

Contract # DTPH56-13-T-000013

Prepared for: U.S. DOT/PHMSA

**Technology Transfer Demonstrations and Post-Mortem Testing of Cast Iron
and Steel Pipe Lined with Cured-in-Place Liners (CIPL)**

**Final Report
(Public Version)**

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December, 2015

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ACKNOWLEDGEMENTS

The authors express their thanks to the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA), Con Edison, National Grid, PECO, and PSE&G for providing support for this project. In particular, we appreciate the expertise, technical oversight and contributions provided by Rick Trieste (Con Edison), George Ragula (PSE&G), Mary Holtzmann (National Grid), and Mark Andraka (PECO).

EXECUTIVE SUMMARY

This report presents the results of a project jointly supported by NYSEARCH/Northeast Gas Association and the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration to evaluate the performance of field-aged cured-in-place pipe liners (CIPL) that had been in service for 10 to 16 years. Pipe sections with these linings were retrieved from two field sites and subjected to 100 years of mechanical aging due to vehicular traffic, undermining/backfill events, and thermal cycling simulations. Vehicular traffic simulations were equivalent to 100 years (2,000,000 cycles) of a repetitive 40-kip (180-kN) tandem axle load with an impact factor of 1.5. Thermal aging was performed by simulating the expected contraction/expansion of a round crack in cast iron (CI) pipe due to a 40 °F (22 °C) seasonal temperature variation in the ground at typical pipe depths.

Specimens were retrieved from two field sites. Six-in. (150-mm)-diameter specimens were retrieved from a location in the Public Service Electric and Gas service area in Elmwood Park, NJ. The CI pipeline was installed in 1949, and a Starline®2000 liner was installed inside the pipeline in 1998. The pipe specimens were extracted in spring 2014 and sent to Cornell University for mechanical aging tests and material property characterization. Twelve-in. (300-mm)-diameter specimens were retrieved from a location in the National Grid service area in South Garden City, Long Island, NY. The CI pipeline was installed in 1951, and a Starline®2000 liner was installed inside the pipeline in 2004. The pipe specimens were retrieved in summer 2014 and testing began March, 2015. The joints of the 6 in. (150 mm) pipes were sealed with cement/mortar and jute caulking. The pipe joints for the 12 in. (300 mm) sections were mechanical clamps with a rubber sealing gasket.

Mechanical aging tests included flexure testing to simulate vehicular traffic, additional bending after an undermining/backfill event, and thermal contraction/expansion cycling to simulate the effects of seasonal variations in temperature. The testing program consisted of four-point bending (flexure) tests, simulating two 50-year-sequences of testing for a total of 100 years. Input displacements representative of deformation imposed by vehicular loading were determined from analytical models, which were validated by full-scale field tests, assuming soil and flexible pavement conditions typically found in gas distribution systems.

Thermal loads in buried piping are a direct result of temperature changes. Data for New York State and other parts of the Northeast US indicate that ground temperatures can fluctuate between 70 and 30 °F (21 and -1 °C). Thus, the maximum design temperature change due to seasonal variations in ground temperature in the northeastern US for typical distribution pipe depths is taken as $\Delta T = 40^{\circ}\text{F}$ (22°C). The anticipated axial movement associated with this temperature fluctuation was determined analytically by assuming the existence of a full circumferential crack in a lined cast iron pipe. One hundred cycles of thermal contraction/expansion were imposed on the test specimens, simulating 100 years of service life under upper bound thermal loading conditions.

No leakage was detected in any specimen throughout all phases of the mechanical aging tests. Following mechanical aging each test specimen was pressure tested. Pressure testing was conducted to a maximum pressure of 150 psig (1,034 kPa) and 90 psig (620 kPa) for 6 in. (150 mm) and 12 in. (300 mm) specimens, respectively. There were no leaks and all pipe sections maintained pressure integrity.

After mechanical testing, the pipe joints were cut longitudinally for visual inspection. The 6 in. (150 mm) joints with the CIPL showed debonding at the separation between bell and spigot that

was confined to a small distance either side of the separation, less than one pipe diameter in total width. This debonding allowed the liner to stretch without experiencing excessive strain, and demonstrated that the CIPL response involves local bonding adjustments that relieve high strain concentrations in the liner. This type of strain reduction is a highly desirable aspect of CIPL performance.

The 12 in. (300 mm) specimens did experience some minor liner damage. It is believed that this distress occurred during the first thermal loading cycle, which caused substantial debonding and some visually observed fiber damage. However, the liner did not leak because the polyurethane membrane remained intact and maintained its capacity to resist high internal gas pressure. This is a very important experimental observation. Fiber damage does not mean that the CIPL will leak because additional capacity is provided by the polyurethane membrane.

Additional material property characterization tests were performed to:

- 1) Characterize the residual tensile properties of the composite liner system as a way to assess the effects of field and mechanical aging on the liner system and their durability, and
- 2) Characterize the residual liner/CI pipe bond (adhesion) strength and assess the durability of the bond strength of field and mechanically aged specimens using lap shear and peel tests.

This allowed for an evaluation of whether the longitudinal and hoop tensile strengths of bonded, field-aged (FA) liner specimens are comparable to those for both bonded and debonded field and mechanically-aged (FMA) liner specimens. The testing showed that the liner strengths were comparable for the 6 in. (150 mm) specimens for FA and FMA liner specimens taken from bonded and unbonded sections of the liners. Thus, 100 years of mechanical aging did not have a significant effect on either the longitudinal or hoop tensile strengths of the 6 in. (150 mm) pipe liners.

For the 12 in. (300 mm) pipe liners, tensile strength reduction was measured in the immediate vicinity of damaged fibers in the debonded sections of the lining. Considerable tensile strength was still present in lining specimens with damaged fibers because the polyurethane membrane was intact, thus providing resistance to tensile test forces. In locations removed from the vicinity of damaged fibers, liner strengths were comparable for FA and FMA liner specimens taken from bonded and unbonded sections of the liners.

The testing for lap and peel strengths allows for an evaluation of whether the lap and peel strengths of the FA and FMA liner specimens are comparable to those of unaged specimens. A comparison of the lap shear strengths of FA and FMA specimens from the 6 in. (150 mm) and 12 in. (300 mm) pipe with the lap shear strengths of unaged specimens of cast iron pipe with Starline[®]2000 liner tested at Cornell in 2002 show no significant difference in the results. Thus, no loss of lap shear strength can be shown over the 10 to 16 years of service life in the field and for the 100 years of mechanical aging imposed on the specimens. These findings are important because the strength of the CIPL system depends strongly on the lap shear strength, especially for resistance to thermally induced contraction/expansion of the pipe at round cracks and the bell/spigot separation in a weak, deteriorated joint.

A comparison of the peel strengths of FA and FMA specimens from the 6 in. (150 mm) pipe with the peel strengths of unaged specimens of 6 in. (150 mm) cast iron pipe with Starline[®]2000 liner tested at Cornell in 2002 show no significant difference in the results. Peel strengths for the 12 in. (300 mm) specimens in this study are not comparable to those of the 6 in. (150 mm) specimens because installation of the liner in the field involves curing under internal pressure substantially

less than that for 6 in. (150 mm) pipe. The reduced pressure will result in a lower peel strength relative to that for the 6 in (150 mm) pipe, which is confirmed by the test results in this study. Thus, a critical conclusion from the testing is that there is no evidence of significant reduction in either lap or peel strength due to field aging over 10 to 16 years in addition to 100 years of mechanical aging.

Peer reviewed literature search reports were completed as part of this project for cured-in-place pipe lining in Japan in addition to North America and Europe.

On October 21, 2014, a live CIPL project demonstration was conducted at Con Edison in the Mt. Vernon, New York area with the Starline®2000 liner system utilizing current state of the art lining procedures on an 8 in. cast iron main and a 6 in. steel main. The 6 in. steel main was lined prior to the demonstration day so it could be inspected with a camera demonstrating second day lining procedures.

On August 20, 2015, a CIPL project workshop and webinar was conducted at the Roosevelt Hotel (45 East 45th Street, N.Y.). Project results were reviewed with industry and regulatory officials.

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Section 1

Technology Transfer Demonstrations and Post-Mortem Testing of Cast Iron and Steel Pipe Lined with Cured-in-Place Liners (CIPL)

1.1 Introduction

The project's work scope included: 1) the compilation of prior CIPL research conducted in the U.S., Europe, and Japan, 2) a live demonstration following state-of-the-art liner field installation procedures on selected field segments of cast iron and steel distribution pipelines, and, 3) extracted field aged CIPL segments (6 in. and 12 in. diameter) of cast iron pipe that were tested for an additional (100) years of simulated in-service equivalent mechanical (traffic loading and ground deformation) and thermal aging (push/pull) cycles at Cornell University's Bovay Laboratory.

This report provides the results of full-scale tests to evaluate the performance of cast iron (CI) gas pipelines that have been in service with cured-in-place liners (CIPL) for 10 to 16 years. Mechanical aging tests to simulate an additional 100 years of in-service life have been completed, and tests to evaluate key material properties of the field and mechanically aged liners have been performed.

NYSEARCH project funding companies PSE&G and National Grid field extracted two sections of lined 6-in. (150-mm)-diameter CI pipe and two sections of lined 12-in. (300-mm)-diameter CI pipe with joints in good working condition. All sections were approximately 8 ft. (2.4 m) long with the joint at the center. After removal of the pipe sections from excavations in the service areas of gas distribution companies participating in the study, the sections were placed into cradles for protection during truck transportation to Cornell University.

Two sets of mechanical tests were performed on the 6-in. (150-mm) and 12-in. (300-mm)-diameter CI joints. The joints are intended to act as a proxy for CI round cracks, as well as weak and degraded joints in the field. Mechanical aging tests include flexure and axial compression/tension tests on CI specimens obtained from the two field sites. These mechanical aging tests were complemented by a suite of longitudinal and hoop tensile strength tests of the liners in addition to lap shear and peel tests of the CI/liner interface.

Flexure tests were performed to simulate truck loading over two 50-year service life cycles for a total of 100 additional years. Axial pull-push tests were performed to simulate the effects of annual temperature changes on the pipe over the two 50-year service life cycles, simulating an additional 100 years of service. The methodology of the testing is as described in O'Rourke, et al. (1996) and Netravali, et al. (2003).

Specimens for laboratory testing both before and after the mechanical aging tests were removed from four CI pipe sections that were sampled at the field sites. Tests were performed to evaluate liner characteristics a) after roughly 10-16 years of service life, and b) an additional 100 years of simulated field traffic and thermal cyclic loading.

This report is organized in eight sections. The first of which provides introductory comments. Section 2 provides a description of the CIPLs and a summary of previous CIPL research. Section 3 presents the methodology developed to simulate aging in the laboratory. A general description of the analytical methods is provided, along with justification for the approach based on field measurements. Sections 4 and 5 present the results of the mechanical aging tests performed on 6- and 12-in. (150- and 300-mm)-diameter CI pipeline segments, respectively, which had been lined with Starline[®]2000 CIPL. The retrieval of the pipeline segments is described, and the test results simulating 100+ years of vehicle loading and thermal cycles are provided. The results of internal pressurization tests following the aging tests are described. Section 6 presents the results of material property testing on the polymeric liner materials from the test pipelines. Several types of tensile strength, lap shear, and peel tests on the liner materials were performed after field retrieval of the specimens and after the additional 100+ years of mechanical aging. The test results are compared with the results of prior testing of similar liners. Section 6 also discusses the project videos, the live CIPL installation demonstration, and the project workshop that presented the results of this project to industry and regulatory officials. Section 7 presents a summary of the project's live CIPL demonstration and presentations. Section 8 presents a summary of the test and research findings, and recommends areas for further investigation. Appendix A is a glossary of terms and definitions referenced in this report.

Section 2

Cured-in-Place Liner Systems and Previous Research

2.1 Introduction

The overall objective of the project is to develop a rigorous engineering and science-based framework for using cured-in-place linings (CIPL) as a safe and practical option in the gas industry. Over the past two decades, *in situ* pipe linings have evolved into a well-established technology (AWWA, 2001; Bainbridge, et al., 2005) that increases the service life of existing utilities without expensive and disruptive excavation and replacement. The concept is to install polymeric linings remotely inside existing, underground pipelines with minimum outside disturbance through trenchless construction procedures (Downey and Heavens, 2007; Kramer et al., 1992). The linings secure continuity of pipeline flow, prevent leakage and intrusion, and provide variable degrees of structural reinforcement. R&D efforts have focused on developing advanced equipment and installation techniques, establishing limit state design approaches for the linings (Alam and Allouche, 2010; Guan et al., 2007), and quantifying the effects of imperfections that may result from the installation process (Bruzzzone et al., 2007; Dhar and Moore, 2001). Cured-in-place linings (CIPL) have benefitted from previous research (Bainbridge et al., 2005; Bruzzzone et al., 2007; Guan et al., 2007; Herzog et al., 2007), and have been used for nearly two decades for *in situ* pipeline rehabilitation. These CIPLs are tubes of woven polyester fabric saturated with thermosetting resin and inserted and cured in existing pipelines. They provide for rapid installation and can accommodate bends and changes in pipe cross-section.

Figure 2.1 provides a three-dimensional cut-away view of the Starline[®]2000 CIPL system, which was used in this work. Typical installation lengths, pipe diameters, and liner thicknesses are summarized in the figure.

2.2 Previous Cornell Research

A substantial body of research exists on CI properties, field performance of CI pipelines, and rehabilitation/repair methods for CI pipe. Over 20 reports have been prepared and circulated by Cornell research on CI pipeline performance and rehabilitation technologies.

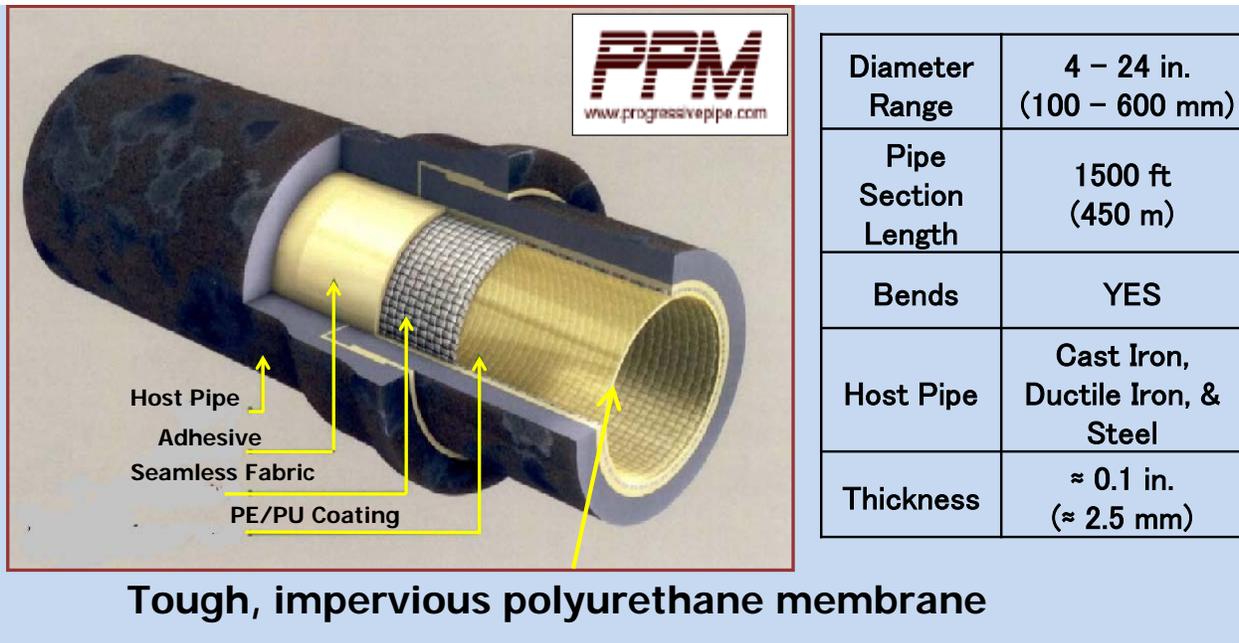


Figure 2.1. Cured-in-Place Lining System (after PPM)

<u>Cast Iron Pipelines</u>	<u>Mechanical Aging & CIPL Systems</u>
<ul style="list-style-type: none"> • Response of Jointed Cast Iron Pipelines to Parallel Trench Construction, NYGAS, 1983 • Factors Affecting the Performance of Cast Iron Pipe, NYGAS, 1984 • Field Tests of Cast Iron Pipeline Response to Shallow Trench Construction, NYGAS, 1984 • Manual for Assessing the Influence of Excavations on Parallel Cast Iron Gas Mains, NYGAS, 1984 • Field Monitoring of Cast Iron Gas Main Response to Deep Trench Construction, NYGAS 1987 • Evaluation of Cast Iron Pipeline Response at Excavation Crossings, NYGAS, 1988 	<ul style="list-style-type: none"> • Evaluating Service Life of Cast Iron Joint Sealing Products and Techniques, NYGAS, 1985 • Evaluating Service Life of Anaerobic Joint Sealing Products and Techniques, Gas Research Institute, 1996 • Advanced Pipeline Support and Stabilized Backfill for Gas Mains, New York Gas Group, 2000 • Evaluation of Starline Cured-in-Place Lining System for Cast Iron Gas Distribution Pipelines NYSEARCH/NGA, 2003 • Longevity Testing of Anaerobic Sealants in Cast Iron Pipe Joints, National Grid, LCC, 2011

Figure 2.2. Major Cornell Research on Cast Iron Pipelines and Mechanical Aging and CIPL Systems

Figure 2.2 lists select research projects that Cornell has undertaken for gas industry research organizations. Testing regimes have been developed for qualifying polymer lining products and for estimating the design life of rehabilitated pipelines (Netravali et al., 2000, 2003). Special testing has been conducted to evaluate seasonal thermal expansion/contraction and traffic load effects on CI mains and joints as well as ground deformation related to undermining and parallel deep trenches and excavations. The testing procedures also involved chemical and material aging assessments of the polymers. Experimental and analytical work by Netravali et al. (2000, 2003) and Jeon et al. (2004) demonstrate the effectiveness of polymer linings for pipelines that have full circumferential cracks and weak joints.

In subsequent sections of this report, the methodologies developed in prior research at Cornell are described with respect to the testing variables for mechanical aging tests, including:

- Pipe joint displacements and rotations for flexure tests that represent 100 years of vehicular traffic effects, and
- Pipe axial displacements that simulate the effects of seasonal temperature changes, representing 100 years of thermal contraction/expansion effects.

Material property tests are discussed in subsequent report sections, which were performed to:

- Characterize the residual tensile properties of the composite liner system as a way to assess the effects of field and mechanical aging on the liner system and its durability, and
- Characterize the residual liner/CI pipe bond (adhesion) strength and its durability using lap shear and peel tests of field and mechanically aged specimens.

Thus, the testing procedures described in this report are the same as those used for over two decades of testing CI pipelines and CIPLs at Cornell. They assure that the methods, as well as the interpretations, are consistent with previous testing and CIPL product development. Of particular importance is the ability to compare the current test results with previous test data to enhance our understanding of the aging effects on complex composite liners and liner/CI interfaces.

2.3 Previous U.S., Europe, and Japan Research

Cured-in-place liners (CIPL) have been installed on cast iron and steel pipelines in natural gas distribution systems in Europe, Japan and North America over the last three decades due to their rehabilitative and renewal qualities and the higher costs, construction risks, and public inconvenience associated with conventional pipeline replacement methods, particularly in congested and difficult to access areas such as river and road crossings or urban areas. Natural gas operators have demonstrated significant economic benefits with CIPL installations, compared to conventional replacement, in addition to reliable and safe operating histories. As an example, Public Service Electric and Gas (PSE&G) has realized more than \$10 million in savings on 40,000 feet of installed CIPL pipe, as compared to conventional pipe replacement, with no history of leakage since beginning CIPL field installations in 1993.

Most of the research and technical studies conducted in the U.S. related to CIP liners installed on natural gas pipelines began in the late 1990's by GRI and NYGAS in collaboration with Battelle and Cornell University, respectively. Initially, technical studies focused on Paltem and Amex liners followed subsequently by the Starline® (200, 2000, 20000) series of liners. Past research by NYGAS, NYSEARCH/Northeast Gas Association, GRI, IGT, Battelle and Cornell University, demonstrated CIPL system safe and reliable functional integrity for up to 50 years when host pipe preparation, cleaning, and installation procedures were optimized for liner/pipe adhesion.

AMEX, Paltem and Starline®2000 cured-in-place liners were installed in North America and Europe and by 2004, more than 300 miles of CIPL gas pipelines had been rehabilitated with the Starline®2000 system alone. By 2013, approximately 732 miles of natural gas distribution pipelines in Japan (2"-36" diameter) had been lined with Paltem under the Japan Gas Association voluntary industry guidelines for the installation of liners for leakage prevention including pre-existing cracks, joint sealing degradation, potential earthquake damage, or host pipe penetration. In Germany, CIPL is an acceptable technique for cast iron replacement where CIPL pipe is treated as new PE pipe for leak detection.

Peer reviewed literature search reports were completed as part of this project for cured-in-place pipe lining in Japan in addition to North America and Europe. Interviews were conducted in Japan with Japanese officials from Osaka Gas, Tokyo Gas, and the Japanese Gas Association (JGA). Both reports detail the body of research conducted on cured-in-place liners for natural gas pipeline applications over the course of the last three decades.

Section 3

Methodology for Mechanical Aging Tests

3.1 Crack Openings in Cast Iron Piping due to Thermal Effects

Analytical models were developed to simulate displacements and rotations imposed on a CI pipeline with a CIPL installed in pipe sections with a round (circumferential) crack or a weak and degraded bell and spigot joint. Previous Cornell research has shown that round cracks will develop in previously lined CI pipe without damaging the lining (Netravali et al., 2000, 2003). One of the attributes of CIPLs, in fact, is their ability to bridge defects, like round cracks, that develop subsequent to liner installation. The introduction of a round crack, however, interrupts the structural continuity of the CI main so that the effects of repetitive traffic loads and thermal expansion/contraction are concentrated at the lined crack locations. Similar mechanical effects will occur at lined pipe sections with weak and degraded bell and spigot joints. The analytical models developed to simulate lined pipe performance at round cracks and weak joints were used to establish laboratory test procedures to simulate repetitive loadings associated with those imposed by the thermal expansion and contraction effects, traffic loading, undermining excavations for services, and backfill effects.

3.1.1 Design Temperature Change

Thermal loads in buried piping are a direct result of temperature changes. Stewart et al. (1999) summarized the seasonal thermal variation, representative of temperature change in New York State and other parts of the Northeast US that would be experienced by buried pipelines. Data were collected at soil depths between 30 and 49 in. (0.8 and 1.2 m), which is in the range of burial depths for typical gas distribution pipe.

The typical lower temperature is on the order of 30 °F (-1 °C). The maximum design temperature change due to seasonal variations in ground temperature in the northeastern US for typical distribution pipe depths is taken as $\Delta T = 40^\circ\text{F}$ (22°C).

3.1.2 Testing Procedure

The imposed joint opening for the axial pull-push tests on 6- and 12-in. (150- and 300-mm)-diameter cast iron (CI) lined pipe specimens was based on the analytical solutions presented by Jeon et al. (2004), which were used in prior CI testing at Cornell University. To perform the analyses, pipe geometric and material properties are required.

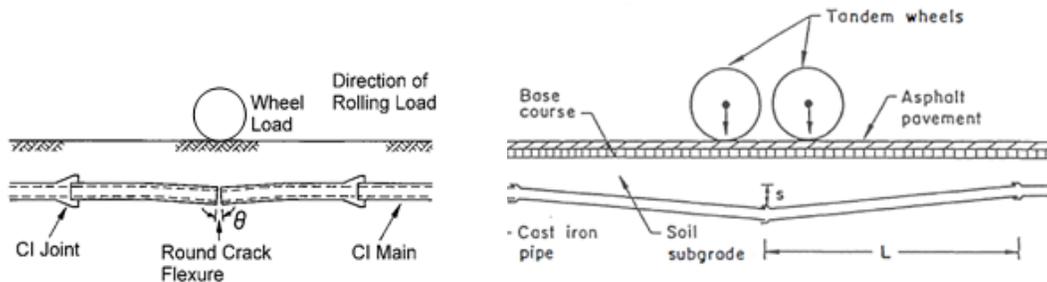


Figure 3.5. Illustrations of Buried Pipeline Deformation due to Applied Traffic Loading

3.2 Traffic Loading Approach

The purpose of the traffic loading simulation tests is to characterize the performance of the lined joints under repetitive deformations caused by traffic loads during the pipeline service life. Figure 3.5 shows the types of loading and pipeline deformations which might occur due to vehicular traffic. Vehicular surface loads are transmitted through the pavement and soil to the underground pipelines imposing flexure and joint rotation. Among other factors, the magnitude of pipeline deformation and joint rotation depend on the applied load, relative stiffness of the pipeline with respect to the surrounding soil that supports it, depth of burial, and stiffness of the joint between individual lengths of pipe. The two important factors for the performance of joints are (1) the magnitude of joint rotation due to the applied load, and (2) ability of the joint to handle the imposed rotation.

To evaluate the effect of traffic loads on the CIPLs, 4-point bending tests were conducted. The deformations imposed were designed to represent the worst-case levels of pipeline deformation in the field.

3.2.1 Number of Applied Traffic Loading Cycles

The number of displacements and rotations accumulating at a round crack or pipeline joint over a service life of 50 years was determined by estimating the number of heavy truck loadings which would occur during this time. One million cycles applied over a 50 year aging life equates to 20,000 cycles per year.

3.2.2 Inputs for Traffic Loading Tests

CI pipelines are subjected to surface loads from vehicular traffic. When surface loading is conveyed to a lined CI main, the CIPL lining will experience maximum deformations (i.e., relative displacement and rotation) at the weakest discontinuity along a pipeline. The presence of a full circumferential fracture, or round crack, is representative of a worst-case discontinuity along a CI pipeline.

Section 4

Mechanical Aging Tests on Six-In. (150-mm)-Diameter Cast Iron Pipe

4.1 Specimen Retrieval for 6 in. (150 mm) CI Joints

NYSEARCH/NGA provided two sections of lined 6-in. (150-mm)-diameter cast iron pipe with joints in good working condition. All sections were approximately 8 ft (2.4 m) long with a joint at the center. An additional straight section of CI also was retrieved for additional testing as necessary.

The 6-in. (150-mm)-diameter specimens were retrieved from a Public Service Gas & Electric (PSE&G) location in Elmwood Park, NJ. The CI pipeline was initially installed in 1949. A Starline®2000 liner was installed by Progressive Pipeline Management in 1998. The pipe specimens were acquired in May, 2014. After removal from the excavations the pipes were placed in protective cradles and shipped to Cornell University. Mechanical aging tests began in July, 2014. Table 4.1 lists the specimen retrieval locations. The two CI sections for testing were identified as Specimens 6-1 and 6-2.

Figure 4.1(a) – (c) shows the excavation and CI pipe at Elmwood Park, NJ. The CI joint is shown in the figures. This was a live gas cut-out. The PSE&G CI line was operating at a low pressure of about 15 in. of water column (102 kPa.) Figure 4.1(d) shows a pipe section immediately after removal. The lining appears very clean with no obvious defects after 16 years of service.

4.2 Joint Configuration for 6 in. (150 mm) CI Joints

Figure 4.2 shows a schematic of the joint in the 6-in. (150-mm) CI pipe. The joints were caulked with cement mortar and jute packing. They were very stiff joints.

Table 4.1. Six-in. (150-mm)-Diameter Cast Iron Joint Retrieval Location

Specimen No.	Diameter and Length	Lined Pipe Location	Liner Installation	Specimen Retrieval Date	Cornell Begins Testing
6-1 and 6-2	6 in. dia., 8 ft (150 mm, 2.4 m)	Elmwood Park, NJ	1998	May 21, 2014	July, 2014



a) Six-in. (150-mm)-Diameter CI Joint in Elmwood Park, NJ



b) Six-in. (150-mm)-Diameter CI Joint Being Cut Out



c) Six-in. (150-mm)-Diameter CI Joint Showing End Cap and Live Gas Plastic Replacement



d) Six-Inch (150-mm)-Diameter CI Section after Removal in May, 2014

Figure 4.1. Pipe Retrieval from PSE&G Site in Elmwood Park, NJ

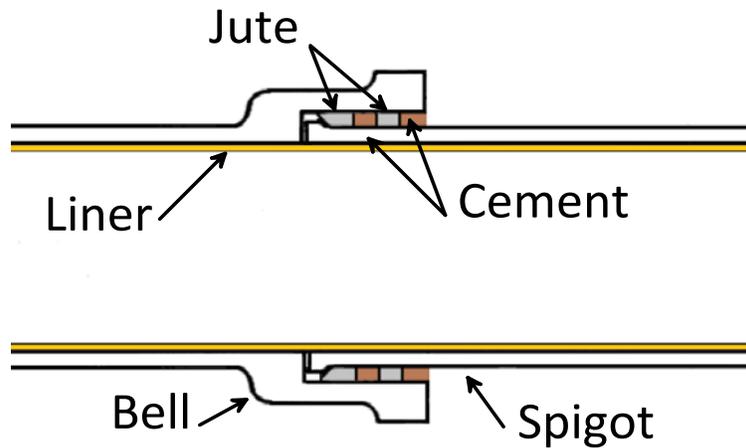


Figure 4.2. Schematic of Cement Caulked Joint for 6 in. (150 mm) Pipe Specimens

4.3 Mechanical Aging Test Results for Specimen 6-1

The purpose of the flexural testing was to simulate the rotation that would be induced in the pipe joint from heavy truck traffic and to apply this rotation to the joint repetitively to simulate loading effects over a 50-year service life. The test setup consisted of orienting the pipe specimen to be simply supported in the vertical direction. Each pipe was oriented as it had been in the ground. The pipes were fitted with Dresser 711 end caps. The overall length of the sections was approximately 8 ft (2.4 m). A photograph of the flexure test setup is shown in Figure 4.3. The inset in the upper right corner of the figure shows the constant moment across the central portion of the pipe section.

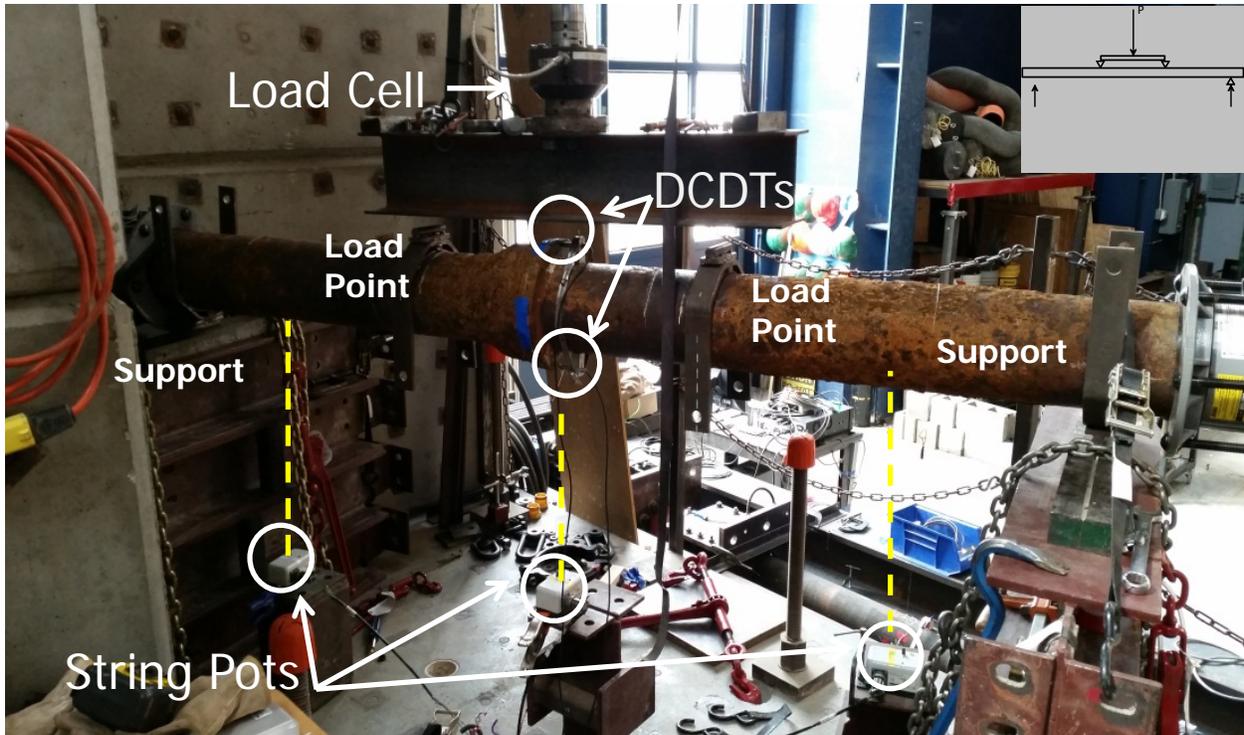


Figure 4.3. Flexure Test Apparatus with 6-in. (150-mm)-Diameter Test Specimen

The pipe specimens were pressurized for the flexure test to 15 in. of water column pressure (102 kPa) using nitrogen. This pressure was selected to be consistent with the low operating pressure of a 6 in. (150 mm) distribution pipeline. This also is consistent with other testing performed at Cornell on distribution-sized CI piping. Consistent with previous testing, one million cycles of pipe deflections simulated truck loading on the joint over a 50-year service life. The testing consisted of vehicular loading followed by thermal cycles, representing 50 years of service. Both sets of aging tests were then repeated, representing an additional 50 year of service, followed by pressure test verification. The deformations applied to the pipe sections to simulate vehicular traffic and undermining/backfill events are relatively small.

Figure 4.9 shows photographs of Specimen 6-1 in the test frame used to apply thermal cycles.

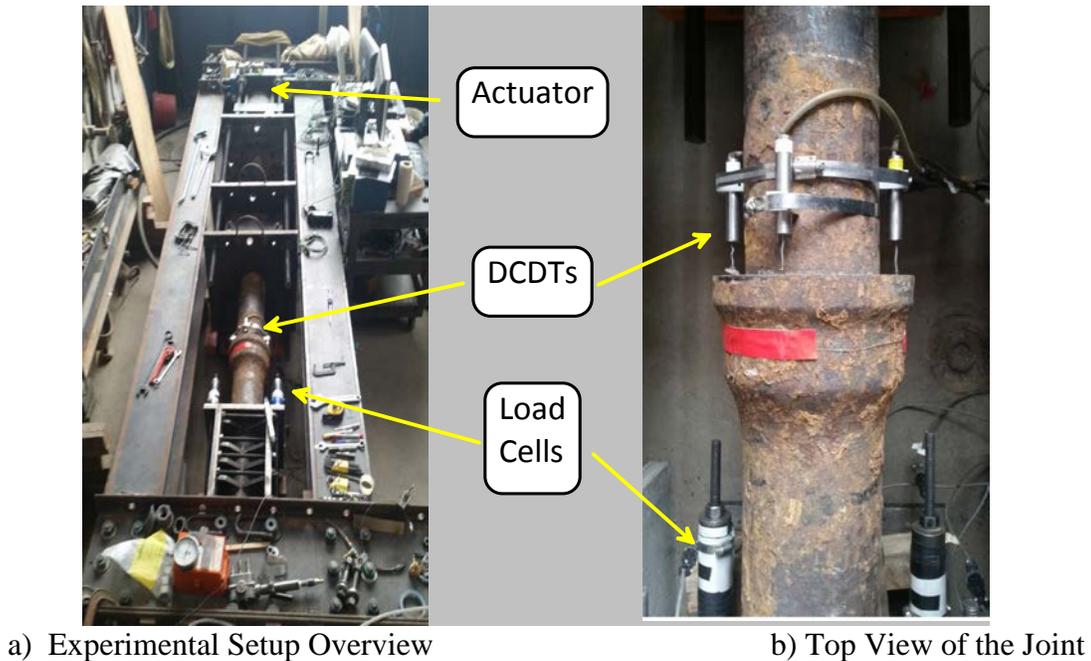


Figure 4.9. Specimen 6-1 in Test Frame for Thermal Loadings

4.3.1 Specimen 6-1: Second Fifty Years of Vehicular Loadings

After the first 50 years of thermal loading, the specimen was returned to the flexural testing load frame, and subjected to an additional 50 years of vehicular traffic.

4.3.2 Specimen 6-1: Second Undermining/Backfill Event

The response to the undermining/backfilling event is roughly twice as large as the prior cyclic loading.

4.3.3 Specimen 6-1: Second 50 Years of Thermal Loadings

The cyclic load-unload curves for the second 50 years of thermal aging are the same shape for the additional 50 cycles. This indicates no major changes in cyclic degradation beyond that which occurred in the very first few cycles of thermal aging.

4.3.4 Specimen 6-1: Post-Test Inspection

Debonding at the separation between bell and spigot was confined to a small distance either side of the separation, less than one pipe diameter in total width. This debonding is a highly desirable characteristic of a well-installed CIPL liner system. The pipe had been cleaned sufficiently to

allow robust adhesion without excessive bonding of the epoxy to CI surfaces. By allowing debonding, the liner could accommodate axial deformations by allowing extension.

Specimen 6-1 did not leak throughout all of the mechanical aging tests. Further, the interior of the pipe section showed the highly desirable effect of local debonding of the liner in the vicinity of the joint.

4.4 Mechanical Aging Test Results for Specimen 6-2

Specimen 6-2 was taken from the same PSE&G location in Elmwood Park, NJ. Thus, the sampling methodology is the same as described previously. The specimen underwent the same loading sequence as Specimen 6-1. The main difference between Specimen 6-1 and 6-2 is that the cement/mortar caulking was removed in Specimen 6-2 prior to any mechanical aging. This allowed the joint to behave as a weakened joint from the start of the vehicular loading. Specimen 6-2 also exhibited additional weakening due to the first thermal cycle.

4.4.1 Specimen 6-2: First 50 Years of Vehicular Loadings

There is not significant change in Specimen 6-2 joint response during the first 50-year-equivalent testing.

4.4.2 Specimen 6-2: First Undermining/Backfill Event

The response to undermining/backfilling is roughly twice as large as the prior cyclic loading (similar to Specimen 6-1).

4.4.3 Specimen 6-2: First 50 Years of Thermal Loadings

Prior to the first thermal loading Specimen 6-2 already has a weakened joint due to the removal of the cement/mortar caulking. As was observed in Specimen 6-1, the joint strength is weakened considerably after the initial expansion/compression cycle. There again is debonding of the CIPL from the pipe caused by these laboratory equivalent thermal loadings.

4.4.4 Specimen 6-2: Second 50 Years of Vehicular Loadings

After the first 50 years of thermal loading the specimen was returned to the flexural testing load frame and subjected to an additional 50 years of vehicular traffic.

4.4.5 Specimen 6-2: Second Undermining/Backfill Event

The response to the undermining/backfilling event is again roughly twice as large as the prior cyclic loading.

4.4.6 Specimen 6-2: Second 50 Years of Thermal Loadings

The cyclic load-unload curves for the second 50 years of thermal aging are the same shape for the additional 50 cycles. This indicates no major changes in cyclic degradation beyond that which occurred in the first few cycles of thermal aging.

4.4.7 Specimen 6-2: Post-Test Pressurization

Following the entire mechanical aging sequence on Specimen 6-2, a pressure verification test was conducted to assure that the liner had not ruptured during the test. The pipe was pressure tested to 90 psig (620 kPa) in roughly 10 psig (7 kPa) increments. There was no leakage. Then the pressure was increased to 150 psig (1,034 kPa). Pipe Specimen 6-2 did not leak after all mechanical aging tests and did not leak after a pressure verification test to 150 psig (1,034 kPa). Visual observations of the liner in the pipe indicated no liner damage.

4.5 Summary of Mechanical Aging Test Results for Specimen 6-1 and 6-2

Two 6-in. (150-mm)-diameter specimens were retrieved from a PSE&G location in Elmwood Park, NJ. The CI pipeline was initially installed in 1949 and lined with Starline[®]2000 in 1998. This pipeline was operating at 15 in. of water column pressure. The pipe specimens were taken in May, 2014. A testing program was developed to simulate 100 years of vehicular loading, several undermining/backfill (trenching) operations followed by additional traffic loadings, and 100 years of thermal expansion/contraction cycling using a design temperature range of $\Delta T = 40^{\circ}\text{F}$ (22°C). The CI joints had cement/mortar and jute packing, which resulted in a very high moment-rotational stiffness. The caulking was removed after the first 50 years of vehicle traffic because:

- 1) The stiffness was very high, and not representative of a round crack with a liner. The purpose of the testing was to simulate aging at a section of lined CI pipe with a round crack or weak and degraded bell and spigot joint.
- 2) Removal of the cement/mortar and jute provided a clear path for leakage should a rupture occur in the liner material, causing a drop in pressure diagnostic of liner failure.

The testing program consisted of four-point bending (flexure) tests, simulating two 50-year-rounds of testing. The deflections and rotations of the joints were measured carefully, and any changes in pipe characteristics of the 100-year period were noted. The flexure tests were performed using displacements and joint rotations consistent with those derived using previous Cornell analytical research. Special undermining/backfill (trenching) events were also replicated in the laboratory testing. The deformations imposed in the pipe from these loadings were about two to three times that used for the normal vehicular loadings. Additional loadings following these events did not indicate any changes in the performance of the CIPL system.

Both CI specimens showed a dramatic change in axial pull-push stiffness after the very first thermal cycle. The first thermal cycle, performed over about 6 hours for the first tension portion, and 4 hours for the completion of the compression cycle, caused substantial debonding of the liner from the pipe. This rate of temperature drop is much faster than the $\Delta T = 40^{\circ}\text{F}$ (22°C) decrease in about 120 days, the typical rate of cooling at gas pipeline depths in the northeast.

This debonding was also reflected as a decrease in rotational stiffness from the first 50 years of vehicular traffic, which had not been subject to thermal cycling, to the second 50 years, which had experienced the first round of 50 years of thermal cycles.

During all phases of the mechanical aging tests, the specimens did not leak. Following these mechanical aging tests, Specimen 6-2 was pressure tested to 90 psig (620 kPa) using water, and the pipe did not leak. The pressure was increased to 150 psig (1,034 kPa) and the pipe continued to maintain pressure integrity.

The pipe joints were cut longitudinally for visual inspection. The 6 in. (150 mm) joints with the Starline[®]2000 CIPL showed debonding at the bell/spigot connection. This debonding allowed the liner to stretch without experiencing excessive strain, which could cause damage to the fibers in the liner. This level of debonding indicates that the CIPL system was performing in a highly desirable way and that after all mechanical testing there was no leakage and no damage to the liner.

Section 5

Mechanical Aging Tests on Twelve-in.- (150-mm)-Diameter Cast Iron Pipe

5.1 Specimen Retrieval for 12 in. (300 mm) CI Joints

NYSEARCH/NGA provided two sections of lined 12-in. (300-mm)-diameter cast iron pipe with joints in good working condition. All sections were approximately 8 ft (2.4 m) long with a joint at the center. An additional straight section of lined CI pipe was also retrieved for additional testing as necessary.

The 12-in. (300-mm)-diameter specimens were retrieved from a National Grid location in South Garden City, Long Island, NY. The CI pipe was installed in 1951. The liner in the pipe was a Starline[®]2000 liner installed by Progressive Pipeline Management in 2004. The pipe specimens were retrieved in August, 2014. After removal from the excavation, the pipes were shipped to Cornell University where mechanical aging tests commenced in March, 2015. Table 5.1 lists the specimen retrieval locations. The two CI sections for testing are identified as Specimens 12-1 and 12-2.

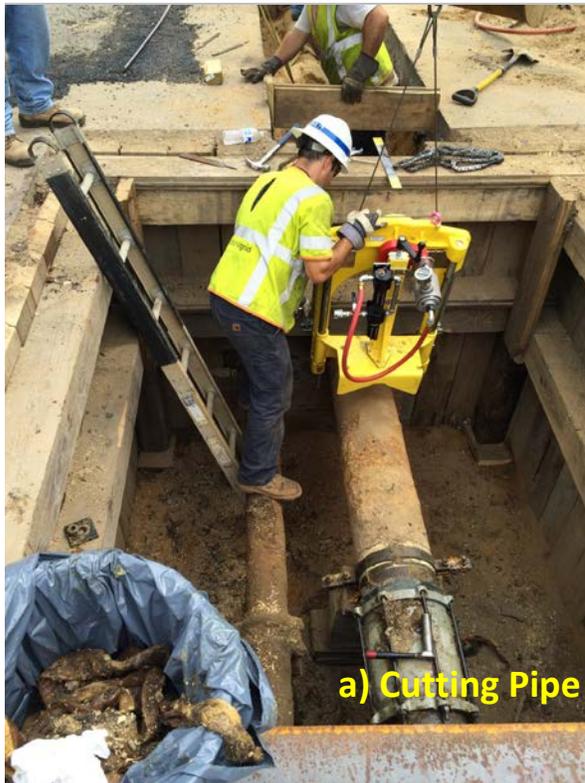
Figure 5.1(a) – (c) show the excavation and CI pipeline at South Garden City. The CI joint is shown in the photos. The National Grid CI pipeline was operating at 60 psig (414 kPa) pressure. Figures 5.2(a) and (b) show two views of a pipe section immediately after removal. Figure 5.2(a) shows the location of the mechanical clamp on the pipe joint. Figure 5.2(b) shows a “bubble” feature, or local protrusion of the liner, at a joint near the pipe crown. The visual appearance of the pipe interior appears quite clean. Figure 5.3(a) shows the pipe joint after field retrieval, with corrosion and scale apparent on the mechanical clamp. Figure 5.3(b) shows the joint after it had been cleaned carefully and de-scaled in the laboratory.

5.2 Joint Configuration for 12 in. (300 mm) CI Joints

Figure 5.4 shows a schematic of the 12 in. (300 mm) CI pipe joint. The joints had an Inner-Tite (or equivalent) mechanical clamp. The rubber gasket is compressed by the cast iron gland, providing a pressure-tight seal.

Table 5.1. Twelve-in. (300-mm)-Diameter Cast Iron Joint Retrieval Location

Specimen No.	Diameter and Length	Lined Pipe Location	Liner Installation	Specimen Retrieval Date	Cornell Begins Testing
12-1 and 12-2	12 in. dia., 8 ft (300 mm, 2.4 m)	South Garden City, LI, NY	2004	August 21, 2014	March, 2015



National Grid,
South Garden City, NY

60 psig (414 kPa) MAOP

Figure 5.1. Pipe Retrieval from National Grid Site in South Garden City, LI, NY



a) Joint Showing Mechanical Clamp

b) Pipe Interior

Figure 5.2 Twelve-in. (300-mm)-Diameter Cast Iron Joint after Field Retrieval



a) Field Retrieval



b) After Lab De-Scaling

Figure 5.3 Twelve-in. (300-mm)-Diameter Joint Condition

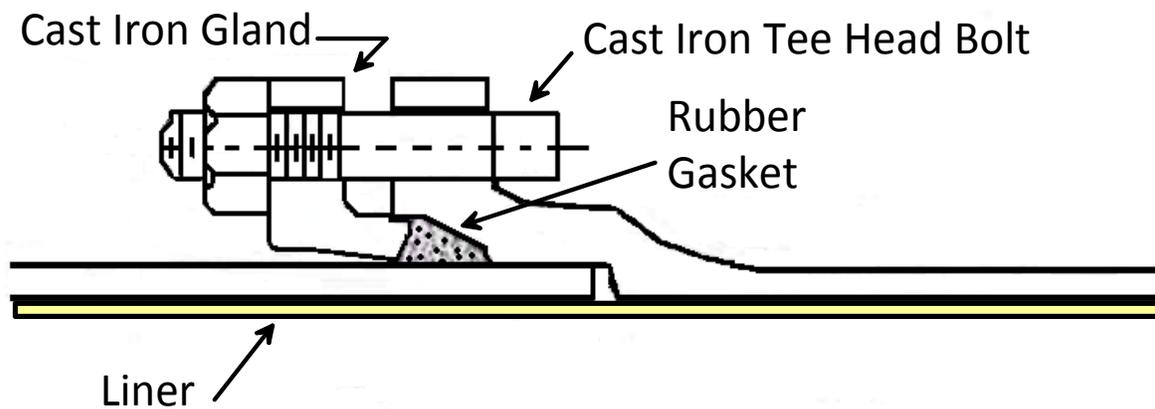


Figure 5.4. Schematic of Mechanical Clamp on 12 in. (300 mm) Pipe Specimens

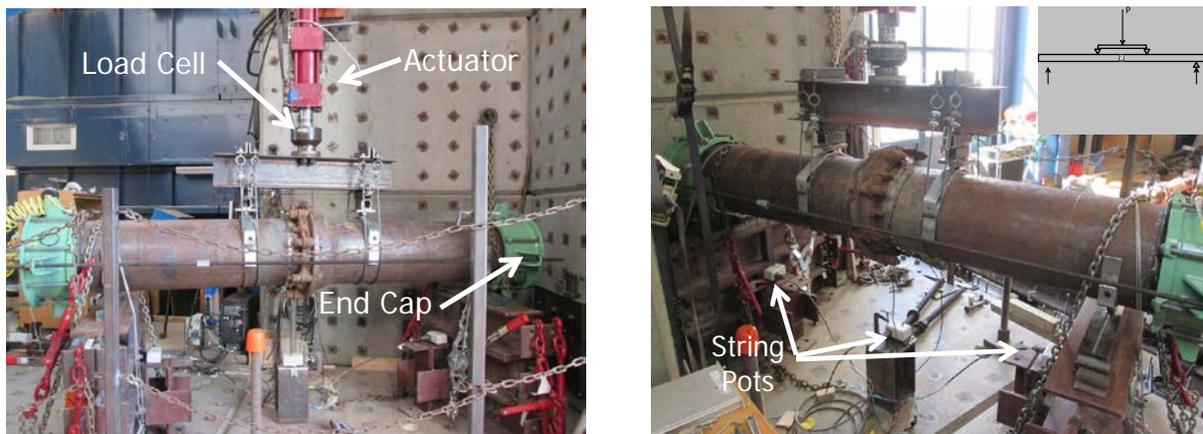


Figure 5.5. Flexure Test Apparatus with 12-in. (300-mm)-Diameter Test Specimen

5.3 Mechanical Aging Test Results for Specimen 12-1

As with the 6-in. (150-mm)-diameter specimens, the purpose of flexural testing for the 12-in. (300-mm)-diameter joints was to simulate joint rotation induced by heavy truck traffic on the road above the pipe, and to apply this rotation to the joint repetitively to simulate the effects of traffic loads over a 50-year service life. Each pipe was orientated as it had been in the ground. The pipe was fitted with Smith-Blair EBR end caps. The overall length of the sections was approximately 8 ft (2.4 m). Photographs of the flexure test setup are shown in Figure 5.5. The inset in the upper right corner of the right-most figure shows the constant moment imposed across the central portion of the pipe section.

The pipe specimens were pressurized for the flexural testing to 15 psig (414 kPa) using nitrogen. As with the prior flexural testing, rotations of the joint were calculated using measurements from either DCDTs or string pot displacements.

Consistent with previous testing, one million cycles of pipe deflections simulated truck loading on the joint over a 50-year service life. The testing consisted of vehicular loading followed by thermal cycles, representing 50 years of service, and then both sets of aging tests were repeated representing an additional 50 year of service, followed by pressure test verification. Additional testing was performed on Specimen 12-2 between the first 50 years of vehicular traffic, and the thermal loadings. Table 5.3 lists these additional considerations. The purpose of these additional observations was to further substantiate the internal condition of the pipe specimen.

Table 5.3. Special Conditions for Specimen 12-2 after Initial Vehicle Loadings

Specimen 12-2	
After first 50 years of vehicle loadings but prior to first fifty years of thermal expansion/contraction cycles	After one thermal cycle, depressurize and take photos, pressure check to 60 psig (414 kPa), re-pressurize to 15 psig (103 kPa) and complete remaining 49 cycles

5.3.1 Specimen 12-1: First 50 Years of Vehicular Loadings

There is not a significant change in the joint response during the 50-year-equivalent testing.

5.3.2 Specimen 12-1: First Undermining/Backfill Event

The undermining/backfill episode represents a relatively severe loading condition, as described in Section 3. The response to the undermining/backfilling event is roughly three times as large as the prior cyclic loading.

5.3.3 Specimen 12-1: First 50 Years of Thermal Loadings

The data show similar trends as the thermal data from Specimens 6-1 and 6-2, beyond their first few cycles. There are marked differences for the data from the first cycle, reflecting the effects of thermally-induced debonding of the liner.

5.3.4 Specimen 12-1: Second Fifty Years of Vehicular Loadings

After the first 50 years of thermal loading, the specimen was returned to the flexural testing load frame, and subjected to an additional 50 years of vehicular traffic effects.

5.3.5 Specimen 12-1: Second Undermining/Backfill Event

The response to the undermining/backfilling event is again roughly twice as large as the prior cyclic loading.

5.3.6 Specimen 12-1: Second 50 Years of Thermal Loadings

The cyclic contraction/expansion curves for the second 50 years of thermal aging are consistent in shape with those for the first 50 cycles. This indicates no major changes in cyclic degradation beyond that which occurred in the initial cycles of thermal aging.

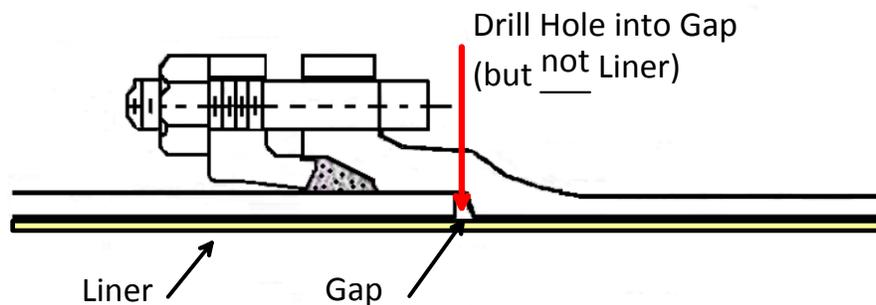


Figure 5.14. Drilling into 12- in. (300)-mm-Diameter CI Bell

5.3.7 Specimen 12-1: Post-Test Pressurization

Following the entire set of mechanical aging tests on Specimen 12-1, a pressure verification test was conducted to assure that the liner had not ruptured during the test. Before the pressure testing, a test hole was drilled into the cast iron bell. This is shown schematically in Figure 5.14. The purpose of the drilled hole was to ensure that, if the liner was ruptured, gas would leak through the rupture and out the drilled hole during pressure testing. If the hole had not been present a non-leaking rubber sealing gasket could have prevented any observable liner leak. The pipe was pressure tested to the operating pressure of 60 psig (414 kPa) in roughly 10 psig (7 kPa) increments.

There was no leakage. Then the pressure was increased to 90 psig (620 kPa). Again there was no leakage.

5.4 Mechanical Aging Test Results for Specimen 12-2

Specimen 12-2 was taken from the same National Grid location in Long Island, NY. Thus, the sampling methodology is the same as described previously. The specimen underwent the same test loading sequence as Specimen 12-1, with the exception of additional inspection, as described

5.4.1 Specimen 12-2: First Undermining/Backfill Event

The response to the undermining/backfilling event is roughly twice as large as that for the prior cyclic loading (similar to Specimen 12-1). The rotational stiffness of Specimen 12-2 is nearly constant during the first 50 years of vehicular loading testing.

5.4.2 Specimen 12-2: First 50 Years of Thermal Loadings

As was observed in previous specimens, beyond the initial cycles the joint strength is considerably weakened. The effects of debonding are again observed in the CIPL load vs. displacement stiffness reduction during the initial thermal loading cycles.

5.4.3 Specimen 12-2: Second 50 Years of Vehicular Loadings

After the first 50 years of thermal loading, the specimen was returned to the flexural testing load frame, and subjected to an additional 50 years of vehicular traffic effects.

5.4.4 Specimen 12-2: Second Undermining/Backfill Event

The response to the undermining/backfilling event is again roughly twice as large as the prior cyclic loading.

5.4.5 Specimen 12-2: Second 50 Years of Thermal Loadings

The cyclic load-unload curves for the second 50 years of thermal aging consistent in shape with those for the first 50 cycles. This indicates no major changes in cyclic degradation beyond that which occurred in the first few cycles of thermal aging.

5.4.7 Specimen 12-2: Post-Test Pressurization

Following the entire mechanical aging sequence on Specimen 12-2, a pressure verification test was conducted to assess the pressure integrity of the liner. Again, a small hole was drilled in the

bell to assure that any liner rupture was detected during pressurization. The pipe was pressure tested to 60 psig (414 kPa) in roughly 10 psig (7 kPa) increments. There was no leakage. Then the pressure was increased to 90 psig (620 kPa). Pipe Specimen 12-2 did not leak after all mechanical aging tests and did not leak after a pressure verification test to 90 psig (620 kPa.).

5.5 Summary of Mechanical Aging Test Results for Specimen 12-1 and 12-2

Two 12-in. (300-mm)-diameter specimens were retrieved from a National Grid location in South Garden City, Long Island, NY. The CI pipeline initially was installed in 1951 and lined with Starline[®]2000 in 2004. This pipeline was operating at 60 psig (414 kPa). The pipe specimens were retrieved in August, 2014. A testing program also was developed to simulate 100 years of vehicular loading, several undermining/backfill (excavation for services) operations followed by additional traffic loadings, and 100 years of thermal expansion/contraction cycling using the same temperature range of $\Delta T = 40^{\circ}\text{F}$ (22°C). The CI joints had mechanical clamps (Inner-Tite or equivalent), which resulted in initial rotational stiffnesses. No additional treatment of the joints, other than de-scaling and cleaning, was performed on either specimen before the mechanical aging tests.

The testing program consisted of four-point bending (flexure) tests, simulating two 50-year-rounds of testing. The deflections and rotations of the joints were measured carefully, and any changes in pipe characteristics over the 100-year period were noted.

As with the testing program for the 6-in. (150-mm) pipe sections, the testing program consisted of four-point bending (flexure) tests, simulating two 50-year-sequences of traffic loading. The flexure tests were performed using displacements and joint rotations consistent with those derived using previous Cornell research. Special undermining/backfill events also were replicated in the laboratory testing. The deformations imposed in the pipe from these loading were about two to three times those associated with the normal vehicular loadings. Additional loadings following these events did not indicate any changes in the performance of the CIPL system.

Both 12-in. (300-mm) CI specimens showed substantial changes in their axial contraction/expansion stiffnesses after the first thermal cycle. The first thermal cycle, performed over about 6 hours for the first tension portion, and 4 hours for the completion of the compression cycle, caused substantial debonding of the liner from the pipe, and possible tearing of the liner fibers. As stated previously, this simulated rate of temperature drop is much faster than the $\Delta T =$

40°F (22°C) decrease over about 120 days, the typical rate of cooling at gas pipeline depths in the northeast. In a field environment, the visco-elastic properties of the polyester fibers along with the polyurethane membrane liner would shed stress during slow cooling. Slow cooling, consistent with the actual seasonal rates of temperature change, would promote local debonding to relieve strain (stress) concentration in the lining. Under these conditions, it is likely that the polyester fabric would have been less damaged.

The debonding also was reflected as a decrease in rotational stiffness after the first round of thermal cycling. As the joints transitioned from the first 50 years to the second 50 years of vehicular traffic loading, the rotational stiffness of both 12 in. (300 mm) pipes was reduced significantly due to thermal cycling.

During all phases of the mechanical aging tests the specimens did not leak. After the mechanical aging tests the pipes were pressurized with nitrogen. Holes were drilled through the CI bell into the gap between the interior surface of the bell and the CIPL. The primary propose of these drilled holes was to make sure any leaking gas could escape and not be restricted by the rubber gasket in the mechanical clamp. This hole was filled with soapy water to assist in the detection of leakage during pressurization. Each specimen was pressure tested to 60 psig (414 kPa), with no joint leakage. Even when the pressure was increased to 90 psig (620 kPa) the liner maintained its pressure integrity.

After pressure testing, the pipes were inspected, and a laser was directed from the outside of the pipe to illuminate the drilled location on the inside of the CIPL. Even though there was some fabric damage, the liner did not leak at pressure 50 % higher than the pipe MAOP.

Section 6

Material Property Tests

6.1 Introduction

This chapter describes the characterization of the residual tensile properties of bonded and debonded liners from both 6-in. and 12-in. (150- and 300-mm)-diameter CI pipe sections retrieved from PSG&E and National Grid service areas, respectively. In addition, lap shear and peel tests were performed to evaluate the strength characteristics along the liner/CI pipe interface.

The material properties were characterized for the CIPL specimens “as received” from the field, and are referred to as being field aged (FA). The FA specimens were taken from a part of the CI pipe where the liner remained bonded to the CI pipe surface. Material properties were also assessed after the mechanical aging procedures were carried out, and are referred to as being field and mechanically aged (FMA). As described in Chapter 3, the mechanical aging procedures consisted of thermal aging (contraction/expansion) and traffic loading cycles equivalent to 100 years of service life in addition to the simulation of undermining effects followed by repetitive vehicular loading of the lined pipe in backfilled soil. The FMA specimens were taken from both bonded and debonded (close to the separation or lip between the spigot and bell) sections of the lining.

The 6-in. (150-mm)-diameter CIPL specimens are distinguished as: 1) FA specimens that had undergone “field aging” for 16 years and, 2) FMA specimens that had undergone “field aging” for 16 years plus mechanical aging equivalent to 100 years of service life. The 12-in. (300-mm)-diameter CIPL specimens are distinguished as: 1) FA specimens that had undergone “field aging” for 10 years and, 2) FMA specimens that had undergone “field aging” for 10 years plus mechanical aging equivalent to 100 years of service life.

6.2 Scope

The scope of the material properties testing part of the work was divided into two parts:

- 1) Characterize the residual tensile properties of the composite liner system as a way to assess the effects of field and mechanical aging on the liner system and its durability, and
- 2) Characterize the residual liner/CI pipe bond (adhesion) strength and assess the durability of the bond strength of field and mechanically aged specimens using lap shear and peel tests.

Consistent with the project scope, material property tests were conducted on both FA and FMA specimens and are described below.

6.3 Material Property Tests

Material property tests consisted of both longitudinal and hoop tensile strength tests on samples of the liner as well as lap shear and peel tests of the liner/CI pipe interface. Test descriptions are provided under the headings below.

6.3.1 Tension Test

Tension tests on bonded and debonded liner samples for both 6-in. (150-mm) and 12-in. (300-mm)-diameter CI pipes were performed using an Instron universal testing machine (Model 5566) using a modified ASTM D 3039/3039M-00 (ASTM, 2000) procedure. Specimen dimensions were modified to match the earlier testing protocol used by Netravali et al. (2003) for characterizing Starline®2000 PSE-35 liner. The liner specimens were tested in both longitudinal and transverse directions.

6.3.2 Lap Shear Test

The lap shear tests were performed on the same Instron universal testing machine (Model 5566) as used for the tension tests to characterize the shear strength between the liners and the CI pipe substrate following a modified ASTM D 3164-97a (ASTM, 1997) procedure. Specimen dimensions were modified to match the earlier testing protocol used by Netravali et al. (2003) for characterizing Starline®2000 PSE-35 liner.

6.3.3 Peel Test

A modified ASTM D 1876-95 (ASTM, 1995) procedure using a 180° peel test method was employed to obtain the peel strength between the lining system and the CI pipe in tensile mode. Specimen dimensions were modified to match the earlier testing protocol used by Netravali et al. (2003) for characterizing Starline®2000 PSE-35 liner. All tests were performed on the same testing machine and measuring systems used for the tensile and lap shear tests.

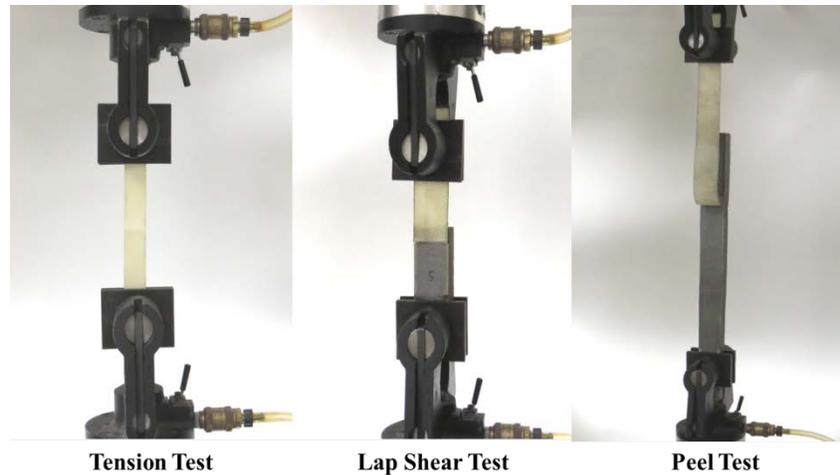


Figure 6.1. Setup for the Tension, Lap Shear and Peel Tests on Instron Universal Tester

The setups for the tension, lap shear and peel tests on the Instron universal tester are illustrated in Figure 6.1.

6.3.4 Field Aging and Mechanical Aging

The test specimens were subjected to both field and mechanical aging, as described under the subheadings that follow.

6.3.4.1 Field Aging

CI gas pipes with the composite lining system were field aged for about 16 years, in the case of 6-in. (150-mm)-diameter pipe, and over 10 years, in the case of 12-in. (300-mm)-diameter pipe, before excavation and transportation to Cornell University. Detailed information about the field aged CI pipe specimen excavations is provided in Sections 4 and 5.

6.3.4.2 Mechanical Aging

Lined CI gas pipes containing a joint were mechanically aged at Cornell, equivalent to 100 years of traffic and thermal expansion/contraction cycling plus undermining and repetitive vehicular loads on lined pipe in the backfilled soil. During the thermal contraction/expansion cycling, the liner debonded locally from the pipe at the joint. The debonding was confined to a small distance either side of the spigot/bell separation, less than one pipe diameter in total width. Both bonded and debonded parts of the liners were characterized for their residual tensile strength.

6.5 Test Results

Material properties were measured by performing longitudinal and transverse tensile tests on the FA (bonded) and FMA (bonded and debonded) linings as well as lap shear and peel tests on bonded specimens. Comparisons are made between the tensile strength data for FA and FMA linings. Comparisons are also made between the lap shear and peel test data for the specimens obtained in the present study with similar test data for Starline[®]2000 PSE-35 liners reported by Netravali et al. (2003). In all cases standard t-tests (Walpole and Myers, 1972) were performed when comparing the data as to assess the statistical significance of the strength comparisons. With only two exceptions, the t-tests confirm that at a 5% level of significance the mechanical aging did not affect the strength properties. One of the exceptions involves peel test results, which are inherently highly variable and affected by small changes in CI pipe/liner interfacial characteristics. The other exception involves 6 in. (150 mm) FMA bonded liner specimen #2 (Specimen 6-2) data for longitudinal tensile strength. Both these exceptions are discussed in conjunction with the appropriate test results under the headings that follow.

6.5.1 Longitudinal Tensile Strength of 6 in. (150 mm) Pipe Liner

The debonding of the liners occurred only at the joints where the maximum liner strains and stresses had developed. The difference between the FA and FMA strengths is not statistically significant.

While there was no difference between the FA bonded and FMA bonded specimen 6-1, at 5% level of significance, specimen 6-2 showed a lower value and was the only one that did not conform to 5% level of significance. It was, however, not significant at 10% level of confidence.

6.5.2 Transverse Tensile Strength of 6 in. (150 mm) Pipe Liner

The average FMA liner strength is very close to that of the FA liner and indicates that there is no significant effect of mechanical aging on the liner strength.

6.5.3 Longitudinal Tensile Strength of 12 in. (300 mm) Pipe Liner

. As in the case of 6 in. (150 mm) pipe liners, 12-1 and 12-2 refer to the two 12 in. (300 mm) pipe liner specimens that were tested in this study. As discussed in Section 5, the debonded area of the

FMA liner consisted of both visually undamaged and partially damaged sections in the vicinity of the joint.

The plots for both FA and FMA liners show similar characteristics, indicating that there is little to no effect of the mechanical aging on the liner tensile behavior in the longitudinal direction.

For FA bonded and FMA debonded specimens it is clear that the difference between the FA and FMA strengths is not statistically significant.

The mean and CV of the longitudinal tensile strength values for FA and FMA bonded specimens are presented in Table 6.9. For FA and FMA bonded specimens, the data show that once again there is no significant effect of mechanical aging on the tensile properties of the liner in the longitudinal direction.

6.5.4 Longitudinal Tensile Strength of Partially Damaged 12 in. (300 mm) Pipe Liner

As mentioned previously, during the mechanical aging (thermal contraction/expansion) process, part of the debonded liner showed visual damage. Close inspection of the specimens indicated that the polyester yarns were damaged while the polyurethane membrane remained intact. Most of the polyester yarn damage occurred during the first thermal contraction/expansion cycle, and was likely caused by the high rate of the test that was completed in just 2-4 hours, about 4 orders of magnitude faster than the natural cycle of a few months.

6.5.5 Transverse Tensile Strength of 12 in. (300 mm) Pipe Liner

For FA bonded and FMA bonded specimens, the average FMA liner strength is very close to that of the FA liner and indicates that there is no significant effect of mechanical aging on the liner strength.

The mean and coefficient of variation of transverse strength values for FA bonded and FMA debonded specimens are presented in Table 6.11. The average FMA liner strength is very close to that of the FA liner and indicates that there is no significant effect of mechanical aging on the liner strength.

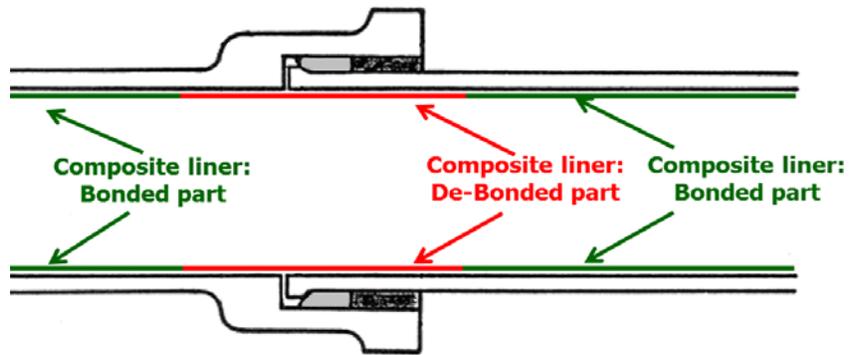


Figure 6.12. Typical Bell and Spigot CI Pipe Joint with Composite Liner Showing both Bonded and De-Bonded Sections of the Pipe after Mechanical Aging Tests

6.5.6 Lap Shear Strength

A longitudinal cross-section through typical bell and spigot CI joint with liner is shown in Figure 6.12. When thermal contraction of the CI pipes occurs, the two adjoining pipe sections are pulled apart and maximum tensile stress and strain are exerted on the liner at the gap between the bell and the spigot. The liner, while stretching, generates shear stresses at the CI pipe/liner interface at that location. This results in the CI pipe/liner interfacial failure in the shear mode. As a result, shear is viewed as the primary mode of CI pipe/liner interfacial failure. The debonded region of the liner has been observed to be within one diameter across the joint gap.

During axial joint displacement, the lining tends to reduce in diameter within the debonded region as the spigot is pulled from the bell. The reduction in diameter is resisted by adhesion in the tensile mode between the CI pipe surface and liner, which is measured in the peel test. It should be recognized that this type of adhesion loss is a secondary mode of failure, which is not as important as the shear resistance between the liner and CI pipe surface.

6.5.6.1 Lap Shear Tests for 6 in. (150 mm) Pipe in the Longitudinal Direction

From the data it is clear that the lap shear strength values remained essentially unchanged after the mechanical aging, suggesting that there was little or no effect of mechanical aging on CI pipe/liner adhesion.

6.5.6.2 Lap Shear Tests for 12 in. (300 mm) Pipe in the Longitudinal Direction

From the data it is clear that the lap shear strength values did not change after the mechanical aging

suggesting that there was little effect of mechanical aging on CI pipe/liner shear strength.

6.5.7 Peel Test

6.5.7.1 Peel Tests for 6 in. (150 mm) Pipe in the Longitudinal Direction

In the peel test the CI pipe/liner failure occurs within a very small linear zone. During the peel tests, once that local zone under stress debonds, the stress is released. Further peeling (pulling) builds up the stress on the next zone until it debonds, again reducing stress. This step-by-step process of building and releasing stress continues through the test and, as a result, the plot has typical stick-slip characteristics. Since the failure occurs in a small zone, the peel test is very sensitive to local bond variations.

Despite the inherent variations, the peel strength values are similar, with the exception of the results for specimen 6-2.

6.5.7.2 Peel Test for 12 in. (300 mm) Pipe in the Longitudinal Direction

The current peel strength values for 12 in. (300 mm) pipe are about half those obtained for the earlier 6 in. (150 mm) pipe study (Netravali et al., 2003). Progressive Pipeline Management personnel were contacted to understand better the field installation procedures for the Starline[®] 2000 PSE-35 liners. The inversion pressure for 12 in. (300 mm) CI pipe is approximately 8 psig (55 kPa) in contrast to about 25-28 psig (\approx 180 kPa) for 6 in. (150 mm) CI pipe. Since the inversion pressure is directly related to the stress imposed on the liner/CI pipe interface during installation and initial curing, it will influence adhesion that develops in the tensile mode between the liner and the CI pipe interior surface. It is likely, therefore, that the lower pressure is responsible for the reduced peel strength.

6.6 Conclusions

The liner tensile testing showed that the liner strengths were comparable for the 6 in. (150 mm) specimens for FA and FMA liner specimens taken from bonded and debonded sections of the liners. Based on these results it can be concluded that 100 years of mechanical aging did not affect the longitudinal tensile strengths of the 6 in. (150 mm) pipe liners. In the hoop direction the liners are also unaffected by mechanical aging.

For the 12 in. (300 mm) pipe liners, tensile strength reduction was measured only in the liner specimens that contained partially damaged yarns, specifically in the debonded sections. Considerable tensile strength was still present in liner specimens with damaged fibers because the stretchable polyurethane membrane was intact. For undamaged specimens removed from the debonded areas, liner strengths were comparable for FA and FMA liner specimens taken from bonded and debonded sections of the liners.

The testing for lap shear and peel strengths of the FA and FMA liner specimens provides an opportunity to determine if the lap shear and peel strengths are affected by mechanical aging. A comparison of the lap shear strengths of FA and FMA specimens from the 6 in. (150 mm) and 12 in. (300 mm) pipe with the lap shear strengths of unaged specimens of cast iron pipe with Starline®2000 PSE-35 liner tested at Cornell in 2003 show no significant difference in the results. Thus, no loss of lap shear strength can be shown over the 10 to 16 years of service life in the field and for the 100 years of mechanical aging imposed on the specimens.

A comparison of the peel strengths of FA and FMA specimens from the 6 in. (150 mm) pipe with the peel strengths of unaged specimens of 6 in. (150 mm) cast iron pipe with Starline®2000 PSE-35 liner tested at Cornell in 2003 show no significant difference in the results. Peel strengths for the 12 in. (300 mm) specimens in this study are not comparable to those of the 6 in. (150 mm) specimens. This is because, as mentioned earlier, installation of the liner in the field involves curing under internal pressure substantially less than that for 6 in. (150 mm) pipe. The lower pressure can be expected to result in a lower peel strength relative to that for the 6 in (150 mm) pipe. The results of this study support this hypothesis. Thus, an important conclusion from this study is that there is no evidence of significant reduction in either lap or peel strength due to field aging over 10 to 16 years in addition to 100 years of mechanical aging when the inversion pressures during CIPL installation are similar.

Section 7

Project Presentations and Demonstration

7.1 Project Videos

On April 28-April 29, 2015, Dave Merte (NYSEARCH Staff), Rick Trieste (Con Edison), Cornell University Staff, and employees of Lowery Street Media, produced a six

minute video demonstrating the CIPL project tests conducted by Cornell University's infrastructure experts on the four extracted field aged lined cast iron test segments. This initial version of the video was available for the AGA Operations Conference held during May of 2015. This video can be viewed at the following link; http://www.nysearch.org/news-info_062215.php. In August of 2015, this six minute NYSEARCH/NGA project video was updated to include the project results and extended to 8 ½ minutes in total length. This updated video was available for the project workshop/webinar held on August 20, 2015 at the Roosevelt Hotel in New York City.

7.2 Live CIPL Field Installation Demonstration

On October 21, 2014, a live CIPL project demonstration was conducted at Con Edison in the Mt. Vernon, New York area with the Starline®2000 liner system utilizing current state of the art lining procedures. In addition to Con Edison and Progressive Pipeline Management (PPM) field support, six members of the NYS Department of Public Service, the PHMSA project manager, NYSEARCH project management, and funding member company representatives attended this demonstration. The Mt. Vernon area selected for the demonstration is an urban environment with heavy traffic and dense residential and commercial above and below grade infrastructure. An 8" CI main on E. Sidney Avenue (between Crary Avenue and N. 3rd Avenue) was lined and a 6" steel main on William Street (between N. Terrace Avenue and Locust Street), lined prior to the demonstration day, was inspected with a camera demonstrating second day lining procedures to attendees (see appendix F).

7.3 Project Workshop

A pre-workshop meeting was held on August 19, 2015, at the Cornell Club in New York City with NYSEARCH/NGA project funders and Cornell University Professors Tom O'Rourke, Harry Stewart, and Anil Netravali. A workshop and webinar held on the following day at the Roosevelt Hotel in New York City on August 20, 2015, presented the technical results to gas industry and regulatory officials noting that after field aging and extraction and more than (100) years of additional simulated field mechanical aging, the CIPL cast iron test segments passed all tests including a post-verification pressure test equivalent to or greater than that required to place a new pipe segment in service.

On August 20, 2015, a CIPL project workshop and webinar was conducted at the Roosevelt Hotel (45 East 45th Street, N.Y.). The workshop/webinar invitation is in Appendix G. Project presentations by Cornell Professors Tom O'Rourke, Harry Stewart, and Anil Netravali,

Dave Merte (NYSEARCH's Project Manager), Bob Smith and Chris McLaren (PHMSA), and George Ragula (PSE&G) were conducted with (22) on site attendees and additional webinar participants representing industry and regulatory officials. In addition to project funding member company representatives, the project workshop/webinar attendees included officials from PHMSA, GTI and the following regulatory jurisdictions: 1) New York, 2) Alabama, 3) South Dakota, 4) Pennsylvania, 5) New Jersey, 6) Kentucky, 7) Connecticut, 8) the District of Columbia, and 9) the City of Pensacola (see appendix G). The project link that includes the workshop presentations, is as follows;

<https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=502>.

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Appendix A
Glossary of Terms

A. 1 Definitions

CI – Cast Iron is a hard, brittle, nonmalleable iron-carbon alloy

CIPL (Cured-in-Place Liner) – Seamless, circular, woven fabric-hose made of polyester yarns and a polyurethane or polyethylene plastic coating bonded as an inner liner into the host pipe using a two-component adhesive

Bonded – CIPL (liner) that adheres to the CI host pipe wall

De-bonded – CIPL (liner) that does not adhere to the CI host pipe wall

Test Segment – A field extracted CIPL eight foot section of 6” or 12” host CI pipe containing a bell and spigot joint (6”) or a mechanical joint (12”)

FA (Field Aged) – A test segment of CIPL (liner) that operated below grade in a natural gas distribution system that was pressurized with natural gas (16 years for 6” CI and 10 years for 12” CI)

FMA (Field and Mechanically Aged) – A test segment of CIPL (liner) that operated below grade that was pressurized with natural gas (16 years for 6” CI and 10 years for 12” CI). Test segments were subsequently extracted from the field and mechanically aged in the laboratory

Post Test Pressurization – The CIPL test segment (liner) is pressurized to 90 psig (12” CI) or 150 psig (6” CI) utilizing either water or nitrogen after completion of all FMA testing

Thermal Cycle - Equivalent to a 120 day or annual freeze/thaw (contraction and expansion) for a CIPL jointed test segment at normal burial depth in the Northeastern U.S.

Undermine Event – A simulated excavation (including backfill) adjacent to a pipe segment. CIPL test segments were subjected to one excavation event followed by an additional 100,000 vehicular traffic loading cycles subsequent to each 50 years of simulated cyclic vehicular loading

Vehicular Traffic Loading Cycles – CIPL test segments were subjected to the annual equivalent of 20,000 heavy truck loadings at normal burial depth (20,000 X 100 years=2,000,000 cycles)

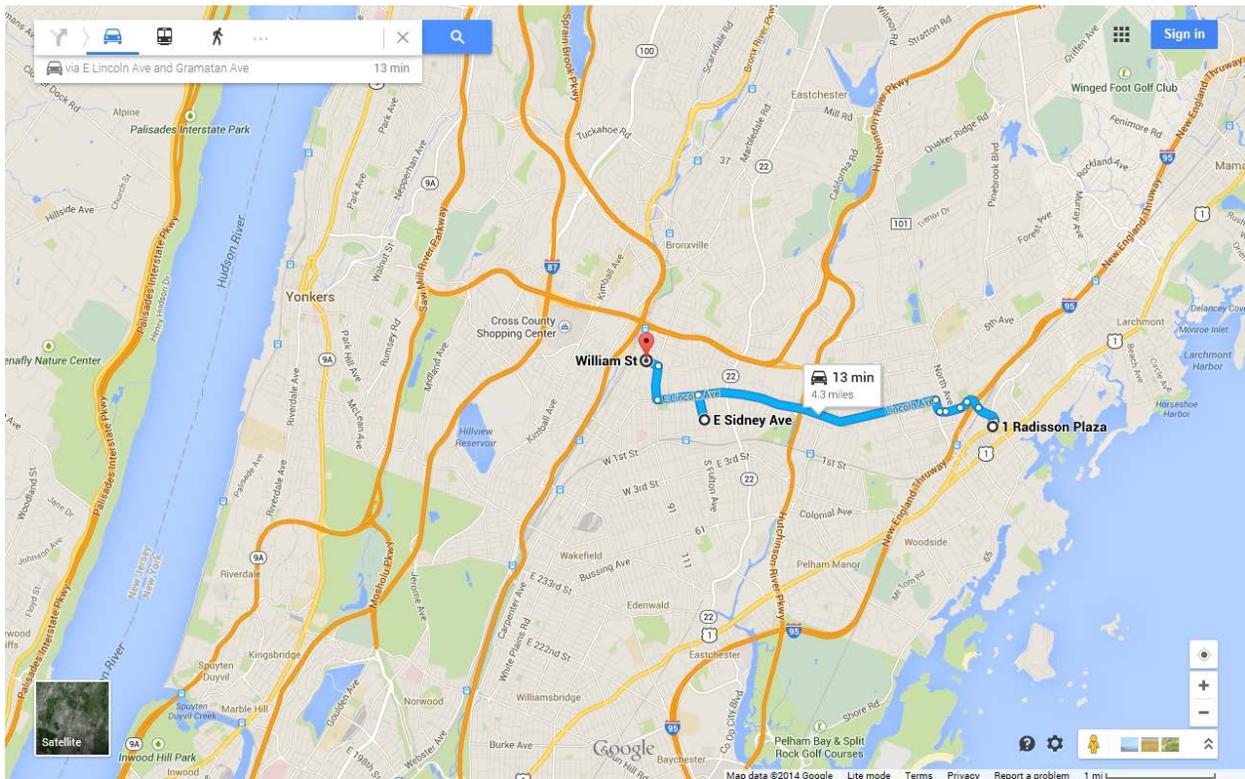
Appendix F
CIPL Project Demonstration Mt. Vernon, New York
Cured-in-Place Liner Installation Demonstration

Tuesday, October 21, 2014 – 9:30 am

Site #1 – E. Sidney Avenue between N. 3rd Avenue & Crary Avenue – Mount Vernon, N.Y.

Site #2 – William Street between N. Terrace Avenue & Locust Street – Mount Vernon, N.Y.

- **Please bring the following required personal protective equipment (PPE) for the field Demonstration (All Attendees)**
 - **Hard Hat**
 - **Safety Glasses**
 - **Traffic Vest**



Note: Please RSVP should you be planning to attend this demonstration. The demonstration will take place rain or shine.

- NYSEARCH Contact – David W. Merte, P.E.
- dmerte@northeastgas.org
- (845) 522-9195 (Cell)

Liner Demonstration Installation Photos



Appendix G

CIPL Project Workshop Roosevelt Hotel, New York City

CIPL PROJECT WORKSHOP AGENDA

AUGUST 20, 2015

8:30am	David Merte, PE – NYSEARCH/NGA Senior Project Manager – CIPL Project Review
9:00am	Operator CIPL Experience – George Rogula – Distribution Technology Manager, PSE&G
9:15am	Harry Stewart, PE – Associate Professor and Director, Civil Infrastructure Laboratories & Thomas O'Rourke – Professor of Engineering – Cornell University – Lined Cast Iron Segment Field Extraction and Mechanical Aging Test Protocols & Results (Heavy traffic, undermine, thermal pullout)
10:10am	Coffee Break
10:25am	Anil Netravali, Ph.D. – Professor Fiber Science and Apparel Design – Cornell University – Post Mortem Test Protocols & Results – CIP Liner Residual Mechanical Properties (Tension, Lap Shear, Peel)
11:15am	David Merte – Q&A, Member Perspectives
11:30am	Lunch Break (on your own)
12:45pm	Chris McLaren & Robert Smith – PHMSA R&D Perspective
1:30pm	CIPL Project Testing & Results - Video
1:45pm	Dave Merte & Chris McLaren – Project Summary & Roundtable Discussion

*The overall objective of the project is to compile and develop information to advance a broad understanding of the potential for using CIPL lined pipe as a safe and practical rehabilitation or renewal option in the natural gas industry.



PROJECT WORKSHOP DETAILS

- ▶ Technology Transfer Demonstrations and post-Mortem Testing of Cast Iron and Steel Pipe Lined Cured-in-Place Liners
- ▶ Workshop Sponsor: NYSEARCH/Northeast Gas Association



Thursday August 20, 2015
8:30am – 3:00pm
The Roosevelt Hotel
45 East 45th Street & Madison Avenue
RSVP Wendy Hansen (NYSEARCH) 973-265-1900 ext: 200
whansen@northeastgas.org

Accommodations: Superior King Beds are available for \$209 (plus fees)
Email Leticia Santana at lsantana@rooseveltnyc.com for your reservations



