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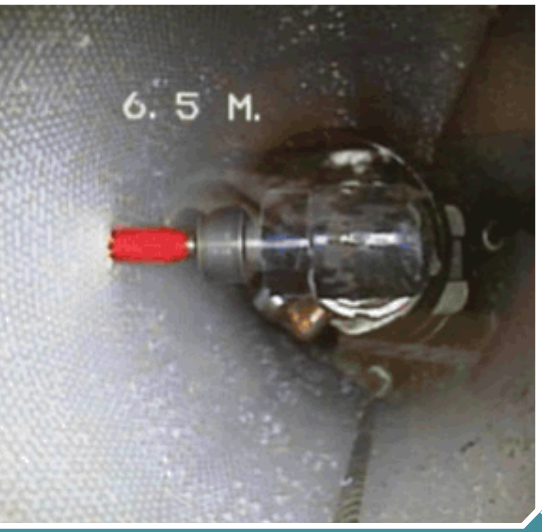
United States Environmental Protection Agency

# Performance Evaluation of Innovative Water Main Rehabilitation Cured-in-Place Pipe Lining Product in Cleveland, Ohio



SCIENCE

Office of Research and Development
National Risk Management Research Laboratory - Water Supply and Water Resources Division

# PERFORMANCE EVALUATION OF INNOVATIVE WATER MAIN REHABILITATION CURED-IN-PLACE PIPE LINING PRODUCT IN CLEVELAND, OH

**by**

**John Matthews, Ph.D., Wendy Condit, P.E., Ryan Wensink, and Gary Lewis**
**Battelle Memorial Institute**

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**Ariamalar Selvakumar, Ph.D., P.E.**
**Task Order Manager**

**U.S. Environmental Protection Agency**
**Urban Watershed Branch**
**National Risk Management Research Laboratory**
**Water Supply and Water Resources Division**
**2890 Woodbridge Avenue (MS-104)**
**Edison, NJ 08837**

**National Risk Management Research Laboratory**
**Office of Research and Development**
**U.S. Environmental Protection Agency**
**Cincinnati, Ohio 45268**

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## DISCLAIMER

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## ABSTRACT

Some utilities are seeking emerging and innovative rehabilitation technologies to extend the service life of and repair a greater portion of their infrastructure systems. However, information on new technologies is not always readily available and easy to obtain. To help provide this information, the U.S. Environmental Protection Agency (EPA) developed an innovative technology demonstration program to evaluate technologies that have the potential to increase the effectiveness of the operation, maintenance, and renewal of aging water distribution and wastewater conveyance systems and reduce costs. This program also could be used to make the technologies' capabilities better known to the industry. This report describes the performance evaluation of a Sanexen Aqua-Pipe® cured-in-place pipe (CIPP) lining product for water main rehabilitation that was demonstrated in Cleveland, Ohio.

The demonstration approach began by developing a demonstration protocol to provide a consistent approach for conducting the project by outlining the approach to plan, coordinate, and perform the demonstration. Specific metrics evaluated under this program included technology maturity, feasibility, complexity, performance, cost, and environmental impact. These metrics were used to identify five emerging and innovative water main rehabilitation technologies for potential demonstration, one of which was the use of a structural CIPP lining, which has potential as a structural alternative to traditional open-cut techniques used in water distribution pipes.

The CIPP lining demonstration was completed over the course of a week on seven lining runs spanning a total of 1,996 ft of 6 in. cast iron water main and each lining run passed post-installation pressure testing. A total of 17 of the 63 service connections (27%) had to be reinstated externally due to connections that were flush, located in folds, blocked, deformed during cleaning, or misaligned with the corporation stops. The evaluation metrics showed that the technology is innovative since it has been used at little more than 20 sites in the U.S. with several utilities expressing their willingness to use the technology in the future. The technology met the project rehabilitation requirements and is considered to be beneficial for small, medium, and large utilities in need of structural alternatives to replacement. The project lasted 10 weeks: two weeks for bypass/excavation; seven weeks for pipe preparation, liner installation, and reconnection with the pipe out of service; and one week for site restoration.

For the service connections, 5% (3 of 63) of the services were reinstated externally due to common issues and another 22% (14 of 63) had to be reinstated externally due to events the manufacturer has rarely encountered. The liner exceeded the requirements of ASTM F-1216, performed in a manner consistent with a fully-structural Class IV CIPP liner, and improved the Hazen-Williams C-factor by nearly 43% from 78.5 to 112.1. The overall demonstration cost was $505,687 for a unit cost of $247.89/liner foot (lf) and the CIPP portion of the project accounted for $374,000 of the total cost for a unit cost of $187.38/lf. An estimated 52,880 pounds (lb) of carbon dioxide ($CO_2$) emissions for on-site operations could have been reduced to 37,600 lb if the lining crew had not mobilized from 600 miles away. A similar replacement project would emit 77,360 lb of $CO_2$ for on-site operations and transportation and up to 6 times more $CO_2$ when considering material production emissions.

The demonstration of the Sanexen Aqua-Pipe® CIPP liner in Cleveland was a successful project providing valuable information on the design, installation, and QA/QC of CIPP used to rehabilitate water mains, but continued improvements should be made in the process for internal reinstatement of services. The project successfully demonstrated an innovative Class IV rehabilitation technology that met the owner's expectations and multiple utilities expressed their willingness to use the technology again. It is recommended that the cleaning process be standardized, and other issues contributing to the need for external reinstatement be studied and improved upon including: flush service connections that cannot be identified in smaller diameter pipes; and difficulty drilling service connections located in folds.

**ACKNOWLEDGMENTS**

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# EXECUTIVE SUMMARY

## Introduction

Some utilities are seeking emerging and innovative rehabilitation technologies to extend the service life of and repair a greater portion of their infrastructure systems. However, information on new technologies is not always readily available and easy to obtain. To help provide this information, the U.S. Environmental Protection Agency (EPA) developed an innovative technology demonstration program to evaluate technologies that have the potential to increase the effectiveness of the operation, maintenance, and renewal of aging water distribution and wastewater conveyance systems and reduce costs. This program could be used to make the technologies' capabilities better known to the industry. This report describes the performance evaluation of a structural cured-in-place pipe (CIPP) lining product for water main rehabilitation that was demonstrated in Cleveland, Ohio.

## Demonstration Approach

A protocol was developed to provide a consistent approach for conducting the project by outlining the approach to plan, coordinate, and perform the demonstration. Execution of the protocol records the use and provides an assessment of the technology, while also providing a documented case study of the technology selection process, application of a consistent design methodology, and application of appropriate quality assurance/quality control (QA/QC) procedures. Specific metrics evaluated under this program include technology maturity, feasibility, complexity, performance, cost, and environmental impact. These metrics were used to identify five emerging and innovative water main rehabilitation technologies for potential demonstration.

One of the five technologies identified for demonstration was the use of a structural CIPP lining, which has potential as a structural alternative to traditional open-cut techniques used in water distribution pipes. This report outlines the demonstration of Sanexen's Aqua-Pipe® CIPP product in Cleveland, Ohio for the City of Cleveland Water Division. CIPP was developed for the wastewater rehabilitation industry more than 40 years ago, but over the past 10 years it has started to emerge as an alternative for water main rehabilitation. This field demonstration allowed for an evaluation of the main benefits claimed and limitations cited by Sanexen for this innovative CIPP technology.

To ensure that the field demonstration was useful to the user community, several factors had to be evaluated including: utility commitment; perceived value; regulatory and stakeholder climate; representativeness of test pipe and site conditions; suitability of test pipe and site conditions to vendor specifications; and site access and safety considerations. The research team consulted with Sanexen and the City of Cleveland Water Division to conduct the demonstration as part of a project that had already been scheduled between the two parties.

## CIPP Lining Demonstration

Site preparation activities included: bypass installation; excavation of access pits; collection of soil and water samples; baseline hydraulic testing; cutting the test pipe; cleaning and drying of the test pipe; placement of defect pipe segments; and service plugging and pre-lining closed-circuit television (CCTV) inspection. Pipe wall thickness and diameter measurements were also taken prior to rehabilitation.

The CIPP lining demonstration was completed over the course of a week on seven lining runs spanning a total of 1,996 ft of 6 in. cast iron water main and each lining run passed post-installation pressure testing. A total of 17 of the 63 service connections (27%) had to be reinstated externally due to connections that were flush, located in folds, blocked, deformed during cleaning, or misaligned with the corporation stops.

## Demonstration Results

The evaluation metrics showed that the technology is innovative since it has been used at little more than 20 sites in the U.S. with several utilities expressing their willingness to use the technology in the future. The outcome of the technology evaluation is described in the technology evaluation metrics listed below:

### Technology Maturity Metric

- Innovative technology used at less than 30 sites in the U.S.
- Improvement over traditional rehabilitation using cement mortar lining (Class IV versus Class I).
- Some data available, but long-term tests are ongoing and the method track record spans 10 years.
- Each utility owner contacted cited positive results and willingness to use the product again.

### Technology Feasibility Metric

- Project required a structural rehabilitation and the technology met the rehabilitation requirements.
- Liner was not installed through any valves or fittings and the runs were without any major bends.
- Incomplete and/or premature curing of the liner was not evident during installation or inspection.

### Technology Complexity Metric

- Beneficial for small, medium, and large utilities in need of structural alternatives to replacement.
- Requires trained installers. Pre- and post-activities can be performed with typical personnel.
- Site preparation requirements are similar to other rehabilitation technology requirements.
- The project lasted 10 weeks: two weeks for bypass/excavation, seven weeks for pipe preparation, liner installation, and reconnection with the pipe out of service, and one week for site restoration.
- 5% (3 of 63) of the services were reinstated externally due to common issues and another 22% (14 of 63) had to be reinstated externally due to events the manufacturer has rarely encountered.

### Technology Performance Metric

- The liner exceeded the requirements of ASTM F-1216.
- Performed in a manner consistent with a fully-structural Class IV CIPP liner.
- Hazen-Williams C-factor was improved by nearly 43% from 78.5 to 112.1.

### Technology Cost Metric

- The overall demonstration cost $505,687 for a unit cost of $247.89/liner foot (lf).
- CIPP portion of the project accounted for $374,000 of the total cost for a unit cost of $187.38/lf.

### Technology Environmental and Social Metrics

- Social disruption was minimal since traffic was not greatly affected and excavation was limited.
- Flush volume required for bypass, jetting, and scraping estimated to be 272,600 gallons (gal).
- Estimated 52,880 pounds (lb) of carbon dioxide ($CO_2$) emissions for on-site operations could have been reduced to 37,600 lb if the lining crew had not mobilized from 600 miles away.
- A similar replacement project would emit 77,360 lb of $CO_2$ for on-site operations and transportation and up to 6 times more $CO_2$ when considering material production emissions.
- If only 5% of the services were reinstated externally, the $CO_2$ impact from the equipment used for site restoration could have been reduced by 50%, an additional 9,480 lb of $CO_2$ emissions.

## Conclusions and Recommendations

The demonstration of the Sanexen Aqua-Pipe® CIPP liner in Cleveland was a successful project providing valuable information on the design, installation, and QA/QC of CIPP used to rehabilitate water mains, but continued improvements should be made in the process for internal reinstatement of services. The project successfully demonstrated an innovative Class IV rehabilitation technology that met the owner's

expectations and multiple utilities expressed their willingness to use the technology again. It is recommended that the cleaning process be standardized, and other issues contributing to the need for external reinstatement be studied and improved upon including: flush service connections that cannot be identified in smaller diameter pipes; and difficulty drilling service connections located in folds.

## TABLE OF CONTENTS

*DISCLAIMER* ..... *i*

*ABSTRACT* ..... *ii*

*ACKNOWLEDGMENTS* ..... *iii*

*EXECUTIVE SUMMARY* ..... *iv*

*TABLE OF CONTENTS* ..... *vii*

*FIGURES* ..... *ix*

*TABLES* ..... *x*

*ABBREVIATIONS AND ACRONYMS* ..... *xii*

*1.0: INTRODUCTION* ..... *1*

**1.1 Project Background** ..... **1**

**1.2 Project Objective** ..... **2**

**1.3 Report Outline** ..... **2**

*2.0: DEMONSTRATION APPROACH* ..... *3*

**2.1 Demonstration Protocol Overview** ..... **3**

**2.2 Technology Selection Approach** ..... **5**

2.2.1 Overview of Innovative Water Main Rehabilitation Technologies ..... 7
2.2.2 Overview of CIPP Water Pipe Rehabilitation ..... 9
2.2.3 Technology Description ..... 10
2.2.4 Design Approach for Structural CIPP Liners ..... 13
2.2.5 Installation of CIPP Liners ..... 15
2.2.6 QA/QC Requirements for CIPP Liners ..... 16
2.2.7 Operation and Maintenance for CIPP Liners ..... 17

**2.3 Site Selection Approach** ..... **18**

2.3.1 Site Selection Factors ..... 18
2.3.2 Site Description ..... 19
2.3.3 Physical/Operating Characteristics of the Test Pipe ..... 22

*3.0: CIPP DEMONSTRATION* ..... *25*

**3.1 Site Preparation** ..... **25**

**3.1.1 Safety and Logistics** ..... 25
3.1.2 Installation of Bypass ..... 26
3.1.3 Excavation Pits and Pipe Access ..... 26
3.1.3.1 Soil Sampling ..... 28
3.1.3.2 Water Sampling ..... 31
3.1.4 Hydraulic Testing ..... 34
3.1.4.1 Leak Detection Survey ..... 34
3.1.4.2 Friction Factor Test ..... 34
3.1.5 Cleaning and Drying of Pipe ..... 35
3.1.6 Defect Installation ..... 38
3.1.6.1 Lab-Prepared Defect Pipe Segment ..... 38
3.1.6.2 Field-Prepared Defect Pipe Segment ..... 39
3.1.7 Service Plugging and Pipe Inspection ..... 40

3.1.7.1 Pre-Lining CCTV of Lining Run #1 ....41
3.1.7.2 Pre-Lining CCTV of Lining Run #2 ....43
3.1.7.3 Pre-Lining CCTV of Lining Run #3 ....44
3.1.7.4 Pre-Lining CCTV of Lining Run #4 ....45
3.1.7.5 Pre-Lining CCTV of Lining Run #5 ....46
3.1.7.6 Pre-Lining CCTV of Lining Run #6. ....47
3.1.7.7 Pre-Lining CCTV of Lining Run #7 ....47
3.1.8 Pipe Wall Thickness and Inner Diameter ....48

**3.2 Technology Application ....48**
**3.2.1 Technology Application Equipment and Process ....49**
3.2.2 CIPP Liner Installation ....51
3.2.3 Post-Installation Pressure Test ....51
3.2.4 Reinstatement of Service Connections ....51
3.2.4.1 Internal Reinstatement ....52
3.2.4.2 External Reinstatement ....52

**3.3 Post-Demonstration Field Verification ....53**
3.3.1 Post-Lining CCTV ....53
3.3.1.1 Post-Lining CCTV of Lining Run #1 ....53
3.3.1.2 Post-Lining CCTV of Lining Run #2 ....54
3.3.1.3 Post-Lining CCTV of Lining Run #3 ....55
3.3.1.4 Post-Lining CCTV of Lining Run #4 ....55
3.3.1.5 Post-Lining CCTV of Lining Run #5 ....56
3.3.1.6 Post-Lining CCTV of Lining Run #6 ....57
3.3.1.7 Post-Lining CCTV of Lining Run #7 ....57
3.3.2 Lining Thickness ....58

**3.4 Defect Sample Collection ....59**
3.4.1 Lab-Prepared Defect Pipe Segment ....59
3.4.2 Field-Prepared Defect Pipe Segment ....60
3.4.3 Sampling Logistics ....60

**3.5 Site Restoration ....60**
3.5.1 Disinfection ....60
3.5.2 Reconnecting the Test Pipe ....60
3.5.3 Backfilling and Site Restoration ....61

**3.6 Post-Rehabilitation Friction Factor Test ....61**

***4.0: DEMONSTRATION RESULTS .... 62***

**4.1 Technology Maturity ....62**

**4.2 Technology Feasibility ....63**

**4.3 Technology Complexity ....64**
4.3.1 Training and Preparation Requirements ....64
4.3.2 Labor and Time Requirements ....64
4.3.3 Process Evaluation ....65

**4.4 Technology Performance ....65**
4.4.1 Liner Thickness ....66
4.4.2 Liner Ovality ....67
4.4.3 Tensile Testing ....68
4.4.4 Flexural Testing ....69
4.4.5 Hardness Testing ....71
4.4.6 Negative Pressure Testing ....74

**4.4.7 Short-Term Pressure Testing**....77
4.4.8 Specific Gravity ....80
4.4.9 Pressure Burst Testing ....80
4.4.10 Raman Spectroscopy Testing....80
4.4.11 Summary ....81

**4.5 Technology Cost ....82**

**4.6 Technology Environmental and Social Impact....82**

***5.0: CONCLUSIONS AND RECOMMENDATIONS .... 86***

**5.1 Conclusions....86**

**5.2 Recommendations ....87**

***6.0: REFERENCES.... 88***

***APPENDIX A .... 92***

***CCTV LOGS .... 92***

***APPENDIX B.... 8***

***BURSTING TESTS.... 8***

**Summary ....1**

Appendix A: CCTV LOGS
Appendix B: BURSTING TESTS

## FIGURES

Figure 2-1. Historical and Projected Average Age of U.S. Water Systems....7
Figure 2-2. Technology Selection for Water Main Rehabilitation ....11
Figure 2-3. Aqua-Pipe® Cross-Section ....12
Figure 2-4. Map of Cuyahoga County Showing the Location of the City of Cleveland ....20
Figure 2-5. Map of the City of Cleveland Depicting the Approximate Demonstration Area ....23
Figure 3-1. Access Pit Plated....25
Figure 3-2. Heat Fusion Welder (left) and 4 in. HDPE Pipe With Service Connection (right) ....26
Figure 3-3. Pit Excavation Activities....27
Figure 3-4. Site Layout and Pit Locations....28
Figure 3-5. Vertical Distribution af Soil Sample Locations ....29
Figure 3-6. Hydrant #1 (left) and Flow Hydrant (right)....35
Figure 3-7. Inside of the Tuberculated Test Pipe....36
Figure 3-8. Hydraulic Jetting Truck (left) and Jetting Hose (right)....36
Figure 3-9. Truck Utilized for Wastewater Filtration ....37
Figure 3-10. Cleaning Winch Truck ....37
Figure 3-11. Steel Scrapers (left) and Rubber Squeegees (right)....38
Figure 3-12. Foam Pig (left) and Blower (right) ....38
Figure 3-13. Installation of Pre-Fabricated Defect Pipe Segment....39
Figure 3-14. Field-Prepared Defect Section ....40
Figure 3-16. Cctv Truck (left) and Robot (right)....41
Figure 3-17. Typical 5/8 in. Penetrating Service (left) and a Slightly Penetrating Service (right) ....42
Figure 3-18. Crack Circling the Pipe around 1 in. Flush Service Connection....42
Figure 3-19. Shifted Joint at 71.6 m from Pit #2 ....43
Figure 3-20. Deep Corrosion at 60.9 m from Pit #2 ....44

Figure 3-21. 1 In. Hole at 77.7 m from Pit #3 ....45
Figure 3-22. 1 In. Hole at 77.7 m from Pit #3 ....46
Figure 3-23. Small Protrusion of Metal at 81.3 m from Pit #6 ....47
Figure 3-24. Impregnated Liner Being Pulled Through Dual Rollers (left) and Winch Truck (right) ....49
Figure 3-25. Roller Attached to the Truck (left) and Roller Attached to the Main (right) ....49
Figure 3-26. Buffer Used to Clean Ends (left) and Addition of Resin at the Ends (right) ....50
Figure 3-27. Launcher Attached to the Liner (left) and to Water via the Boiler Truck (right) ....50
Figure 3-28. Boiler Truck Reservoirs (left) and Boiler Tank (right) ....51
Figure 3-29. Internal Reinstatement of a Service Connection ....52
Figure 3-30. Service Reinstated Internally (left) and Blocked (right) ....54
Figure 3-31. Typical Fold at 10:00 (left) and Folds at a Shifted Joint (right) ....54
Figure 3-32. Service Located in a Fold ....56
Figure 3-33. Multiple Folds (left) and a Circumferential Fold (right) ....58
Figure 3-34. Exhumation of Lab-Prepared Defect Section ....59
Figure 3-35. Exhumation of Field-Prepared Defect Section ....60
Figure 3-36. Valve Being Replaced (left) and Installation of a New Hydrant (right) ....61
Figure 4-1. Exhumed Defected Sample ....64
Figure 4-2. Location of Thickness Specimens (left) and Measuring With a Digital Caliper (right) ....66
Figure 4-3. Measuring Ovality Before Buckling Test (left) and After Buckling (right) ....67
Figure 4-4. Ovality of Host Pipe (Red), Liner Before Buckling (Green), and after Buckling (Blue) ....67
Figure 4-5. Samples for Tensile Test (left) and Testing Machine (right) ....68
Figure 4-6. Stress-Strain Curves from Tensile Testing ....69
Figure 4-7. Samples Prepared for Bending Test (left) and Bending Test (right) ....69
Figure 4-8. Stress Vs. Strain Curves ....70
Figure 4-9. Specimen for Shore D Hardness Test (left) and a Shore D Hardness Tester (right) ....71
Figure 4-10. Shore D Hardness of the Liner at the Crown ....71
Figure 4-11. Shore D Hardness of the Liner at the Springline ....72
Figure 4-12. Shore D Hardness of the Liner at the Invert ....72
Figure 4-13. Hand-Held Portable Barcol Hardness Tester (left) and Taking Measurements (right) ....72
Figure 4-14. Barcol Hardness of the Liner at the Crown ....73
Figure 4-15. Barcol Hardness of the Liner at the Springline ....73
Figure 4-16. Barcol Hardness of the Liner at the Invert ....74
Figure 4-17. Exhumed Sample Showing Resin that has Leached Out ....74
Figure 4-18. Breaking the Host Pipe (left) and Cutting the Liner Specimen (right) ....75
Figure 4-19. Specimen With a Cap on one Side (left) and the with Caps on both Sides (right) ....75
Figure 4-20. Complete Experimental Setup ....76
Figure 4-21. Deflection Readings during the Vacuum Test ....76
Figure 4-22. Buckling Test: Close-Up of Quick Connector (left) and Both Quick Connectors (right) ....77
Figure 4-23. Resin Inside the Cap (left) and the Host Pipe and Liner Placed on the Cap (right) ....77
Figure 4-24. Pouring Resin to Attach the Cap to the Host Pipe ....78
Figure 4-25. Leak Test (left) and Adding Green Coloring to the Water (right) ....78
Figure 4-26. Bleeding out of the Air (left) and Purging the Line (right) ....79
Figure 4-27. 20 PSI Pressure (left) and No Signs of Distress (right) ....79
Figure 4-28. 60 PSI Pressure (left) and No Signs of Distress (right) ....79
Figure 4-29. 140 PSI Pressure (left) and No Signs of Distress (right) ....80
Figure 4-30. Specific Gravity of the Samples ....80
Figure 4-31. Results of Raman Spectroscopy Testing ....81
Figure 4-32. Transport Vehicles Required Each Day During Bypass Installation ....83
Figure 4-33. Results from E-Calc Showing Impact of Transport Vehicles ....83
Figure 4-34. Equipment Required for Bypass Installation ....83

## TABLES

Table 2-1. Technology Metrics Used for Evaluation ....4
Table 2-2. Summary of Innovative Water Main Rehabilitation Technologies ....9
Table 2-3. Physical Properties of Aqua-Pipe® ....13
Table 2-4. Typical Design Parameters ....15
Table 2-5. Summary of Potential Installation Issues for CIPP Liners ....17
Table 2-6. Typical Water Quality Information for Cleveland ....20
Table 2-7. Summary of Historical, Operational, and Environmental Characteristics of Test Pipe ....24
Table 3-1. Summary of Pit Dimensions and Volume of Soil Removed ....27
Table 3-2. Distances of Each Lining Run ....27
Table 3-3. Summary of Soil Sample Analytical Testing ....30
Table 3-4. Soil Sampling Results ....30
Table 3-5. Water Sampling Results ....31
Table 3-6. Pre-Rehabilitation 'C-Factor' Results ....35
Table 3-7. Pre-Lining CCTV Inspection of Lining Run #1 ....41
Table 3-8. Pre-Lining CCTV Inspection of Lining Run #2 ....43
Table 3-9. Pre-Lining CCTV Inspection of Lining Run #3 ....44
Table 3-10. Pre-Lining CCTV Inspection of Lining Run #4 ....45
Table 3-11. Pre-Lining CCTV Inspection of Lining Run #5 ....46
Table 3-12. Pre-Lining CCTV Inspection of Lining Run #6 ....47
Table 3-13. Pre-Lining CCTV Inspection of Lining Run #7 ....48
Table 3-14. Wall Thickness and Inside Diameter Measurements ....48
Table 3-17. Pressure Testing Results ....51
Table 3-18. Summary of Service Reinstatement Methods ....53
Table 3-19. Post-Lining CCTV Inspection of Lining Run #1 ....53
Table 3-20. Post-Lining CCTV Inspection of Lining Run #2 ....55
Table 3-21. Post-Lining CCTV Inspection of Lining Run #3 ....55
Table 3-22. Post-Lining CCTV Inspection of Lining Run #4 ....56
Table 3-23. Post-Lining CCTV Inspection of Lining Run #5 ....57
Table 3-24. Post-Lining CCTV Inspection of Lining Run #6 ....57
Table 3-25. Post-Lining CCTV Inspection of Lining Run #7 ....58
Table 3-26. Thickness Measurements of CIPP Liner ....59
Table 3-6. Pre-Rehabilitation 'C-Factor' Results ....61
Table 4-1. Estimate of Time and Labor Requirements for Major Activities ....65
Table 4-2. Summary of Thickness Measurements ....66
Table 4-3. Results from Tensile Testing (Longitudinal Direction) ....68
Table 4-4. Specimens Used for Bending Testing ....69
Table 4-5. Test Result of Bending Test on the Ring Sample ....70
Table 4-6. Buckling Test Protocol ....78
Table 4-7. Summary of Test Data for Aqua-Pipe® Cipp Liner ....81
Table 4-8. Cost Summary for Cleveland Demonstration ....82
Table 4-9. Estimated Wastewater Volumes ....82
Table 4-10. Total $Co_2$ Emissions for Each Major Activity ....84
Table 4-11. Equipment Specifications ....84
Table 5-1. Technology Evaluation Metrics Conclusions ....86

## ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| ANSI | American National Standards Institute |
| ASTM | American Society for Testing and Materials |
| AWWA | American Water Works Association |
| BNQ | Bureau de Normalisation du Québec |
| BPA | bisphenol-A |
| BRL | below reporting limit |
| C | Hazen-Williams Coefficient of Roughness |
| CCTV | closed circuit television |
| CIPP | cured-in-place pipe |
| $CO_2$ | carbon dioxide |
| COC | contaminant of concern |
| CWD | Cleveland Water Division |
| CWS | Charleston Water System |
| DDC | Department of Design and Construction |
| EIA | Energy Information Administration |
| EPA | U.S. Environmental Protection Agency |
| ER | external reinstatement |
| gal | gallons |
| gpd | gallons per day |
| gpm | gallons per minute |
| HDD | horizontal directional drilling |
| HDPE | high density polyethylene |
| I/I | infiltration and inflow |
| IR | internal reinstatement |
| ISTT | International Society for Trenchless Technology |
| lb | pounds |
| lf | linear foot |
| LVDT | linear variable displacement transducer |
| L/hr | liter/hour |
| MCL | maximum contaminant level |
| MGD | million gallons per day |
| mm | millimeters |
| MUD | Metropolitan Utilities District |
| NASTT | North American Society for Trenchless Technology |
| NRMRL | National Risk Management Research Laboratory |
| NSF | National Sanitation Foundation |
| NTU | nephelometric turbidity unit |
| O&M | operation and maintenance |

| | |
|---|---|
| ORP | oxidation-reduction potential |
| ppm | parts per million |
| psi | pounds per square inch |
| PVC | polyvinyl chloride |
| QA | quality assurance |
| QAPP | Quality Assurance Project Plan |
| QC | quality control |
| TC | Terrace Construction |
| TDS | total dissolved solid |
| TO | Task Order |
| TOC | total organic carbon |
| TSS | total suspended solid |
| TTC | Trenchless Technology Center |
| UTM | universal testing machine |
| VOC | volatile organic compound |
| WRAS | Water Regulations Advisory Scheme |

# 1.0: INTRODUCTION

## 1.1 Project Background

As part of the U.S. Environmental Protection Agency's (EPA's) Aging Water Infrastructure Research Program, research is being conducted, in collaboration with water and wastewater utilities, to improve and evaluate innovative technologies that can reduce costs and increase the effectiveness of the operation, maintenance, and renewal of aging drinking water distribution and wastewater conveyance systems (EPA, 2007). The EPA National Risk Management Research Laboratory (NRMRL) awarded Task Order (TO) No. 58, entitled *Rehabilitation of Wastewater Collection and Water Distribution Systems*, under the Scientific, Technical, Research, Engineering, and Modeling Support Contract No. EP-C-05-057 as part of this research. This research includes field demonstration studies of emerging and innovative rehabilitation technologies, which is intended to make the capability of these technologies better known to the water and wastewater industry, allowing their applications to be promoted in the U.S.

Although the tools available for infrastructure renewal today are much different than 40 years ago and are generally effective, the average rate of system renewal is still inadequate to keep pace with increasing needs, quality demands, and continually deteriorating systems (EPA, 2009). There is substantial room for improvement in existing technologies and for the development of new technologies, offering opportunities to make more effective investments in renewal. Many utilities are seeking improved rehabilitation technologies to extend the service life of their assets and fix larger portions of their systems with current funding levels; however, information on new and emerging technologies is not always readily available or easy to obtain. This critical gap was identified by stakeholders participated in the Workshop hosted by the EPA on Innovation and Research for Water Infrastructure for the 21st Century (EPA, 2006). The lack of knowledge on the performance of innovative technologies and the limited ability to determine the most cost-effective, long-term rehabilitation methods for water distribution and wastewater collection systems was identified as a key area of needed research (EPA, 2007).

Several innovative and emerging technologies were identified by the project team based on industry experience, extensive state-of-technology literature reviews, and stakeholder input at an International Technology Forum conducted in Edison, New Jersey in September 2008 (EPA, 2009). It is known that well documented demonstration projects by credible independent organizations can play an important role in accelerating the development, evaluation, and acceptance of new technologies. The benefits of a technology demonstration program to these various groups are summarized below:

**Benefits to Utilities**

- Reduced risk of experimenting with new technologies and new materials on their own
- Increased awareness of innovative and emerging technologies and their capabilities
- Assistance in setting up strategic and tactical rehabilitation plans and programs
- Identification of design and quality assurance/quality control (QA/QC) issues

**Benefits to Manufacturers/Technology Developers**

- Opportunity to advance technology development and commercialization
- Opportunity to accelerate the adoption of new technologies in the U.S.
- Opportunity to lay the groundwork for design standards that may accelerate market penetration

**Benefits to Consultants and Service Providers**

- Opportunity to compare performance and cost of similar products in a consistent manner
- Access to standards and specifications for new technologies
- Education of best practices on pre- and post-installation procedures and testing

This report provides impartial third-party assessment of the effectiveness, longevity, expected range of applications, and life-cycle cost of the demonstrated technology to assist utilities in better decision making on whether rehabilitation or replacement is more cost effective and in selecting rehabilitation technologies for use. The demonstration described in this report resulted in the successful installation of a Class IV structural cured-in-place pipe (CIPP) liner on 1,996 ft of 6 in. cast iron water main in Cleveland, Ohio. This report discusses the activities involved with liner installation, which includes pre-installation activities such as bypass construction, access pit excavation, and hydraulic testing; installation activities such as service capping, CIPP pull-in and curing, and service reinstatement; and post-installation activities such as liner pressure testing, laboratory testing, and site restoration. This report also conducts a full product evaluation based on the demonstration results and recommendations to study important issues such as the need for open-cut replacement of some difficult services to help fully understand this technology more.

## 1.2 Project Objective

The report is intended to meet the following objectives:

- Provide the framework, protocols, metrics, and site selection criteria for selection of rehabilitation technologies for subsequent field demonstrations.
- Evaluate, under field conditions, the performance and cost of an innovative, structural, CIPP lining technology used to rehabilitate a 6 in. cast iron water distribution main in Cleveland, Ohio.
- Discuss the results of the demonstration and make recommendations as to what other areas relating to the product should be examined further.

The report describes data collection, analyses, and project documentation associated with the second of two field demonstrations of rehabilitation technologies performed under Task 7 of TO 58 in accordance with EPA NRMRL's Quality Assurance Project Plan (QAPP) Requirements for Applied Research Projects (EPA, 2008).

## 1.3 Report Outline

The report is organized into the following sections:

**2.0: Demonstration Approach**
Discussion of the demonstration program approach including an innovative rehabilitation technology overview and the technology selection approach.

**3.0: CIPP Demonstration**
Documentation of the field demonstration including site preparation, pipe cleaning and liner installation, QA/QC procedures, sample collection, and site restoration.

**4.0: Demonstration Results**
Discussion of the demonstration results and assessment of the technology based on comparison with the outlined evaluation metrics.

**5.0: Conclusions and Recommendations**
Summary of the demonstration including execution of demonstration protocol and effectiveness of the demonstrated technology, and recommendations for areas needing further examination.

# 2.0: DEMONSTRATION APPROACH

This section outlines the overall approach of the field demonstration protocol, technology selection, and site selection for the field demonstration of emerging and innovative rehabilitation technologies. The overall approach is outlined to provide consistency and guiding principles for conducting and documenting field demonstrations of water main rehabilitation technologies in a manner that will encourage acceptance of the test results by water utilities.

## 2.1 Demonstration Protocol Overview

The demonstration of emerging and innovative technologies requires explicit and repeatable testing criteria if the technologies are to be understood and approved. A protocol was developed to provide a consistent approach and a guide for conducting demonstrations in a manner that encourages acceptance of the outcomes and results by water utilities. The demonstration protocol addressed issues involved in gaining the approval for the use of innovative and emerging technologies by:

- Integrating user input from the International Technology Forum for defining the standards that new technologies must meet before they are considered acceptable (EPA, 2009).
- Providing for independent verification of the claims of technology vendors.
- Sharing information about innovative technologies among peer user groups.
- Supporting utilities and technology developers in bringing a new product to a geographically and organizationally diverse market.

A QAPP was developed, which outlined the approach to plan, coordinate, and execute the field demonstration protocol with the specific objectives of evaluating, under field conditions, the performance and cost of an innovative, structural CIPP lining for water main rehabilitation.

The QAPP described the overall objectives and approach to the EPA's field demonstration program, the technology and site selection factors considered, and the features, capabilities, and limitations of the selected technology, which are summarized below. The demonstration protocol was executed by completing the following steps:

- Prepared and obtained EPA approval for the QAPP based on the demonstration protocol;
- Gathered technology data for methods meeting the technology and site selection criteria;
- Secured a commitment from Cleveland Water Division (CWD) for the demonstration;
- Secured a commitment from Aqua-Pipe®/Sanexen to perform the demonstration;
- Documented and conducted the field demonstration as outlined in the demonstration protocol;
- Processed and analyzed the results of the field demonstration; and
- Prepared a report, peer-reviewed article, and presentation summarizing the results.

This demonstration report not only records the use of the CIPP lining technology, but also provides a documented case study of the technology selection process, design, QA/QC metrics, and the preparation for life-cycle management of the asset. In performing the field demonstration, the technical and QA/QC procedures specified in the QAPP were followed closely unless otherwise stated. Any procedure that was not followed and the reason why is noted in the remaining sections. Special aspects of the EPA demonstration program which were aimed at adding value to the water rehabilitation industry are described below.

- **Demonstrate application of a consistent design methodology.** Leadership in the area of design standards development for trenchless rehabilitation technologies has been slow to evolve in North America. The design of a liner can be non-structural, semi-structural or fully structural depending on the level and type of deterioration in the host pipe. This determination is often subjective with little guidance provided by the expert community. An important role of the EPA demonstration project was to identify design parameters and specifications for the selected technologies and apply a consistent design methodology based on the vendor recommendations or industry defined standards.
- **Demonstrate application of appropriate QA/QC procedures.** The success of a rehabilitation project depends largely on proper installation QC and the inspection and assessment activities that fall under QA. The level of the qualification testing and QA requirements vary from technology to technology and in some cases there is no clear industry quality standard. The EPA demonstration program provided an opportunity to examine the current QA practices and identify areas for improvement. For technologies lacking an industry quality standard, QA/QC procedures recommended by the vendor and the utility were reviewed and adopted to the field demonstration project.
- **Provide a technology assessment.** The EPA demonstration program assesses the short-term effectiveness and cost of the selected technologies in comparison with the respective vendor specifications and identifies conditions under which the demonstrated technology can be best applied. Suggestions on necessary improvements for the technology, the installation procedures, and QA/QC procedures are also provided. Metrics that were used to evaluate the capabilities and limitations and document rehabilitation technology application, performance, and cost are summarized in Table 2-1. The evaluation of the technology versus these metrics is described in Section 4.
- **Demonstrate life-cycle plan for ongoing evaluation.** Long-term data regarding the performance of various rehabilitation systems is scarce and needed. Life-cycle data would enable decision makers to make fully informed cost-benefit decisions. The demonstration project lays the groundwork for assisting utilities in developing life-cycle plans for the ongoing evaluation of rehabilitation technology performance. The EPA demonstration program could be used to collect baseline data which would enable comparative evaluation of the technology's deterioration during subsequent retrospective investigations for successful installations. In addition, long-term laboratory and/or accelerated aging tests combined with model simulation could be used in predicting the longevity and long-term performance of technologies and could ultimately assist utilities in making better asset management planning decisions.

**Table 2-1. Technology Metrics Used for Evaluation**

| Technology Maturity Metrics |
|---|
| • Maturity and status of the technology were assessed as emerging, innovative, or conventional. New technologies that are commercially available overseas, but not yet widely applied in the U.S. market, were considered emerging with respect to U.S. applications.<br>• Interest is in the demonstration of novel and emerging technologies that are commercially available and represent more than an incremental improvement over conventional methods.<br>• Availability and strength of supporting performance data (full-scale data carry more weight than pilot-scale data) and patent citation (if applicable).<br>• Comments and feedback from utility owners and consultants with experience from previous installations. |

**Table 2-1. Technology Metrics Used for Evaluation (Continued)**

| Technology Feasibility Metrics |
|---|
| • Determination of the nature of the problem faced in the pipe (e.g., structural, semi-structural, or non-structural rehabilitation) and the applicability of the technology in meeting the rehabilitation requirements.<br>• Suitability of the technology to the hydraulic and operating conditions of the pipe, the type of pipe material, and any challenging pipe configurations (e.g., non-circular pipes, bends, valves, and fittings).<br>• Formal consideration of the anticipated failure modes and documentation of design procedures. |
| **Technology Complexity Metrics** |
| • Adaptability to and widespread benefit for small- to medium-sized utilities.<br>• Level of training required for the installer, pre- and post-installation and maintenance requirements.<br>• Site preparation requirements and needs (including pipe cleaning, number and size of excavations, and effect on traffic flow).<br>• Estimated time and labor requirements for the overall rehabilitation project and speed of installation including documentation of the length of time that the pipe is out of service and/or bypassed.<br>• Evaluation of the installation process, procedures, and problems encountered.<br>• Documentation of the efficiency of the connection restoration system for services, end terminations, branches, and valves. |
| **Technology Performance Metrics** |
| • Evaluation of manufacturer-stated performance versus actual performance.<br>• Development of a QA/QC plan and documentation of its outcome and adequacy.<br>• Evaluation of the ability to handle non-ideal conditions and potential damage during installation.<br>• Expected visual appearance and geometric uniformity after installation including closed-circuit television (CCTV) inspection to record the presence or absence of installation defects such as a micro-annulus, air voids, coating holidays, longitudinal folds, and blisters.<br>• Ability to achieve rehabilitation design specifications such as: a) infiltration/inflow (I/I) reduction; b) achieving design flexural and tensile strengths based on laboratory testing of coupon samples; and c) measuring as-installed liner thickness and annular gap compared to design values.<br>• Evaluation of impact on hydraulic/flow properties and friction headloss.<br>• Established procedures for tracking long-term effectiveness, projected longevity, and accelerated testing to provide evidence of durability. |
| **Technology Cost Metrics** |
| • Document costs for conducting the technology demonstration, including design, capital, and operation and maintenance (O&M) costs and calculating a unit cost estimate.<br>• Evaluate overall level of social disruption (an estimate of social costs is highly site specific and beyond the scope of the demonstration project). |
| **Technology, Environmental, and Social Metrics** |
| • Assess utilization of chemicals or waste byproducts that have an unintended impact on the environment or water quality (e.g., the use of bisphenol-A [BPA] in epoxies or styrene in CIPP resins).<br>• Assess quantity of waste byproducts produced (e.g., flush water volume or soil requiring off-site disposal).<br>• Evaluate the overall "carbon footprint" of a technology compared to open cut and its ability to reduce net impacts to the environment and social disruption to the community. |

## 2.2 Technology Selection Approach

Several innovative and emerging rehabilitation technologies were identified by the project team based on industry experience, extensive state-of-technology literature reviews, and input from stakeholder participants at an International Technology Forum (EPA, 2009). Using this information, rehabilitation technologies that have the potential for demonstration in the field were identified and recommended based on the research conducted under TO 58 and stakeholder input. The technology selection criteria identified by the project team and forum stakeholders in considering innovative rehabilitation technologies for inclusion into a field demonstration program follow the six general guidelines listed below which are based on the evaluation metrics in Table 2-1:

- **Maturity of the technology.** Forum stakeholders indicated that they were primarily interested in novel and emerging technologies that are commercially available. The technologies should be truly novel and more than incremental improvements over conventional methods (EPA, 2009). The level of maturity is evaluated through the date of market entry, the strength of supporting performance data (full-scale data carry more weight than pilot-scale data), feedback from previous installation sites, and a patent citation, if applicable.
- **Applicability to site conditions.** The potential of the innovative technology as a compliance strategy for the site-specific conditions are identified. The nature of the problem in the pipe (e.g., structural, semi-structural, or non-structural rehabilitation) will ultimately drive technology selection. The hydraulic and operating conditions of the pipe, the type of pipe material, and challenging pipe configurations (e.g., non-circular pipes, bends, valves, fittings) also play a role in technology selection and its feasibility or applicability to site-specific conditions.
- **Complexity of installation.** Forum stakeholders were interested in the technology adaptability to and widespread benefit for small to medium-sized utilities and in measuring the ease of installation of technologies (EPA, 2009). The complexity of the technology refers to the level of training required for the installer, pre- and post-installation requirements, and maintenance requirements. An estimate of the time and labor requirements for installation and maintenance should be provided and technologies that limit the length of time a pipe is out of service or bypassed were preferred.
- **Performance of the technology.** This criterion was evaluated based on the capabilities and limitations of the technology and investigation of potential advances over existing and competing technologies. The technology vendor's performance claims were compared to actual performance in the field. Examples include evaluating claims of I/I reduction, sanitary sewer overflow/combined sewer overflow reduction, reducing frequency of breaks for water mains, restored structural integrity, leakage reduction and improved maintenance tracking/management. Third-party evaluations and the collection of appropriate QA/QC information are important components for the adequate assessment of performance data.
- **Direct and indirect costs.** A critical factor in the evaluation of technologies is the cost of installation (direct cost) and cost for periodic inspection and cleaning (indirect cost). The typical installation cost on a per-unit basis (i.e., cost per linear foot) is provided. Warranties or guarantees on performance should be provided. Tracking of social costs such as the disruption of traffic is highly site specific and beyond the scope of this study.
- **Environmental and social factors.** Technologies may utilize chemicals or produce waste byproducts that have an unintended impact on the environment or water quality (e.g., the use of BPA in epoxies or styrene in CIPP resins). Technology selection took this factor into account. Forum stakeholders were also interested in technologies that would reduce the overall "carbon footprint" of a project compared to open cut and/or reduce net impacts to the environment and indirect costs to the community (EPA, 2009).

Under TO 58, efforts were made to solicit candidate rehabilitation technologies at an international level through International Technology Forum input, a comprehensive literature search for the state-of-technology reviews, and through societies such as the North American Society for Trenchless Technology (NASTT) and the International Society for Trenchless Technology (ISTT). This generated a list of three wastewater and five water distribution candidate technologies for field demonstration. It was also indicated by stakeholders at the International Technology Forum that technology needs were especially high for water main rehabilitation (EPA, 2009). For this reason, the two field demonstrations performed under TO 58 focused on the gaps and needs for innovative water main rehabilitation technologies.

2.2.1 Overview of Innovative Water Main Rehabilitation Technologies. Through the course of the research efforts of TO 58, it was recognized that very few water utilities in the U.S. have begun to utilize trenchless rehabilitation technologies other than cement mortar lining. The water infrastructure in North America is older than the wastewater infrastructure and at the current pace of replacement (less than 1% per year) and rate of installation of new pipes, the average age of the drinking water infrastructure will gradually approach the commonly accepted design life of 50 years in 2050 as shown in Figure 2-1 (EPA, 2002).

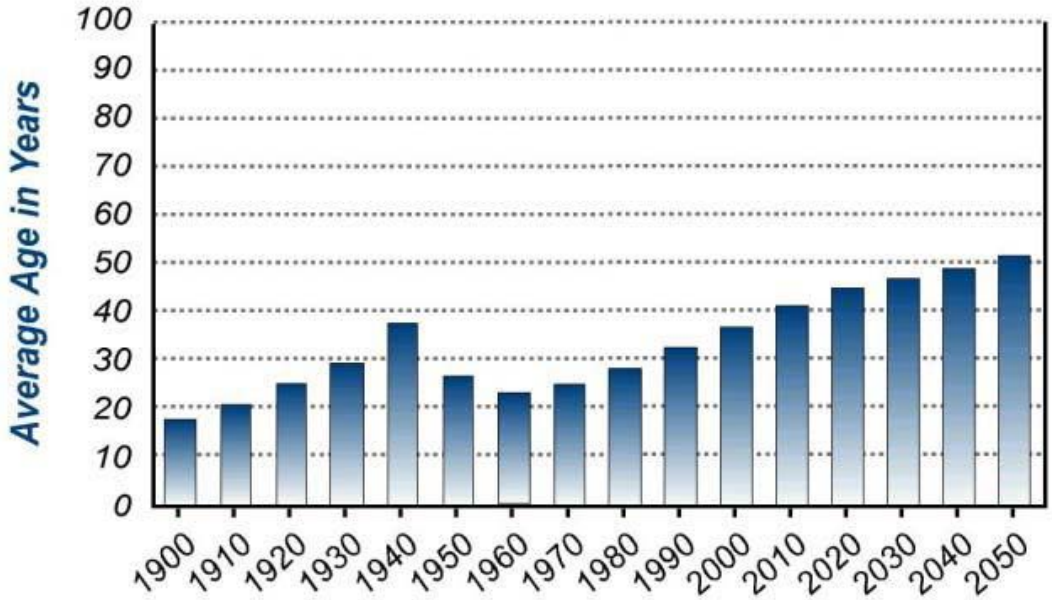


**Figure 2-1. Historical and Projected Average Age of U.S. Water Systems (EPA, 2002)**

Many pipes have been known to operate longer than their design life, but the frequency of failures increases with the age and therefore degradation of the infrastructure. This means that unless a more aggressive rehabilitation program is adopted by water utilities, communities are going to be hit with significantly increasing repair costs in the near future. Water rates have historically been set at levels that do not truly reflect the value of this precious commodity, and there has been a general reluctance to adopt rate structures that would provide for the necessary funding to make water utilities self-supporting and sustainable (EPA, 2009). There are seven key technical challenges for water main rehabilitation identified as part of the TO 58 research efforts are outlined below:

- **Variety of pipe materials.** There is a wide variety of piping materials in water distribution systems requiring rehabilitation including challenges associated with appropriate and safe options for asbestos cement pipes. Ferrous pipes such as cast iron and ductile iron represent over 60% of the water distribution network in the U.S., so rehabilitation options for these types of pipes is important (American Water Works Association [AWWA], 2004).
- **Limited inspection options.** Effective inspection and condition assessment of water pipe is generally difficult or extremely costly to carry out. Targeting mains for rehabilitation and replacement is largely centered on performance assessment such as main break frequency or severity, water quality problems or poor hydraulic characteristics. Recently, emphasis on structural defects has shifted to improved leak-detection technologies that seek to reduce the loss of water and quickly identify faulty pipe to reduce the cost of repair and consequence of failure.

- **Need for improved design standards.** Leadership in the area of design standards development for trenchless replacement technologies for water mains has been slow to evolve in North America. The design of a liner can be non-structural, semi-structural, or fully structural dependent on the level and type of deterioration in the host pipe. This determination is often subjective with little guidance provided by the expert community.
- **Innovation needs in water main rehabilitation technologies.** Thinner composite liners that reduce the amount of cross-section loss would be favored by water utilities. There is also an emerging trend for the development of "high-build" organic polymers that can provide semi-structural benefits to support the operation of deteriorated pipelines. There is a need to streamline the product approval process as National Sanitation Foundation (NSF) Standard 61 approval is a requirement for the use of new water main rehabilitation technologies. The market barriers for water main rehabilitation have resulted in a limited number of contractors with water main rehabilitation experience meaning that utilities are reluctant to try new technologies especially with inexperienced installers.
- **Service disruption during rehabilitation.** Water main rehabilitation will continue to lag behind sewer rehabilitation in the U.S. unless practical solutions can be developed for addressing the time out of service required and the need for rapid disinfection and return to service to minimize the bypass requirements. Rehabilitation methods that reduce or eliminate the need for temporary service lines are viewed favorably for demonstrations.
- **Reinstatement of service connections.** There is a need for trenchless reinstatement of service lines without street excavation and to ensure that the trenchless method results in reliable connections under pressurized conditions. Service connections made using keyhole technologies would be a need where internal reconnection is not feasible.
- **Operation and maintenance issues.** Lack of maintenance access to water mains is an issue, due to the lack of manholes as with wastewater mains. Also, the techniques for the repair of pipes with liners are not well understood by crews in charge of O&M in a water utility and adding new unfamiliar materials and technologies is often reluctantly received.

The five water main rehabilitation technologies indentified by the research team which meet the six general technology selection criteria, meet the American National Standards Institute (ANSI)/NSF International 61 standard, and address most of the key technical concerns are summarized in Table 2-2.

**Table 2-2. Summary of Innovative Water Main Rehabilitation Technologies**

| Technology/ Vendor | Market Date/ Status/Size | Description | Rationale/Benefit for Demonstration |
|---|---|---|---|
| Aqua-Pipe®/ Sanexen | 2000 in Canada; 2005 in U.S./ Innovative/ 6 to 12 in. | Composed of two concentric, tubular, plain woven seamless polyester jackets with a polymeric membrane bonded to the interior. The liner is impregnated with a specific thermoset epoxy resin. Hot water cure. Class IV (AWWA) fully structural liner. | Most experience to date in Canada. Higher strength than standard CIPP. Novel robotic platform to re-establish service connections from within host pipe. |
| AquaLiner/ AquaLiner Ltd. | 2008 in Europe; U.S. distributor under selection in 2010/ Emerging/ 8 to 12 in. | Inserts a glass fiber-reinforced polypropylene sock into a deteriorated pipe. After sock insertion, a silicone rubber inflation tube pushes a heated pig through the composite, melting the sock against the pipe, which then cools to form a solid glass-reinforced thermoplastic liner. | Emerging technology still in the incubation phase. Solid glass-reinforced thermoplastic liner that is fully structural (Class IV) and results in a thin liner that minimizing loss of flow. No mixing of resins so long shelf life and minimizes release of chemicals. |
| InsituMain™/ Insituform | 2009/ Emerging/ 6 to 36 in. | Composed of an epoxy composite layer that is reinforced with fiberglass and polyester fiber materials. It has a polyethylene layer on the inside pipe surface. Composite materials are saturated with a thermosetting epoxy resin, which is cured using hot water. | An AWWA Class IV fully structural pressure rated CIPP technology for water mains. In 6 in. and larger pipes, service connections can be made by robotic remote access using mechanical sealing apparatus. |
| NordiPipe™/ Norditube Sekisui | 2002 in Europe; 2010 in U.S./ Innovative/ 6 to 48 in. | Has a glass fiber-reinforced layer between two non-woven felt layers. Tube is impregnated with epoxy and a coating of polyethylene is on the interior for potable water applications. CIPP liner is installed via inversion, using air pressure or a water column, and is cured with steam or hot water. | An AWWA Class IV fully structural pressure rated CIPP technology for water mains. |
| Scotchkote™ 269/ 3M™ | 2009/ Emerging/ 4 to 12 in. | Rapid-setting polyurea lining 3.5 millimeters (mm) thick. 10 minute cure time for inspection. Ready for return to service in 60 min. Made of 100% solids after cure and has no volatile organic compounds (VOCs). Suitable for inner corrosion or as a semi-structural (AWWA Class III) liner. | Provides for semi-structural rehabilitation to bridge gaps/holes in the host pipe; rapid return to service minimizes service disruption and need to maintain bypass. Minimizes blockage of service lines, eliminating need for open-cut service reconnection. |

2.2.2 Overview of CIPP Water Pipe Rehabilitation. CIPP rehabilitation began in the 1970s and has been primarily used in the gas and sewer industry. Typically, the composite materials used consist of polymeric felts that are impregnated with resin. Materials of choice for the felts range from a variety of fabrics and polymers including polyester, polypropylene, and fiberglass. The resin used for impregnation

has primarily consisted of polyester and vinyl ester resins. Over time different methods of installation have been used including pulled-in-place and inversion. Pulled-in-place liners, such as Aqua-Pipe®, involve the insertion of the liner into the host pipe by pulling the liner from one access pit to another with a pulling mechanism such as a winch (Sanexen, 2010). Inversion is a technique that involves the expansion of a tube inside a host pipe by using pressurized air or water.

The most common method of rehabilitation for water mains (i.e., cement mortar linings) have been applied only for non-structural corrosion and taste control, but innovative CIPP liners capable of providing fully structural benefits to support the operation of deteriorated pipelines are emerging in the market. Three different CIPP products have been introduced into the U.S. market in the last five years which can be used for structural (AWWA Class IV) applications. Figure 2-2 presents the primary technology selection factors that would be used to select among a fully structural, semi-structural, or non-structural solution for water main rehabilitation.

QA criteria that have been included in past CIPP project specifications are presented below. Utility owners can choose the criteria that best suit their needs and system. Work is judged satisfactory and compliant if the following requirements are met:

- Minimum liner thickness should be calculated according to the requirements of American Society for Testing and Materials (ASTM) F-1216 (ASTM, 2009a).
- The tensile and flexural tests used in the liner thickness calculations have to be carried out on a composite material sample according to ASTM D-638 and ASTM D-790, respectively (ASTM, 2007a and 2008a).
- The inside diameter of the rehabilitated pipe shall not be smaller than 90% of the inside diameter of the original pipe. The utility owner should verify the allowable inside diameter of the rehabilitated water main versus hydraulic capacity requirements.
- The Hazen-Williams Coefficient of Roughness (C) should be equal to or higher than 120.
- Following rehabilitation and before the reinstatement of service connections, the water main shall be submitted to a hydrostatic pressure test according to ASTM F-1743 (ASTM, 2008b).
- Most rehabilitation projects request thickness design calculations, verification of the inside diameter, and hydrostatic pressure tests.

As outlined in this report, the second of two demonstrations conducted under TO 58 was undertaken in Cleveland, Ohio, by CWD using Sanexen's fully-structural CIPP lining product known as Aqua-Pipe®. The remainder of this section provides background information on the use of CIPP liners for structural water main rehabilitation and reviews design, QA/QC, installation, and O&M considerations associated with the technology.

2.2.3 Technology Description. As described above, CIPP has been used in the wastewater industry for more than 40 years, but only in the last five years has it been introduced into the water rehabilitation industry in the U.S. Sanexen, in collaboration with the National Research Council of Canada, developed Aqua-Pipe® around the year 2000 and introduced the product in the U.S. in 2005. At present, the company advises that more than 1.5 million lf has been installed throughout North America (Belisle, 2011). The company has different licensees in North America and has undertaken a small number of projects in the U.S. (New York City, Cleveland, Minneapolis, Atlanta, etc.).

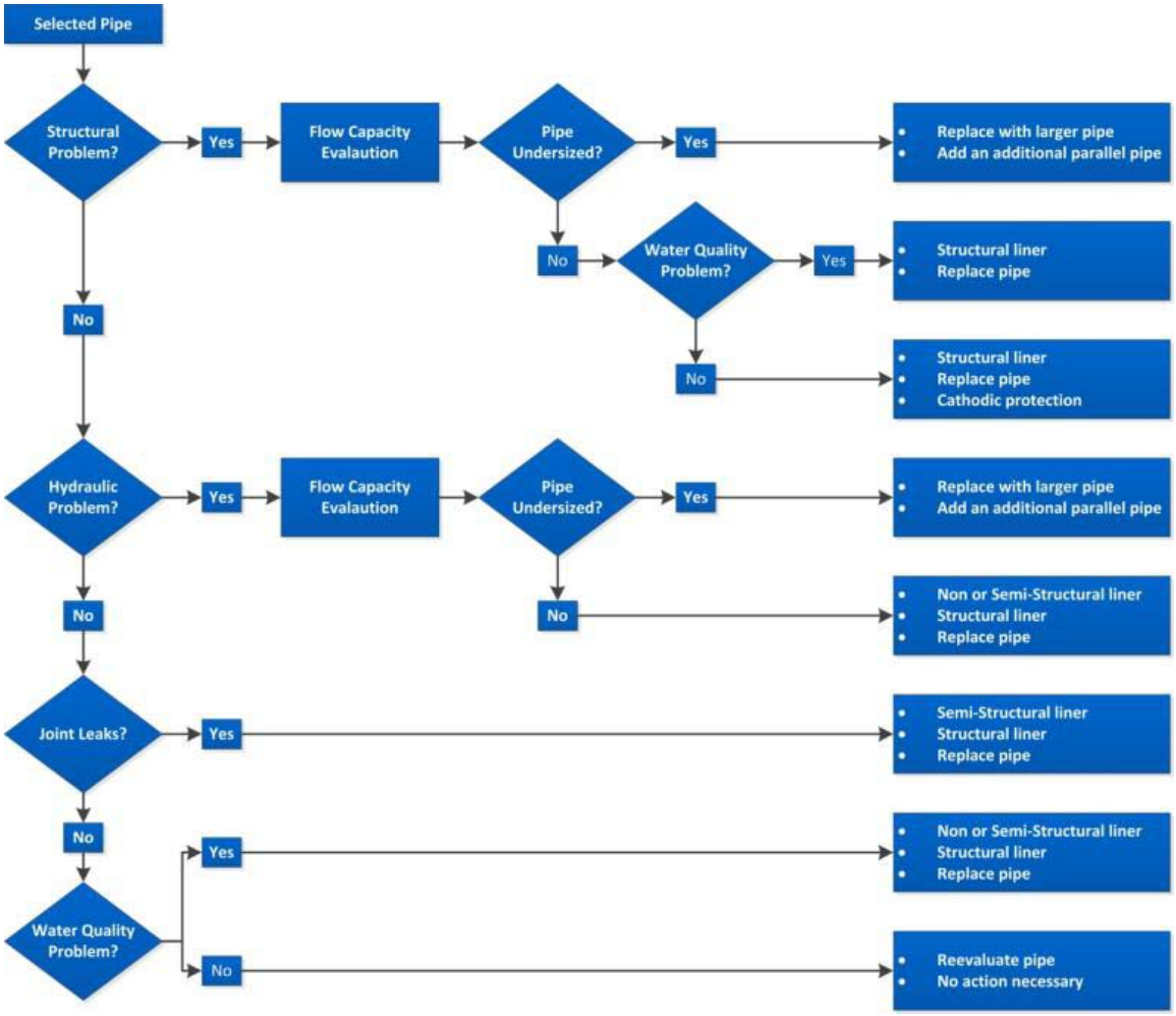


**Figure 2-2. Technology Selection for Water Main Rehabilitation (Adapted from Deb et al., 2002)**

The Aqua-Pipe® CIPP liner consists of two woven seamless polyester jackets, of which the inner jacket has a polymeric membrane bonded to the interior to ensure water tightness. The liner is impregnated at the work site in a purpose built vehicle where the resin is injected between the jackets and distributed by feeding the liner through a nip roller. The liner is designed and tested in accordance with the procedures set out in ASTM F-1216 and physical properties are determined in accordance with ASTM F-1216 (ASTM, 2009a). The liner is installed according to ASTM F-1743 (2008b).

Aqua-Pipe® is available in diameters of 6, 8, 10, and 12 in. and has an operating pressure capability of up to 150 pounds per square inch (psi) (10 bar). The smooth polyurethane coating provides for a Hazen-Williams friction coefficient (C) greater than 120. Aqua-Pipe® can be installed in lengths up to 500 feet between access pits. The liner is installed by pulling the liner in place and pushing a pig through the liner using water pressure to form the liner to the pipe wall. Circulating hot water for 90 minutes and then holding under pressure for up to 12 hours completes the curing process. The service connections are reinstated from within using a remote controlled mechanical robot to cut open the taps. Aqua-Pipe® is certified to NSF/ANSI Standard 61 and it is also certified to BNQ Standard 3660-950 (2003) in Canada and the Water Regulations Advisory Scheme (WRAS) Standard (2009) in the UK. The cross section can be seen in Figure 2-3.

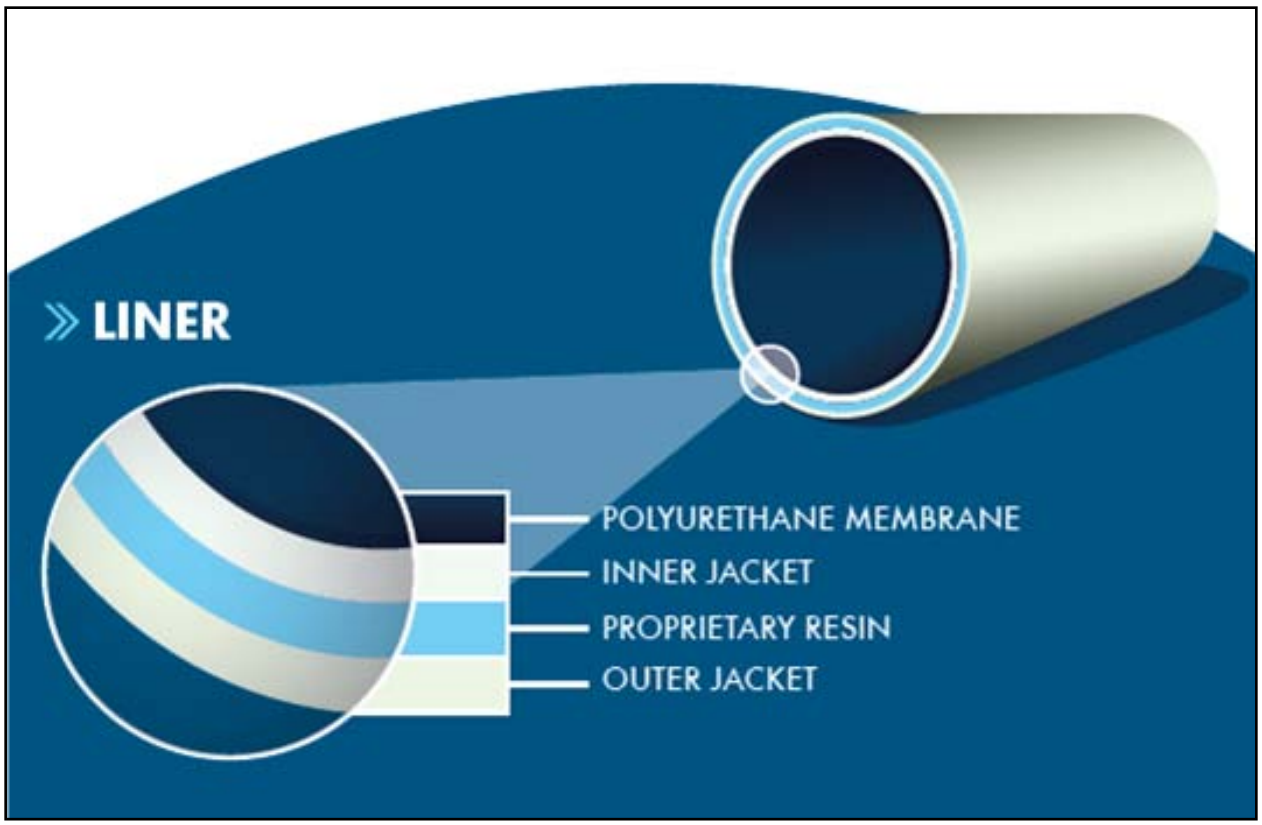


**Figure 2-3. Aqua-Pipe® Cross-Section (courtesy of Sanexen)**

The field demonstration allowed evaluation of the main benefits claimed and limitations cited by Aqua-Pipe® which are listed below (Aqua-Pipe, 2011):

**Main benefits claimed**

- Structural trenchless technology exclusively designed for drinking water distribution systems
- Possibility to line pipes those are difficult to access (underneath bridges, highways, etc.)
- No future maintenance required
- Excavate access pits at each end of the section
- Future dry and pressure taps of service connections easily carried out
- Little excavation when compared to traditional open-cut
- Possibility to line through bends
- Adjacent infrastructures not disturbed by work
- Less complaints from residents during work
- Increased pressure and flow capacity
- Corrosion resistance
- Regained structural capacity
- Rehabilitation costs generally 20 to 40% less expensive than traditional open-cut
- Prevention of water main breaks
- Reduced treatment and pumping costs
- No further intervention on rehabilitated water mains
- Reduced social costs

**Main limitations cited**

- Difficulty reinstating services robotically that are: misaligned; flush with the pipe surface (no nipple); or located under a liner wrinkle
- The length of renewal is limited to 500 ft
- Excavation of access pits may be necessary around bends >45° and at valve and fitting locations
- Material property data are all based on short-term testing procedures

Short-term mechanical properties from the Aqua-Pipe® suggested specifications are shown in Table 2-3 (Sanexen, 2011a). As discussed in Section 2.2.4, the design service life of 50 years is calculated from ASTM F-1216. Based on the material properties and design, the product is a fully-structural (Class IV) according to AWWA M28 (2001), which means Aqua-Pipe® is a stand-alone structural liner that can withstand all dead and live loads and internal pressures, including vacuum, without the help of the strength of the existing pipe. If the host pipe is depressurized, Aqua-Pipe® will resist the external dead and live loads. Aqua-Pipe® can withstand operating pressures up to 150 psi.

**Table 2-3. Physical Properties of Aqua-Pipe® (Sanexen, 2011a)**

| Property | Standard | Value | ASTM F-1216 |
|---|---|---|---|
| Tensile Strength | ASTM D-638 | 10,000 psi | 3,000 psi |
| Tensile Elongation | ASTM D-638 | 20% | N/A |
| Flexural Strength | ASTM D-790 | 10,000 psi | 4,500 psi |
| Flexural Modulus | ASTM D-790 | 350,000 psi | 250,000 psi |
| Short Term Pressure | N/A | > 400 psi | N/A |
| Resists Full Vacuum | N/A | -14.7 psi | N/A |

2.2.4 Design Approach for Structural CIPP Liners. Aqua-Pipe® is designed according to the ASTM F-1216 section for fully deteriorated pressure pipe (ASTM, 2009a). This standard covers all CIPP that is to be installed in an underground condition and designed to withstand all external loads and full internal pressure. The design thickness is calculated using three methods from five equations, with the largest thickness being selected for the design. Each of the following equations has been rearranged to solve for liner thickness (t). The first design equation (ASTM F-1216, X1.1) calculates the minimum thickness required to resist buckling under external hydrostatic pressure as follows:

where

| | | |
|---|---|---|
| $t$ | = | thickness of the CIPP lining (in.) |
| $D$ | = | mean inner pipe diameter (in.) |
| $K$ | = | enhancement factor (typically 7) |
| $E_L$ | = | long-term modulus of elasticity for the liner material (psi) |
| $C$ | = | ovality reduction factor = |
| $\Delta$ | = | % ovality = |
| $D_{min}$ | = | minimum inner pipe diameter (in.) |
| $P$ | = | external pressure due to ground water (psi) = |
| $H_{w1}$ | = | height of ground water above pipe invert (ft) |
| $N$ | = | safety factor (typically 2) |
| $\nu$ | = | Poisson's ratio (0.3) |

Additionally, as per section ASTM F-1216, X1.4, when the pipe is subject to a vacuum load, the CIPP liner should be designed as a gravity pipe with the external hydrostatic pressure increased by an amount equal to the negative pressure ($P_v$).

When the pipe is out of round, the bending stresses must be calculated to ensure the CIPP liner does not exceed the long-term flexural strength of the material. This equation (ASTM F-1216, X1.2) calculates the bending stress using the thickness ($t$) from Equation 1 as follows, which must be less than the CIPP long-term flexural strength ($S_L$):

where

| | | |
|---|---|---|
| S | = | long-term flexural strength for a liner with thickness (t) calculated in Equation 1 (psi) |
| P | = | external pressure due to ground water (psi) = |
| $H_{w1}$ | = | height of ground water above pipe invert (ft) |
| N | = | safety factor (typically 2) |
| Δ | = | % ovality = |
| D | = | mean inner pipe diameter (in.) |
| $D_{min}$ | = | minimum inner pipe diameter (in.) |
| DR | = | dimension ratio = D/t |
| t | = | thickness calculated in Equation 1 (in.) |
| $S_L$ | = | long-term flexural strength for the liner material (psi) |

The third design equation (ASTM F-1216, X1.3) calculates the minimum thickness required to withstand hydraulic, soil, and live loads without collapsing as follows:

where

| | | |
|---|---|---|
| t | = | thickness of the CIPP lining (in.) |
| D | = | mean inner pipe diameter (in.) |
| N | = | safety factor (typically 2) |
| $q_t$ | = | total external pressure on pipe (psi) = |
| $H_{w2}$ | = | height of ground water above pipe crown (ft) |
| w | = | soil density (lb/ft$^3$) |
| H | = | height of soil above pipe crown (ft) |
| $R_w$ | = | water buoyancy factor (0.67 min) = |
| $W_s$ | = | live load (psi) |
| C | = | ovality reduction factor = |
| Δ | = | % ovality = |
| $D_{min}$ | = | minimum inner pipe diameter (in.) |
| $E_L$ | = | long-term modulus of elasticity for the liner material (psi) |
| B’ | = | coefficient of elastic support (inch pounds) = |
| $E'_s$ | = | modulus of soil reaction (psi) |

Two checks must be performed to ensure a minimum thickness is met. The first check is for bending stress (Equation 2) with the total external pressure on the pipe ($q_t$) substituted for the pressure due to ground water ($P$). The second check uses the fourth design equation (ASTM F-1216, X1.4) to ensure the minimum pipe stiffness is met using the thickness ($t$) from Equation 3 as follows:

where

| | | |
|---|---|---|
| E | = | initial modulus of elasticity for the liner material (psi) |
| D | = | mean inner pipe diameter (in.) |
| t | = | thickness of the CIPP lining from Equation 3 (in.) |
| F | = | minimum pipe stiffness = 0.093 (inch pounds) |

The fifth design equation (ASTM F-1216, X1.7) calculates the minimum thickness required to withstand internal pressure only as follows:

where

| | | |
|---|---|---|
| t | = | thickness of the CIPP lining (in.) |
| D | = | mean inner pipe diameter (in.) |
| $\sigma_{TL}$ | = | long-term (time corrected) tensile strength for CIPP (psi) |
| $P_i$ | = | internal pressure (psi) |
| N | = | safety factor (typically 2) |

The minimum thickness should be calculated by all four methods when faced with a fully deteriorated pressure pipe condition, which is what Aqua-Pipe® is designed for, and the largest of the four values should be used for a given project. The parameters in Table 2-4 are typically used in the design process in addition to the manufactures standards and ASTM F-1216 parameters.

**Table 2-4. Typical Design Parameters (Sanexen, 2010)**

| Parameter | Value |
|---|---|
| Ovality of Host Pipe | 2% minimum |
| Host Pipe Condition | Fully deteriorated |
| Modulus of Soil Reaction ($E'_s$) | 700 psi minimum |
| Factor of Safety against Buckling | 2 minimum |
| Live Load ($W_s$) | AASHTO HS20-44 Loading under roadways<br>AASHTO E-80 Loading under railroads |
| Soil Unit Weight (w) | 120 lbs/ft$^3$ minimum<br>(if no boring data is available in vicinity) |
| Creep Reduction Factor | 50% maximum |
| Internal Pressure ($P_i$) | System Working Pressure |
| Depth of Cover (H) | As indicated in bid documents |

2.2.5 Installation of CIPP Liners. The following is a brief overview of the major steps involved in the installation of a CIPP liner for water main rehabilitation. The work will typically last four to five weeks from the installation of the temporary water supply to site restoration and cleanup including the following steps (Sanexen, 2010):

- Locating the pipe – locate the water main and adjacent utilities
- Soil type determination – minimize risk for the contractor during access pit excavation

- Notice to residents – inform residents of work to be performed
- Temporary water supply – install and connect residents to temporary bypass system
- Access pits – excavate pits at both ends of the pipe (typically 9 ft × 6 ft and 12 in. below the pipe)
- Pipe cleaning – mechanically clean the pipe via chain reamer and water jetting (drag scraping or rack feed bore is not recommended )
- Inspection and plugging – pre-lining CCTV inspection and plugging of service connections
- CIPP installation – impregnation of the liner, insertion by pulling in, and liner curing
- Hydrostatic pressure test – pressure test before the reinstatement of service connections
- Opening service – internal reinstatement of service connections robotically
- Reconnection to system – the main is connected to the system and disinfected for return to service
- Surface restoration – pits are backfilled and the surfaces are restored
- Site cleanup – the bypass is disassembled and the site is cleaned

The timing and duration of each of these steps were documented during this project to establish the level of complexity of the CIPP lining installation process. Technologies that limit the length of time a water main is out of service or bypassed were preferred by water utilities and are an important measure of technology performance.

2.2.6 QA/QC Requirements for CIPP Liners**.** As part of the demonstration protocol, development of appropriate QA/QC activities (i.e., the steps used to evaluate the performance and proper application of the CIPP liner) were identified as follows:

- **Ensure proper surface preparation.** Internal pipe surfaces must be cleaned of rust and scale to allow the composite liner to bond to the host pipe and restore the hydraulic capacity of the pipe.
  - Clean the interior of the pipe using the vendor-recommended method
  - Dry wall of pipe according to the requirements of the material being applied (swab and air)
  - Pre-lining inspection of the pipe to ensure proper cleaning and drying (CCTV).
- **Compare lining thickness to design value.** The lining thickness is the key design parameter to ensure the specifications have been met. Additionally, the inside diameter of the rehabilitated pipe shall not be smaller than 90% of the inside diameter of the original pipe. (The utility owner should verify the allowable inside diameter of the rehabilitated water main versus the hydraulic capacity requirements.)
  - Ultrasonic thickness gauge can be used to measure thickness as specified in ASTM E797 (ASTM, 2005a)
  - Calipers can be used to measure the thickness manually from the pipe ends
- **Ensure leakage free operation and adequate flow capacity.** After liner installation, and prior to reinstatement of services, the lined pipe should be pressure-tested for leakage. This is typically accomplished by maintaining the mean operating pressure within the lined pipe for an hour, and no significant pressure drop should be observed. The Hazen-Williams C-factor can be measured via a flow test to determine the amount of headloss caused by friction from flow in the pipe before and after lining. The Hazen-Williams C-factor should be equal to or higher than 120.
  - Hydrostatic pressure test as indicated in Section 8.3 of ASTM F-1743 (ASTM, 2008b)
  - Hazen-Williams flow test to determine improvement in headloss caused by friction
- **Compare lining samples to manufacturer performance specifications.** The flexural and tensile strength of samples removed from the field will determine if the field product met the product design standards.
  - Flexural strength and modulus are measured by ASTM D-790 (ASTM, 2007a)
  - Tensile strength is measured by ASTM D-638 (ASTM, 2008a)

Another important aspect of a field demonstration protocol which must be understood to adequately assess technology performance is the potential failure mode and installation issues that may arise. These potential issues are summarized in Table 2-5 and can arise from material issues, installation issues, structural failures, or other factors external to the pipe.

**Table 2-5. Summary of Potential Installation Issues for CIPP Liners**

| Potential Issue | Description | Relevance to Protocol |
|---|---|---|
| Improper Surface Preparation | Internal pipe surfaces must be cleaned of rust and scale to allow the composite liner to bond to the host pipe and restore the hydraulic capacity of the pipe. | Pre-lining inspection to document adequacy of surface preparation. |
| Improper Forming and Curing | CIPP liners must be formed and cured correctly to ensure proper material properties. Improper curing can result from incorrect pressure, temperature, or cure time. | Pressure, temperature, and cure time will be recorded and material tests will be conducted. |
| Liner Thickness Not Achieved | Insufficient thickness can occur if the liner becomes stretched or an insufficient amount of resin is impregnated into the liner. | Thickness will be measured in the field and in the lab with calipers and with an ultrasonic gauge. |
| Structural Failure | Pressurized host pipes and liners must withstand internal pressure from normal operating conditions in the lined pipe and/or from short-term pressure surges caused by water hammer. In addition, during installation and/or maintenance activities when the line is depressurized, the external hydraulic head from groundwater should not exceed the flexural strength of the liner to avoid the risk of buckling. | Mechanical properties will be tested including tensile strength; flexural strength; hardness; and a hydrostatic buckling test. Prepared defects of varying sizes and types will be examined in exhumed pipe samples and pressure tested in the lab. |
| Hydraulic Issues | CIPP liners, combined with cleaning operations, are expected to improve the hydraulic characteristics of the pipe by removing tuberculation and providing a thin liner and smooth surface to maximize flow capacity. | Pre-and post-lining flow tests will be performed to determine any improvements to the Hazen-Williams C-factor. |

2.2.7 Operation and Maintenance for CIPP Liners**.** Before the liner is put into service the services are reinstated internally with a remote control robot. The robot is fitted with a cutting bit that will cut through the liner and plug. The robot must be water tolerant and small enough to fit in a 6 in. main, while still allowing for the movement necessary to reach and penetrate the service connections. If the liner adjacent to a service connection is accidentally pierced during this reconnection, the section of pipe has to be replaced using a local excavation.

If non-protruding service connections flush with the pipe surface are encountered, an internal locator is required to find them for reinstatement. The equipment and methods presently used allow the Aqua-Pipe® installers to keep the percentage of excavations for service reinstatement below 10% of the total service connection openings, which was part of this demonstration evaluation.

The new liner does not require maintenance once it has been installed and the corrosion free liner will not allow deposits to attach or form on the inside wall of the pipe. Periodic flushing of the water main or other operations are only required if the utility owner deems it necessary for water quality purposes. The new liner can be dry or pressure tapped and the only precaution would be to make sure that the water utility workers use a saddle, a sharp shell cutter, and make sure that they have cut through the walls of both the existing pipe and the liner (a written procedure is available from the manufacturer).

If a cut has to be performed on a section of rehabilitated pipe, the same procedure as regular pipe can be used. The pipe should be cut with a circular saw equipped with a sharp diamond blade, removed and replaced with a new section of pipe and fittings along with a coupling for closure and no special end seals are required (Sanexen, 2010).

## 2.3 Site Selection Approach

This section outlines the overall site selection factors, provides a description of the selected host site, and reviews the physical and operating characteristics of the test pipe designated for the second of two field demonstrations planned under the research efforts for TO 58.

2.3.1 Site Selection Factors**.** To ensure that the field demonstration results are useful to the water utility user community, the field site and conditions of the test pipe had to be representative of typical applications for the selected CIPP technology. Consequently, the operational conditions of the test pipe (e.g., pipe type, structural integrity, pipe pressure, etc.) and environmental conditions (i.e., drinking water quality and subsurface conditions) of a potential host site had to be appropriate for the technology being considered. Another important consideration in site selection was the water utilities' willingness to participate in the study.

Site selection was largely dependent on the utilities' rehabilitation needs, their understanding of the condition of pipe assets within their system, the availability of time and resources to contribute to the study, and a strong motivation to advance the state of emerging and innovative technologies. The site selection process also depends on the willingness of local stakeholders (such as the city, county, neighborhood residents) to host a demonstration that may involve surface disruption in their right-of-ways or temporary bypassing of their utilities. The following factors were considered in the site selection process for the EPA demonstration program of innovative rehabilitation technologies:

- **Utility commitment.** How willing is the utility to use an innovative rehabilitation technology and to provide the required time and resource commitments to the project?
- **Perceived value.** What is the number of interested utility participants? Is the technology and test pipe rehabilitation need of national-scale or regional-scale interest?
- **Regulatory and stakeholder climate.** How willing are local and state officials to work with the research team and utility concerning requirements (e.g., NSF 61 approval, etc.) to permit use of an innovative technique? Will the local stakeholders (city, county, and neighborhood residents) consent to the potential disruption caused by the construction activities including traffic control and bypass needs?
- **Representativeness of test pipe and site conditions.** How typical are the candidate field demonstration site conditions to problems commonly faced by most utilities?
- **Suitability of test pipe and site conditions to vendor specifications.** Are the test pipe operating and environmental site conditions suitable when compared to the technology vendor's stated application limitations? This includes consideration of the following:
  - Pipe size (diameter and length)
  - Pipe material and joint types
  - Pipe age
  - Operating and surge pressure conditions
  - Pipe configurations (e.g., number of service connections, hydrants, bends, shape, etc.)
  - Availability of CCTV or other inspection technology reports to determine asset condition
  - Availability of O&M history and understanding of failure modes

- **Site access and safety considerations.** Are the site conditions suitable for a safe and secure field demonstration? This includes consideration of the following:
  - Site accessibility, including traffic control requirements
  - Space requirements and restrictions to access (right-of-way)
  - Security of testing equipment and availability of support facilities for bypass and flushing
  - Proximity of site to high-voltage overhead power lines, natural gas pipelines or other utilities
  - Proximity of site to contaminants/toxics in the soil or groundwater
  - Proximity of site to high decibel noise sources
  - Proximity of site to fault zones or active faults
  - Closeness to fire and police protection, including fire lines

Site selection process for this second of two field demonstration involved employing a collaborative approach with utilities and vendors in an effort to identify candidate sites for the planned demonstration study. As part of this process, a dialogue with Sanexen, the manufacturer of Aqua-Pipe®, and the CWD was initiated. Sanexen and the CWD indicated that Aqua-Pipe® was currently planned for a pilot installation as part of a much larger cement mortar lining initiative being undertaken by CWD. Therefore, the City of Cleveland and Aqua-Pipe® were selected for this demonstration study. The overall responsibilities of the technology vendor (Sanexen) were defined as follows:

- Provide vendor specifications, design, and installation information for the technology
- Provide the technology for evaluation during the field demonstration
- Provide equipment and labor needed for the duration of the demonstration
- Provide data from the field demonstration to verify performance and cost of the technology
- Review and provide comments on the draft field demonstration report

The overall responsibilities of CWD were defined as follows:

- Provide historic data on the physical and operating conditions of the test pipe
- Coordinate use of the test site, ensuring access to the test site by Battelle, EPA, and Sanexen
- Support the field demonstration by providing facilities, needed utilities, and pipe access
- Ensure safety requirements are communicated to and met by all involved parties
- Assist Battelle staff and vendors in testing of the rehabilitation technology at the test site
- Review and provide comments on the draft field demonstration report.

2.3.2 Site Description. The City of Cleveland is located in northeastern Ohio on the southern shore of Lake Erie, approximately 60 miles (100 km) west of the Pennsylvania border (see Figure 2-4). It was founded in 1796 near the mouth of the Cuyahoga River, and became a manufacturing center owing to its location at the head of numerous canals and railroad lines. The city proper has an estimated population of 478,403 and is the center of the Greater Cleveland Area, which is the largest metropolitan area in Ohio.

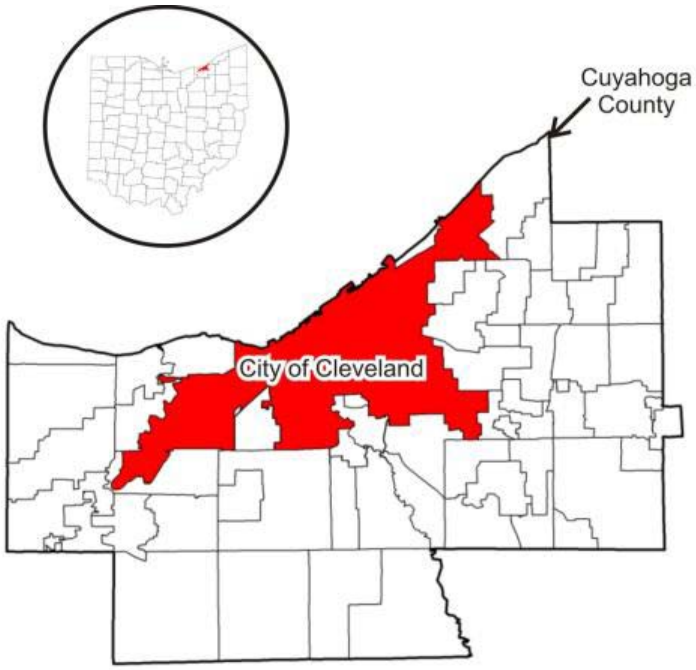


**Figure 2-4. Map of Cuyahoga County Showing the Location of the City of Cleveland**

CWD was created in 1853 and charged with the responsibility for collecting, treating, pumping, and distributing water and providing related water service to customers within its service areas. CWD operates a major public water supply system which serves not only the City of Cleveland, but also 70 suburban municipalities in Cuyahoga, Medina, Summit, and Geauga Counties. The Division is an emergency standby provider for systems in three other counties. The present service area covers over 640 square miles and serves over 1.5 million people.

In the 2008 Annual Report (CWD, 2008), the aggregate metered consumption of water in the City constituted 34% of the total metered consumption in the service area, while consumption in the direct service communities and master meter communities constituted 57% and 9%, respectively. Operating revenue in 2008 increased 0.7% to $242.2 million from $240.6 million in 2007. A water rate increase of approximately 7.3%, which was partially offset by a decrease in metered water consumption of 4.5%, contributed to this increase. Operating expenses, exclusive of depreciation, increased 3.3% to $143.8 million compared to $140.2 million in 2007. The $3.6 million increase in operating expenses in 2008 was primarily due to increases in utilities, healthcare and indirect costs. CWD uses surface water drawn from four intakes in Lake Erie as the source of drinking water and supplies water to 1.5 million people in 70 communities. Lake Erie is a part of the Great Lakes watershed. Table 2-6 presents typical water quality information for the City of Cleveland.

**Table 2-6. Typical Water Quality Information for Cleveland**

| Contaminant | MCL | CWD Result or Range |
|---|---|---|
| **Volatile Organics (mg/L)** | | |
| Benzene | 0.005 | ND |
| Bromobenzene | NR | ND |
| Bromochloromethane | NR | ND |
| Bromomethane | NR | ND |
| tetrachloride | 0.005 | ND |

**Table 2-6. Typical Water Quality Information for Cleveland (Continued)**

| Contaminant | MCL | CWD Result or Range |
|---|---|---|
| Chlorobenzene | 0.1 | ND |
| Chloroethane | NR | ND |
| Chloromethane | NR | ND |
| 2-Chlorotolulene | NR | ND |
| 4-Chlorotoluene | NR | ND |
| Dibromomethane | NR | ND |
| 1,2-Dichlorobenzene | 0.6 | ND |
| 1,3-Dichlorobenzene | 0.6 | ND |
| 1,4-Dichlorobenzene | 0.6 | ND |
| Dichlorodifluoromethane | NR | ND |
| 1,1-Dichloroethane | NR | ND |
| 1,2-Dichloroethane | 0.005 | ND |
| 1,1-Dichloroethene | 0.007 | ND |
| cis-1,2-Dichloroethylene | 0.07 | ND |
| trans-1,2-Dichloroethylene | 0.1 | ND |
| Dichloromethane | 0.005 | ND |
| 1,2-Dichloropropane | 0.005 | ND |
| 1,3-Dichloropropane | NR | ND |
| 2,2-Dichloropropane | NR | ND |
| 1,1-Dichloropropene | NR | ND |
| 1,3-Dichloropropene | NR | ND |
| Ethylbenzene | 0.7 | ND |
| Hexachlorobutadiene | NR | ND |
| Isopropylbenzene | NR | ND |
| 4-Isopropyltoluene | NR | ND |
| Napthalene | NR | ND |
| n-Propylbenzene | NR | ND |
| Styrene | 0.1 | ND |
| 1,1,1,2-Tetrachloroethane | NR | ND |
| 1,1,2,2-Tetrachloroethane | NR | ND |
| Toluene | 1 | ND |
| 1,1,1-Trichloroethane | 0.2 | ND |
| Tetrachloroethene | 0.005 | ND |
| 1,2,3-Trichlorobenzene | NR | ND |
| 1,2,4-Trichlorobenzene | 0.07 | ND |
| Trichloroethene | 0.005 | ND |
| 1,1,2-Trichloroethane | 0.005 | ND |
| Trichlorofluoromethane | NR | ND |
| 1,2,3-Trichloropropane | NR | ND |
| Vinyl chloride | 0.002 | ND |
| Xylenes | 10 | ND |
| **Radionuclides (pCi/L)** | | |
| Beta Emitters (pCi/L) | 50 | ND |
| Alpha Emitters (pCi/L) | 15 | ND |
| **Synthetic Organics (mg/L)** | | |
| Alachlor | 0.002 | ND |
| Atrazine | 0.003 | ND |
| Simazine | 0.004 | ND |
| **Inorganics (mg/L)** | | |
| Aluminum | NR | ND |
| Antimony | 0.006 | ND |

**Table 2-6. Typical Water Quality Information for Cleveland (Continued)**

| Contaminant | MCL | CWD Result or Range |
|---|---|---|
| Arsenic | 0.01 | ND |
| Barium | 2 | 0.017 |
| Berylium | 0.004 | ND |
| Cadmium | 0.005 | ND |
| Chromium | 0.1 | ND |
| Copper (90th percentile) | 1.3 | 0.101 |
| Cyanide | 0.2 | ND |
| Fluoride | 4 | 1 |
| Iron | NR | ND |
| Lead (90th percentile) | 0.015 | 0.008 |
| Manganese | NR | 0.018 |
| Mercury | 0.002 | ND |
| Molybdenum | NR | ND |
| Nickel | 0.1 | ND |
| Nitrate | 10 | 0.4 |
| Potassium | NR | ND |
| Selenium | 0.05 | ND |
| Silica | NR | 1.6 |
| Silver | NR | ND |
| Sodium | NR | 10.7 |
| Strontium | NR | 0.16 |
| Thallium | 0.002 | ND |
| Vanadium | NR | ND |
| Zinc | NR | 0.014 |
| **Miscellaneous (mg/L, unless otherwise noted)** | | |
| Chloride | 250 | 18 |
| Color | 15 | <1 |
| Odor | 3 | 1 |
| Total Dissolved Solids | 500 | 160 |
| Calcium | NR | 33 |
| Magnesium | NR | 9 |
| Total Organic Carbon | No Value | 2 |
| pH | >7.0 | 7-7.6 |
| Alkalinity | NR | 80 |
| Orthophosphate | >0.8 | 0.8-1.3 |
| Hardness (as CaCO3) | NR | 120 |
| Turbidity (NTU) | 0.3 | 0.05 |
| Total Coliform | <5% | 1.87% |
| **Disinfection Byproducts** | | |
| Total Trihalomethanes | 0.08 | 0.026 |
| Haloacetic Acids | 0.06 | 0.037 |
| Organic Halides | NR | 94 |
| Haloacetic Nitriles | NR | 4.3 |

mg/L – milligrams per liter
µg/L – micrograms per liter
NR – not regulated
MCL – maximum contaminant level
ND – not detected

2.3.3 Physical/Operating Characteristics of the Test Pipe. As shown in Figure 2-5, the demonstration study was conducted using a portion of a distribution main (referred to herein as "the test pipe") running underneath Ferncliffe Avenue between West 190th and Rocky River Drive in the City of Cleveland.

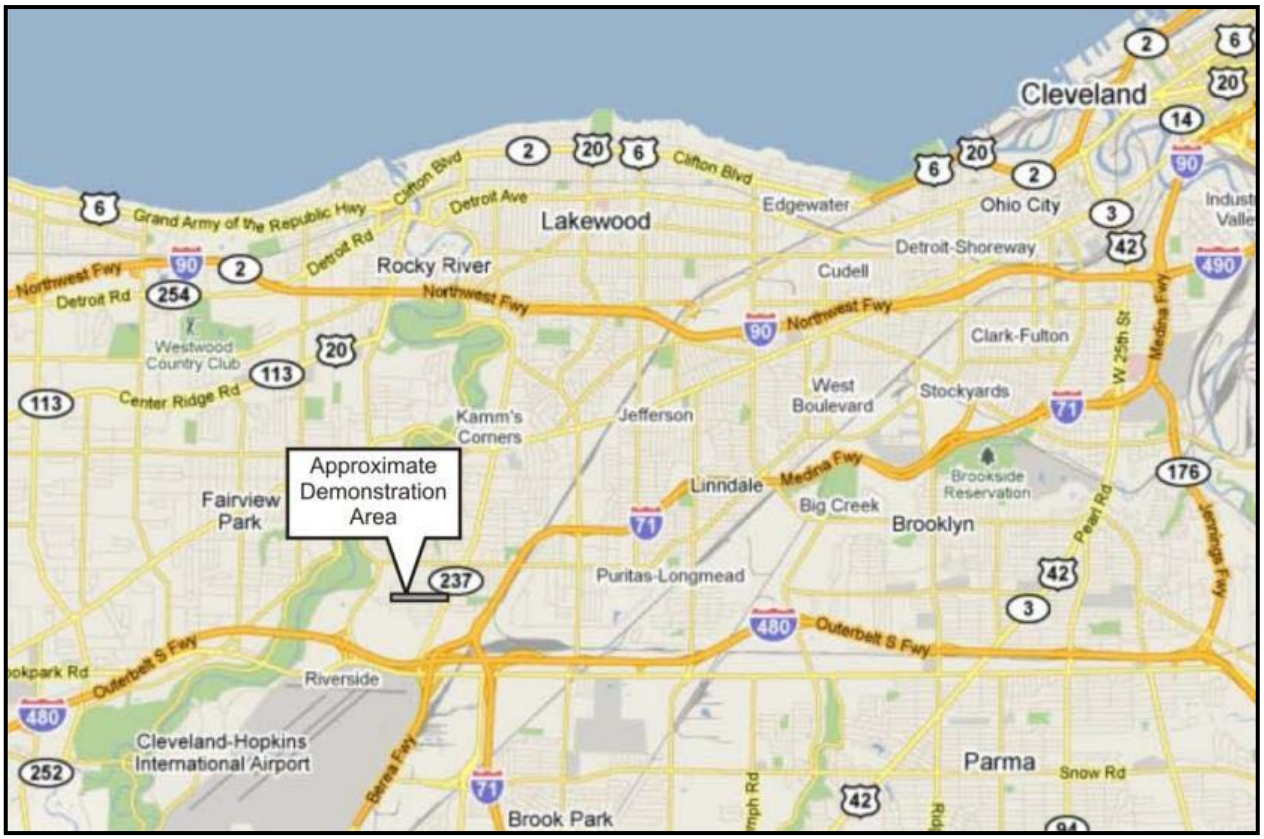


**Figure 2-5. Map of the City of Cleveland Depicting the Approximate Demonstration Area**

The test pipe, which was installed in 1914 and in 1949, is 2,040 ft of 6 in. unlined cast iron main, running east-west underneath Ferncliffe Avenue. The test pipe typically operates at a pressure of approximately 60 psi while transmitting approximately 0.86 million gallons per day (MGD) of flow. Table 2-7 summarizes the historical, operational, and environmental characteristics of the test pipe. As indicated in Table 2-7, relevant soil parameters, such as moisture, pH, resistivity, redox potential, etc., are not available for the native soil adjacent to the test pipe, therefore, soil samples were collected and analyzed for general geochemical parameters as discussed in Section 3.1.3.2. Based on the 2009 climate data, the monthly average temperature for the area around Cleveland ranges from 20°F in January to 73°F in August.

**Table 2-7. Summary of Historical, Operational, and Environmental Characteristics of Test Pipe**

| | |
|---|---|
| ***Historical*** | |
| Pipe ID and Material | 6 in. Cast Iron |
| Installation Date | 1914 & 1949 |
| Pipe Joint-to-Joint Length (ft) | 17.7 (5.4 m) & 11.8 (3.6 m) |
| Pipe Outer Diameter (in.) | 7 |
| Pipe Class | Unknown |
| Pipe Wall Thickness (in.) | 0.5 |
| Approximate Total Pipe Length (ft) | 1914: 1,809 & 1949: 263 |
| Burial Depth (ft below ground surface) | Typically 6, but can't verify without excavation |
| Pipe Internal Lining | None |
| Pipe Lining Thickness (in.) | N/A |
| Pipe External Coating | Unknown |
| Type of Joints | Unknown |
| Land Use over Main | Residential traffic |
| Leak History (recorded) | Unknown |
| Date of First Joint Break (recorded) | Unknown |
| Date of First Pipe Break (recorded) | 1/7/1987 |
| ***Operational*** | |
| Typical Operating Flow (MGD) | 0.86 |
| Typical Operating Pressure (psi) | ~60 |
| Friction Factor | C-factor ~120 |
| Water pH (S.U.) | 6.6 to 7.2 |
| ***Environmental*** | |
| Soil Parameters (moisture, pH, resistivity, redox potential, etc.)[(a)] | Historical data not available[(a)] |
| Average Monthly Temperature (°F)/ Humidity (%) for 2009[(b)] | Aug. 73.6°F/67 %<br>Sep. 66.0°F/71%<br>Oct. 53.2°F/66% |

[(a)] Soil characterization was performed before the demonstration project (see Section 3.1.2.1).
[(b)] Based on data obtained for Weather Underground (wunderground.com).

## 3.0: CIPP DEMONSTRATION

This section outlines the activities involved with the CIPP lining field demonstration including site preparation, technology application, post-demonstration field verification, defect sample collection, site restoration, and post-demonstration hydraulic testing.

### 3.1 Site Preparation

To successfully execute the planned demonstration, various site preparation activities were required. These activities included: installation of the temporary bypass system; excavation of several access pits to expose the test pipe; hydraulic testing to collect baseline data; cutting into the test pipe to provide access for cleaning, drying, and inspecting the pipe; and pre-lining inspection with a CCTV camera while plugging the service connections. Additionally, cutting and drilling were required to support the installation of defects in a field-defect section and the insertion of the lab-defect pipe segment. Details relating to these site preparation activities are provided in this section.

**3.1.1 Safety and Logistics.** Throughout the demonstration project, individual excavation areas along Ferncliffe Avenue were secured from West 190th Street (to the west) to Rocky River Drive (to the east). CWD and its subcontractors, Terrace Construction (TC) and Sanexen, were responsible for traffic control.

The demonstration took place over the course of 10 weeks from layout of the bypass system (week of August 16) to removal of the bypass system (week of October 18). A typical day began around 7:00 a.m. and activities each day were normally completed by 4:00 p.m. A local road dig permit was obtained to conduct the planned excavations in the public right-of-way along Ferncliffe Drive. Open pits were marked with cones and caution tape and TC plated all pits at the end of each day to avoid accidents during the evenings and on weekends as shown in Figure 3-1.

**Figure 3-1. Access Pit Plated**

The Battelle team had at least one staff member on site each day for the majority of the preparation activities and two staff members were on site during the week of lining. The Battelle team maintained constant coordination with CWD and its subcontractors throughout the demonstration project to ensure that all field data were collected as planned in the QAPP. Level D personal protective equipment,

including hard hats, safety glasses, steel-toed shoes, and safety vests, were required for all site visitors. All visitors were also required to sign in with the Battelle team representative each day.

3.1.2 Installation of Bypass**.** TC began laying out the bypass on Tuesday, August 17, 2010 to supply water to the residents on Ferncliffe Avenue and completed the installation and connection of each house except one on August 26 (six total working days). The bypass system, which consisted of 4 in. high density polyethylene (HDPE) pipe, was installed from a fire hydrant on Rocky River Drive, down Ferncliffe Avenue, and ended at a fire hydrant on West 190$^{th}$ Street. The 4 in. HDPE pipe was installed using heat fusion welding. The pieces of HDPE pipe were held axially by a clamping device to allow subsequent operations to take place. Once the pipe was clamped, the ends were reamed with a machining tool to establish clean, parallel mating surfaces, perpendicular to the centerline of each pipe. A heating plate was then inserted between the faced ends, and the pipe was drawn together against the heating plate. Once the correct melt temperature was reached, the heating plate was quickly removed, and the melt ends were drawn together with the clamp where it was held until the joint cooled. The specified force on the joint was continuous, and held until the joint cooled. A small melt bead formed at the joint and at completion, the fused pipe was removed from the welding machine.

The 4 in. HDPE bypass pipe contained fittings for 1 in. flexible hoses that were connected to each residence. Figure 3-2 shows the heat fusion welder and the 1 in. flexible hose used for connecting the bypass piping to the houses on Ferncliffe Avenue. TC opted not to chlorinate the bypass system for disinfection purposes unless initial water samples for bacteriological analysis tested positive. The bypass system was initially flushed at 600 gallons per minute (gpm) for 15 min and then allowed to flow at a rate of 100 gallons per day (gpd) for seven days, which generated approximately 9,700 gal of wastewater. After the bypass system was flushed, water samples were collected for bacteriological analysis. The water samples passed bacteriological analysis; therefore, disinfection of the bypass system was not necessary.

**Figure 3-2. Heat Fusion Welder (left) and 4 in. HDPE Pipe with Service Connection (right)**

3.1.3 Excavation Pits and Pipe Access**.** A total of nine excavation pits were excavated from August 23 to September 2, 2010 to support the project (Figure 3-3). Pits #1, #2, #3, #4, #6, #7, #8, and #9 were used for installing the CIPP liner and Pit #5 was used for installing the lab-defect section and retrieving both the lab-defect and field-defect sections once the liner installation was complete.

The dimensions of the eight pits required for the demonstration study and the one additional pit used for installing the defect sections (referred to as Pit #5) are summarized in Table 3-1. The depth of each pit

below the ground surface was needed to provide access for cleaning and drying of the pipe, pre- and post-lining inspection with a CCTV camera, and use of the CIPP liner installation equipment.

**Figure 3-3. Pit Excavation Activities**

**Table 3-1. Summary of Pit Dimensions and Volume of Soil Removed**

| Pit | Length, in. (ft) | Width, in. (ft) | Depth, in. (ft) | Volume of Soil, $ft^3$ ($yd^3$) |
|---|---|---|---|---|
| #1 | 117 (9.75) | 68 (5.67) | 90 (7.50) | 414 (15.3) |
| #2 | 108 (9.00) | 68 (5.67) | 86 (7.17) | 366 (13.5) |
| #3 | 118 (9.83) | 68 (5.67) | 78 (6.50) | 362 (13.4) |
| #4 | 119 (9.92) | 72 (6.08) | 86 (7.17) | 426 (15.8) |
| #5 (Test Pit) | 114 (9.50) | 69 (5.75) | 87 (7.25) | 396 (14.7) |
| #6 | 110 (9.17) | 69 (5.75) | 79 (6.58) | 347 (12.9) |
| #7 | 102 (8.50) | 67 (5.58) | 88 (7.33) | 348 (12.9) |
| #8 | 112 (9.33) | 64 (5.33) | 91 (7.58) | 377 (14.0) |
| #9 | 110 (9.17) | 63 (5.25) | 91 (7.58) | 365 (13.5) |
| **All Pits** | **Waste volume of soil requiring off-site disposal** | | | **3,401 (126.0)** |

The pits were outlined and "de-rocked" by cutting through the pavement with a demolition saw and removing the pavement above the soil with a backhoe. The broken-up pavement was placed in a dump truck and sent to be recycled. After the pits were "de-rocked", a backhoe was used to excavate the soil and gain access to the pipe. The estimated volume of soil removed during excavating of the pits was 3,401 $ft^3$ (Table 3-1). Table 3-2 summarizes the length of each of the seven lining runs.

**Table 3-2. Distances of Each Lining Run**

| Lining Run | Start Pit | End Pit | Length, ft (m) |
|---|---|---|---|
| #1 | #1 | #2 | 249 (76.0) |
| #2 | #2 | #3 | 313 (95.5) |
| #3 | #3 | #4 | 295 (90.0) |
| #4 (includes test sections) | #4 | #6 | 297 (90.5) |
| #5 | #6 | #7 | 292 (89.0) |
| #6 | #7 | #8 | 297 (90.5) |
| #7 | #8 | #9 | 253 (77.0) |
| | | **Total Length** | **1,996 (608.5)** |

The distance of each lining run allowed for the rehabilitation of the entire test pipe running underneath Ferncliffe Avenue. Pit locations were strategically located to allow for the replacement of valves and hydrants. Each run was less than the maximum application length of 500 ft suggested by Sanexen and near the typical installation distance of 350 ft. Originally Pits #3 and #4 were intended to serve as the locations for the lab-defect and field-defect pipe segments, respectively. However, the contractor decided to use Pits #3 and #4 for lining. Therefore, Pit #5 was used for installation of both defect sections in the middle of lining run #4. The location of Pit #5 in the middle of a lining runs was necessary to provide a representative sample that would not have been possible if the defect sections would have been placed at the beginning or end of a lining run. The location of the nine excavation pits is shown in Figure 3-4 across the approximate 2,040 ft (1,996 ft that was lined and 44 ft of sections replaced between lining runs) distance.

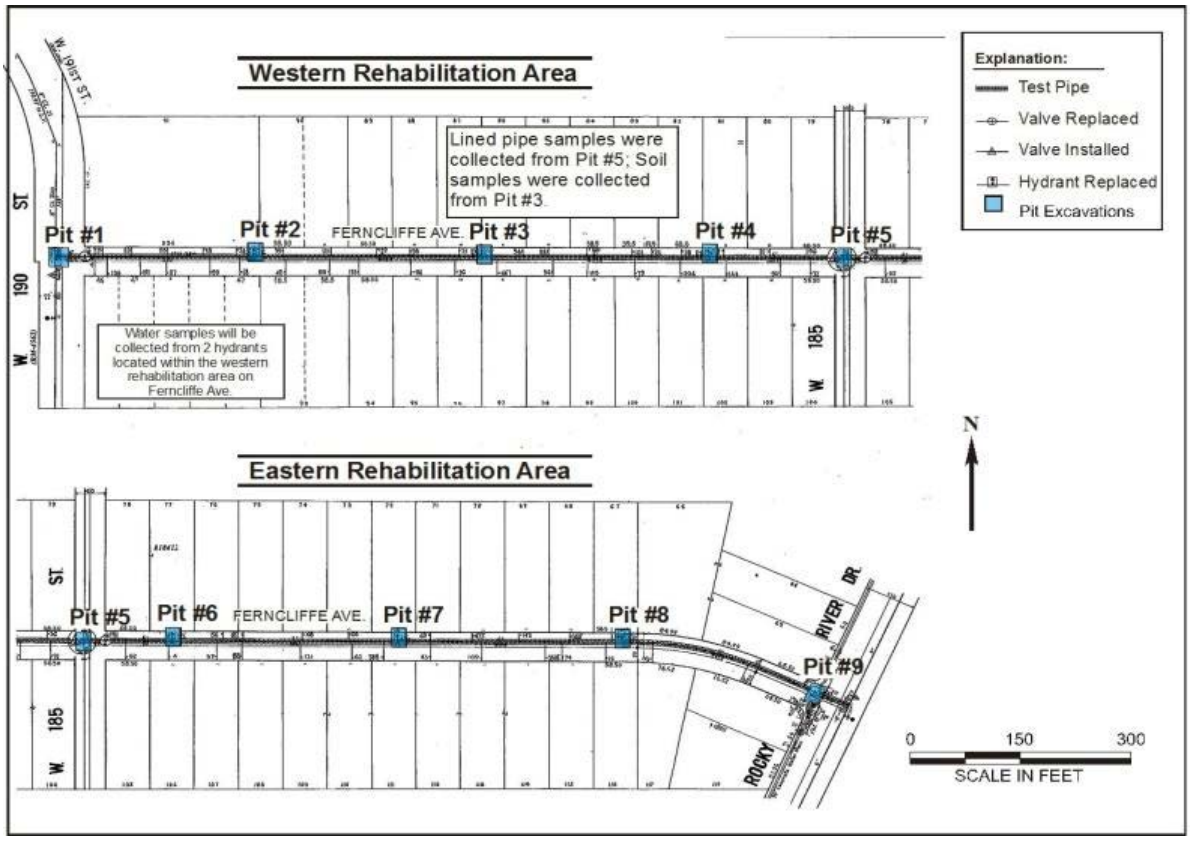


**Figure 3-4. Site Layout and Pit Locations**

***3.1.3.1 Soil Sampling.*** Several measurable soil properties have been linked to rates and extent of cast iron pipe failure in situ as well as in laboratory experiments. These properties are mostly chemical (pH, sulfide concentration, chloride concentration); however, some are mechanical in nature (shrink/swell capacity, heterogeneities, and compaction) and still others are chemical, but seen as surrogate measurements for mechanical properties (cation exchange capacity, for example, can be seen as an indirect indicator of shrink/swell capacity). All of these measurements taken together are thought to contribute to the soil corrosivity potential. The long-term performance of the structural CIPP lining might be impacted by the current and future condition of the cast iron host pipe and the stressors or aging factors in its environment. For this reason, several soil parameters were analyzed as discussed below.

Soil samples were collected on August 21, 2010, from six grab sampling locations within Pit #3: (1) a location immediately below the pavement and subgrade; (2) a location approximately 2 ft below subgrade; (3) a location approximately 3 ft below subgrade; (4) immediately above the pipe crown approximately 4 ft below subgrade; (5) at the bedding along the spring line; and (6) at the bedding immediately below the invert. Figure 3-5 provides a graphical depiction of the vertical distribution of all soil sampling locations described above. A small hand shovel was used to carefully remove the overlying native soil samples and the bedding samples surrounding the test pipe during excavation of Pit #3. All soil and bedding samples were placed into sample containers for analysis.

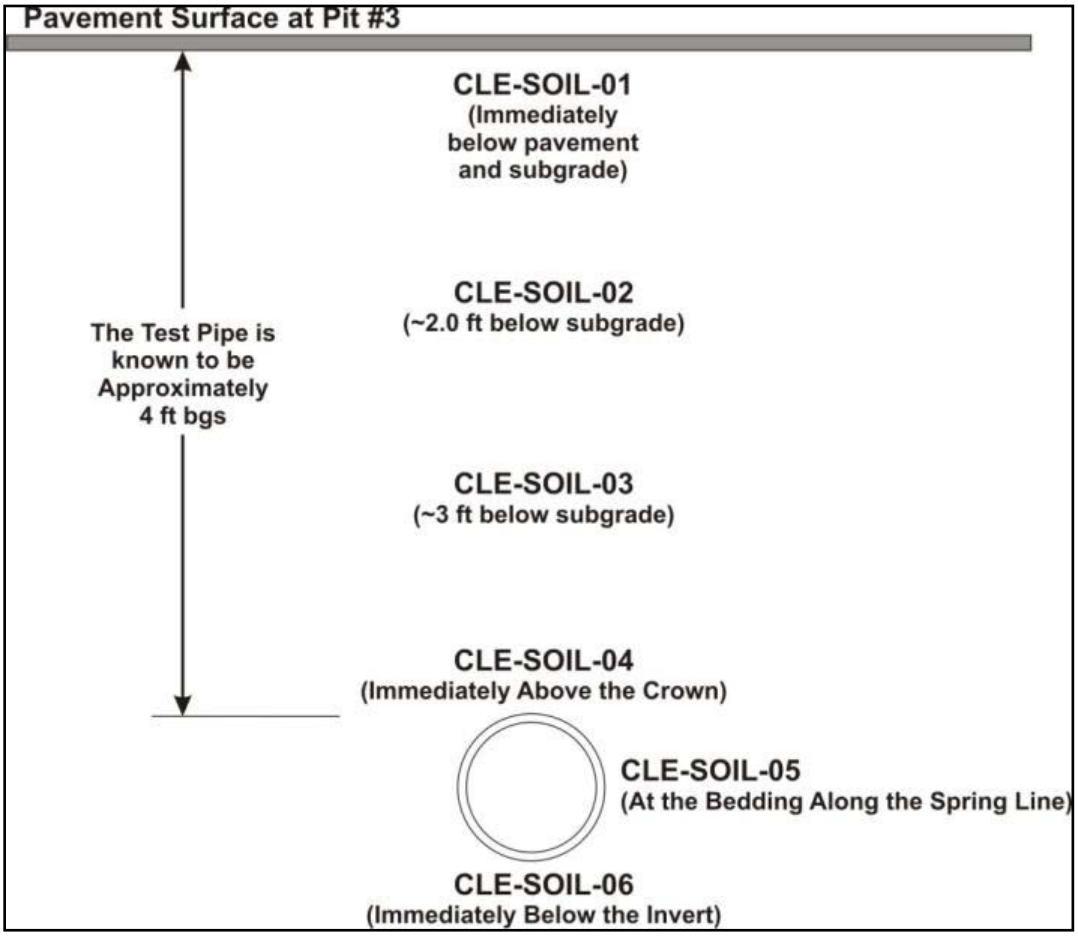


**Figure 3-5. Vertical Distribution of Soil Sample Locations**

As summarized in Table 3-3, soil samples from all six sampling locations were placed into glass jars and sent for analysis of particle size distribution according to ASTM C-136 (i.e., sieve analysis) (ASTM, 2006) and geochemical parameters. Table 3-3 describes the parameters that were analyzed to characterize the geochemistry and the associated corrosivity of native soil and bedding adjacent to the test pipe. All sample containers were sealed to retain moisture, the cap of the jar was wrapped with Teflon® tape to ensure that a competent seal was achieved, and the entire jar was covered with aluminum foil to reduce any effects of incidental light contacting the sample. The soil samples were analyzed by Test America for the parameters listed in Table 3-3.

**Table 3-3. Summary of Soil Sample Analytical Testing**

| Soil Measurement | Method of Analysis | Reference |
|---|---|---|
| ***Particle Size Distribution*** | | |
| Particle Size | Sieve analysis to determine particle size distribution of bedding | ASTM C-136 (2006) |
| ***Geochemical Analysis*** | | |
| Moisture Content | Determine water (moisture) content of soil by direct heating | ASTM D-4959 (2007b) |
| pH | Standard test method for pH of soil | ASTM D-4972 (2001) |
| Electrical Resistivity | Measure soil resistivity using two-electrode soil box method | ASTM G-187 (2005b) |
| Oxidation-Reduction Potential (ORP) | Standard test method for measurement of oxidation-reduction potential (ORP; redox) of soils | ASTM G-200[(a)] (2009c) |
| Cation Exchange Capacity | Standard method where soil is mixed with excess of ammonium acetate to determine the exchange of ammonium cations for exchangeable cations present in the soil | EPA 9080 (1986a) |
| Sulfide Concentration | Acid soluble and acid insoluble sulfides: distillation | EPA 9030B (1996a) |
| Sulfate Concentration | Standard test method for water-soluble sulfate in soil | ASTM C-1580 (2009d) |
| Chloride Concentration | Chloride: colorimetric, automated ferricyanide | EPA 9250 (1986b) |

[(a)] Formally ASTM WK12508 as reported in the QAPP.

Soil testing results are presented in Table 3-4. All six consisted of mostly silt, clay (73%), sand (24%) with some gravel (3%) on average. The geochemical analysis showed that the Cleveland site soil was not highly corrosive. The soil pH ranged from 7.9 to 9.4 with a corrosive soil defined as having a pH less than 5.5. The chloride concentration averaged 168 parts per million (ppm) and sulfate concentration averaged 26 ppm, with a corrosive soil defined as having chloride concentrations greater than 500 ppm and sulfate concentrations greater than 2,000 ppm. Electrical resistivity ranged from 1,094 to 1,392 ohm-cm with a minimum resistivity value for soil less than 1,000 ohm-cm, indicating the presence of high quantities of soluble salts and a higher propensity for corrosion (CalTrans, 2003).

**Table 3-4. Soil Sampling Results**

| Analyte | Reporting Limit | Unit | Sampling Location (CLE) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Soil-01 | Soil-02 | Soil-03 | Soil-04 | Soil-05 | Soil-06 |
| ***Particle Size Distribution*** | | | | | | | | |
| Gravel | N/A | % | 1.3 | 7.5 | 4.7 | 5.0 | 0.7 | 0.4 |
| Sand | N/A | % | 20.9 | 25.0 | 25.9 | 26.3 | 22.7 | 22.7 |
| Course Sand | N/A | % | 2.5 | 3.9 | 4.2 | 3.4 | 2.6 | 3.1 |
| Medium Sand | N/A | % | 6.2 | 8.4 | 8.5 | 9.1 | 7.6 | 7.7 |
| Fine Sand | N/A | % | 12.2 | 12.7 | 13.2 | 13.8 | 12.5 | 11.9 |
| Silt | N/A | % | 34.9 | 30.1 | 35.3 | 32.5 | 36.6 | 40.7 |
| Clay | N/A | % | 42.9 | 37.4 | 34.1 | 36.2 | 40.0 | 36.2 |
| ***Geochemical Analysis*** | | | | | | | | |
| Solids (%) | 10 | % | 85.1 | 82.2 | 80.2 | 82.7 | 81.3 | 80.7 |
| pH (solid) | N/A | S.U. | 9.4 | 8.6 | 8.3 | 8.3 | 8.4 | 7.9 |
| Electrical Resistivity | N/A | ohm-cm | 1,243 | 1,243 | 1,094 | 1,392 | 1,343 | 1,293 |
| ORP | 10 | mV | 383 | 385 | 384 | 333 | 353 | 345 |
| Cation Exchange | 2.42 | meq/100g | 10.3 | 7.0 | 8.1 | 12.2 | 9.8 | 6.7 |
| Sulfide | 35.3 | mg/kg | BRL | BRL | BRL | BRL | BRL | BRL |
| Sulfate | 11.8 | mg/kg | 42.1J | 45.7J | 26.4J | 15.0J | 19.9J | 9.3B,J |
| Chloride | 11.8 | mg/kg | 148 | 172 | 235 | 137 | 130 | 187 |

N/A = not applicable J = estimated value BRL = below reporting limit

***3.1.3.2 Water Sampling.*** Certification under NSF Standard 61 is required for all lining material to be used for drinking water applications. This standard addresses materials and products that directly contact drinking water such as process media, protective materials, joining and sealing materials, pipes, mechanical devices, and mechanical plumbing devices. Under this standard, materials are tested for contaminant leaching and to certify that contaminant levels are within acceptable limits for the protection of human health and the environment. The suite of water parameters tested under this standard includes:

- pH by EPA method 150.1 (EPA, 1982);
- total dissolved solids by EPA method 160.1 (EPA, 1971a);
- total suspended solids by EPA method 160.2 (EPA, 1971b);
- turbidity by EPA method 180.1 (EPA, 1993a);
- iron and manganese by EPA method 200.7 (EPA, 1994);
- chloride, fluoride, nitrite, nitrate, phosphate, and sulfate by EPA method 300.0 (EPA, 1993b);
- total alkalinity by EPA method 310.1 (EPA, 1978);
- ammonia by EPA method 350.1 (EPA, 1993c);
- total organic carbon by EPA method 415.1/SM 5301B (EPA, 1974);
- VOCs by EPA method 524.2 (EPA, 1995a);
- silica by EPA method 200.7/6010B (EPA, 1996b);
- arsenic, calcium, copper, lead, magnesium, and sodium by SM 3113B (Standard Methods, 1999); and
- organic compounds and BPA by EPA method 525.2 (EPA, 1995b), which was used in place of EPA method 625 (for organic compounds) and liquid chromatography (BPA).

Accordingly, water sampling and analysis were conducted as part of the Cleveland demonstration. Prior to rehabilitation of the test pipe, the source water quality was characterized by collecting and analyzing water samples from two fire hydrants (CLE-01 and CLE-02) on Ferncliffe Avenue between West 190th Street and Rocky River Drive. Water samples were collected from each water sampling location during three separate sampling efforts: (1) baseline sampling prior to rehabilitation on August 12; (2) post-rehabilitation sampling once the pipe was brought back into service immediately following disinfection on October 21; and (3) post-rehabilitation sampling one week after the test pipe had been brought back into service October 27. Table 3-5 presents the results of the three sampling efforts for both locations.

**Table 3-5. Water Sampling Results**

| | | | | CLE-01 | | | CLE-02 | | |
|---|---|---|---|---|---|---|---|---|---|
| **Analyte** | **RL** | **MCL** | **Unit** | **8/12** | **10/21** | **10/27** | **8/12** | **10/21** | **10/27** |
| ***Field Water Quality Parameters*** | | | | | | | | | |
| pH | N/A | >7.0 | S.U. | 7.4 | 6.76 | 6.62 | 7.28 | 6.49 | 6.25 |
| Temperature | N/A | N/A | °C | 25.6 | 17.5 | 17.7 | 28.3 | 19.1 | 18.9 |
| DO | N/A | N/A | mg/L | 6.93 | 6.49 | 6 | 6.75 | 6.57 | 6.39 |
| ORP | N/A | N/A | mV | 466.5 | 569.2 | 494.1 | 418.5 | 398.6 | 365.9 |
| Free Cl (as $Cl_2$) | N/A | N/A | mg/L | 0.69 | 0.66 | 0.8 | 0.18 | 0.62 | 0.77 |
| Total Cl (as $Cl_2$) | N/A | N/A | mg/L | 0.73 | 0.78 | 0.95 | 0.36 | 0.69 | 0.87 |
| ***Lab Water Quality Parameters*** | | | | | | | | | |
| pH | 1 | >7.0 | S.U. | 7.64 | 8.06 | 7.31 | 7.5 | 7.56 | 7.28 |
| Alkalinity | 1 | N/A | mg/L | 95.6 | 84.4 | 88.9 | 82.2 | 100 | 104 |
| Turbidity | 0.1 | 0.3 | NTU | 19 | 0.53 | 0.75 | 8.2 | 0.8 | 7.2 |
| Chloride | 0.1 | 250 | mg/L | 18.8 | 18.9 | 17.9 | 21.9 | 13.4 | 22.1 |
| Fluoride | 0.1 | N/A | mg/L | 1.25 | 1.09 | 0.901 | 1.12 | 0.861 | 0.877 |

**Table 3-5. Water Sampling Results (Continued)**

| Analyte | RL | MCL | Unit | CLE-01 | | | CLE-02 | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 8/12 | 10/21 | 10/27 | 8/12 | 10/21 | 10/27 |
| Nitrate (as N) | 0.05 | 10 | mg/L | 0.1 | 0.12 | 0.17 | 0.1 | 0.13 | 0.18 |
| Nitrite (as N) | 0.05 | N/A | mg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Ammonia (as $NH_3$) | 0.05 | N/A | mg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Sulfate | 0.1 | N/A | mg/L | 23.4 | 21.1 | 24.3 | 24.6 | 21.8 | 27.2 |
| Orthophosphate (as OPO4) | 0.1 | > 0.8 | mg/L | 0.696 | 0.885 | 0.917 | 0.585 | 0.882 | 0.879 |
| Silica (as SiO2) | 215 | N/A | µg/L | 1550 | 1860 | 2080 | 1150 | 1870 | 2110 |
| TDS | 2 | 500 | mg/L | 166 | 120 | 146 | 154 | 102 | 134 |
| TSS | 4 | N/A | mg/L | 72 | BRL | BRL | 10 | 4 | BRL |
| TOC | 0.5 | N/A | mg/L | 2 | BRL | 2.9 | 3 | BRL | 0.94 |
| Arsenic | 5 | 10 | µg/L | 5.87 | BRL | BRL | BRL | BRL | BRL |
| Calcium | 1 | N/A | mg/L | 23.9 | 27.6 | 31 | 30.6 | 27.7 | 31.2 |
| Copper | 20 | 1,300 | µg/L | BRL | BRL | BRL | 33 | BRL | BRL |
| Iron | 30 | 300 | µg/L | 916 | 49 | 70 | 926 | 617 | 642 |
| Lead | 2 | 15 | µg/L | 3.25 | BRL | BRL | 11.5 | BRL | BRL |
| Magnesium | 0.1 | N/A | mg/L | 8.42 | 8 | 8.44 | 8.2 | 8 | 8.4 |
| Manganese | 20 | N/A | µg/L | 249 | BRL | BRL | 62 | 66 | 22 |
| Sodium | 1 | N/A | mg/L | 10.3 | 7.56 | 8.28 | 19.6 | 7.56 | 8.4 |
| AtrazIne | 0.3 | 3 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Aldrin | 30 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Alachlor | 0.2 | 2 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Benzo(a)pyrene | 0.1 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Butachlor | 10 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Di(2-ethylhexyl)adipate | 0.6 | 400 | µg/L | BRL | 1.27 | BRL | BRL | 0.72 | 0.73 |
| Di(2-ethylhexyl)phthalate | 0.6 | 6 | µg/L | 2.8 | 3.03 | 1.39 | BRL | 2.17 | 1.19 |
| Dieldrin | 20 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Metribuzin | 1 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Methoxychlor | 0.1 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Metolachlor | 5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Hexachlorobenzene | 0.1 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Propachlor | 10 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Simazine | 0.35 | 4 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,1,1,2-Tetrachchloroethane | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,1,1-Trichlorethane | 0.5 | 200 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,1,2,2-Tetrachloroethane | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,1,2-Trichloroethane | 0.5 | 5 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,1-Dichloroethane | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,1-Dichloroethene | 0.5 | 7 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,1-Dichoropropene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,2,3-Trichlorobenzene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,2,3-Trichloropropane | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,2,4-Trichlorobenzene | 0.5 | 70 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,2,3-Trimethylbenzene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,2-Dichlorobenzene | 0.5 | 600 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,2-Dichloroethane | 0.5 | 5 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,2-Dichloropropane | 0.5 | 5 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,3,5-Trimethylbenzene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,3-Dichlorobenzene | 0.5 | 600 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,3-Dichloropropane | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 1,4-Dichlorobenzene | 0.5 | 600 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 2,2-Dichloropropane | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |

**Table 3-5. Water Sampling Results (Continued)**

| Analyte | RL | MCL | Unit | CLE-01 | | | CLE-02 | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 8/12 | 10/21 | 10/27 | 8/12 | 10/21 | 10/27 |
| 2-Chlorotoluene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 4-Chlorotoluene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| 4-Isopropyltoluene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Benzene | 0.5 | 5 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Bromobenzene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Bromochloromethane | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Bromodichloromethane | 0.5 | 80 | µg/L | 8.72 | 5.61 | 7.87 | 8.43 | 5.5 | 6.65 |
| Bromoform | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Bromomethane | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Carbon Tetrachloride | 0.5 | 5 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Chlorobenzene | 0.5 | 100 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Chloroethane | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Chloroform | 0.5 | 70 | µg/L | 15 | 7.39 | 9.92 | 14.4 | 7.47 | 9.39 |
| Chloromethane | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Cis-1,2-Dichloroethane | 0.5 | 70 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Cis-1,3-Dichloropropene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Dibromochloromethane | 0.5 | 60 | µg/L | 3.99 | 2.5 | 2.92 | 3.54 | 2.37 | 2.67 |
| Dibromomethane | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Dichlorodifluoromethane | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Epichlorohydrin | 40 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Ethyl Benzene | 0.5 | 700 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Hexachlorobutadiene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Isopropylbenzene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Methylene Chloride | 0.5 | 20 | µg/L | BRL | BRL | BRL | BRL | 1.06 | BRL |
| Napthalene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| n-Butyl Benzene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| n-Propyl Benzene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| sec-Butylbenzene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Styrene | 0.5 | 100 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| tert-Butylbenzene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Tetrachloroethene | 0.5 | 5 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Toluene | 0.5 | 1,000 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Trans-1,2-Dichloroethene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Trans-1,3-Dichlorpropene | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Trichloroethene | 0.5 | 5 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Trichlorofluoromethane | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Trichlororfluormethane | 0.5 | N/A | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Vinyl Chloride | 0.5 | 2 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Xylenes (total) | 0.5 | 10,000 | µg/L | BRL | BRL | BRL | BRL | BRL | BRL |
| Bisphenol A | 5 | N/A | µg/L | 20.8 | BRL | BRL | 5.24 | BRL | BRL |

RL = reporting limit BRL = below reporting limit MCL = maximum contaminant limit
J = estimated value

The two hydrants were relatively similar in water quality. The water was moderately hard with its alkalinity ranging from 82.2 mg/L to 104 mg/L in both hydrants. The pH of the water in both hydrants was within or slightly below the acceptable neutral range for drinking water of 6.5 to 8.5. The lining operations did not appear to significantly affect the alkalinity or pH of the water based on post-disinfection samples. Both total and free chlorine was above the recommended 0.5 mg/L for drinking water in both hydrants with little difference in total and free chlorine with each sampling event.

Turbidity typically should be less than 1 nephelometric turbidity units (NTU) in drinking water. The turbidity of both hydrants were greater than 5 NTU at 19 and 8.2 NTU, respectively, during baseline, but the turbidity in both hydrants decreased to below 1 NTU immediately after the post-lining disinfection event. One week after disinfection, the turbidity of the hydrant CLE-02 returned to a similar concentration seen during baseline. The total suspended solid (TSS) decreased significantly in the post-lining samples and remained below reporting limit (BRL) one week after disinfection. Total iron and manganese concentrations were also generally lower in the post-lining samples, potentially due to the cleaning and removal of tuberculation and subsequent lining of the cast iron pipe. Total dissolved solids (TDS) and total organic carbon (TOC) both decreased right after disinfection, then rebounded a week after disinfection. The concentrations of fluoride, chloride, nitrate, sulfate, orthophosphate, and silica did not show any significant changes from the baseline sampling event.

Although several contaminants of concern (COCs) were detected in the water from both hydrants, none were detected above their maximum contaminant levels (MCLs). Arsenic (MCL 10 µg/L) and lead (secondary standard 15 µg/L) were both detected during the baseline sampling, but were not detected after the post-lining disinfection event. Di(2-ethylhexyl)adipate (although not detected during baseline) was detected after disinfection at concentrations far below its MCL. The other COCs bromodichloromethane, chloroform, and dibromochloromethane were detected at levels comparable to the baseline samples and are byproducts of the disinfection of the drinking water at the treatment plant. The appearance of BPA during baseline sampling is not typical; however, after disinfection the BPA was below reporting limit, which is required by the NSF and BNQ certifications.

3.1.4 Hydraulic Testing. Hydraulic tests (i.e., flow and leak detection survey, pressure, and friction coefficient) were planned to be conducted prior to rehabilitation and once the liner installation was completed to evaluate the effectiveness of the rehabilitation technology. The pre- and post-rehabilitation tests included a leak detection survey, flow test, and friction coefficient test, which are described in the following subsections.

Pressure testing was scheduled to be conducted prior to the rehabilitation and after lining to evaluate the effectiveness of the rehabilitation to reduce pressure loss and associated water loss within the test pipe. However, CWD did not want to subject the water main and service connections to unnecessary stress during the test and therefore opted not to conduct the tests. Pressure tests were performed on individual lining runs prior to reinstatement of the services, as discussed in Section 3.2.3.

***3.1.4.1 Leak Detection Survey.*** An acoustic leak detection survey was conducted to determine the presence or absence of leaks along the test pipe. This test provides an advanced indication of any leaks related to structural issues in the test pipe. The results of the survey indicated that no leaks were detected.

***3.1.4.2 Friction Factor Test.*** The Hazen-Williams C-factor is the primary criteria used for determining if a liner reduces friction losses and restores hydraulic capacity to rehabilitated pipes. Utilities typically assume a C-factor of approximately 50 for unlined cast iron pipes in their original condition prior to lining. The Aqua-Pipe® lining was anticipated to result in a higher C-factor of as much as 120, which Sanexen claims can be achieved following the installation of an Aqua-Pipe® liner. The ability of the liner to improve the hydraulic characteristics of the test pipe was evaluated as part of the field demonstration. The Hazen-Williams friction coefficient is calculated using the formula below:

where

$C$ = Hazen-Williams Coefficient of Roughness (C-factor)

$C_f$ = Unit Conversion Factor (4.52)

$Q$ = Flow through Test Section, gpm
$P$ = Friction Loss, psi per foot of pipe (psi/ft)
$D$ = Internal Diameter of Test Section (in.)

The field test was conducted by isolating the 2,040 ft long test pipe segment between West 190th Street and Rocky River Drive underneath Ferncliffe Street. Three hydrants, two pressure hydrants (first and fifth hydrants west of Rocky River Drive) and one flow hydrant (the sixth hydrant west of Rocky River Drive) were utilized during the test. Figure 3-6 shows Hydrant #1 with pressure gauge installed and the flow hydrant used to induce flow and measure flow rate via a pitot tube.

**Figure 3-6. Hydrant #1 (left) and Flow Hydrant (right)**

Pressure gauges were installed at the two pressure hydrants (upstream and downstream) to measure headloss across the pipe length, which was 1,195 ft between hydrants, and the third downstream hydrant was used to induce flow and measure flow rate via a pitot tube. This frictional headloss and the flow rates were input into Equation 6 to calculate the C-factor as shown in Table 3-6.

**Table 3-6. Pre-Rehabilitation C-Factor Results**

| Parameter | Hazen-Williams Flow Test | |
|---|---|---|
| | 1 | 2 |
| Length of Test Section, ft | 1,195 | |
| Diameter of Test Section (D), in. | 6 | |
| Total Head Loss, ft | 31.67 | 15.00 |
| Total Head Loss, psi | 13.71 | 6.50 |
| Friction Loss (P), psi/ft | 0.011475 | 0.005435 |
| Flow (Q), gpm | 340.28 | 236.11 |
| C-factor | 76.98 | 79.99 |
| **Average C-factor** | **78.49** | |

The average C-factor of the tuberculated test pipe shown in Figure 3-7 prior to rehabilitation was 78.49. A post-rehabilitation Hazen-Williams flow test to check the improvement was conducted on August 3, 2011 and the results are discussed in Section 3.6.

3.1.5 Cleaning and Drying of Pipe**.** For proper installation of the CIPP liner, effective cleaning had to be performed for the sections that were to be lined. Before each section could be cleaned, water flow had to be stopped to isolate the test pipe and then the entire test section was flushed of all water,

which took place on Tuesday, August 31. TC used a three-step method to clean the main that included: hydraulic jet cleaning, scraping, and swabbing once access was gained to the test pipe by cutting out sections in each access pit.

**Figure 3-7. Inside of the Tuberculated Test Pipe**

The initial phase for cleaning each pipe section was hydraulic jet cleaning. The hydraulic jetting truck was equipped with a high-pressure water pump and a hose that had a special nozzle, shown in Figure 3-8. The hose was fed through the pipe section and emitted a jet of water at 2,000 psi to remove debris and deposits from the interior of the pipe.

**Figure 3-8. Hydraulic Jetting Truck (left) and Jetting Hose (Right)**

Any deposits remaining in the pipe were broken up to allow for easy removal during phase two, drag scraping. The hose was fed each way through the pipe section two times for a total of four passes. The wastewater generated from hydraulic jetting was pumped into the back of a filtration truck (Figure 3-9) that contained a sediment filter and then allowed to overflow onto the street. Approximately 1 gal of wastewater was generated during each pass per foot of water main for a total estimated wastewater volume of 7,984 gal.

**Figure 3-9. Truck Utilized for Wastewater Filtration**

Once hydraulic jet cleaning was completed on each pipe section, drag scraping was conducted to remove the remaining loose material in the pipe. Drag cleaning involves using a winch truck (Figure 3-10) to pull a mechanical cleaner, composed of steel scraper blades and rubber squeegees through the pipe.

**Figure 3-10. Cleaning Winch Truck**

The blades of the steel scraper (Figure 3-11) are flexible and allow it to negotiate slight bends in the pipe. Both ends of the cleaner were attached to winch trucks located at both ends of the section being cleaned. The mechanical cleaner was first dragged in one direction and then the other. While the mechanical cleaner was dragged through the pipe, water was pumped at a rate of 300 gpm in one direction to flush any remaining solids from the pipe. This process was repeated two times for each pipe section and each scraping pass took approximately 45 minutes. As during hydraulic jetting, the water generated from the process was pumped out of the excavation pit, through a sediment filter, and allowed to overflow on to the ground. After drag scraping the pipe, the blades were taken off of the winch and the squeegees (Figure 3-11) were dragged through the pipe in each direction. Based on the flowrate and time, the estimated volume of wastewater generated during drag-scraping was 252,000 gal.

**Figure 3-11. Steel Scrapers (left) and Rubber Squeegees (right)**

The final phase of cleaning and drying took place immediately prior to lining activities. Sanexen dried each pipe section by swabbing the pipe with a foam pig and then circulating hot air for 30 minutes. The foam pigs, made of open-cell polyurethane foam, were dragged through the pipe using a winch and then an Allegro Com-Pax-Ial blower circulated hot air through each pipe section to evaporate any moisture remaining in the pipe (Figure 3-12).

**Figure 3-12. Foam Pig (left) and Blower (right)**

3.1.6 Defect Installation**.** Prior to performing the pre-lining CCTV inspection, two defect sections were installed in the middle of lining run #4. The field-prepared defect section utilized a piece of the cast iron host pipe and the lab-prepared defect section consisted of 6 in. cast iron pipe section. In the rehabilitation of a cast iron water main, a number of through holes, voids, or gaps in joints may be expected to potentially be present in a pipe as well as longitudinal and circumferential cracks, which are a common failure mechanism in cast iron pipes.

***3.1.6.1 Lab-Prepared Defect Pipe Segment.*** In order to obtain lined pipe samples, a 6 ft pre-fabricated defect pipe segment was machined prior to the field demonstration and shipped to the site for installation into the test pipe prior to lining. The pre-fabricated defect section was machined by Battelle's

machine shop using a 70-year old 6 in. cast iron pipe, which is similar to the general specifications of the test pipe. The segment, which was installed on Tuesday, September 7, included two-ring break defects and an incompetent bell joint, as discussed below:

- **Simulated Joint Defect.** The pipe was cut and reassembled so that a joint occurred within the re-laid section of pipe. The joint was set to have a gap of 6 mm (0.25 in) between the bell and spigot, so as to resemble a leaking joint/failed packing material. The joint was fixed externally to maintain the gap during transport and installation at the field demonstration site.
- **Ring Break**. Two circumferential fractures ("ring breaks") were introduced by cutting the test pipe into two segments, and introducing a 6 mm (0.25 in) gap between the sections before reattaching the two segments using an external clamp mechanism.

The pre-fabricated defect pipe segment was installed in an excavated pit east of Pit #5 on Ferncliffe Avenue that was required to cut out a valve in the water main. The test pipe was carefully lowered into the pit using lifting straps and a backhoe. The test pipe was attached to the existing pipe using 6 in. couplings. Figure 3-13 shows the pre-fabricated defect pipe segment prior to and during installation activities.

**Figure 3-13. Installation of Pre-Fabricated Defect Pipe Segment**

***3.1.6.2 Field-Prepared Defect Pipe Segment.*** In addition to the pre-fabricated defect section discussed above, field-prepared defects were machined into a 6 ft section of the test pipe in Pit #5 prior to lining on Tuesday, September 7. The pipe segment consisted of the original 6 in. cast iron pipe, which was inspected to determine whether any structural defects were present. The simulated defects that were field-prepared in the segment (Figure 3-14) are summarized below:

- **Large Corrosion Holes**. Larger corrosion areas that might develop after the lining is installed will be modeled by cutting two circular holes, one 12 mm and the other with an 18 mm in diameter. These manufactured larger corrosion holes were plugged to provide a smooth interior surface for relining and then the plugs were removed in the laboratory for internal pressure testing after lining. The test pressure used is suggested to be twice the mean operating pressure and higher to test the liner to failure. Testing to liner failure is best suited within a laboratory setting and will help to determine the maximum size of opening that can be addressed by the liner.
- **Longitudinal and Circumferential Cracks**. Longitudinal and circumferential cracks were modeled by sawing out a rectangular defect in the pipe wall. The simulated cracks were 6 mm wide by both 25 mm and 100 mm long, respectively. The coverage of each type of crack was

examined in the exhumed section at the end of the testing period. The pressure testing will demonstrate the product's ability to span the cracks in each direction.

- **Large Pipe Fracture**. Large pipe fractures were simulated by installing two fractures, one of which is 1 in. wide by 3 in. long, and another 1 in. long by 3 in. wide. These fractures are intended to simulate more extreme failure scenarios that a CIPP liner could potentially address in a pressurized water main.
- **Service Tap Installation**. After the pipe was shipped back to the laboratory, a tap was installed into the test section of the rehabilitated line using the manufacturer's recommended procedures. The service tap was pressure tested to evaluate the performance of the liner in situations where additional service taps are installed into a rehabilitated water main.

**Figure 3-14. Field-Prepared Defect Section**

3.1.7 Service Plugging and Pipe Inspection**.** CCTV, which is a commonly used method for inspecting the interior of empty pipes, was used to conduct both pre- and post-lining inspections. Records were maintained to document adverse pipe conditions or other defects that could limit the performance or affect the application of the CIPP liner. The pre-lining CCTV inspection provides a visual evaluation of the interior pipe surface prior to installation of the CIPP liner and allows for the insertion of plugs into each service connection to prevent the migration of resin into the service during liner curing.

Prior to conducting the CCTV, Sanexen used a digital roto-wheel and the curb-stops on the street to map the approximate location of each service connection in each lining segment. This was conducted to make sure all service connections were accounted for during the capping process. Once a lining section was mapped out above ground, the service connections inside the main were located, inspected, and then capped with an HDPE plug using a remote-controlled robot equipped with an air-actuated piston and cartridge of HDPE plugs. The robot is water tolerant and small enough to fit in the 6 in. diameter pipe and still allow for the freedom of movement necessary to reach and plug the service connections.

Once each service connection in a lining run was capped, a final pre-lining CCTV inspection was conducted using a CCTV camera and specialized equipment with video viewing and recording capabilities which was operated by the CCTV truck (Figure 3-15). The location of each service

connection as well as any pipe conditions that could limit the effectiveness of the liner were documented on the video as well as on CCTV log sheets. It was important to accurately record the locations of each service connection to allow for reinstatement after lining. Hard copies of the CCTV log sheets of the pre-lining CCTV inspections are included in Appendix A.

**Figure 3-15. CCTV Truck (left) and Robot (right)**

***3.1.7.1 Pre-Lining CCTV of Lining Run #1.*** The pre-lining inspection is a key component of the installation process because it provides information relating to the degree of cleaning of the pipe prior to the start of a lining operation. Other conditions that were inspected for included the presence of leaking valves and ferrules, leaking stop taps, dropped joints, protruding ferrules, structural failures (cracks, holes), re-cleaning requirements, debris, and standing water. Lining run #1 was the first section to be inspected and have the services plugged, which took place on Wednesday, September 8. The results of the final pre-lining inspection for lining run #1 from Pits #2 to #1, which took 12 minutes to complete, are presented in Table 3-7.

**Table 3-7. Pre-Lining CCTV Inspection of Lining Run #1**

| Item | Address | Location | Distance (m) | Comment |
|---|---|---|---|---|
| Pit #2 | N/A | N/A | 1.0 | Start, 09/08/2010 |
| Service | 18901 | at 11:30 | 4.2 | 5/8 in. Penetrating Service |
| Service | 18902 | at 01:00 | 6.0 | 5/8 in. Penetrating Service |
| Service | 18905 | at 11:00 | 16.5 | 5/8 in. Penetrating Service |
| Service | Vacant | at 01:30 | 18.9 | 5/8 in. Penetrating Service |
| Water | N/A | Bottom ¼ | 26.5 to 31.0 | Standing water ¼ of the pipe deep |
| Service | 18910 | at 01:30 | 33.3 | 5/8 in. Penetrating Service |
| Service | 18909 | at 10:30 | 33.8 | 5/8 in. Penetrating Service |
| Repair | N/A | at 02:00 | 34.4 | Repair, Hole Roughly 3 in. Diameter |
| Service | 18913 | at 11:00 | 43.8 | 5/8 in. Small Penetrating Service |
| Service | 18914 | at 01:30 | 47.1 | 5/8 in. Penetrating Service |
| Service | 18923 | at 12:00 | 57.2 | 1 in. Non-Penetrating Service (Crack) |
| Service | 18924 | at 02:00 | 58.4 | 5/8 in. Penetrating Service |
| Water | N/A | Bottom ½ | 61.0 to 70.0 | Standing water ½ of the pipe deep |
| Joint | N/A | 360° | 70.0, 70.6, 71.6 | Offset Joints |
| Pit #1 | N/A | N/A | 74.7 | End (12 minutes) |

The 74.7 m lining run had 10 services along its length, eight of which were typical 5/8 in. penetrating services. One other 5/8 in. service was only slightly penetrating at 43.8 m from Pit #2 and the difference in penetration is shown in Figure 3-16.

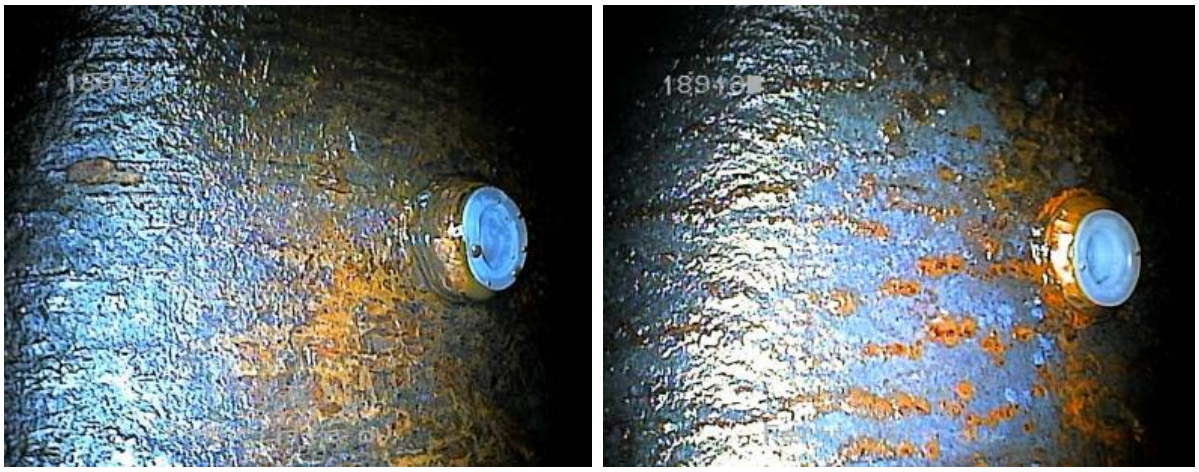

**Figure 3-16. Typical 5/8 in. Penetrating Service (left) and a Slightly Penetrating Service (right)**

The remaining service was a 1 in. non-penetrating (flush) service at 57.2 m from Pit #2. The 1 in. service connection was flush with the internal pipe wall and had a crack which circled the pipe at that location as shown in Figure 3-17.

**Figure 3-17. Crack Circling the Pipe around 1 in. Flush Service Connection**

Other items of note included two locations of standing water that had to be removed before lining could commence. Also, immediately following the second location of standing water near the end of the inspection, three joints had shifted approximately ½ in. on short replacement sections, shown in Figure 3-18. Also of note is that the pipe sections on lining run #1 were typically 5.4 m (17.7 ft) long, whereas the pipe sections were typically 3.6 m (11.8 ft) for all remaining six lining runs.

**Figure 3-18. Offset Joint at 71.6 m from Pit #2**

***3.1.7.2 Pre-Lining CCTV of Lining Run #2.*** The final pre-lining inspection for lining run #2 took place on Thursday, September 9. The results of the final pre-lining inspection from Pits #2 to #3, which took 12 minutes to complete, are presented in Table 3-8.

**Table 3-8. Pre-Lining CCTV Inspection of Lining Run #2**

| Item | Address | Location | Distance (m) | Comment |
|---|---|---|---|---|
| Pit #2 | N/A | N/A | 1.0 | Start, 09/09/2010 |
| Service | 18824 | at 11:00 | 10.9 | 5/8 in. Penetrating Service |
| Service | 18823 | at 12:30 | 11.7 | 1 in. Non-Penetrating Service (Crack) |
| Service | 18813 | at 01:00 | 29.0 | 1 in. Non-Penetrating Service |
| Service | 18814 | at 11:00 | 29.2 | 1 in. Non-Penetrating Service (Crack) |
| Service | 18807 | at 01:00 | 41.0 | 1 in. Non-Penetrating Service |
| Service | 18808 | at 11:00 | 47.7 | 5/8 in. Penetrating Service |
| Corrosion | N/A | at 05:00 | 57.8 | Deep Corrosion |
| Corrosion | N/A | at 09:00 | 60.9 | Deep Corrosion |
| Service | 18802 | at 11:00 | 61.4 | 5/8 in. Small Penetrating Service |
| Service | 18801 | at 01:00 | 61.6 | 5/8 in. Small Penetrating Service |
| Service | 18713 | at 01:00 | 79.0 | 5/8 in. Small Penetrating Service |
| Service | 18714 | at 12:00 | 80.3 | 5/8 in. Penetrating Service |
| Pit #3 | N/A | N/A | 89.0 | End (12 minutes) |

The 89 m lining run had 10 services along its length, three of which were typical 5/8 in. penetrating services. Three other 5/8 in. services were slightly penetrating and the remaining four services were 1 in. non-penetrating services, two of which had cracks circling the pipe at their location. Two other items of note were areas of deep corrosion at 57.8 m and 60.9 m (Figure 3-19) from Pit #2.

**Figure 3-19. Deep Corrosion at 60.9 m from Pit #2**

***3.1.7.3 Pre-Lining CCTV of Lining Run #3.*** The final pre-lining inspection for lining run #3 took place on Wednesday, September 15. The results of the final pre-lining inspection from Pits #3 to #4, which took 11 minutes to complete, are presented in Table 3-9.

**Table 3-9. Pre-Lining CCTV Inspection of Lining Run #3**

| Item | Address | Location | Distance (m) | Comment |
|---|---|---|---|---|
| Pit #3 | N/A | N/A | 1.0 | Start, 09/15/2010 |
| Service | 18712 | at 11:00 | 2.1 | 5/8 in. Penetrating Service |
| Service | 18707 | at 01:00 | 4.8 | 5/8 in. Penetrating Service |
| Service | 18706 | at 11:00 | 14.8 | 5/8 in. Penetrating Service |
| Service | 18702 | at 11:00 | 25.3 | 5/8 in. Penetrating Service |
| Service | 18701 | at 01:00 | 26.8 | 5/8 in. Penetrating Service |
| Service | 18614 | at 11:30 | 41.2 | 5/8 in. Small Penetrating Service |
| Service | 18613 | at 12:30 | 41.9 | 5/8 in. Small Penetrating Service |
| Service | 18612 | at 11:00 | 58.5 | 5/8 in. Penetrating Service |
| Service | 18607 | at 12:30 | 59.8 | 1 in. Non-Penetrating Service |
| Service | 18608 | at 11:00 | 65.8 | 5/8 in. Penetrating Service |
| Hole | N/A | at 11:00 | 77.7 | 1 in. Hole |
| Service | 18601 | at 01:00 | 77.9 | 5/8 in. Penetrating Service |
| Service | 18602 | at 11:00 | 78.0 | 5/8 in. Penetrating Service |
| Pit #4 | N/A | N/A | 87.8 | End (11 minutes) |

The 87.8 m lining run had 12 services along its length, nine of which were typical 5/8 in. penetrating services. Two other 5/8 in. services were slightly penetrating and one service was a 1 in. non-penetrating services. One other item detected in the inspection was a 1 in. hole located at 77.7 m from Pit #3 (Figure 3-20), which may have been an abandoned service.

**Figure 3-20. 1 in. Hole at 77.7 m from Pit #3**

***3.1.7.4 Pre-Lining CCTV of Lining Run #4.*** The final pre-lining inspection for lining run #4 took place on Friday, September 10. The results of the final pre-lining inspection from Pits #4 to #6, which took 12 minutes to complete and includes both defect sections, are presented in Table 3-10.

**Table 3-10. Pre-Lining CCTV Inspection of Lining Run #4**

| Item | Address | Location | Distance (m) | Comment |
|---|---|---|---|---|
| Pit #4 | N/A | N/A | 1.0 | Start, 09/10/2010 |
| Service | 18514 | at 11:00 | 5.6 | 5/8 in. Penetrating Service |
| Service | 18513 | at 01:30 | 6.0 | 5/8 in. Small Penetrating Service |
| Service | 18507 | at 02:00 | 22.2 | 5/8 in. Small Penetrating Service |
| Service | 18508 | at 11:30 | 23.3 | 5/8 in. Penetrating Service |
| Service | 18502 | at 11:30 | 38.6 | 5/8 in. Small Penetrating Service |
| Service | 18502 | at 02:00 | 40.3 | 5/8 in. Small Penetrating Service |
| Defect | N/A | N/A | 47.0 to 48.8 | Field-Defect Section |
| Defect | N/A | N/A | 52.2 to 54.0 | Lab-Defect Section |
| Service | 18418 | at 12:00 | 66.3 | 5/8 in. Penetrating Service |
| Service | 18419 | at 02:00 | 70.4 | 3/4 in. Small Penetrating Service |
| Service | 18412 | at 11:00 | 85.9 | 5/8 in. Small Penetrating Service (not on video) |
| Service | 18413 | at 02:00 | 87.4 | 3/4 in. Small Penetrating Service (not on video) |
| Pit #6 | N/A | N/A | 87.5 | End (12 minutes, Not on Video) |

The 89.2 m lining run had 10 services along its length, three of which were typical 5/8 in. penetrating services. Five other 5/8 in. services were slightly penetrating and two services were ¾ in. slightly penetrating services. Other items of note included the field-defect section located approximately 47.0 to 48.8 m from Pit #4 (Figure 3-21) and the lab-defect section located approximately 52.2 to 54.0 m from Pit #4, respectively. It should also be noted that the final two services at locations 86.0 and 87.0 m from Pit #4 are not included on the final pre-lining inspection due to video difficulties near the end of the lining run, although both services had already been inspected and plugged.

**Figure 3-21. 1 in. Hole at 77.7 m from Pit #3**

***3.1.7.5 Pre-Lining CCTV of Lining Run #5.*** The final pre-lining inspection for lining run #5 took place on Thursday, September 16. The results of the final pre-lining inspection from Pits #6 to #7, which took 10 minutes to complete, are presented in Table 3-11.

**Table 3-11. Pre-Lining CCTV Inspection of Lining Run #5**

| Item | Address | Location | Distance (m) | Comment |
|---|---|---|---|---|
| Pit #6 | N/A | N/A | 1.0 | Start, 09/16/2010 |
| Service | 18407 | at 02:00 | 16.2 | 3/4 in. Small Penetrating Service |
| Service | 18406 | at 11:00 | 19.2 | 5/8 in. Small Penetrating Service |
| Service | 18401 | at 01:00 | 25.7 | 5/8 in. Small Penetrating Service |
| Service | 18400 | at 11:00 | 26.4 | 5/8 in. Small Penetrating Service |
| Hole | N/A | at 12:00 | 48.0 | 1 in. Hole |
| Service | 18350 | at 12:00 | 49.4 | 5/8 in. Small Penetrating Service |
| Service | 18349 | at 01:00 | 50.0 | 3/4 in. Small Penetrating Service |
| Service | 18344 | at 12:00 | 68.3 | 5/8 in. Small Penetrating Service |
| Service | 18343 | at 01:00 | 70.0 | 3/4 in. Small Penetrating Service |
| Protrusion | N/A | at 10:30 | 81.2 | Small Protrusion of Metal |
| Service | 18337 | at 01:00 | 82.0 | 1 in. Non-Penetrating Service |
| Pit #7 | N/A | N/A | 86.8 | End (10 minutes) |

The 86.8 m lining run had nine services along its length, five of which were 5/8 in. slightly penetrating services. Three other ¾ in. services were slightly penetrating and one 1 in. non-penetrating services was located at 82.0 m from Pit #6. Other items detected in the inspection included a 1 in. hole located 48 m from Pit #6 and a small protrusion of metal located at 81.2 m from Pit #6, shown in Figure 3-22.

**Figure 3-22. Small Protrusion of Metal at 81.3 m from Pit #6**

***3.1.7.6 Pre-Lining CCTV of Lining Run #6.*** The final pre-lining inspection for lining run #6 took place on Thursday, September 16. The results of the final pre-lining inspection from Pits #8 to #7, which took 10 minutes to complete, are presented in Table 3-12.

**Table 3-12. Pre-Lining CCTV Inspection of Lining Run #6**

| Item | Address | Location | Distance (m) | Comment |
|---|---|---|---|---|
| Pit #8 | N/A | N/A | 1.0 | Start, 09/16/2010 |
| Service | 18307 | at 11:00 | 4.8 | 5/8 in. Penetrating Service |
| Service | 18308 | at 01:00 | 5.8 | 5/8 in. Small Penetrating Service |
| Service | 18314 | at 12:30 | 21.6 | 5/8 in. Penetrating Service |
| Service | 18313 | at 12:00 | 23.8 | 5/8 in. Small Penetrating Service |
| Service | 18319 | at 11:30 | 30.8 | 5/8 in. Non-Penetrating Service |
| Service | 18320 | at 12:30 | 41.0 | 5/8 in. Penetrating Service |
| Service | 18325 | at 12:00 | 56.7 | 3/4 in. Penetrating Service |
| Service | 18326 | at 12:30 | 60.4 | 5/8 in. Penetrating Service |
| Service | 18332 | at 12:30 | 76.2 | 5/8 in. Penetrating Service |
| Service | 18331 | at 11:00 | 76.4 | 3/4 in. Penetrating Service |
| Pit #7 | N/A | N/A | 88.4 | End (10 minutes) |

The 88.4 m lining run had 10 services along its length, five of which were typical 5/8 in. penetrating services. Two other 5/8 in. services were slightly penetrating and one 5/8 in. service was non-penetrating (flush). The remaining two services were ¾ in. penetrating services.

***3.1.7.7 Pre-Lining CCTV of Lining Run #7.*** The final pre-lining inspection for lining run #7 took place on Thursday, September 16. The results of the final pre-lining inspection from Pits #8 to #9, which took 7 minutes to complete, are presented in Table 3-13.

**Table 3-13. Pre-Lining CCTV Inspection of Lining Run #7**

| Item | Address | Location | Distance (m) | Comment |
|---|---|---|---|---|
| Pit #8 | N/A | N/A | 1.0 | Start, 09/16/2010 |
| Service | 18301 | at 01:00 | 6.7 | 5/8 in. Penetrating Service |
| Service | 18211 | at 02:00 | 48.6 | 5/8 in. Small Penetrating Service |
| Hole | N/A | at 04:00 | 58.6 | 1 in. Hole |
| Hole | N/A | at 04:00 | 58.7 | 1 in. Hole |
| Pit #9 | N/A | N/A | 76.1 | End (7 minutes) |

The 76.1 m lining run had two services along its length, one 5/8 in. penetrating service and one 5/8 in. slightly penetrating service. The run also had two 1 in. holes located at 58.6 m and 58.7 m from Pit #8, respectively.

3.1.8 Pipe Wall Thickness and Inner Diameter. Prior to the demonstration study, the wall thickness and inner diameter of the test pipe were not exactly known, although the inner diameter of the test pipe was assumed to be 6 in. Therefore, the actual dimensions were recorded as part of the field demonstration protocol. A digital caliper was used to measure the wall thickness of the test pipe at 3, 6, 9, and 12 o'clock positions as well as the inside diameter at each pipe opening that was exposed within each excavation pit. Table 3-14 presents the wall thickness and inside diameter measurements recorded from each excavation pit.

**Table 3-14. Wall Thickness and Inside Diameter Measurements**

| Test Pit | Pipe End | Lining Run | ID, mm | Wall Thickness, mm | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 12:00 | 3:00 | 6:00 | 9:00 | Avg. |
| 1 | East | 1 | 150.5 | 11.45 | 10.40 | 15.60 | 11.43 | 12.22 |
| 2 | East | 1 | 150.5 | 11.45 | 12.48 | 14.58 | 11.46 | 12.49 |
| | West | 2 | 150.8 | 11.43 | 11.43 | 11.46 | 11.44 | 11.44 |
| 3 | East | 2 | 150.8 | 14.80 | 12.99 | 10.68 | 12.79 | 12.82 |
| | West | 3 | 150.7 | 14.24 | 12.66 | 13.12 | 10.39 | 12.60 |
| 4 | East | 3 | 150.8 | 11.11 | 15.06 | 16.21 | 13.22 | 13.90 |
| | West | 4 | 150.8 | 12.72 | 12.61 | 13.01 | 13.29 | 12.91 |
| 6 | East | 4 | 154.0 | 13.74 | 13.09 | 10.90 | 13.13 | 12.72 |
| | West | 5 | 154.0 | 14.04 | 12.03 | 14.16 | 14.17 | 13.60 |
| 7 | East | 5 | 149.7 | 15.51 | 11.06 | 13.22 | 15.35 | 13.79 |
| | West | 6 | 153.8 | 12.85 | 12.00 | 12.65 | 11.62 | 12.28 |
| 8 | East | 6 | 153.6 | 12.55 | 14.26 | 12.82 | 11.58 | 12.80 |
| | West | 7 | 153.9 | 13.01 | 14.18 | 12.25 | 11.89 | 12.83 |
| 9 | West | 7 | 153.4 | 12.88 | 14.38 | 12.62 | 11.83 | 12.93 |
| | **Average** | **Test Pipe** | **152.0** | **12.98** | **12.76** | **13.09** | **12.40** | **12.81** |

The average thickness of the test pipe wall was 12.81 mm (0.5 in.), with a standard deviation of 1.4 mm (0.05 in.). The average inner diameter of the test pipe was 152 mm (5.98 in.), with a standard deviation of 1.68 mm (0.07 in.).

## 3.2 Technology Application

The CIPP lining of the test section took place between September 10 and 18, 2010. The Aqua-Pipe® lining process involves three main activities: liner impregnation with epoxy resin; insertion in the host pipe; and curing.

**3.2.1 Technology Application Equipment and Process**. The installation process requires the use of several pieces of equipment including the wetout rig, pig launcher and catcher, and boiler truck. The wetout rig is a specialized refrigerated truck, which contains equipment for impregnating the liner with resin and pulling the liner through rollers to distribute the resin throughout the tube. The low temperature of the truck delays the reaction of the two parts that make up the resin.

The liner is made of a two-ply woven seamless polyester jacket, which allows the resin to penetrate the material and harden in place. The combined effect of the polyester material with a hardened resin results in a composite liner. The resin is shot into the liner with a specialized gun that has a pointed tip, which can be inserted between the two jackets. The liner is impregnated as it is being pulled into the main with a winch truck through dual rollers, which distribute the resin, shown in Figure 3-23.

**Figure 3-23. Impregnated Liner Being Pulled Through Dual Rollers (left) and Winch Truck (right)**

The liner is pulled over a set of rollers prior to entering the main to keep the liner flat, shown in Figure 3-24. One roller is attached to the back of the refrigerated truck and the second is attached to the water main.

**Figure 3-24. Roller Attached to the Truck (left) and Roller Attached to the Main (right)**

Once the liner has been completely pulled into place, the pig launcher and pig catcher are attached to both ends of the liner. Before these two apparatuses are attached to the liner, the ends of the main are buffed and additional resin is hand applied to the ends as a precaution to ensure a good seal, shown in Figure 3-25.

**Figure 3-25. Buffer Used to Clean Ends (left) and Addition of Resin at the Ends (right)**

The pig launcher and catcher, which are used to expand the liner to the host pipe wall, are attached to the liner with metal straps (Figure 3-26). The launcher is then hooked up to the bypass system via a hose attached to the boiler truck, shown in Figure 3-26. The boiler truck supplies pressurized water to the pig launcher, which then sends the pig from the launcher to the catcher, which took about 5 minutes for each lining run.

**Figure 3-26. Launcher Attached to the Liner (left) and to Water via the Boiler Truck (right)**

The boiler truck contains large reservoirs of water, which are pumped into the boiler tank and used for liner curing, shown in Figure 3-27. The boiler truck is connected to both the pig launcher and catcher to allow for constant circulation of the water. The truck is used to first circulate cold water under pressure for 30 minutes and then hot water at 65°C is circulated for 90 minutes to cure the liner. The curing process heats the impregnated liner to initiate a reaction between the reactants of the polymer resin. The reaction causes the polymer resin to reticulate and harden to confer mechanical rigidity to the liner.

**Figure 3-27. Boiler Truck Reservoirs (left) and Boiler Tank (right)**

3.2.2 CIPP Liner Installation. The seven individual lining runs took place over the course of nine days from September 10 to 18. The resin and hardener lot numbers for each lining run were 100080052 and 10080053, respectively. Of all seven lining runs, lining run #3 took approximately 30 minutes longer to pull into place because issues with a winch truck limited the speed in which the liner was pulled. The typical pull-in duration was around 85 min at a rate of 3 to 4 ft/min and all liners were allowed to form for 20 to 25 min and cure with hot water for 90 min. The number of epoxy kits used ranged between eight and ten per lining run.

3.2.3 Post-Installation Pressure Test. Pressure testing on each lining segment was conducted after CIPP liner curing to evaluate the effectiveness of the rehabilitation. The rehabilitated pipes were pressurized to 125 psi and a pressure gauge was monitored throughout the one-hour pressure test to ensure make-up water did not exceed the amount permitted. The permitted amount of make-up water is equal to 1 liter/hour (L/hr) per 280 ft of length. The results were recorded on log sheets and are presented in Table 3-15.

**Table 3-15. Pressure Testing Results**

| Lining Run | Date | Length, ft | After Curing, days | Start Flow Meter, L/hr | End Flow Meter, L/hr | Make-up Water Permitted, L/hr | Make-up Water Obtained, L/hr |
|---|---|---|---|---|---|---|---|
| #1 | 09/14/10 | 249 | 4 | 33,425.5 | 33,425.5 | 0.89 | 0.0 |
| #2 | 09/15/10 | 313 | 2 | 33,448.8 | 33,449.0 | 1.12 | 0.2 |
| #3 & #4 | 09/18/10 | 590 | 2/4 | 33,565.9 | 33,565.9 | 2.11 | 0.0 |
| #5 & #6 | 09/21/10 | 590 | 4 | 33,614.3 | 33,614.3 | 2.11 | 0.9 |
| #7 | 09/22/10 | 252 | 4 | 33,658.4 | 33,658.4 | 0.90 | 0.2 |

3.2.4 Reinstatement of Service Connections. The reinstatement of the service connections included both internal and external reinstatement. Internal reinstatement is the preferred method and less disruptive than external reinstatement. After pre-lining CCTV and service plugging, it was reported that about four services would need to be reinstated externally, but some conditions created the need to externally reinstate an additional 13 service connections as discussed in the following subsections.

***3.2.4.1 Internal Reinstatement.*** Once the liner was installed, cured, and pressure tested, the service connections to the main were located and opened to provide service and allow water to flow back to the users. The same remote-control robot used to cap the services was used to reinstate the services. The robot was equipped with an air-actuated drill bit used to cut through the liner and permit free flow of water through the service connection. Figure 3-28 presents photographs taken from the video monitor as a service connection was being reinstated.

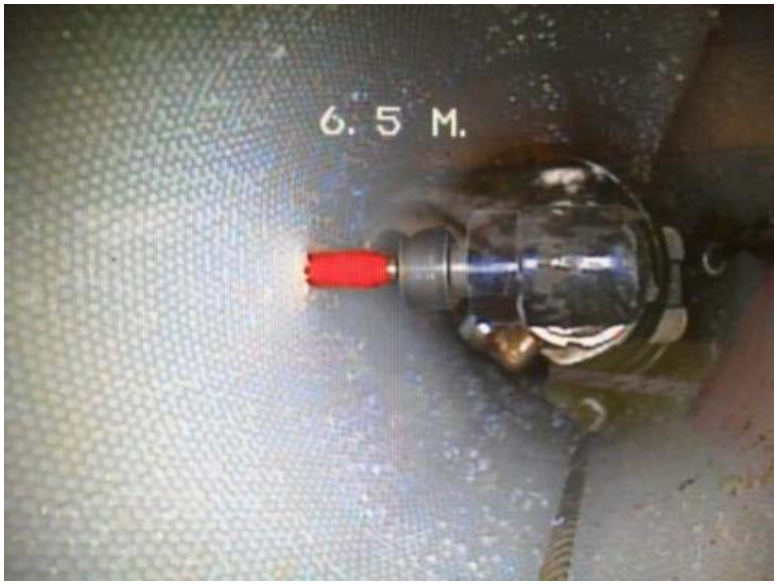


**Figure 3-28. Internal Reinstatement of a Service Connection**

During internal reinstatement of the service connections, a total of 17 of the 63 service connections (27%) were unable to be reinstated internally. The reasons that the service connections could not be reinstated internally included: (1) non-protruding (flush) service connections that could not be identified post-rehabilitation; (2) blocked service connections or service located in a fold (block/fold); (3) incomplete service capping due to corporation stops that were deformed during cleaning that allowed resin to get behind the plug and block the connection (deform); and (4) difficulty drilling due to misalignment of the existing saddle and corporation stop with service connection hole (misalign). Three of the 17 services (5% of the services) needing to be reinstated externally were due to reasons 1 and 2, which are issues commonly seen by the manufacturer. The remaining 14 external reinstatements (22% of the services) were due to reasons 3 and 4, which the manufacturer categorizes as extraordinary events, rarely encountered in water main rehabilitation projects.

***3.2.4.2 External Reinstatement.*** The misalignment of the existing saddle and service connection hole (reason #4) accounted for six external reinstatements and would be dated back to when the service connections were installed. The vendor reports that this is the first time that they have experienced this issue at a job site, but the prevalence of this type of defect in drinking water service line installations was not further investigated. The other eight external reinstatements were due to the corporation stops that were deformed due to the use of drag scrapers during the cleaning process (reason #3), which resulted in poor plug sealing, thereby allowing resin to migrate behind the plug and into the service connection. Although drag scraping is often used for cement mortar lining, it is not recommended when internal plugging and reinstatement of service connections are required.

A total of 13 additional excavation pits were required to gain access to the 17 service connections that required external reinstatement. The service connections were reinstated externally using a drill bit to drill through the service into the interior of the pipe. Table 3-16 summarizes the service connection reinstatements. The causes for external reinstatement are numbered based on the four reasons cited in Section 3.2.4.1. The method of reinstatement for each individual service is outlined in the post-installation CCTV inspection tables in the following section.

**Table 3-16. Summary of Service Reinstatement Methods**

| Lining Run | Date | Total Connections | Reinstatement Internal | Reinstatement External | Flush | Block/ Fold | Deform | Misalign |
|---|---|---|---|---|---|---|---|---|
| #1 | 09/20/10 | 10 | 6 | 4 | 0 | 1 | 3 | 0 |
| #2 | 09/20/10 | 10 | 5 | 5 | 0 | 0 | 1 | 4 |
| #3 | 09/21/10 | 12 | 11 | 1 | 0 | 0 | 0 | 1 |
| #4 | 09/21/10 | 10 | 6 | 4 | 0 | 1 | 3 | 0 |
| #5 | 09/21/10 | 9 | 6 | 3 | 1 | 0 | 1 | 1 |
| #6 | 09/22/10 | 10 | 10 | 0 | 0 | 0 | 0 | 0 |
| #7 | 09/22/10 | 2 | 2 | 0 | 0 | 0 | 0 | 0 |
| | **Total** | **63** | **46** | **17** | **1** | **2** | **8** | **6** |

## 3.3 Post-Demonstration Field Verification

Post-demonstration field verification testing conducted to evaluate the performance of the CIPP liner included post-lining inspection with a CCTV camera robot. Other tests included were measurements to verify the thickness of the liner and post-lining hydraulic testing.

3.3.1 Post-Lining CCTV. The post-lining CCTV inspection provided a visual assessment of the quality of the liner once the services had been reinstated internally. The results of the post-lining CCTV inspections are documented on DVDs and hard copies of the CCTV logs are included in Appendix A. A description of each post-lining inspection is described below.

***3.3.1.1 Post-Lining CCTV of Lining Run #1.*** The post-lining inspection of lining run #1 occurred on Monday, September 20 from Pits #2 to #1. The inspection took 11 minutes to complete and the results are summarized in Table 3-17.

**Table 3-17. Post-Lining CCTV Inspection of Lining Run #1**

| Item | Address | Location | Distance (m) | Comment | Services |
|---|---|---|---|---|---|
| Pit #2 | N/A | N/A | 1.0 | Start, 09/20/2010 | N/A |
| Service | 18901 | at 11:30 | 4.3 | 5/8 in. Penetrating Service (Deform) | ER |
| Service | 18902 | at 01:00 | 6.1 | 5/8 in. Penetrating Service | IR |
| Service | 18905 | at 11:00 | 16.6 | 5/8 in. Penetrating Service | IR |
| Service | Vacant | at 01:30 | 18.9 | 5/8 in. Penetrating Service | IR |
| Service | 18910 | at 01:30 | 33.2 | 5/8 in. Penetrating Service Flushed | IR |
| Service | 18909 | at 10:30 | 33.7 | 5/8 in. Penetrating Service | IR |
| Service | 18913 | at 11:00 | 43.7 | 5/8 in. Small Penetrating Service | IR |
| Service | 18914 | at 01:30 | 47.1 | 5/8 in. Penetrating Service (Deform) | ER |
| Service | 18923 | at 12:00 | 57.1 | 1 in. Non-Penetrating Service (Block) | ER |
| Service | 18924 | at 02:00 | 58.3 | 5/8 in. Penetrating Service (Deform) | ER |
| Joint | N/A | 360° | 69.5, 71.5 | Offset Joints | N/A |
| Pit #1 | N/A | N/A | 74.6 | End (11 minutes) | N/A |

As outlined in Table 3-16, six of the 10 services were reinstated completely internally (IR). The remaining four services (18901, 18914, 18923 and 18924) were located, but had to be reinstated externally since they were deformed during cleaning and blocked by the resin. These four services required external reinstatement (ER), which was accomplished with three excavation pits. Figure 3-29 shows a service that was reinstated internally and one of the four which were blocked, requiring external reinstatement.

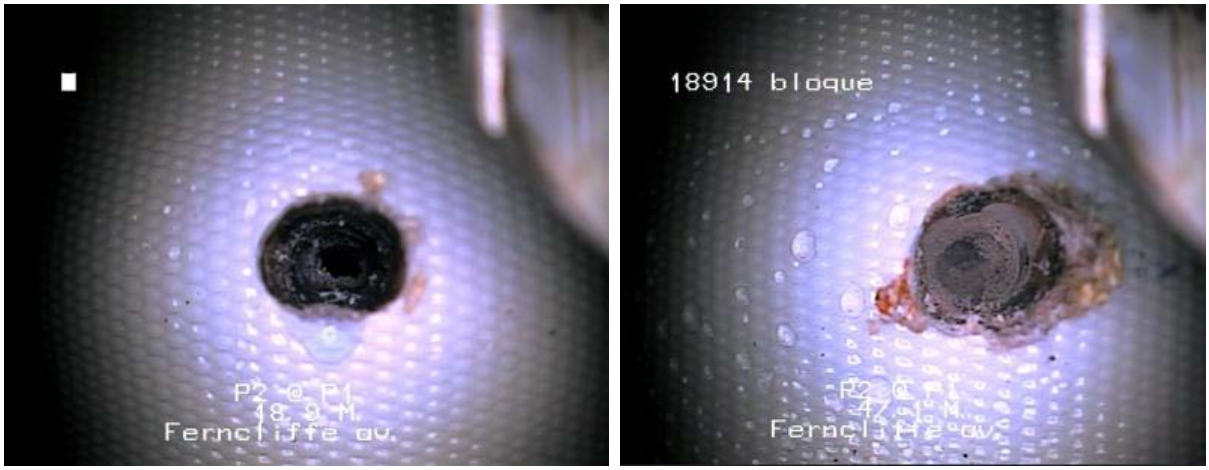


**Figure 3-29. Service Reinstated Internally (left) and Blocked (right)**

Throughout the inspection, a small fold was present at the 10:00 location until 58.0 m from Pit #2. The remainder of the 26.6 m of test pipe had a fold which rotated to different locations, specifically when encountering the shifted joints around the 70.0 m mark. Figure 3-30 shows the typical fold located at 10:00 and the shifting fold at a shifted joint. The fold exists because the liners are slightly oversized to account for changes in the inner diameter of the host pipe, thereby ensuring the minimum design thickness is met throughout the segment.

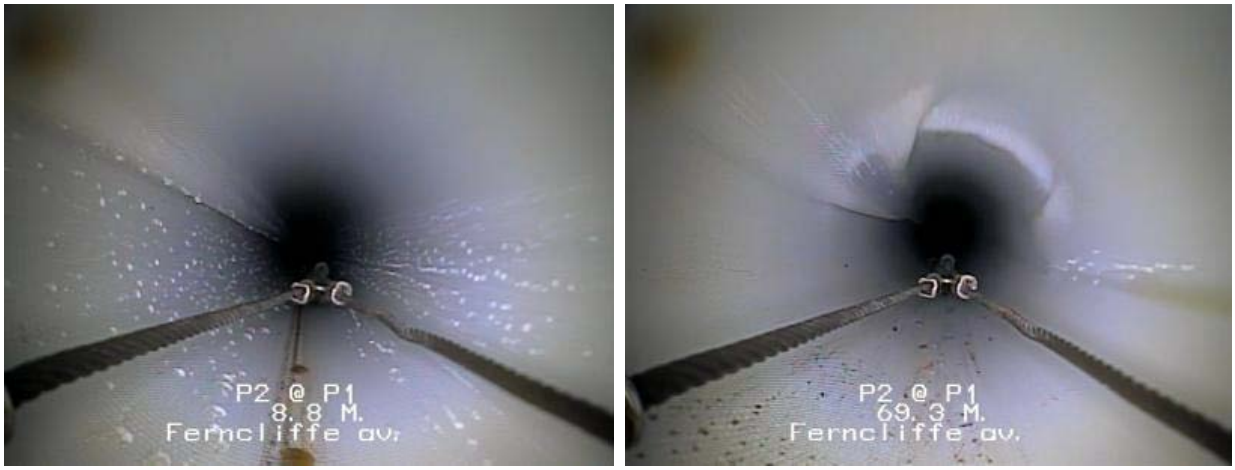


**Figure 3-30. Typical Fold at 10:00 (left) and Folds at a Shifted Joint (right)**

***3.3.1.2 Post-Lining CCTV of Lining Run #2.*** The post-lining inspection of lining run #2 occurred on Monday, September 20 from Pits #2 to #3. The inspection took 14 minutes to complete and the results are summarized in Table 3-18.

**Table 3-18. Post-Lining CCTV Inspection of Lining Run #2**

| Item | Address | Location | Distance (m) | Comment | Services |
|---|---|---|---|---|---|
| Pit #2 | N/A | N/A | 1.0 | Start, 09/20/2010 | N/A |
| Service | 18824 | at 11:00 | 10.9 | 5/8 in. Penetrating Service Flushed | IR |
| Service | 18823 | at 12:30 | 11.7 | 1 in. Non-Penetrating Service (Misalign) | ER |
| Service | 18813 | at 01:00 | 29.0 | 1 in. Non-Penetrating Service (Misalign) | ER |
| Service | 18814 | at 11:00 | 29.2 | 1 in. Non-Penetrating Service (Misalign) | ER |
| Service | 18807 | at 01:00 | 41.0 | 1 in. Non-Penetrating Service (Misalign) | ER |
| Service | 18808 | at 11:00 | 47.7 | 5/8 in. Penetrating Service | IR |
| Service | 18802 | at 11:00 | 61.4 | 5/8 in. Small Penetrating Service | IR |
| Service | 18801 | at 01:00 | 61.5 | 5/8 in. Small Penetrating Service Flushed | IR |
| Service | 18713 | at 01:00 | 78.9 | 5/8 in. Small Penetrating Service | IR |
| Service | 18714 | at 12:00 | 80.3 | 5/8 in. Penetrating Service (Deform) | ER |
| Pit #3 | N/A | N/A | 88.9 | End (14 minutes) | N/A |

Five of the 10 services were successfully reinstated internally. One of the remaining five services (18714) was located, but had to be reinstated externally due to being deformed during cleaning. The remaining four services (18823, 18813, 18814, and 18807) had to be reinstated externally due to misalignment between the saddle and corporation stop. The five external reinstatements required four excavation pits. The section also had a small fold throughout the inspection.

***3.3.1.3 Post-Lining CCTV of Lining Run #3.*** The post-lining inspection of lining run #3 occurred on Tuesday, September 21 from Pits #3 to #4. The inspection took 13 minutes to complete and the results are summarized in Table 3-19.

**Table 3-19. Post-Lining CCTV Inspection of Lining Run #3**

| Item | Address | Location | Distance (m) | Comment | Services |
|---|---|---|---|---|---|
| Pit #3 | N/A | N/A | 1.0 | Start, 09/21/2010 | N/A |
| Service | 18712 | at 11:00 | 2.1 | 5/8 in. Penetrating Service Flushed | IR |
| Service | 18707 | at 01:00 | 4.9 | 5/8 in. Penetrating Service Flushed | IR |
| Service | 18706 | at 11:00 | 14.9 | 5/8 in. Penetrating Service Flushed | IR |
| Service | 18702 | at 11:00 | 25.4 | 5/8 in. Penetrating Service Flushed | IR |
| Service | 18701 | at 01:00 | 26.8 | 5/8 in. Penetrating Service Flushed | IR |
| Service | 18614 | at 11:30 | 41.3 | 5/8 in. Small Penetrating Service Flushed | IR |
| Service | 18613 | at 12:30 | 41.9 | 5/8 in. Small Penetrating Service Flushed | IR |
| Service | 18612 | at 11:00 | 58.6 | 5/8 in. Penetrating Service Flushed | IR |
| Service | 18607 | at 12:30 | 59.8 | 1 in. Non-Penetrating Service (Misalign) | ER |
| Service | 18608 | at 11:00 | 65.9 | 5/8 in. Penetrating Service Flushed | IR |
| Service | 18601 | at 01:00 | 77.9 | 5/8 in. Penetrating Service Flushed | IR |
| Service | 18602 | at 11:00 | 78.1 | 5/8 in. Penetrating Service Flushed | IR |
| Pit #4 | N/A | N/A | 87.7 | End (13 minutes) | N/A |

Of the 12 services, 11 were successfully reinstated internally and were flushed. The remaining service (18607) had to be reinstated externally due to misalignment between the saddle and corporation stop. The section also had a small fold throughout the inspection.

***3.3.1.4 Post-Lining CCTV of Lining Run #4.*** The post-lining inspection of lining run #4 occurred on Tuesday, September 21 from Pits #4 to #6, before the two defect sections were extracted. The inspection took 12 minutes to complete and the results are summarized in Table 3-20.

**Table 3-20. Post-Lining CCTV Inspection of Lining Run #4**

| Item | Address | Location | Distance (m) | Comment | Services |
|---|---|---|---|---|---|
| Pit #4 | N/A | N/A | 1.0 | Start, 09/21/2010 | N/A |
| Service | 18514 | at 11:00 | 5.6 | 5/8 in. Penetrating Service (Deform) | ER |
| Service | 18513 | at 01:30 | 6.0 | 5/8 in. Small Penetrating Service (Deform) | ER |
| Service | 18507 | at 02:00 | 22.2 | 5/8 in. Small Penetrating Service | IR |
| Service | 18508 | at 11:30 | 23.4 | 5/8 in. Penetrating Service (Deform) | ER |
| Service | 18502 | at 11:30 | 38.6 | 5/8 in. Small Penetrating Service | IR |
| Service | 18502 | at 02:00 | 40.3 | 5/8 in. Small Penetrating Service | IR |
| Service | 18418 | at 12:00 | 66.3 | 5/8 in. Penetrating Service | IR |
| Service | 18419 | at 02:00 | 70.4 | 3/4 in. Small Penetrating Service (Fold) | ER |
| Service | 18412 | at 11:00 | 85.9 | 5/8 in. Small Penetrating Service | IR |
| Service | 18413 | at 02:00 | 87.4 | 3/4 in. Small Penetrating Service | IR |
| Pit #6 | N/A | N/A | 87.5 | End (12 minutes) | N/A |

Six of the 10 services were successfully reinstated internally. Three of the remaining four services (18514, 18513, and 18508) was located, but had to be reinstated externally due to being deformed during cleaning. The section also had a small fold throughout the inspection. The remaining service (18419) was drilled out partially, but due to its location in the middle of the fold, shown in Figure 3-31, had to be reinstated externally. The four external reinstatements required three excavation pits.

**Figure 3-31. Service Located in a Fold**

***3.3.1.5 Post-Lining CCTV of Lining Run #5.*** The post-lining inspection of lining run #5 occurred on Wednesday, September 22 from Pits #6 to #7. The inspection took 11 minutes to complete and the results are summarized in Table 3-21.

**Table 3-21. Post-Lining CCTV Inspection of Lining Run #5**

| Item | Address | Location | Distance (m) | Comment | Services |
|---|---|---|---|---|---|
| Pit #6 | N/A | N/A | 1.0 | Start, 09/22/2010 | N/A |
| Service | 18407 | at 02:00 | 16.3 | 3/4 in. Small Penetrating Service | IR |
| Service | 18406 | at 11:00 | 19.2 | 5/8 in. Small Penetrating Service (Fold) | IR |
| Service | 18401 | at 01:00 | 25.9 | 5/8 in. Small Penetrating Service (Deform) | ER |
| Service | 18400 | at 11:00 | 26.4 | 5/8 in. Small Penetrating Service (Flush) | ER |
| Service | 18350 | at 12:00 | 49.6 | 5/8 in. Small Penetrating Service | IR |
| Service | 18349 | at 01:00 | 50.2 | 3/4 in. Small Penetrating Service | IR |
| Service | 18344 | at 12:00 | 68.5 | 5/8 in. Small Penetrating Service | IR |
| Service | 18343 | at 01:00 | 70.2 | 3/4 in. Small Penetrating Service | IR |
| Service | 18337 | at 01:00 | 82.0 | 1 in. Non-Penetrating Service (Misalign) | ER |
| Pit #7 | N/A | N/A | 86.8 | End (11 minutes) | N/A |

Six of the nine services were successfully reinstated internally. One of the remaining three services (18401) was located, but had to be reinstated externally due to being deformed during cleaning. One of the two remaining services (18400) was non-protruding and had to be reinstated externally. The remaining service (18337) had to be reinstated externally due to misalignment between the saddle and corporation stop. The three external reinstatements required two excavation pits.

***3.3.1.6 Post-Lining CCTV of Lining Run #6.*** The post-lining inspection of lining run #6 occurred on Wednesday, September 22 from Pits #8 to #7. The inspection took 11 minutes to complete and the results are summarized in Table 3-22. All 10 services were successfully reinstated internally. Two services (18332 and 18331) were not flushed, but excavations were not required to flush the services at a later time.

**Table 3-22. Post-Lining CCTV Inspection of Lining Run #6**

| Item | Address | Location | Distance (m) | Comment | Services |
|---|---|---|---|---|---|
| Pit #8 | N/A | N/A | 1.0 | Start, 09/22/2010 | N/A |
| Service | 18307 | at 11:00 | 4.8 | 5/8 in. Penetrating Service | IR |
| Service | 18308 | at 01:00 | 5.8 | 5/8 in. Small Penetrating Service | IR |
| Service | 18314 | at 12:30 | 21.6 | 5/8 in. Penetrating Service | IR |
| Service | 18313 | at 12:00 | 23.9 | 5/8 in. Small Penetrating Service | IR |
| Service | 18319 | at 11:30 | 31.0 | 5/8 in. Non-Penetrating Service | IR |
| Service | 18320 | at 12:30 | 41.2 | 5/8 in. Penetrating Service | IR |
| Service | 18325 | at 12:00 | 56.9 | 3/4 in. Penetrating Service | IR |
| Service | 18326 | at 12:30 | 60.5 | 5/8 in. Penetrating Service | IR |
| Service | 18332 | at 12:30 | 76.3 | 5/8 in. Penetrating Service Not Flushed | IR |
| Service | 18331 | at 11:00 | 76.6 | 3/4 in. Penetrating Service Not Flushed | IR |
| Pit #7 | N/A | N/A | 88.3 | End (11 minutes) | N/A |

***3.3.1.7 Post-Lining CCTV of Lining Run #7.*** The post-lining inspection of lining run #7 occurred on Wednesday, September 22 from Pits #8 to #9. The inspection took 9 minutes to complete and the results are summarized in Table 3-23. Both services were successfully reinstated internally.

**Table 3-23. Post-Lining CCTV Inspection of Lining Run #7**

| Item | Address | Location | Distance (m) | Comment | Services |
|---|---|---|---|---|---|
| Pit #8 | N/A | N/A | 1.0 | Start, 09/22/2010 | N/A |
| Service | 18301 | at 01:00 | 6.7 | 5/8 in. Penetrating Service | IR |
| Service | 18211 | at 02:00 | 48.6 | 5/8 in. Small Penetrating Service | IR |
| Fold | N/A | 360° | 74.7 | Circumferential Fold | N/A |
| Pit #9 | N/A | N/A | 76.1 | End (9 min) | N/A |

Lining run #7 had a continuous fold which stretched the entire length of the run similar to each of the other six lining runs. The run did, however, contain multiple folds in several locations, as shown in Figure 3-32, and a circumferential fold at 74.7 m from Pit #8, which prevented the passing of the CCTV camera after multiple attempts. This circumferential fold (Figure 3-32, right) is caused by excess material that was not equilibrated during insertion and accumulated by the pig during forming.

**Figure 3-32. Multiple Folds (left) and a Circumferential Fold (right)**

3.3.2 Lining Thickness**.** The post-lining thickness verification was intended to be conducted with an ultrasonic gauge using an Olympus Model 37DLP ultrasonic sensor according to ASTM E797-05 (ASTM, 2005a). However, the gauge was not capable of performing the check, although it was calibrated for the CIPP material using samples provided by Aqua-Pipe®. Therefore, after lining of the test pipe, a digital caliper was used to measure the entire wall thickness (i.e., pipe wall plus liner) at 3, 6, 9, and 12 o'clock positions in each access pit. Those measurements were subtracted from the pipe wall thickness measurements taken prior to lining presented in Table 3-14. A summary of the thickness measurements is shown in Table 3-24. Based on the comparison between the measurements collected in the field before and after lining, the average lining thickness for each end ranged from 2.93 mm (0.12 in.) to 4.66 mm (0.18 in.), averaging 3.66 mm (0.14 in.).

**Table 3-24. Thickness Measurements of CIPP Liner**

| Test Pit | Pipe End | Lining Run | Wall Thickness, mm | | | | |
|---|---|---|---|---|---|---|---|
| | | | 12:00 | 3:00 | 6:00 | 9:00 | Avg. |
| 1 | East | 1 | 2.34 | 2.66 | 3.82 | 3.27 | 3.02 |
| 2 | West | 1 | 3.50 | 2.35 | 2.62 | 3.25 | 2.93 |
| | East | 2 | 4.26 | 3.45 | 3.84 | 4.33 | 3.97 |
| 3 | West | 2 | 2.56 | 3.61 | 3.05 | 5.46 | 3.67 |
| | East | 3 | 4.14 | 3.26 | 4.44 | 4.12 | 3.99 |
| 4 | West | 3 | 4.33 | 4.74 | 4.88 | 4.67 | 4.66 |
| | East | 4 | 4.03 | 3.48 | 3.13 | 4.31 | 3.74 |
| 6 | West | 4 | 3.02 | 3.13 | 3.47 | 3.40 | 3.26 |
| | East | 5 | 3.33 | 2.36 | 3.01 | 4.68 | 3.35 |
| 7 | West | 5 | 4.12 | 3.82 | 1.79 | 3.55 | 3.32 |
| | East | 6 | 2.75 | 3.79 | 3.81 | 1.86 | 3.05 |
| 8 | West | 6 | 5.79 | 3.57 | 3.44 | 4.60 | 4.35 |
| | East | 7 | 4.05 | 4.73 | 4.11 | 3.24 | 4.03 |
| 9 | West | 7 | 2.73 | 4.28 | 4.13 | 4.66 | 3.95 |
| | **Average** | **Test Pipe** | **3.64** | **3.52** | **3.54** | **3.92** | **3.66** |

## 3.4 Defect Sample Collection

Upon completion of lining, curing and pressure testing of lining run #4 between Pits #4 and #6, the pre-fabricated and field-prepared defect sections were exhumed and transported to Battelle for further handling on Wednesday, September 22.

3.4.1 Lab-Prepared Defect Pipe Segment. During the exhumation process, the lab-prepared defect segment was supported by a lifting strap attached to the bucket of a backhoe. Once the defect pipe segment was secured, the couplings used to secure the defect-pipe segment to the test pipe were removed and the liner was cut using a sawzall. As instructed by Sanexen, a stream of water was directed over the liner while the liner was cut to minimize the amount of heat to which the liner would be subjected. Once detached from the test pipe, the defect pipe segment was then lifted out of the excavation pit (Figure 3-33) onto a "V-shaped" support cribbing.

**Figure 3-33. Exhumation of Lab-Prepared Defect Section**

3.4.2 Field-Prepared Defect Pipe Segment**.** Upon completion of the pipe rehabilitation, the field-prepared defect pipe segment was exhumed from Pit #5. The exhumation process was identical to the process used to exhume the lab-prepared defect pipe segment with the exception of having to cut through the pipe and the liner. A demolition saw was initially used to cut through the pipe down to the liner. Once the liner was reached, a sawzall was used. As instructed by Sanexen, a stream of water was directed over the pipe and liner during all sawing activities. The defect pipe segment was then lifted out of the excavation pit by a lifting strap as shown in Figure 3-34.

**Figure 3-34. Exhumation of Field-Prepared Defect Section**

3.4.3 Sampling Logistics**.** After being transported to Battelle, the exhumed pipe segments were crated and shipped via flat bed truck to Louisiana Tech University's Trenchless Technology Center (TTC) for storage and laboratory testing. The pipe segments were transported with a chain of custody form. TTC verified that the exhumed pipe segments arrived intact and were suitable for proposed testing.

3.5 Site Restoration

Site restoration was expected to include disinfection of the system, reconnecting the test sections together and back to the system with new ductile iron pipe segments, and backfilling each of the access pits and patching the pavement with asphalt.

3.5.1 Disinfection**.** CWD did not require TC to disinfect the water main after it was reconnected to the water system. However, bacteriological testing was conducted prior to placing the water main back into service. Samples were taken on October 15 and 18 from a fire hydrant on Ferncliffe Ave. and the results of both tests were negative.

3.5.2 Reconnecting the Test Pipe**.** After CIPP lining, it was necessary to reconnect the test pipe to the system including all valves, hydrants, and pipe sections, which took place between September 27 and October 7. This included replacement of pipe sections with segments of new 6 in. ductile iron pipes in Pits #1 through #9; replacement of valves; and replacement of hydrants (shown in Figure 3-35). End seals were not required at the rehabilitated pipe extremities and there were no documented issues or difficulties with reconnecting the test pipe to the system.

**Figure 3-35. Valve being Replaced (left) and installation of a New Hydrant (right)**

3.5.3 Backfilling and Site Restoration**.** Backfilling the rehabilitated test pipe was conducted as per CWD specifications. The purpose of backfill was not only to fill the access points, but also to protect the pipe and provide support for valves and hydrants. Backfilling took place in conjunction with reconnection activities and surface restoration took place between October 27 and November 2. In all, more than 90 cubic yards of low strength mortar and 20 cubic yards of concrete were used to backfill the 9 access and 13 service reconnection pits. Surface restoration was completed with 28 gal of SS-1 tack coat and 20 tons of 448 Type 1 asphalt. All additional pieces of pipe, extra fittings, and incidental materials including excess spoil material were removed from the jobsite during site cleanup activities and all pavements were cleaned. Grass areas negatively affected by the demonstration were reseeded and replaced with sod. Any damaged pavement was replaced according to local specifications and standards.

## 3.6 Post-Rehabilitation Friction Factor Test

A post-rehabilitation Hazen-Williams flow test was performed on August 3, 2011 to evaluate the improvement in flow of the test section. Two separate tests were conducted on the test segment. The first test used the first, second, third, and fourth hydrants west of Rocky River Drive and the second test used the third, fourth, fifth, and sixth hydrants west of Rocky River Drive. This frictional headloss and the flow rates were input into Equation 6 to calculate the C-factor as shown in Table 3-25.

**Table 3-25. Post-Rehabilitation C-Factor Results**

| Parameter | Hazen-Williams Flow Test | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| Length of Test Section, ft | 598 | | 600 | |
| Diameter of Test Section (D), in. | 6 | | | |
| Total Head Loss, ft | 13.33 | 8.33 | 12.50 | 7.08 |
| Total Head Loss, psi | 5.77 | 3.61 | 5.41 | 3.07 |
| Friction Loss (P), psi/ft | 0.009652 | 0.006032 | 0.009021 | 0.005109 |
| Flow (Q), gpm | 444.44 | 333.33 | 444.44 | 333.33 |
| C-factor | 110.38 | 106.74 | 114.49 | 116.76 |
| **Average C-factor** | **112.10** | | | |

The average C-factor of the post-rehabilitated test pipe was 112.1. The average C-factor was less than the 120 that was anticipated from the rehabilitation, but it was a significantly greater than the pre-rehabilitation C-factor of 78.5, resulting in an improvement of nearly 43%.

# 4.0: DEMONSTRATION RESULTS

This section presents the results of the demonstration including a detailed evaluation of the technology based on the evaluation metrics defined in Section 2.2. As outlined in Section 2.1, a key aspect of the demonstration study was to assess the demonstrated technology based on the metrics outlined in Table 2-1. The metrics that were used to evaluate and document the Sanexen Aqua-Pipe® CIPP products are described below.

## 4.1 Technology Maturity

The Sanexen Aqua-Pipe® CIPP product is classified as innovative in terms of maturity based on its usage and supporting performance data. CIPP technology has been successfully used for rehabilitation of wastewater mains for 40 years, but has only been adapted to use for drinking water mains in the last 10 years. The product has been in use in Canada since 2000 and was first used in the U.S. in Naperville, IL in the summer of 2006 (Vose and Loiacono, 2007). More than 1,500,000 lf (284 miles) has been installed in North America to date (Belisle, 2011). The Aqua-Pipe® product is a fully-structural Class IV solution, which is a benefit when compared to the most common water main rehabilitation technology (cement mortar lining). In the U.S., the product has been used at more than 20 sites as of early 2011 including:

- Cleveland, OH
- Naperville, IL
- Omaha, NE
- New York City, NY
- Charleston, SC
- Elmendorf AFB, AK
- Clinton, MI
- Atlanta, GA
- Minneapolis, MN

As part of the technology evaluation, four utilities provided direct information about their experiences with the product including Clinton, Charleston, Omaha, and New York City. The township of Clinton, Michigan has used Aqua-Pipe® to rehabilitate cast iron water main on two occasions: first in August of 2007 for 2,200 ft of 8 in. (Tingberg and Janicki, 2008) and the second in November of 2010 for 4,300 ft of 12 in. The first project included an additional section of main, which was replaced by open-cut to compare the costs of the two technologies. The total cost (i.e., cleaning, inspection, service reinstatements, etc.) of the first project, which included internal reinstatement of 51 services, was $148/lf. The city was very pleased with the product, which led to the second project. The second project included 26 service reinstatements, only one of which had to be reinstated externally and the total cost for the project was $170/lf. The city plans to do more projects with this technology in the future as funding becomes available (Janicki, 2011).

The installation in Charleston, South Carolina took place in the fall of 2009 on 2,000 ft of 8 in. ductile iron, unlined cast iron, and cement lined cast iron. The mains were roughly 30 years old and located in an isolated area on an old Navy base. The installation of the liner was successful. Even though the main did not contain any active services, the requested demonstration of the reconnection process could not be performed since the existing services had to be abandoned. Unique aspects of the pilot study included lining through two tee-sections: one of which was successful and one of which plugged up the section and required a repair. Lining through tee-sections is not recommended by Sanexen, but Charleston Water System (CWS) decided they wanted to test it out. Also, an attempt at installing a new service on the lined

main was made, which was unsuccessful as the drill bit stretched the polymeric membrane of the liner considerably before breaking through the material. This attempt was performed by an inexperienced contractor unfamiliar with the manufacturer tapping procedure. CWS will use this pilot project for considering CIPP technology for additional projects in its historic downtown area (Benjock, 2011).

The project in Omaha for the Metropolitan Utilities District (MUD) took place in the fall of 2009 and involved the rehabilitation of 1,460 ft of 10 in. and 1,090 ft of 12 in. cast iron mains dating back as far as 1895 in the Old Market District (Schovanec and Cote, 2011). Although this area had very few breaks, the opportunity to address these 100+ year old mains would be limited in the future due to the restoration of original cobblestone pavements in the area, scheduled for late 2009. MUD took the opportunity to address these mains prior to the City's pavement restoration projects and chose structural lining over alternative methods such as open cut and pipe bursting. The project included nine lining runs, all of which were successfully installed and passed pressure testing. The main had a total of 86 service connections: 32 of which were reinstated robotically; 35 of which were abandoned and robotically plugged; and 19 which had to be reconnected externally due to their size. Omaha was pleased with the results of the project and has recently used structural CIPP lining to rehabilitate another main and plans to use it more in the future (Schovanec, 2011).

For the installation in New York, the City planned to rehabilitate approximately 9,000 ft of the 48 in. diameter water main located on the west side of Madison Ave. The majority of the water main was rehabilitated using fold-and-form, but the Department of Design and Construction (DDC) decided to test CIPP on a small section of the 12 in. water main located on the east side of the street. Aqua-Pipe® was used to rehabilitate a 230 ft section of cast iron in the winter of 2010, which was originally constructed in 1881, making the main nearly 120 years old (Ng and Loiacono, 2011). DDC was pleased with the technology overall and anticipates using the product on more projects in the future. Areas of note include the use of bypass lines, which are difficult to use in an environment like Manhattan due to security issues and the difficulty for use with large buildings. Another potential limitation for New York's future use is the limitation around a certain degree of bends as New York City has many mains with vertical and horizontal bends so that the mains can avoid the multitude of other utilities underground (Ng, 2011).

In addition to the installation history cited above, performance data are also available in the Aqua-Pipe® rehabilitation manual (Sanexen, 2010). The manual contains material physical properties, design parameters, and product specifications and certifications, including the ANSI/NSF 61 Certificate. The manual does not contain long-term testing results as the tests are currently being carried out by a third-party laboratory at the time of this report.

## 4.2 Technology Feasibility

The Sanexen Aqua-Pipe® product is marketed as a Class IV liner capable of providing a fully structural solution for renewing water mains. Essentially, the product forms a pipe within a pipe which is capable of surviving possible failure of the host pipe. The structural performance of the liner is discussed in Section 4.4, but the installed product was considered applicable to the rehabilitation requirements of this demonstration. Challenging pipe configurations were not encountered as the liner was not installed through any valves or fittings and the lining runs were without any major bends.

Anticipated failure modes considered included incomplete curing of the liner or premature curing of the liner prior to full insertion. Neither of these failure modes was evident during the installation and curing process or during post-installation inspections. After post-installation inspections and exhumation of the two defect sections, visual inspections were also made to determine the ability of the liner to bridge the pre-installed defects, shown in Figure 4-1. The liner did bridge each of the pre-installed defects, fit tightly inside the host pipe, and there was no measurable annular space between the two.

**Figure 4-1. Exhumed Defected Sample**

## 4.3 Technology Complexity

The use of structural CIPP liners for water mains is a sound alternative to open-cut replacement and the traditional non-structural rehabilitation technology cement mortar lining. CIPP liners offer a similar level of rehabilitation with less disruption to the surface when compared with open-cut replacement, as excavations are typically spaced at 300 ft apart. Cement mortar liners, which require similar excavations for access, are non-structural and only applicable to taste and corrosion control. Therefore, this technology is considered beneficial for small, medium, and large utilities in need of structural alternatives to open-cut replacement. Various aspects that contribute to the complexity of the technology such as training requirements, site preparation activities, labor requirements, etc., are discussed below.

4.3.1 Training and Preparation Requirements. Although the demonstration described in this report was performed by Sanexen, the product can be installed by licensed contractors that have been trained to install the CIPP liner. The liner cannot be installed by untrained personnel, which is common for the majority of rehabilitation technologies, but the pre- and post-installation activities and maintenance operations can be performed by typical utility contactors and personnel. It is important that the cleaning process used by the contractor be coordinated ahead of time to ensure consistency with the manufacturer recommendations to avoid damage or deformation to the corporation stops prior to rehabilitation. Site preparation activities, as discussed in Section 3.1, include bypass installation, pipe cleaning, and excavation of access pits, all of which are required by other rehabilitation technologies. The technology's effect on traffic flow is limited due to reduced excavation when compared with full length open-cut replacement, but traffic control in the form of cones and signs is needed in and around excavations.

4.3.2 Labor and Time Requirements. The time and labor for each of the major installation functions is provided in Table 4-1 to outline the overall requirements for a typical installation. Since several activities (i.e., excavation, cleaning, reconnection and site restoration, and bypass removal) had varying crew sizes, the total number of labor hours is provided for the specified number of days with average hours per day provided. The total Sanexen labor hours for the entire CIPP liner installation including service capping, liner installation and curing, pressure testing, and reinstatement of services

internally, are shown in a lump sum. Individual activity durations are described in the appropriate subsections in Section 3.

**Table 4-1. Estimate of Time and Labor Requirements for Major Activities**

| Activity | Labor Required | Time Required |
|---|---|---|
| Bypass Piping (Entire test section) | F and 3L | 166 hrs total (6 days, ~7 hr/day) |
| Pit Excavation | F, L, O and T<br>F, L and O/T | 164 hrs total (5 days, ~8 hr/day)<br>99 hrs total (4 days, ~8 hr/day) |
| Test Section Cleaning | F and 2L to 3L | 195 hrs total (6 days, ~8 hr/day) |
| Capping, CIPP Installation and Internal Services | O<br>1R and 3LI | 116 hrs total (12 days, ~9.5 hr/day)<br>384 hrs total (12 days, ~8 hr/day) |
| Reconnection and Site Restoration | F, O, 1L to 5L, and T | 476 hrs total (13 days, ~7 hr/day) |
| Bypass Removal | 2F, O, and 6L | 47 hrs total (2 days, ~6.5 hr/day) |

Labor is identified as: F, contractor foreman; L, laborers; O, backhoe operator; T, truck driver; R, robot operator; and LI, liner installers.

The test pipe was taken out of service once the bypass was put online on Tuesday, August 31, 2010 and the test pipe was put back online on Thursday, October 21, 2010. Therefore, the test pipe was out of service and bypassed for seven weeks and two days.

4.3.3 Process Evaluation. The installation process has been optimized over the 10+ year installation history in Canada and 5+ year history in the U.S. One aspect of the installation that is manual and not automated is the impregnation of the liner with resin during installation, which is performed with a hand-held gun. The installation process provides the technician with the proper liner/resin ratios to be used during wet out, which are accounted for in QC by a counter and flow meter. In addition, the resin is mechanically measured using pre-determined spacing between two compression rollers for each specific liner diameter. This is used in order to assure the liner/epoxy ratio requirements. An automated measure of the amount of resin being inserted into the liner would allow for QC of the resin.

Some issues related to mechanical difficulty and unexpected events occurred during the installation. Mechanical issues with the capping robot delayed the capping for a few days while the problem was worked out. The issue turned out to be a power issue and not a mechanical failure as originally thought, and once discovered, capping and inspection resumed uninterrupted. The other issue observed during the demonstration was the number of services requiring externally reinstatement. As discussed in Sections 3.2.4.1 and 3.2.4.2, 17 of the 63 active services (27%) had to be reinstated externally by excavation due to various issues. These issues reduced the benefit of limited excavation for this project, since the external service reinstatements required additional 13 excavations pits. Of the 17 services requiring external reinstatement, 14 were due to reasons 3 and 4 (previously cited in Section 3.2.4.1), which the manufacturer categorizes as extraordinary events that rarely occur in water main rehabilitation projects. CWD reported that after service plugging, only four services were expected to require external reinstatement. The additional 13 services requiring external reinstatement came as a surprise to CWD and some of the benefits of using the product were negated due to the additional required excavations.

## 4.4 Technology Performance

Technology performance was evaluated in the field and the lab through the use of the QA/QC procedures outlined in Section 2.2.6. Field QA/QC of surface preparation was accomplished by cleaning and drying the test pipe and proper preparation was verified by the pre-installation CCTV inspection. Water tightness of each section was verified in the field via post-installation pressure tests, all of which passed

as documented in Section 3.2.3. The following sections discuss the results of the laboratory testing used to evaluate the manufacturer-stated claims of performance versus actual liner performance.

4.4.1 Liner Thickness. The liner thickness was measured in the field and the lab to verify the design thickness was met, shown in Table 4-2. The design thickness was calculated using ASTM F-1216 as described in Section 2.2.4. Conservative design thicknesses were obtained from Equations 1, 3, and 5 by assuming a groundwater table level 1.8 m (6 ft) above the invert of the pipe. Design thicknesses were calculated to be 1.8 mm (0.07 in.) to support the water table, 2.5 mm (0.10 in.) to support the water table plus vacuum condition, 2.4 mm (0.09) to support dead and live loads, and 2.3 mm (0.09) to support internal water pressure, with the largest (e.g., 2.5 mm) taken as the minimum design thickness.

**Table 4-2. Summary of Thickness Measurements**

| Measurement Location (Method) | Avg. (mm.) | Min. (mm.) | Max. (mm.) | Standard Deviation |
|---|---|---|---|---|
| **Minimum Design Thickness** | **2.50** | **N/A** | **N/A** | **N/A** |
| Lining Run #1 (Field) | 2.98 | 2.34 | 3.82 | 0.56 |
| Lining Run #2 (Field) | 3.82 | 2.56 | 5.46 | 0.89 |
| Lining Run #3 (Field) | 4.32 | 3.26 | 4.88 | 0.51 |
| Lining Run #4 (Field) | 3.50 | 3.02 | 4.31 | 0.46 |
| Lining Run #5 (Field) | 3.33 | 1.79 | 4.68 | 0.94 |
| Lining Run #6 (Field) | 3.70 | 1.86 | 5.79 | 1.17 |
| Lining Run #7 (Field) | 3.99 | 2.73 | 4.73 | 0.68 |
| **All Lining Runs** | **3.66** | **1.79** | **5.79** | **0.85** |
| Defect Sections, Crown (Lab) | 4.67 | 4.17 | 5.13 | 0.20 |
| Defect Sections, Invert (Lab) | 4.83 | 4.47 | 5.56 | 0.22 |
| Defect Sections, Springline (Lab) | 4.64 | 4.27 | 5.03 | 0.21 |
| **Defect Sections, All (Lab)** | **4.72** | **4.17** | **5.56** | **0.23** |

For determining the thickness of the liner samples in the laboratory, specimens from three different locations were used: the pipe's springline, crown, and invert. At each location, a strip of liner (approximately 1 in. wide) was cut out (Figure 4-2, yellow lines) and six specimens (approximately 0.5 in. long each) were cut out of each strip. It should be noted that on one side of the liner (at left springline), there was a noticeable fold in the liner and the strip was cut out in two parts avoiding the fold (see Figure 4-2, left). Ten thickness readings were taken around each specimen (a total of 180 readings) using a digital caliper with an accuracy of ±0.0001 (Figure 4-2, right).

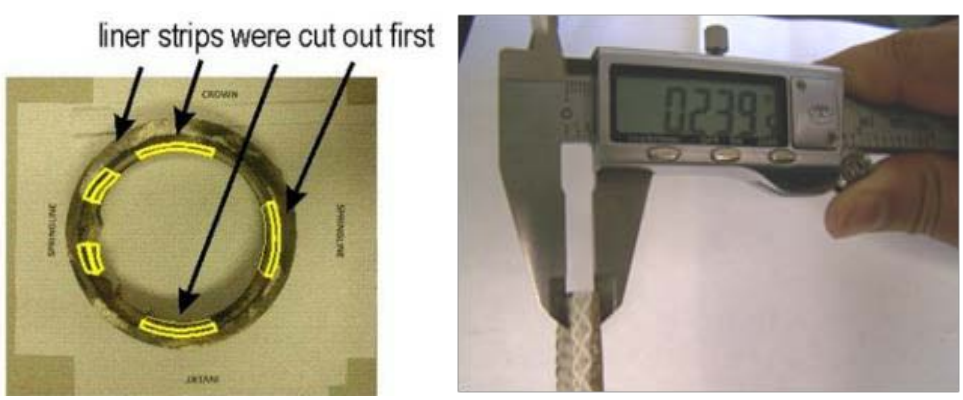


**Figure 4-2. Location of Thickness Specimens (left) and Measuring with a Digital Caliper (right)**

The average measured thicknesses and their standard deviations were determined in the lab from the test sections and the overall average thickness was calculated to be 4.72 mm. The average thickness showed the lab measurements to be more than 1 mm larger on average (i.e., 4.72 mm, lab, to 3.66 mm, field). This is most likely due to the location of the measurements, as the field measurements were taken at the ends of the lining runs where the liner can stretch. In all cases, the average measured CIPP wall thicknesses were more than 1 mm greater than the design thickness of 2.5 mm.

4.4.2 Liner Ovality. To accurately map any deformation inside the liner, a profile plotter developed at the TTC was used. The system features a linear variable displacement transducer (LVDT) connected to a motor-gear system that rotates around the inner circumference of the liner. An encoder system provides position information regarding the location around the pipe at which the data are taken. The liner was placed inside a steel pipe, simulating a host pipe, and the profile plotter's centerline was carefully aligned with that of the liner. The whole section was 14 in. long. Ovality was measured near the middle of the section, at three cross-sections spaced 1 in. apart. Continuous readings were taken around the circumference of each cross-section and averaged, shown in Figure 4-3. The procedure was repeated after the liner had been tested for buckling to identify any change in the liner ovality. A profile plot taken before and after the buckling test is shown in Figure 4-4.

**Figure 4-3. Measuring Ovality before Buckling test (left) and after Buckling (right)**

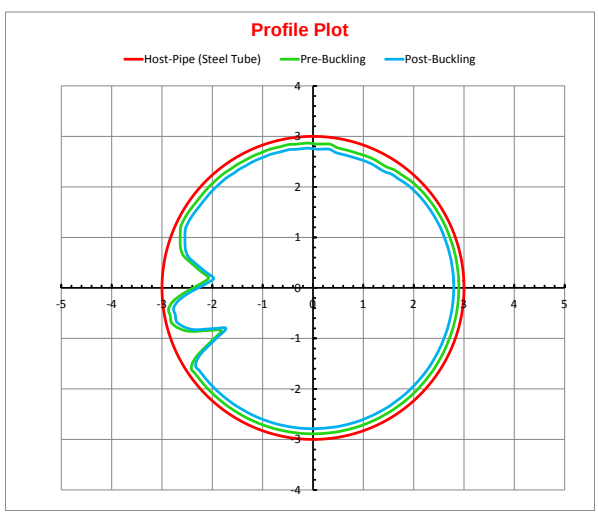


**Figure 4-4. Ovality of Host Pipe (red), Liner before Buckling (green), and after Buckling (blue)**

The diameters measured when including the folded section, which are values from around 135° to 225°, were excluded in the ovality calculations since the values would skew the calculations. Based on plots of this pipe section, the fold represented approximately 25% of the circumference of the liner. The equation in ASTM F-1216 does not account for the folding in the ovality calculation, which is something that could be addressed in the future. The mean and minimum diameters measured outside of the folded section by the plotter were 5.76 in. and 5.61 in., respectively. A resulting liner ovality measure of 2.5% was calculated according to the equation provided in ASTM F-1216. The ovailty used in ASTM F-1216 liner design of 2% is an assumption, but the 2.5% measured after bucking is within the 5% maximum used in F-1216 for calculating maximum loads (ASTM, 2009a).

4.4.3 Tensile Testing. The tensile tests conducted at the TTC used specimens that were cut from the retrieved liner samples in accordance with ASTM D-638 (ASTM, 2008a; Figure 4-5) for measuring the liner's tensile strength. A total of five specimens were prepared (cut in longitudinal direction) and tested in the testing machine as shown in Figure 4-5.

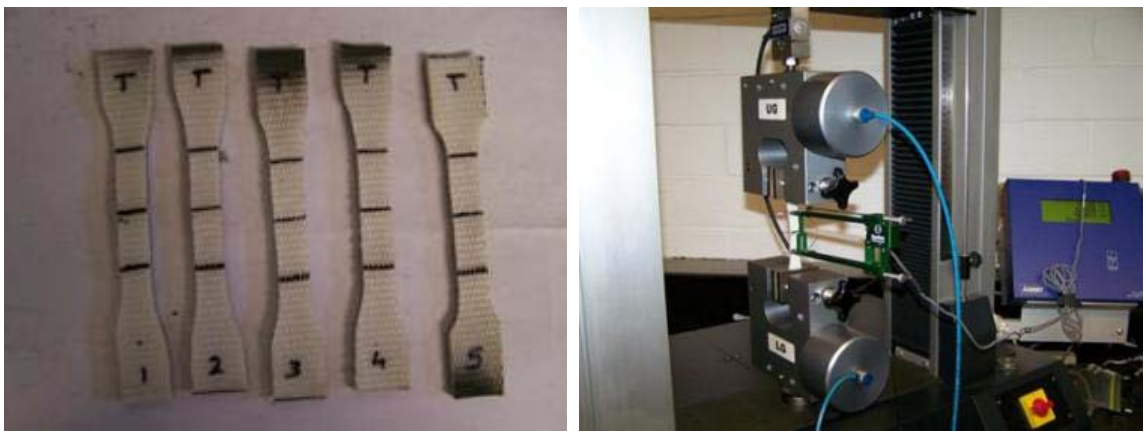


**Figure 4-5. Samples for Tensile Test (left) and Testing Machine (right)**

The results of tensile testing are shown in Table 4-3. Using the information given in Table 4-3, the stress-strain curves for all specimens was plotted, as shown in Figure 4-6. The average peak tensile stress for all five samples is 9,415 psi, which is more than triple the 3,000 psi required by ASTM F-1216. The liner performed very well despite the defects that were installed into the test sections

**Table 4-3. Results from Tensile Testing (Longitudinal Direction)**

| Location | Area[(a)] ($in^2$) | Peak load (lb) | Peak stress (psi) | Tensile modulus (psi) |
|---|---|---|---|---|
| 1 | 0.0966 | 923 | 9,555 | 780,000 |
| 2 | 0.0914 | 812 | 8,888 | 486,000 |
| 3 | 0.0855 | 825 | 9,645 | 440,000 |
| 4 | 0.0918 | 867 | 9,463 | 486,000 |
| 5 | 0.0875 | 833 | 9,525 | 389,000 |
| **Average** | **0.0906** | **852** | **9,415** | **516,200** |

(a) The thickness of the inner polyurethane liner, which ranges from 0.4 to 0.6 mm, is not considered in the area calculations.

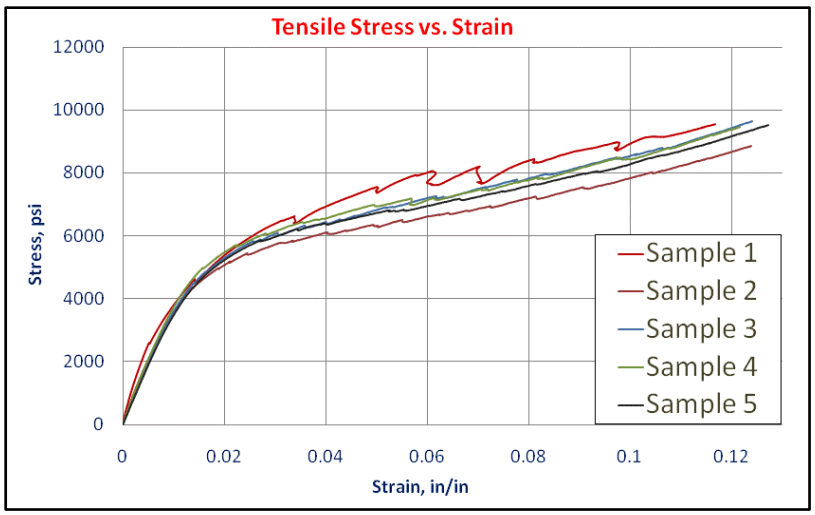


**Figure 4-6. Stress-strain Curves from Tensile Testing**

4.4.4 Flexural Testing. Five specimens (Figure 4-7, left) were cut from the retrieved liner specimen in accordance with ASTM D-790 (ASTM, 2007a) for measuring the liner's flexural strength and flexural modulus of elasticity. All sides of the specimens were smoothed using a grinder and a table router. A water jet cutter could not be used due to curvature of the liner. Testing was performed using an ADMET eXpert 2611 universal testing machine (UTM) shown in Figure 4-7 (right). Table 4-4 lists the dimensions and moment of inertia area for all specimens.

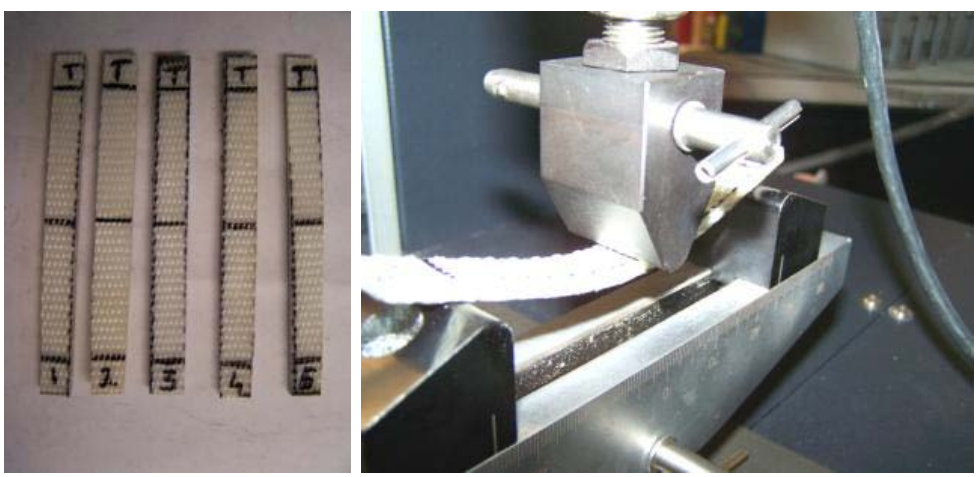

**Figure 4-7. Samples Prepared for Bending Test (left) and Bending Test (right)**

**Table 4-4. Specimens Used for Bending Testing**

| Specimen | Span (in.) | Dimension | | Moment of Inertia of Area (in.$^4$) |
|---|---|---|---|---|
| | | Width (in.) | Depth (in.) | |
| 1 | 4 | 0.459 | 0.1524 | 0.0001354 |
| 2 | 4 | 0.515 | 0.1704 | 0.0002123 |
| 3 | 4 | 0.501 | 0.1494 | 0.0001392 |
| 4 | 4 | 0.493 | 0.1504 | 0.0001398 |
| 5 | 4 | 0.479 | 0.1494 | 0.0001331 |

Using the information listed in Table 4-4, the peak bending stress was calculated, shown in Table 4-5 and the flexural stress vs. strain graph was plotted for all samples (Figure 4-8). Peak load, peak shear stress, and flexure modulus were obtained from the software 'MtestW' that operates the ADMET eXpert 2611 UTM. Deflection was calculated using the formula given by ASTM D-790. Peak bending stress was calculated from the peak load value achieved using the following expression:

where,

$\sigma$ = Bending stress
$P$ = Peak load
$L$ = Span length
$D$ = Depth of the specimen
$I$ = Moment of inertia of area

**Table 4-5. Test Result of Bending Test on the Ring Sample**

| Specimen | Peak load (lb) | Flexural modulus (psi) | Deflection (in.) | Peak bending stress (psi) |
|---|---|---|---|---|
| 1 | 13.77 | 350,000 | 0.387 | 7,750 |
| 2 | 21.70 | 370,000 | 0.368 | 8,707 |
| 3 | 13.73 | 357,142 | 0.368 | 7,376 |
| 4 | 15.79 | 367,500 | 0.410 | 8,496 |
| 5 | 13.51 | 390,000 | 0.347 | 7,582 |
| **Average** | **15.70** | **366,928** | **0.376** | **7,982** |

The average peak bending stress for all five specimens was 7,982 psi, 3,500 psi more than the 4,500 psi required by ASTM F-1216. The average flexural modulus was 366,928 psi, 115,000 psi more than the 250,000 psi required by ASTM F-1216.

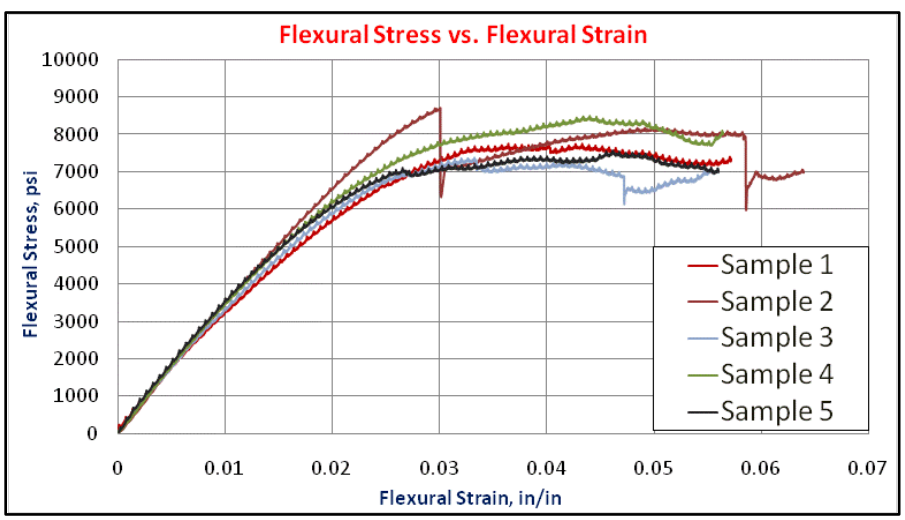


**Figure 4-8. Stress vs. Strain Curves**

4.4.5 Hardness Testing. The Durometer (Shore D) hardness test (ASTM D-2240; ASTM, 2005c) is used to determine the relative hardness of soft materials, such as thermoplastic and thermosetting materials. This test measures the penetration of a specified indenter into the subject material under predetermined force and time (Figure 4-9).

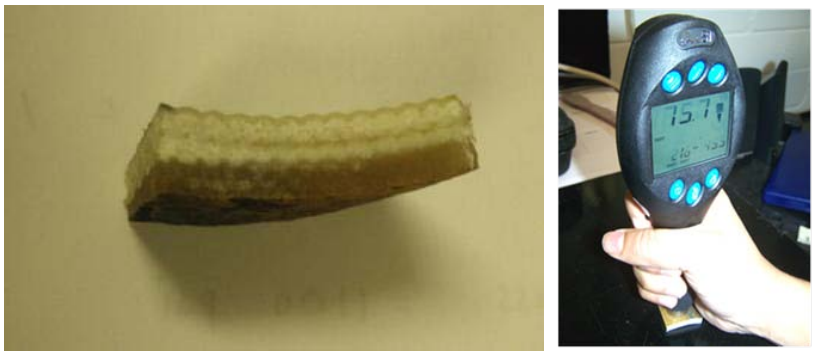

**Figure 4-9. Specimen for Shore D Hardness Test (left) and a Shore D Hardness Tester (right)**

The Shore D hardness scale utilizes a weight of 10 lb and a tip diameter of 0.1 mm. For interpreting the results, a Shore D hardness scale value of 50 represents the hardness of a solid wheel (e.g., similar to those used by forklifts), while a value of 80 represents the hardness of paper making rollers. Six specimens at each of the three locations of the exhumed sample (i.e., crown, springline, and invert) that were used in the thickness measurements were subjected to the Shore D hardness test.

For each specimen, a total of 18 readings were taken on the outer surface of the liner (towards the host pipe wall) and another 18 readings on the inner surface of the liner. The average calculated values and their standard deviations are shown in Figure 4-10, 4-11, and 4-12. The weighted average of Shore D hardness was calculated to be:

- For the inner surface: 42.1 ±2.2 (crown), 39.8 ± 5.4 (springline), and 40.2 ± 1.4 (invert)
- For the outer surface: 64.8 ±2.2 (crown), 66.2 ± 5.1 (springline), and 60.8 ± 1.5 (invert)

The inner surfaces have lower hardness values compared with the outer surface of the liner.

**Figure 4-10. Shore D Hardness of the Liner at the Crown**

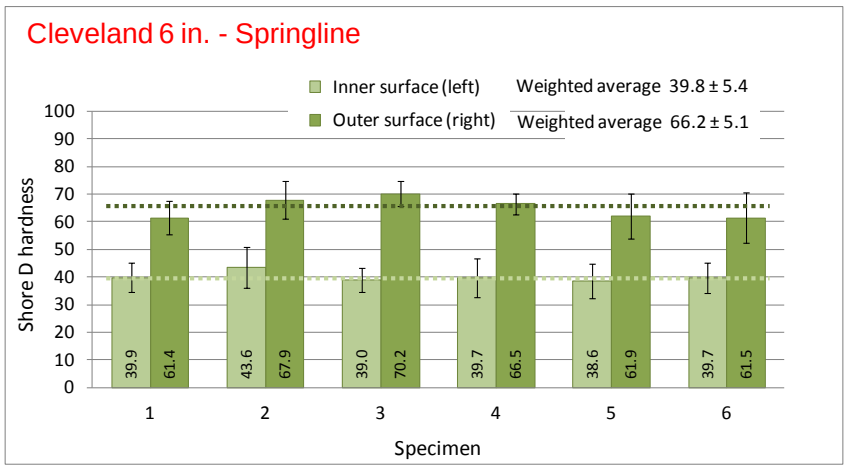


**Figure 4-11. Shore D Hardness of the Liner at the Springline**

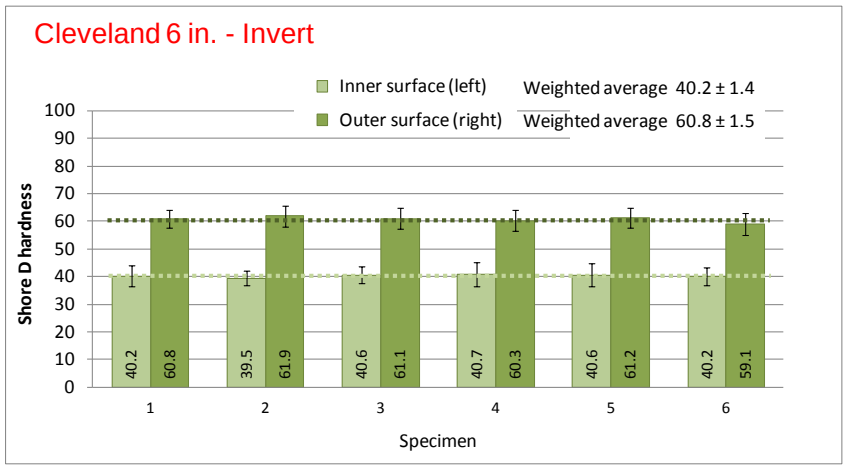


**Figure 4-12. Shore D Hardness of the Liner at the Invert**

The six specimens from each of three locations were also subjected to the Barcol hardness test, using the equipment as shown in Figure 4-13. For each specimen, a total of 18 readings were taken on the outer surface using a hand-held portable Barcol hardness tester (Figure 4-13) and another 18 readings were taken on the inner surface.

**Figure 4-13. Hand-Held Portable Barcol Hardness Tester (left) and Taking Measurements (right)**

Similarly to the Durometer (Shore D) hardness test, it was found that the measured inner surface hardness values were lower than those measured on the outer surface. The average calculated values and their standard deviations are shown in Figures 4-14, 4-15, and 4-16. The weighted average of Barcol hardness was calculated to be:

- For the inner surface: 2.2 ± 0.3 (crown), 2.1 ± 0.3 (springline), and 1.9 ± 0.3 (invert)
- For the outer surface: 9.7 ± 1.4 (crown), 9.4 ± 1.4 (springline), and 9.9 ± 1.1 (invert)

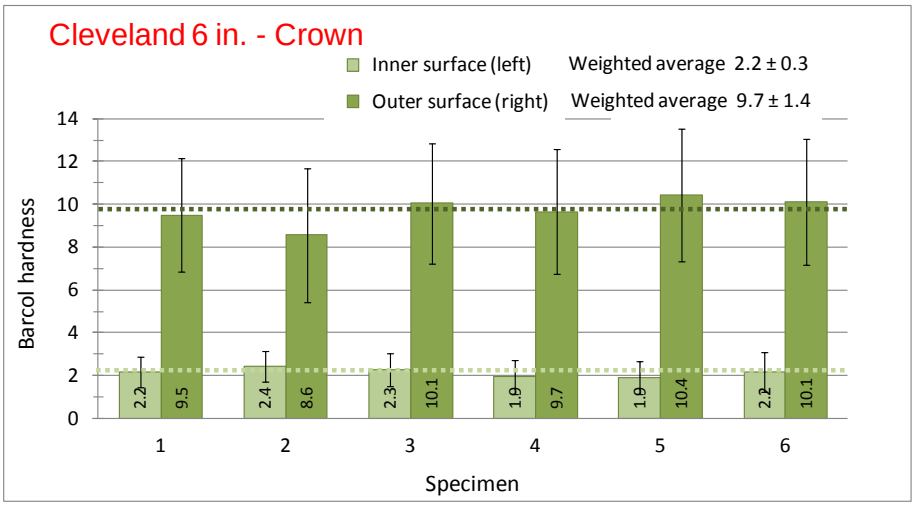


**Figure 4-14. Barcol Hardness of the Liner at the Crown**

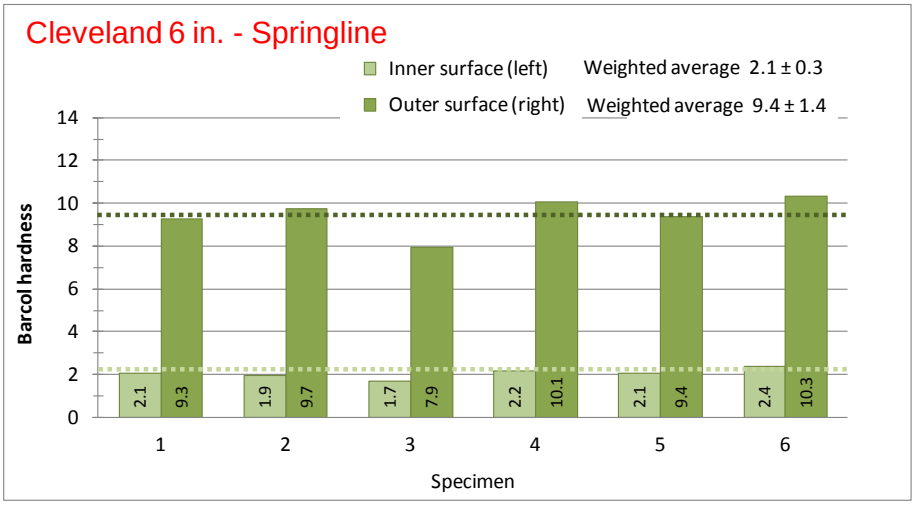


**Figure 4-15. Barcol Hardness of the Liner at the Springline**

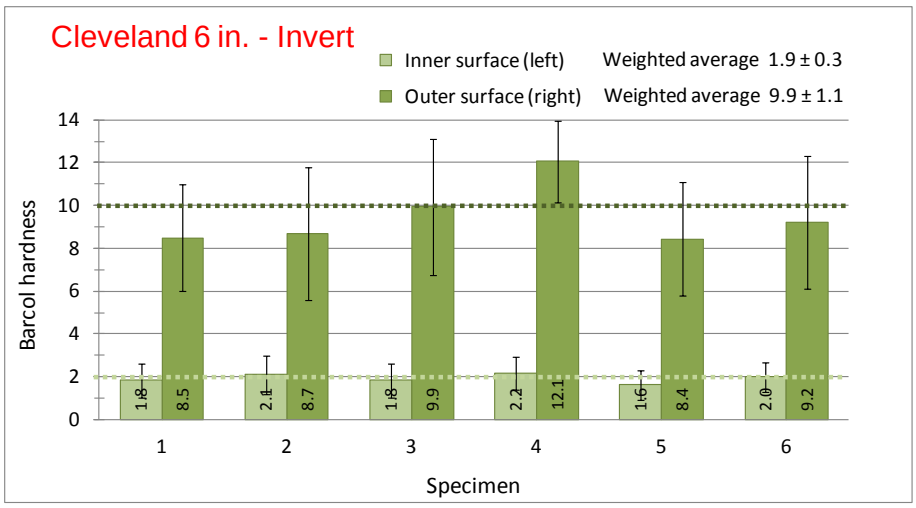


**Figure 4-16. Barcol Hardness of the Liner at the Invert**

The softer inner surface is due to the presence of a thin polyurethane layer on the inside of the liner that causes lower hardness values. This polyurethane layer is present for water tightness and has no structural properties. There was some resin leaching through the defect holes that were made prior to the lining installation (Figure 4-17), which might have caused an unequal distribution of the resin, and thus contributed partially to softer inner surface.

**Figure 4-17. Exhumed Sample Showing Resin That Has Leached Out**

4.4.6 Negative Pressure Testing. To perform the negative pressure or vacuum test, the ductile iron host pipe was first carefully broken by hammering and by utilizing a manually operated hydraulic press to enable removing the liner from the host pipe while minimizing the possibility of damaging the liner (Figure 4-18, left). Using a hand saw next, a 2 ft long section was cut out from the released liner (Figure 4-18, right) where cured resin areas were showing on the surface of the liner due to the defects (approximately 2 in. × 1 in.) that had been created in the host pipe prior to the relining.

**Figure 4-18. Breaking the Host Pipe (left) and Cutting the Liner Specimen (right)**

The two caps necessary for closing and sealing the specimen for the test were manufactured by cutting a circular steel plate, 6.5 in. in diameter using a water jet cutter, and welding it to a short piece of steel pipe (3 in. long). A provision to a quick connector was attached to one cap. Polyurea was next poured inside one cap and the liner was inserted into it and held until cured (Figure 4-19, left). The procedure was repeated to attach the other cap to the farther end of the specimen and the final specimen is shown in Figure 4-19 (right).

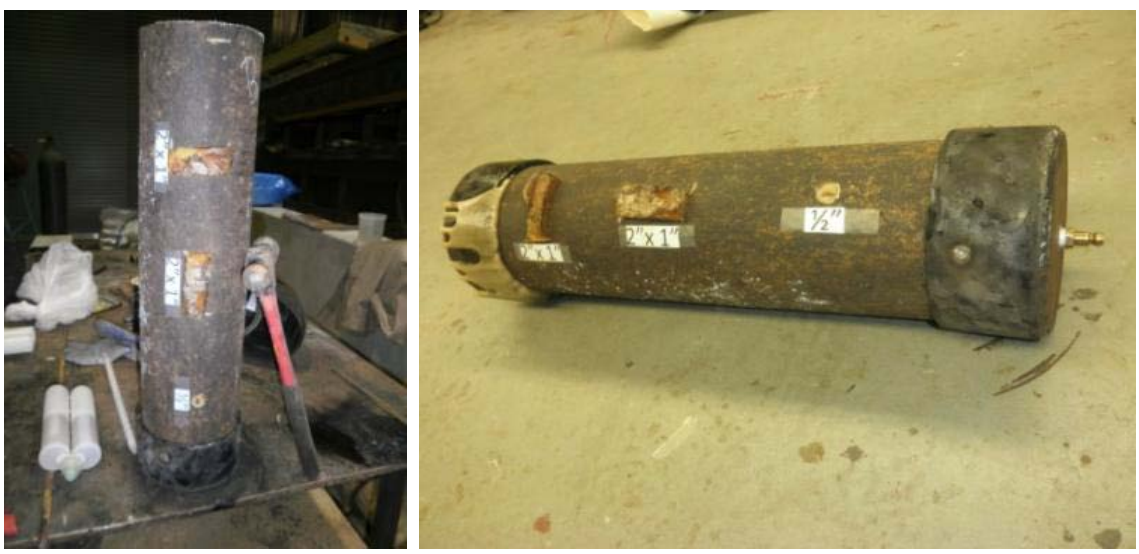


**Figure 4-19. Specimen with a Cap on One Side (left) and the with Caps on Both Sides (right)**

The sealed specimen was placed on top of a custom-made support as shown in Figure 4-20. Four LVDTs were installed on the specimen: one on the crown, two on the spring-lines, and one on the invert, to monitor and record any deflection induced by the vacuum inside the specimen. A vacuum pump of 100 kilopascals, kPa (1 bar) capacity was turned on and the vacuum was gradually created by sucking the air out of the specimen. The gauge pressure was gradually increased to 1 bar and held at this level for 70 hours.

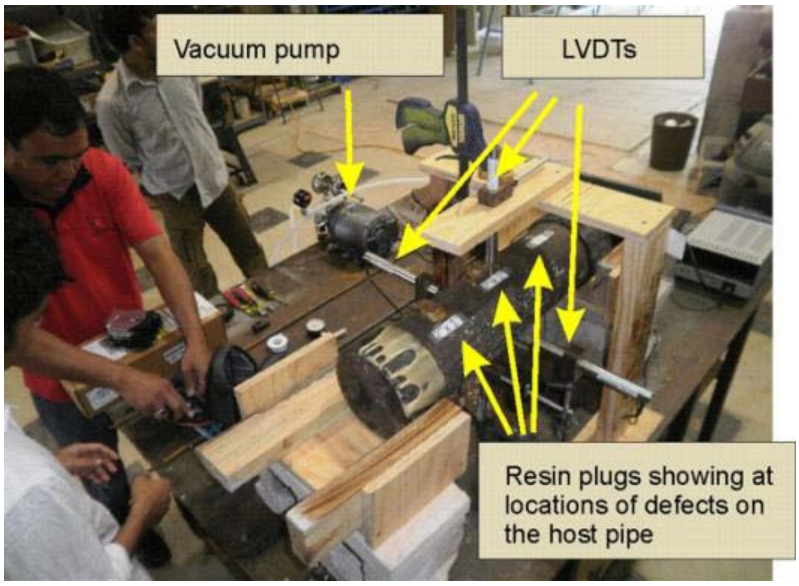


**Figure 4-20. Complete Experimental Setup**

Figure 4-21 shows deflections measured by the LVDTs, which were very small (i.e., less than 0.003 in.). The LVDT in the liner's crown (where defects manufactured in the host pipe prior to relining were located) measured slightly larger deflections compared to other LVDTs where measured values were close to zero. The liner withstood the vacuum force (-14.5 psi) for 70 hours with very little deflection.

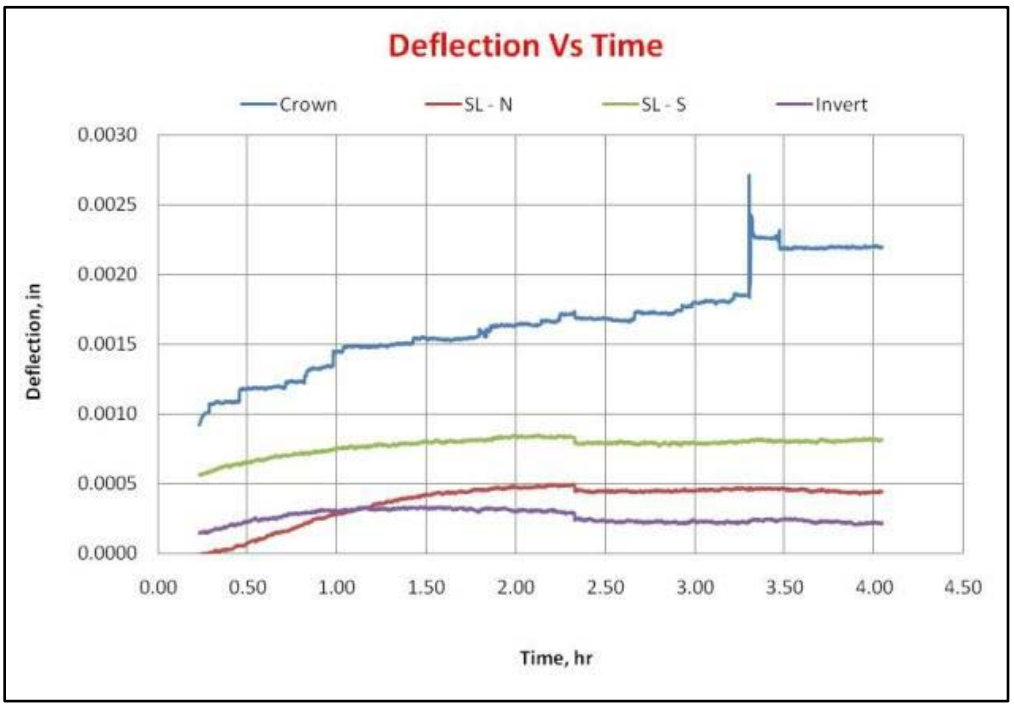


**Figure 4-21. Deflection Readings during the Vacuum Test**

**4.4.7 Short-Term Pressure Testing**. The liner was taken out of the host pipe and a 14 in. long section cut out as described in Section 4.4.6 (vacuum test). A 0.5 in. thick, 6 in. inner diameter steel pipe that would act as a host pipe for the short-term pressure test (buckling test) was prepared by drilling two threaded holes on the opposite sides of the host pipe to attach quick connectors as shown in Figure 4-22.

**Figure 4-22. Buckling Test: Close-up of Quick Connector (left) and Both Quick Connectors (right)**

The liner was placed inside the steel pipe and two custom-designed caps were fabricated for the ends. A small, elevated platform was placed inside the cap and resin was poured and later, the pipe with the liner was placed on the cap as shown in Figure 4-23.

**Figure 4-23. Resin inside the Cap (left) and the Host Pipe and Liner placed on the Cap (right)**

Next, the inner side of the outer flange of the cap and outer side of the host pipe were filled with resin to seal the cap to the host pipe in the cap. Resin was also poured between the inner side of the inner flange of the cap and interior side of the liner. Following the same procedure, the opposite side of the pipe was also capped as shown in Figure 4-24.

**Figure 4-24. Pouring Resin to Attach the Cap to the Host Pipe**

A leak test was first performed on the sample using green food coloring to trace any leaks (Figure 4-25) in order to confirm that the specimen was ready for the external pressure (buckling) test.

**Figure 4-25. Leak Test (left) and adding Green Coloring to the Water (right)**

The buckling test was performed according to the protocol outlined in Table 4-6. Pressure was applied using a high pressure pump and some of the pressure steps are shown in Figures 4-26 through 4-29. There were no visible leaks or deformations observed on the liner during the test up to a final pressure of 140 psi.

**Table 4-6. Buckling Test Protocol**

| Reading | Pressure (psi) | Duration (mins) | Remarks |
|---|---|---|---|
| 1 | 0 | 15 | Space between the host pipe and liner flooded to bleed out air |
| 2 | 5 | 2 | Check for any leak |
| 3 | 10 | 5 | No visible leak or deformation on the liner |
| 4 | 20 | 10 | No visible leak or deformation on the liner |
| 5 | 30 | 15 | No visible leak or deformation on the liner |
| 6 | 60 | 30 | No visible leak or deformation on the liner |
| 7 | 100 | 30 | No visible leak or deformation on the liner |
| 8 | 120 | 30 | No visible leak or deformation on the liner |
| 9 | 140 | 60 | No visible leak or deformation on the liner |

**Figure 4-26. Bleeding Out of the Air (left) and Purging the Line (right)**

**Figure 4-27. 20 psi Pressure (left) and No Signs of Distress (right)**

**Figure 4-28. 60 psi Pressure (left) and No Signs of Distress (right)**

**Figure 4-29. 140 psi Pressure (left) and No Signs of Distress (right)**

4.4.8 Specific Gravity. Specific gravity was measured utilizing the displacement method in accordance with ASTM D-792 (ASTM, 2008c). The standard specifies that any convenient size specimen can be used for this testing. The weight of 10 specimens was measured in air and in water, and specific gravity was calculated for each specimen using the equation advised in ASTM D-792. The average specific gravity for the sample was calculated to be 1.154 and standard deviation 0.093 as shown in Figure 4-30.

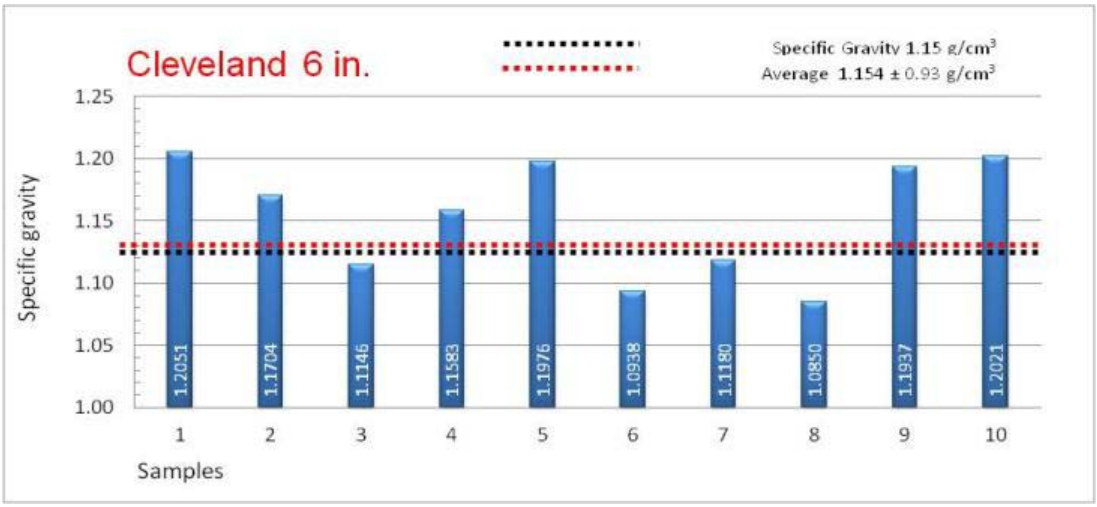


**Figure 4-30. Specific Gravity of the Samples**

4.4.9 Pressure Burst Testing. The exhumed host pipe/liner sample delivered to the TTC did not have sufficient length for also preparing a sample that could be used in pressure bursting tests. Therefore, results from bursting tests performed on a different yet very similar pipe relined several years ago using the same CIPP liner in Canada (Allouche and Moore, 2005) is discussed in Appendix B.

4.4.10 Raman Spectroscopy Testing. The Raman spectroscopy testing was completed by TTC and the results of the tests are shown in Figure 4-31. The tests were conducted on six samples, four of which were base samples for comparison and two samples taken from the liner retrieved from the field. The field samples were taken from the crown and invert of the liner.

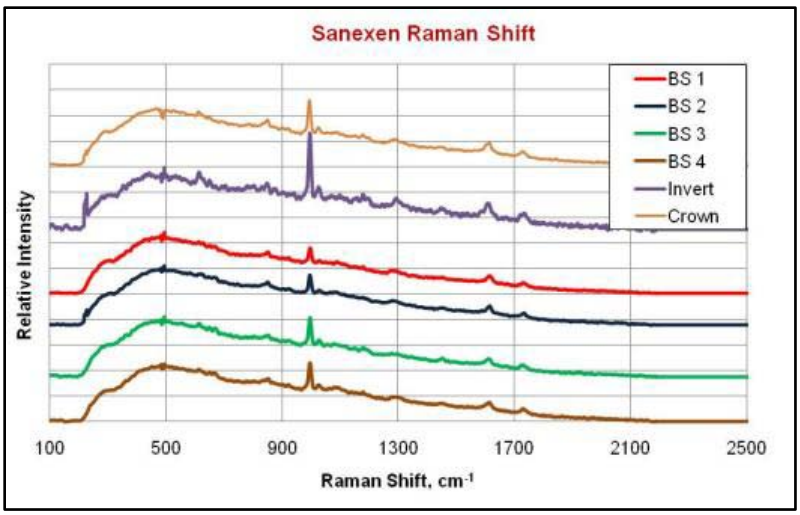


**Figure 4-31. Results of Raman Spectroscopy Testing**

The field retrieved samples showed similar peaks to the base samples although not the same magnitude. This means that no resin degradation has occurred, which should be expected since the liner was not exposed to water for very long before being exhumed. This test is useful in providing baseline data, which can be used for future comparison to help indentify resin degradation over time.

4.4.11 Summary. Table 4-7 summarizes the test results for the testing of the Sanexen Aqua-Pipe® CIPP liner used in the Cleveland demonstration compared with the minimum design values.

**Table 4-7. Summary of Test Data for Aqua-Pipe® CIPP Liner**

| Test | Suggested Specification[(a)] | Minimum Design (ASTM F-1216) | Average Lab Value |
|---|---|---|---|
| Liner Thickness, mm (in.) | 2.5 (0.10) | 2.5 (0.10) | 4.72 (0.19)[(b)] |
| Pipe/Liner Ovality, % | 2.0 | N/A | 2.5 |
| Tensile Strength, psi (MPa) | 10,000 (68.9) | 3,000 (20.7) | 9,415 (64.9) |
| Flexural Strength, psi (MPa) | 10,000 (68.9) | 4,500 (31.0) | 7,982 (55.0) |
| Flexural Modulus, psi (MPa) | 350,000 (2,413) | 250,000 (1,724) | 366,928 (2,530) |
| Inner/Outer Hardness, Shore D | N/A | N/A | 40.7/63.9 |
| Inner/Outer Hardness, Barcol | N/A | N/A | 2.1/9.7 |
| Short-Term Pressure, psi (MPa) | N/A | N/A | 140 (0.97) |
| Negative Pressure, psi (MPa) | -14.5 (-0.10) | N/A | -14.5 (-0.10) |
| Specific Gravity, g/cm$^3$ | 1.150 | N/A | 1.154 |

[(a)] Manufacturer suggested specification as of May 2011.
[(b)] Includes thickness of polyurethane liner

The tensile and flexural strengths measured in the lab were lower than the suggested manufacturer specification. This could be due to the fact that samples were taken from test sections of pipe containing several installed defects, which allowed some resin to escape during curing. In all, the liner mechanical properties (i.e., tensile strength, flexural strength, and flexural modulus) exceeded the minimum requirements for ASTM F-1216 despite those installed defects. The liner did perform in a manner consistent with a fully-structural, Class IV CIPP liner.

## 4.5 Technology Cost

The costs for the CIPP demonstration and associated activities are documented in Table 4-8. The cost item 'Structural CIPP lining" contains the costs for: setting up and disconnecting the 4 in. bypass; excavation and restoration of all 22 access pits for installation and service reconnection; cleaning, capping of service, CIPP installation, and internal service reinstatement; external service restatement; hydrant and valve replacement; and pipe reconnection and site restoration. In all, the demonstration resulted in a cost of $505,686 for the 2,040 ft test section (i.e., test section length includes the lined sections plus the replacement sections in between lining runs) for a unit cost of $247.89/lf. The structural CIPP portion of the project accounted for $374,000 of the project total for the 1,996 lf of main that was lined for a CIPP only unit cost of $187.38/lf.

**Table 4-8. Cost Summary for Cleveland Demonstration**

| Cost Item | Units | Unit Price | Cost |
|---|---|---|---|
| Bypass piping | 2,063.5 lf | $17.00 | $35,079.50 |
| 4 - cast iron valves | 4 each | $4,506.00 | $18,024.00 |
| 3 – replacement valves | 3 each | $4,506.00 | $13,518.00 |
| 6 – replacement hydrants | 6 each | $6,542.00 | $39,252.00 |
| 2 - hydrant risers | total | $989.83 | $989.83 |
| Replacement of main/pavement at Rocky River & Ferncliffe | total | $22,723.52 | $22,723.52 |
| Service connection | total | $2,100.00 | $2,100.00 |
| Structural CIPP lining | 1,996 lf | $187.38 | $374,000.00 |
| | | **Total** | **$505,686.85** |

## 4.6 Technology Environmental and Social Impact

Aqua-Pipe® is marketed as an alternative with low green house gas or carbon dioxide ($CO_2$) equivalent emissions when compared to conventional methods. The installation method required access pits at intervals of about 285 ft, reducing the equipment noise, disposal trucks, and hauling of bedding and backfill materials compared with open-cut. For this project, the advantage was reduced by the addition of 13 excavation pits for reinstatement of 17 service connections that could not be reinstated internally.

The estimated volume of wastewater generated during field activities was monitored and the total amount of wastewater generated during the demonstration project was 272,607 gal as shown in Table 4-9. The bypass system was initially flushed at 600 gpm for 15 minutes and the flowrate was reduced to 100 gpd for 7 days. During hydraulic jetting, approximately 1 gal/ft of water was used for the 1,996 ft test pipe and each pipe section was hydraulic-jetted four times. A flowrate of approximately 300 gpm was used during drag scraping and the time needed to drag-scrape the length of each test section was approximately 30 min and each of the seven test sections was drag-scraped four times. After lining, each test section was cured by circulating hot water, with every foot of 6 in. diameter pipe containing 1.47 gal.

**Table 4-9. Estimated Wastewater Volumes**

| Activity | Flow Rate | Time | Wastewater, gal |
|---|---|---|---|
| Bypass Flushing | 600 gpm<br>100 gpd | 15 mins<br>7 days | 9,000<br>700 |
| Hydraulic-Jetting | 1 gal/ft = 1994 gal/pass | 4 passes | 7,976 |
| Drag-Scraping | 300 gpm | 120 mins/section | 252,000 |
| Liner Curing | 1.47 gal/ft = 2931 gal | N/A | 2,931 |
| | | **Total** | **272,607** |

In addition to the reduced environmental and social impact, the product is marketed as a technology with low $CO_2$ equivalent emissions compared to traditional open cut. $CO_2$ equivalents or green house gases make up the carbon footprint and include $CO_2$, $CH_4$, and $N_2O$. Among the tools available commercially to show the benefits of similar technologies is the e-Calc tool, which was developed at Arizona State University for horizontal directional drilling (HDD) manufacturer Vermeer to illustrate the advantages of using trenchless technologies. The e-Calc was used to calculate the environmental impact for each of the major activities included in construction including: laying out and setting up the bypass; excavating the access pits; cleaning and swabbing; CIPP liner installation; site restoration; and bypass removal. The tool takes into account specific vehicle and equipment parameters, such as the vehicle parameters shown in Figure 4-32, to calculate the emissions including $CO_2$, shown in the results in Figure 4-33.

| Transport Details | | | | | Fuel Details | | Project Details | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Name | Make | Model Year | Gross Vehicle Weight (GVW) (lbs.) | Mileage (mi) | Type | Sulfur (%) | Altitude | Number of Trips | Oneway Distance (mi) | Return Distance (mi) |
| Utility Van | Ford E-350 | 2000 | 8,501-10,000 | 1000 | Diesel | 0.05 | Low | 6 | 30 | 30 |
| Truck | Ford F-650 | 2000 | 19,501-26,000 | 1000 | Diesel | 0.05 | Low | 6 | 30 | 30 |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |

Print Form | Go To Next Method | Summary | RESET

**Figure 4-32. Transport Vehicles Required Each Day during Bypass Installation**

| HC (lbs) | CO (lbs) | NOx (lbs) | PM (lbs) | CO2 (S/T) | SOx (lbs) |
|---|---|---|---|---|---|
| 0.23 | 1.03 | 2.82 | 0.09 | 0.31 | 0.19 |
| 0.48 | 1.31 | 5.69 | 0.14 | 0.47 | 0.29 |
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.7 lbs | 2.3 lbs | 8.5 lbs | 0.2 lbs | 0.78 S/T | 0.5 lbs |

**Figure 4-33. Results from e-Calc Showing Impact of Transport Vehicles**

The total carbon emissions from lying out and connecting the bypass piping for vehicles and equipment were equal to 1.02 short tons or roughly 2,040 lbs of $CO_2$. The equipment used during this activity and input into e-Calc included the use of two generators to power the heat fusion welder for fusing the 6 in. HDPE bypass piping and a chainsaw for cutting the pipe, as shown in Figure 4-34.

| Equipment Details | | | | | | | Fuel Details | | Project Details | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Name | Model | Power (hp) | Model Year | Engine Tech. | Useful Hours | Cum. Hrs Used | Type | Sulfur (%) | Representative Equipment Cycle | Power Used (%) | Use (hrs) |
| Boldor | PC30H | 5.5 | 2005 | Tier 2 | 5000 | 50 | Gas | 0.33 | Other Construction Equipment | 90 | 32 |
| Bluemax | Gen 4000 | 6.5 | 2005 | Tier 2 | 5000 | 50 | Gas | 0.33 | Other Construction Equipment | 90 | 32 |
| Chainsaw | Oregon | 3 | 2005 | Tier 2 | 5000 | 50 | Gas | 0.33 | Other Construction Equipment | 90 | 10 |

**Figure 4-34. Equipment Required for Bypass Installation**

The e-Calc process was completed for each of the major activities and the impacts from each of the major activities are summarized in Table 4-10. During these calculations, some assumptions had to be made as to the year and size of the engine of some pieces of equipment. Table 4-11 outlines the year and sizes used to determine the emissions in Table 4-10. In all, the entire demonstration portion of the project contributed more than 52,000 lb of $CO_2$ emissions.

**Table 4-10. Total $CO_2$ Emissions for Each Major Activity**

| Activity | $CO_2$ Emissions |
|---|---|
| Bypass layout and hookup (equipment and vehicles) | 1.02 short tons (2,040 lb) |
| Excavating access pits (equipment and vehicles) | 5.30 short tons (10,600 lb) |
| Cleaning and Swabbing (equipment and vehicles) | 4.13 short tons (8,260 lb) |
| Lining with mobilization/demobilization (equipment and vehicles) | 5.89 short tons (11,780 lb) |
| Site restoration (equipment and vehicles) | 9.84 short tons (19,680 lb) |
| Bypass disconnection (equipment and vehicles) | 0.26 short tons (520 lb) |
| **Total** (Including All Activities) | **26.44 short tons (52,880 lb)** |
| **Total** (Without 600 mile Mobilization and 13 Additional Pits) | **18.80 short tons (37,600 lb)** |

**Table 4-11. Equipment Specifications**

| Equipment | Year/HP | Activity | Use (hr) |
|---|---|---|---|
| CAT 420E Backhoe | 2005/93 | Excavation/ Cleaning/ Lining/ Restoration | 44/ 20/ 25/ 93 |
| Honda GX 160 Trash Pump | 2005/5 | Cleaning/ Lining/ Restoration | 20/ 20/ 10 |
| Boldor PC30H Generator | 2005/5.5 | Bypass | 32 |
| Bluemax 4000 Generator | 2005/6.5 | Bypass | 32 |
| Oregon Chainsaw | 2005/3 | Excavation | 10 |
| Deutz Winch Motor | 2005/50 | Cleaning | 48 |
| Kubota GL 7000 Generator | 2005/11 | Lining | 23 |
| Mole Generator | 2005/11 | Restoration | 11 |
| Ford 6550 Backhoe | 2005/70 | Restoration | 16.5 |
| C-24 Compressor | 2005/2 | Restoration | 16 |
| Ingersoll Rand Roller | 2005/175 | Restoration | 7 |
| Tack Buggy | 2005/50 | Restoration | 8 |
| Skid Steer | 2005/40 | Restoration | 4 |

One of the largest contributors of $CO_2$ for the Cleveland demonstration was the mobilization of the lining crew vehicles, which were driven 600 miles to Cleveland from Montreal for mobilization and another 600 miles for demobilization. The mobilization/demobilization accounted for 14% of the estimated $CO_2$ footprint. By removing the mobilization/demobilization activities, the total $CO_2$ emissions would be lowered from 26.44 short tons (52,880 lb) to 22.73 short tons (45,460 lb). As the technology became more mature, it would be expected that more local contractors could be licensed and trained to install the product.

The activity with the most $CO_2$ emissions for this demonstration was site restoration, which was affected by the excavation pits required for installation access (9 pits) and the service reinstatements, which required an additional 13 pits. If only 5% (3 of 63) of the services were reinstated externally, the $CO_2$

impact from the equipment used for site restoration could have been reduced by 50%, reducing the overall emissions by 4.91 short tons (9,480 lb) from 26.44 short tons (52,880 lb) to 21.52 short tons (43,040 lb). If this reduction was combined with the removal of mobilization/demobilization, the total $CO_2$ impact could be reduced from 26.44 short tons (52,880 lb) to 18.8 short tons (37,600 lb), or 71 %.

The environmental impact of the demonstration can be compared to a typical pipe replacement by estimating the impact of installing 1,996 ft of new 6 in. cast iron main. The bypass layout and hookup for both projects would be similar (1.02 short tons), but the impact of the excavation, installation, and restoration would be the primary difference in the environmental impact. The original excavation of the access pits required 6 days of labor and equipment, but the full excavation of 1,996 ft required to install a new 6 in. ductile iron main while reinstating services would take around 20 days and equates to an estimated $CO_2$ emission impact of 17.7 short tons, up from 5.3 short tons. Bypass disconnection would also be similar for both projects (0.26 short tons), but surface restoration again would require more than three times as much labor and equipment time (i.e., 5.91 short tons by 3.33 or 19.7 short tons).

In all, the $CO_2$ emissions in short tons from a pipe replacement project including bypass setup (1.02) and disconnection (0.26), excavation and pipe installation (17.7), and site restoration (19.7) and assuming the host pipe is abandoned in place, would amount to an estimated 38.68 short tons (77,360 lb) of $CO_2$ emissions. This is approximately two times higher than the adjusted total for the lining demonstration (from which the 600 mile mobilization activity and excavation of an additional 13 pits had been removed). To put the $CO_2$ emissions in prospective, the $CO_2$ emissions for the U.S. in 2008 were 5.833 billion metric tons, which translates to 19.2 tons or 38,400 lb per person in one year (Energy Information Administration [EIA], 2010). Therefore, the savings realized from using the lining method, which was roughly 19.9 tons, versus an open-cut replacement would account for more than 100% of one person's $CO_2$ emissions for one year.

The comparison of on-site operations estimated above (i.e., 18.8 shorts tons for 2,000 ft of Aqua-Pipe) is comparable to the 33 short tons of $CO_2$ estimated by Sanexen for one mile of Aqua-Pipe (Sanexen, 2011b). The calculations above do not account for $CO_2$ emissions due to material production, which accounts for the majority of the $CO_2$ equivalent emissions when calculating a complete carbon footprint. Sanexen calculated that when material production is taken into account, green house gases are reduced by 84% or 1/6 the total for an open-cut project (Sanexen, 2011b). This value was not independently verified for this project, but the Sanexen report was verified by BNQ according to the requirements of the international standard ISO 14064-3 (Sanexen, 2011b). The BNQ is accredited by the Standards Council of Canada, which confers international recognition in the field of green house gas quantification.

# 5.0: CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

The demonstration of the Sanexen Aqua-Pipe® CIPP liner in Cleveland, Ohio was a successful project that provided valuable information on the design, installation, and QA/QC for CIPP used to rehabilitate water mains. Table 5-1 summarizes the overall conclusions for each metric used to evaluate the technology.

**Table 5-1. Technology Evaluation Metrics Conclusions**

| |
|---|
| **Technology Maturity Metrics** |
| • Innovative technology used at less than 30 sites in the U.S.<br>• Improvement over traditional rehabilitation using cement mortar lining (Class IV versus Class I).<br>• Some data available, but long-term testing are ongoing and the method track record spans 10 years.<br>• Each utility owner contacted cited positive results and wiliness to use the product again. |
| **Technology Feasibility Metrics** |
| • Project required a structural rehabilitation and the technology met the rehabilitation requirements.<br>• Liner was not installed through any valves or fittings and the runs were without any major bends.<br>• Incomplete and/or premature curing of the liner was not evident during installation or inspection. |
| **Technology Complexity Metrics** |
| • Beneficial for small, medium, and large utilities in need of structural alternatives to open cut replacement.<br>• Requires trained installers. Pre- and post-installation activities can be performed with typical personnel.<br>• Site preparation requirements are similar to other rehabilitation technology requirements.<br>• Lasted 10 weeks: two weeks for bypass/excavation, seven weeks for pipe preparation, liner installation and reconnection while pipe was out of service, and one week for remaining site restoration.<br>• 5% (3 of 63) of the services had to be reinstated externally due to commonly seen issues and another 22% (14 of 63) had to be reinstated externally due to extraordinary events the manufacturer has rarely encountered. |
| **Technology Performance Metrics** |
| • Mechanical testing showed that the field applied liner exceeded the requirements of ASTM F-1216.<br>• Performed in a manner consistent with a fully-structural Class IV CIPP liner.<br>• Hazen-Williams C-factor was improved by nearly 43% from 78.5 to 112.1. |
| **Technology Cost Metrics** |
| • The overall demonstration cost $505,687 for a unit cost of $247.89/lf.<br>• The CIPP portion of the project accounted for $374,000 of the total cost for a unit cost of $187.38/lf. |
| **Technology, Environmental and Social Metrics** |
| • Social disruption was minimal since traffic was not greatly affected and excavation was limited.<br>• Flush volumes required for bypass, jetting, and drag scraping were estimated to be 272,600 gal.<br>• Estimated 52,880 lb of $CO_2$ emissions for on-site operations, which could have been reduced to 37,600 lb if the lining crew had not mobilized from 600 miles away. (A similar replacement project would emit 77,360 lb of $CO_2$.)<br>• A similar replacement project would emit 77,360 lb of $CO_2$ for on-site operations and transportation and up to 6 times more $CO_2$ when considering material production emissions.<br>• If only 5% of the services were reinstated externally, the $CO_2$ impact from the equipment used for site restoration could have been reduced by 50%, an additional 9,480 lb of $CO_2$ emissions. |

This project resulted in the successful demonstration of an innovative Class IV water main rehabilitation technology, which is an improvement over traditional Class I rehabilitation techniques. The technology met the owner's requirements for the project and multiple utilities that had used the technology expressed their willingness to use the technology again. The entire demonstration took place over the course of 10

weeks including: two weeks for setting up the bypass and excavating access pits; seven weeks for pipe preparation, liner installation, and reconnection to the system while the pipe was out of service; and one week for remaining site restoration activities. Laboratory mechanical testing showed that the liner exceeded the minimum requirements of ASTM F-1216 and performed in a manner consistent with a fully-structural Class IV CIPP liner.

## 5.2 Recommendations

In all, the demonstration was successful, but continued improvements should be made in the process for internal reinstatement of services. For this demonstration, issues commonly encountered resulted in 5% of the services needing to be reinstated externally, while another 22% of the services had to be reinstated externally due to pre-existing issues with service line/saddle alignment, which have rarely been encountered by the manufacturer. The 27% of services reinstated externally more than doubled the amount of excavation and surface restoration required for the project. It is recommended that the cleaning process, which contributed to deformation of eight of the 17 (47%) services requiring external reinstatement, be standardized in order to avoid damaging or deforming the corporation stops prior to rehabilitation. It is also recommended the other issues contributing to the need for external reinstatement be studied and improved upon including: (1) flush service connections that cannot be identified in smaller diameter pipes; and (2) difficulty drilling service connections located in folds. In addition, because folds in the liner are considered a typical installation occurrence (from over-sizing of the liner to ensure adequate coverage), it is recommended that the design equations be modified to take into account this folding (currently the design equations in ASTM F-1216 do not account for the folding in the ovality calculation). This could help to potentially establish the amount of folding that could be tolerated without a decline in the structural performance of the liner.

## 6.0: REFERENCES


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# APPENDIX A

## CCTV LOGS

The following figures are field logs written by the CCTV operator. Included in the logs are the pre-lining CCTV logs, which include post-lining comments for lining runs #1 through #7 (Figures A-1 through A-7).

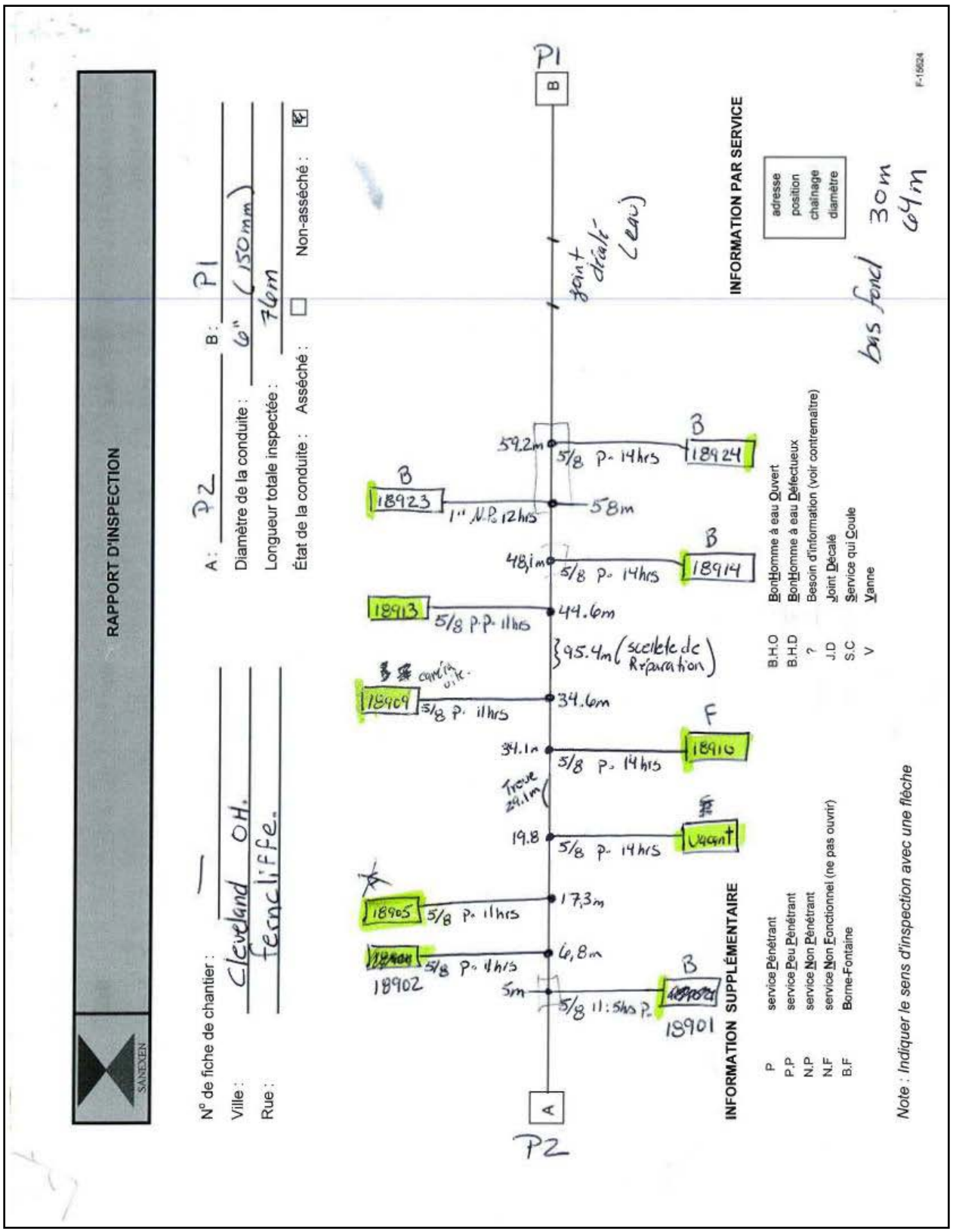


**Figure A-1. CCTV Log for Lining Run #1**

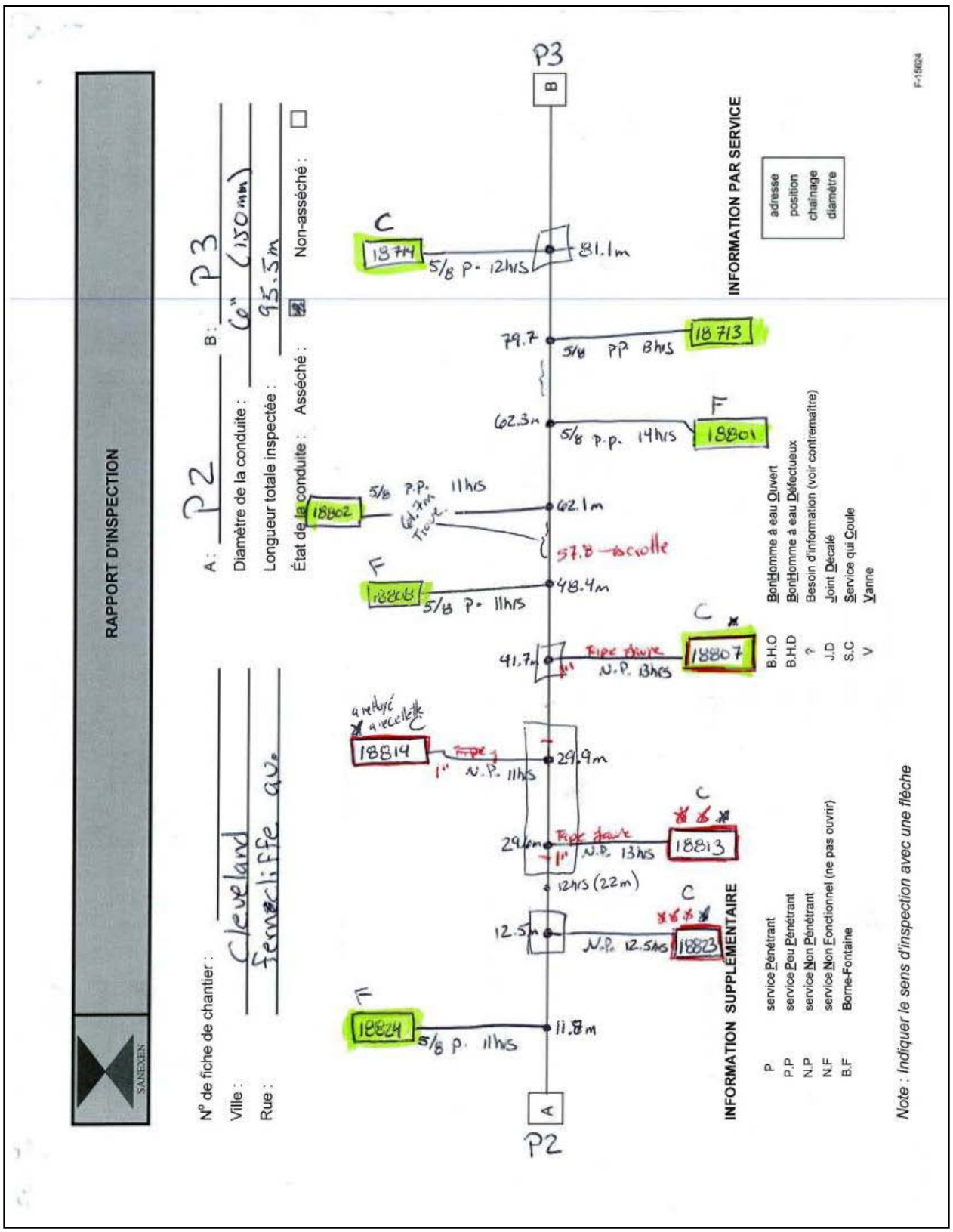


**Figure A-2. CCTV Log for Lining Run #2**

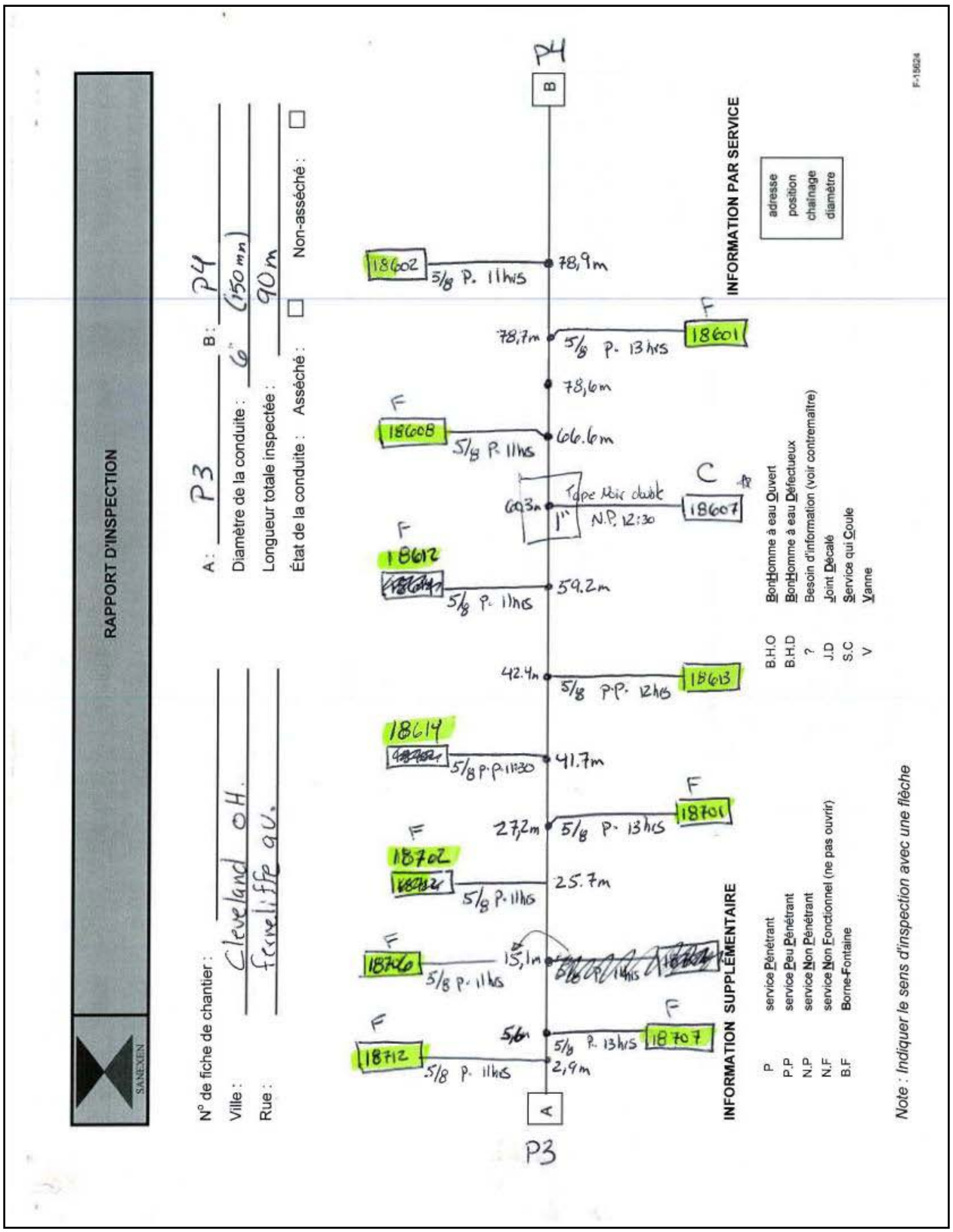


**Figure A-3. CCTV Log for Lining Run #3**

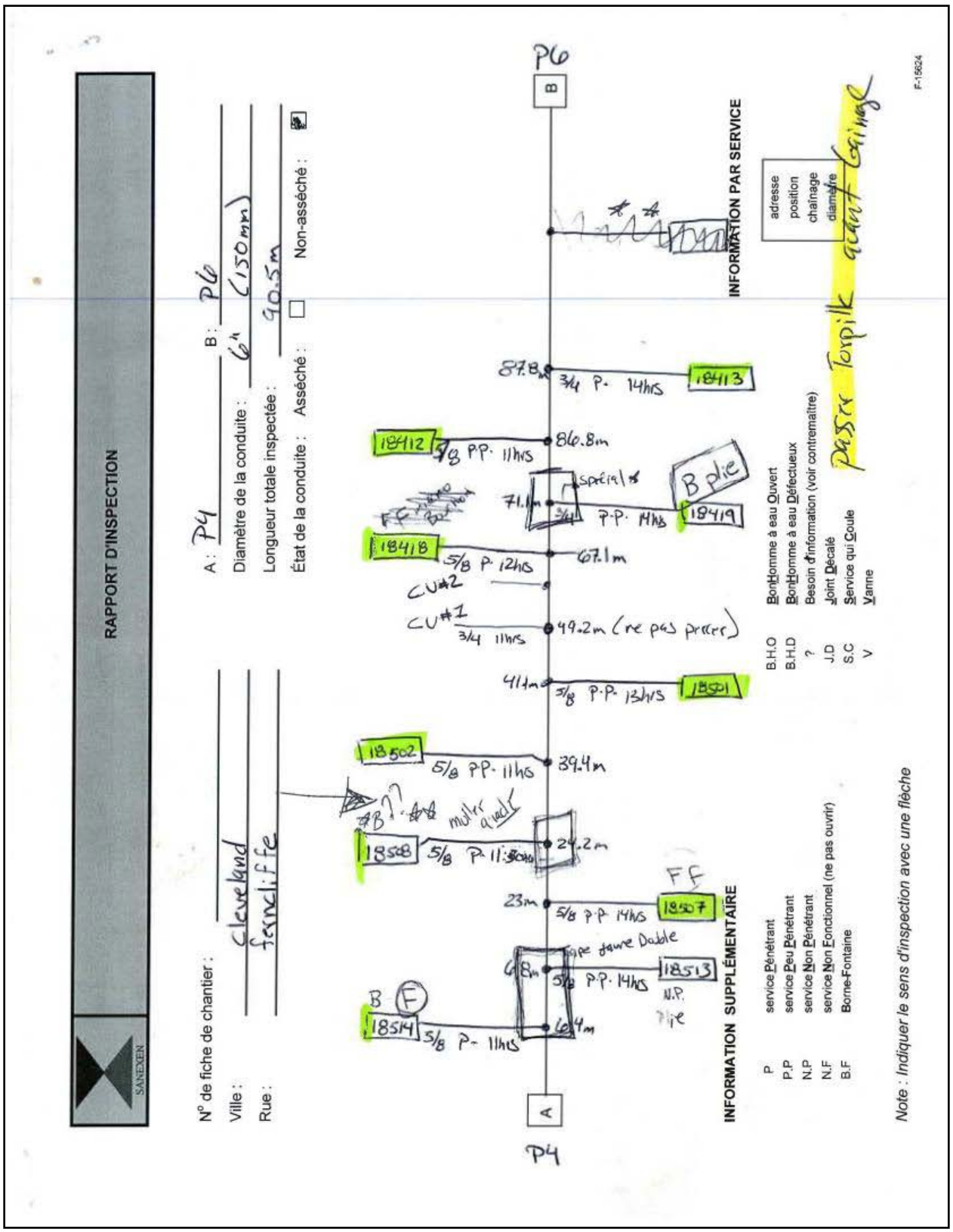


**Figure A-4. CCTV Log for Lining Run #4**

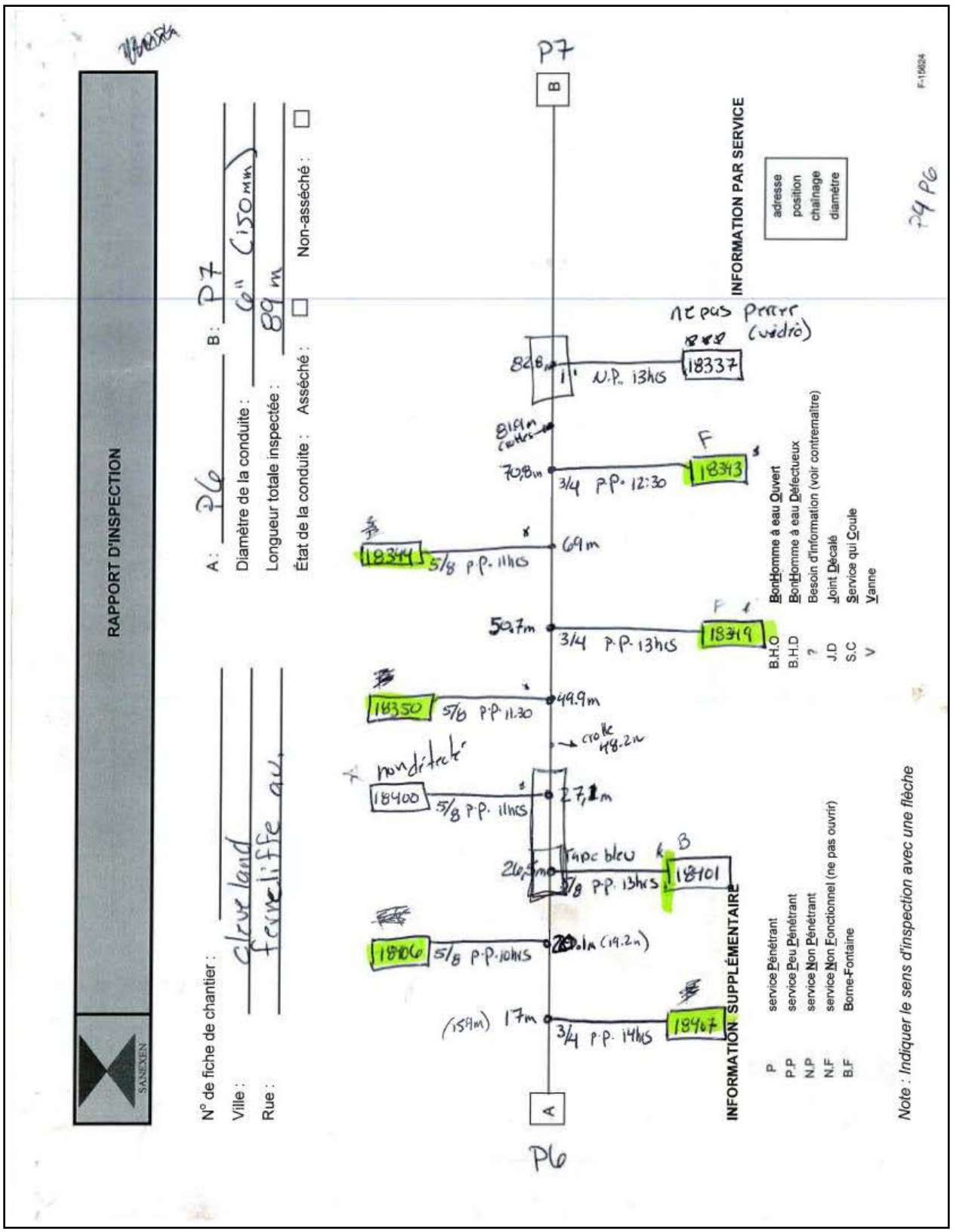


**Figure A-5. CCTV Log for Lining Run #5**

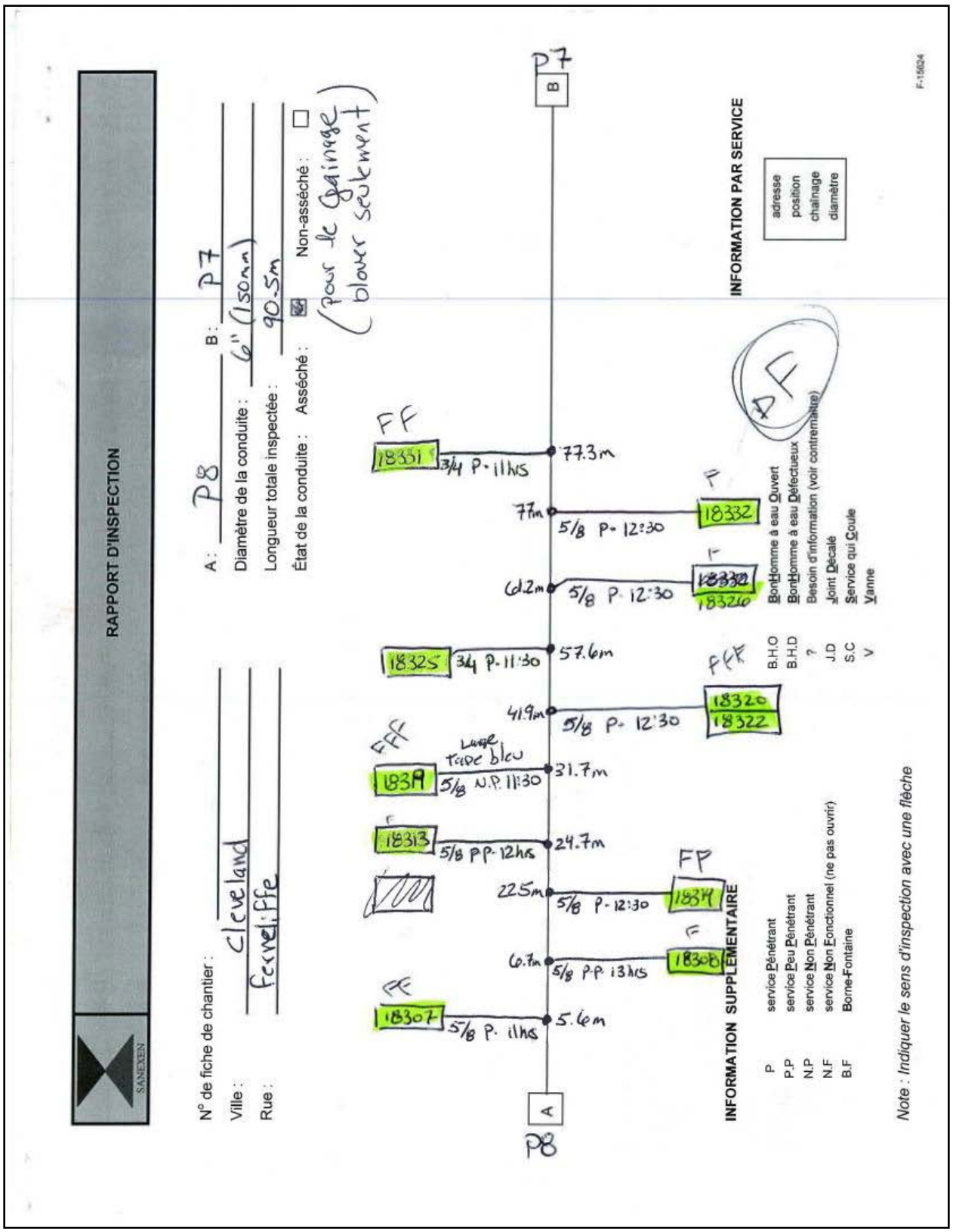


**Figure A-6. CCTV Log for Lining Run #6**

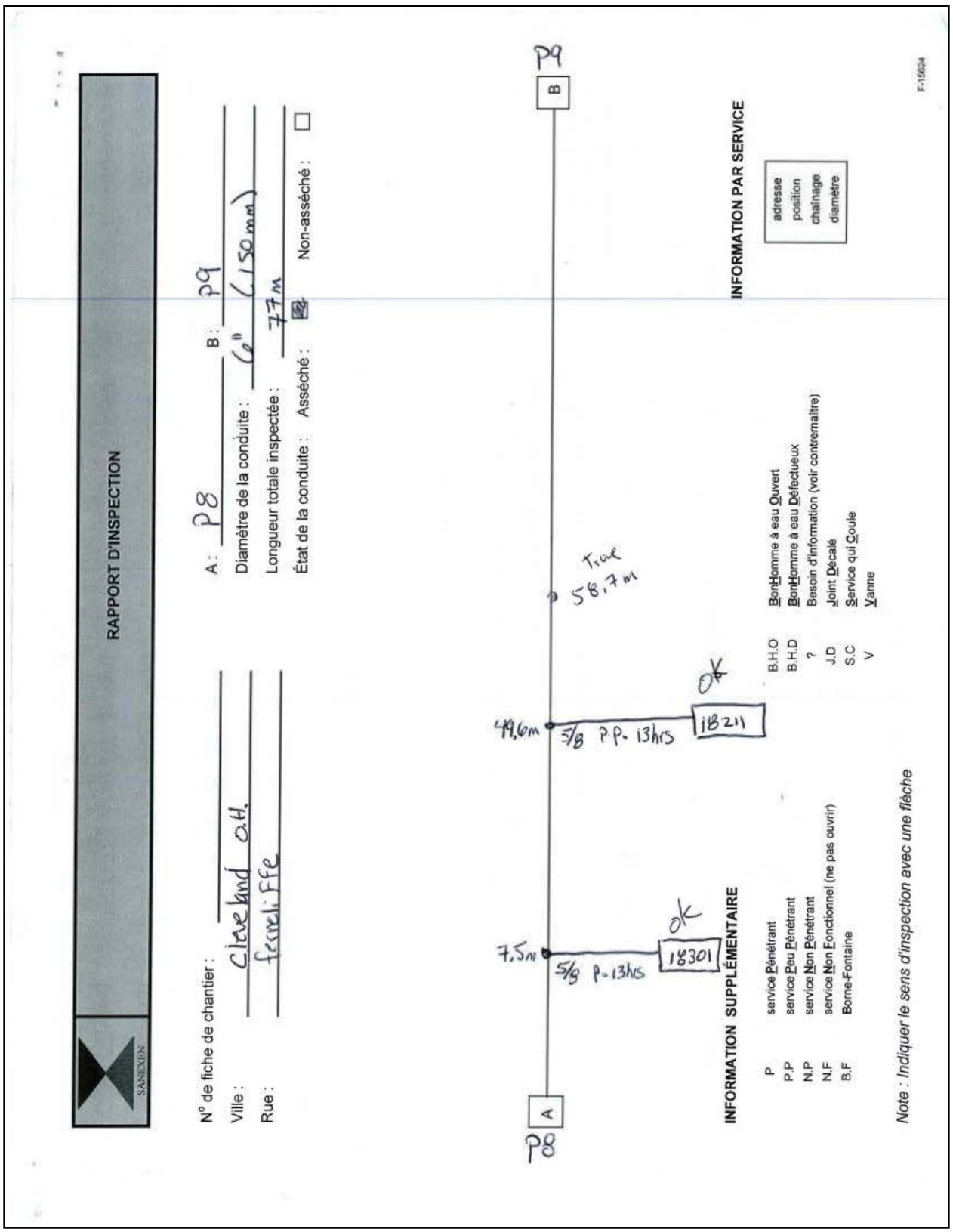


**Figure A-7. CCTV Log for Lining Run #7**

# APPENDIX B

# BURSTING TESTS

The exhumed host pipe and liner sample delivered to TTC did not have sufficient length for preparing a sample that could be used in pressure bursting tests. Therefore, results from bursting tests performed on a different yet very similar pipe relined several years ago using the same CIPP liner in Canada (Allouche and Moore, 2005) is discussed below.

The host pipe was a 6 in. cast iron water main approximately 3,300 ft long, which had been relined using Aqua-Pipe® in 2003. Exhumed liner samples are shown in Figure B-1 (left). For performing the testing, a custom-made pressure cell was fabricated at the University of Western Ontario shown in Figure B-1 (right). Pipe specimens filled with water were placed into the cell, one at a time, which had 12 rods for restraining the ends of the tested specimen. The apparatus could generate an internal pressure of up to 725 psi with an accuracy of up to ±5 psi.

**Figure B-1. Exhumed Liner Samples (left) and a Custom-made Pressure Cell (right)**

A total of eight short-term (quick burst) tests and one long-term bursting test were completed on the specimens, as listed in Table B-1.

**Table B-1. List of Bursting Tests Performed on the Aqua-Pipe® Lined Specimens**

| Test | Pressure | Objective/Specimen |
|---|---|---|
| #1 | 400 psi | Short-term hydrostatic pressure capacity of the host pipe/liner system/ Straight section with a bell-joint (Figure D-2) |
| #2 | 550 psi | Fire hydrant tee with two bells (Figure D-3) |
| #3 | 550 psi | Straight section with a stainless steel repair clamp (Figure D-5) |
| #4 | 550 psi | Specimen from Test #3 with the repair clump removed (Figure D-5) |
| #5 | 310 psi | Specimen from Test #4, with additional damage (Figure D-6) |
| #6 | 310 psi | Role of longitudinal folds creating high strain concentrations in the liner/ Straight section with a long longitudinal fold (Figure D-7) |
| #7 | 300 psi | Integrity of a tap connection subjected to high, prolonged internal pressure/ Specimen with three tap connections spaced 6 in. apart (Figure D-9) |
| #8 | 250 psi | Identify potential problems with inserting new taps/ Same specimen as in Burst Test #7 |

Summary

From a material prospective (i.e., flexural strength, elastic modulus, ductility) the Aqua-Pipe® liner is capable of resisting internal pressures as high as 550 psi under burst test conditions, while spanning a gap

8 in. long and 6 in. wide in the host pipe with a maximum deformation of 0.27 in. (7 mm). The Aqua-Pipe® liner is capable of sealing a ring break and extensive corrosion pits in the host pipe under an internal pressure of 550 psi. A significant decline in the structural performance of the liner is possible if certain undesirable construction practices are used, such as excessive over-sizing of the liner and uneven or incomplete wet-out of the liner, in the case of a fully deteriorated host pipe.

While the long-term effect of such voids on the structural performance of the liner-tap connection interface could not be determined in this testing program, no failure was observed in and around the interface area when it was subjected to an internal pressure of 300 psi over 135 minutes. When performing a live tap on a lined cast iron pipe using standard tapping equipment, the liner beneath the tap is not completely removed; thus, the risk exists that the partially cut liner tab will detach at some later time and plug a downstream tap connection. A tight fitting liner of minimum thickness 5 mm can resist buckling under full vacuum (equivalent to about 15 psi of external pressure). The liner can withstand 9 psi of external pressure if unconfined (a design value of 4.5 psi using a factor of safety of 2).