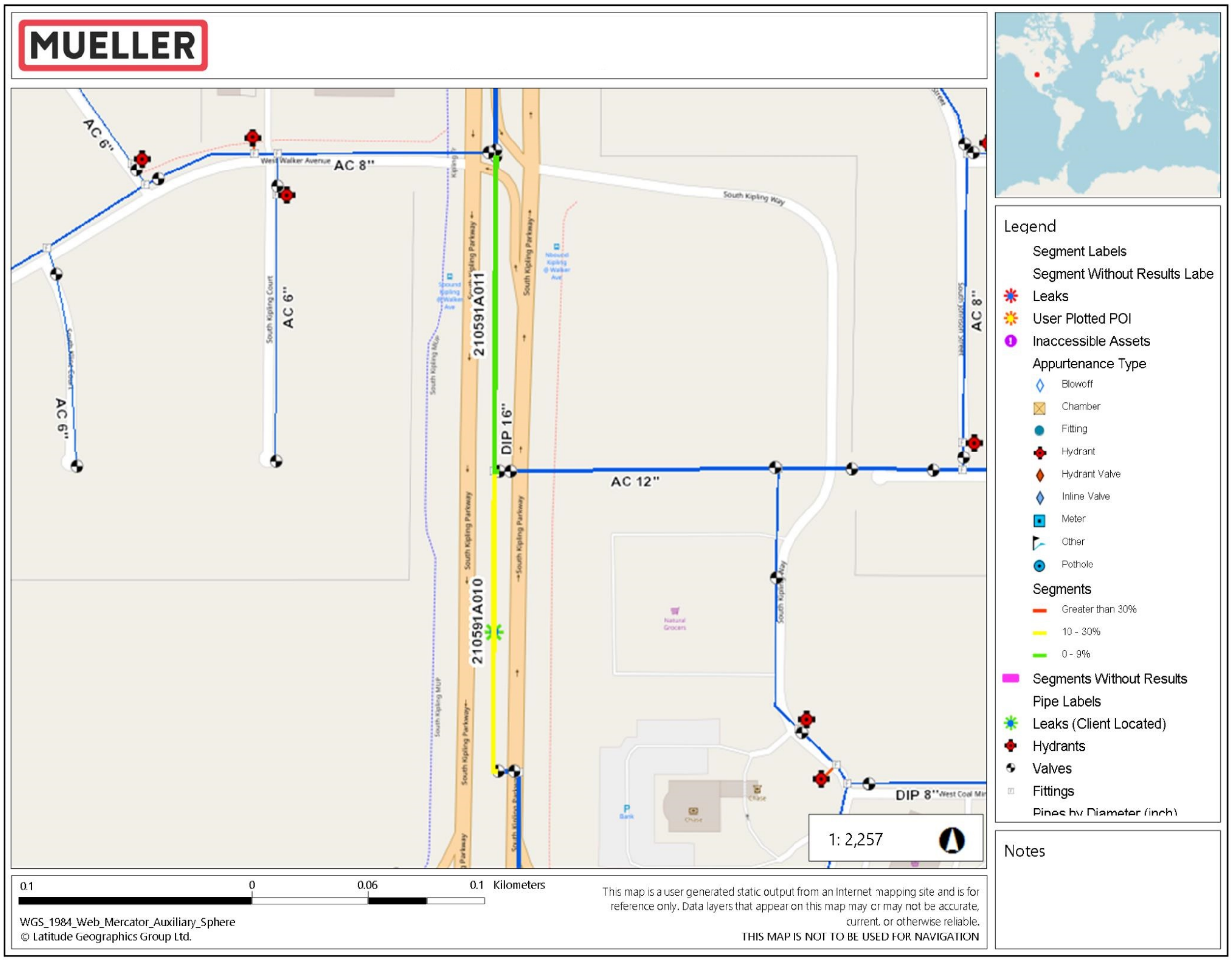

Figure A-5:

Table A-5: ePulse® Condition Assessment Results

Segment	Street	Blue Sensor	White Sensor	Length	Pipe Size	Pipe Material	Nominal Thickness	Effective Wall Thickness	% Change from Nominal Thickness
				(feet)	(in)		(in)	(in)	
210591A010		11229918	VV10725697	368	16	DIP	0.36	0.30	-17
210591A011		11229918	VV10724004	376	16	DIP	0.36	0.34	-5

APPENDIX B INTERPRETATION OF RESULTS

B.1 DISTRIBUTION OF DEGRADATION WITHIN SEGMENTS

Each ePulse® result represents an average condition within a segment between two sensor attachment points. Pipe conditions may vary within a segment. The condition at any one point in the segment may not reflect the average conditions within that segment.

To obtain the effective wall thickness mechanically, one would divide a pipe into hoops, measure the thickness of structural material around the circumference of each hoop (i.e., graphite, tuberculation product, or asbestos cement with the calcium leached out would not be counted), and then average the values.

For example, any of the following descriptions will hold true for a pipe with a loss of 25 percent:

1. Circumferentially uniform loss of 25 percent along the entire segment.
2. Circumferentially uniform loss of 50 percent along half of the segment, but 0 percent loss along the other half of the segment.
3. Loss of 25 percent at the crown of the pipe along the entire segment, but 0 percent loss along any other point in the circumference along the entire segment.

These descriptions hold true for asbestos cement, metallic, and reinforced concrete mains.

When considering the water aggressiveness as a mechanism for corrosion, the degradation can be assumed to be relatively uniform across the length of the main. If pipes are unlined (bare), internal degradation may be attributed to a combination of localized pitting and the formation of tuberculation, which can also be accompanied by the formation graphitic corrosion (leaching of iron from the metal matrix).

B.2 VALIDATION

As of January 2019, a total of 173 ePulse® validation results have been provided by clients or third parties. While some clients have requested confidentiality, we can present the result in aggregate.

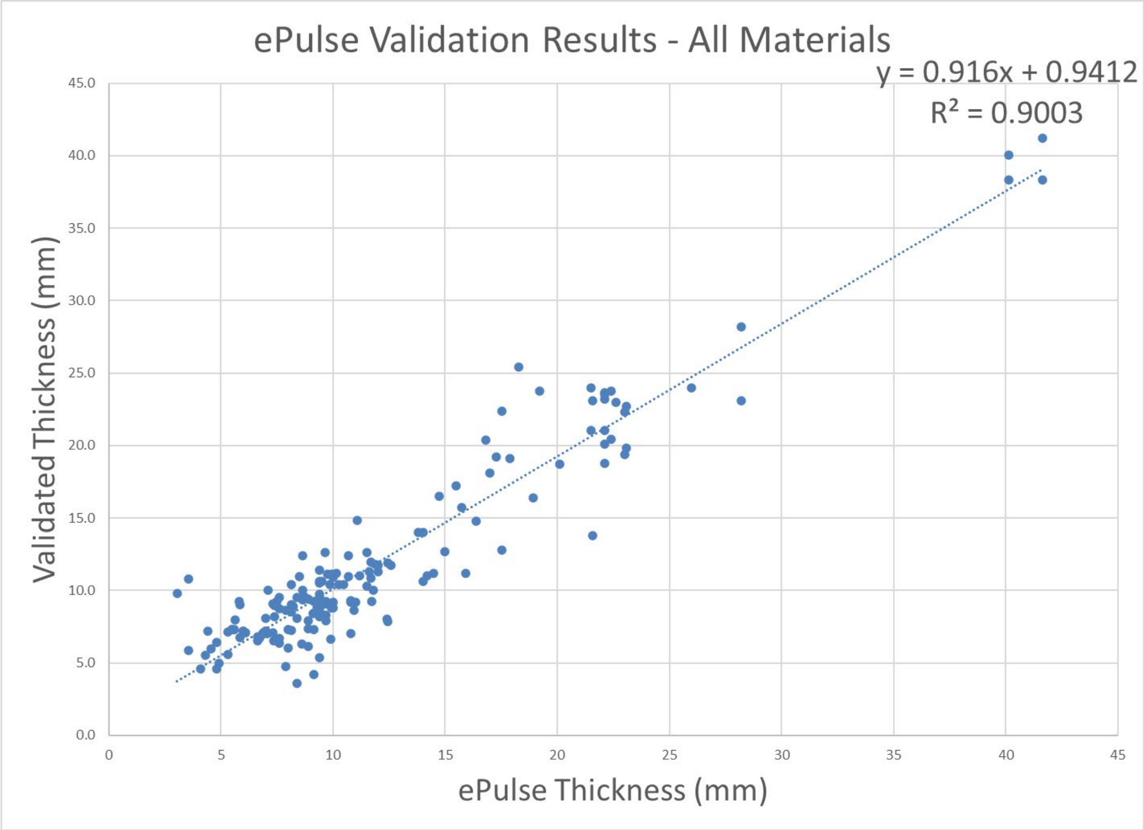

Figure B.2-1: ePulse® Validations On All Materials

Two elements of the chart are noteworthy. First, the R^2 value—known as the coefficient of determination—measures how well ePulse® results predict validation results. In other words, the R^2 value is the proportion of total variation of outcomes in validation results explained by the ePulse® results. An R^2 of 1 indicates that the data match perfectly, while an R2 of 0 indicates that the ePulse® results cannot be used to predict the validated results at all. For non-destructive testing methods, an R^2 value above 0.5 represents strong predictive ability.

The correlation coefficient R is the square root of the R^2 value. For example, an R^2 value of 0.5 means the same thing as a correlation of 0.71.

The equation ($y = \alpha + \beta x$) indicates how well calibrated the ePulse® measurements are, on average. Values of α close to zero and of β close to 1 indicate good calibration. For non-destructive testing methods, a β greater than 0.5 and an α less than 25 percent of the average value represent good calibration.

Note that the variation between the ePulse® results and validation measurements is not the same thing as the error in the ePulse® results. It is actually the combination of the error in the ePulse® results and the random variation in point samples versus the true average.

Comparing ePulse® results to the results of validations will overestimate the actual error in the ePulse® results. This is because the ePulse® results are averages over segments of about 100 m (~328 ft) in length, whereas the validation results indicate thickness at a single point or a small sub-segment. Each validation measurement will have a random error versus the true average over that segment. The difference between an ePulse® measurement and a validation measurement can be understood as follows:

ePulse® - Validated = (ePulse® – True_Average) + (True_Average – Validated)

Even if the ePulse® results perfectly match the true average (ePulse® – True_Average = 0), we would still expect to see a difference between validation results and ePulse®:

ePulse® - Validated = (True_Average – Validated)

Actual pipe conditions vary randomly along the sample, so the difference between the true average and validation results should be a normal distribution around zero. If ePulse® is effectively measuring the true average, the same pattern should be present in the difference between the ePulse® and the validated results. The actual distribution is shown in Figure B.2-3 and appears to match the expected pattern.

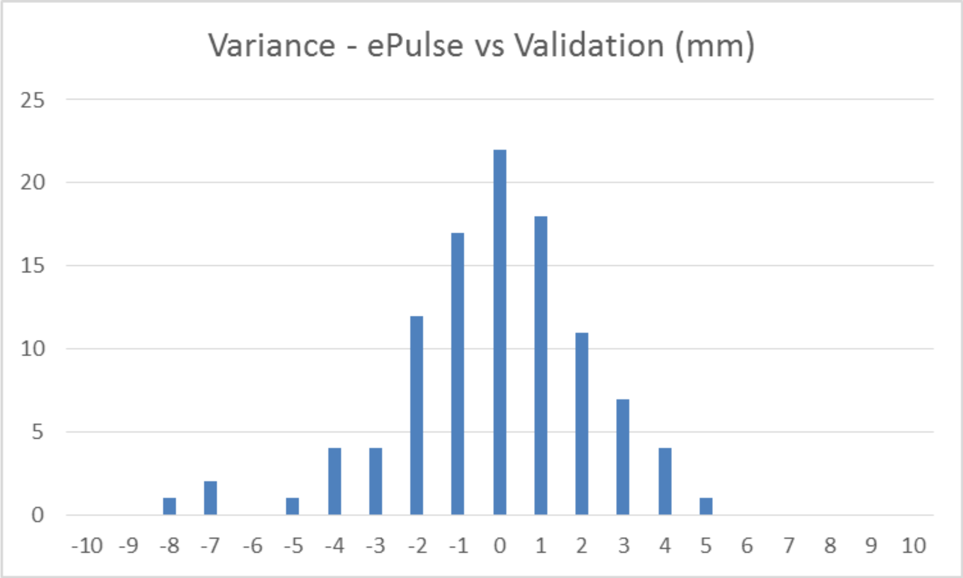

Figure B.2-2: Variance between ePulse® results and validation results

There are a small number of outliers, which likely represent errors in those ePulse® measurements. The remainder of the data match the expected normal distribution.

B.3 LIMITATIONS

Certain factors can affect the accuracy of the results presented in this report. Some of these factors are explained below.

Modulus of Elasticity

The modulus of elasticity of the pipe material is one factor in calculating the effective wall thickness. While Echologics has significant experience estimating the modulus of elasticity based on the material, age, and region of manufacture, the accuracy of the results can be improved by testing the actual modulus of elasticity of an exhumed sample of the pipe. If interested, please contact Echologics for more information.

Statistical Variation

The values generated by ePulse® testing are averaged for a segment of pipe that ranges from 300-600 feet long, with some segments as long as 700 feet. Averaging allows for the possibility of having small lengths that are severely degraded within the segment. Since this degradation may not be shown in the final result, the value presented describes the general condition of the pipe and may not show future potential point failures.

Sensitivity Analyses and Considerations

Several variables may affect accurate analysis:

- Inaccurate distance measurements.
- Variance in manufacturing tolerances.
- Variance in the modulus of elasticity of the material.
- Unknown pipe repairs.
- Inadequate correlation signals.

Attempts are made to reduce error throughout the testing process.

Distance Measurement

An accurate distance measurement is crucial for an accurate assessment. In general, a 1 percent error in distance measurement can result to more than a 2 percent error in the final percentage of thickness lost. For this reason, we prefer to use potholes or in-line valves, since it is a point-to-point measurement. As the number of bends and/or elevation changes between the sensor connection points increases, so does the potential error in the distance measurement.

Pipe Manufacturing Tolerances

Small differences in nominal specifications will occur between pipes due to differences in manufacturers and tolerances. These differences commonly range from between 5 and 10 percent, depending on the manufacturer and the material. Furthermore, a contractor may have installed a pipe that exceeds the minimum specifications. Under these circumstances, the measurements may show a pipe with an effective wall thickness greater than expected. This is particularly true of older pipes as their tolerances were not adhered to as strictly.

The material properties used for calculations are selected using conservative estimates. This provides for a worst-Cle scenario analysis.

Repair Clamps on Previous Leaks

Acoustic waves are primarily water borne. As such, a small number of repair clamps will have an insignificant effect on the test results, since the acoustic wave will bypass the clamps.

Modulus of Elasticity

A change in elastic modulus of 10 percent will cause a change in the calculated thickness by approximately 10 percent. The elastic modulus is known for common materials used in the manufacturing of pressure pipe, but this value can vary among manufacturers and depends on the manufacturing process and the quality of the material.

Similar to pipe manufacturing tolerances, the material properties used for calculations are selected using conservative estimates. This provides for a worst-Cle scenario analysis.

Unaccounted for Replacement of Pipe Sections during Repairs

Acoustic waves propagate differently depending on the pipe material. This effect remains true for short pipe replacements that are unaccounted for with different materials and can result in significant error. For example, a new 6-meter-long (~20 feet) ductile iron repair in a 100-meter-long (~328 feet) CIt iron pipe section of average condition will produce a small error of +3.5 percent in measured effective wall thickness. However, the same repair made with PVC pipe would produce an error of -41 percent in measured effective wall thickness.

Preferably, pipe sections selected for testing should be free of repaired sections. If this condition does not exist, the impact of the repaired pipe section can be accounted for with accurate information for the age, location, length, material type, and class of the repair pipe section.

Inadequate Correlation Signals

Inadequate correlation signals can sometimes occur in the field. The following are some of the conditions that may cause an inadequate correlation:

1. The presence of plastic repairs in metallic pipes, which can cause poor propagation of sound.
2. Loose or worn components in fittings used for the measurements, such as valve or hydrant stems.
3. Large air pockets in the pipe which heavily attenuate acoustic signals.
4. Heavily tuberculated pipe, particularly old CIt iron or unlined ductile iron pipes, which can attenuate the acoustic signals to such an extent that a correlation is of very low quality.

APPENDIX C GLOSSARY OF TECHNICAL TERMS

Acoustic Wave Speed	Also known as wave speed, wave velocity, velocity. It is the speed at which a coupled-mode pressure wave travels along a pipe.
Blue/White Station	A piece of equipment where a sensor is connected to transmit the data to a central location. Typically stations are color-coded blue or white.
Coherence	Measure of similar vibration frequency between two channels (blue and white stations or a node pair).
Correlation	The process of comparing two acoustic signals for similarity in the time domain. Echologics uses correlation to judge the time delay between two signals to determine the location of leaks along a pipeline.
In-Bracket	A noise source within the span of pipe between two stations or nodes.
Leak Discovered	A point along a pipe that is likely losing water to the surrounding soil and environment. For a leak to be classified as discovered, a field technician must acquire at least three pieces of unique evidence that suggest existence and location.
No Leak Discovered	No evidence of leakage was discovered, or a POI was under investigation and determined not to be a leak.
Out-of-Bracket	A noise source outside the span of pipe between two stations or nodes.
Point of Interest	Evidence of some form of noise or energy on the pipe. There is not enough evidence to classify a point of interest as a leak.
Segment	A section of pipe surveyed in one measurement. The length of the segment is the distance between two sensors.
Sensor	A device used to measure physical or chemical properties of a system. In the context of this report, this term is typically used as a reference to a vibration sensor.
Site	A neighborhood or area within which a segment of pipe exists.

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