WAREHAM FIRE DISTRICT
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August 7, 2018

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MassDEP - Division of Municipal Services
20 Riverside Drive
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RE Final Report for the Round 4 AMP Grant
Project Number BWR 2018 – 04
Project Name: Water Infrastructure Assessment and Planning Grant
Wareham Fire District – Water Department

Dear Mr. Rodgers:

Please find the final report for the above referenced project. If you have any further questions regarding the matter, I can be reached at 508-295-0450.

Best regards,

Andrew Reid PE BCEE
Water Superintendent

Attachment:
Final Report

The following tasks were proposed as work items as part of the contract. The results for each task are reported and discussed.

1. **Task 1 - Meetings**

Objective: Wareham Water will meet with Kleinfelder and Echologics® through the duration of the project. This will consist of a kick-off meeting, a mid-project meeting and a review of results presented to the Board of Water Commissioners at a publicly posted regular meeting at the end of the project. Wareham Water will provide grant administration and fiscal/progress reporting.

Status: Wareham Water has performed a kick-off meeting for the project. From that meeting the segment of pipes to be tested were selected and dates to perform the work were also determined.

Work Remaining: The results of this report are to be shared with the Board of Water Commissioners on at the September 17, 2018 board meeting.

2. **Task 2 - Identify the sections of pipe to be tested**

Objective: The project team will prioritize and decide on the sections of pipe to be tested using ePulse® technology. The goal is to select representative sections throughout the district so that results could be applied to other segments of similar characteristics.

Status: Wareham Water selected 6 samples of size, age and material of water mains to be evaluated for condition assessment and to provide data for the long-term water main replacement program. Wareham Water utilized Echologics® to provide the acoustic testing using their "E-Pulse" method. Wareham Water also collected two-feet in length pipe samples for burst testing by McWane one of the industry's leading pipe manufacturer. Table 1 lists the pipe selections, age, material, diameter and location. While it is best to obtain physical sections of pipe which correspond with locations where Echologics® will be testing, it was not necessarily easily done in all cases. Hence where deviations were taken, pipe in similar soil, age, and material were selected.

Table 1: Pipe Characteristics for Testing

Age	Diameter	Material	Acoustic Testing Location
1936	10"	Cast Iron	Cranberry Highway/Warr Avenue/Driftwood Lane
1936	6"	Cast Iron	Broadmarsh Avenue/Pilgrim Ave.
1999	12"	Ductile Iron	Plymouth Ave
1999	8"	Ductile Iron	Lake Avenue
1967	12"	Asbestos Cement	Gault Road
1967	8"	Asbestos Cement	Papermill Road

Age	Diameter	Material	Pipe Sample Collection (Destructive Testing)
1936	10"	Spun Cast Iron	Driftwood Lane
1936	8"	Pit Cast Iron	Great Neck Road
1990	12"	Ductile Iron	Bourne Hill Road
1999	8"	Ductile Iron	Priscilla Ave at Lake Ave
1970	12"	Asbestos Cement	Hathaway Road
1967	8"	Asbestos Cement	Papermill Road

Work Remaining: Task Completed.

3. **Task 3 - Non-destructive testing using ePulse® technology**

Objective: Echologics® will proceed to test the segments identified in Task 2. Data will be compiled and reported by Echologics® maintaining the existing Asset ID of each pipe segment.

Status: Non-destructive testing is complete. Final report provided in Appendix A.

Work to Remaining: Task Completed.

4. **Task 4 - Destructive testing**

Objective: Wareham Water, as time and weather permits, will dig up on segment of each pipe material (D.I., C.I. and A.C.). Segments were shipped McWane Pipe for destructive testing.

Status: The samples we shipped to McWane Pipe. After receiving the pipe, McWane Pipe indicated that that they could not test the AC pipe (incorrectly listed as fiberglass in the report). Thus, the four iron pipe segments were tested. The summary of the results is provided in Table 2. The final report is provided in Appendix B.

Table 2 – Pipe Destructive Testing Results

Specimen	Tensile Strength, psi DI Design = 42,000 psi	Max. Test Pressure, psi	Notes
8-inch Ductile	49,500	1,800	No break
12-inch Ductile	53,500	1,100	Testing apparatus cap failed to hold past pressure
8-inch Pit Cast	No value due to pipe break.	1,580	Catastrophic failure
10-inch Spun Cast	29,500	N/A	Sample too short for pressure test – threaded connection leaked.

A 12-inch pipe was used to determine the target minimum thickness (or alternatively percent corroded) using the data above as well as ANSI/AWWA 150/A21.50 – Thickness Design of

Ductile Iron Pipe. The results are used as a criterion for pipe replacement. The results are provided in Table 3.

Table 3: Required Thickness for a 12-inch Pipe for Type 1 Laying Conditions

Stress	12 Inch Pipe Required Thickness, in.
Ductile Iron	
Internal Pressure (Design Yield)	0.06
Internal Pressure (Test Yield)	0.05
Bending Due to Earth and Truck Load	0.19
Deflection	0.16
Cast Iron	
Internal Pressure (Test Yield)	0.08
Bending Due to Earth and Truck Load – 20 ft span	0.51
Bending Due to Earth and Truck Load – 15 ft span	0.30
Bending Due to Earth and Truck Load – 10 ft span	0.13

Notes

1. Boundaries for D.I. Calculation
    a. Service Pressure 100 psig
    b. Surge Pressure = 100 psig
    c. Depth of Bury = 3 feet.
    d. Note that the 0.08-inch thickness service allowance and 0.06-inch thickness casting allowance have not been included in this table.
2. Boundaries for C.I Calculation (Handbook of DI and CI Pipe – 1978)
    a. Maximum beam stress is 14,000 psi (p 77)
    b. Span is 20 feet
    c. Load is 1,425 lb/ft

Wareham Water does not have records on the class of pipe installed at all locations. However, the standard typically followed was class thickness 52. The listed thickness for this class pipe is 0.37 inch. From Table 3, the bending stress controls the minimum thickness of the pipe at 0.19 inches, which is 51% of the of the original thickness or 49% corroded. Similarly, cast iron pipe (pit and spun) case pipe, due to its material properties, does not handle tension as well as ductile iron. As such, the thickness must be larger to allow for less bending. Again, assuming the average bending span is 15 feet (pipe lengths typically came between 10 and 20 feet long) and the average manufactured thickness is 0.65 inches, yields approximately 53% corrosion. This was considered a good target for replacing a cast iron pipe.

Thus, as a round number 50% pipe loss was used as a target for pipe replacement.

Work to be Remaining: Task Completed.

5. **Task 5 – Update Risk and life-cycle cost analysis**

Objective: Data from the segments tested will be used by Kleinfelder to update the GIS information of the distribution system. The data will be used by Kleinfelder to update the existing 50-year forecast model based on risk. This model calculates risk from age and condition information over a 50-year period and assigns actions such as pipe replacement or renewal based on risk scores and dominating failure modes, based on a decision model. Model outputs include segment ID's, renewal/replacement actions, and estimated costs over the 50-year simulation. A sensitivity analysis will be conducted to assess the degree by which uncertainty associated with the non-tested segments of pipe affects the results. This model will be used to update the priorities and estimated costs for pipe replacement and cleaning and lining for the years 1-5 (Primary List of Assets) and 6-10 (Secondary List of Assets). The simulation outputs will also include actions to be undertaken on the subsequent years (11 to 40).

Status: The following is providing a discussion of the results.

A. Model Overview

Kleinfelder created a 50-year simulation model in Excel, that deteriorates water mains over time, and applies renewal and replacement strategies at the asset level (each asset is one water main segment as defined in the GIS), in each simulation step. The simulation step used is five years. The model prioritizes activities at each time-step based on each asset's consequence scores, so that assets with higher consequence (critical assets) have priority over the rest. The prioritization is used to distribute activities (and therefore, costs), over the simulation span. The model uses budgets at each time-step as inputs not to be surpassed by the total costs of replacements and renewals.

The model considers three failure modes:

- External corrosion
- Tuberculation
- Fire flow adequacy

The model uses a Priority Score for each asset based on the asset's overall consequence factor, which is derived from the asset's ratings under:

- Social Impacts (or impacts to the consumer)
- Economic Impacts (economic impacts to the town and its businesses)

This model was developed for asbestos cement pipes, cast iron pipes, and ductile iron pipes. Plastic pipes were left out of the simulation. PVC and HDPE pipes account for 5.3 miles of the system (3.4% of the total).

The model is designed to be run with the @Risk software add-in to provide a sensitivity analysis of the uncertainties. Uncertainties considered in this analysis are all the pipe's thicknesses and their corrosion rates.

A.1. Model Inputs

The model uses the following inputs:

General Input Parameters

- **Year of Analysis**: First year of the simulation.
- **Year of Hydraulic Model**: Year when the hydraulic model was conducted and calibrated. This is year is assigned to the C value of the pipe (Hazen-Williams C, roughness coefficient).

- **PCI/SCI Cutoff Year**: this number is used to differentiate between pit cast iron pipe (PCI) and spun cast iron pipe (SCI). The default number is set to 1936 based on knowledge of the system but the user can change this number to an earlier year. This number overwrites the material indicated in the GIS.
- **C Value Deterioration**: Number of points the C value drops per year, to represent tuberculation. It only applies to cast iron pipes. Default value is 1.

Decision Model Parameters

- **Corrosion Threshold**: Percent of corrosion beyond which an action is taken. The model assigns a renewal strategy to segments that have corrosion over this threshold. The user might change this value to any value. Echologics suggests segments with more than 30% corrosion require to be either replaced or lined. A more realistic threshold would be 50% based on the discussion under Task No. 4. We ran the analysis under several scenarios using both 30% and 50%.
- **C value Threshold**: Value of the Hazen-Williams C factor under which an action is taken. The default value is 50, meaning that pipes with C values less than 50 would need to be replaced.
- **Fire Flow Adequacy Threshold**: Pipes with Fire Flow Adequacy scores less than this value would need to be replaced. Default value is 5. Details about how this score is calculated are presented in subsequent sections.
- **Renewal/Replacement Alternatives**: Possible alternatives used by the model. These alternatives are associated with each failure mode and each material to create a decision model. The model is presented in Table 4. The alternatives considered are:
  - Do Nothing
  - Structural Lining
  - Replace with Ductile Iron Pipe (Replace with DI)
  - Replace with larger diameter ductile iron (Replace with DI+)

Table 4 - Decision Model

Decision Model

	FM: Corrosion % Corrosion > than	FM: Turberculation C value < than	Fire Flow Adequacy Capacity Score < than
Material/ Threshold	30%	50	5
AC	Structural Lining	Replace with DI	Replace with DI+
DI	Replace with DI	Replace with DI	Replace with DI+
PCI	Replace with DI	Replace with DI	Replace with DI+
SCI	Replace with DI	Replace with DI	Replace with DI+

Unit Costs

The model uses replacement and structural lining costs for the different types of assets and their corresponding diameters. Table 5 Displays the unit costs used in this analysis.

Table 5 - Unit Costs, $/LF

Unit Costs

Material	Diameter	Replace with DI	Replace with DI+	Structural Lining
Metal	6	$ 150.00	$ 150.00	$ 200.00
Metal	8	$ 150.00	$ 180.00	$ 200.00
Metal	10	$ 180.00	$ 190.00	$ 200.00
Metal	12	$ 190.00	$ 225.00	$ 200.00
Metal	16	$ 225.00	$ 260.00	$ 250.00
Metal	20	$ 260.00	$ 280.00	$ 250.00
Metal	24	$ 280.00	$ 320.00	$ 250.00
AC	6	$ 180.00	$ 180.00	$ 250.00
AC	8	$ 180.00	$ 216.00	$ 250.00
AC	10	$ 216.00	$ 228.00	$ 250.00
AC	12	$ 228.00	$ 270.00	$ 250.00
AC	16	$ 270.00	$ 312.00	$ 300.00
AC	20	$ 312.00	$ 336.00	$ 300.00
AC	24	$ 336.00	$ 400.00	$ 300.00

Deterioration Parameters

The model uses pipe thickness (inches) and corrosion rates (mm/year) to calculate the extent of the corrosion in each segment. Both thicknesses and corrosion rates are inputs to the model, but need to be entered with a minimum, a likely, and a maximum value. Table 6 displays the interface for entering these values:

Table 6 – Pipe Thickness and Deterioration Parameters

Deterioration Model (Corrosion)

	Thickness (in)			Deterioration Rates (mm/yr)		
Class Type	Min	Likely	Max	Min	Likely	Max
AC-6	0.455	0.555	0.685	0.120	0.163	0.270
AC-8	0.555	0.760	0.810	0.120	0.163	0.270
AC-10	0.830	0.927	1.060	0.120	0.163	0.270
AC-12	0.960	1.090	1.190	0.120	0.163	0.270
AC-16	1.230	1.334	1.485	0.120	0.163	0.270
AC-20	1.640	1.728	1.820	0.120	0.163	0.270
AC-24	1.980	2.068	2.160	0.120	0.163	0.270
AC-30	1.560	1.645	1.900	0.120	0.163	0.270
SCI-6	0.440	0.453	0.480	0.021	0.053	0.298
SCI-8	0.429	0.532	0.652	0.021	0.053	0.298
SCI-10	0.500	0.530	0.609	0.021	0.053	0.298
SCI-12	0.540	0.653	0.737	0.021	0.053	0.298
PCI-6	0.385	0.430	0.550	0.025	0.053	0.249
PCI-8	0.484	0.540	0.691	0.025	0.053	0.249
PCI-10	0.496	0.579	0.725	0.025	0.053	0.249
PCI-12	0.474	0.644	0.795	0.025	0.053	0.249
DI-6	0.250	0.270	0.310	0.027	0.071	0.480
DI-8	0.250	0.330	0.388	0.027	0.071	0.480
DI-10	0.260	0.290	0.350	0.027	0.071	0.480
DI-12	0.280	0.370	0.403	0.027	0.071	0.480
DI-16	0.340	0.360	0.400	0.027	0.071	0.480
DI-20	0.380	0.393	0.420	0.027	0.071	0.480
DI-24	0.430	0.433	0.440	0.027	0.071	0.480

Budgets

The model uses budgets for each 5-year step, not to be exceeded by the activities selected based on the decision model. Budget inputs are displayed in Table 7.

Table 7 – Budgets

#	Year	Budegt	Actual Costs (5 yr)	Actual Costs (1 yr)	Avg Corr.
0	2023	$ 10,000,000	$ 9,998,732	$ 1,999,746	43.56%
5	2028	$ 10,000,000	$ 9,999,712	$ 1,999,942	46.80%
10	2033	$ 10,000,000	$ 9,997,784	$ 1,999,557	50.39%
15	2038	$ 10,000,000	$ 9,998,559	$ 1,999,712	53.54%
20	2043	$ 10,000,000	$ 9,996,925	$ 1,999,385	56.23%
25	2048	$ 10,000,000	$ 9,998,120	$ 1,999,624	58.78%
30	2053	$ 10,000,000	$ 9,999,955	$ 1,999,991	61.82%
35	2058	$ 10,000,000	$ 9,999,952	$ 1,999,990	65.17%
40	2063	$ 10,000,000	$ 9,392,847	$ 1,878,569	68.03%
45	2068	$ 10,000,000	$ 9,995,202	$ 1,999,040	72.09%
50	2073				76.28%
			$ 99,377,787		
		Yearly Average	**$ 1,987,556**		

GIS Inputs

For each segment, the model requires:

- **Asset ID:** Unique identifier of the segment. This is used to map results back into the GIS after the simulations are done
- **GIS Material:** Material as indicated in the GIS. The model can overwrite this material for cast iron pipes based on the year of installation
- **Diameter:** pipe diameter in inches
- **Year Installed**
- **Street:** where the main is located
- **C value** from last hydraulic model
- **Length of the segment**, in feet
- **Consequence score for social impacts:** developed in previous years and assigned to each segment via GIS analysis
- **Consequence score for economic impacts:** developed in previous years and assigned to each segment via GIS analysis
- **Fire Flow Adequacy Score:** developed from available fire flow data and needed fire flow data. Details are presented in section 2.3

A.2. Model Assumptions

- All replacements will be made with ductile iron pipe
- Same thresholds for acceptable corrosion levels, acceptable C values and acceptable fire flow capacity are applied through the system
- Only cast-iron pipes undergo tuberculation
- New pipes have a starting C value of 140

- Structural-lined pipes have 0 corrosion
- New pipes are assigned a fire flow capacity score of 8 (more than sufficient fire flow)
- Consequence scores remain static during the simulation

A.3. How the Model Works

Before conducting any simulation, the data needs to be prepared. Some of these steps are conducted by the model, some are done manually.

1. The model assigns material to each segment based on the material from the GIS, and the override that happens based on year of installation. That only affects cast iron pipes. The pit cast iron/spun cast iron year is used to assign either pit cast iron (PCI) or spun cast iron (SCI) to the pipes that had a generic "cast iron" material in the GIS.
2. From material, diameter and year of installation, the model calculates each segment's "cohort value", which is a code that indicates the material, diameter, and decade when the pipe was installed (e.g. AC-6-1973).
3. The model takes the averages, weighted by length, of the C values, by cohort. These values are used to assign C values to segments with no data.
4. The model assigns a thickness to each pipe segment based on its diameter and material, and the data entered on the deterioration parameters table (see Table 6). For the simple version of the simulation, the thickness considered is the "Likely" thickness. When pairing the model with @Risk, each segment is assigned a thickness using a Pert distribution with the minimum, likely and maximum values entered in the deterioration parameters table.
5. The model assigns a deterioration rate to each pipe segment based on its diameter and material, and the data entered on the deterioration parameters table (see Figure 3). For the simple version of the simulation, the deterioration rate considered is the "Likely" rate. When pairing the model with @Risk, each segment is assigned a deterioration rate using a Pert distribution with the minimum, likely and maximum values entered in the deterioration parameters table.
6. The model calculates the average estimated service life of the system (as if it was brand new), based on all the thicknesses, lengths, deterioration rates and deterioration threshold, weighted by length.
7. The model converts the consequence scores to a priority score from 1-10.
8. The model calculates Replacement Costs for replacing with ductile iron pipe, for replacing with a larger diameter ductile iron pipe, and for doing a structural lining. These costs are stored and used for when the actual action is selected.

At each time-step the model:

1. Calculates each segment's age. If the pipe had been replaced or structurally lined on the previous time-step, the age of the pipe is assigned to 5 years (because it uses a 5-year time-step). Otherwise, it calculates the age as 5 + previous time-step's age.
2. Calculates corrosion extent in mm. This calculation depends on the age of the pipe, and its corresponding corrosion rate. Pipes that had been replaced on the previous

year with DI pipe, are assigned the DI corrosion rate. Structurally lined pipes are assigned a corrosion value of 0.

3. Calculates the percent of corrosion from the corrosion extent and the pipe thickness (in mm). Pipe thickness is adjusted to the correct value if pipes had been replaced with larger diameters of DI in previous years.
4. The model calculates the system's percent corrosion weighted by length, which represents an overall status at the beginning of this time-step. It does the same for the C value and the Fire Flow adequacy score.
5. Calculates the corresponding C value. Only CI pipes undergo tuberculation, and therefore for the rest of the materials, the C value stays fixed over time. For CI pipes, C value is calculated as the C value deterioration rate per year, times the number of years since the hydraulic model, for pipes that have not been replaced. Replaced pipes get a C value of 140, and this will not change since DI won't deteriorate under this failure mode.
6. Calculates Fire Flow Capacity. This value is calculated at the beginning on the simulation and remains static unless a segment it's replaced, in which case it's assigned the value of 8.
7. Calculates the corresponding action that should be taken under the corrosion failure mode, according to the threshold selected, the material, and the corresponding action identified on the decision model input (see Table 4).
8. Calculates the corresponding action that should be taken under the tuberculation failure mode, according to the threshold selected, the material, and the corresponding action identified on the decision model input (see Table 4).
9. Calculates the corresponding action that should be taken under the fire flow adequacy failure mode, according to the threshold selected, the material, and the corresponding action identified on the decision model input (see Table 4).
10. Calculates the most overarching action that should be taken based on the three actions selected. Replacing with larger diameter dominates over replacing with same diameter, which dominates over structural lining the pipe, which dominates over doing nothing. The dominant action of the three failure modes is identified and stored in the field "Preliminary Action".
11. Calculates the costs of executing the preliminary action, for each segment, based on the segment length, the preliminary action identified, and the unit costs entered (see Table 5).
12. Calculates the total preliminary costs for the entire system for that year
13. Adds the total preliminary costs by Priority. The renewal/replacement costs for segments with priority one are added, and then the costs for assets with priority two, and so on. Based on each year's budget, the model determines up to which priority level assets can be addressed that year. For example, on a given year, the budget might only allow to address assets on priority levels one and two, and some of the assets on priority level 3. A given priority level is then flagged as Included in CIP "yes", "no" or Partial".
14. The model flags all segments with action items included in the CIP, and the ones that are in the partially included category.

15. The model selects the items on the partially included category for as long as the cost doesn't go over the budget for that time period. These are then the final actions identified for that time-step.

B. Specific Calculations and Values

Specifics about the model are described in this section.

B.1. Thickness

Actual thickness of mains is unknown through the system. Kleinfelder used available data from the city of Boston to compile recorded thicknesses of water mains. The dataset contained nominal thicknesses and corrosion levels for 4,371 records. Additionally, Kleinfelder compiled thickness information from other sources including:

Kleinfelder used this dataset to identify a minimum, likely and maximum value of thicknesses for the different asset types in Wareham. The thickness information is presented in Table 6 – Thickness and Deterioration Parameters. When available, the thickness data provided by Echologics was used as the likely value.

B.2. Deterioration Rates

Similarly, Kleinfelder used deterioration rates from the City of Boston, and the deterioration rates provided by Echologics to identify a likely, minimum and a maximum deterioration rate for asbestos cement pipes, ductile iron pipes, pit cast iron and spun cast iron. From these analysis, two scenarios were developed:

<u>Scenario A:</u> This scenario uses the average deterioration rates from Echologics, but the minimum and maximum rates are from the City of Boston or from literature. This scenario injects significant uncertainty on the simulation given the range of possible values.

<u>Scenario B:</u> This scenario uses the average deterioration rates from Echologics, and the minimum and maximum rates from the Echologics dataset. This scenario injects less uncertainty on the simulation, than scenario A, but it could misrepresent the actual system since the Echologics dataset is composed of only 23 records, which are not representative of the entire system. This scenario is used on simulations to address how uncertainty can affect the outcomes of the model.

B.3. Fire Flow Adequacy

Fire flow adequacy scores were assigned based on available needed fire flow (NFF) and available fire flow (AFF) data. Each pipe segment has a minimum, an average and a maximum NFF and a minimum, an average, and a maximum AFF. This information was calculated during last year's AMP effort.

All assets with Minimum AFF greater than the maximum needed were grouped as Group "E" and assigned a score of 10 (best score). All assets with maximum AFF below the minim NFF where grouped as group "A" and given a score of 1. Assets with maximum AFF greater than the minimum needed but below the average needed where tagged as group “B”. In this group, the assets with Average AFF below the minimum NFF were assigned a score of 2, and the ones with Average AFF greater than the minimum NFF were assigned a score of 3. Assets in Group C had a maximum AFF greater than the average NFF but below the Max NFF. In Group C, assets with Average AFF less than the needed got a score of 4, while the ones with greater average AFF than the average needed got a score of 5. Assets with Max AFF greater than the maximum NFF were assigned to group D, with scores of 8 for the assets with average AFF below the maximum NFF and of 9 to those with average AFF greater than the maximum NFF.

Figure 1 depicts the scoring system used to rank each segment based on these numbers.

C. Scenarios and Results

The model was run using @Risk, an add-on to Excel, allows for assigning probability distributions to inputs. @Risk generates many input simulations based on the probability parameters and computes the statistics of the outputs that the user selects to track. This methodology is called Monte-Carlo simulation, and it is used to assess the impacts of unknowns or uncertainties to outcomes. In general, asset management relies in data that is either loosely gathered or has considerable amount of uncertainty associated with it. For example, estimated service life of assets depends on many factors, and can vary a lot.

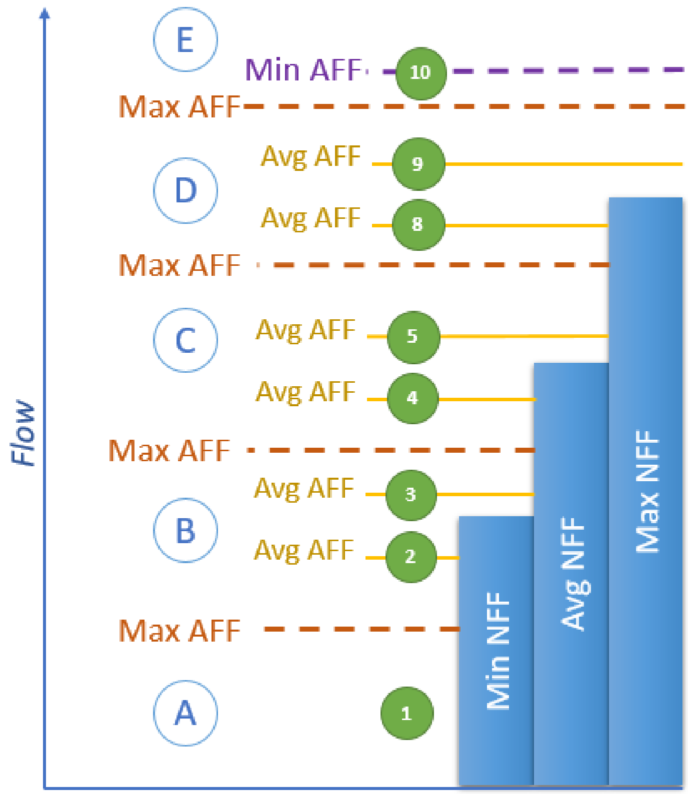
Two sets of input parameters were treated as @Risk Inputs: the pipe thicknesses and their deterioration rates. Both sets (see Table 6- Thickness and Deterioration parameters). For both sets, the probability of distribution used was a *Pert* distribution, which is bound by a minimum and a maximum value. It is typical to use this distribution when not much is known about the data.

@Risk outputs, those to be track for statistical analysis after the Monte-Carlo simulation were: Average estimated service life of the system, total costs (over the 50-year span), average yearly costs, and average system corrosion extent at the end of the simulation.

The following scenarios were analyzed:

- Unlimited budget, with wide range of deterioration rates, and corrosion threshold of 50%
- 2-Million/year budget, with wide range of deterioration rates, and corrosion threshold of 50%
- Custom Scenario, also using wide range of deterioration rates, corrosion threshold of 50%, and a custom budget.

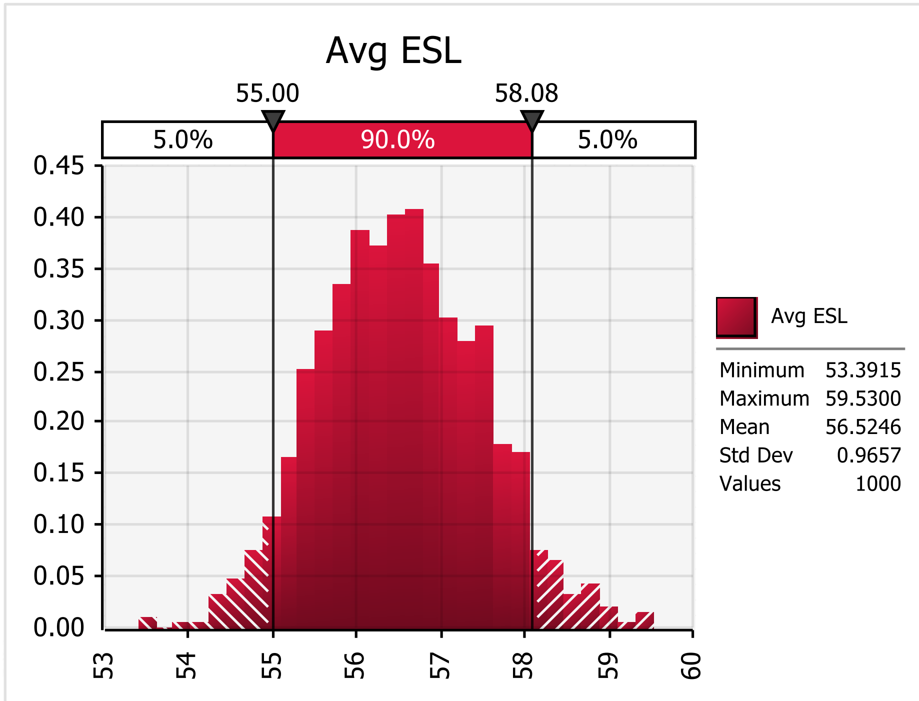
Figure 1- Fire Flow Adequacy Scoring



C.1.Unlimited Budget Scenario

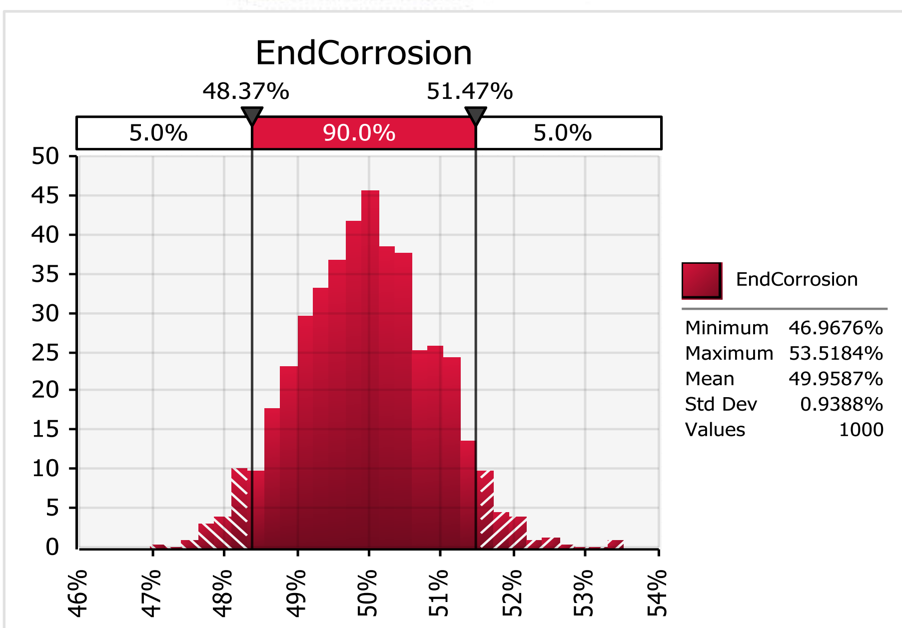
Under this scenario, the average estimated service life of the system (Avg ESL) is 56.52 with values ranging between 55 and 58.

Figure 2 - Average System ESL Distribution



The average percentage of corrosion at the end of the simulation ranged between 47% and 53.52 % and mean of just under 50%. However, the system achieves very low levels of corrosion after the fifth year and well through the 45th year (around 20%) (see Figure 4).

Figure 3 - Distribution of Average System Corrosion at the end of Simulation (Year 50)

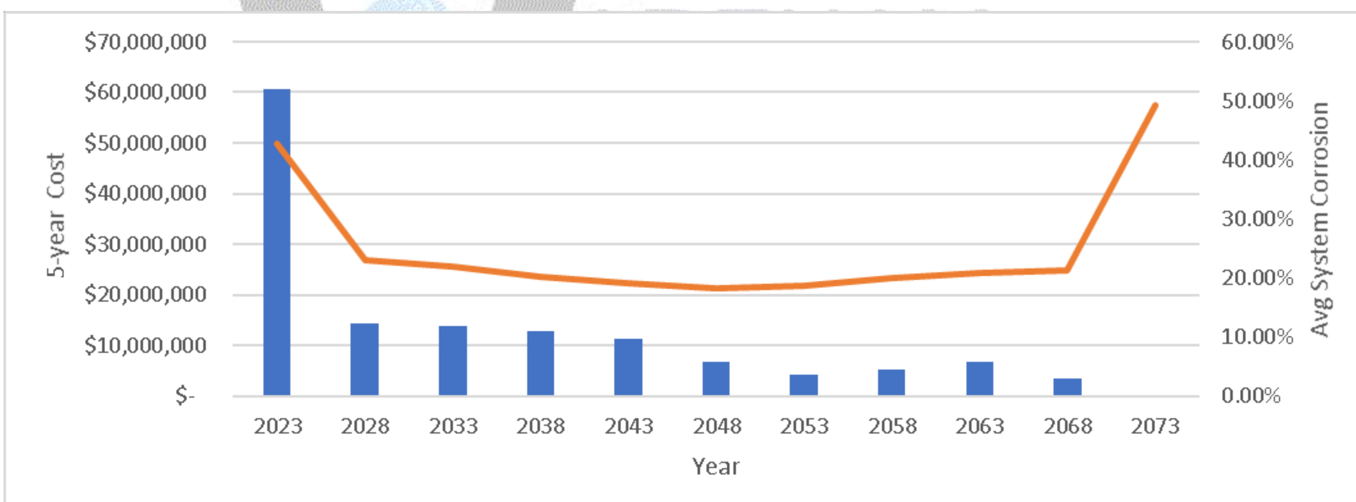


The total investment over 50-year period for this simulation was $137.8 M but ranged between $132.0 M and $142.9 M. Figure 8 displays the results on a time-step basis. Keep in mind that the data in Figure 8 corresponds to one iteration only.

Table 1 - Unlimited Budget Scenario Results (for one iteration)

	Year	Budegt	Actual Costs (5 yr)	Actual Costs (1 yr)	Avg Corr.	Corr. Delta	Avg. C	Cval Delta	Avg FireF
0	2023	$ 500,000,000	$ 60,627,388	$ 12,125,478	42.80%		103.2		8.80
5	2028	$ 500,000,000	$ 14,357,437	$ 2,871,487	23.02%	-85.91%	118.9	13.16%	8.86
10	2033	$ 500,000,000	$ 13,848,059	$ 2,769,612	21.93%	-4.97%	121.9	2.45%	8.73
15	2038	$ 500,000,000	$ 12,808,985	$ 2,561,797	20.26%	-8.25%	124.2	1.86%	8.60
20	2043	$ 500,000,000	$ 11,243,957	$ 2,248,791	19.06%	-6.28%	126.6	1.94%	8.50
25	2048	$ 500,000,000	$ 6,757,208	$ 1,351,442	18.23%	-4.57%	128.7	1.63%	8.39
30	2053	$ 500,000,000	$ 4,255,721	$ 851,144	18.57%	1.81%	130.4	1.33%	8.31
35	2058	$ 500,000,000	$ 5,147,557	$ 1,029,511	19.95%	6.91%	131.5	0.83%	8.27
40	2063	$ 500,000,000	$ 6,768,029	$ 1,353,606	20.79%	4.04%	132.1	0.45%	8.25
45	2068	$ 500,000,000	$ 3,332,276	$ 666,455	21.25%	2.18%	133.5	1.02%	8.19
50	2073				49.19%	56.81%	134.6	0.82%	8.16
			$ 139,146,617						
		Yearly Average	$ 2,782,932						

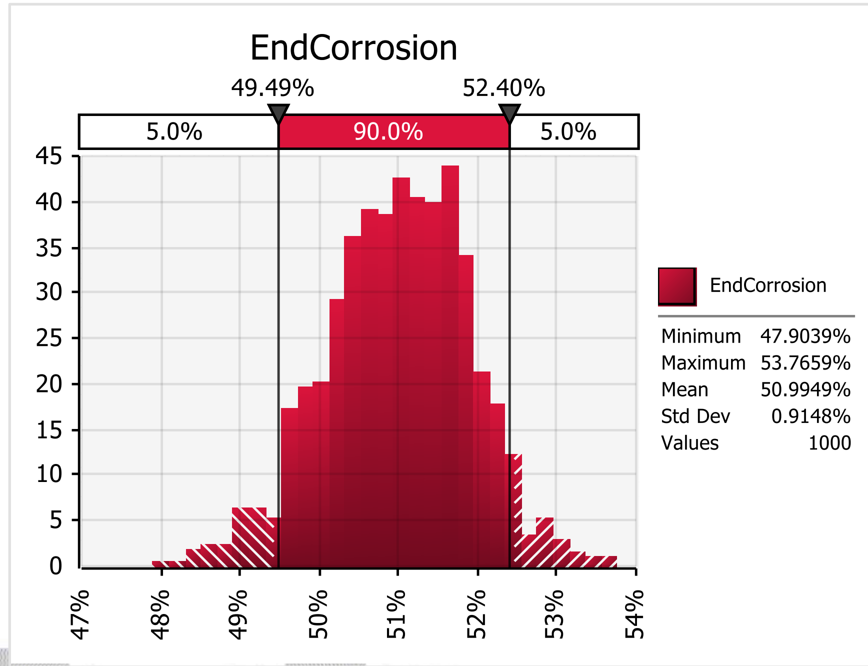
Figure 4 - Unlimited Budget Results (one iteration)



C.2.$2M/Year Budget Scenario

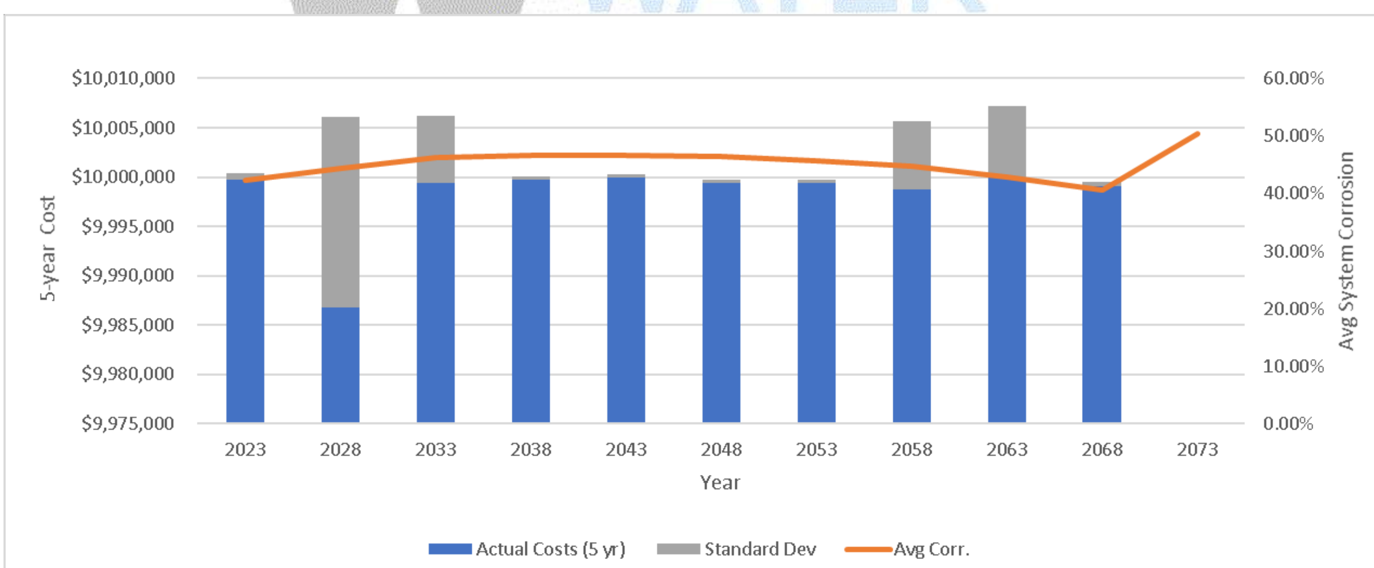
This scenario is bound by a constrained budget of $2.0 M a year, which is $10M for each 5-year period. In this simulation, the average ESL of the system also ranged between 55-58 years, which makes sense since we are using the same parameters as in the previous scenario. The corrosion rate at year 50th is also similar to the one on the previous scenario:

Figure 5 - Distribution of Average System Corrosion at the end of Simulation (Year 50)



The main difference between these two scenarios is the corrosion rates through the 50-year period, as displayed in Figure 6.

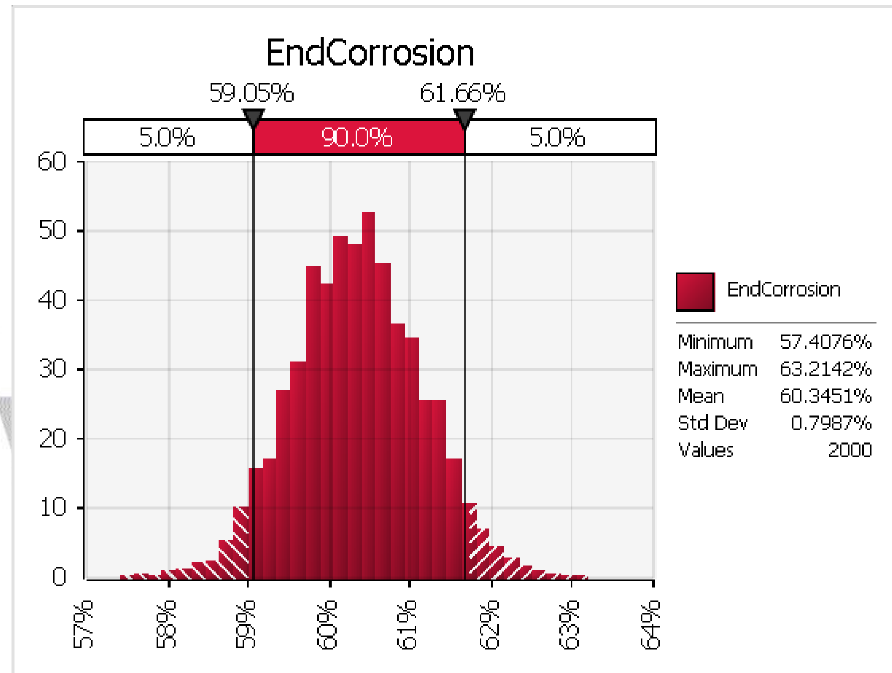
Figure 6 - $2M per year Scenario Results



C.3.Custom Budget Scenario

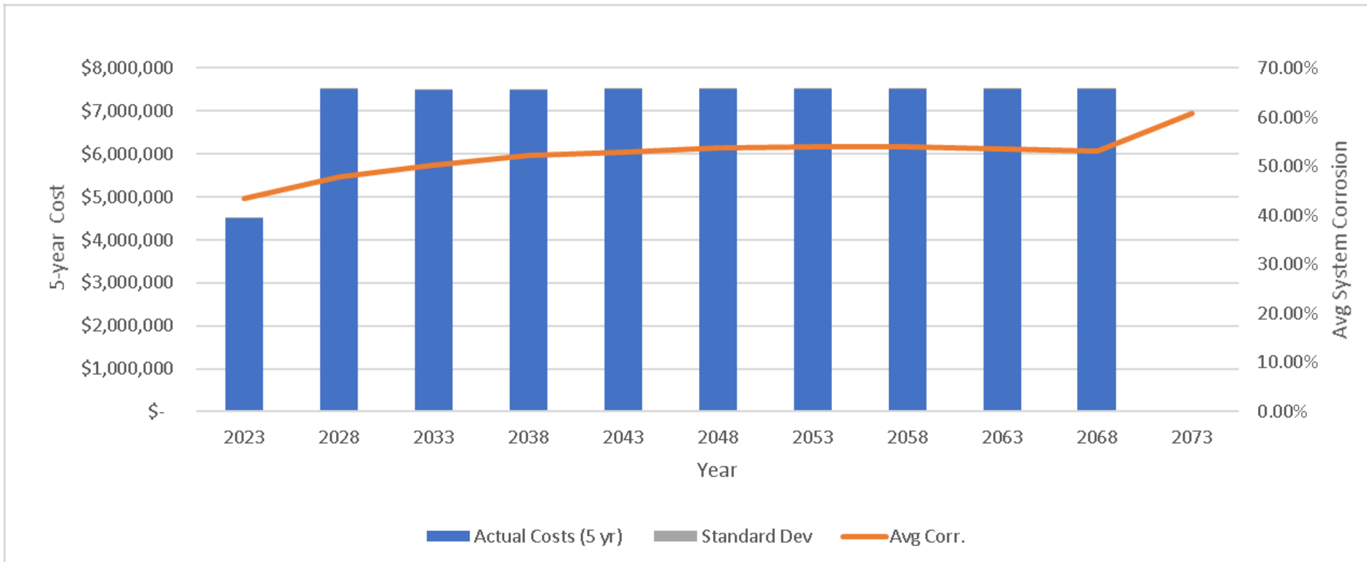
This scenario was set with a budget of $1.5 M starting in year 2025, and the same parameters of deterioration as in the previous simulations. With tighter budgets, the corrosion rates get higher. The distribution of average system corrosion by year 50th is shown below:

Figure 7 - Corrosion Extent by Year 50th



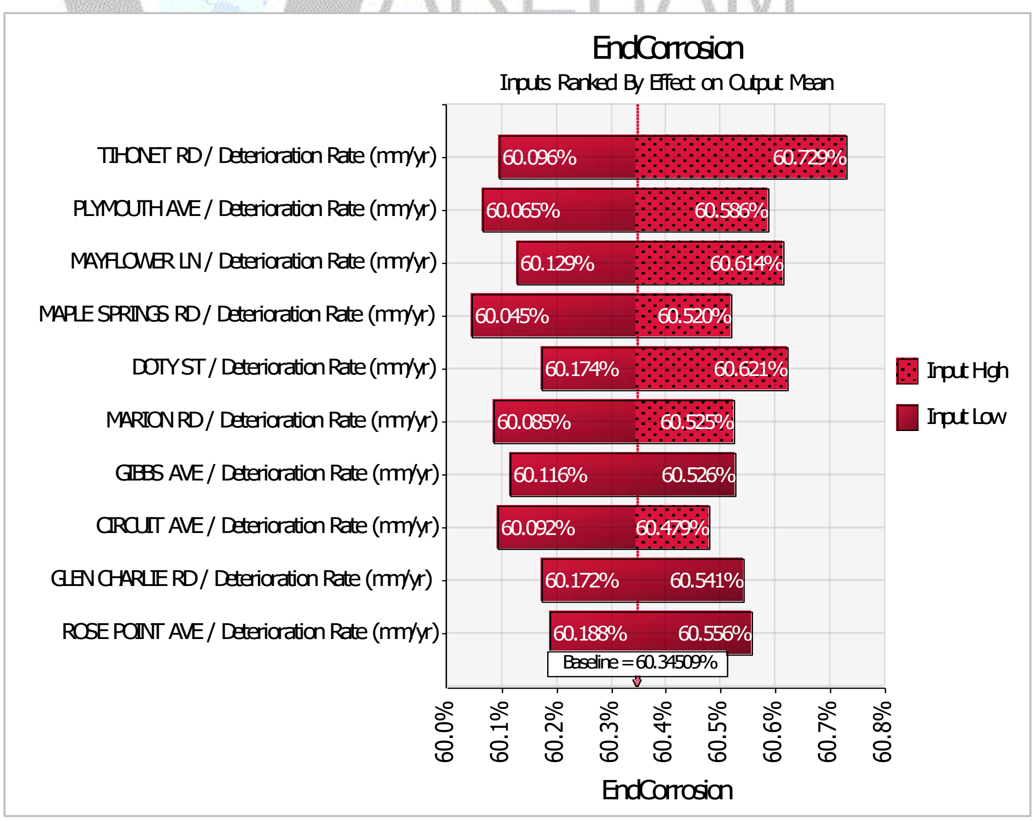
With this budget, the system seems to stay right at the 50% level of corrosion in average through the simulation, as shown in Figure 8.

Figure 8 - Custom Budget Scenario Results



The tornado chart on Figure 9 displays the streets with higher impact on the final corrosion rate of the system.

Figure 9- Assets with Higher Impact on Corrosion



Work to Remaining: Task Completed.

6. Task 6- Update AM/FSP and Pipe Replace / Rehabilitation Schedule

Objective: Kleinfelder will update the Asset Management and Fiscal Sustainability Plan (AM/FSP) with the data gathered and results obtained in this project. The AM/FSP will follow the requirements of this grant.

Status: Tables 9 and 10 display the renewal/replacement options identified by the system for years 0-5 (Primary List of Assets) and 5-10 (Secondary List of Assets).

Work to Remaining: Task Completed. The next step outside of this grant is to start the budgeting process which requires the Board of Water Commissioner approval as well as the Prudential Committee approval to meet the targeted dates.

Table 9- Actions for 2023-2028 (Primary List of Assets), by length (feet)

Street Name	Replace with Ductile Iron	Replace with larger diameter ductile iron	Structural Lining	Grand Total
BAYBERRY RD		516		516
BEACH PLUM LN		380		380
BRANDY HILL RD	1,403			1,403
CEDAR ISLAND RD	407			407
CHARGE POND RD		82		82
CHARLOTTE FURNACE RD		281		281
CHURCH AVE	187			187
COUNTY RD	1,689			1,689
CRANBERRY HWY		11,514	530	12,044
CROMESET POINT RD		150		150
CROMESET RD	1,733	3,283		5,016
CURLEW WY		556		556
CUSHMAN RD		1,376		1,376
DEPOT ST		94		94
DONNA RD		1,597		1,597
DOTY ST		65		65
ELM ST	10			10
EMMA LN		382		382
EXPRESS DR		749		749
FELLOWSHIP CIR		534		534
GATEHOUSE DR		51		51
GRACE LN		170		170
GRIFFIN WY		871		871

Street Name	Replace with Ductile Iron	Replace with larger diameter ductile iron	Structural Lining	Grand Total
HARVEST CIR		12		12
HEATHER HILL RD	433			433
JOHN ST		322		322
KENDRICK RD	1,954	447		2,402
LITTLE BROOK RD		594		594
LITTLE HARBOR RD		570		570
MAIN ST		201		201
MARION RD		430		430
MARKS COVE RD	1,072			1,072
MAYFLOWER RIDGE DR	1,182			1,182
MINOT AVE	539			539
NARROWS RD	150			150
NOBSKA WY		476		476
PATTERSON BROOK RD		2,609		2,609
PINE NEEDLE LN		997		997
PLOVER RD		335		335
POND EDGE TRAIL		1,921		1,921
QUAIL LN		467		467
RED PINE LN		1,024		1,024
ROSEBROOK WY		600		600
SANDWICH RD	479	467		946
SANTOS RD		295		295
SIPPICAN RD	307			307
STATION ST		449		449
STOCKTON SHORT CUT		434		434
TOBEY RD	1,910	2,562		4,472
TOW RD		849		849
TYLER AVE		14		14
VIKING DR		84		84
WARR AVE		510		510
WILLOW ST		251		251
WINDY HILL DR		564		564
(blank)		685		685
Total	13,455	40,816	530	54,802

Table 10 - Actions for 2028-2032 by Length (feet) (Secondary List of Assets)

Street Name	Replace with DI	Structural Lining	Grand Total
10th AVE		566	566
12th AVE		651	651
14th AVE		637	637
16th AVE		680	680
6th AVE		269	269
AGAWAM BEACH RD		849	849
ASA AVE		230	230
ATLANTIC AVE		453	453
BAY VIEW AVE		427	427
BRANDY HILL RD	444		444
BRIARWOOD DR		1,020	1,020
BURR PKWY		169	169
CARTER AVE		270	270
CARVER RD		3,374	3,374
CENTRAL AVE		516	516
COONEHASSETT RD		530	530
CRANBERRY HWY		9,409	9,409
DINO RD		84	84
EIGHTH AVE		577	577
ELM ST	727		727
FRANCONIA AVE		283	283
FRANKIE AVE		259	259
FRANKLIN ST		371	371
GARAGE ST		80	80
GLADSTONE AVE		340	340
IRENE AVE		695	695
JUDSON ST		672	672
KENDRICK RD	217		217
KIRSTEN LN	189		189
MAIN ST		1,111	1,111
MALLARD RD		738	738
MARION RD		1,654	1,654
MICHAEL DR		322	322
MINOT AVE		1,299	1,299
MORSE AVE		882	882
PARTRIDGE PATH		574	574
PERRY AVE		300	300
PHEASANT AVE		669	669

Street Name	Replace with DI	Structural Lining	Grand Total
PINEHURST DR		17	17
PLEASANT ST		610	610
RAE AVE		49	49
ROOSEVELT ST		1,096	1,096
SANDPIPER TER		1,546	1,546
SAWYER ST		520	520
SHADY LN	486		486
TERN ST		483	483
TOBEY RD	160		160
TONY'S LN		201	201
TREMONT RD		699	699
VIKING DR		620	620
WANKINQUOAH AVE	384		384
WASHINGTON DR		724	724
WREN TER		719	719
Total	2,606	38,239	40,845

Appendix A -
Echologic Report

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Technical**Report**

echologics
A Mueller TECHNOLOGIES COMPANY

Wareham Fire District

Water Department

Title: Leak Detection and Condition Assessment

Client: Wareham Fire District Water Department

Report Classification: Final

Date: July 24, 2018

Echologics Reference #: 42218039

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Executive Summary

Echologics LLC (Echologics) provided leak detection and condition assessment services for the Wareham Fire District (Wareham). Echologics surveyed two miles of 6 to 12 inch asbestos cement (AC), cast iron (CI) and ductile iron (DI) pipe. Echologics' field personnel completed the survey in Wareham, Massachusetts between May 8th, 2018 and May 10th, 2018. Echologics performed leak detection and condition assessment using the ePulse® method. This report presents the information gathered from these services including the location of suspected leaks and the results of ePulse® testing.

Summary of key results

Leak detection:

- No leaks were discovered at the time of the survey.

Condition Assessment:

- 3 segments appear to be in good condition with less than a 10% loss in original wall thickness.
- 5 segments appear to be in moderate condition with 10% to 30% loss in original wall thickness.
- 14 segments appear to be in poor condition with over 30% loss in original wall thickness.

Table of Contents

1. Project Background

Wareham Fire District Water Department (WFD) engaged Echologics LLC (Echologics) to gain information on critical segments of their asbestos cement (AC), cast iron (CI), and ductile iron (DI) main in order to address two primary objectives:

- Investigate the system for the existence of any potential leaks
- Determine the condition of the tested AC, CI, and DI mains
- Demonstrate Echologics deployment of ePulse on distribution mains

To achieve these objectives, Echologics utilized its patented ePulse® technology to determine the current condition of the pipe. In addition to condition assessment, leak detection was performed simultaneously with this survey. This report provides detailed information on how these objectives have been met.

WFD is interested in testing (coupon sampling) a variety of different material and diameter pipe with ePulse® in order to validate the results and determine if the ePulse® method is a valid long term approach for gauging pipe life. Validation procedures can be found in Appendix F.

The project included two miles of 6 inch to 12 inch mains spread over five sites as illustrated below in Figure 1-1.

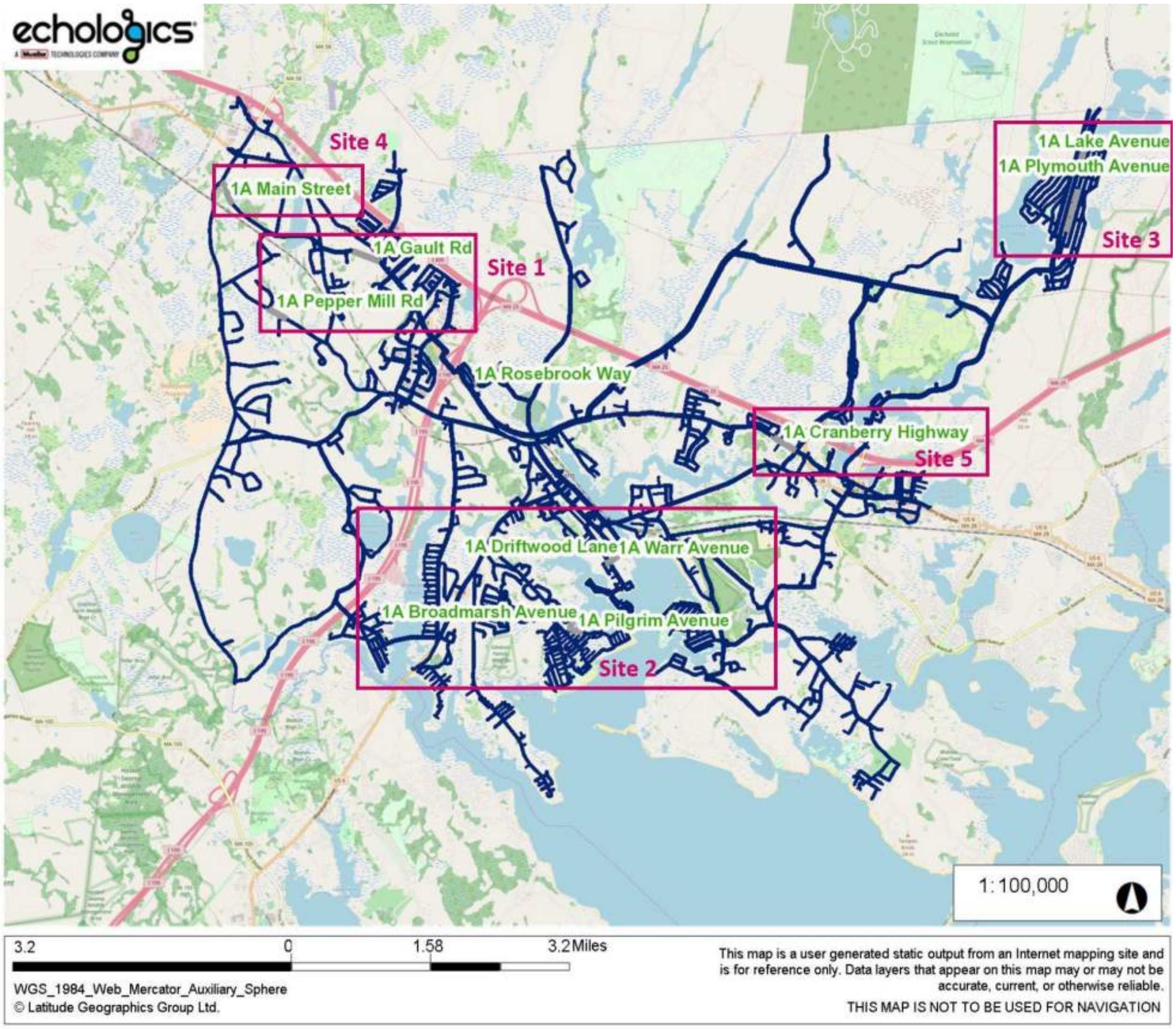

Figure 1-1: System Overview and Site Locations

Field tests began on May 8th, 2018 and required three days to complete with a two-person field team. The sites were selected by the client based on the desire to test three different pipe materials with varying diameters. WFD made the selection in order to obtain a samples from the entire water system.

Echologics used the pipe properties shown in Table 1.1. Echologics assumed the pipe classes listed below based on most common pipe classes for the pipe material and the install year provided by Wareham Fire Department Water District. The equivalent thickness includes the nominal thickness of the pipe plus an equivalent thickness of the lining as it contributes to the structural thickness of the pipe.

Table 1-1: Pipe properties

Site	Pipe Material	Install Year	Pressure Class	Internal Diameter	Nominal Thickness	Lining Thickness	Equivalent Thickness
				(in)	(in)	(in)	(in)
1,4	AC	1967	150	8	0.76	N/A	0.76
1,4	AC	1967	150	12	1.09	N/A	1.09
2	PCI	1936	150	6	0.43	N/A	0.43
2	PCI	1936	150	10	0.54	N/A	0.54
3	DI	1999	52	8	0.33	0.0625	0.36
3	DI	1999	52	12	0.37	0.0625	0.41
5	PCI	1936	150	10	0.54	N/A	0.54

2. Results

2.1 Leak Detection

No leaks were detected during the time of the survey.

2.2 ePulse® Condition Assessment

ePulse® measures the mean minimum remaining hoop thickness. The technology combines acoustic data measured in the field with information about a pipe's manufacturing to calculate its current hoop thickness. The pipe's material, internal diameter, and modulus of elasticity are all critical variables in this calculation. ePulse® condition assessment calculates the percentage of hoop thickness loss by comparing the measured thickness to the design thickness. The results are also presented as a qualitative category indicating the expected condition of the main. Table 2-1 shows these qualitative condition categories. Results marked "NR" indicate that no result was attainable on a pipe segment.

Table 2-1: Qualitative Categories and Color Coding

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

As the calcium leaches out of the asbestos cement matrix, AC mains degrade structurally rather than physically. Echologics measures the mean remaining structural hoop thickness rather than the physical thickness. For more information on how to interpret the AC ePulse® condition assessment results refer to Table B.2-1 and Condition Interpretation in Asbestos Cement Mains in appendix B.2 ePulse® Condition Assessment. The AC condition assessment results are presented in Table 2-2.

Table 2-2: Asbestos Cement ePulse® Condition Assessment Results

Segment	Site	Street	Pipe Asset ID(s)	Distance	Pipe Material	Internal Diameter	Equivalent Thickness	Remaining Thickness	% Change from Nominal
				(ft)		(in)	(in)	(in)	
80391A002	1	Pepper Mill Rd	1000372, 1001462	359	AC	8	0.76	0.51	-33%
80391A003	1	Pepper Mill Rd	1000372	293	AC	8	0.76	0.52	-32%
80391A004	1	Pepper Mill Rd	1000372, 1001391	286	AC	8	0.76	0.52	-31%
80391A005	1	Gault Rd	1000909	177	AC	12	1.09	0.59	-46%
80391A006	1	Gault Rd	1000909	497	AC	12	1.09	0.68	-38%
80391A007	1	Gault Rd	1000909	622	AC	12	1.09	0.72	-34%
80391A020	4	Main Street	1001228	644	AC	8	0.76	0.44	-42%
80391A021	4	Main Street	1956417, 1001228	482	AC	8	0.76	0.48	-37%

Metallic mains degrade physically as their structural integrity decreases. This often happens through corrosion which can be localized or along the entire length of the pipe. Echologics measures the mean minimum physical remaining thickness in the pipe. For more information on how to interpret the metallic ePulse® condition assessment results refer to Table B.2-1 and Condition Interpretation in Metallic Mains in appendix B.2 . The metallic main condition assessment results are presented in Table 2-3.

Table 2-3: Metallic Main ePulse® Condition Assessment Results

Segment	Site	Street	Pipe Asset ID(s)	Distance	Pipe Material	Internal Diameter	Equivalent Thickness	Remaining Thickness	% Change from Nominal
				(ft)		(in)	(in)	(in)	
80391A008	2	Driftwood Lane	1001581, 1956541	222	PCI	10.02	0.54	0.31	-43%
80391A009	2	Warr Avenue	1000408	184	PCI	10.02	0.54	0.38	-30%
80391A010	2	Warr Avenue	1000407, 1000408	644	PCI	10.02	0.54	0.33	-38%
80391A011	2	Pilgrim Avenue	1000064, 1001217, 1001190	563	PCI	6.04	0.43	0.24	-45%
80391A012	2	Broadmarsh Avenue	1000873, 1001190	684	PCI	6.04	0.43	0.26	-40%
80391A013	2	Broadmarsh Avenue	1000873, 1001190	226	PCI	6.04	0.43	0.28	-36%
80391A014	3	Plymouth Avenue	1000345, 1001532	385	DI	12.46	0.41	0.37	-8%
80391A015	3	Plymouth Avenue	1001532	647	DI	12.46	0.41	0.39	-4%
80391A016	3	Plymouth Avenue	1001532	639	DI	12.46	0.41	0.35	-15%
80391A017	3	Lake Avenue	1000919, 1001184, 1001756	605	DI	8.39	0.36	0.26	-30%
80391A018	3	Lake Avenue	1000087,1001184, 1001756	662	DI	8.39	0.36	0.34	-5%
80391A019	3	Lake Avenue	1000087, 1001756	658	DI	8.39	0.36	0.28	-23%
80391A022	5	Cranberry Highway	1001729	722	PCI	10.02	0.54	0.42	-22%
80391A023	5	Cranberry Highway	1001729, 1001290, 1004737	440	PCI	10.02	0.54	0.46	-15%

2.2.1 Calibration

An important aspect of determining the pipe wall degradation is the water bulk modulus equation. By testing a new pipe with the same water supply as the test sites, Echologics can determine which water bulk modulus to use for the system. Echologics performed a water bulk modulus calibration using 12-inch DI pipe on Rosebrook Way. For the assumed pipe specifications please see Appendix A.3 Pipe Property Details.

2.2.2 General Observations

Based on the assumed pipe specifications, the AC and PCI pipe is highly degraded whereas the DI pipe is in good to moderate condition. The degradation seems to be related to pipe material and install year in this system.

3. Recommendations and Next Steps

Echologics has provided information for WFD on the condition of two miles of main. The ePulse® testing was able to isolate three sections with less than 10% loss in average pipe wall thickness, five sections with a loss of 10% to 30% and 14 sections with a loss greater than 30%. These findings will assist the rehabilitation planning efforts of WFD.

Echologics' condition assessment results are an effective and valuable component of the asset management process for prioritization of pipeline repair and rehabilitation. Each water network will have its own dominant degradation mechanism, as well as unique local considerations.

Echologics recommends that Wareham Fire District Water Department use the results presented in this report in combination with other data and information available from additional services. This additional asset information may include:

- **Soil Corrosivity**. This comparison will help determine if external corrosion due to aggressive soil is a significant degradation mechanism for these mains. For example, if corrosive soils are discovered and the main is in poor condition, the degradation is likely related to soil conditions.
- **Water Aggressiveness**. This comparison will reveal whether or not the water is a mechanism for uniform degradation. For example, aggressive water would suggest that some of the degradation is caused from the inside; this 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 that are at increased risk of failure. These factors are not necessarily related, as it is possible for pipes to have high break rates for reasons other than pipe wall degradation.
- **Consequence of Failure**. Combining condition assessment results with consequence of failure analysis is used to generate a risk assessment.

Comparing Echologics' results with some of the aforementioned datasets, will allow for Wareham Fire District to direct their rehabilitation efforts in a cost effective manner by creating a global rehabilitation picture which takes all sources of degradation into consideration.

3.1.1 Modulus of Elasticity

The modulus of elasticity of the pipe material is one of the factors in the calculation of the mean minimum hoop thickness. While Echologics has significant experience estimating the modulus of elasticity based on the material, age, and region of manufacture, we can improve the accuracy of the results by testing the actual modulus of elasticity of an exhumed sample of the pipe. If interested, please contact Echologics for more information.

3.1.2 Pipe Specifications

Detailed pipe specifications were not available for all pipes surveyed. Although Echologics has made reasonable assumptions for internal diameter, material and original hoop thickness, the results can be improved if accurate pipe specifications can be provided. If WFD can find original specifications or determined the specification after exhuming pipe coupons (to verify diameter, material and thickness assumptions), Echologics can reprocess the data based on the updated information.

3.1.3 Statistical Variation

The values generated by ePulse® testing are averaged for a segment of pipe which ranges in length from 150 feet to 700 feet. This averaging allows for the possibility of having small lengths within the segment which are severely degraded. This degradation will not be shown in the final result. Therefore it is important to note that the value presented describes the general condition of the pipe and may not show future potential point failures.

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4. Disclaimer

This report is intended to be used as a guide only. All forms of non-destructive testing involve an inherent level of uncertainty. Such testing is dependent on input parameters, and outputs can be significantly affected by variation from assumed parameters. This report includes certain suggestions and recommendations made by Echologics which are based on, among others, (i) the findings included in the report, (ii) its experience and (iii) an understanding of the client's particular requirements. Echologics acknowledges that the client may use this report to consider potential opportunities for pipeline replacement/rehabilitation; however, Echologics disclaims any liability that may arise in connection with decisions based on these suggestions or recommendations or their implementation.

Appendix A Detailed Results

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

A.1 Site Details

An overview map of the site along with drawn qualitative ePulse® results of the tested segments is shown in Figure A.1: System Overview and Site Locations below.

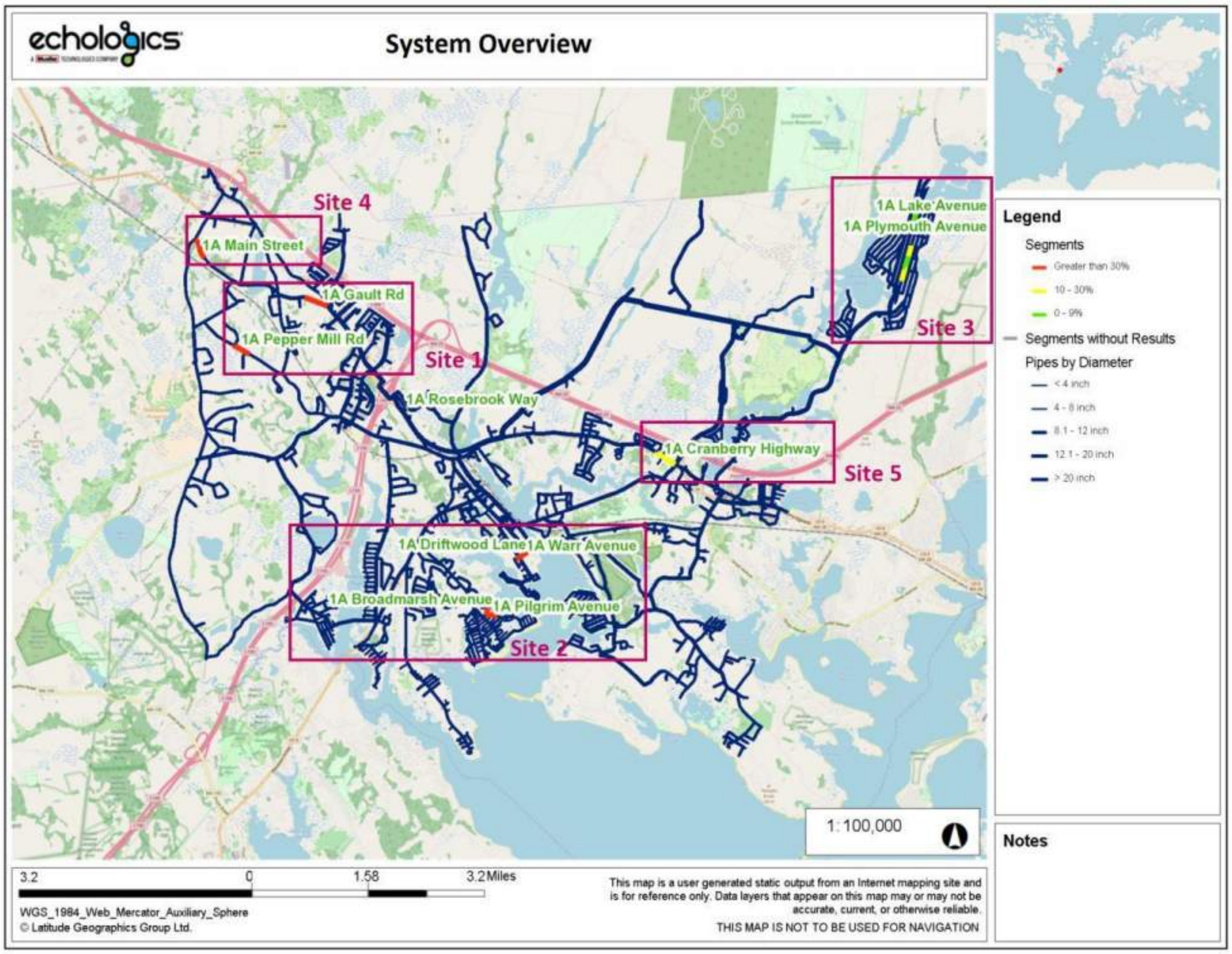


Figure A.1: System Overview and Site Locations

A.2 Leak Detection Result Details

No leaks were detected during the time of the survey

A.3 Pipe Property Details

The pipe properties used in this project are presented in detail in Table A.3-1: Pipe Properties, which were provided by WFD.

Table A.3-1: Pipe Properties

Segment	Site	Pipe Material	Pressure Class	Install Year	Diameter	Nominal Thickness	Lining Thickness	Equivalent Thickness
					(in)	(in)	(in)	(in)
80391A001	Calibration	DI	52	2010	12	0.37	0.0625	0.41
80391A002	1	AC	150	1967	8	0.76	N/A	0.76
80391A003	1	AC	150	1967	8	0.76	N/A	0.76
80391A004	1	AC	150	1967	8	0.76	N/A	0.76
80391A005	1	AC	150	1967	12	1.09	N/A	1.09
80391A006	1	AC	150	1967	12	1.09	N/A	1.09
80391A007	1	AC	150	1967	12	1.09	N/A	1.09
80391A008	2	PCI	150	1936	10	0.54	N/A	0.54
80391A009	2	PCI	150	1936	10	0.54	N/A	0.54
80391A010	2	PCI	150	1936	10	0.54	N/A	0.54
80391A011	2	PCI	150	1936	6	0.43	N/A	0.43
80391A012	2	PCI	150	1936	6	0.43	N/A	0.43
80391A013	2	PCI	150	1936	6	0.43	N/A	0.43
80391A014	3	DI	52	1999	12	0.37	0.0625	0.41
80391A015	3	DI	52	1999	12	0.37	0.0625	0.41
80391A016	3	DI	52	1999	12	0.37	0.0625	0.41
80391A017	3	DI	52	1999	8	0.33	0.0625	0.36
80391A018	3	DI	52	1999	8	0.33	0.0625	0.36
80391A019	3	DI	52	1999	8	0.33	0.0625	0.36
80391A020	4	AC	150	1968	8	0.76	N/A	0.76
80391A021	4	AC	150	1968	8	0.76	N/A	0.76
80391A022	5	PCI	150	1936	10	0.54	N/A	0.54
80391A023	5	PCI	150	1936	10	0.54	N/A	0.54

A.4 ePulse® Condition Assessment Result Details

Table A4-1 presents the results of the AC ePulse® testing. Table A4-2 presents the results of the metallic main ePulse® testing. Detailed results follow for all sites and segments based on the assumed pipe classes.

Table A4-1: Asbestos Cement ePulse® Condition Assessment Result Details

Segment	Site	Street	Pipe Asset ID(s)	Distance	Pipe Material	Internal Diameter	Equivalent Thickness	Remaining Thickness	% Change from Nominal
				(ft)		(in)	(in)	(in)	
80391A002	1	Pepper Mill Rd	1000372, 1001462	359	AC	8	0.76	0.51	-33%
80391A003	1	Pepper Mill Rd	1000372	293	AC	8	0.76	0.52	-32%
80391A004	1	Pepper Mill Rd	1000372, 1001391	286	AC	8	0.76	0.52	-31%
80391A005	1	Gault Rd	1000909	177	AC	12	1.09	0.59	-46%
80391A006	1	Gault Rd	1000909	497	AC	12	1.09	0.68	-38%
80391A007	1	Gault Rd	1000909	622	AC	12	1.09	0.72	-34%
80391A020	4	Main Street	1001228	644	AC	8	0.76	0.44	-42%
80391A021	4	Main Street	1956417, 1001228	482	AC	8	0.76	0.48	-37%

Table A4-2: Metallic Main ePulse® Condition Assessment Result Details

Segment	Site	Street	Pipe Asset ID(s)	Distance	Pipe Material	Internal Diameter	Equivalent Thickness	Remaining Thickness	% Change from Nominal
				(ft)		(in)	(in)	(in)	
80391A008	2	Driftwood Lane	1001581, 1956541	222	PCI	10.02	0.54	0.31	-43%
80391A009	2	Warr Avenue	1000408	184	PCI	10.02	0.54	0.38	-30%
80391A010	2	Warr Avenue	1000407, 1000408	644	PCI	10.02	0.54	0.33	-38%
80391A011	2	Pilgrim Avenue	1000064, 1001217, 1001190	563	PCI	6.04	0.43	0.24	-45%
80391A012	2	Broadmarsh Avenue	1000873, 1001190	684	PCI	6.04	0.43	0.26	-40%
80391A013	2	Broadmarsh Avenue	1000873, 1001190	226	PCI	6.04	0.43	0.28	-36%
80391A014	3	Plymouth Avenue	1000345, 1001532	385	DI	12.46	0.41	0.37	-8%
80391A015	3	Plymouth Avenue	1001532	647	DI	12.46	0.41	0.39	-4%
80391A016	3	Plymouth Avenue	1001532	639	DI	12.46	0.41	0.35	-15%
80391A017	3	Lake Avenue	1000919, 1001184, 1001756	605	DI	8.39	0.36	0.26	-30%
80391A018	3	Lake Avenue	1000087,1001184, 1001756	662	DI	8.39	0.36	0.34	-5%
80391A019	3	Lake Avenue	1000087, 1001756	658	DI	8.39	0.36	0.28	-23%
80391A022	5	Cranberry Highway	1001729	722	PCI	10.02	0.54	0.42	-22%
80391A023	5	Cranberry Highway	1001729, 1001290, 1004737	440	PCI	10.02	0.54	0.46	-15%

Site 1: Pepper Mill Rd – Gault Rd, segments 2 – 7

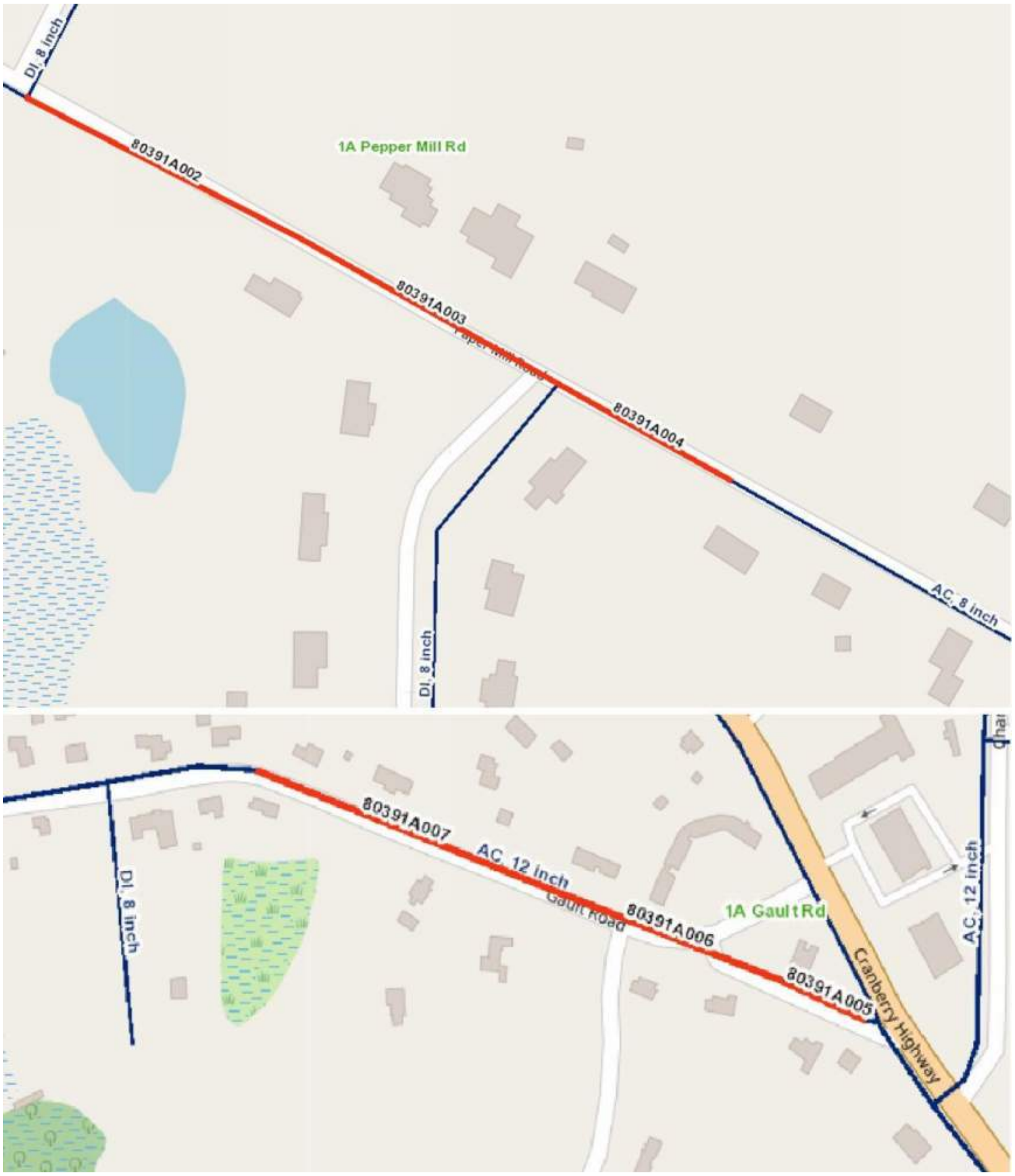


Figure A.4-1: Map illustrated qualitative ePulse® results for Site 1

ePulse® results indicate that both the 8-inch AC main and the 12-inch AC main are in poor condition with 31% to 46% loss in structural wall thickness. Wall thickness measurements range from 0.51 to 0.52 inches for the 8-inch main and from 0.59 to 0.72 for the 12-inch one. The site-specific results are listed in Table A4-3 and illustrated on Figure A.4-1.

Table A4-3: ePulse® results for Site 1

Segment	Street	Distance	Pipe Material	Diameter	Equivalent Thickness	Remaining Thickness	% Change from Nominal
		(ft)		(in)	(in)	(in)	
80391A002	Pepper Mill Rd	359	AC	8	0.76	0.51	-33%
80391A003	Pepper Mill Rd	293	AC	8	0.76	0.52	-32%
80391A004	Pepper Mill Rd	286	AC	8	0.76	0.52	-31%
80391A005	Gault Rd	177	AC	12	1.09	0.59	-46%
80391A006	Gault Rd	497	AC	12	1.09	0.68	-38%
80391A007	Gault Rd	622	AC	12	1.09	0.72	-34%

Site 2: Driftwood Ln, Warr Ave, Pilgrim Ave, Broadmarsh Ave, Segments 8 – 13

Figure A.4-2: Map illustrated qualitative ePulse® results for Site 2

ePulse® results indicate that both the 6-inch CI main and the 10-inch CI main are in poor condition with 30% to 45% loss in structural wall thickness. Wall thickness measurements range from 0.24 to 0.28 inches for the 6-inch main and from 0.31 to 0.38 for the 10-inch one. The site-specific results are listed in Table A4-4 and illustrated on Figure A.4-2.

Table A4-4: ePulse® results for Site 2

Segment	Street	Distance	Pipe Material	Diameter	Equivalent Thickness	Remaining Thickness	% Change from Nominal
		(ft)		(in)	(in)	(in)	
80391A008	Driftwood Ln	222	PCI	10	0.54	0.31	-43%
80391A009	Warr Ave	184	PCI	10	0.54	0.38	-30%
80391A010	Warr Ave	644	PCI	10	0.54	0.33	-38%
80391A011	Pilgrim Ave	563	PCI	6	0.43	0.24	-45%
80391A012	Broadmarsh Ave	684	PCI	6	0.43	0.26	-40%
80391A013	Broadmarsh Ave	226	PCI	6	0.43	0.28	-36%

Site 3: Plymouth Ave, Lake Ave, Segments 14 – 19

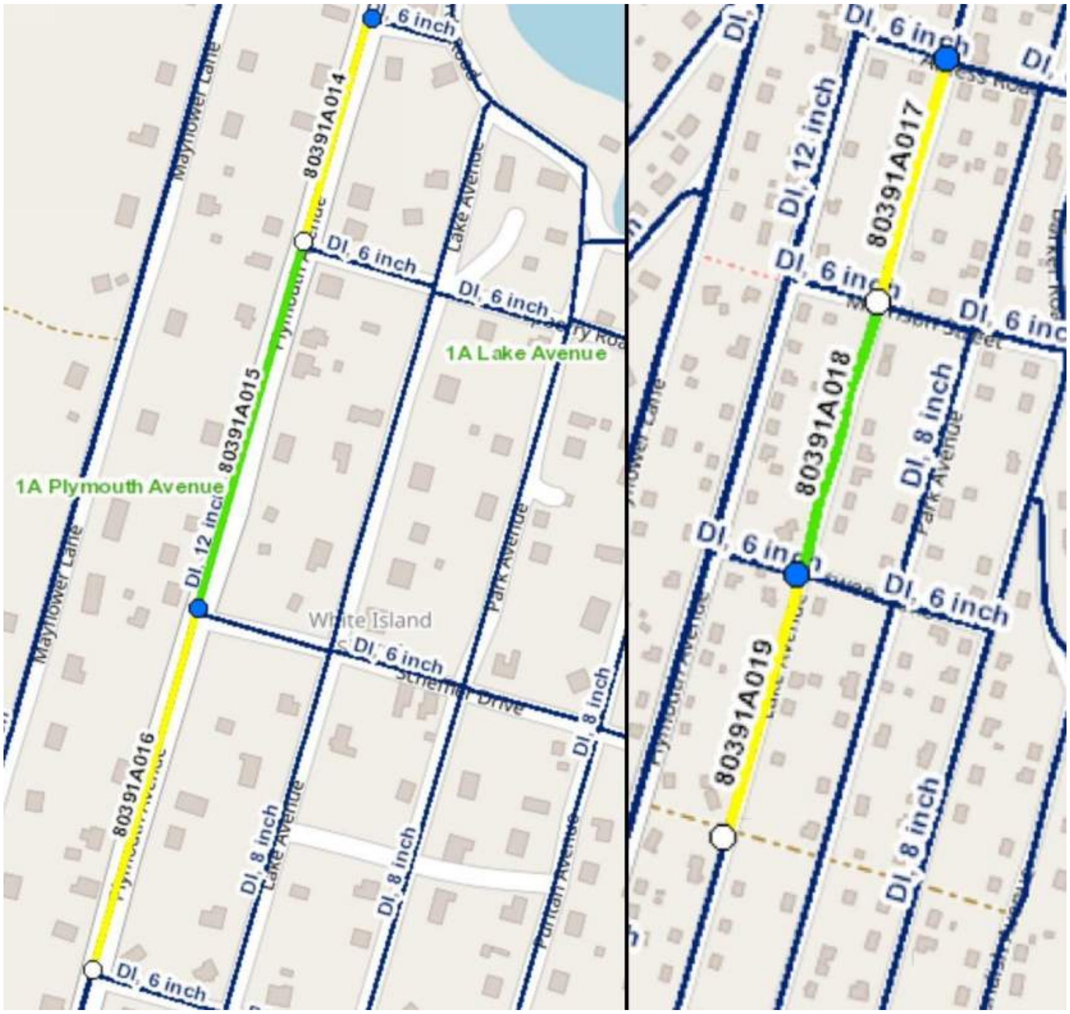


Figure A.4-3: Map illustrated qualitative ePulse® results for Site 3

ePulse® results indicate that both the 8-inch DI main and the 12-inch DI main are in good to moderate condition with 5% to 30% loss in structural wall thickness. Wall thickness measurements range from 0.26 to 0.34 inches for the 8-inch main and from 0.35 to 0.39 for the 12-inch one. The site-specific results are listed in Table A4-5 and illustrated on Figure A.4-3.

Table A4-5: ePulse® results for Site 3

Segment	Street	Distance	Pipe Material	Diameter	Equivalent Thickness	Remaining Thickness	% Change from Nominal
		(ft)		(in)	(in)	(in)	
80391A014	Plymouth Ave	385	DI	12	0.41	0.37	-8%
80391A015	Plymouth Ave	647	DI	12	0.41	0.39	-4%
80391A016	Plymouth Ave	639	DI	12	0.41	0.35	-15%
80391A017	Lake Ave	605	DI	8	0.36	0.26	-30%
80391A018	Lake Ave	662	DI	8	0.36	0.34	-5%
80391A019	Lake Ave	658	DI	8	0.36	0.28	-23%

Site 4: Main St, Segments 20, 21

Figure A.4-4: Map illustrated qualitative ePulse® results for Site 4

ePulse® results indicate that the 8-inch AC main is in poor condition with 37% to 42% loss in structural wall thickness. Wall thickness measurements are 0.44 inches for Segment 20 and 0.48 inches for Segment 21. The site-specific results are listed in Table A4-6 and illustrated on Figure A.4-4.

Table A4-6: ePulse® results for Site 4

Segment	Street	Distance	Pipe Material	Diameter	Equivalent Thickness	Remaining Thickness	% Change from Nominal
		(ft)		(in)	(in)	(in)	
80391A020	Main Street	644	AC	8	0.76	0.44	-42%
80391A021	Main Street	482	AC	8	0.76	0.48	-37%

Site 5: Cranberry Highway, Segments 22, 23

Figure A.4-5: Map illustrated qualitative ePulse® results for Site 5

ePulse® results indicate that the 10-inch CI main is in moderate condition with 15% to 22% loss in structural wall thickness. Wall thickness measurements are 0.42 inches for Segment 22 and 0.45 inches for Segment 23. The site-specific results are listed in Table A4-7 and illustrated on Figure A.4-5.

Table A4-7: ePulse® results for Site 5

Segment	Street	Distance	Pipe Material	Diameter	Equivalent Thickness	Remaining Thickness	% Change from Nominal
		(ft)		(in)	(in)	(in)	
80391A022	Cranberry Highway	722	PCI	10	0.54	0.42	-22%
80391A023	Cranberry Highway	440	PCI	10	0.54	0.46	-15%

Appendix B Interpretation of Results

B.1 EchoWave® Leak Detection

When Echologics discovers a noise on a main, it can be classified as a leak or a point of interest (POI). If further investigation reveals negative results, it is classified as no leak discovered. Within all Echologics reports, if no mention is made of leaks on a given section, it may be assumed that the result of the test is no leak discovered.

No Leak Discovered

When a negative correlation is matched with poor coherence, it is concluded that no leak was detected. In effect, there is no indication of a noise source of any sort, and therefore that there is no other evidence of leakage. Where possible, leak simulations are performed to confirm the absence of leaks and to ensure equipment functionality.

Point of Interest (POI)

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 is 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. This does not indicate a conclusive leak, however it is recommended that Wareham Fire District perform a secondary investigation. This will confirm the presence and location of the leak, as there is evidence of some form of noise inside the pipe.

Leak

Three pieces of conclusive evidence must be acquired for a Point of Interest to be upgraded to a Leak. This includes but is not limited to 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 in order to provide a positive 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.

B.2 ePulse® Condition Assessment

ePulse® condition assessment measures the mean minimum hoop thickness (for asbestos cement or metallic mains) or mean hoop stiffness (for reinforced concrete). Where the original nominal thickness (or stiffness) is available, results are also presented as a percentage loss, and as a category indicating a qualitative description of the expected condition of the main.

Qualitative Condition Description Categories

The color-coding and descriptions in **Table B.2-1.** are used for the results presented in all ePulse® condition assessment reports.

Table B.2-1: Color Coding and Hoop Thickness Loss Qualitative Descriptions

Change in Hoop Thickness	Description	Color Code	Description	
			Asbestos Cement Mains	Metallic Mains
Less than 10%	Good	Green	Minor levels of degradation and/or isolated areas with minor loss of structural thickness	Minor levels of uniform corrosion or some localized areas with pitting corrosion.
10% to 30%	Moderate	Yellow	Considerable levels degradation and loss of structural thickness. Moderate levels of cement leeched away from asbestos matrix.	Considerable levels of uniform surface or internal corrosion and/or localized areas of pitting corrosion.
Greater than 30%	Poor	Red	Significant degradation and loss of structural thickness. Substantial levels of cement leeched away from asbestos matrix.	Significant uniform corrosion and/or numerous areas of localized pitting corrosion.

These descriptions are based on Echologics' experience and with validation of results through the exhumation of pipe samples tested. Following the table, more detail is provided as to the expected condition of different types of main in each condition category, along with examples of validation of the ePulse® method on each type of main.

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 within the segment may not reflect the average conditions within that segment.

The ePulse® method tests the mean minimum hoop thickness of the pipe, which is not the same as the average thickness of the pipe.

The pipe is least able to resist this axi-symmetric expansion at the locations where the hoop thickness is at a minimum. Material properties are then used to calculate the hoop thickness which would provide exactly this stiffness. This is referred to as the mean minimum hoop thickness.

To obtain this same value mechanically, you would need to: divide a pipe into hoops; measure the thinnest section 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 these.

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

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

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

Condition Interpretation in Asbestos Cement Mains

As asbestos cement pipes age and degrade, they will not lose physical thickness, but will 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, and therefore does not contribute to the structural thickness. The ePulse® method measures the remaining structural hoop thickness (also known as the effective hoop thickness), as illustrated in Figure B.2-1, rather than the actual physical hoop thickness (which will generally remain at the nominal hoop thickness).

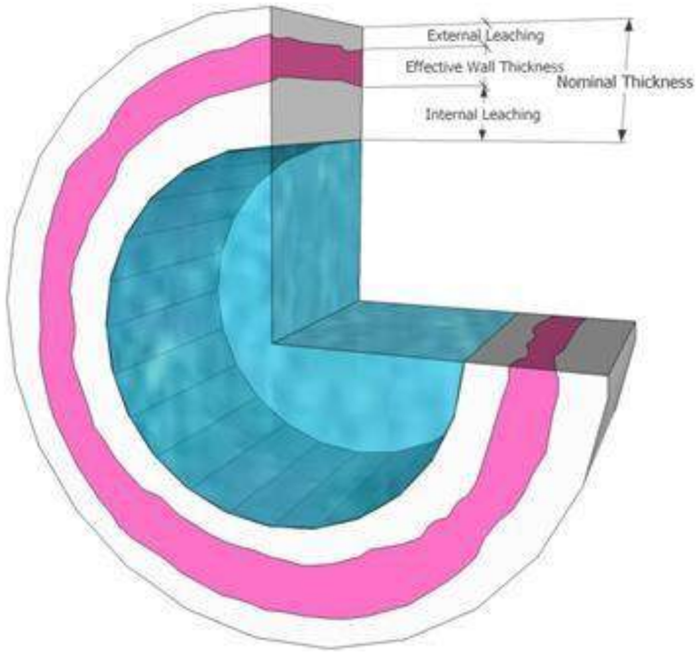


Figure B.2-1: Structural Hoop Thickness in Asbestos Cement Pipe

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 B.2-5 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 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 B.2-2: Examples of Different Levels of Corrosion in Metallic Pipe

Validation

As of the February 2016, a total of 104 ePulse® validation results have been provided to Echologics by our clients or third parties. Some clients have requested confidentiality, however we are able to present the result in aggregate.

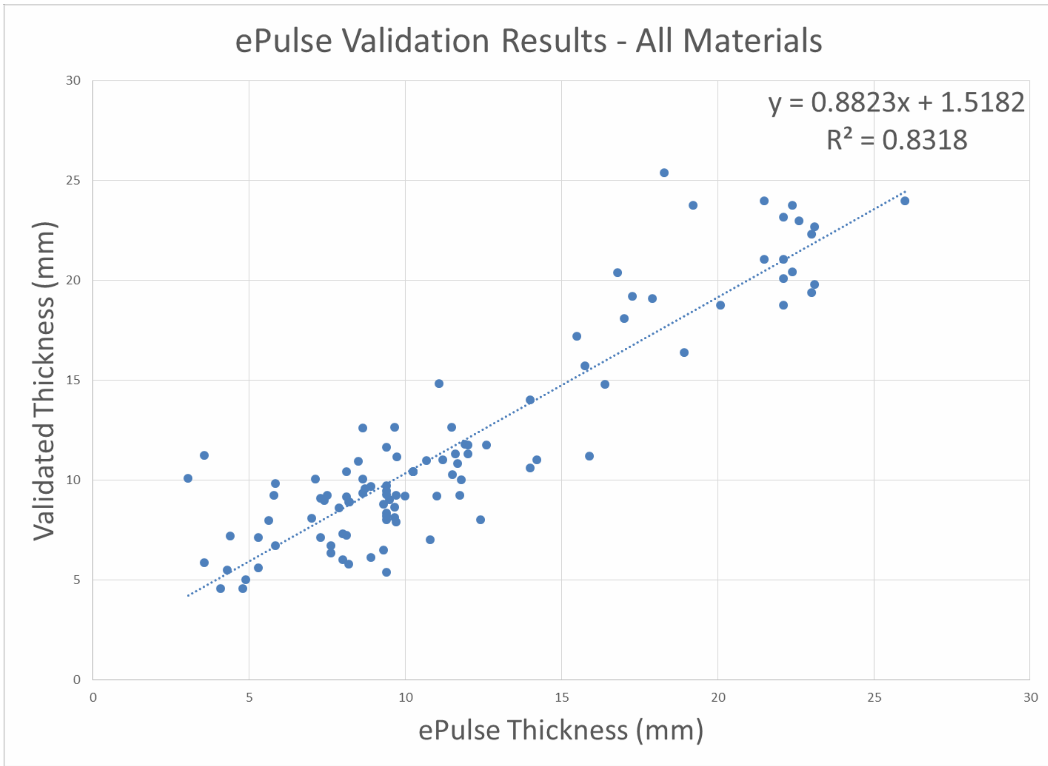


Figure B.2-3: ePulse® Validations On All Materials

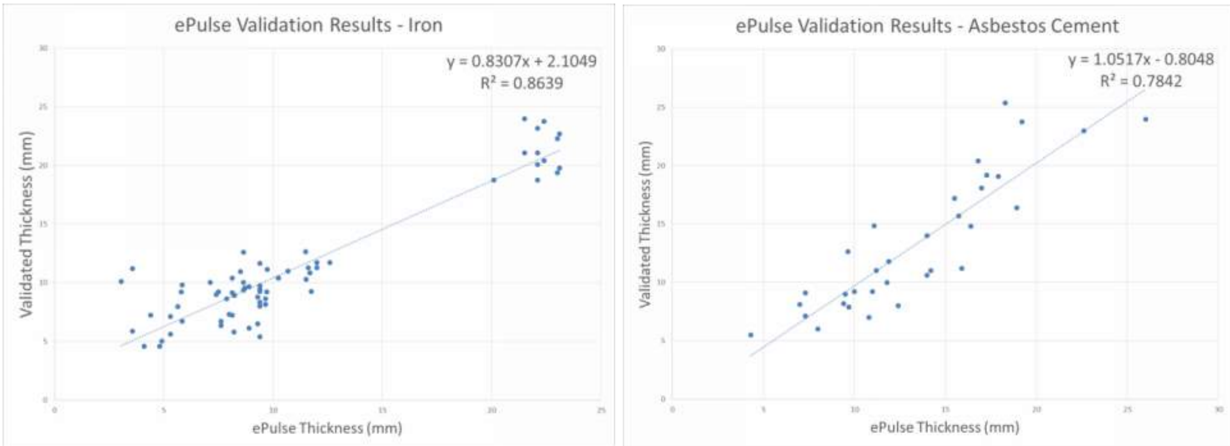


Figure B.2-4: ePulse® Validations On All Iron Pipes (left) and Asbestos Cement Pipes (right)

Two factors are worth attention in the charts.

The R^2 value is known as the coefficient of determination. This provides a measure of how well validation results are predicted by ePulse® results. It 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 R^2 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 power.

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% 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 over-estimate the actual error in the ePulse® results. The reason for this is that the ePulse® results are averages over segments of about 100 m (300 ft) in length, whereas the validation results indicate the thickness at a one 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:

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 will vary randomly along the sample, so the difference between the true average and validation results should be a normal distribution centered around zero. If ePulse® is effectively measuring the true average, we should see the same pattern in the difference between the ePulse® and Validated results. The actual distribution is shown in Figure B.2-5, and appears to match the expected pattern.

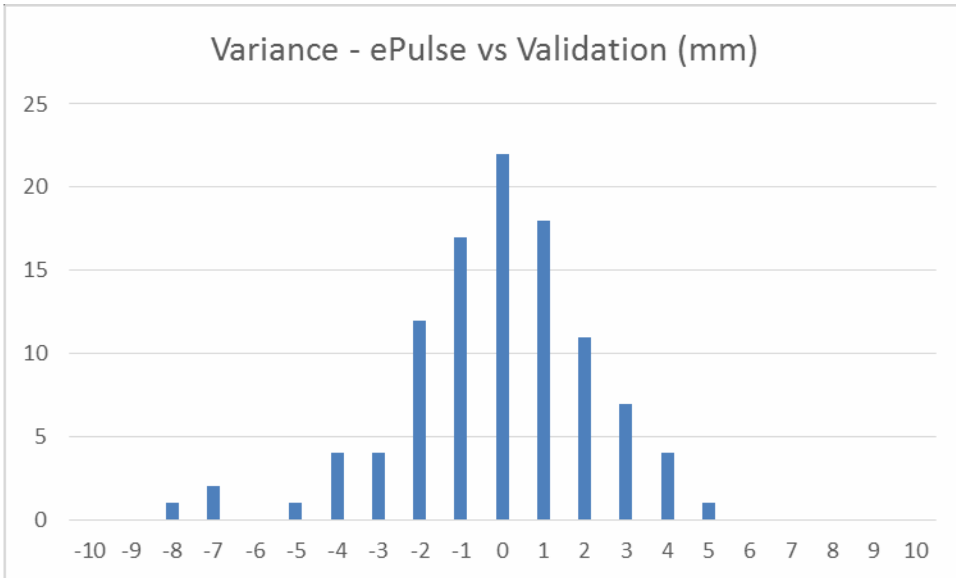


Figure B.2-5: Variance between ePulse® results and validation results

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 Sensitivity Analyses and Considerations

Echologics is constantly committed to reducing error during every step of the testing process. There are factors that may introduce error into the analysis. These errors may be caused by one or more of the following: inaccurate distance measurements, variance in manufacturing tolerances, variance in the modulus of elasticity the material, unknown pipe repairs, or inadequate correlation signals.

Distance Measurement

An accurate distance measurement is crucial for an accurate assessment. In general, a 1% error in distance measurement can result to more than a 2% error in final percentage of thickness lost. For this reason, our preference is to use potholes or in-line valves, as these provide the most accurate distance measure, 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% 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 a hoop thickness that is 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-case 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% will cause a change in the calculated thickness by approximately 10%. The elastic modulus is known for common materials used in the manufacturing of pressure pipe, but this value can vary among manufacturers. It is dependent on the manufacturing process and the quality of the material. The material properties used for calculations are selected using conservative estimates. This provides for a worst-case scenario analysis.

Unaccounted for Replacement of Pipe Sections during Repairs

Acoustic waves propagate differently depending upon the pipe material. This effect remains true for unaccounted for short pipe replacements 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) cast iron pipe section of average condition, will produce a small error of +3.5% in measured hoop thickness. However, the same repair made with PVC pipe would produce an error of -41% in measured hoop thickness.

Preferably, pipe sections selected for testing should be free of repaired sections. However, if this condition does not exist, the impact of the repaired pipe section can be accounted for, provided accurate information is available 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 cast 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 Detailed Methodology

C.1 Leak Detection

The methodology employed is known as the cross-correlation method. A correlator listens passively for noise created by a leak. If one is detected, it uses the time delay between sensors to determine the position of the leak. The following procedure was used to conduct the leak detection survey:

1. For each location surveyed, the distance between the sensors was measured.
2. Sensors were mounted either directly on the pipe or were connected to the water column with hydrophones.
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 is performed on-site to determine if any leaks are present.

C.2 ePulse® Mean Minimum Hoop Thickness Testing

A section of pipe is the length bracketed by two contact points on the main. An out-of-bracket noise source is located outside of that segment. A known noise source may be used to determine the acoustic wave velocity in a segment of pipe. Knowing the distance between the sensors, the acoustic wave velocity (*v*) will be given 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.

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 directly on the pipe.
3. A new correlation measurement is performed and stored as a wave file for further analysis and confirmation off-site. Data is analysed further to obtain an optimum correlation, ensuring an accurate velocity measurement.

Wave Velocity Equation

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

Equation C.2-1: Wave Velocity - Thickness Model

$$v = v_o \times \sqrt{\frac{1}{1 + \frac{D_i}{t_r} \times \frac{K_l}{E}}}$$

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 often 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. Echologics' 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.

Appendix D Abbreviations

AC	Asbestos Cement: Pipe wall construction consisting of asbestos cement.
BWP	Bar Wrapped Pipe: Pipe wall construction comprising of a concrete core, a steel cylinder and reinforcing steel bars.
CI	Cast Iron: Pipe wall construction consisting of cast iron. This includes pipes classified as pit cast iron or spun cast iron as well.
CL	Concrete lined: Indicates whether or not a specific pipe type has some form of concrete lining. This abbreviation will typically follow a pipe type abbreviation Ex: DICL for ductile iron concrete lined.
DI	Ductile Iron: Pipe wall construction consisting of ductile iron.
GIS	Geographic Information System: A system designed to capture, store, manipulate, analyze, manage, and present all types of spatial or geographical data.
GPS	Global Positioning System: a global system of satellites used to provide precise positional data and global time synchronization.
IB	In-Bracket. Please refer to the technical glossary.
OOB	Out-of-Bracket. Please refer to the technical glossary.
PCCP	Pre Stressed Concrete Cylinder Pipe: Pipe wall construction comprising of a concrete core, a steel cylinder and pre-stressed high tension wires.
PCI	Pit Cast Iron: Pipe wall construction consisting of pit cast iron.
PE	Poly Ethylene: Pipe wall construction consisting of poly ethylene.
POI	Point of Interest. Please refer to the technical glossary.

PVC	Poly Vinyl Chloride: Pipe wall construction consisting of poly vinyl chloride.
SCI	Spun Cast Iron: Pipe wall construction consisting of spun cast iron.
St	Steel: Pipe wall construction consisting of steel.

Appendix E Glossary of Technical Terms

Acoustic Wave Speed	Also known as: wave speed, wave velocity, velocity. 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 colour 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 technologies use correlation to judge the time delay between two signals. This allows for determination of the location of leaks along a pipeline.
In-Bracket	A noise source that is within the span of pipe between two Stations or Nodes.
Leak Discovered	A point along a pipe that is likely loosing 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 investigate and it was determined that it was not a leak.
Node	A piece of equipment where a sensor is connected to transmit the data to a central location. Typically nodes are paired with other nodes as part of a large array installed on a pipeline or in an area.
Out-of-Bracket	A noise source that is 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 will be typically used as a reference to a vibration sensor.
Site	A neighbourhood or area within which a segment of pipe exists.

Appendix F   Condition Assessment Validation

Echologics recommends the following procedure to validate ePulse™ measurements on asbestos cement pipe and metallic mains. Appendix E describes recommended coupon extraction and labelling process, individual sample analysis, and recommended validation techniques. This will allow for the most applicable comparison between ePulse™ and the validation data.

Echologics Condition Assessment Validation on Asbestos Cement Pipe

Submitted By: Echologics, LLC

January 10, 2017

Echologics recommends the following procedure to validate ePulse™ measurements on asbestos cement pipe. This document describes recommended coupon extraction and labelling process, individual sample analysis, and recommended validation techniques. This will allow for the most applicable comparison between ePulse™ and the validation data.

The coupon sample analysis process in as follows:

Coupon Sample Extraction and Labeling

1. Coupon samples must be at least two feet in length, not including the bell or spigot.
2. Appropriately name the coupon according to the projects' site name.
3. Clearly identify the top of the pipe.
4. Maintain a list including the following information:
   - Pipe diameter and material
   - Street name and closest street address
   - Closest intersection
   - Echologics' segment number
   - Other site observations
5. Store the sample in a moisture free environment to prevent additional degradation.

Echologics will perform the following procedure to validate ePulse™ results.

Sample Analysis

The client shall consider the pipe sample as a number of hoops, each having a width of "X" (as shown in Figure 1 below). Divide the hoops into sectors similar to the hours on a clock and measure the minimum thickness in each sector around the loop.

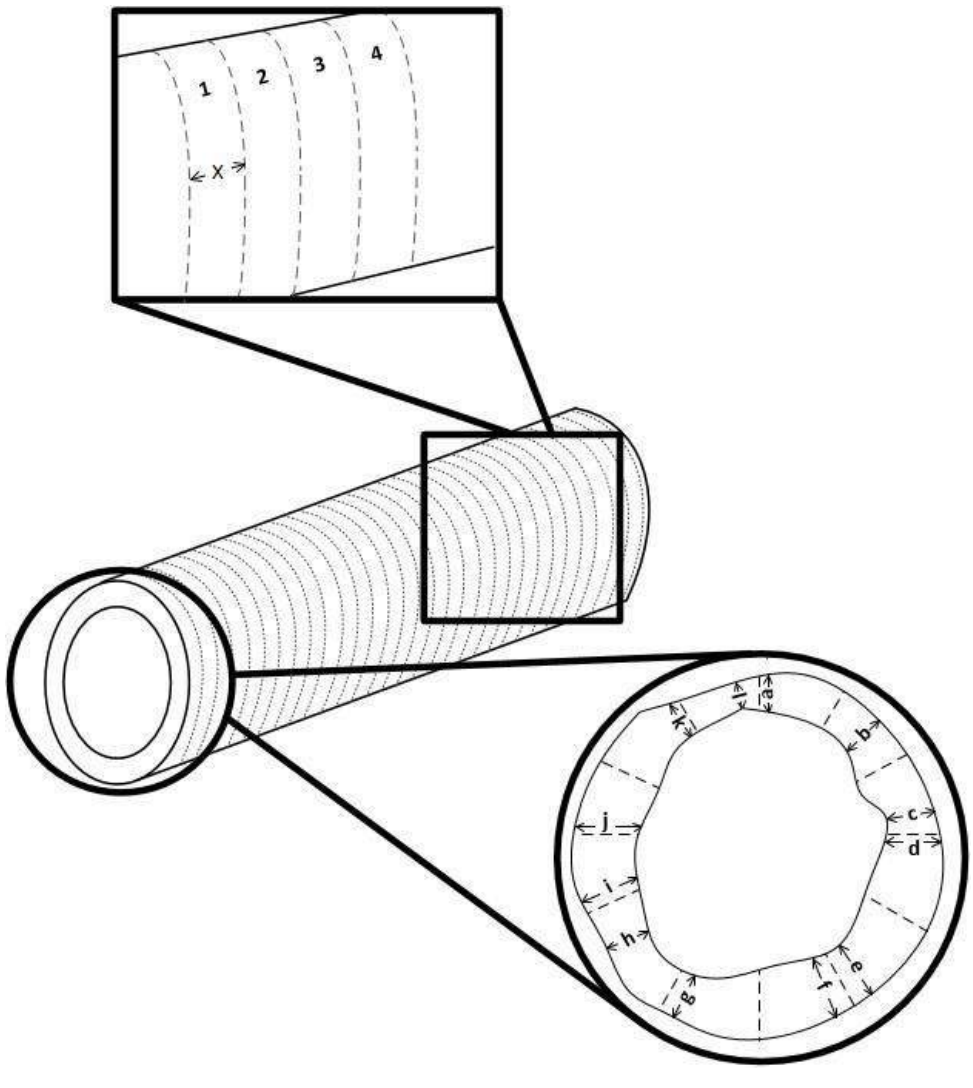


Figure 1: Description of Pipe Segment

Enter the figures from each sector into a chart as shown below in Figure 2. Sections A, B, C …L represent the sector from which the measurement was taken and 1, 2, 3 …N represent the hoop in question. Identify the minimum thickness in each hoop between A to L. Average these minimum thicknesses between all the hoops in the coupon sample to determine the "overall average". Compare the "overall average" to the ePulse™ thickness. This is the most applicable comparison to the average minimum structural wall thickness that ePulse™ provides.

	A	B	C	…	L	Min
1						Min in Hoop 1
2						Min in Hoop 2
3						Min in Hoop 3
…						…
N						Min in Hoop N
Average of Min's						overall average

Figure 2: Measurements from Each Hoop of Pipe Sample

Echologics can also test the modulus of elasticity of the sample to allow for more accurate ePulse™ calibrations if required. This testing will be completed following ASTM standard methods.

Potential Validation Techniques

Echologics will use a combination following validation techniques, as required:

1. **Hydrostatic pressure test (burst strength test)** is an effective method to validate ePulse results. The burst strength test is both the best predictor of pipe failure and also the closest to the average minimum structural wall thickness that ePulse™ measures.
2. **Phenolphthalein Dye Test** indicates the fraction of the pipe wall which still contains calcium as an estimate of the structural wall thickness. For best results, the dye must be applied on a fresh cut and the surface of the cross-section must be polished well.
3. **Chemical analysis** using Electron Dispersive Spectroscopy (EDS) - Semi-quantitative chemical analysis using EDS at polished cross-sections is used to determine the compositional gradients.
4. **Crush strength testing** uses the pipe's ability to withstand compressive stress as a means of calculating the wall thickness.

Echologics Condition Assessment Validation on Metallic Pipe

Drafted By Jay Shah and Kevin Laven, Echologics

January 2, 2017

Echologics recommends the following procedure to validate ePulse™ measurements on metallic pipe. This document provides background on previous validation results and the statistical treatment of validations, and also describes recommended coupon extraction and labelling process, individual sample analysis, and recommended validation techniques. This will allow for the most applicable comparison between ePulse™ and the validation data.

1. Background on Previous Validations

As of the date of this document, a total of 104 ePulse validation results have been provided to Echologics by our clients or third parties. Some clients have requested confidentiality, however we are able to present the result in aggregate.

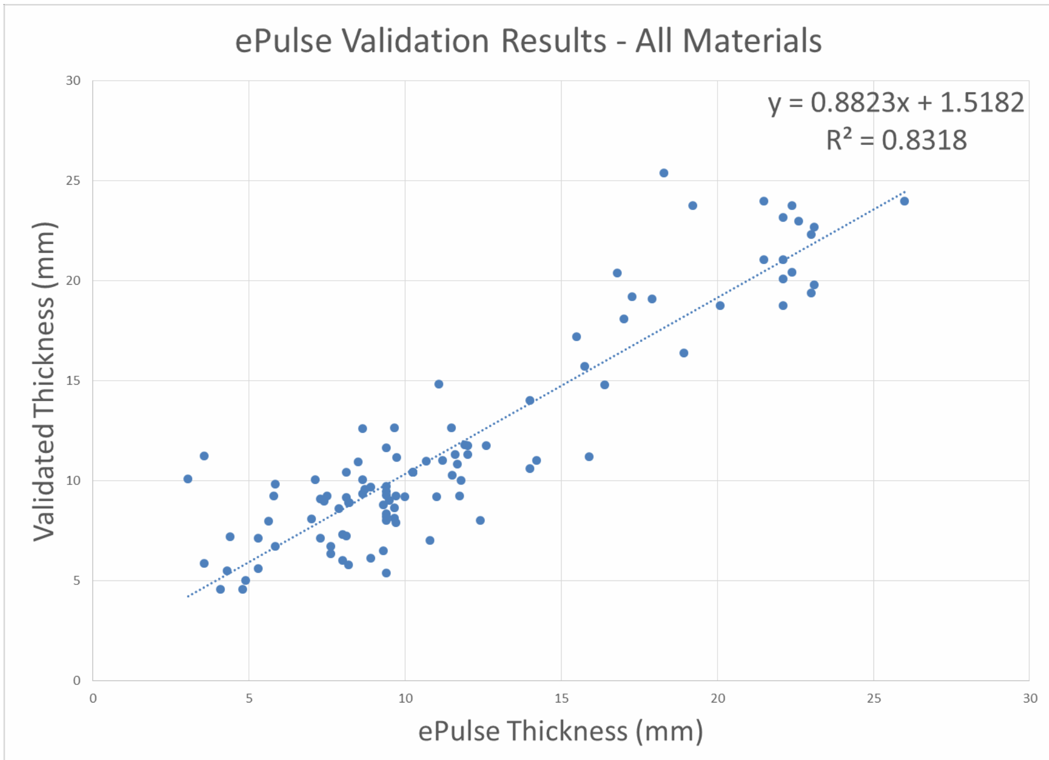


Figure 1: ePulse validations on all materials

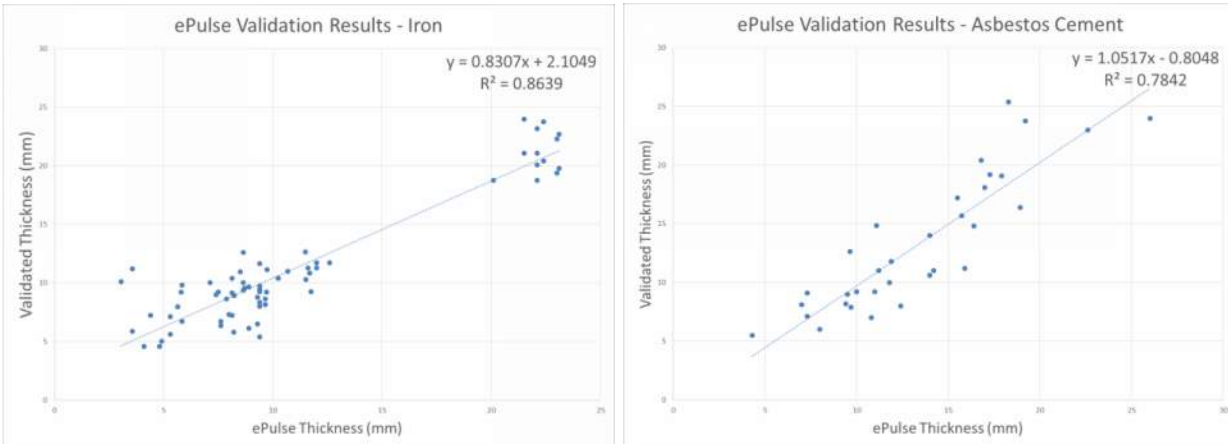


Figure 2: ePulse validations on all iron pipes (left) and asbestos cement pipes (right)

Two factors are worth attention in the charts.

The R^2 value is known as the coefficient of determination. This provides a measure of how well validation results are predicted by ePulse results. It 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 R^2 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 power.

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% 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 **<u>and</u>** the random variation in point samples versus the true average.

Comparing ePulse results to the results of validations will over-estimate the actual error in the ePulse results. The reason for this is that the ePulse results are averages over segments of about 100 m (300 ft) in length, whereas the validation results indicate the thickness at a one 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:

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 will vary randomly along the sample, so the difference between the true average and validation results should be a normal distribution centered around zero. If ePulse is effectively measuring the true average, we should see the same pattern in the difference between the ePulse and Validated results. The actual distribution is shown in Figure 3, and appears to match the expected pattern.

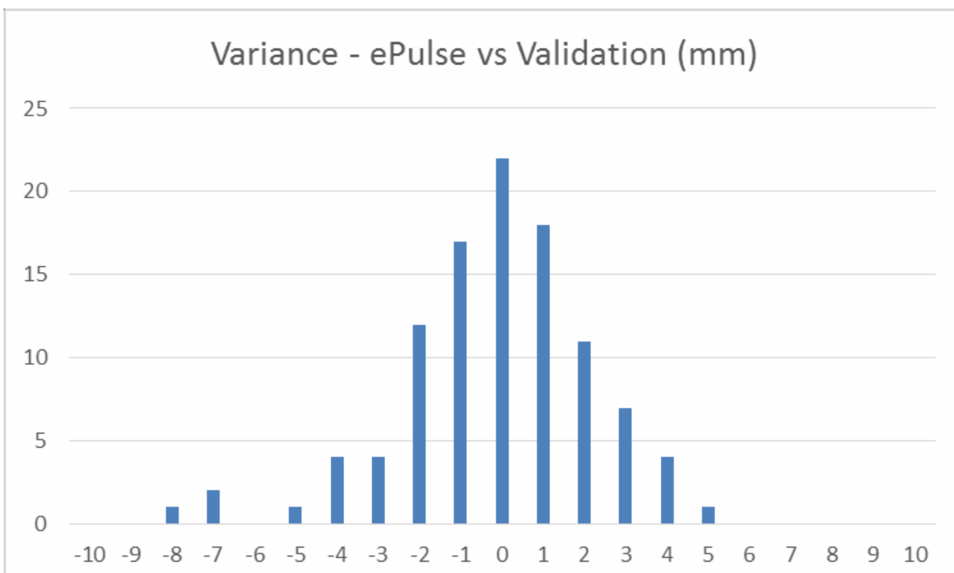


Figure 3: Variance between ePulse results and validation results

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.

2. Coupon Sample Extraction and Labeling

Care must be taken to label samples quickly and accurately after extraction, particularly when multiple samples are taken. A common source of error in a validation process is losing track of which samples were extracted from which locations.

The recommended coupon sample extraction and labeling process is as follows:

1. Samples should be at least 60 cm (2 feet) in length, not including the bell or spigot.
2. Appropriately name the coupon according to the projects' site name. Immediately upon extraction, mark the extracted sample with its name at two points, and also record the name on a written record indicating where it was extracted from.
3. Clearly identify the top of the pipe.
4. Maintain a list including the following information:
   - Pipe diameter and material
   - Street name and closest street address
   - Closest intersection
   - Echologics' segment number
   - Other site observations
5. Store the sample in a moisture free environment to prevent additional degradation.
6. Samples must be sandblasted (grit blasted) to remove tuberculation and graphitization. Care must be taken not to grit blast for so long that healthy iron is removed from the samples as well.

3. Sample Analysis Procedure

The recommended coupon sample extraction and labeling process is as follows:

The client shall consider the pipe sample as a number of hoops, each having a width of "X" = 15 cm (6 in), as shown in Figure 4 below. Divide the hoops into sectors similar to the hours on a clock and measure the minimum thickness in each sector around the loop.

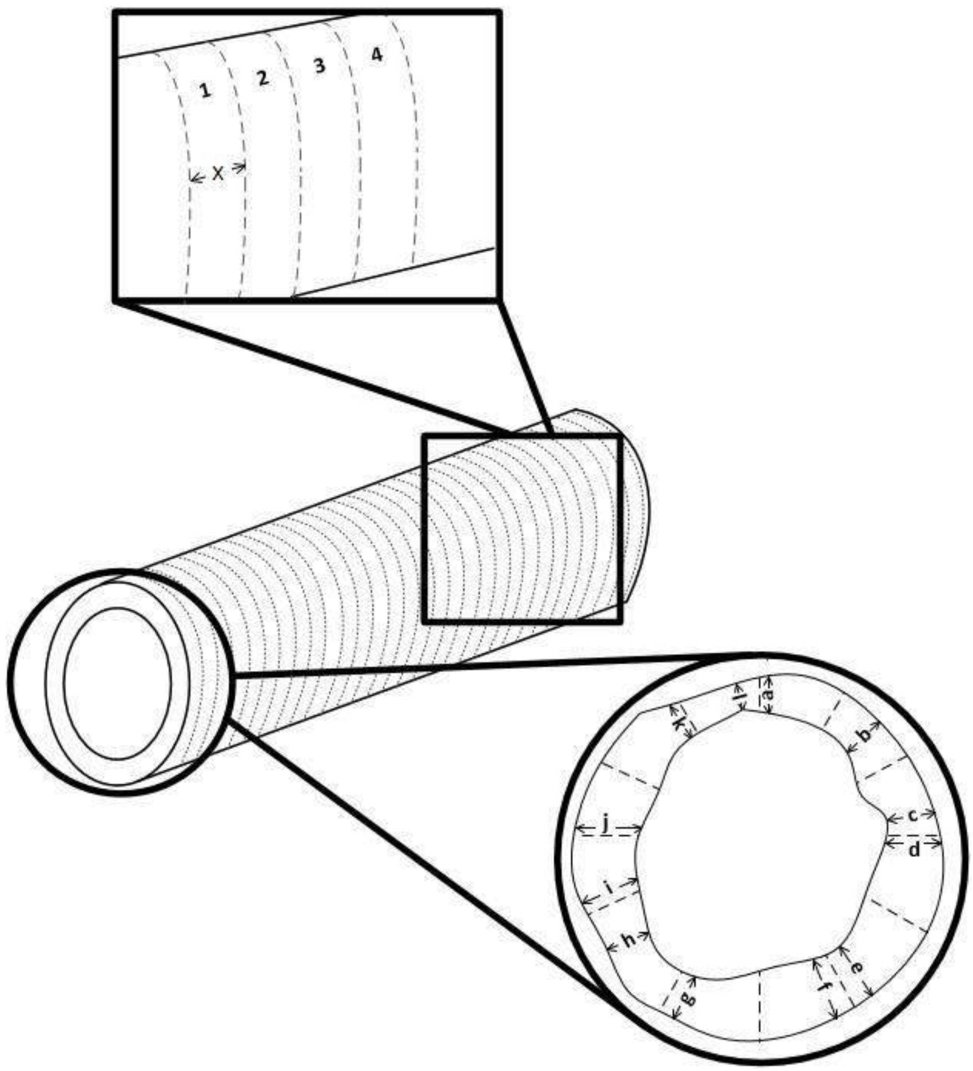


Figure 4: Description of Pipe Segment

Enter the figures from each sector into a chart as shown below in Figure 5. Sections A, B, C …L represent the sector from which the measurement was taken and 1, 2, 3 …N represent the hoop in question. Identify the minimum thickness in each hoop between A to L. Average these minimum thicknesses between all the hoops in the coupon sample to determine the “overall average”. Compare the “overall average” to the ePulse™ thickness. This is the most applicable comparison to the average minimum structural wall thickness that ePulse™ provides.

	A	B	C	…	L	Min
1						Min in Hoop 1
2						Min in Hoop 2
3						Min in Hoop 3
…						…
N						Min in Hoop N
					Average of Min's	overall average

Figure 5: Measurements from Each Hoop of Pipe Sample

Echologics can also test the modulus of elasticity of the sample to allow for more accurate ePulse™ calibrations if required. This testing will be completed following ASTM standard methods.

It is important to note that the values generated by ePulse™ testing are averaged for a segment of pipe which ranges in length from 100 m (300 feet) to 200 m (600 feet). This averaging allows for the possibility of having small lengths within the segment with different degradation levels than the average condition. ePulse measurements describe the general condition of the pipe segment tested and may not be equivalent to the measurements from a single pipe sample. Exhuming a large number of samples from one segment increases the likelihood of the different measurement methods matching up.

4. Validation Measurement Techniques

Echologics recommends that one or more of the following validation techniques be used, as required:

1. **External Electromagnetic Testing**. This method is performed at various locations along the main. The results provide a high-resolution grid of internal and external wall thickness, which includes internal voids. This method also has the benefit of being non-destructive and non-invasive, and can be performed without grit blasting the sample. Several technologies are available, including Broadband Electromagnetics, Remote Field Testing, and Magnetic Flux Leakage.
2. **Pipe Coupon Sampling**. Generally, a number of 1 meter (3 foot) or longer pipe samples are exhumed, cleaned and grit blasted. Individual corrosion pits are measured in each zone using a pit depth gauge, and recorded in the chart for analysis. As an alternative to using a pit gauge, a more complete measurement can be made of the pipe wall through 3D laser scanning or photogrammetry.

5. Analysis of Validation Results

The goal of a validation exercise is to confirm or disprove the hypothesis that ePulse results and validation results are both measurements of the same underlying actual average wall thickness.

Two different statistical approaches are available. Which one to use depends on how much variation there is among the validation samples.

5.1 Checking for Agreement of the Means

If the validations show little variation, they were likely taken from pipes with similar average wall thickness. In this case the correct approach is to examine the means of the two validation samples and the corresponding ePulse samples.

A simple means of testing this is to calculate the mean (in Excel, the AVERAGE function) and standard deviation (in Excel, the STDEV.S function) of the validation results, and also calculate the mean and standard deviation of the ePulse results. If the means differ by less than the standard deviations, they are said to agree.

A more robust approach is to use a statistical test of a null hypothesis. In this case, the null hypothesis is that “there is no difference between the mean values of the ePulse and Validation results.” This can be computed using the Student’s T-Test, and a 95% confidence interval. If the null hypothesis is disproven by this means that the underlying averages are different (i.e. that ePulse is returning incorrect results). This can be computed in Excel as follows (for an example with 10 ePulse results in column A and 10 validation results in column B):

=IF(TTEST(A1:A10,B1:B10,2,1)<0.05, "Validation Failed","Validation Succeeded")

5.2 Checking for Correlation

If the validations show substantial variation, they likely represent pipes with a variety of average wall thicknesses. In this case the correct approach is to examine the correlation between the two data sets.

A simple means of testing this is to create a scatter plot with the ePulse results on the X Axis and the validation results on the Y axis. Create a linear trend line on the plot, and display the R^2 value. As noted in Section 1, an R^2 value above 0.5 represents strong predictive power. 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% of the average value represent good calibration.

Appendix B -
McWane Pipe Report

McWane Ductile Ohio
Charles Weaver
R&E Manager – Product Testing
2266 South Sixth Street
Coshocton, OH 43812
Charles.weaver@mcwaneductile.com
O 740-202-7451 C 740-294-8570

Customer:
Wareham Fire District
2550 Cranberry Highway
Wareham, MA 02571
Phone: 508-295-0450
Cell: 508-294-1076

To whom it may concern:

The following burst, yield and product type testing was conducted for Wareham Fire District. The results attached are to be used for informational purpose. McWane Ductile is not advising nor implying that products that were tested are good or bad. McWane Ductile is just supplying data for the Wareham Fire District. All test results are compared to ductile iron standards. Please see below and attached for testing results.

Burst Testing Results:

8" Ductile Iron Sample

Capped, filled and pressurized to 1800 psi with no failures.

12" Ductile Iron Sample

Capped, filled and pressurized to 1100 psi with no failures of the pipe sample. Testing apparatus broke at 1100 psi. No signs of cracks or holes in the pipe sample.

10" Spun Cast Iron Sample

Sample was too short to get a good test. The sample had to have the threads cut of the end to get good seal during testing. Sample was capped, filled and pressurized to 600 psi before the cap started to leak. Test was tried again with same results.

8" Pit Cast Iron Sample

Capped, filled and pressurized to 1580 psi when the side of the sample broke out.

Fiber Glass Pipe Samples

The Fiber glass pipe samples that were supplied to McWane Ductile Ohio for testing. Was not tested due to unknown material type and/or unknown additives that are in the pipe sample during its manufacturing process for health reasons and that the sizes of the pipe did not match any of McWane Ductile cap sizes.

14.28” diameter sample was not tested

9.39” diameter sample was not tested

Physical Test Results

See attached for Physical testing of the 8” Ductile, 12” Ductile, 10” Spun Cast and 8” Pit Cast samples.

If there is any questions concerning the testing that was conducted, please contact Charles Weaver at 740-294-8570 or email charles.weaver@mcwaneductile.com.

Thank you,

Have an Iron Strong Day,

Charles Weaver

McWane Ductile Ohio

R&E Manager – Product Testing

10"

Product testing

~~Returned Material~~

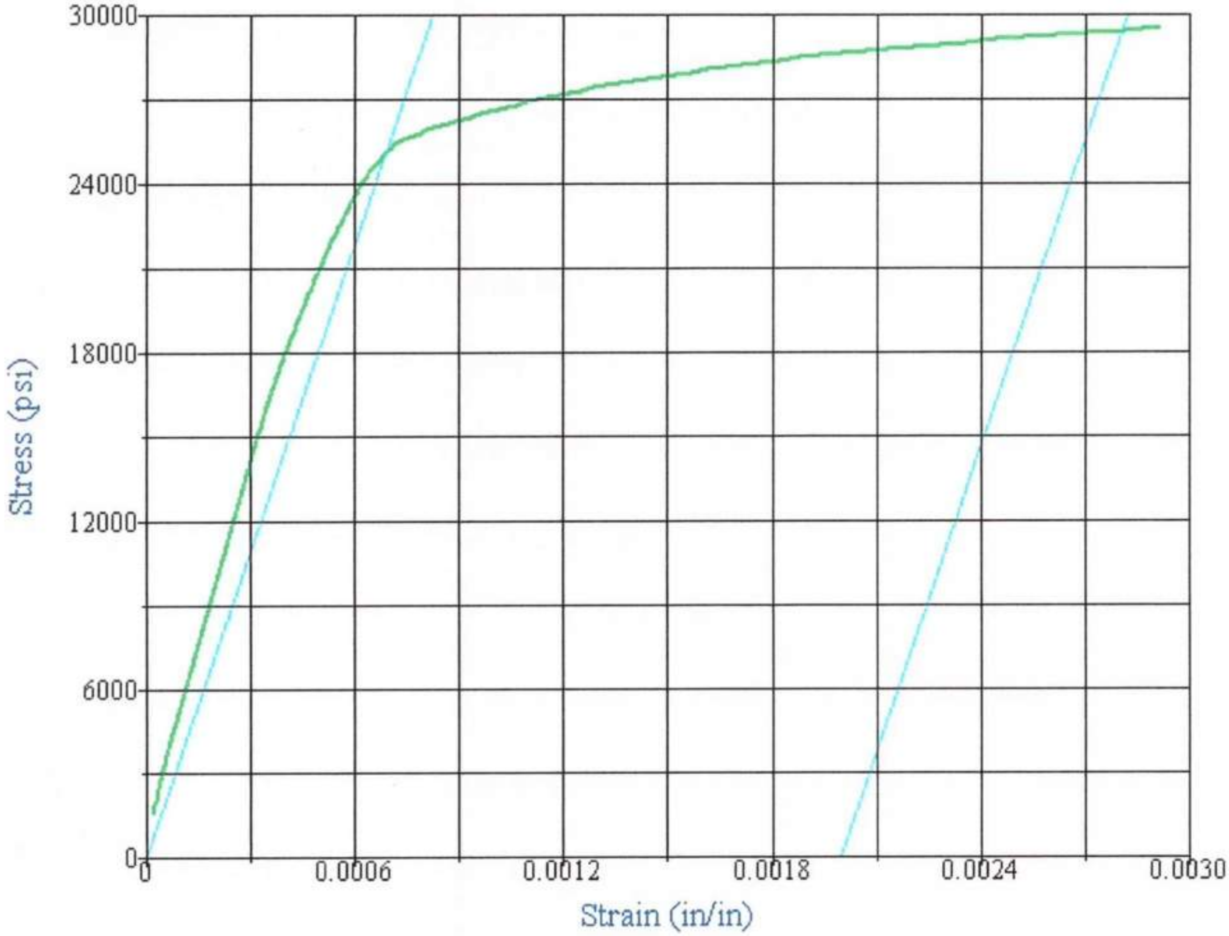
Spun Cast Iron

Physical Test Results

Date ____________________ Requestor ______________________________

Circle all out-of-specification results

Tensile Specimen Data							42,000 Min. PSI	60,000 Min. PSI		10% Min	Rockwell "B" (reference only)			8.0 ft.-lbs. Min.	Microstructure			
Pipe Size	Wall Thickness	Dia.	Area	Gage Length	Yield Load	Breaking Load	Yield Str. PSI	Tensile Str. PSI	Elong (Inc.)	Elong %	Out	Mid	In	Charpy Impact	Carbide	Pearlite	Ferrite	Nodulant
10	.457	.251	.0495	.990	1457	1461	29,500	29,500	1.013	2	76	80	82	2.0	0	2	85	4/650



Test Summary

Counter:	15906
Elapsed Time:	00:00:34
Procedure Name:	.250
Start Date:	7/17/2018
Start Time:	8:23:26 PM
End Date:	7/17/2018
End Time:	8:24:00 PM
Workstation:	Clow Water Systems
Tested By:	chad
MyNote:	product test 10 "
PipeSize:	
CM:	
Class:	

Test Results

Diameter:	0.2510 in
Area:	0.0495 in²
Peak Load:	1461 lbf
Secant Modulus:	36487000 psi
Load at Offset:	1457 lbf
Tensile Strength:	29520 psi
Total Elongation:	2.32 %
Pretest Punch Length:	.9900 in
Posttest Punch Length:	1.0130 in
Stress at Offset:	29430 psi

8" #2

Product testing

Pit Cast Iron

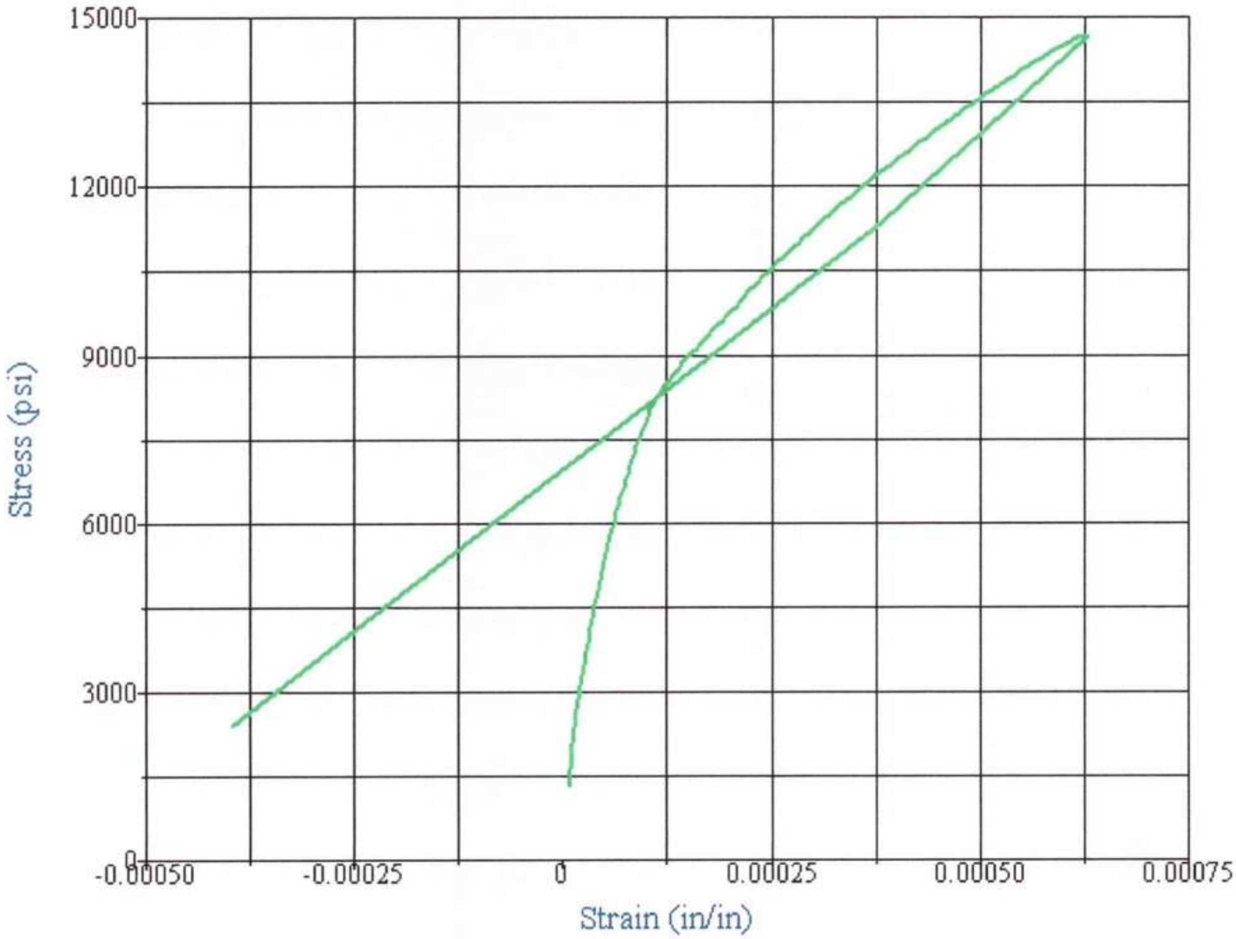
Returned Material

Physical Test Results

Date ____________________ Requestor ______________________________

Circle all out-of-specification results

Tensile Specimen Data							42,000 Min. PSI	60,000 Min. PSI		10% Min	Rockwell "B" (reference only)			8.0 ft.-lbs. Min.	Microstructure			
Pipe Size	Wall Thickness	Dia.	Area	Gage Length	Yield Load	Breaking Load	Yield Str. PSI	Tensile Str. PSI	Elong (Inc.)	Elong %	Out	Mid	In	Charpy Impact	Carbide	Pearlite	Ferrite	Nodulant
8	.398										91	96	97	1.3	6	8	79	5/212



Test Summary

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Procedure Name:	.250
Start Date:	7/17/2018
Start Time:	7:47:04 PM
End Date:	7/17/2018
End Time:	7:47:20 PM
Workstation:	Clow Water Systems
Tested By:	chad
MyNote:	product test # 2
PipeSize:	
CM:	
Class:	

Test Results

Diameter:	0.2565 in
Area:	0.0517 in²
Peak Load:	759 lbf
Secant Modulus:	Failed
Load at Offset:	Failed
Tensile Strength:	14680 psi
Total Elongation:	0.81 %
Pretest Punch Length:	.9905 in
Posttest Punch Length:	.9985 in
Stress at Offset:	Failed

8" #1

Product testing

~~Returned Material~~

Ductile

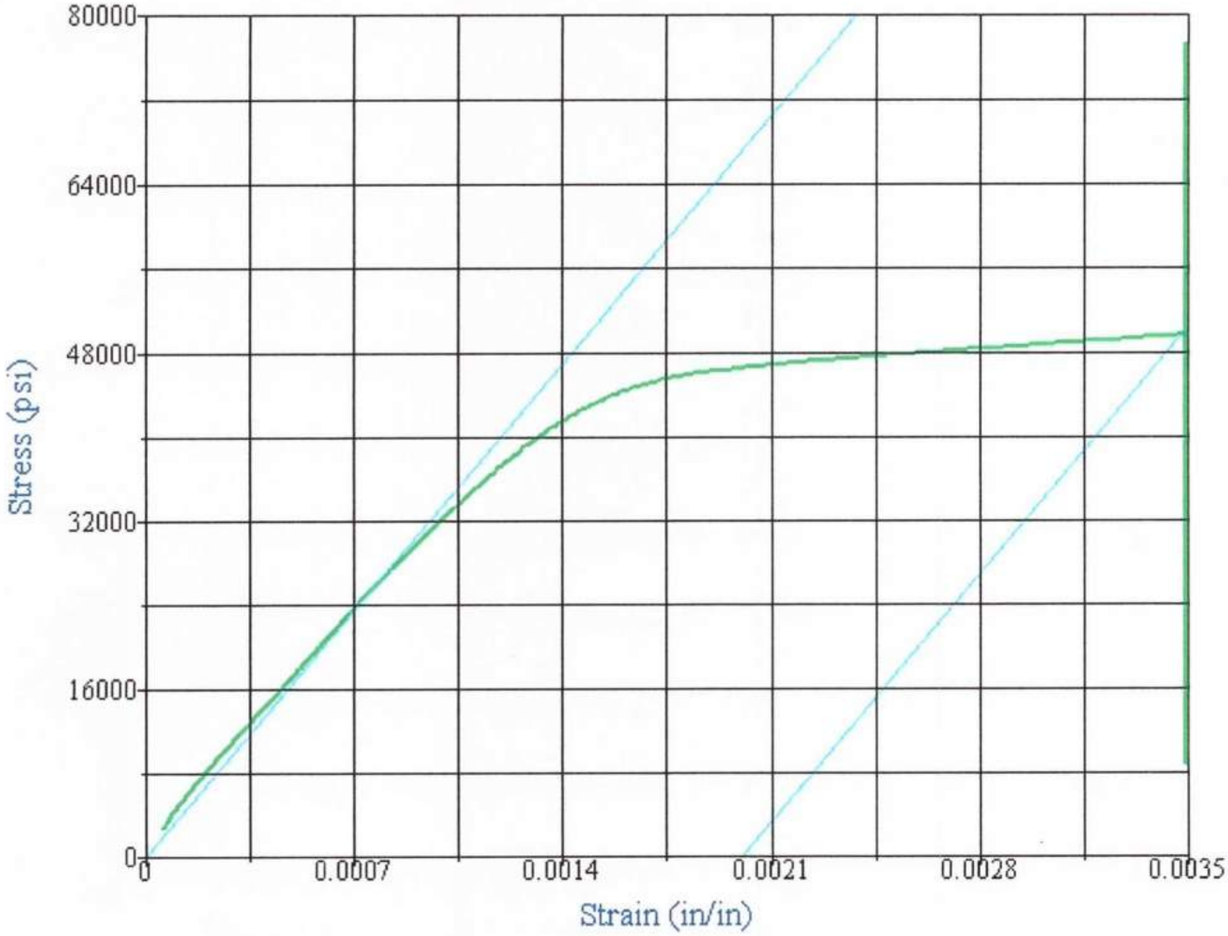
Physical Test Results

Date ____________________

Requestor ________________________________

Circle all out-of-specification results

Tensile Specimen Data							42,000 Min. PSI	60,000 Min. PSI		10% Min	Rockwell "B" (reference only)			8.0 ft.-lbs. Min.	Microstructure			
Pipe Size	Wall Thickness	Dia.	Area	Gage Length	Yield Load	Breaking Load	Yield Str. PSI	Tensile Str. PSI	Elong (Inc.)	Elong %	Out	Mid	In	Charpy Impact	Carbide	Pearlite	Ferrite	Nodulant
8	.301	.176	.0245	.693	1216	1894	49,500	77,500	.799	15	89	90	88	10.0	0	16	73	82/535



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Procedure Name:	.175
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Start Time:	7:16:49 PM
End Date:	7/17/2018
End Time:	7:18:48 PM
Workstation:	Clow Water Systems
Tested By:	chad
MyNote:	product test # 1
CM:	
PipeSize:	
Class:	

Test Results	
Diameter:	0.1765 in
Area:	0.0245 in²
Peak Load:	1894 lbf
Secant Modulus:	33575000 psi
Load at Offset:	1216 lbf
Tensile Strength:	77310 psi
Total Elongation:	15.30 %
Pretest Punch Length:	.6930 in
Posttest Punch Length:	.7990 in
Stress at Offset:	49630 psi

12" #1

Product Testing   Ductile

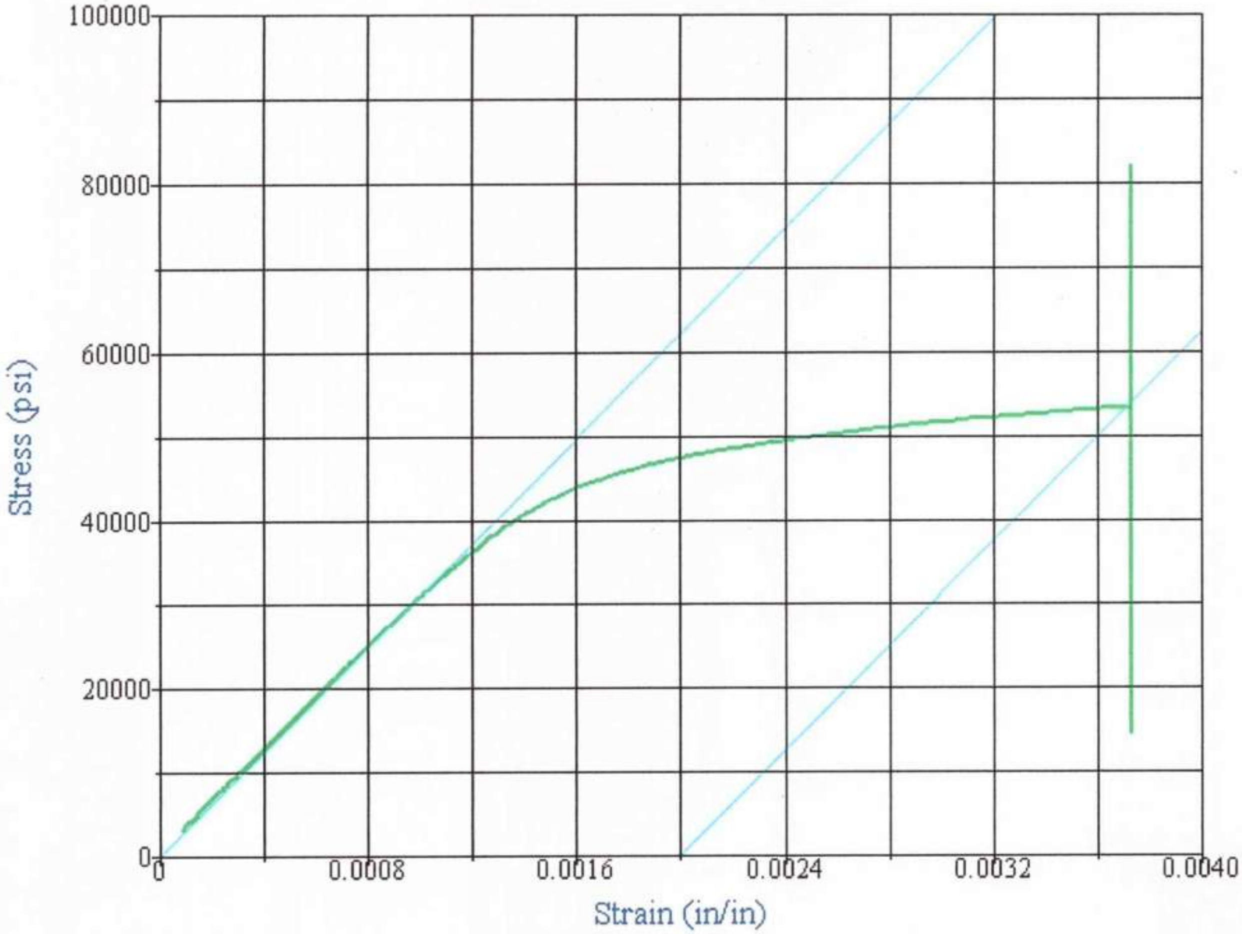
Returned Material

Physical Test Results

Date 7-17-18   Requestor ____________________

Circle all out-of-specification results

Tensile Specimen Data							42,000 Min. PSI	60,000 Min. PSI		10% Min	Rockwell "B" (reference only)			8.0 ft.-lbs. Min.	Microstructure			
Pipe Size	Wall Thickness	Dia.	Area	Gage Length	Yield Load	Breaking Load	Yield Str. PSI	Tensile Str. PSI	Elong (Inc.)	Elong %	Out	Mid	In	Charpy Impact	Carbide	Pearlite	Ferrite	Nodulant
12"	.324	.170	.0228	.693	1218	1874	53,570	82,000	.795	15	82	86	85	10.5	Ø	22	73	42/139



Test Summary	
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Start Time:	5:47:04 AM
End Date:	7/17/2018
End Time:	5:49:08 AM
Workstation:	Clow Water Systems
Tested By:	chad
MyNote:	product testing #1
CM:	
PipeSize:	12
Class:	

Test Results	
Diameter:	0.1705 in
Area:	0.0228 in²
Peak Load:	1874 lbf
Secant Modulus:	31095000 psi
Load at Offset:	1218 lbf
Tensile Strength:	82190 psi
Total Elongation:	14.71 %
Pretest Punch Length:	.6935 in
Posttest Punch Length:	.7955 in
Stress at Offset:	53420 psi