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A Retrospective Evaluation of Cured-in-Place Pipe (CIPP) Used in Municipal Gravity Sewers

SCIENCE

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A Retrospective Evaluation of Cured-in-Place Pipe (CIPP) Used in Municipal Gravity Sewers

by

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DISCLAIMER

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ABSTRACT

Pipe rehabilitation and trenchless replacement technologies have seen a steadily increasing use and represent an increasing proportion of the annual expenditure on operations and maintenance of the nation's water and wastewater infrastructure. Despite public investment in use of these technologies, there has been little quantitative evaluation of how these technologies are performing. The major reasons for retrospective evaluation of rehabilitation systems are needed include: data gaps in predicting remaining asset life of pipes and how long rehabilitation techniques can extend that life; and to assess whether the originally planned lifetime is reasonable based on current condition. The goals of this project were to draw attention to the need for this type of evaluation and to develop evaluation protocols that are technically and financially feasible for carrying out these evaluations.

The initial project focuses on cured-in-place pipe (CIPP) liners because they were the first trenchless liners (other than conventional slipliners) to be used in pipe rehabilitation and they hold the largest market share. The pilot testing used CIPP samples from both large and small diameter sewers in two cities that were in excellent condition after being in use for 25, 23, 21, and 5 years, respectively. Testing on the liners included thickness, annular gap, ovality, density, specific gravity, porosity, flexural strength, flexural modulus, tensile strength, tensile modulus, surface hardness, glass transition temperature, and Raman spectroscopy. In addition, environmental data was gathered as appropriate including: external soil conditions and pH, and internal waste stream pH. Three of the liners had already been in service for nearly half of their originally expected service life, but overall, there is no reason to anticipate that the liners evaluated will not last for their intended lifetime of 50 years and perhaps beyond.

Given the insights provided by the pilot studies, an expansion of the retrospective study is recommended to create a broader database to better define the expected life of sewer rehabilitation technologies. Specifically, it is recommended that the retrospective program be extended to: cover additional CIPP sample retrieval in other cities, pilot studies of other rehabilitation technologies; capture locally interpreted data from other cities; encourage sewer agencies to keep as-installed material test data for later comparison with follow-up testing; and adapt, develop, and/or calibrate non-destructive testing (NDT) methods that could use small physical samples that are easily retrieved robotically from inside the pipe.

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EXECUTIVE SUMMARY

Pipe rehabilitation and trenchless pipe replacement technologies have seen a steadily increasing use over the past 30 to 40 years and represent an increasing proportion of the approximately $25 billion annual expenditure on operations and maintenance of the nation's water and wastewater infrastructure (EPA, 2002). Despite the massive public investment represented by the use of these technologies, there has been little formal and quantitative evaluation of whether they are performing as expected and whether rehabilitation is indeed cost-effective compared to replacement.

The major reasons for an interest in a retrospective evaluation of pipe rehabilitation systems are:

- The biggest data gap in asset management for pipeline systems involving rehabilitation is prediction of the remaining asset life for the existing pipe and how long rehabilitation techniques can extend that life. Municipalities have expressed a strong desire for some hard data on the current condition of previously installed systems to validate or correct the assumptions made at the time of rehabilitation.
- Since several of the major pipe lining techniques have now been in use for at least 15 years (some nearly 30 years in the U.S. and 40 years internationally), it is a good time to undertake such an investigation to assess whether the originally planned lifetime (typically assumed to be 50 years) is reasonable based on the current condition of the liner.

While the long-term goal of the retrospective evaluation effort is to provide significant and credible feedback on performance to the system owners and the engineers who specify rehabilitation and replacement technologies, a few isolated evaluations of projects with a variety of existing and service conditions cannot provide statistically significant data. Thus, the goals for the effort within this project are to draw attention to the need for this type of evaluation and to develop evaluation protocols that are technically and financially feasible for carrying out evaluations of the main rehabilitation and trenchless replacement technologies. The protocols should produce useful results at a cost that municipalities will be willing to pay to participate in the data collection. The subsequent drive will be to encourage municipalities and other system owners to conduct their own evaluations and then to contribute their data to a common database where the results can be aggregated on a national basis. The initial project described in this report focuses on cured-in-place pipe (CIPP) liners because they were the first trenchless liners (other than conventional slipliners) to be used in pipe rehabilitation and because they hold the largest market share within relining technologies. The pilot testing used CIPP samples from both large and small diameter sewers in two cities: Denver, CO and Columbus, OH. For the small diameter (8 in.) sewers in each city, a 6 ft section of pipe and liner was exhumed from a convenient site. For the larger diameter sewers (36 to 48 in. diameter), CIPP liner samples were cut from the interior of the pipe and the liner patched in situ.

Testing on the liners included thickness, annular gap, ovality, density, specific gravity, porosity, flexural strength, flexural modulus, tensile strength, tensile modulus, surface hardness, glass transition temperature, and Raman spectroscopy. In addition, environmental data was gathered as appropriate to each retrieval process including: external soil conditions and pH, and internal waste stream pH. The findings from the testing conducted so far are presented in detail in this report and a short overall summary is given below.

All of the samples retrieved from the four locations involved in the pilot study testing were in excellent condition after being in use for 25 years, 23 years, 21 years, and 5 years, respectively. Three of these liners had already been in service for approximately half of their originally expected service life. Two samples had a flexural modulus value that was lower than the originally specified value, but this cannot be tied directly to deterioration of the liner over time. In the case of the Denver 48-in downstream liner, in particular, it appears likely that the poor physical test properties may have resulted from variability within the liner rather than a change over time. Some indication of a softening of the interior surface of the liner that was exposed most to the waste stream (interior invert and spring lines) relative to the interior crown location and that of the exterior surface of the liner was noted in surface hardness testing. However, it is not yet possible to isolate any effect on the resin liner itself from the hydrolysis of the handling layer that was originally present on the inside surface of the CIPP liner. For newer CIPP liners, a different handling/inner layer with greater durability is used.

In Denver, a few specific defects were noted at different locations in closed-circuit television (CCTV) inspections of nearly 5,800 ft of CIPP liners installed at the same time as the retrieved sample. Most of these appeared to relate to poor practices in cutting or reinstating lateral connections and only three appeared potentially unrelated to lateral reinstatement issues. These were a local liner bulge, a separation of the liner from the wall of the pipe, and a local tear in the liner.

Overall, there is no reason to anticipate that the liners evaluated in this pilot study will not last for their intended lifetime of 50 years and perhaps well beyond.

Given the insights provided by the pilot studies in Denver and Columbus, an expansion of the retrospective evaluation study is recommended to create a broader national database that would help to better define the expected life of sewer rehabilitation technologies. Specifically, it is recommended that the pilot studies and retrospective evaluation program be extended to cover the following activities:

- Additional CIPP sample retrieval in other cities with a wider variety of site and sewage flow characteristics.
- Pilot studies of other sewer rehabilitation technologies – focusing initially on those with the greatest number of years of service. As with the current CIPP study, the pilot study would seek to identify the most useful quantitative tests that could be used to evaluate performance, degradation, and expected remaining life.
- A broader survey to capture the locally interpreted data from a wide range of cities on their experiences with rehabilitation technologies.
- An effort to encourage sewer agencies to keep as-installed material test data for later comparison with follow-up testing. This should include working with the most widely used database and asset management systems to make sure that such information can readily be incorporated and identified using their software.
- Adaptation, development, and/or calibration of non-destructive testing (NDT) methods plus similar efforts for material test methods that could use small physical samples that are easily retrieved robotically from inside the pipe and for which the damage could be easily repaired. Several quantitative liner characterization tests that could be expected to be developed for robotic deployment within sewer mainlines of 8-in. diameter and larger have been identified as part of this project.

The outcome of an effective evaluation process would be to address one of the largest unknowns in terms of decision-making for engineers carrying out life-cycle cost/benefit evaluations and to facilitate the sharing of lining performance data among municipalities in a systematic and transferable manner. Evaluating rehabilitation technologies that have already been in service for a significant length of time could also provide data that could be used immediately by other municipalities (e.g., what properties/defects are critical; what accelerates deterioration) and could establish benchmarks for vendors against which they can improve their products (i.e., it could become a driver for achieving excellence). It is an opportune time for such a concerted push in terms of evaluation because there has been a significant time in service for many technologies and there is a continued strong investment in the use of the technologies across the U.S.

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ABBREVIATIONS AND ACRONYMS

AMP	Asset Management Period
ASTEE	Association Scientifique et Technique pour l'Eau et l'Environnement
ASTM	American Society for Testing and Materials
ATH	alumina trihydroxide
a.u.	arbitrary units
ATV	Abwassertechnische Vereinigung (German Wastewater Technical Association)
BW	Brisbane Water
CAC	Communauté d'Agglomeration de Chartres
CAHB	Communauté d'Agglomeration Les Hauts-de-Bièvre
CEN	Comité Européen de Normalisation (European Committee for Standardization)
CERIU	Centre d'Expertise et de Recherche en Infrastructures Urbaines
CCTV	closed-circuit television
CIPP	cured-in-place pipe
DAQ	data acquisition system
DEFRA	Department of the Environment, Food and Rural Affairs
DRO	diesel range organics
DSC	differential scanning calorimetry
DVGW	Deutscher Verein des Gas- und Wasserfaches e.V. - Technisch-wissenschaftlicher Verein (German Technical and Scientific Association for Gas and Water)
DWI	Drinking Water Inspectorate
EA	U.K. Environment Agency
EPA	U.S. Environmental Protection Agency
FTIR	Fourier transform infrared
GIS	geographic information system
GRO	Gasoline Range Organics
GRP	Glass Reinforced Plastic
GS	Göttingen Stadtentwässerung
I/I	infiltration and inflow
IKT	Institut für Unterirdische Infrastruktur gGmbH (Institute for Underground Infrastructure)
ISTT	International Society for Trenchless Technology
JASCOMA	Japan Sewer Collection Maintenance Association
JIWET	Japan Institute of Wastewater Technology
JPRQAA	Japan Pipe Rehabilitation Quality Assurance Association
JSWA	Japan Sewerage Works Agency
LVDT	linear variable displacement transducer
MLIT	Ministry of Land, Infrastructure and Construction (Japan)
NASTT	North American Society for Trenchless Technology

NDT	non-destructive testing
NRMRL	National Risk Management Research Laboratory
OD	oven dry
OFWAT	Office of Water Services
PE	polyethylene
psi	pounds per square inch
psia	pounds per square inch absolute
PUB	Public Utilities Board (Singapore)
PUBC	PUB Consultants Private Limited
PVC	polyvinyl chloride
QA	quality assurance
QAPP	Quality Assurance Protocol Plan
QC	quality control
QUU	Queensland Urban Utilities
SgSTT	Singapore Society for Trenchless Technology
SOP	standard operating procedure
SPR	spiral pipe renewal
SRM	Sewer Rehabilitation Manual (U.K.)
SSD	saturated surface dry
STW	Severn Trent Water
SW	Sydney Water
TBL	Technische Betriebe der Stadt Leverkusen
TBPB	tert-butyl peroxybenzoate peroxide
Tg	glass transition temperature
TGA	thermo-gravimetric analysis
TO	task order
TPH	total petroleum hydrocarbons
TTC	Trenchless Technology Center
TW	Thames Water
TWA	Thames Water Authority
UTM	Universal Testing Machine
UV	ultraviolet
VCP	vitrified clay pipe
VOC	volatile organic compound
WEFTEC	Water Environment Federation Technical Exhibition and Conference
WIS	Water Industry Specifications (U.K.)
WRc	Water Research Centre (U.K.)

1.0: INTRODUCTION

This report forms part of a project funded by the U.S. Environmental Protection Agency (EPA) to study and support technology development for the rehabilitation of water distribution and wastewater collection systems. During the early stages of this project, the need for a quantitative, retrospective evaluation of the performance of pipe rehabilitation systems emerged. Pipe rehabilitation and trenchless pipe replacement technologies have seen a steadily increasing use over the past 30 to 40 years and represent an increasing proportion of the approximately $25 billion annual expenditure on operations and maintenance of the nation's water and wastewater infrastructure (EPA, 2002). Despite the massive public investment represented by the use of these technologies, there has been little formal and quantitative evaluation of whether they are performing as expected and whether rehabilitation is indeed cost-effective compared to replacement. The need for such information was reinforced by the participants at an international technology forum held as part of the project activities in September 2008. It was noted at the forum that the City of Montreal and a number of cities in Germany have already engaged in efforts to revisit previous rehabilitation projects to characterize their level of in-service performance to assess any evidence of deterioration (Sterling et al., 2009). Information collected on these and other international experiences with cured-in-place pipe (CIPP) liners are included in this report.

The major reasons for interest in a retrospective evaluation of pipe rehabilitation systems are:

- The biggest data gap in asset management for pipeline systems involving rehabilitation is prediction of the remaining asset life for the existing pipe and how long rehabilitation techniques can extend that life. Municipalities have expressed a strong desire for some hard data on the current condition of previously installed systems to validate or correct the assumptions made at the time of rehabilitation.
- Since several of the major pipe lining techniques have now been in use for at least 15 years (some nearly 30 years in the U.S. and 40 years internationally), it is a good time to undertake such an investigation to assess whether the originally planned lifetime (typically assumed to be 50 years) is reasonable based on the current condition of the liner.

The outcome of an effective evaluation would be to address one of the largest unknowns in terms of decision-making for engineers carrying out life-cycle cost/benefit evaluations and to facilitate the sharing of lining performance data among municipalities in a systematic and transferable manner. This type of evaluation can provide answers to the question "How long can I extend the life of the asset if I rehabilitate it instead of replacing it?" but can also start to fill one of the biggest gaps in knowledge about rehabilitation technologies that exists today – their expected lifetimes under a variety of installation and service conditions. Evaluating rehabilitation technologies that have already been in service for a significant length of time could provide data that could be used immediately by other municipalities (e.g., what properties/defects are critical; what accelerates deterioration) and could establish benchmarks for vendors against which they can improve their products (i.e., it could become a driver for achieving excellence).

It is an opportune time for such a concerted push in terms of evaluation because there has been a significant time in service for many technologies and there is a continued strong investment in the use of the technologies across the U.S.

While the long-term goal of the retrospective evaluation effort is to provide significant and credible feedback on performance to the system owners and the engineers who specify rehabilitation and replacement, a few isolated evaluations of projects with a variety of existing and service conditions cannot provide statistically significant data. Thus, the goals for the effort within this project are: to draw attention to the need for this type of evaluation and to develop evaluation protocols that are technically and financially feasible for carrying out evaluations of the main rehabilitation and trenchless replacement technologies. The protocol should produce useful results at a cost that municipalities will be willing to pay to participate in the data collection. The subsequent drive will be to encourage municipalities and other system owners to conduct their own evaluations and then to contribute their data to a common database where the results can be aggregated on a national basis. The initial project focuses on CIPP liners because they were the first trenchless liners (other than conventional slipliners) used in pipe rehabilitation and because they hold the largest market share within relining technologies. It is intended to use the experiences derived from the evaluation of CIPP liners described in this report to develop similar technology-appropriate protocols for other rehabilitation systems.

1.1 Organization of Protocol Development and Field Studies

The research team for the retrospective evaluation effort was comprised of Battelle as Project Manager with the Trenchless Technology Center (TTC) at Louisiana Tech University taking the lead in developing the test protocol and carrying out the liner testing. Jason Consultants was responsible for carrying out a review of what other cities around the world are doing with respect to long-term evaluations of their lining programs. Jason Consultants also assisted with field inspections and evaluation of test results.

The project stages generally followed the progression of activities outlined below:

- A comprehensive list of field investigations and laboratory testing was developed that could be used to evaluate the current condition of a CIPP liner and provide information on its potential longevity.
- A written summary of the proposed liner evaluation protocol and its expected benefits was prepared that could be used in discussions with interested municipalities.
- Municipalities were identified that would be interested in assisting with a retrospective evaluation of previously installed CIPP liners and that had CIPP liners with as many years of service as possible.
- Detailed discussions were entered into with the identified municipalities to discuss their participation in the study and the division of responsibilities and costs for the field retrieval of samples. To reduce project costs, it was planned to retrieve samples from two distinct sites at each municipality.
- Once the sites were agreed upon, the detailed planning of the sample retrieval was undertaken, the field work carried out, and the test sections/samples shipped to the TTC for testing.
- The tests carried out on the liners were evaluated as to the nature and extent that they provide information regarding the liner's condition relative to its condition immediately following installation and also for their cost-effectiveness in a more widespread liner evaluation program.
- Conclusions from the initial testing were developed and recommendations were formed as to a suitable retrospective evaluation protocol for wider use in the U.S.

This work was carried out in parallel with a broader set of interviews with municipalities and sewer agencies internationally to determine whether any international efforts were underway in terms of retrospective evaluations and, if so, what types of evaluation and testing were being used.

1.2 Organization of the Report

Following the introduction to the concept and development of the retrospective evaluation effort provided in this Section, the main body of the report focuses on CIPP liners which have been the initial target of the retrospective study. Section 2 provides a review of the development and use of CIPP as a rehabilitation technology. Section 3 discusses the development of the draft evaluation protocol that was discussed with the two cities that participated in this initial study. Sections 4 and 5 provide the detailed studies carried out on two separate liners in each city. Section 6 compares the results obtained across the four liners and Section 7 discusses the implications of the sample retrieval process and testing used in these pilot studies on a suitable protocol for wider implementation across the U.S. The results of the international scan are reported in Section 8 and the overall summary and recommendations for further work are provided in Section 9.

2.0: CIPP TECHNOLOGY DEVELOPMENT

2.1 Introduction

CIPP technology is one of a family of trenchless rehabilitation methods that allows the renewal of a buried pipe without the full excavation of the pipe from the ground surface. Such rehabilitation methods applied to sewer mainlines include the use of CIPP, close-fit linings, grout in place, spiral-wound linings, panel linings, spray-on/spin-cast linings, and chemical grouting as illustrated in Figure 2-1. Pipe repair (e.g., repair sleeves) and replacement methods (e.g., sliplining and pipe bursting) may also be carried out using trenchless technology approaches. Further information on these various repair, replacement, and rehabilitation technologies can be found in a companion EPA report (Sterling et al., 2010).

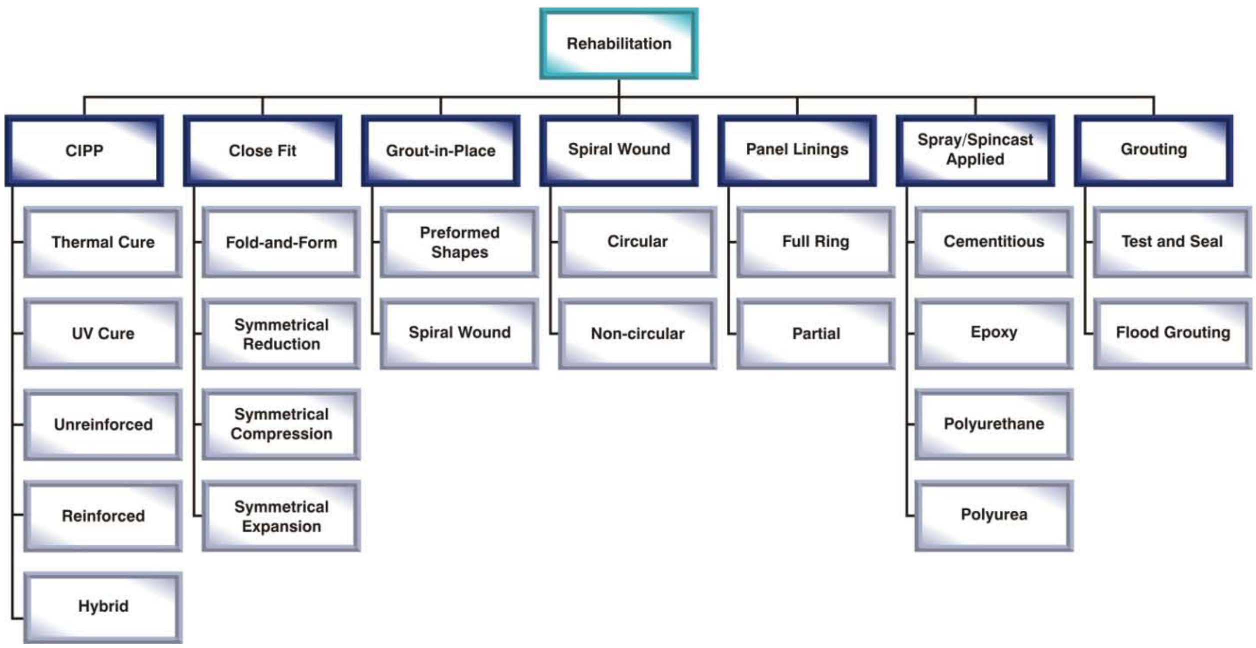


Figure 2-1. Rehabilitation Approaches for Sewer Mainlines

Some of these rehabilitation and trenchless replacement technologies vary significantly in their applicability to various aspects of host pipe condition. Examples of typical issues are:

- Extent of cleaning required (e.g., high level of cleaning required for spray coatings and close-fit lining systems; low level needed for pipe bursting)
- Sensitivity of method to minor variations in pipe's internal diameter
- Adaptability of the method to cope with pipe-diameter changes within a rehabilitation segment.

Technologies also vary significantly in their requirements for sewage flow interruption or bypassing of the sewer line. The significance of this requirement increases as the sewer diameter increases, reflecting larger and more continuous sewage flows and more critical backup requirements for the bypass operations.

Some sections of a sewer system may be in good overall structural condition, but have leaking cracks or joints that allow excessive infiltration and inflow (I/I) into the system. Other pipes may need partial or complete upgrading of the structural condition of pipe to withstand internal pressures, or external soil and groundwater pressures.

The focus of this initial retrospective evaluation was chosen to be CIPP liners used in gravity sewer systems. This choice was made on the basis of the extensive current use of this technology in the U.S. market. Apart from sliplining, CIPP was the earliest trenchless relining technology used in the U.S. with liners that have been in service for up to 30 years in the U.S. and nearly 40 years in the U.K. A more detailed description of CIPP rehabilitation and related research and testing as related to its use for the rehabilitation of gravity sewer mainlines follows in the rest of this section.

2.2 Cured-in-Place Pipe

2.2.1 Historical and Commercial Background. The first known municipal use of a CIPP lining occurred in 1971 in the relining of a 230-ft (70-m) length of the Marsh Lane Sewer in Hackney, East London. This 100-year old brick egg-shaped sewer had dimensions of 3.85 ft × 2 ft (1,175 mm × 610 mm). The work was carried out by inventor Eric Wood supported by entrepreneurs Doug Chick and Brian Chandler and following this successful trial, they registered the company Insituform Pipes and Structures, Ltd., and proceeded to market the technology and make improvements in the materials, preparation, and application of the technology (Downey, 2010). It should be noted that this first installation was a pull-in-and-inflate liner – inversion was not possible until coated felt was used in 1973. The name and structure of the Insituform family of companies have changed over the years and, over time, other companies have entered the market with similar and competitive technologies.

Eric Wood applied for the first patent on the CIPP process on August 21, 1970 in the U.K. and was granted his first U.S. Patent on the process (U.S. Patent No. 4009063) on February 22, 1977. After granting licenses to British contractors to begin using this new process to rehabilitate sewers in England, Insituform expanded its business in 1976 by granting licenses to contractors in mainland Europe and in Australia. In 1976, Wood began licensing his process to contractors in North America. In 1994, however, the patent for Insituform's inversion process expired and this resulted in new competition in the trenchless rehabilitation industry (Rose and Jin, 2006). Another important patent related to the process concerned vacuum impregnation. The U.S. version of this patent was granted on December 28, 1982 (U.S. Patent No. 4366012). The patent expired on February 5, 2001. U.S. patents on various aspects of the CIPP process are still being sought and granted, e.g., U.S. Patent Nos. 5798013 and 6679966 issued in 1998 and 2004 related to the Brandenburger CIPP lining process and U.S. Patent No. 6942426 related to control of the thermal curing process granted to Kampbell and Cuba in 2005. Insituform has continued to file a variety of patents related to CIPP. These include U.S. Patent No. 4135958, granted on January 23, 1979, which includes a discussion of the light curing of liners and "Method for Remote Lining of Side Connections" (U.S. Patent No. 4434115) issued on February 28, 1984.

In 1976, the first Insituform® liner was installed in the U.S. in a 12-in.-diameter line in Fresno, California. Since then, approximately 19,000 miles (100 million ft) of CIPP liner have been installed by U.S.-based Insituform contractors (Osborn, 2011). The original installations involved an inverted resin-felt composite liner impregnated with polyester resin and cured with hot water. Other companies also started installing CIPP liners in the U.S. through the 1980s and 1990s. These include the Inliner® system which was first introduced in 1986 with over 9 million ft installed since then. Other longstanding liner suppliers that are still operating include National Liner® and Masterliner®.

Other early municipal users of CIPP in the U.S. included the Washington Suburban Sanitary Commission (from 1978) (Hannan, 1990) and the City and County of Denver (from 1984) (Barsoom, 1993). St. Louis, Houston, Baltimore, Little Rock, Memphis, and Indianapolis were among other cities that established early CIPP rehabilitation programs (Iseley, 2011). By 1990, four liner systems were reported to be available in the U.S. (see Table 2-1).

Table 2-1. CIPP Products Available in the U.S. in 1990 and Their Characteristics (Hannan, 1990)

Liner Parameter	Product			
	Insituform	**Paltem**	**In-Liner**	**Insta-Pipe**
Insertion	Inversion using water head	Inversion using air pressure	Winched into place	Floated and winched into place
Materials	Non-woven tube materials and thermoset resin	Woven and non-woven tube materials and thermoset resin	Non-woven tube materials and thermoset resin	Woven and non-woven tube materials & epoxy thermoset resin
Curing Process	Circulating hot water	Circulating hot steam	Circulating hot water	Circulating hot air

As the original patents on key aspects of the CIPP process expired, the breadth of competition increased. Overall, since 1971, it is estimated that about 40,000 miles (210 million ft) of CIPP liners have been installed worldwide. It is by far the leading method for rehabilitating gravity sewers.

2.2.2 The CIPP Process. A CIPP project involves a variety of investigative, planning, and execution phases. Once a line has been identified as needing rehabilitation or replacement, the characteristics of the line and the problems experienced will determine if the CIPP process is a suitable candidate for replacement. CIPP is generally available in diameters of 4 to 120 in., depending (especially in the larger diameters) on the supplier's and contractor's capabilities and experience. Guidance on this type of decision can be found in a variety of published sources on rehabilitation technologies and in the literature from manufacturers and suppliers. Software to support the method selection process also has been developed and a review of such software development can be found in Matthews et al. (2011).

Prior to the relining work, the existing host pipe will be carefully examined (typically using a closed-circuit television [CCTV] camera inspection) and any necessary additional measurements (such as pipe diameter) are collected. Data on pipe depth, soil type, and groundwater conditions will also be gathered.

Based on this data, the following major design parameters would be determined for the use of CIPP in gravity flow sewers:

- Accurate measurements of the internal diameter of the host pipe and any variations in diameter along individual sections of pipe to be relined.
- Any ovality in cross-section dimensions for the host pipe (more than 10% ovality is typically not considered suitable for relining with CIPP because of greatly increased thickness requirements for the liner).
- Whether the host pipe is considered structurally sound (i.e., the lining is not required to support the surrounding soil loading). If the pipe is not considered structurally sound, then additional data regarding the potential soil loading is required.

- The depth of the pipe below the groundwater level (the maximum depth is often used when the groundwater depth varies). This water pressure acts on the outside of the liner through the defects present in the host pipe. The liner thickness is calculated to provide an adequate safety factor against local buckling of the liner under the external water pressure.

The key American Society for Testing and Materials (ASTM) standards pertaining to different types of CIPP liner installation are shown in Table 2-2. The structural requirements of the liner are designed in all of the standards using the procedures specified in ASTM F1216. This is based primarily on formula for the buckling of thin liners restrained within a host pipe. Since a CIPP liner is a thermoset plastic material, it exhibits creep displacements over time under constant load and hence its resistance to buckling over long loading periods is much less than its short-term buckling resistance. This is accounted for in the F1216 design approach by using an estimate of the effective modulus of deformation of the liner over the planned design life of the rehabilitation. This effective modulus value typically is established by using extended (often 10,000 hour) creep and/or buckling tests for the liner/liner material. The measured values are then extrapolated to the typical 50-year design life values. Much research has been carried out and many papers written on the analysis of long-term buckling in such liners. References to a selection of these papers are provided within the text at the end of this section.

Table 2-2. Key ASTM Standards Covering CIPP Installations

ASTM F1216	Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube
ASTM F1743	Standard Practice for Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Cured-in-Place Thermosetting Resin Pipe (CIPP)
ASTM F2019	Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Pulled-in-Place Installation of Glass Reinforced Plastic (GRP) Cured-in-Place Thermosetting Resin Pipe (CIPP)
ASTM F2599	Standard Practice for the Sectional Repair of Damaged Pipe by Means of an Inverted Cured-in-Place Liner

The required thickness of the liner depends on the effective long-term modulus of the liner, its Poisson's ratio, its mean diameter, its ovality, and the chosen safety factor, as well as the external loading conditions provided by the groundwater pressure and/or external soil/traffic loadings. An important factor in the ASTM buckling equation is a correction factor (K) for the degree of buckling restraint provided by the close fit of the liner within the host pipe. However, in typical designs, only a single fixed value (K = 7.0) is used for this parameter.

In most cases, the application of the ASTM F1216 equations results in a conservative design for the required thickness of the liner (Zhao et al., 2005). Conservatism can occur for a variety of reasons, e.g., because the groundwater loading used for design is seldom at the assumed value, because only a limited section of the pipe has the ovality assumed in the design, because the contractor chooses to exceed the minimum required value of liner modulus to make sure of product acceptance, and/or because the buckling restraint factor is conservative for the application considered. Such conservatism may provide a cushion against unacceptable performance in failure modes not considered explicitly in the design process (e.g., local imperfections in the shape of the host pipe) and accommodate liner flaws that are not identified by the quality assurance (QA) or quality control (QC) procedures such as locally weak or porous areas of the liner.

Once the liner materials, liner cross section, curing method, and installation procedure have been decided, the project execution can occur. Most CIPP liners are impregnated with resin (also known as “wet out”) in a factory setting. Typically, a vacuum impregnation process is used to allow the resin to flow more easily into the liner fabric and to more fully saturate it. Prior to 2001, this vacuum impregnation process was covered by a separate Insituform patent and, hence, other CIPP lining companies often used modified procedures to work around the patent. After wet out and during transport to the site, thermally-cured liners are kept in refrigerated storage or in a chilled condition to avoid premature curing of the liner.

Small diameter liners (e.g., for sewer laterals) and very large liners can be wet out at the site. For small liners, this can be for convenience and is facilitated by the relative ease of handling a small diameter liner during wetting out. For large diameter liners, the large liner thickness coupled with the large host pipe diameter means that the lay-flat liner becomes too heavy or too wide to transport when wet out. However, on-site wet out puts an extra burden on QC for the impregnation process.

When the impregnated liner is ready, it is introduced into the host pipe to be relined. This can be done by inversion of the liner along the host pipe using water or air pressure or by pulling the liner into place and then inflating it to a close fit using water or air (see Figure 2-2).

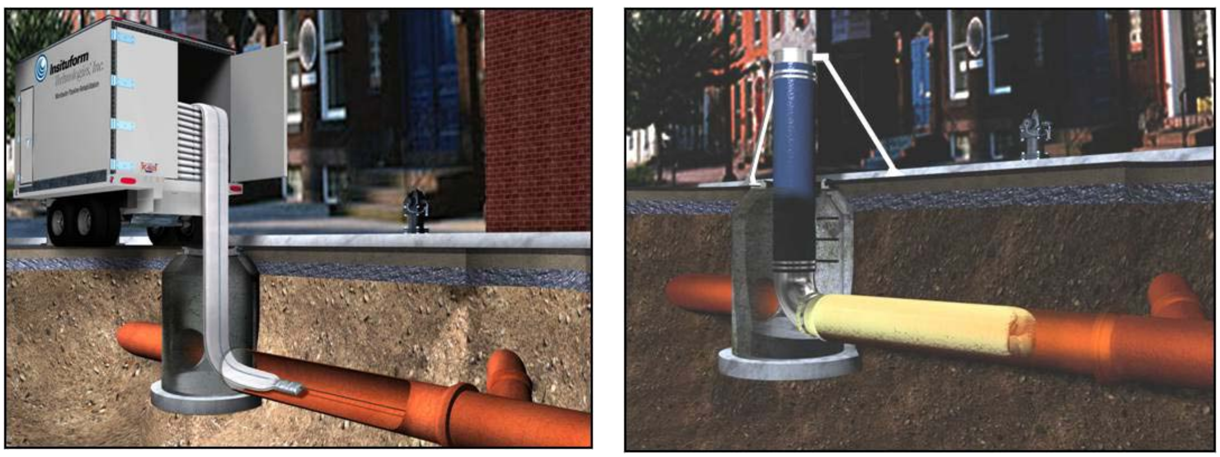


Figure 2-2. CIPP Installation Options: Liner Pull-in (Left) and Liner Inversion (Right) (Courtesy Insituform Technologies, Inc.)

Once the uncured liner is in place and held tightly against the host pipe, the liner is cured using hot water, steam or ultraviolet (UV) light causing the liner resin to become a cross-linked and solid liner material. The curing procedures (e.g., time and temperature curves for thermal curing and UV light intensity and advance rate for UV curing) are important in making sure that the full thickness of the liner becomes properly cured and that thermal or other stresses are not introduced into the liner in a partially cured state.

Following the full curing of the liner and removal of any accessory installation materials, the restoration of lateral connections can be carried out. These are typically simply restored by cutting openings at the lateral connection. A dimpling of the liner can aid in the identification of the position of the connection, but such dimpling is less identifiable in liners with higher strength fabrics. If the CIPP liner has a significant annular space and if the connection is not grouted or sealed to the sewer lateral, then this connection can be a source of continued infiltration into the mainline sewer. Research into the magnitude of this effect can be found, for example, in Hall and Matthews (2004), Bakeer et al. (2005), and Bakeer and Sever (2008).

Figure 2-3 highlights the main differences in CIPP technologies available today based on tube construction, method of installation, curing method, and type of resin. The original CIPP product was a needled felt tube, impregnated with polyester resin that was inverted into a sewer through a manhole and cured using hot water. This product is still used for gravity sewers.

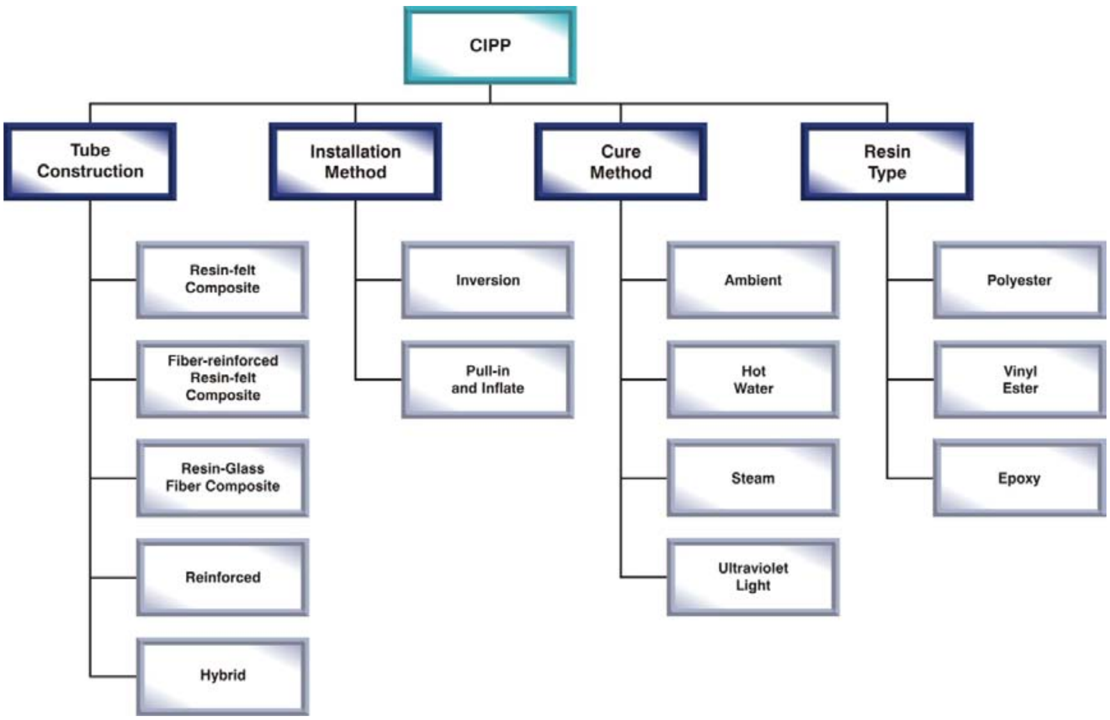


Figure 2-3. Summary of Common CIPP Technologies

The following sections describe the major generic technology variants for CIPP rehabilitation in terms of the tube construction, choice of resin, cure method, and insertion method. Appendix A in the companion EPA report (Sterling et al., 2010) contains datasheets provided by some of the most established vendors for specific products representing these variants. Due to the wide range of manufacturers and contractors offering CIPP rehabilitation, it was not possible to represent all products with individual datasheets in that report.

2.2.3 Installation Method: Inversion or Pull-In. From the first installation of CIPP in 1971 until 1973, the installation method involved a pull-in-and-inflate procedure. In this method, the uncured liner is pulled into position directly as shown in Figure 2-2. An outer layer confines the resin during impregnation and pull-in. This layer remains between the cured CIPP liner and the host pipe, which reduces the potential for interlock between the resin and the host pipe, but fully confines the resin, thus avoiding the potential for blocked laterals and washout of the resin by high groundwater inflows. Either an internal hose (called a calibration hose) inflates the liner within the host pipe and holds it under pressure until the liner is cured, or the ends are tied or plugged and the liner is simply inflated while curing.

In 1973, coated felt was introduced allowing the liner inversion process to be used (see Figure 2-2). In this process, the impregnated but uncured liner is forced by water or air pressure to turn itself inside out along the host pipe section to be lined. Since there is a sealing layer outside the felt tube, this liner can be impregnated with resin and still handled easily prior to installation. When the liner is inverted, this sealing layer becomes the inner surface of the CIPP liner. The uncured resin can then flow into cracks and openings in the host pipe to lock the liner in place. For structural purposes, a small amount of excess resin ensures that sufficient resin is available to give the required liner thickness. However, too much resin can cause problems such as blocking sewer laterals. A second advantage of the inversion approach is that the liner is not dragged, relative to the host pipe, as it is installed; rather, the liner unfurls itself along the pipe, sealing off infiltration and displacing standing water in the pipe as it moves along the pipe as well as reducing the potential for physical damage to the liner. In early CIPP installations, the coating layer was a sacrificial polyurethane layer expected to hydrolyze over time. Today, more permanent coating layers are used – either a different polyurethane (PU) layer or a polyethylene (PE) layer. A future area of research could be the performance of the PU/PE layers during installation and over the long term.

Variations of each method (inversion or pull-in-and-inflate) are used, depending on the circumstances. For example, a PE tube, or a separate layer of coated felt, can first be inverted into the host pipe as a "preliner" and then the actual liner inverted inside the first tube. This will eliminate concern about resin washout if high groundwater inflows are present.

2.2.4 Tube Construction. Initially the CIPP tube (also called "bag") construction was made of a needled polyester felt and served only as a carrier for the resin. In this construction, the resin is the dominant contributor to the mechanical properties of the system. Other forms of tube construction entered the marketplace in the U.S. during the 1990s. These may involve the inclusion of reinforcing materials such as fiberglass, aramid fibers or carbon fibers in some configuration. The reinforcement may be positioned at selected points within the thickness of the tube wall or the wall may consist primarily of braided reinforcing layer(s) (Rahaim, 2009).

Reinforced tube construction has been in use in Europe for longer than in the U.S. and allows the designer/contractor to design a thinner CIPP liner and one with a wider range of application. The reinforcing layers within the resin become a significant contributor to the mechanical properties of the finished liner. This leads to a more complex mechanical behavior of the liner and the reduced thicknesses are more susceptible to the effects of host pipe and liner imperfections on the structural analysis. Studies of new composite tube materials can be found (e.g., Akinci et al. [2010]).

Liner thicknesses may vary from around 0.12 in. (3 mm) in small-diameter shallow pipes to over 2 in. (50 mm) in large-diameter deep pipes. In the construction planning for the CIPP project, consideration needs to be given to the forces that will be exerted on the tube during the installation process. For the inversion process, sufficient pressures must be exerted to allow the liner to "invert". For the pull-in process, the liner tube construction must provide sufficient tensile strength for the pull-in and resistance to damage or tearing during the insertion. Liners to be installed on steep-gradient pipes pose particular challenges for water inversion and curing because sufficient pressure must be available at the upper end of the pipe to allow the inversion to occur, but the pressure at the lower end of the pipe must not be so high as to cause liner tearing or excessive thinning. In designing the tube thickness, consideration needs to be given to the maximum pressure exerted on the liner as it cures so that the final thickness of the liner meets the project specifications. The contractor or supplier calculates these parameters based on the site information and planned installation procedures.

2.2.5 Choice of Resins for CIPP. The following discussion of resin chemistries is summarized from a paper on "Resin Choices for Cured-in-Place Pipe Applications" by Rose and Jin (2006). According to Rose and Jin (2006), there are three main chemistries of thermoset resins that are well-suited for use in CIPP applications. These are polyester, vinyl ester, and epoxy resins.

The most commonly used resins are isophthalic polyester resins (used in perhaps more than 80% percent of the CIPP market worldwide [Downey, 2011]). These are usually medium reactivity, rigid, and corrosion-grade resins with a high viscosity when compared to standard laminating resins. They typically contain fumed silica to help prevent resin drainage from the upper portion of the pipe liner during the curing process. They are a good choice for most municipal sewer applications due to their lower cost in comparison with vinyl ester and epoxy resins and an adequate level of water and chemical resistance. Iso-polyesters impregnate liner materials well and can be cured even when ambient temperatures drop to near or below freezing.

Fillers can be used in the resin (especially in larger diameter liners) to increase the flexural modulus of the cured liner which, in turn, reduces the required thickness of the liner – saving material and cost. Fillers also improve the heat transfer characteristics of the resin. The filler is usually alumina trihydrate (ATH) or more recently talc.

Three other types of polyester resins have been used in sewer line rehabilitation. One type involves polyester resins based on terephthalic acid. These resins have greater tensile toughness and a higher heat distortion temperature than standard polyester resins but require higher processing temperatures, pressures, and cycle times which increase costs. Another polyester resin is based on orthophthalic anhydride and has been used in Europe. This type of resin is not currently used in CIPP applications in North America and is viewed as a low quality resin choice and it is not capable of meeting the chemical resistance requirements of ASTM F1216. Polyester resins based on bisphenol fumarate offer outstanding resistance to caustic and oxidizing environments making them an excellent choice for sewer lines requiring a high degree of chemical and temperature resistance. However, this type of resin is highly reactive and can suffer from blisters in the liner coatings or discoloration in the liner making their appearance less desirable. Some manufacturers offer resin blends of isophthalic and terephthalic, but blends with orthophthalic resin may not be capable of meeting the chemical resistance requirements of ASTM F1216

Vinyl ester resins are typically used in applications where improved chemical and temperature resistance is necessary. They also provide better initial and retained structural properties than the standard polyester CIPP resins. The resins are styrenated, bisphenol A – extended epoxy polymers containing reactive methacrylate end groups. Vinyl ester resins are substantially more expensive than the standard polyester resins. A less-used variant of the vinyl ester resin is a urethane-modified vinyl ester resin.

Epoxy resins are also used in CIPP applications. The higher cost of epoxy resins means that they are primarily used in pressure pipe and potable water applications. They can also be used where it is important to avoid the release of styrene odors – such as in the relining of sewer laterals. The odor release of epoxy resins depends on the use of volatile components in the formulation – and high solids content epoxies release the least odor.

Rahaim (2009) also discusses recent developments in thermosetting resins to provide resins that are more capable of handling corrosive environments, and higher pressure applications. Some products continue to be styrene based whereas others have no styrene and some even have no hazardous air pollutants (HAPs) and no volatile organic compounds (VOCs). Some resins are considerably more expensive than their contemporary counterparts, some more economical. Rahaim (2009) suggests that care also needs to be exercised to make sure that replacements for styrene offer tangible benefits in terms of odor reduction and potential contamination concerns.

2.2.6 Thermal Curing Process. Thermal curing of CIPP liners is the most widely used curing method in North America. Thermal curing includes supply of heat via contact with hot water, steam, or hot air or by allowing the liner to cure by exposure to ambient temperatures.

Ambient curing is typically only used for small diameter pipes (e.g., laterals) and is sensitive to climatic conditions. The slow rate of curing reduces productivity and increases the sewer's out-of-service time making its use in sewer mainlines uneconomical. Hot water curing is the original curing method for CIPP and can be used in the curing of liners for the full range of host pipe diameters. Steam curing provides a more rapid cure than hot water, and thus increasing job site efficiency. It involves less process water, but increases safety issues. It is only used in the small to medium diameter range because the evenness of curing conditions is harder to control in large diameter pipes and over long installation lengths. The steam has less "thermal mass" which makes the curing more susceptible to circulation problems whereby either insufficient heat is provided to allow a complete cure of the resin or excess heat from the resin exotherm is not removed causing a resin boil. Also, the formation of condensate pools in the liner invert needs to be avoided as this can also lead to inadequate curing of this region of the liner. In both cases, temperature measurements are taken as the liner cures to track the exothermic reaction and to ensure complete cure of the resin. The installation procedures and QA/QC requirements will change according to the curing method chosen.

Smaller mainline CIPP liners are typically prepared to the appropriate diameters and impregnated ("wet out") with resin in the factory. They are then shipped in a refrigerated truck to the job site for insertion and curing. Lateral liners (3- to 4-in. diameter) are frequently impregnated by hand onsite. Large-diameter liners are also wet out onsite using special wetout facilities. Care needs to be taken that a liner does not begin to cure before or during the installation process.

Figure 2-4. UV Light Curing Train

2.2.7 Ultraviolet Light Cured Liners. UV light cured liners were developed and used in Europe by Inpipe from 1986 (Downey, 2011). A German company, Brandenburger GmbH, later became a widespread provider of resin pre-impregnated, UV-light-cured laminates for sewer rehabilitation. In 1997, Brandenburger began promoting its technology outside Germany. Its U.S. licensee, Reline America, Inc., was established in 2007 to distribute this UV-cured, glass-reinforced CIPP liner to licensed contractors. In this product, a seamless, spirally wound, glass-fiber tube is impregnated with polyester or vinylester resins. The seamless liner has both an inner and outer film; the outer film blocks UV light. The inner film is removed after curing. The shelf life of the impregnated liner is approximately 6 months. The liner is available in diameters from 6 in. to 48 in. and can be used in circular, oval, and egg-shaped pipes. Reline America reports that up to 60-in. liners will be available in the near future and that individual installation lengths of up to 1,000 ft are possible. The liner tube is winched into the existing pipe and inflated with air pressure (6 to 8 pounds per square inch [psi]) and then cured using a UV light train (see Figure 2-4). For QA/QC purposes, in addition to CCTV inspection of the line before and after curing, a record of the liner's inner air pressure during curing, the curing speed (ft/min), and resin reaction temperatures (infrared sensors) are all monitored. Other vendors of UV-cured CIPP include BKP Berolina, LightStream, and Saertex.

2.2.8 Emerging and Novel CIPP Technologies. One of the latest glass-reinforced CIPP liners to enter the U.S. market is Berolina Liner® from BKP Berolina Polyester GmbH in Germany. CIPP Corporation is the U.S. licensee. The liner was first used in Europe in 1997 and outside Europe beginning in 2001. At the time of this report, there have not been any U.S. installations, but the liner has been used in Canada (Hamilton, Ontario). The liner is composed of glass fiber and/or polyester webs impregnated with polyester or vinylester resin. Uniquely, the layers are overlapped and staggered giving the tube variable stretching capability. After placement of a protective film sleeve covering the lower half of the host pipe, the liner is installed by pulling it in place, which can be accommodated by the axial strength of the glass fiber. The tube, which is expanded by inflating it with compressed air, can be inspected with a CCTV camera before polymerization. Once it is confirmed that the liner is correctly placed, it is then UV-cured (Roeling, 2009). The liner has a protective inner film and a UV-resistant outer film. The inner film is removed after installation. The outer film prevents resin from migrating into laterals, as well as from entering cracks in the host pipe. The outer film also prevents significant styrene emissions. A rehabilitated length of up to 1,200 ft is reportedly possible. The Berolina Liner is available in diameters of 6 to 40 in., with thicknesses ranging from 0.08 to 0.47 in.

Insituform I-Plus Composite™ is a thermal curing liner developed to reduce the need for high liner thicknesses in large-diameter pipes and/or with high external groundwater pressures. The liner cross section includes fiber-reinforcing layers at the liner's top and bottom surfaces. These give the liner a very high strength and stiffness, allowing the liner's overall thickness to be reduced (Hahn, 2007).

2.3 North American Experience with CIPP

2.3.1 Experiences and Case Histories. As indicated above, CIPP liners have been in use in the U.S. since 1976. Judging by their continued and expanding level of use, system owners generally have been happy with the installation and continued performance of CIPP liners. However, there is rather sporadic documentation in the literature of the level of problems experienced, the nature of specific defects that may occur and what steps need to be taken when defects do occur. Some papers that provide information on significant or extensive experiences with CIPP include Driver and Olson (1983), Hannan (1990), Barsoom (1993), Hudson (1993), Larsen et al. (1997), Hutchinson (1998), Llagas and Cook (2004), Kahn (2005), Kahn and Dobson (2007), Lindsey (2007), Schwarz (2007), Kurz et al., (2009), and Lehmann et al. (2009).

In addition, many project case history descriptions can be found in conference proceedings of the North American Society for Trenchless Technology (NASTT), International Society for Trenchless Technology (ISTT), the Pipeline Division of the American Society of Civil Engineers, the Water Environment Federation Technical Exhibition and Conference (WEFTEC) and other specialty conferences of the Water Environment Federation, and the Underground Construction Technology (UCT) conference. A few examples include Bonanotte and Kampbell (2004), Hansen (2005), Nelson et al. (2005), Pennington et al. (2005), Martin (2007), Dawson (2008), and Brand et al. (2009).

2.3.2 Testing and QA/QC. Since CIPP was introduced in the U.S. and has grown in popularity, various standards and test procedures have been developed to govern its use. In addition to the ASTM standards governing its use and testing (see Sterling et al., 2010, Appendix B), design guidelines and best practices can be found in sources such as Bennett et al. (1995) and the NASTT best practices short course for CIPP (www.nastt.org/training_curedInPlace.php).

Municipalities, consultants, and industry members have reported on their experiences in testing and QA/QC practices. Such references include Pang et al. (1995), Yoshimura et al. (2006), and Herzog et al. (2007). Recent work on QA/QC practices and testing procedures can be found in Lee and Ferry (2007), Araujo et al. (2009), Gumbel (2009), Knight and Sarrami (2009), and Kampbell et al. (2011).

The need to develop adequate design procedures and to test products for CIPP application led to an intensive series of research efforts focusing on pipe rehabilitation using thin, polymer liners within host pipes subjected to external loads. This research includes the following papers: Guice et al. (1993), Guice et al. (1994), Straughan et al. (1995), Li and Guice (1995), Falter (1996, 2004, 2008), Omara et al. (1997), El-Sawy and Moore (1998), Straughan et al. (1998), Hall and Zhu (2000), Zhao et al. (2001), Zhu and Hall (2001), Kapasi and Hall (2002), Thépot (2003), Zhao et al. (2005), and Zhao and Whittle (2008). This is by no means a complete list, but should provide a good starting point for in-depth study. The list does not include work on the behavior of internally pressurized liners for water main or force main renovation.

Research on the appropriate external loadings to be designed for CIPP installations has also been carried out, including Spasojevic et al. (2004), Spasojevic et al. (2007), Law and Moore (2007), and Moore (2008).

If the types or ratio of resins are an area of concern, QA/QC using nuclear magnetic resonance testing can be carried out to make this determination. Research on the properties of resins used for CIPP includes Kleweno (1994), Hayden (2004), and Bruzzone et al. (2008).

2.3.3 Environmental Issues. The principal issue rose about the environmental impacts of CIPP materials and their installation has been the release of styrene into the process water (or other water present in the host pipe) and into the air. This has been a significant issue in Europe encouraging changes in the way that CIPP is manufactured and supplied and the switch to UV-cured liners for smaller diameter CIPP rehabilitation. UV-cured liners (such as the German Brandenburger liner) use gas-tight membranes to minimize the release of styrenes during storage and installation and the UV-cure process does not require water or steam into which styrenes could leach before curing. Papers and reports discussing this issue in the U.S. include Lee (2008), Donaldson (2009), and Kampbell (2009). In most areas of the U.S., styrene-based CIPP resins with thermal curing are still in use, but closer attention to reducing gaseous styrene emissions and capturing water/condensate containing styrene is generally being practiced. The smaller quantities of liquid water present during steam curing means that water contamination is more easily handled in steam cures than in water cures (Kampbell, 2009).

There is very little information concerning the environmentally-caused degradation of CIPP. Two references identified on this topic are Sever et al. (2005) and Potvin et al. (2008). In the evaluations of the oldest CIPP liners from the current study (see Sections 4 and 5), it was noted that the coating layer on the interior of the polyester resin was degraded or missing in the areas exposed to flow. This coating layer was used to isolate the polyester resin from the environment during impregnation, installation, and curing. Once cured, the layer had essentially served its purpose. Long-term exposure to water caused the polyurethane film used in early installations to breakdown due to hydrolysis, a process of slow but temperature-dependent dissolution. In newer liners, both improved formulations of polyether polyurethane (which has good resistance to hydrolysis) and PE are used as a coating material. The longevity of both coating materials is expected to be greatly improved over the original form of polyurethane coating.

3.0: DEVELOPMENT OF CIPP EVALUATION METHODOLOGY

3.1 Review of Potential Alternatives

A variety of approaches to evaluate the state of deterioration of previously installed liners were considered in the initial stages of the project. Table 3-1 indicates the main alternatives considered and the advantages and disadvantages of each approach. Through a detailed literature search and the specific international scan effort described in Section 8, the research team was only able to find scattered efforts to thoroughly evaluate the long-term performance of rehabilitated sewer sections. Most typically, the rehabilitated sections were only evaluated using CCTV immediately following the installation and then perhaps periodically using CCTV depending on the overall inspection strategy of the agency. In some cases, this would mean a regular CCTV inspection at intervals of a number of years, while in other cases it may mean no follow up since the rehabilitated section would be moved to the lowest priority for inspection.

Table 3-1. Potential Evaluation Strategies for Liner Deterioration

Evaluation approach	Advantages	Disadvantages
Targeted or periodic CCTV inspection	• Relatively low cost • Familiar to agencies • Can uncover other operating problems such as potential blockages • Can provide broad coverage of relined sections within an agency leading to statistically meaningful results	• Can only identify deterioration or defects that are easily identified by CCTV inspection • No material properties obtained • Liner distortion difficult to identify • Not possible to evaluate intermediate stages of deterioration
Advanced scanning and non-destructive testing (NDT) methods	• More detail on such aspects as liner distortion, development of external voids, etc.	• More expensive than CCTV • Data that can be gathered still would not presently allow evaluation of intermediate stages of deterioration
Recovery of destructive samples from select locations	• Physical samples of the liner are available for a variety of tests • Variation of material properties from as-installed requirements can be determined • Comparison with NDT methods possible to build future NDT evaluation procedures	• Expense of retrieving physical samples limits the number of samples that can be recovered and hence the statistical validity of results in terms of system-wide performance • Expense can limit the wish of agencies to participate in a national evaluation program

3.2 Goals for a Specific Retrospective Evaluation Using the Draft Protocols

The goals of the retrospective evaluation of a rehabilitation technology in a specific municipality are:

- To gather quantitative data on the current condition of a specific rehabilitation system using a draft protocol for the inspection, defect classification, sample collection, testing, analysis, and storage of such data.
- To evaluate the protocol as to its appropriateness for use under field conditions in a municipality. Will it produce the desired data? Is the terminology used universally accepted and understood by the municipal engineering community? Is it excessively burdensome on the utility? Can the data collected be used effectively to guide asset management decisions?
- To compile the evaluation results into a common database so that cities can understand how the systems that they are investing in today have performed over their commercial life to date.

3.3 Preliminary Outline of Anticipated Protocol for CIPP Evaluation

The project team initiated discussions early on with municipalities interested in participating in the project in order to aid in the development of the data collection protocols. A preliminary outline was prepared that was intended to give the municipality an idea of the anticipated scope of the evaluation and a chance to make suggestions to improve the protocol or increase its feasibility for the municipality before it was finalized. The utility owners were expected to collaborate on the project and provide in-kind contributions associated with the following:

- Providing historic and current background data, maps, and drawings to the Battelle team;
- On-site support for field testing and sample collection for destructive testing, such as traffic control, utility locating and designation, excavation and surface restoration at access points, and CCTV inspection; and
- On-site support for non-destructive testing (NDT), such as pipeline cleaning, traffic control, utility locating and designation, excavation of access points, and other relevant site work.

More detail on the anticipated protocols and municipal interactions are provided below.

3.3.1 Identification of Municipal Partners

- The municipality would have at least 10 years of experience with CIPP installations – preferably more. Experience with more than one contractor and/or technology supplier would be a plus.
- The evaluation protocol was intended to be initially applied to mainline gravity sewers in the 8 in. to 24 in. range, although the diameter range was open to adjustment if special opportunities were presented themselves.
- The municipality would be willing to help to identify appropriate segments for quantitative evaluation.
- The municipality would be willing and able to provide a reasonable level of design and construction data for the rehabilitated segments – i.e., quantitative data that would establish the as-installed condition and engineering parameters for the liner.

- The municipality would be willing to provide the equipment and labor to retrieve field samples of a lined pipe for evaluation or field support for NDT of other lined segments.
- Members of the EPA project team would be on site for the sample retrieval and liner evaluation in the field. The project team would also be responsible for all liner testing and analysis carried out off site and would provide a report of the data collected and its interpretation to the municipality.
- The municipality will have the option to not have their name associated with specific data or analyses conducted.

3.3.2 Identification of Segments for Evaluation

- Ideal segments for evaluation would be where a dig up and replacement of a rehabilitated segment is planned for reasons other than problems in the rehabilitated line or where a dig up and removal of a pipe segment can be scheduled prior to street repaving, etc.
- If a dig up and replacement of a segment was not possible, then an area where a physical sample could be removed from within the line would be considered. This could be adjacent to a manhole or in a pipe large enough for the removal of a sample with adequate dimensions for physical property testing (e.g., 2 in. by 6 in. coupons).
- NDT measurements would also be applied to segments where physical samples are removed to determine if the same conclusions concerning liner properties could be derived from the non-destructive measurements (either within the line or where the liner was accessible at a manhole).
- Mainline segments where lateral rehabilitation was planned could also provide an opportunity to remove samples adjacent to the lateral and then covering the removed coupon areas with a T-Liner type of lateral rehabilitation that included an integral mainline collar.
- In order to test the application of the protocols and monitor time and cost to perform the evaluations, it was anticipated that two different line segments would be selected in each cooperating utility.

3.3.3 Availability of Historical Data. The following historical data would preferably be available for use in the retrospective evaluation (it was realized that not all the elements of the list below would be available):

- Location and length of lined segment, slope of pipe
- Type and diameter of host pipe and condition of the host pipe prior to rehabilitation (partially or fully deteriorated, any recorded ovality, etc.)
- Repair history prior to rehabilitation
- Estimated flow data, frequency of surcharging, and any substantial changes since rehabilitation
- Soil conditions and/or backfill conditions at the time of pipe construction
- Any evidence of soil voids outside the pipe prior to rehabilitation
- Any special chemical aspects to the wastewater carried in the rehabilitated pipe
- CCTV data pre- and post-rehabilitation

- Date of rehabilitation
- Rehabilitation technology used (including specific variations such as inverted vs. pull in, use of a pre-liner, type of cure used [e.g., hot water, steam, ambient])
- Construction records for the selected rehabilitation location
- Inspection reports for the selected rehabilitation location
- Material test data for the materials used in the rehabilitation: manufacturer-provided data and preferably actual test data on the installed materials
- Any samples retained in storage that were retrieved during the construction process
- Municipal employees familiar with the specific rehabilitation installation.

3.3.4 Retrieval of Field Samples (Dig up and Replace Sample). The type and dimensions of field samples retrieved would be determined in conjunction with the preferred segments for evaluation. In the case of an opportunity to dig up and replace a sample, the following protocol was envisaged:

- A pipe sample length of at least 18 in. (preferably at least 36 to 48 in. would be retrieved). The lined pipe segment would be boxed and shipped to Louisiana Tech University for liner evaluation and testing.
- The type and condition of the host pipe and the surrounding backfill would be noted during excavation together with confirmation of pipe depth, pavement type and thickness, and other factors relevant to pipe loading conditions.
- The orientation of the pipe sample would be marked on the pipe at the time of retrieval.
- Laboratory test samples would be retrieved from these full pipe samples in the laboratory.
- Various in-situ non-destructive evaluation methods would also be applied adjacent to the removed section and at the manholes at either end of the segment.

3.3.5 In-Situ Evaluation. In the case that dig up and replacement of a segment would not be possible, the evaluation would be carried out using non-destructive or minimally destructive evaluation (e.g. coupon sampling) methods. The exact methods to be used were to be determined during the continuing protocol development, but would ideally include most or all of the following:

- Cleaning of the line and temporary stoppage or bypassing of flow in the segment
- CCTV inspection of the line to carefully document any defects, discolorations, etc.
- Laser profiling for accurate internal dimensional checks of the finished liner (e.g., assessing ovality).
- Ultrasonic thickness measurements (by hand close to manholes)
- Feeler gauge measurement of the annular gap adjacent to the manhole
- Surface hardness measurements (by hand close to manholes) – if the diameter of the host pipe was sufficient to apply such measurements
- Physical sample retrieval (if feasible) for laboratory testing of constituent, material, and structural properties of the liner, e.g., Barcol or Shore hardness, and laboratory glass transition (Tg) testing to measure the degree of cure, tensile strength, and short-term modulus

- Measurements and/or physical samples would be located in both the upper and lower portions of the pipe. Locations would preferably be chosen to correspond with the locations of samples taken at the time of installation.
- At least three samples or three of each type of measurement would be taken for the accessible section of the liner. More measurements to define any differences around the perimeter of the liner cross-section would be made where this was feasible.

In addition to the methods identified above which are in current practice, the project team would evaluate other potential non-destructive or minimally-destructive methods to collect quantitative data on the liner condition. These methods would not necessarily be available during initial trials of the protocol.

For the evaluations carried out in Denver and Columbus, described in the following two sections, physical samples large enough for laboratory testing of properties were able to be retrieved and, hence only, selected non-destructive inspections and/or measurements were made in the field to complement the laboratory evaluations.

3.3.6 Evaluation of Results. The intent of this project is to explore the most appropriate protocols for broad use in retrospective evaluations of CIPP liners in gravity sewer systems and to provide a roadmap for how a consistent database of quantitative performance can be assembled by municipalities and utility owners. The results from the initial application and testing of the protocol were not expected to provide any definite results concerning the broad longevity of the liner system since there are not enough sample locations to provide a statistical basis for conclusions about the rehabilitation performance. However, the testing was expected to provide feedback about whether the test results conform to the expectations of the municipality or show a significant deviation. In this regard, liners with little deterioration in material or structural performance provide some reassurance about longevity expectations, whereas liners that show greater than expected deterioration could raise a flag that this issue should be evaluated more carefully.

Specific data sought from the retrospective evaluation trials include:

- Typical/dominant defects seen in the rehabilitation technology;
- Typical locations for such defects (i.e., near manhole, at crown of pipe, etc.); and
- Quantitative properties to assist in the evaluation of the current condition and expected remaining life of the rehabilitation (e.g., thickness, flexural strength, stiffness modulus, and creep properties).

The results collected from each individual utility eventually can be aggregated with those from other utilities providing a broader statistical background for the performance of a particular rehabilitation method.

3.4 Test Plans and Quality Assurance

Prior to conducting each of the Denver and Columbus retrospective evaluation programs, a Quality Assurance Protocol Plan (QAPP) was developed to ensure the quality and validity of the field and laboratory test data that would be used in further analysis. Each QAPP was approved by the Quality Assurance Officer for the U.S. EPA National Risk Management Research Laboratory (NRMRL).

Tables 3-2 and 3-3 provide a combined summary of the field and laboratory measurements for both sites at each of the Denver and the Columbus evaluations. A few variations in the proposed plan were necessary due to project and site circumstances and these changes are noted in the tables.

The critical measurements for this research were identified to be the tensile stress, flexural stress, and modulus of elasticity of the retrieved samples. These laboratory measurements were conducted on all of the samples retrieved from the Denver and Columbus evaluations described in the following two sections. The results of the laboratory testing were compared with the material specifications for the original relining work or directly with as-installed test results where available. The tensile strength was measured with a minimum of three samples for each pipe segment. The flexural stress and modulus of elasticity were measured with a minimum of five samples for each pipe segment. The standard operating procedure (SOP) outlined in each of the relevant ASTM standards listed in Table 3-3 was followed.

Table 3-2. Field Measurement Plans

Field Measurements	No. of Measurements	Sample	Test Standard/ Instrument	Notes
Soil conditions + bedding	Denver: 6 per site Columbus: 6 per site	Grab samples	See Table 3-3	Field visual inspection and soil lab analysis
Liner + host pipe specimen	1 each	Denver 8 in. clay pipe (6 ft length); Columbus 8 in. clay pipe (6 ft length)	N/A	Shipped to TTC for further testing
Liner only specimen	3 total	Denver 2 pieces each 2 ft × 2 ft; Columbus 1 piece 2 ft × 4.3 ft	N/A	Shipped to TTC for further testing
Visual liner inspection	Continuous	N/A	N/A	Digital photos as applicable and possible.
Liner thickness (Prior to Sample Retrieval)	Denver: mobile equipment not available; Columbus: 36 in. pipe 8 measurement; 8 in. pipe 5 × 2 = 10 measurements.	N/A	ASTM E797-05 Ultrasonic Thickness. Measurement (Olympus Model 37DLP)	36 in. pipe: 3 meas. within panel ; 5 meas. in host pipe (both spring lines, crown and 45° on each side) 8 in. pipe: 5 meas. as above on each cut face
Liner thickness (After Sample Retrieval)	Panel samples: 4 8 in. pipe samples: 8 × 2 × 2 = 32	N/A	Caliper / ruler	Panels: 1 meas. on each edge 8 in. pipes: Meas. at 45° for each cut face at each end of sample
Annular gap	Denver: 8 in. only 8 × 2 × 2 = 32 meas. Columbus: 36 in. pipe: 4 × 2 = 8 measurements 8 in. pipe: 8 × 2 = 16 measurements	N/A	Feeler gauge	8 in. pipes: meas. at 45° both cut faces, both ends. 36 in. pipe sample: 2 meas. on remaining liner at each edge of removed panel.

N/A = Not Available

Table 3-3. Laboratory Evaluation and Measurement Plans

Laboratory Measurements	Samples	No. of Measurements (each site)	Sample Size	Test Standard/ Instrument	Notes
Density	All samples	Denver 7 Columbus 7	N/A	ASTM D792	N/A
Porosity	All samples	Denver 1 Columbus 1	N/A	Mercury vapor intrusion test	N/A
Tensile Strength and Elongation at Failure	8 in. clay	Denver: 3 Columbus: 3	0.75 in. × 7.2 in. each	ASTM D638	N/A
Tensile Strength and Elongation at Failure	Panel samples	Denver: 3 Columbus: 3	1.13 in. × 9.7 in. each	ASTM D638	N/A
Flexural Strength and Flexural Modulus	8 in. clay	Denver: 5 Columbus: 5	1 in. × 5 ft each	ASTM D790	N/A
Flexural Strength and Flexural Modulus	Panel samples	Denver: 5 Columbus: 5	2 in. × 12 in. each	ASTM D790	N/A
Short-term liner bucking strength	8 in. clay	Denver: 1 Columbus: 1	4 ft sample length	ASTM F1216	Modified according to sample condition
Pipe Ovality	8 in. clay	Denver and Columbus: 1 each	1 ft	Profile plotter	Measurements continuous in buckling test sample
Durometer (Shore) Hardness	All samples	5 each	N/A	ASTM D2240	N/A
Barcol Hardness	All samples	5 each	N/A	ASTM D2583	Added for comparison with other listed results
Apparent Specific Gravity	All samples	3 each	2 in. × 2 in.	ASTM D792	N/A
Glass Transition Temperature	All samples	2 each	3 in. × 0.5 in.	ASTM E1356 Differential Scanning Calorimetry (DSC)	N/A
Visual Liner Inspection	All samples	Continuous	N/A	N/A	Surface film, leakage, corrosion, bacterial growth, etc.
Soil Analysis	Denver and Columbus Excavated samples only (8 in.)	N/A	500 g	ASTM C136 sieve analysis; ASTM C128 density; ASTM D2216 moisture content; and Thermo Orion meter for soil pH	N/A
Raman Spectroscopy	All samples	3 each	2 in. × 2 in.	Raman Systems R-3,000 Spectrometer with a 785 nm diode laser excitation source	Comparison with similar virgin resins made when feasible

N/A = Not Available

3.4.1 Additional Testing Concepts. As the protocols were further developed in discussion with the City of Denver and the City of Columbus, some additional avenues for testing or evaluation were proposed either by the City or the research team. These are listed in Table 3-4 together with comments on the potential value of the testing, expected difficulties in testing or interpretation, and the use of the testing in the current pilot project. The main area of interest was to try to identify potentially useful new approaches that could provide an indication of any liner deterioration – either NDT methods that could be deployed within a pipeline or destructive methods that only required a small sample of liner material. Such tests could then be correlated with the standard tests in this study to see if a relationship appeared to resist. If so, then the promising tests could be evaluated further in future projects to fully establish the validity of the approach.

Table 3-4. Additional Testing/Evaluation Concepts Considered

Test	Description	Potential Value	Difficulties	Application for pilot study
Thermo-Gravimetric Analysis (TGA)	Measures the weight loss of the sample as it is heated to show the temperatures at which degradation takes place.	This provides information about the organic components and could identify degradation of the CIPP material. Again, comparison of surface material versus core material and/or control samples would be useful.	The challenge is developing a testing protocol that accounts for the VOCs common to many resins used in CIPP installations.	Preliminary tests during this study did not yield interpretable data, potentially due to too high temperature gap
Fourier-Transform Infrared (FTIR) Spectroscopy	Identifies the nature of chemical bonds and the crystalline phases that formed in the material.	If the resin is known, or if samples of the resin are available, spectra from the field samples can be compared to the resin. If controls are not available, spectra can be examined for signs of degradation such as oxidation products.	None.	Not used. One challenge for a retrospective evaluation is obtaining good control samples for virgin materials that may no longer be on the market. Raman spectroscopy was used for the purposes of this study.
Compression Strength Testing	Provides a material strength parameter.	Would provide values for comparison with flexural and tensile test values.	Liner thickness and curved shape not suitable for compression test.	Not used.
Fractography	Examines fracture surfaces under a microscope.	Gain insight into what type of failures are occurring in liner materials.	Complement to other testing to failure.	Not used.
Rebound (Schmidt) Hammer	Data on surface properties and shallow delaminations. Used principally for concrete materials.	Might provide insight into surface deterioration of liner materials and/or evidence of delamination in thin liners.	Current equipment too large to use in small dia. pipes. Value of measurements unclear.	Not followed up at this time. Shore and Barcol surface hardness measurements made instead.
Chemical-Resistance	Measures the strength loss of samples that have been exposed to chemicals.	Would determine if the specimens were still in compliance with the chemical-resistance requirements of Table X2.1 of ASTM F1216.	None.	Not used.

4.0: CITY OF DENVER RETROSPECTIVE STUDY

4.1 Introduction

The initial discussions were held with the City of Denver during August 2009 about the City's willingness to participate in the retrospective evaluation pilot studies. It was known that the City had been one of the early adopters of CIPP lining in the U.S. The draft protocol outlined in Section 3 was provided to the City so that they could understand the nature of the program and the requested role of the City. After the City indicated its interest in participation on August 19, 2009, a face-to-face meeting was organized and held in Denver on September 22, 2009.

At the meeting, the City identified a series of sewer mainlines in a residential area that had been relined using CIPP in 1984. An additional advantage to the identified lines was that they were in alley locations (low traffic) and that the alley pavement surface had areas that had been identified for replacement. The City wished to complete the dig up of the 8-in. pipe and liner before winter and, hence, the field work was organized for October 27, 2009. A CCTV inspection was made of several of the sewer lines that had been relined in 1984 and the evaluations of liner defects seen from those inspections are given in Section 4.2.17. However, the CCTV inspection was not used in this instance to pick a particular location for the sample retrieval.

A second option for sample retrieval was identified as a brick sewer of 48-in. diameter that had a CIPP liner installed in 1987. This liner had already had a physical sample removed for follow up testing in 1995 and, hence, another point of comparison for any degradation would be available. The retrieval work and re-patching of the liner in this instance was carried out by one of the local CIPP contractors in the Denver area (Wildcat Construction Co., Ltd.). The sample retrieval for this location was carried out on May 20, 2010.

4.2 Site 1: 25-year Old CIPP Liner in an 8-in. Clay Pipe

4.2.1 Host Pipe and Liner Information

Location:	City of Denver, CO: Monroe Street and 1st Street
Host pipe:	Circular, 8 in. diameter, vitrified clay pipe (VCP)
Burial depth:	5 ft (above crown)
Liner dimensions:	8 in. diameter; 6 mm thick
Resin:	Reichhold 33-060; an isophthalic, polyester, unfilled resin
Primary catalyst:	Perkadox 16
Secondary catalyst:	Trigonox C
Felt:	Unwoven fabric (similar to products used today)
Seal:	Polyurethane, 0.015 in. thick (today CIPP liners use polyethylene coating)
Year liner installed:	1984
Liner vendor:	Insituform
Resin supplier:	Reichhold
Tube manufacturer:	Insituform

4.2.2 Timeline for Fieldwork.

Tuesday, October 27, 2009

7:00 AM	Contractor's (Brannan) crew began staging equipment and preparing the site for the excavation.
7:30 AM	Precut portion of the concrete paving slab in the alley was removed.
7:50AM	After removal of the concrete slab, a soil sample was taken at the sub-grade level, immediately beneath the concrete slab (sample No. 1 of 6).
8:00AM	Excavation was halted and sample No. 2 of 6 collected from the bottom of the trench, 2 ft below sub grade.
8:20AM	Excavation was halted and sample No. 3 of 6 collected from the bottom of the trench, 4 ft below sub grade and approximately 10 in. above the crown of the pipe.
8:25AM	One of the Brannan crew members hand dug with a shovel and sample No. 4 of 6 was collected just above the crown of the pipe.
8:30AM	Hand digging continued and sample No. 5 of 6 was collected along the spring line of the pipe.
8:40AM	Sample No. 6 of 6 was collected with continued hand digging at the invert of the pipe. Work was suspended while waiting for the Hydrovac truck to arrive.
10:50AM	Hydrovac truck arrived and removed the soil around the host pipe to minimize disruption.
11:40AM	Removal of the soil immediately surrounding the pipe was completed by hand digging and a plastic shrink wrap material was applied in multiple layers to support the pipe joints.
12:00N	A support cribbing, constructed of two 2 in. × 12 in. wood planks was joined together to form a "V" shaped support for the specimen. This was placed under the specimen and the voids between the pipe and the support structure were filled for added support with foam packing material. The 6 ft specimen was then lashed to the wooden support structure with bungee cords, and additional layers of the shrink wrap material were applied. Two lifting slings were then fitted to the pipe specimen and the excavator. Support tension approximating the weight of the specimen was applied to minimize stress and movement during the cutting and extraction of the specimen.
12:10PM	A gasoline powered cut off saw with a diamond dust embedded blade was used to cut the specimen, and the specimen was lifted from the trench by the excavator and held suspended for annular gap measurements.
12:15PM	Measurements of the annular gap between the host pipe and liner were taken with a feeler gauge at both ends of the specimen and at both ends of the remaining pipe before the repair was made. The annular gap measurements were taken from the crown and at 45 degree intervals along the circumference of the pipes, moving clockwise while facing the end of the pipe being measured.
12:40PM	Measurements were completed and Brannan crew finished wrapping the specimen (lifting straps enclosed in wrapping) and loaded the specimen into the bed of a truck for transport to Crating Technologies (see Figure 4-1).

Monday, November 2, 2009

Specimen was received at TTC.

Figure 4-1. Images of the Recovered Specimen

4.2.3 Visual Inspection of the Liner. Overall the liner appeared to be in good shape. The polyurethane coating seemed to be eroded away at the invert of the pipe. Upon discussion with the vendor (Insituform), it was established that the polyurethane laminate coating was intended to serve as a sacrificial layer and act as a barrier for preventing resin from entering the interior of the tube. It was expected that this coating would hydrolyze over time (a chemical reaction causing the breakdown of certain polymers). The vendor was surprised to find out that most of the polyurethane layer remained intact (modern CIPP liners typically utilize a PE or a more durable polyurethane coating, which is considered to be a permanent layer). In locations where the polyurethane coating hydrolyzed, the fibers into which the polyurethane coating dissolved were exposed and somewhat loose. However, the resin-impregnated felt beneath it was solid and intact. The stitched seam holding together the CIPP tube was found to be in good condition. Signs of wear were restricted to the bottom third of the tube. A deposit made up of silt and what appeared to be residue of an organic matter was found at the invert of the CIPP liner (Figure 4-2).

Figure 4-2. Images of the Inner Surface of the 25-year Old, 6-ft Long CIPP Liner Section

4.2.4 **Locations of Soil Samples.** The trench was divided into six regions (Figure 4-3) for soil sampling. Soil samples collected from each region were placed in airtight bags to avoid foreign contamination and/or loss of moisture. The samples were numbered as shown in Table 4-1.

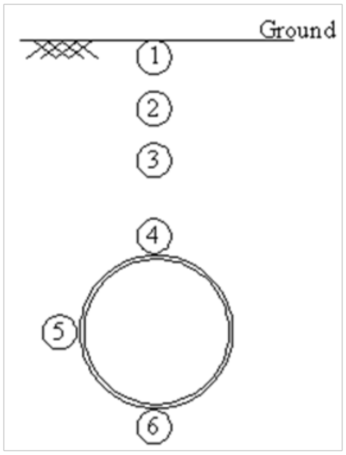


Figure 4-3. Location of Soil Sample Collection Place (Denver 8-in. Site)

Table 4-1. Designation of Collected Soil Samples for Denver 8-in. Site

Soil Sample Location	Sample ID
Sub-grade	1
2 ft below sub-grade	2
4 ft below sub-grade	3
Just above crown	4
Bedding along the spring line	5
Bedding under the invert	6

4.2.5 Analysis of Soil Samples. Standard test methods ASTM C136 and ASTM C128 were followed to classify the soil and determine its particle size distribution. In addition to those tests, the pH of the soil samples was measured using a pH meter.

4.2.5.1 Particle Size Distribution. ASTM C136, a standard testing method used for performing sieve analysis on geological material, was followed for the particle size distribution analysis. Based on visual inspection, soil samples were categorized as fine aggregates. For this analysis, 500 g of soil material was taken from each of the six soil samples and placed on a No. 4 sieve. For all samples, more than 90% of the particles passed through a No. 4 (4.76 mm) sieve, suggesting that the analysis procedure for fine aggregates should be followed. The resulting gradation curves are shown in Figure 4-4.

Based on grain size distribution, both the backfill and bedding soils can be considered to be sandy soils. The steep slopes of the resulting gradation curves for the samples taken from the spring line and invert elevations suggest that the bedding material consists of uniform (poorly-graded) soil. For the other locations, the gradation of soil was determined to be a fair-graded material. Review of bore logs collected as part of utility construction projects performed in nearby areas revealed that the native soil in the top 5 ft consist of sandy-silt underlying by gravelly sand (between 5 ft and 12 ft).

4.2.5.2 Soil Specific Gravity and Absorption. ASTM C128 standard method was used to calculate the density, relative density, and absorption of fine aggregates. Soil material weighing 500 g was taken from each of the six samples for the needed tests. The results are listed in Table 4-2.

4.2.5.3 Soil Moisture Content. ASTM D2216 is a test method used to determine the moisture content in soils and rocks by mass. Samples weighing 1,000 g from each of the six locations were placed in an oven for a period of 24 hr. After 24 hr, the soil samples were weighed and returned to the oven for an additional 24 hr period. The process was repeated until the difference between two subsequent measured weights was less than 1 g. At this point the soil was assumed to be moisture free. Moisture content values for the six soil samples are listed in Table 4-3.

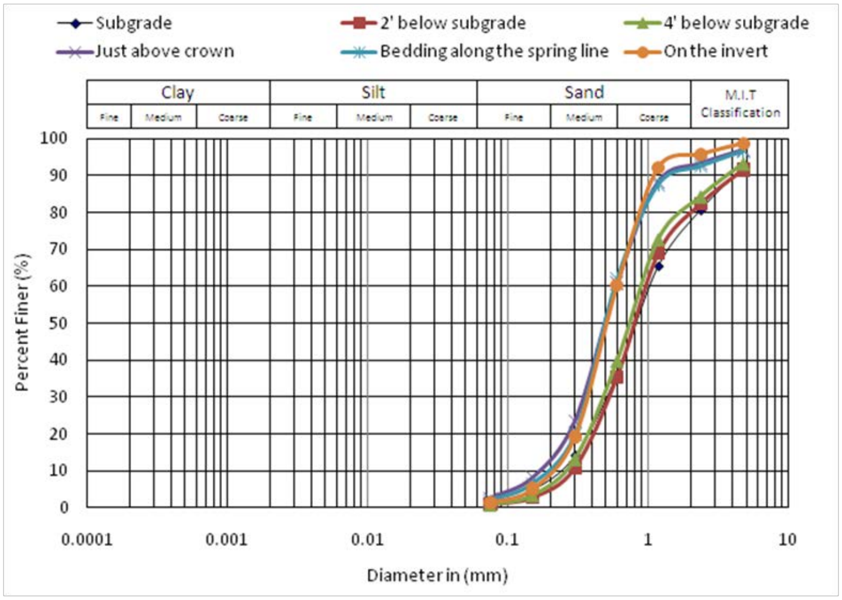


Figure 4-4. Soil Grain Size Distribution (Denver 8-in. Site)

Table 4-2. Soil Specific Gravity and Absorption (Denver 8-in. Site)

Sample ID	Soil (g)	Bulk Specific Gravity (OD)*	Bulk Specific Gravity (SSD)**	Apparent Specific Gravity	Absorption (%)
1	500	2.04	2.25	2.59	10.40
2	500	1.94	2.14	2.41	9.99
3	500	1.96	2.17	2.48	10.77
4	500	1.95	2.09	2.27	7.25
5	500	1.94	2.07	2.22	6.32
6	500	2.24	2.36	2.56	5.62

*OD: Oven dry.
** SSD: Saturated surface dry.

Table 4-3. Soil Moisture Content (Denver 8-in. Site)

Sample ID	% Moisture Content
1	9.59
2	8.99
3	9.51
4	6.85
5	6.37
6	5.59

4.2.6 Measurement of Acidity, Alkalinity, and pH. The pH of the soil embedment and the solid sediments collected from the pipe invert were measured using a Thermo Orion pH meter (Figure 4-5). The soil samples were placed in a pan (which was rinsed using distilled water) and distilled water was added to the samples. The soil sample was then stirred, and the pH probe was inserted into the soil-water mixture. The process was repeated for the sediments collected from the bottom of the liner on the inside of the pipe. The pH values of the bedding soil, backfill soil, and the sediments are listed in Table 4-4.

Figure 4-5. Measurement of pH Using a pH Meter

Table 4-4. Soil pH at Designated Locations and Sewage pH (Denver 8-in. Site)

Designation	Soil, pH	Sample	Sediment, pH
1	7.46	1	6.59
2	7.23	2	6.35
3	6.53	3	6.14
4	4.20	-	-
5	3.84	-	-
6	4.03	-	-

The soil samples collected from around the pipe (bedding material) were found to be rather acidic in comparison to the upper backfill soil. The soil pH ranged from 3.8 to 7.5 with a corrosive soil defined as having a pH less than 5.5. Therefore, the soil above the crown and in the bedding material adjacent to the pipe (samples 4, 5, and 6) would be considered corrosive. The sediments inside the pipe were found to be only slightly acidic with an average pH of 6.4, as expected from a residential wastewater stream. Thus, it is not likely that the liner was subjected to a rigorous chemical attack during its service life.

4.2.7 Annular Gap. Measurements of the annular gap between the liner and the host pipe were taken at 45 degree intervals around the circumference of the liner. The removal of the host pipe plus liner allowed measurements to be taken on both sides of each cut face, resulting in a total of four measurement locations for each of the 8 o'clock positions around the liner circumference. The measurement results are provided in Table 4-5.

The maximum annular gap measurement was 3.3 mm, but the average annular gap value was only approximately 0.9 mm compared to the nominal liner thickness of 6 mm. Annular gap is of interest in liner performance for several reasons. Structurally, a tight liner with small annular gap will have a better resistance to external buckling for the same thickness of liner. A tight liner is also more likely to be locked into place within the host pipe by minor irregularities and joints in the host pipe, limiting the potential longitudinal movement of the liner due to temperature changes or other forces that may act on the liner. From an infiltration perspective, a tight liner limits the flow of water in the annular space that may bypass the liner by entering the lined pipe at lateral reconnections or at the manholes (if these are not sealed). The measurements taken on this liner indicate that it remains a tightly fitting liner.

Table 4-5. Denver 8-in. Liner Annular Gap Measurements

Location	North End of Specimens (mm)	South End of Specimens (mm)	North End of Remaining Pipe (mm)	South End of Remaining Pipe (mm)
Crown	3.31	0.66	1.04	0.13
45° crown – Right SL	0.10	0.44	0.64	0.20
Right spring line	2.55	0.43	0.46	0.58
Right haunch	0.58	0.43	0.64	0.58
Invert	1.76	0.59	0.71	1.24
Left haunch	0.68	0.43	0.20	0.20
Left spring line	0.89	0.59	0.20	0.20
45° crown – Left SL	0.10	0.57	0.64	0.20

4.2.8 Liner Thickness. A total of 72 readings were taken to measure the thickness at different locations around the pipe circumference. These readings were taken using a caliper with a resolution of ±0.0001 in. The average thickness of the liner is shown in Figure 4-6. The thickness of the liner was found to vary slightly around the circumference of the liner with the maximum thickness at the crown (5.98 mm ± 0.07 mm) and slightly lower values at the spring line (5.93 mm ± 0.11 mm) and the invert (5.91 mm ± 0.09 mm). This was attributed mostly to the erosion of the polyurethane coating layer (approximately 0.38 mm thick), originally placed on the internal surface of the liner, at the invert zone. The average measured thicknesses after 25 years in service were all slightly lower than the designed thickness of the liner (6 mm) although some individual readings were higher. No ultrasonic field measurements of liner thickness were possible in the field and when attempted in the laboratory the measurements were not successful. A discussion of this issue is provided in Section 6.

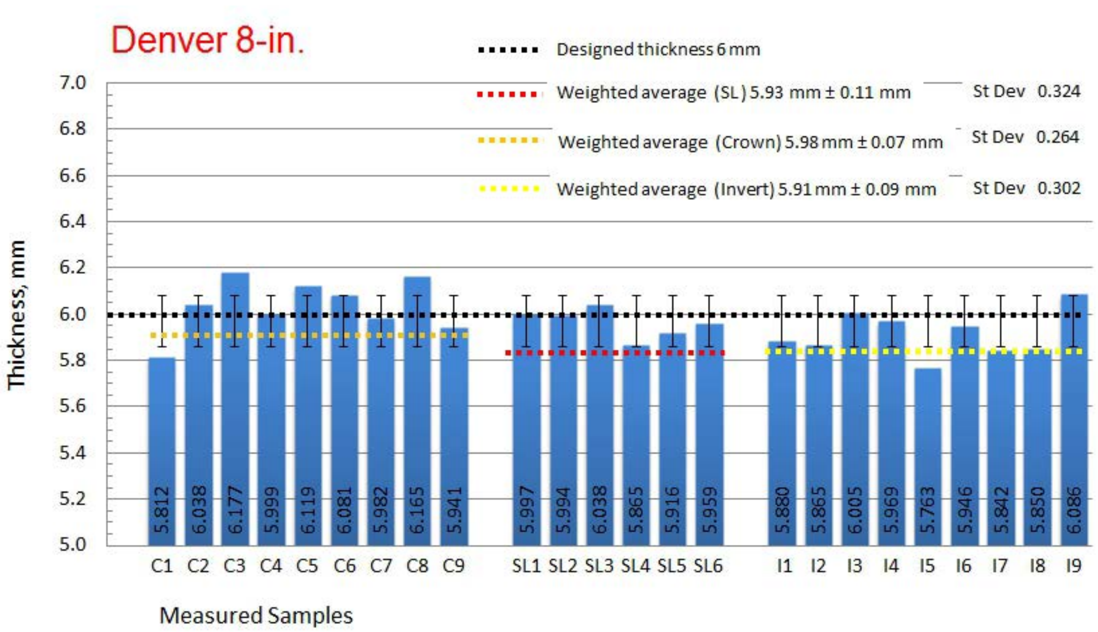


Figure 4-6. Average Thickness at Different Locations on the Liner

4.2.9 Specific Gravity and Porosity. For this liner, the specific gravity and porosity of the liner were measured using a mercury penetration test carried out by Micrometrics Analytical Services. The test data indicated that the bulk density (at 0.54 pounds per square in. absolute [psia]) was 1.0731 g/mL, the apparent skeletal density was 1.2762 g/mL and the porosity was 15.915%. The specific gravity was also measured by TTC with a higher value reported (1.159 ± 0.93 compared to the 1.0731 value measured in the mercury penetration test). The TTC value is closer to the specific gravity of 1.19 measured by Insituform on a sample sent to them for parallel testing (see Table 4-9). The full Micrometrics test reports for all the liners tested are included in Appendix C and the results are discussed further in Section 6.

4.2.10 Ovality. A profile plotter (Figure 4-7) was used to accurately map any deformation inside the liner. 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 is taken.

Figure 4-7. Profile Plotter Setup

The liner was placed inside a circular polyvinyl chloride (PVC) tube, as if it was inside a host pipe, and careful measurements were taken to ensure that the liner center was aligned with the measuring device. Next, the profile plotter was aligned with the center of the CIPP liner tube. Continuous readings were taken around the circumference of three cross-sections spaced 1 in. apart and averaged. The liner was found to be approximately circular with reference to its center (green line in Figure 4-8). On the spring line to spring line plane, the liner had a slightly larger diameter than on the crown-invert plane, most likely due to geometrical imperfections in the original host pipe. The percent ovality based on the ovality definition in ASTM F1216 is 5.07%. The red and blue lines are shown in connection with the liner buckling test that was carried out on this liner and which is described in Section 4.2.12. When a host and/or liner are oval in shape, the larger radius of curvature in the flatter section of the oval liner reduces the ability of the liner to resist external buckling pressures. This is taken into account in the design equations for the liner in ASTM F1216. When pipe ovality exceeds 5%, the structural impact on liner strength becomes more significant.

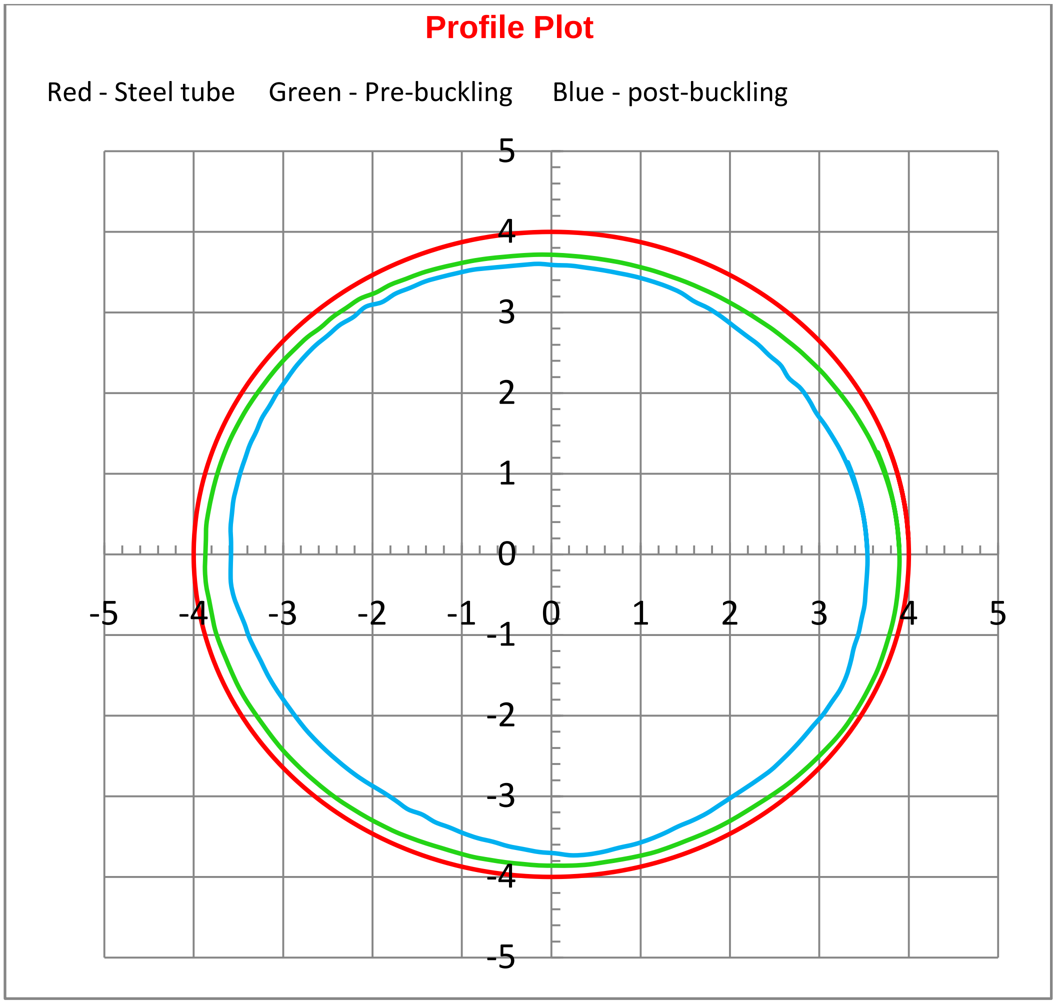


Figure 4-8. Ovality of the Denver 8-in. Liner (Average of Three Cross-Sections Spaced 1 in. Apart)

4.2.11 Flexural Testing and Tensile Testing. Flexural testing on specimens taken from the 8-in. Denver liner was carried out both by TTC and Insituform (the supplier of the original CIPP liner). The test preparations and results are described in detail for the TTC testing and these are then compared with the results provided by Insituform from their testing.

At TTC, specimens as described in ASTM D790 and D638 were cut from the crown, spring line, and invert of the retrieved CIPP liner using a router and a band saw. A total of nine specimens were prepared and tested (three from each location). The sides of specimens were smoothed using a grinder. The water jet cutter could not be used as the dimensions of the liner cutouts were too small to hold inside the cutting board. The specimens were marked as shown in Figure 4-9 and Table 4-6. The laboratory set-ups for the flexural and tensile testing are shown in Figures 4-10 and 4-11, respectively. The results of the flexural and tensile testing for the Denver 8-in. liner are summarized in Tables 4-7 to 4-9 and Figures 4-12 to 4-13.

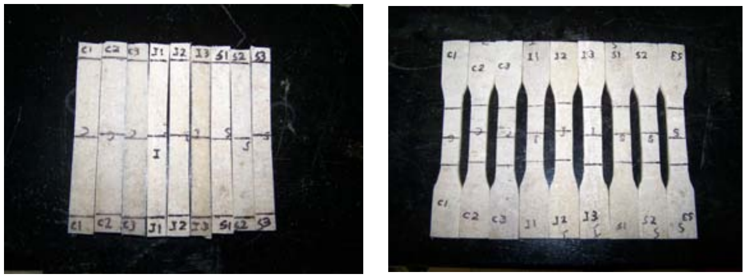


Figure 4-9. Liner Specimens - Bending (Left) and Tensile (Right) (Denver 8-in. Liner)

Table 4-6. Marking of Specimens (Denver 8-in. Liner)

Location	Sample ID
From the crown	Crown 1; Crown 2; Crown 3
From the spring line	SL 1; SL 2; SL 3
From the invert	Invert 1; Invert 2; Invert 3

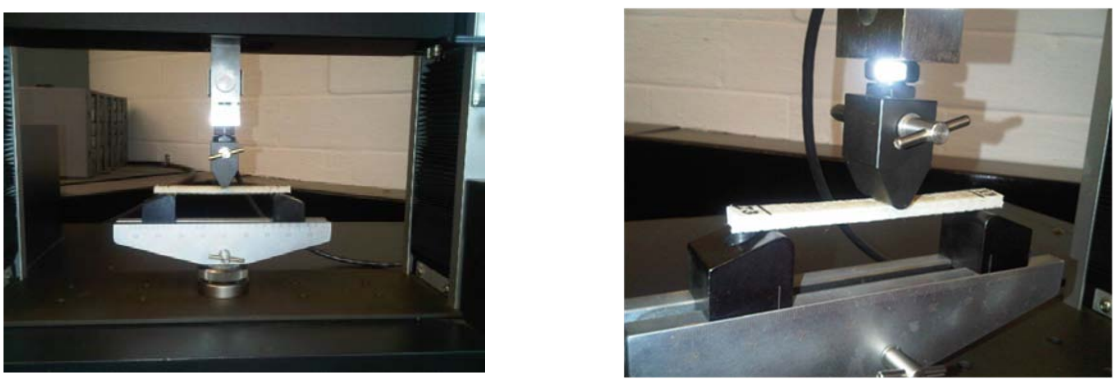


Figure 4-10. Flexural Testing in Accordance with ASTM D790

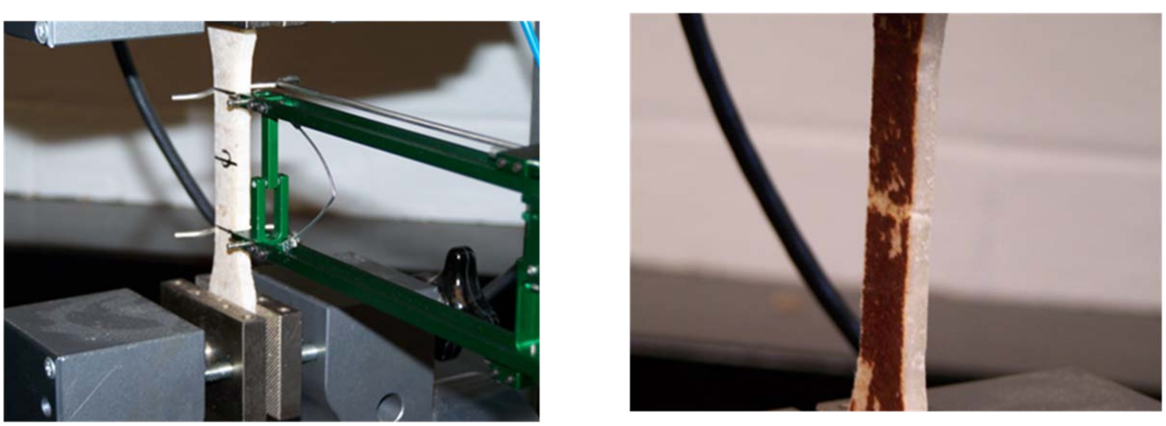


Figure 4-11. Tensile Testing Specimens Before (Left) and After the Test (Right)

Table 4-7. Results from Flexural Testing (Denver 8-in. Liner)

Location on pipe	Peak load (lb)	Peak bending stress (psi)	Peak shear stress (psi)	Flexural modulus (psi)
Crown 1	36.63	6,316	251	331,269
Crown 2	39.24	6,329	254	310,634
Crown 3	36.95	6,718	271	347,401
Average	-	**6,454±228**	**259±11**	**329,768±18,429**
SL 1	29.00	6,170	243	322,611
SL 2	33.62	7,309	275	359,245
SL 3	31.29	6,657	264	338,276
Average	-	**6,712±571**	**260±16**	**340,044±18,381**
Invert 1	33.29	7,083	283	319,351
Invert 2	32.06	6,412	256	325,894
Invert 3	36.73	7,815	308	363,382
Average	-	**7,103±702**	**282±26**	**336,209±23,759**
Overall Average	-	**6,756±546**	**267±20**	**335,340±18,186**

Table 4-8. Results from Tensile Testing (Denver 8-in. Liner)

Location on Pipe	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Mod. E (psi)
Crown 1	0.1327	430.47	3,244	405,111
Crown 2	0.1344	417.85	3,109	479,861
Crown 3	0.1351	376.52	2,787	350,396
Average	-		**3,047±235**	**411,789±64,990**
SL 1	0.1607	447.55	2,785	401,369
SL 2	0.1437	459.14	3,195	400,884
SL 3	0.1462	437.34	2,991	400,954
Average	-		**2,990±205**	**401,069±262**
Invert 1	0.1325	407.38	3,075	389,787
Invert 2	0.1452	465.17	3,204	473,405
Invert 3	0.1493	428.88	2,873	402,825
Average	-	-	**3,051±167**	**422,006±44,988**
Overall average	-	-	**3,029±179**	**411,621±40,548**

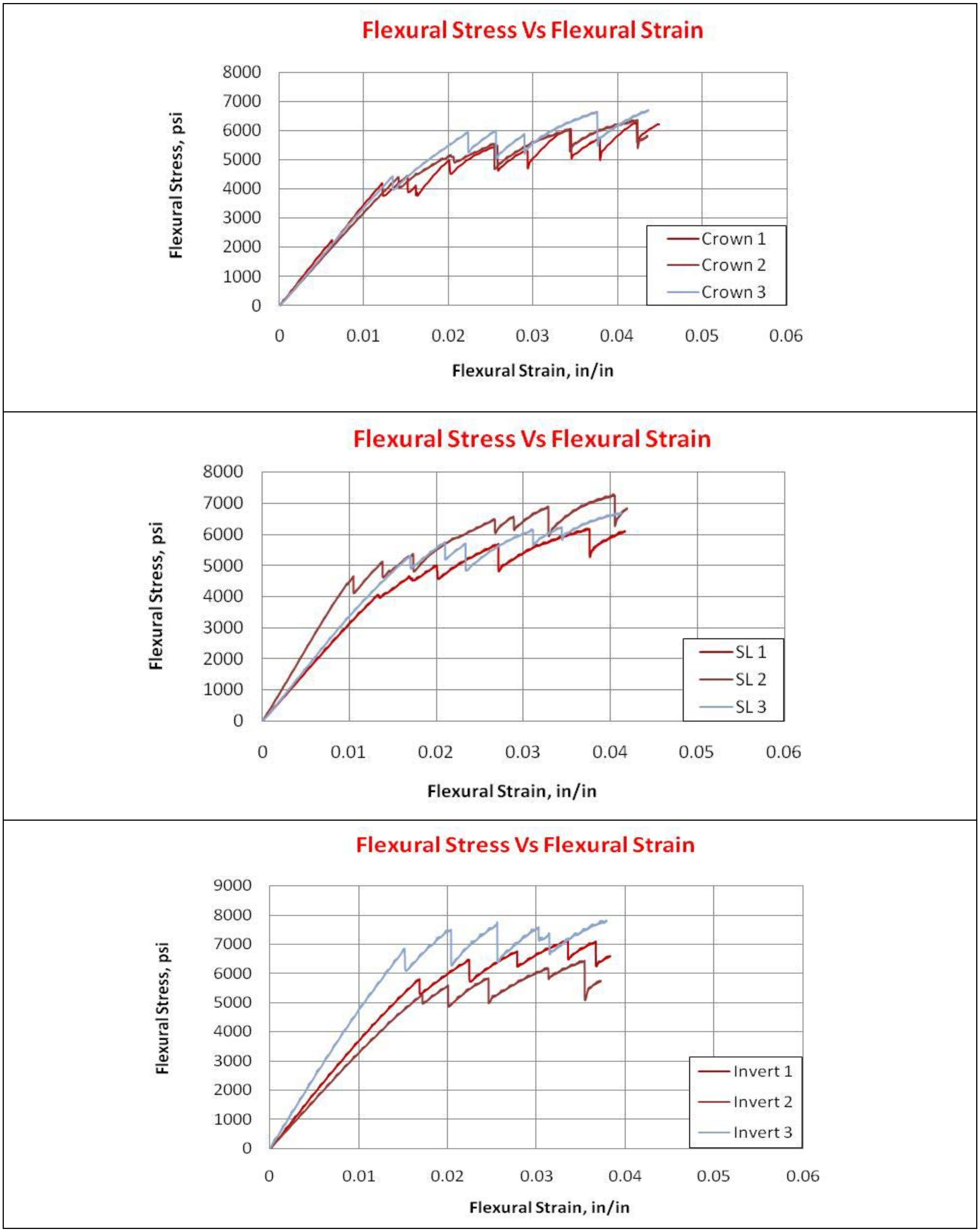


Figure 4-12. Stress-Strain Curves from Flexural Testing of Specimens (Denver 8-in. Liner)

Table 4-9. Comparison of Test Data from TTC and Insituform

	Tensile Break Strength (psi)		Tensile Modulus E (psi)		Tensile Elong. at Break (%)		Flexural Break Strength (psi)		Flexural Modulus E (psi)		Barcol Hardness (Inner) Type D 934-1		Specific Gravity	
	TTC*	Insitu Form	TTC	Insitu Form	TTC	Insitu Form	TTC	Insitu Form	TTC	Insitu Form	TTC	Insitu Form	TTC	Insitu Form
	3,244	2,500	405,111	-	2.0	2	6,316	7,400	331,269	520,000	43	40	1.16	1.19
	3,109	2,400	479,861	-	3.5	1	6,329	7,000	310,634	530,000	39	35	-	1.18
	2,787	2,100	350,396	-	4.5	1	6,718	6,500	347,401	470,000	39	35	-	1.19
	2,785	-	401,369	-	1.5	-	6,170	6,400	322,611	430,000	-	41	-	1.19
	3,195	-	400,884	-	3.3	-	7,309	7,300	359,245	520,000	-	39	-	1.19
	2,991	-	400,954	-	3.4	-	6,657	-	338,276	-	-	-	-	-
	3,075	-	389,787	-	2.0	-	7,083	-	319,351	-	-	-	-	-
	3,204	-	473,405	-	3.5	-	6,412	-	325,894	-	-	-	-	-
	2,873	-	402,825	-	4.5	-	7,815	-	363,382	-	-	-	-	-
Mean	**3,029**	**2,333**	**411,621**	**-**	**3.1**	**1.3**	**6,757**	**6,920**	**335,340**	**494,000**	**40**	**38**	**1.16**	**1.19**
Std. Dev	**179**	**208**	**40,548**	**-**	**1.1**	**0.6**	**546**	**455**	**18,186**	**42,778**	**4**	**3**	**-**	**0**

* The sample that was sent to Insituform was a piece of the host pipe with the liner inside. The liner extended a few inches on each of the host pipe joint.

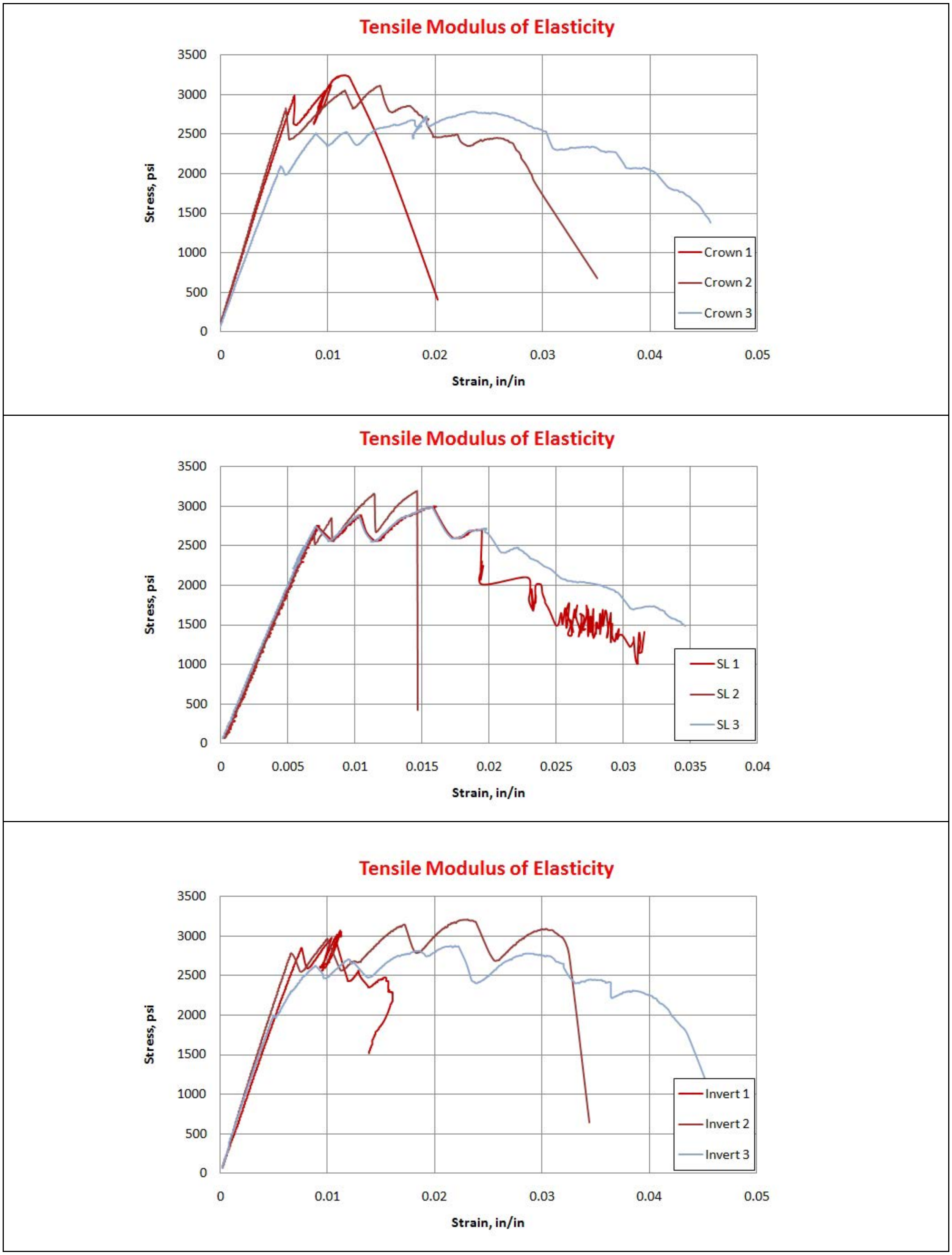


Figure 4-13. Stress-Strain Curves from Tensile Testing of Specimens (Denver 8-in. Liner)

4.2.12 Buckling Test. A steel mechanical tube was prepared for the test to act as a host pipe for the liner. The tube was 2 ft long and machined to accommodate the slight ovality of the liner (the tube thickness was reduced 1/16 in.). Two 3/8 in. threaded holes were made on the opposite sides of the mechanical tube. Quick connectors were fixed to the pipe through the holes to allow attaching the pressure system (see Figure 4-14).

The liner was inserted into the tube by manually pushing it into place. IPEX™ pipe joint lubricant was applied to the inside of the tube to ease the sliding of the liner. The liner was beveled on both ends using an air operated disk sander, and finished flush with the end of the pipe (Figure 4-15).

Figure 4-14. Machined Mechanical Tube (Left) and a Threaded Hole on the Tube (Right)

Figure 4-15. Liner Inside the Pipe and Beveling of the Liner

Two specially designed, open-ended, conical steel caps filled with high temperature silicon and polyurea were prepared and used to maintain the seal at the ends of the test specimens (Figures 4-16 and 4-17). The caps were pressed against each end of the pipe specimen using threaded rods and were designed to ensure that the annular space between the inner wall of the pipe and outer wall of the liner was sealed. This high level of effort and precision was considered paramount to allow effective sealing of the annulus under elevated internal pressure, while allowing free access to the interior of the pipe for conducting frequent deformation measurements of the liner.

A pressure gage was connected to one of the threaded holes and the other was fitted with a quick connector for applying water pressure (Figure 4-18). A nitrogen gas pressure bladder system was used to convert normal water supply pressure to a high water pressure for the testing (4-19).

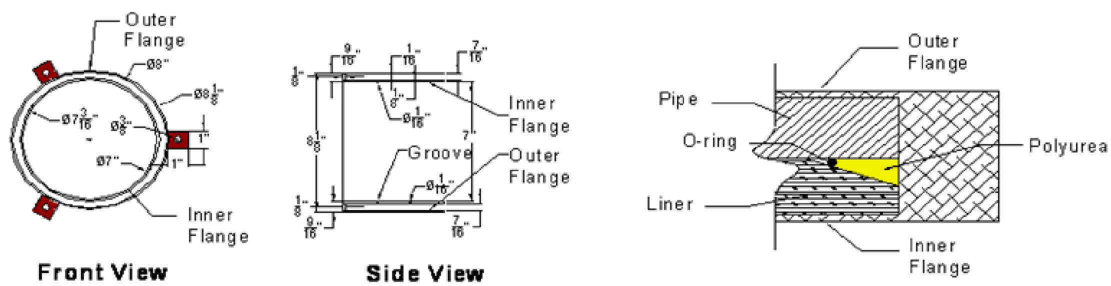


Figure 4-16. Drawing of a Pressure Cap

Figure 4-17. Experimental Setup Showing the Threaded Rod

Figure 4-18. Pressure Gage and Pressure Application Installed on the System

Figure 4-19. Nitrogen Gas Pressure Bladder System for Supplying the Test Pressure

A profile plotter developed at TTC was used to monitor the profile of the interior of the liner both before and after testing (see Figure 4-20). This system is equipped with an LVDT rotating a full circle in one and one-half minutes. The voltage reading changes as the tip of the LVDT moves and those readings were collected using a HP 3479A data acquisition system (DAQ). Later, the readings were processed to obtain the actual profile of the inside of the liner. It was difficult to use the profile plotter during the test itself due to the probability of water splash inside the liner and a rapid liner buckling at failure. However, a post buckling profile was obtained and is shown in Figure 4-8.

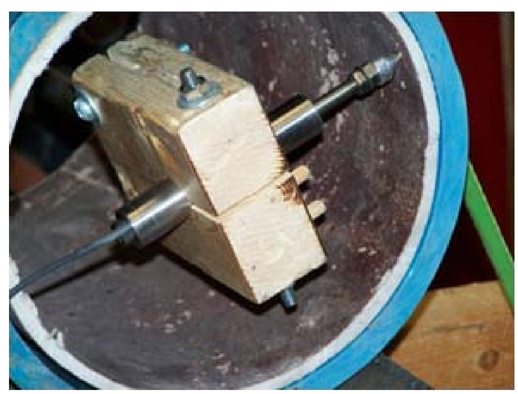


Figure 4-20. Profile Plotting – LVDT Rotating on the Inner Circumference

Although there were some leaks during the test, the liner held 40 to 45 psi (equivalent to 92 to 104 ft of water head) for approximately 1 hour in total. The applied pressure spiked during the test to a value of 200 psi, but was quickly reduced again to the 40 to 45 psi range (Figure 4-21).

Even with the brief peak at 200 psi pressure, visible evidence did not show a buckling failure of the liner although there was evidence of water leaks through the liner that indicated some localized failures (Figure 4-22).

Figure 4-21. Pressure on the Liner at Intervals During the Test

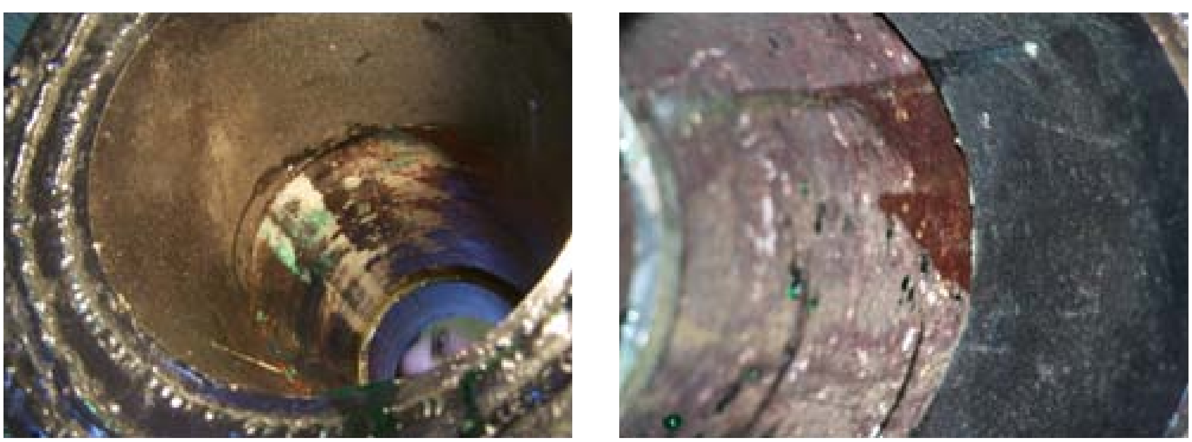


Figure 4-22. Localized Leak on the Liner – Green Spots Due to Green Food Color

4.2.13 Shore D Hardness. Durometer (Shore) hardness (ASTM D2240) 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 specified conditions of force and time.

Specimens measuring approximately 1 in. × 1 in. were cut from the crown, spring line, and invert of the retrieved CIPP liner using a band saw. All Shore tests were performed using the Shore D hardness scale, which utilizes a weight of 10 lb (4,536 g) and a tip diameter of 0.1 mm. A total of 144 readings were performed on samples taken from the crown, spring line, and invert. Tests were conducted on the inner and outer surfaces. The average recorded values are shown in Figure 4-23 and the recorded values are rounded to integer values in the discussion below. It can be seen that there is a progression of increased hardness from the inner invert surface of the liner (56), through the inner spring line surface (59) to the inner crown surface of the liner (63). The outer side of the liner enclosed by the host pipe was neither in contact with the soil nor with the waste stream, and provided hardness values of between 74 and 80 with an average of 77. This is approximately 38% higher than the inner invert surface and still significantly (22%) higher than the inner crown surface. This could suggest that the constant contact with the waste stream might result in progressive softening of the liner material (although some differences in hardness may be caused by the presence or eroded condition of the polyurethane layer). It is also not clear at the moment as to how a rougher surface that has been subjected to erosion may compare with a previously smooth surface even if there are no chemical changes involved. The hardness results are compared with the other liner tests and across all the retrospective sites in Section 6.

4.2.14 Barcol Hardness. In addition to the Shore hardness tests, tests were conducted using the Barcol hardness test (ASTM D2583) which uses a spherical-ended indenter. This allowed comparison with the hardness testing conducted by Insituform and the results and comparison are shown in Table 4-9. The TTC Barcol hardness results are shown in Figure 4-24. The results for the inner surface of the liner showed less differences between the crown, spring line, and invert (average values of 43, 39 and 39, respectively [rounded to integer values]) than the Shore D hardness testing. The outer surface results for the crown, spring line, and invert were 46, 39 and 42, respectively. The differences between the inner and outer surface values at the crown, spring line, and invert were 6%, 2% and 9%, respectively, with the outer surface always having the higher value. In the Barcol testing, the average outer surface value of 42 is 8% higher than the inner invert surface value of 39. Overall, the TTC results involving 972 measurements gave a mean Barcol hardness of 41±5 and the Insituform testing of five measurements gave a mean Barcol hardness of 38±3. The average of all the TTC inner surface readings gave a mean Barcol hardness of 40±4. Interpretation of the hardness results across all of the sites is provided in Section 6.

Since a surface hardness test is simple and quick to perform, and it might serve as a basis for a non-destructive in-situ test for CIPP liners, the TTC is planning to conduct additional Shore and/or Barcol hardness tests on a number of recently cured CIPP specimens that employ different types of resins to explore possible relationships.

Figure 4-23. Shore D Hardness Readings for the Liner's Inner and Outer Surfaces (Denver 8-in. Liner)

Figure 4-24. Barcol Hardness Readings for the Liner's Inner and Outer Surfaces (Denver 8-in. Liner)

4.2.15 Raman Spectroscopy. Raman spectroscopy was used to assess the liner material's degree of aging. The specimens used were ½ in. × ½ in. as only a very small surface area of the sample is required for collecting Raman spectra. The specimens were polished using a mechanical polisher and cleaned with distilled water.

Raman spectroscopy is a technique based on inelastic scattering of monochromatic light, usually from a laser source. Inelastic scattering refers to change in the frequency of photons in the monochromatic light upon interaction with a sample. Photons of the laser light are absorbed by the sample and then reemitted. The frequency of the reemitted photons is shifted in comparison with the original monochromatic frequency, a phenomenon called the "Raman Effect". This shift provides information about vibrational, rotational, and other low frequency transitions in the molecules, which are indicators of degradation and breakdown of the resin at its most fundamental (molecular) level.

Spectra from 200 to 2100 cm^{-1} were collected using an R-3000 HR Raman spectrometer utilizing a 785 nm diode laser operating at 290 mW via a fiber optic probe. Integration time was 30 seconds. As shown in Figure 4-25, the measured intensity of the Raman signal in arbitrary units (a.u.) is plotted on the y-axis, while the wave length in cm^1 is plotted on the x-axis.

The plots are nearly identical for the base resin and liner used for 25 years, with no significant change in the intensity of the peaks or region shift, indicating high chemical stability. Additional tests were carried out on the exterior surface of the liner, but no significant changes from the spectra shown in Figure 4-25 were detected.

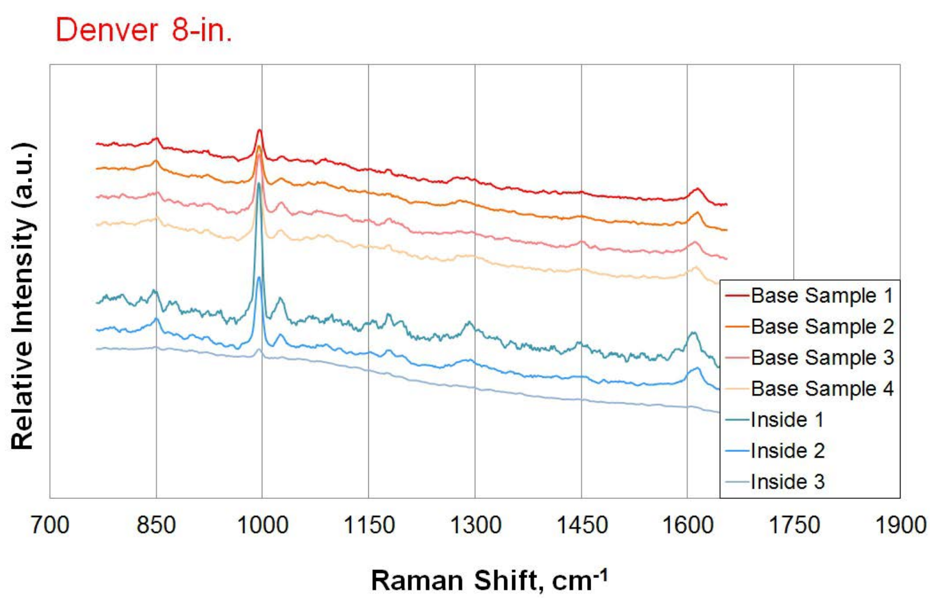


Figure 4-25. Raman Spectra (Denver 8-in. Liner)

4.2.16 Differential Scanning Calorimetry (DSC). DSC is used to perform thermal characterization studies on thermosetting resins. As the components in a resin system cure, heat is evolved which is measured by the DSC. When no significant heat of cure is observed, then it is assumed that the resin sample is completely or 100% cured. DSC can also be used to measure the glass transition temperature (Tg) or softening temperature of a thermoset resin. Tg represents the region in which the resin transforms from a hard, glassy solid to a viscous liquid. As a thermosetting resin cures, the Tg increases and the heat of cure decreases. These changes can be used to characterize and quantify the degree of cure of the resin system (Perkins-Elmer, 2000).

Four samples of the CIPP liner labeled crown, spring line, invert, and virgin resin material were tested. The Tg determination followed ASTM E1356-08 "Standard Test Method for Assignment of the Glass Transition Temperatures by Differential Scanning Calorimetry." The mass of each sample was measured with a Mettler AT261 Delta Range balance and calorimetry was conducted with a Perkin Elmer Diamond DSC that includes an Intracooler cooling accessory. The DSC was calibrated per manufacturer's specifications using indium and zinc standards. The DSC testing is summarized in Table 4-10.

Table 4-10. Perkin Elmer Diamond DSC Testing Parameters

Sample Pans	Testing Environment	Temperature Program
Aluminum Pans	Nitrogen	1. Heat from -40° C to 225° C at 10° C/min 2. Hold for 10 minutes at 225° C 3. Cool from 225° C to -40° C at 20° C/min 4. Hold for 5 minutes at -40°C 5. Heat from -40° C to 225° C at 10° C/min

Glass transition, Tg, values were calculated based on the methodology described in ASTM E1356-08 using the midpoint temperature, Tm, of the extrapolated onset and end temperatures of the transition range. The midpoint temperature is the most commonly used as the glass transition temperature as it has been found to have higher precision and is more likely to agree with the Tg measured by other methods. Minimal gravimetric loss was observed (approximately 3.5% of weight or less) as a result of the imposed thermal cycle indicating, that the samples were thermally stable over the range of temperatures evaluated. The gravimetric data is summarized in Table 4-11.

Table 4-11. Gravimetric Data for DSC Test (Denver 8-in. Liner)

Sample	Run	Sample Weight (mg)	Post Analysis Weight (mg)	Weight loss (%)
Invert	1	7.19	7.11	1.1
Invert	2	8.89	8.65	2.7
Crown	1	10.45	10.21	2.3
Crown	2	13.89	13.8	0.6
Spring line	1	12.05	11.7	2.9
Spring line	2	10.86	10.48	3.5
Virgin Resin	1	6.68	6.63	0.7
Virgin Resin	2	14.88	14.82	0.4

As summarized in Table 4-10, the initial thermal program (steps 1-4) was performed to remove any previous thermal history. The final heat scan step (step 5) of the temperature program was used for quantification as this scan contains a known thermal history. The calculated Tg values are summarized in Table 4-12.

Table 4-12. Sample Tg Determination (Denver 8-in. Liner)

Sample	Run	Tg (°C)
Invert	1	122.65
Invert	2	117.52
Crown	1	122.31
Crown	2	119.11
Spring line	1	134.63
Spring line	2	129.76
Virgin Resin	1	123.57
Virgin Resin	2	124.59

The average Tg for the control samples was 124.08°C (+/- 0.72°C) and the average Tg for the field samples was 124.33°C (+/- 6.57°C) as measured by ASTM Method E1356-08 with DSC. In general, an increase in the Tg is a function of curing and represents the increase in the molecular weight of the resin system (Perkins-Elmer, 2000). The Tg results suggest a similar level of curing between the virgin resin (control sample) and the aged material samples, with the field samples exhibiting slightly higher variability in Tg values from the spring line to invert.

4.2.17 CCTV Inspection of Area Sewers for Denver 8-in. Site. The City of Denver ordered CCTV scans of the lines in the area from which the sample was retrieved. Also, historical maintenance reports of these lines were requested. A total of nearly 5,800 ft of sewer line was imaged in the period September 24-28, 2009. A preliminary review of the CCTV reports suggested that the liner is in good condition overall. Several tap break-in defects were noted as well as lining failure at undercut connections, which could allow for root intrusion between the lateral outer wall and the liner covering the interior of the main pipe. This could be attributed to the robotic cutters used by the industry 25 years ago, which were far less sophisticated and accurate than the units used today. Some of the images reveal root intrusion via tap connections, resulting in a partial blockage of the sewer line, but the liner itself appears to be intact in these images. On the line stretch in the alley between Garfield Street and Jackson Street (between 3rd and 4th Avenues), at chainage 212.6 ft, there is what appears to be a liner failure in the vicinity of a tap break in. Another liner failure was found at the alley between Jackson Street and Garfield Street, from the first manhole north to the first manhole south to 1st Avenue. At chainage 20.8 ft, a bulge was found at the invert of the liner that prevented further advancement of the CCTV equipment. A third liner failure location was identified in the line running in the alley between Jackson and Harrison Streets, as it crosses 3rd Avenue, at chainage 239.8 ft. This liner failure appears to be attributed to improper restoration of a nearby lateral connection. A significant portion of the polyurethane coating was hydrolyzed along this line. A lining failure attributed to a connection cut shift was noted at 2nd Avenue and Jackson Street. Similar occurrences of a liner connection cut shift were noted on a couple of other lines. A location where the liner appears to be detached from the host pipe was located at chainage 39 ft, in the alley between 3rd Avenue and Garfield Street.

In summary, CCTV inspection of three parallel 8-in. VCP sewer lines lined using the CIPP lining method in the mid to late 1980s, was completed. All sewer lines run in the allies between Monroe and Garfield Streets (Line 'A'), Garfield and Jackson Streets (Line 'B'), and Jackson and Harrison Streets (Line 'C'). The survey area was bound at the south end by Ellsworth Avenue and at the north end by 5th Avenue. In total, 5,797 linear feet of CIPP lined pipe were imaged. A number of defects in the liner were noted by the operator. With the exception of three locations, all defects appear to be related to poor restoration of the lateral connections following lining of the mainline, which in some cases allowed for root intrusion between the outer wall of the lateral and the liner. Another liner defect which was noted on multiple occurrences was a connection tap shift, potentially due to relative movement of the lateral with respect to the mainline or movement of the liner within the host pipe. Three liner defect events were identified that are not related to the restoration of a lateral connection: (1) a bulge in the liner, (2) a detachment of the liner from the host pipe wall, and (3) what appears to be a tear in the liner, possibly due to inaccurate lateral restoration attempt (cut is located approximately 1.5 in. from the edge of a lateral connection).

4.3 Site 2: 48 in. Equivalent Diameter Egg-Shaped Brick Sewer

4.3.1 Host Pipe and Liner Information. A 48-in. diameter brick sewer pipe, originally installed in the early 1900s near Union Station in Denver, CO, was relined with a CIPP liner in 1987 under Denver Project PCO-609 Union Station. The CIPP-repaired section lies under 19th Street (see Figure 4-26). Manhole MH B-3 located at the crossing of the 19th Street and Wynkoop Street divides the rehabilitated section into two parts: the lining thickness was 18 mm upstream (270 ft length between manholes B-1 and B-3) and 13.5 mm downstream (186 ft length between manholes B-3 and B-5).

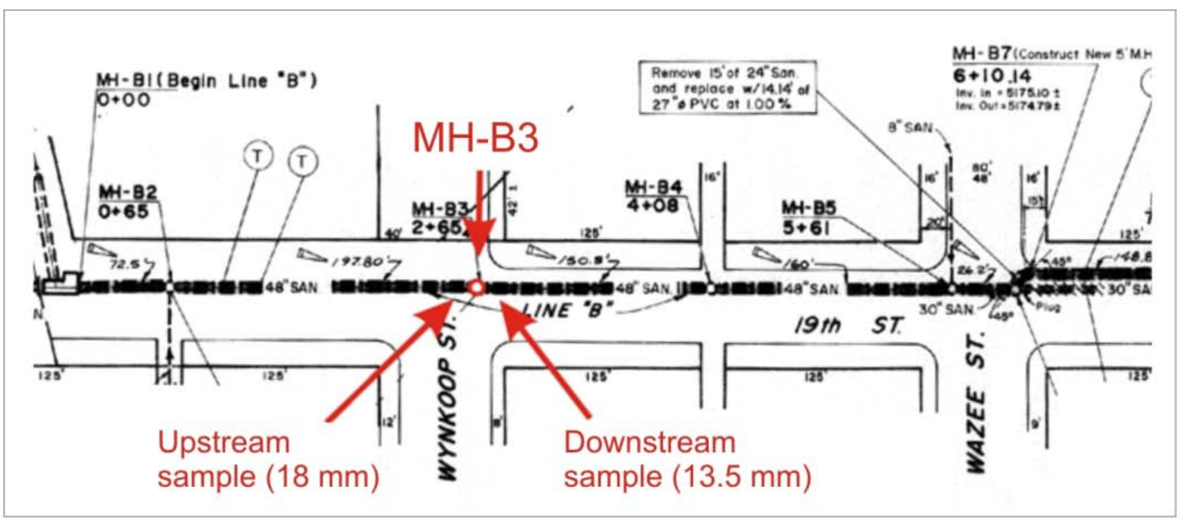


Figure 4-26. Layout and 2010 Sample Locations for the Denver 48-in. Liner

4.3.2 Sample Removed and Tested in 1995. Insituform Technologies removed one sample from the installed CIPP liner and tested it in 1995 (at the time the liner was eight years old). The sample was taken from adjacent to manhole B3 and the liner thickness was measured to be 18 mm. Test methods for tensile testing were based on ASTM D638 and for flexural testing based on ASTM D790. The results are shown in Table 4-13. It should be noted that there was some confusion about the data recorded for the sample in that the sample was marked as coming from an oval-shaped 48-in. equivalent diameter brick sewer in this location, whereas the actual sewer in this location is circular. Such discrepancies are often impossible to resolve after many years have passed since the data was recorded. The flexural strength (average of 6,900 psi) and flexural modulus of elasticity (average of 490,000 psi) were both well above the specified values at the time of installation (4,500 psi and 250,000 psi, respectively). Overall comparisons can be found in Section 6.

Table 4-13. Historic Sampling Results for the CIPP Liner Tested in 1995 (Denver 48-in. Liner)

Sample	Tensile Break Strength (psi)	Tensile Elongation at Break (%)	Flexural Break Strength (psi)	Flexural Modulus of Elasticity (psi)
1	2,500	1.8	7,400	520,000
2	2,400	1.3	7,000	530,000
3	2,100	1.3	6,500	470,000
4	-	-	6,400	430,000
5	-	-	7,300	520,000
Mean	2,300	1.5	6,900	490,000
Std Dev	170	0.2	400	40,000

4.3.3 Sample Retrieval in 2010. Two samples, each approximately 2 ft × 2 ft, were exhumed from the installed liner on May 20, 2010, by Wildcat Civil Services of Kiowa, CO with Jack Row, the General Superintendent, on site. (The liner age at this time was 23 years.) Both samples were taken from the crown of the pipe at a distance about 4 ft from manhole B-3 (one upstream and the other downstream of the manhole). The samples were sent to TTC for testing. Figure 4-27 shows images of the recovered specimens.

Figure 4-27. Images of the Recovered Samples from the Denver 48-in. Liner

4.3.4 Annular Gap. Annular space measurements were not collected for this sample due to the circumstances of sample retrieval.

4.3.5 Liner Thickness

4.3.5.1 Downstream Sample. For determining the liner thickness of the downstream sample, 10 readings were taken at six different locations around the sample (a total of 60 readings) using a micrometer with a resolution of ±0.0001 in. The average calculated values and their standard deviations are shown in Figure 4-28. The weighted average for the sample thickness measurements was calculated to be 13.9 mm and the weighted error ±0.3 mm.

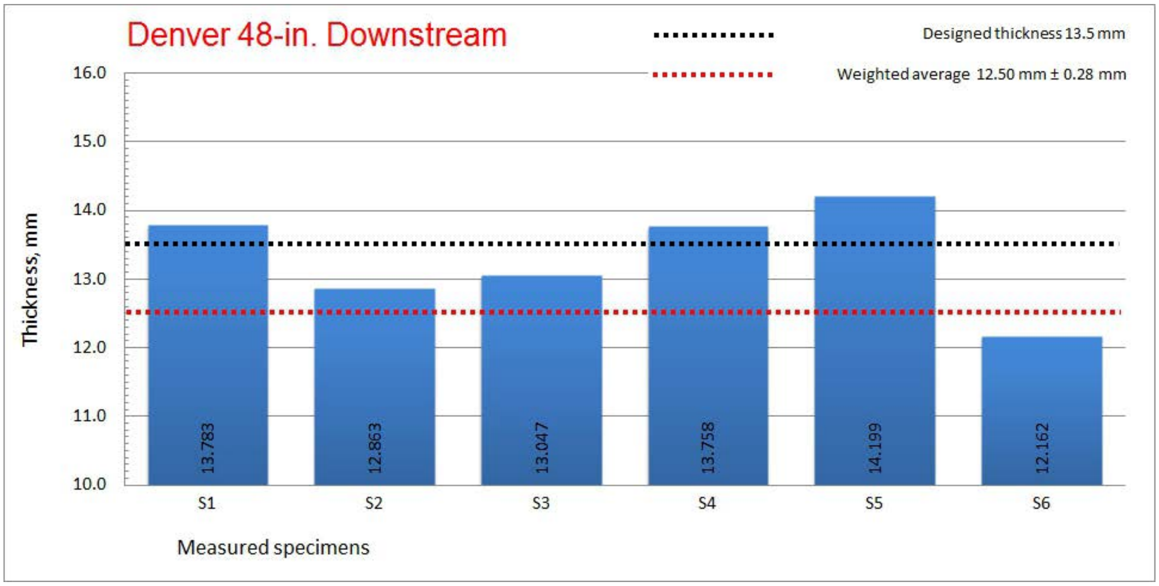


Figure 4-28. Thickness for Denver 48-in. Downstream Sample

4.3.5.2 Upstream Sample. For determining the liner thickness of the upstream sample, an 18 in. × 18 in. panel was cut into nine squares (6 in. × 6 in.) and thickness was measured along the edges. Three 'inner' squares were next cut into four squares each, and again thickness was measured along the edges. In summary, a total of 18 sets of readings were taken, where each set contained 10 readings, amounting to a total of 180 readings. The average calculated values and their standard deviations are shown in Figure 4-29. The weighted average for the sample thickness measurements was calculated to be 14.2 mm and the weighted error ±0.2 mm.

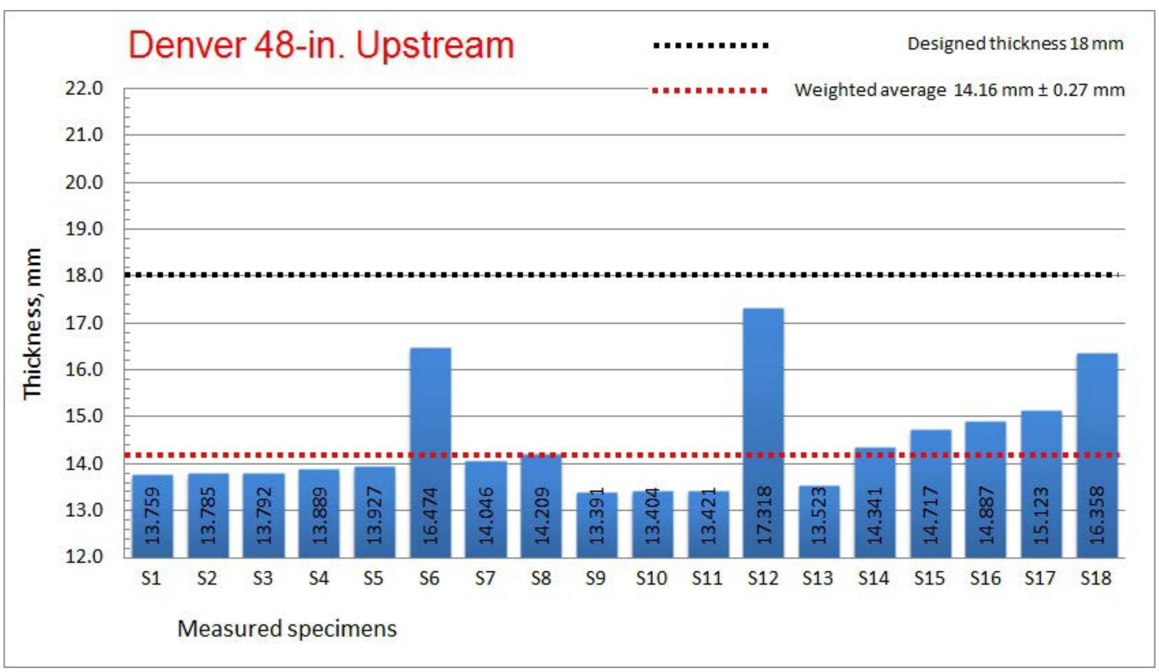


Figure 4-29. Thickness for Denver 48-in. Upstream Sample

4.3.6 Specific Gravity and Porosity

4.3.6.1 Introduction. Specific gravity was measured by the displacement method in accordance with ASTM D792. The standard specifies that any convenient size specimen can be used for this testing. A weighing scale (Figure 4-30) fitted with a hook at the bottom was placed on a bench having a circular hole in the middle. A small wire basket was hung from the hook (Figure 4-31). A thermometer to measure the water temperature was hung from the bottom of the bench.

Figure 4-30. Weighing Scale, Model Mettler PM200

Figure 4-31. Wire Basket and Thermometer

A bucket full of water was placed on top of a screw jack. The screw jack helped in elevating the bucket and immersing the specimen in water. A sinker was also used to sink the specimens. Details of the instrumentation are shown in Figure 4-32.

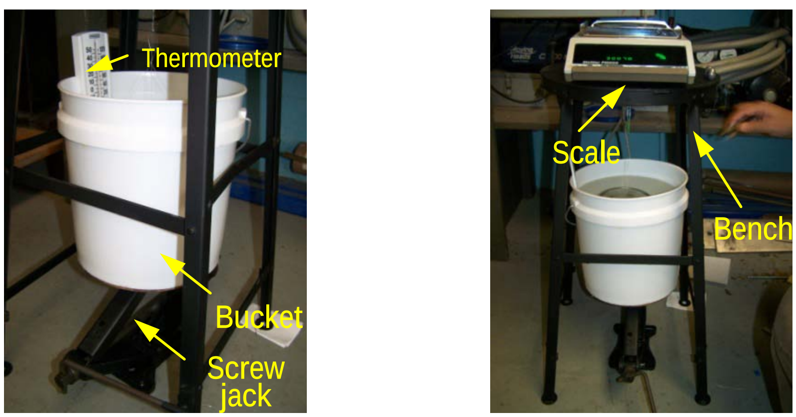


Figure 4-32. ASTM D792 Setup

The weight of each specimen was measured in air and water. The weight of the wire basket was also measured in water. Each time the immersed depth for the wire basket was kept identical. Specific gravity was calculated for each specimen using the equation provided in ASTM D792.

The bulk specific gravity of the liner comprises a mixture of resin, fabric, coating, and air. It is a useful measure to check whether the liner meets the theoretical specific gravity based on the weighted contribution of its components. Low specific gravities typically indicate higher porosities in the liner. The results of the specific gravity measurements across all of the liners tested are discussed in Section 6.

4.3.6.2 Downstream Sample. Seven specimens from the downstream sample were used in this test. The average specific gravity for the sample was calculated to be 1.07 and standard deviation 0.04.

In addition to the TTC laboratory measurements of specific gravity, measurements of density and porosity of a sample from this liner specimen were made by Micrometrics Analytical Services. In its testing (using mercury penetration for the porosity determination), the bulk density (at 0.54 psia) was 1.1645 g/mL, the apparent (skeletal) density was 1.3123 g/mL, and the porosity was 11.262%. The full test report is provided in Appendix C.

4.3.6.3 Upstream Sample. Seven specimens from the upstream sample were used in the TTC testing for specific gravity. The average specific gravity for the sample was calculated to be 1.08 and standard deviation 0.03.

In addition to the TTC laboratory measurements of specific gravity, measurements of density and porosity of a sample from this liner specimen were made by Micrometrics Analytical Services. In its testing (using mercury penetration for the porosity determination), the bulk density (at 0.54 psia) was 1.1618 g/mL, the apparent (skeletal) density was 1.2933 g/mL, and the porosity was 10.171%. The full test report is provided in Appendix C.

4.3.7 Flexural Testing

4.3.7.1 Downstream Sample. Specimens were cut from the retrieved downstream CIPP liner sample in accordance with ASTM D790 for measuring the liner's flexural strength and flexural modulus of elasticity. A total of five specimens were prepared and tested. The sides of the specimens were smoothed using a grinder and a table router. The 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) as shown in Figure 4-33. Table 4-14 lists the dimensions and moment of inertia for all specimens. Table 4-15 and Figure 4-34 summarize the flexural test results for the Denver 48-in. downstream sample.

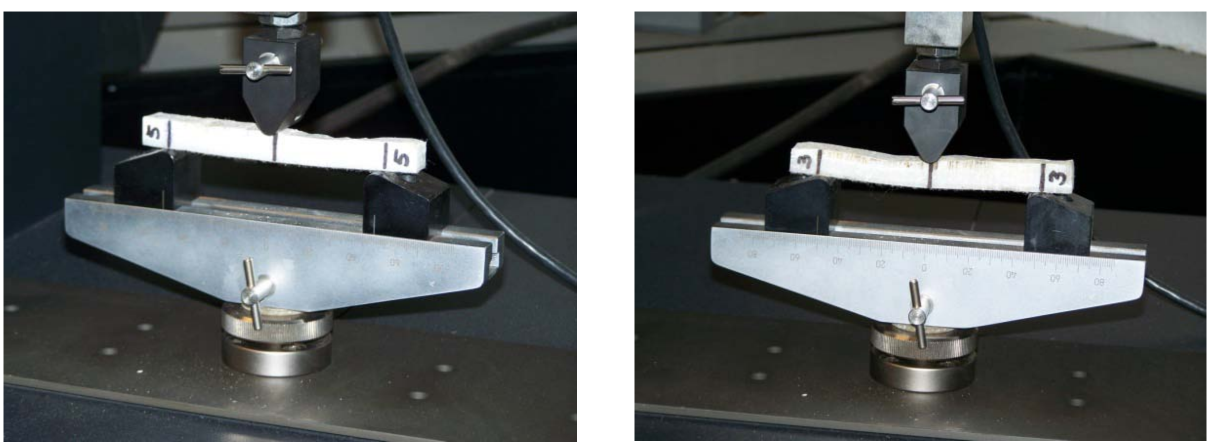


Figure 4-33. Flexural Test in Accordance with ASTM D790

Table 4-14. Geometric Data for Flexural Test Specimens (Denver 48-in. Downstream Sample)

Sample ID	Span (in.)	Dimension		Moment of Inertia (in.^{4})
		W (in.)	D (in.)	
1	4	0.495	0.523	0.005901
2	4	0.512	0.500	0.005333
3	4	0.500	0.500	0.005208
4	4	0.496	0.532	0.006224
5	4	0.517	0.513	0.005816

Using the information in Table 4-14, the following figures were drawn:

- Load data and deflection data at mid-point for all samples.
- Flexural stress and strain graphs for all samples.

Peak load, peak shear stress, and flexural modulus were obtained from the software 'MtestW' that operates the ADMET eXpert 2611 UTM. Peak bending stress is calculated from the peak load value achieved using the following formula.

where

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

Table 4-15. Flexural Test Results for Denver 48-in. Downstream Sample

Location on Pipe	Peak Load (lb)	Peak Bending Stress (psi)	Peak Shear Stress (psi)	Flexural Modulus (psi)
1	155	6,873	599	340,145
2	158	7,418	618	290,124
3	154	7,371	614	314,932
4	161	6,867	609	282,343
5	150	6,628	567	287,254
Average and Std. Dev.	-	7,031±346	601±21	302,960±24,303

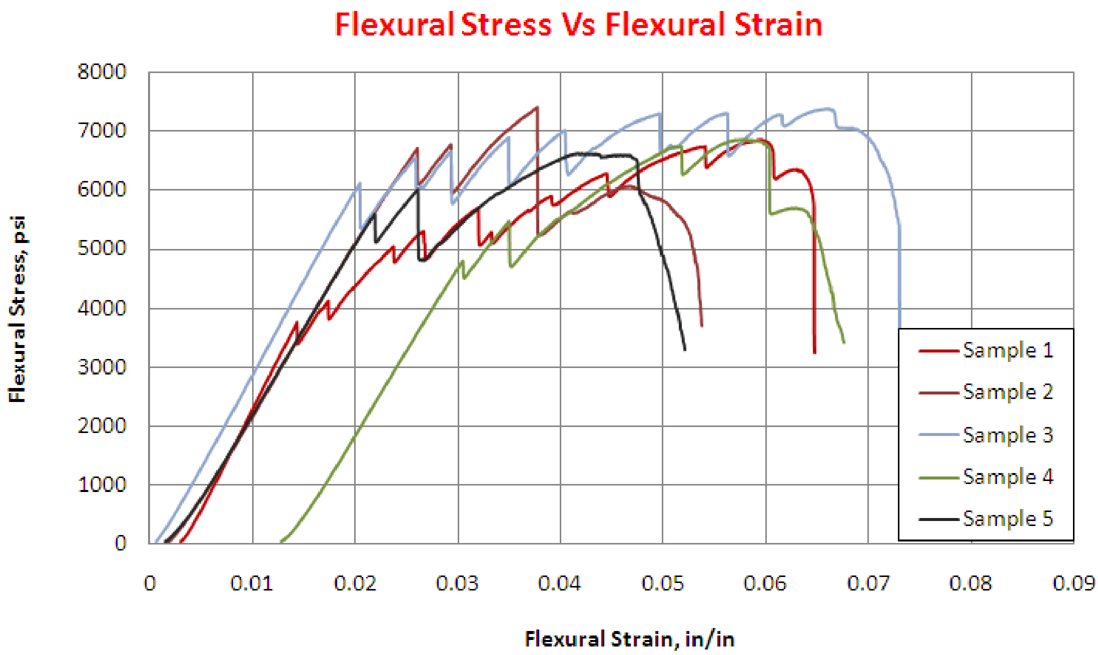


Figure 4-34. Flexural Stress-Strain Curves for Denver 48-in. Downstream Sample

4.3.7.2 Upstream Sample. Specimens were cut from the retrieved upstream CIPP liner and tested for flexural strength and flexural modulus of elasticity in the same manner as specimens from the downstream sample (Table 4-16). The results of testing are provided in Tables 4-17 and 4-18 and Figures 4-35 and 4-36.

For this particular set of samples, the flexural test results, particularly the flexural modulus, were unusually low compared to the other samples tested in this project. It was decided to repeat a new set of five samples to see if an error in the testing procedures or a localized weak spot in the liner might have caused the low values. The original test results are termed "Set 1" and the repeated tests are termed "Set 2". It can be seen that there is a significant difference between the two sets of results with the second set meeting all of the ASTM minimum values for a new liner and the first set meeting the peak bending stress value, but falling significantly below on the flexural modulus. It appears most likely that the area of the liner used for the first set of tests was of poorer quality than for the second set of tests. The interpretation of these results in comparison with the test results for all the retrospective sites is discussed in Section 6.

Table 4-16. Geometric Data for Flexural Test Specimens for Denver 48-in. Upstream Sample

Sample ID	Span (in.)	Dimension		Moment of Inertia (in.^{4})
		W (in.)	D (in.)	
1	4	0.490	0.540	0.0064298
2	4	0.470	0.540	0.0061673
3	4	0.478	0.558	0.0069207
4	4	0.534	0.556	0.0076486
5	4	0.518	0.568	0.0079103

Table 4-17. Flexural Test Results for Denver 48-in. Upstream Samples (Set 1)

Location on Pipe	Peak Load (lb)	Peak Bending Stress (psi)	Peak Shear Stress (psi)	Flexural Modulus (psi)
1	107.56	4,517	407	169,445
2	105.26	4,608	415	168,437
3	112.76	4,546	423	167,678
4	156.45	5,686	527	221,749
5	161.59	5,801	549	185,801
Average and Std. Dev.	-	5,032±652	464±68	182,622±23,126

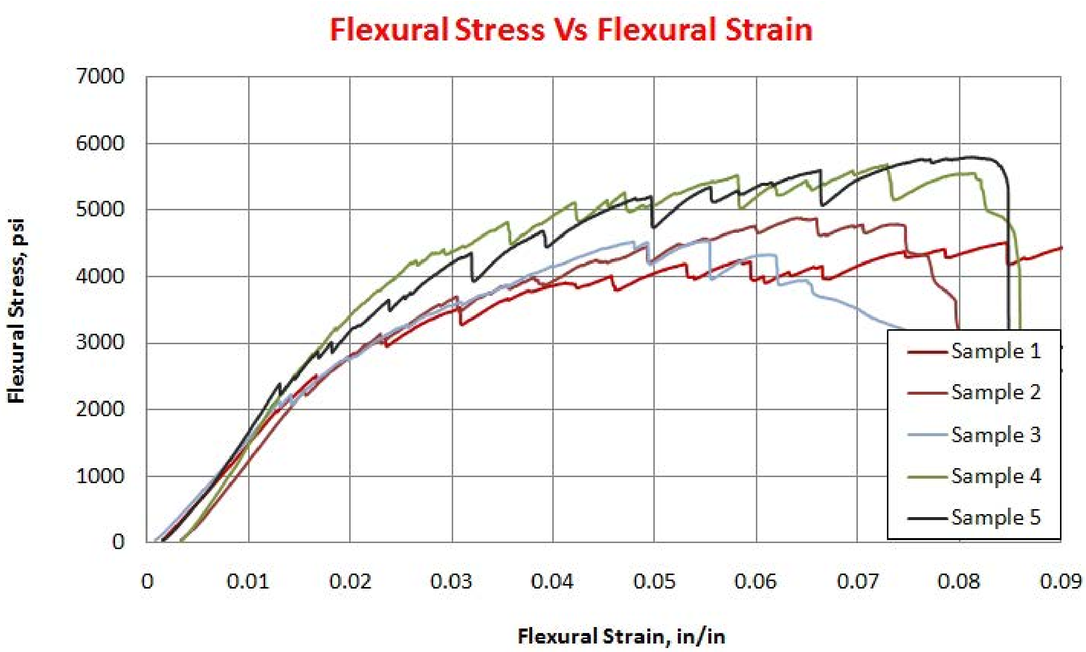


Figure 4-35. Flexural Stress-Strain Curves for the Denver 48-in. Upstream Liner (Set 1)

Table 4-18. Flexural Test Results for Denver 48-in. Upstream Samples (Set 2)

Location on Pipe	Peak Load (lb)	Peak Bending Stress (psi)	Peak Shear Stress (psi)	Flexural Modulus (psi)
1	139	5,012	476	276,920
2	156	6,027	559	187,218
3	149	7,486	589	369,998
4	162	6,159	541	270,265
5	167	5,900	540	214,134
Average and Std. Dev.	-	6,117±888	541±41	263,707±70,398

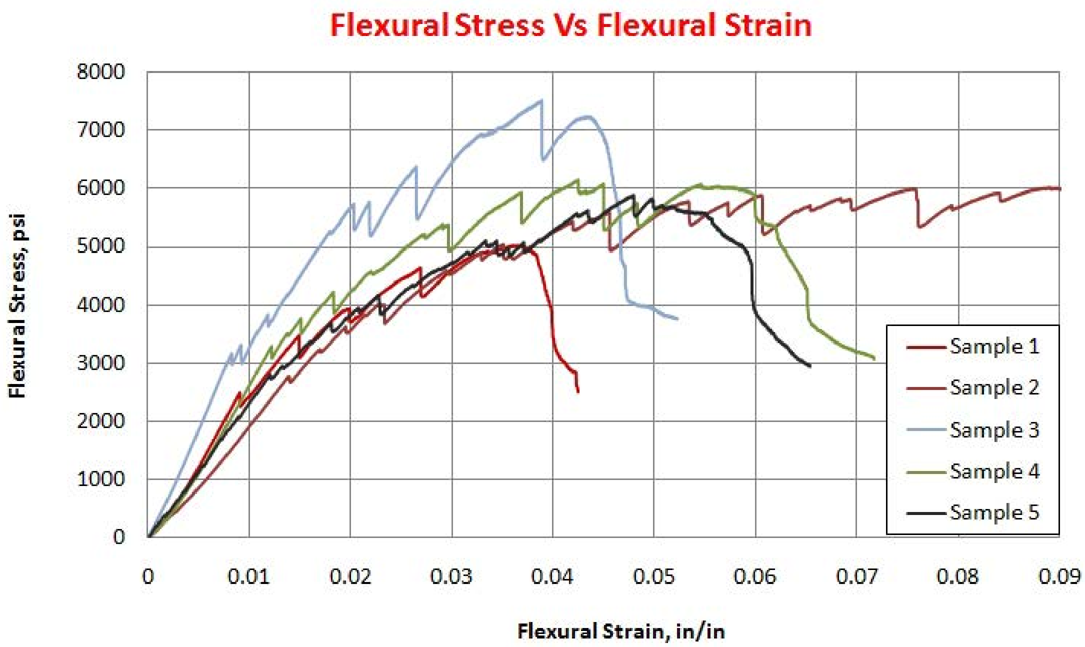


Figure 4-36. Flexural Stress-Strain Curves for Denver 48-in. Upstream Liner (Set 2)

4.3.8 Tensile Testing

4.3.8.1 Downstream Sample. Specimens were cut from the retrieved downstream CIPP liner sample in accordance with ASTM D638 (see Figure 4-37) for measuring the liner's tensile strength. A total of five specimens were prepared and tested. The results of testing are shown in Table 4-19.

Using the information given in Table 4-19, the stress-strain curves for all samples were drawn, as shown in Figure 4-38.

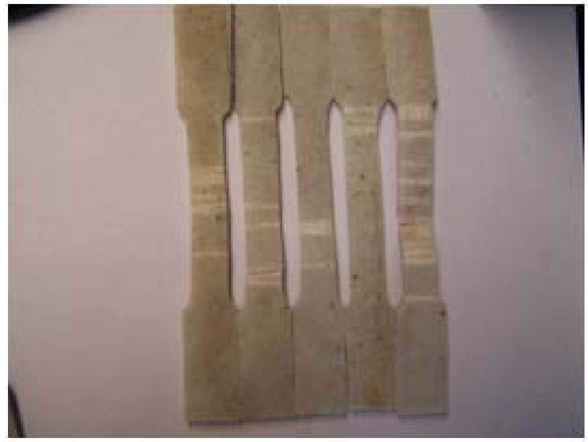


Figure 4-37. Tensile Specimens for Denver 48-in. Downstream Sample: Before the Test (Left) and Following the Test (Right)

Table 4-19. Tensile Test Results for Denver 48-in. Downstream Sample

Location on Pipe	**Area ($in.^2$)**	**Peak Load (lb)**	**Peak Stress (psi)**	**Tensile Modulus (psi)**
1	0.2733	785.36	2,874	405,345
2	0.2611	813.76	3,117	364,283
3	0.3203	862.47	2,693	405,639
4	0.2888	867.73	3,005	288,786
5	0.3467	1139.19	3,286	448,047
Average and Std. Dev.	-	-	**2,995±227**	**382,420±60,141**

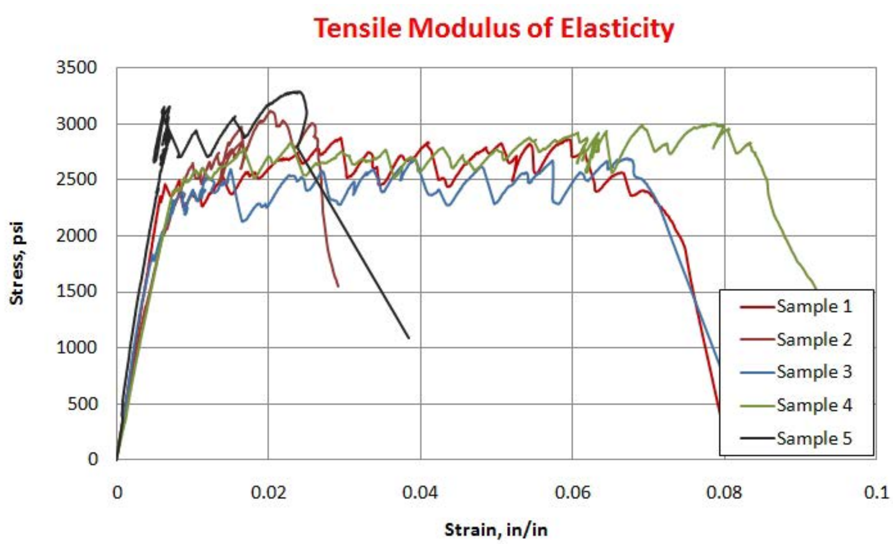


Figure 4-38. Stress-Strain Curves from Tensile Testing for Denver 48-in. Downstream Sample

4.3.8.2 Upstream Sample. Specimens were cut from the retrieved upstream CIPP liner and tested for tensile strength in the same manner as specimens from the downstream sample. The results of testing are provided in Table 4-20 and shown in Figure 4-39.

Table 4-20. Tensile Test Results for Denver 48-in. Upstream Sample

Location on Pipe	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.3052	923	3,023	451,779
2	0.2641	858	3,250	431,712
3	0.2822	904	3,203	324,920
4	0.2991	1064	3,557	466,379
5	0.2846	856	3,009	459,145
Average	**-**	**-**	**3,208±222**	**426,787±58,396**

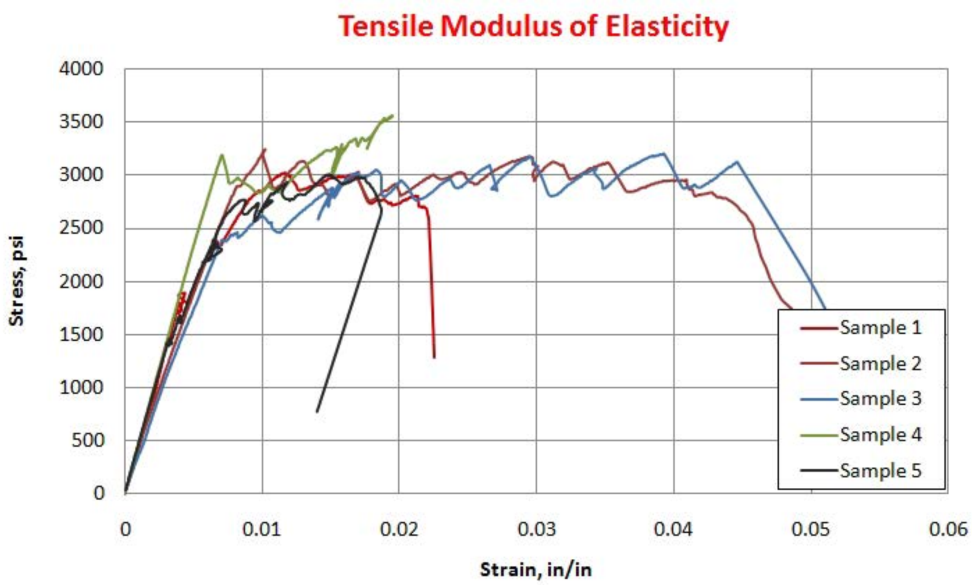


Figure 4-39. Stress-Strain Curves from Tensile Testing of Denver 48-in. Upstream Samples

4.3.9 Shore D Hardness

4.3.9.1 Introduction. The Durometer (Shore D) hardness test (ASTM D2240) 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. The Shore D hardness scale utilizes a weight of 10 lb (4,536 g) and a tip diameter of 0.1 mm. For the purpose of interpreting the results, a Shore D hardness scale value of 50 represents the hardness of a solid tire (e.g., similar to those used by forklifts), while a value of 80 represents the hardness of paper-making rollers.

4.3.9.2 Downstream Sample. Specimens measuring approximately 1 in. × 1 in. were cut from the retrieved downstream sample of the CIPP liner using a band saw. A total of 10 specimens were prepared and tested. A total of 36 tests were conducted on each sample: 18 tests on the inner surfaces and 18 tests on the outer surfaces. The average calculated values and their standard deviations are shown in Figure 4-40. The average and standard deviation of the Shore D hardness for the sample inner surface was calculated to be 65±3 and for the outer surface 79±2. The differences between the inner and outer surfaces of the liner follow the same pattern as the reading for the Denver 8-in. liner. The outer side of the liner enclosed by the host pipe was neither in contact with the soil nor with the waste stream. The significance of this result is explored in Section 6.

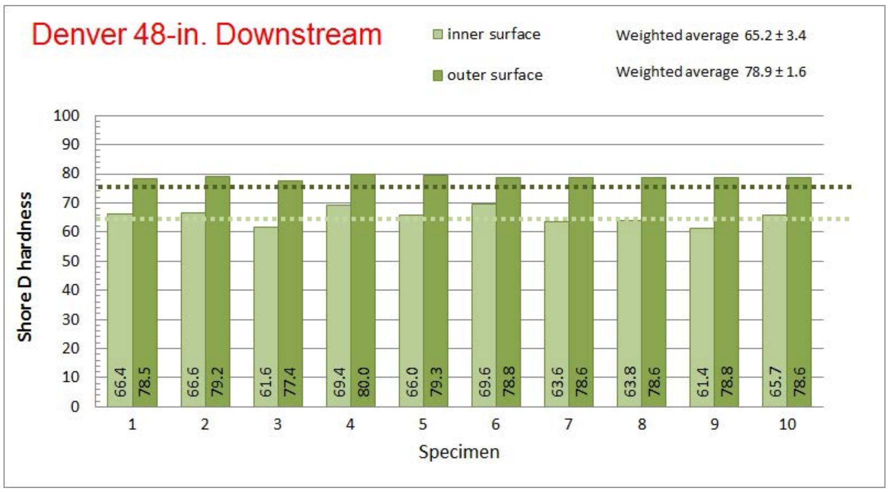


Figure 4-40. Shore D Hardness for Denver 48-in. Downstream Sample

4.3.9.3 Upstream Sample. A total of seven specimens were prepared and tested. A total of 50 tests were conducted on each sample: 25 tests on the inner surfaces and 25 tests on the outer surfaces. The average calculated values and their standard deviations are shown in Figure 4-41. An average of 25 readings at both the inner and outer surface of each of seven specimens is shown. The weighted average and standard deviation of the Shore D hardness for the sample inner surface was calculated to be 47±2 and for the outer surface 63±3.

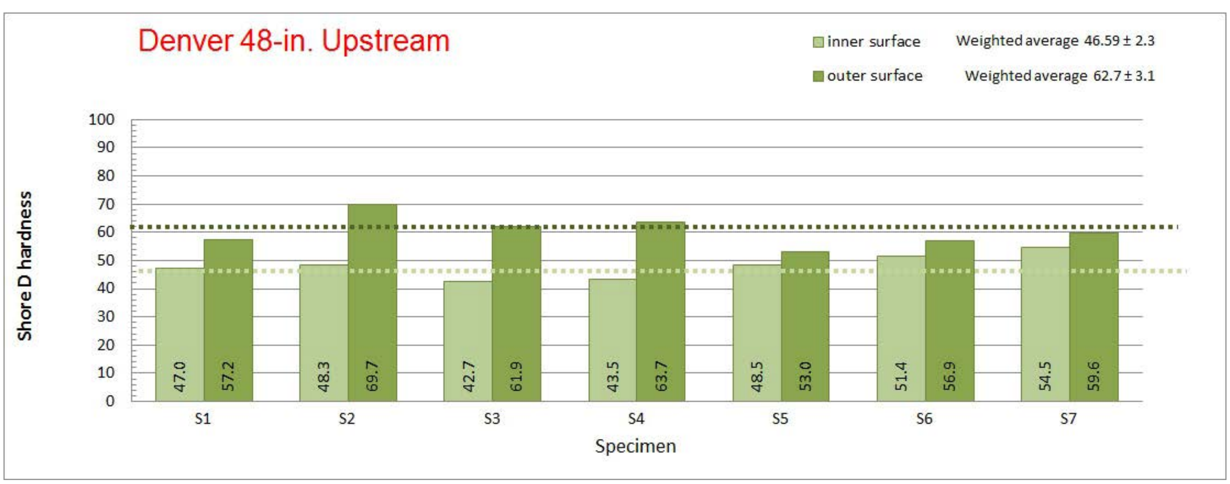


Figure 4-41. Shore D Hardness for Denver 48-in. Upstream Sample

4.3.10 Barcol Hardness

4.3.10.1 Downstream Sample. Seven specimens from the exhumed downstream sample were subjected to the Barcol test (ASTM D2583). Due to the presence of dust and debris on the outer wall of the exhumed CIPP slabs (Figure 4-42), a belt sander was used to achieve a smooth surface. The inner surface of each sample was kept unaltered (Figure 4-43). A wooden base was prepared to match the thickness of the specimens, and the Barcol hardness tester (Figure 4-44) was placed on that platform to conduct the test (Figure 4-45).

Figure 4-42. Original Outer Surface (Denver 48-in. Downstream Sample)

Figure 4-43. Smoothed Outer Surface (Top Row) and Inner Surface (Bottom Row) (Denver 48-in. Downstream Sample)

Figure 4-44. Barcol Hardness Tester, Taking a Measurement

Figure 4-45. Barcol Hardness Test Setup

For each specimen a total of 30 readings were taken: 15 on the outer surface and 15 on the inner surface. 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 Figure 4-46. The weighted average of Barcol hardness for the sample inner surface was calculated to be 16.5 and the weighted error ±1.5, and for the outer surface 29.3 ±1.3.

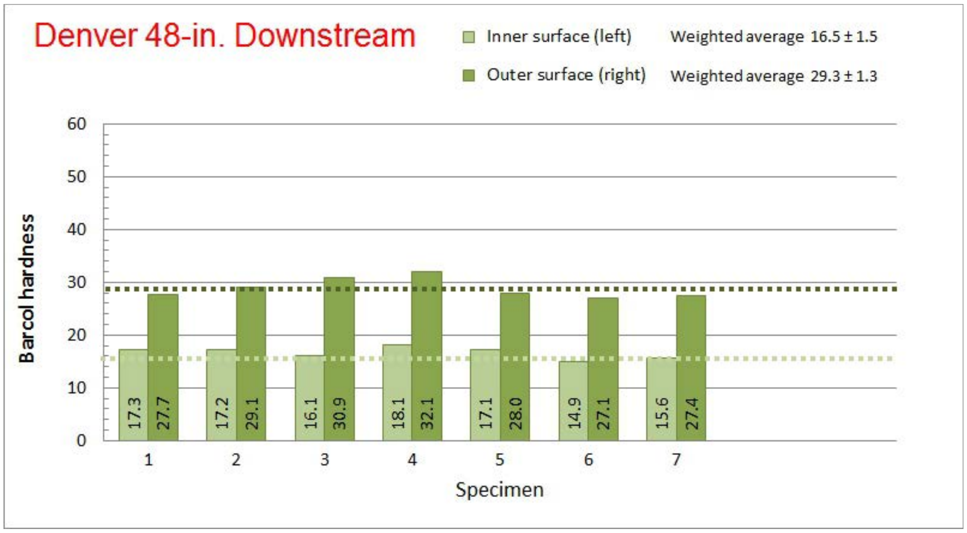


Figure 4-46. Barcol Hardness of Denver 48-in. Downstream Sample

4.3.10.2 Upstream Sample. Twenty-five hardness readings on the inner and outer side of seven samples were taken. The average calculated values and their standard deviations are shown in Figure 4-47. An average of 25 readings at both the inner and outer surface of each of seven specimens is shown. The weighted average and standard deviation of the Barcol hardness for the sample inner surface was calculated to be 14.9±1.8 and for the outer surface 18.4 ±2.4.

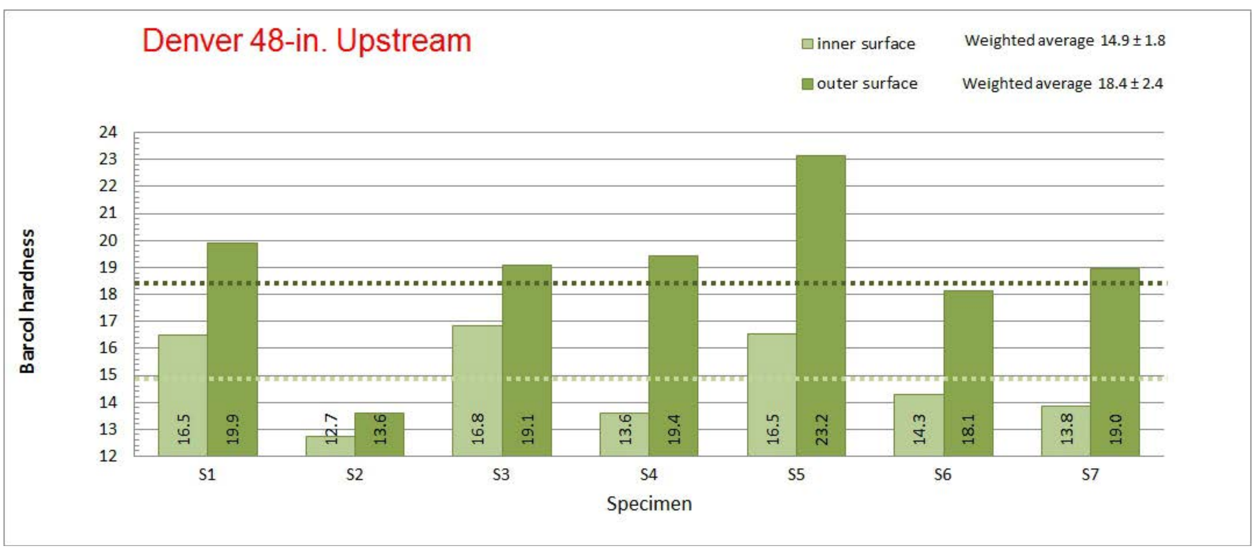


Figure 4-47. Barcol Hardness of Denver 48-in. Upstream Sample

4.3.11 Raman Spectroscopy

4.3.11.1 Introduction. The general Raman spectroscopy procedures as described for the Denver 8-in. liner were repeated for each of the Denver 48-in. downstream and upstream samples. Samples of the resin type used for the original CIPP installations were obtained from the manufacturer for comparison.

4.3.11.2 Downstream Sample. The Raman spectroscopy plots for the Denver 48-in. downstream sample are shown in Figure 4-48. Four plots are shown for each of the virgin resin, inside liner surface, and exterior liner surface. The location of peaks is generally the same for the plots for each location with the exterior surface exhibiting the most variability. A discussion of the possibilities for using Raman spectroscopy for liner evaluation is given in Section 6.

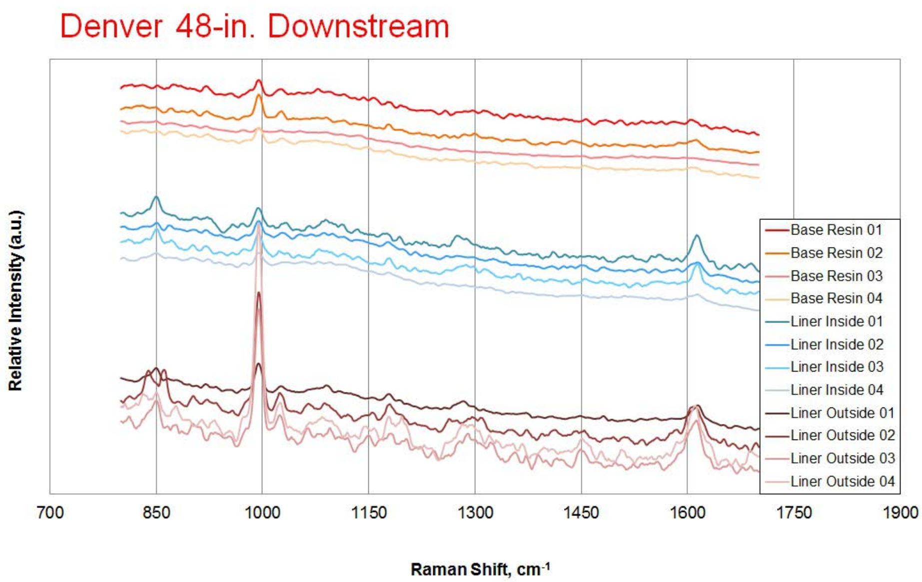


Figure 4-48. Raman Spectroscopy Plots (Denver 48-in. Downstream)

4.3.11.3 Upstream Sample. The Raman spectroscopy plots for the Denver 48-in. upstream sample are shown in Figure 4-49. Four plots are shown for each of the virgin resin, inside liner surface, and exterior liner surface. The location of peaks is generally the same for the plots for each location with the exterior surface exhibiting the most variability. A discussion of the possibilities for using Raman spectroscopy for liner evaluation is given in Section 6.

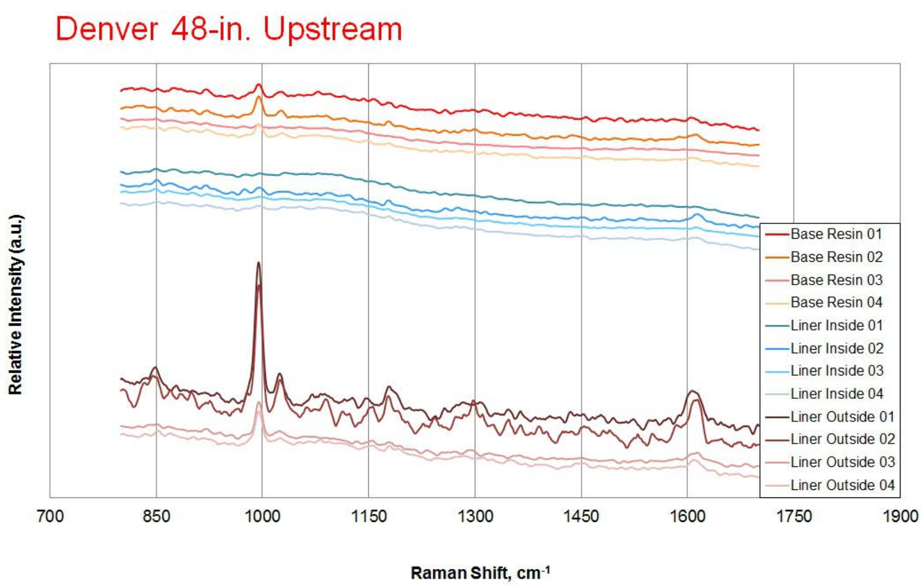


Figure 4-49. Raman Spectroscopy Plots (Denver 48-in. Upstream)

4.3.12 Comparison of 1995 and 2010 Test Results. Table 4-21 provides a tabulated comparison of the 1995 and 2010 test results for the Denver 48-in. liner. In comparing the results, it should be known that the 1995 sample was retrieved only from the upstream side of the manhole (a separate installation from the downstream with a different liner thickness). A summary of the combined results for all four sites evaluated is given in Section 6 where the significance of the various results is explored.
The average thickness (14.2 mm) of the TTC-tested upstream sample (taken from the crown area of the liner) was less than the liner thickness specified for this liner (18 mm). The specific gravity of both the upstream and downstream liners as measured by TTC according to ASTM D792 (1.07 and 1.08, respectively) were lower than the results reported in the mercury penetrometer testing (1.16) and lower than the results reported by Insituform from its testing (1.19).

All of the Denver 48-in. liner samples exceed the specified flexural strength for the liner and all of the samples, except for one set of tests on the TTC-tested upstream sample, exceed the specified flexural modulus for the liner. The average flexural modulus value measured for the initial set of coupons from the TTC-tested upstream sample (182,622 psi) is much lower than any of the other flexural modulus values reported in this study. The correlation of low values of flexural modulus with other liner properties such as tensile elongation at break, tensile strength, specific gravity, and porosity is explored in Section 6. Whether lower than specified values can be attributed to liner aging, to original installation issues, or to testing variability is also discussed in Section 6.

Table 4-21. Comparison of 1995 and 2010 Test Results for the Denver 48-in. Liner

Property	No. of Samples	Test Standard	Minimum Specification	Insituform (1995)	TTC (2010)	TTC (2010)
Sample location	-	-	-	*MH B3*	*Upstream MH B3*	*Downstream MH B3*
Age, years	-	-	-	8	23	23
Design Thickness, mm	-	-	-	18	18	13.5
Thickness, mm	-	-	-	18	14.2 ± 0.2	13.9 ± 0.3
Shore D Hardness (inner surface)	18 or 26 each	ASTM D2240	-	-	47 ± 2	65 ± 3
Shore D Hardness (outer surface)					63 ± 3	79 ± 2
Barcol Hardness (inner surface)	15 or 25 each	ASTM D2583	-	-	14.9 ± 1.8	16.5 ± 1.5
Barcol Hardness (outer surface)					18.4 ± 2.4	29.3 ± 1.3
Specific Gravity	7	ASTM D792	-	1.19	1.08 ± 0.03	1.07 ± 0.04
	1	Mercury Penetrometer	-	-	1.16	1.16
Flexural Strength, psi	5	ASTM D790	4,500	6,900 ± 400	5,032±652 6,117±888	7,031 ± 346
Flexural Modulus of Elasticity, psi	5	ASTM D790	250,000	490,000 ± 40,000	182,622±23,126 263,707±70,398	302,960 ± 24,303
Tensile Strength, psi	3	ASTM D638	-	2,300 ± 170	3,208±222	2,995 ± 227

5.0: CITY OF COLUMBUS RETROSPECTIVE STUDY

5.1 Introduction

The initial discussions were held with the City of Columbus, OH in January 2010 about the City's willingness to participate in the retrospective evaluation pilot studies. The draft protocol outlined in Section 3 was provided to the City so that they could understand the nature of the program and the requested role of the City. After the City indicated its interest in participation, a face-to-face meeting was organized and held in Columbus on February 16, 2010. The City offered two sites for sample retrieval. The first site was located in the suburb of Clintonville, OH and was offered due to a future project to upsize the sewer on this street. This site involved retrieval of a 6-ft section of CIPP from a 5-year old, 8-in. CIPP of a VCP installed in 2005. The second site was a 21-year old, 36-in. CIPP installed in 1989 in a brick sewer near downtown Columbus at Pearl and Gay Streets. The City of Columbus collaborated on this project and provided in-kind support for sample collection and on-site support for field testing and destructive testing (traffic control, utility locating and designation, excavation, and surface restoration at access points, and CCTV inspection).

5.2 Site 1: 5-year Old CIPP Liner in 8-in. Clay Pipe

This section describes the retrospective evaluation of a CIPP liner installed in Clintonville, OH in 2005. Although relatively new, the pipe was found suitable for destructive testing because it was already scheduled for upsizing due to insufficient hydraulic capacity. A short (6-ft) section of the pipe with the CIPP liner was carefully exhumed and sent to TTC, where comprehensive laboratory testing was performed.

5.2.1 Host Pipe and Liner Information

Location:	Richards Road and Foster Street in Clintonville, OH
Host pipe:	Circular, 8 in. diameter, VCP, installed in 1924
Burial depth:	6 ft (above crown)
Liner dimensions:	8 in. diameter; 6 mm thick
Resin:	ARPOL MR 12018
Primary catalyst:	Perkadox 16
Secondary catalyst:	Tert-Butyl Peroxybenzoate Peroxide (TBPB)
Felt:	Unwoven fabric
Seal:	Polyethylene coating, 0.015 in. thick
Year liner installed:	2005
Liner vendor:	Reynolds Inliner
Resin supplier:	Ashland
Tube manufacturer:	Liner Products of Paoli, IN.

5.2.2 Timeline for Fieldwork

Tuesday, April 13, 2010

7:30 AM	Contractor's (Bale) crew began staging equipment and preparing the site for the excavation.
8:00 AM	Excavation began on asphalt roadway. The asphalt layer was approximately 4 in. thick with 4 in. of road base material compacted beneath. The excavation was carried out between manholes 0233S0013 and 0233S0010, from 254 ft to 264 ft west of manhole 0233S0013.
8:05 AM	After removal of the asphalt pavement, a soil sample was taken at the sub-grade level. Sample No. 1 was collected and placed in a 1 gallon plastic bag. All samples were collected with a spade shovel and hand loaded into sample containers.
8:30 AM	Excavation was halted and sample No. 2 was collected from the bottom of the trench at a depth of 3 ft.
9:45 AM	In-service, 4 in. diameter, vitrified clay lateral was encountered. The lateral entered the main line from the south with a 90° bend. At the connection, concrete was poured to assist in keeping the lateral in place at the main line. No noticeable leaking was detected in this area. There was also a second, inactive lateral on the north side of the excavation.
10:00 AM	Excavation encountered crown of pipe. Excavation was halted and sample No. 3 was collected from 6 ft below grade and immediately above the crown of the pipe. Sample No. 4 was collected from the side of the trench at elevation 5 ft below grade.
10:05 AM	Excavation activity entered the area surrounding and below the pipe. Formation l consisted predominantly of native shale. Visual observation suggested good compaction around the pipeline. The bedding material was undisturbed with a solid beam support and good support at the spring lines. Normal condensation was observed around the outside of the clay host pipe. The clay host pipe was installed with 2 ft joints.
10:55 AM	Sample No. 5 was collected with continued hand digging at the spring line level of the pipe.
11:10 AM	Sample No. 6 was collected with continued hand digging at the invert of the pipe. Bedding beneath the invert consisted mainly of native shale. Traces of excess resin from the installation were observed and a resin sample collected for future consideration.
11:30 AM	Once the line was 90% exposed, shims and bracing were used to support the host pipe. The pipe was lashed to a wooden support structure and layers of the shrink wrap material were applied. Two lifting slings were then fitted to the pipe specimen and the excavator. It should be noted that the host pipe with CIPP was not fully supported several times during the excavation and removal process, acting as a simple supported beam. One section of lateral was damaged during excavation and was removed so that the excavation around the pipe could be completed.
14:00 AM	One wastewater sample (Richards-8) was collected for pH and total petroleum hydrocarbons (TPH) including gasoline range organics (GRO) and diesel range organics (DRO).
14:05 PM	Another wastewater sample (Richards-8D) was collected for pH and TPH GRO/DRO.
14:15 PM	The shoring box was set and a temporary line was put in place for the lateral that was removed. Steel plates were placed over the excavation and cold patch around the edges.
15:15 PM	Measurements of the annular gap between the host pipe and liner were taken using a feeler gauge at both ends of the specimen and at both ends of the remaining pipe before the repair is made.
15:30 PM	The construction crew finished wrapping the specimen and loaded the specimen into the bed of a truck.

April 16, 2010

The specimen was received at TTC (see Figure 5-1).

Figure 5-1. Images of the Recovered Specimen (Columbus 8-in. Liner)

5.2.3 Visual Inspection of Liner. The visual inspection in the field was documented by Ed Kampbell of Jason Consultants. The liner appeared to be in good shape overall (see Figure 5-2). The polymeric film on the CIPP appeared to be intact with no evidence of hydrolysis. In-situ measurements indicated that the CIPP was at least 6.0 mm thick around the circumference, with the greatest thickness observed being approximately 6.5 mm. The annular space was very small, including that at the branch connection. A large amount of resin was formed around the circumference of the liner at each branch connection location. There was no evidence of external hydrostatic loading (no visible signs of a seasonal water table). The resin-impregnated felt was solid and intact. The stitch holding together the CIPP tube was found to be in good condition. Signs of wear were restricted to the bottom third of the tube. The liner varied significantly in external diameter as it accommodated the short pipe segments between the four branches.

Figure 5-2. Images of the Inner Surface of the 5-year Old Columbus 8-in. Liner

5.2.4 Locations of Soil Samples. The trench was divided into six regions (Figure 5-3). Soil samples collected from each region were placed in airtight bags to avoid foreign contamination and/or loss of moisture. The samples were numbered as shown in Table 5-1.

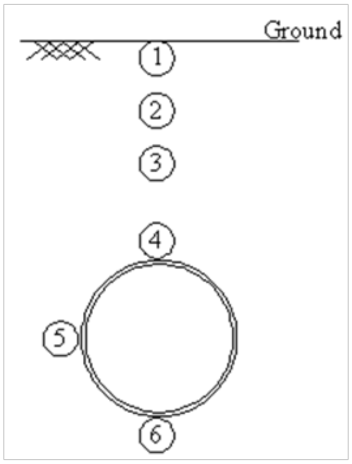


Figure 5-3. Location of Soil Samples (Columbus 8-in. Site)

Table 5-1. Designation of Collected Soil Samples (Columbus 8-in. Site)

Soil Sample Location	Sample ID
Subgrade 2 + 63	1
3 ft below subgrade	2
5 ft below subgrade	3
6 ft below subgrade - just above crown	4
Bedding along the spring line	5
On the invert	6

5.2.5 Analysis of Soil Samples. Standard test methods ASTM C136 and ASTM C128 were followed to classify the soil and determine its particle size distribution. In addition to these tests, the pH of the soil samples was measured using a pH meter.

5.2.5.1 Particle Size Distribution. The soil gradation analysis followed ASTM C136. Based on visual inspection, the soil samples were categorized as fine aggregates. Some large particles (e.g., asphalt, rocks) (see Figure 5-4) were also present, but were considered a foreign material and were excluded from the sieve analysis. For the analysis, 500 g of soil material was taken from each of the six soil samples and placed on a No. 4 sieve (4.76 mm). For all samples (excluding the large foreign material), 85 to 95% of the particles passed through the No. 4 sieve.

Figure 5-4. Collected In-Situ Soil Samples (Columbus 8-in. Site)

The resulting gradation curves are shown in Figure 5-5.

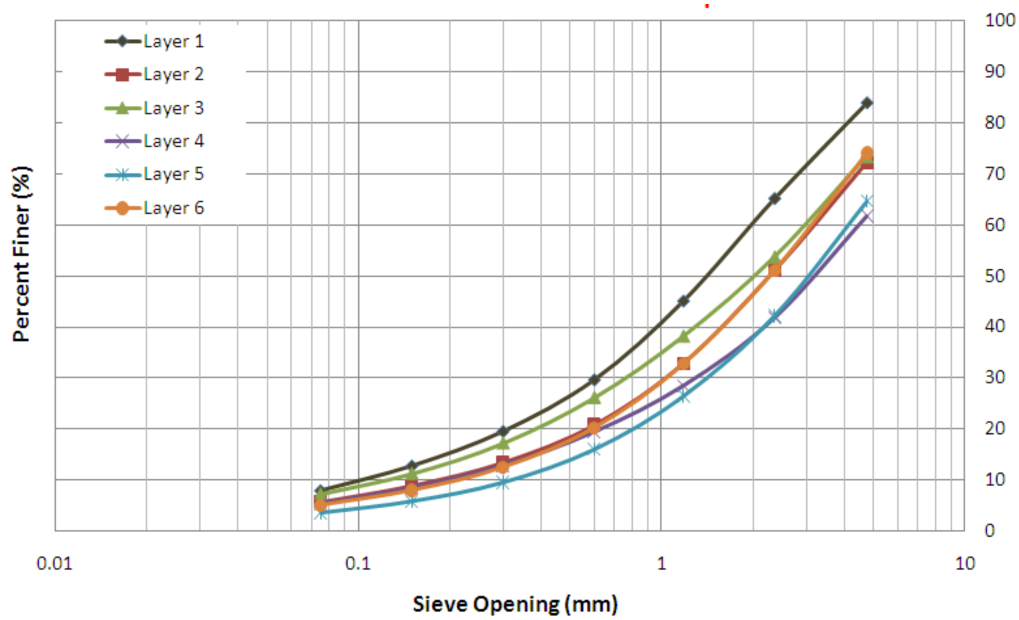


Figure 5-5. Grain Size Distribution of Soil Samples (Columbus 8-in. Liner Site)

Based on the grain size distribution, both the backfill and bedding soils can be considered to be sandy soils. The flatter slopes of the resulting gradation curves suggest that the bedding and surrounding soil are well-graded.

5.2.5.2 Soil Specific Gravity and Absorption. This standard testing method is used to calculate the density, relative density, and absorption of fine aggregates. Soil material weighing 500 g was taken from each of the six samples for performing the needed tests. The results are listed in Table 5-2.

Table 5-2. Soil Specific Gravity and Absorption Results (Columbus 8-in. Site)

Sample ID	Soil (g)	Bulk Specific Gravity (OD)*	Bulk Specific Gravity (SSD)**	Apparent Specific Gravity	Absorption (%)
1	500	2.28	2.42	2.65	6.04
2	500	1.73	2.07	2.61	19.59
3	500	1.57	1.98	2.63	25.53
4	500	1.52	1.97	2.78	29.77
5	500	1.18	1.59	1.99	34.41
6	500	1.56	1.96	2.60	25.44

*OD: Oven dry.
** SSD: Saturated surface dry.

5.2.5.3 Soil Moisture Content. ASTM D2216 is a test method used to determine the moisture content in soils and rocks by mass. Samples weighing 1,000 g from each of the six locations were placed in an oven for a period of 24 hr. After 24 hr, the soil samples were weighed and returned to the oven for an additional 24-hr period. The process was repeated until the difference between two subsequent measured weights was less than 1 g. At this point, the soil was assumed to be moisture free. Moisture content values for the six soil samples are listed in Table 5-3.

Table 5-3. Soil Moisture Content Results (Columbus 8-in. Site)

Sample ID	Moisture Content (%)
1	5.65
2	16.47
3	19.77
4	17.34
5	22.54
6	23.83

5.2.6 Measurement of Acidity, Alkalinity, and pH. The pH of the soil embedment and the solid sediments collected from the pipe invert were measured using a Thermo Orion and a sympHony SP70P pH meter (see Figure 5-6). The soil samples were placed in a pan (which was rinsed using distilled water) and distilled water was added to the samples. The soil sample was then stirred, and the pH probe was inserted into the soil-water mixture. The process was repeated for the sediments collected from the bottom of the liner on the inside of the pipe. The pH values of the bedding soil, backfill soil, and the sediments are listed in Table 5-4.

Figure 5-6. Measurement of pH (Columbus 8-in. Soil Samples)

The pH of soil samples collected from around the pipe (bedding material) and the backfill soil were found to be somewhat alkaline ranging from 7.3 to 8.9. The sediments inside the pipe were also found to be slightly alkaline (with an average pH of 7.6) as expected from a residential wastewater stream. These measurements do not provide any indication of a severe service environment for the liner.

Table 5-4. Soil pH at Designated Locations and Sewage pH (Columbus 8-in. Site)

Designation	Soil, pH	Sample	Sewage, pH
1	7.89	1	8.01
2	8.74	2	7.46
3	7.92	3	7.29
4	8.85	-	-
5	7.87	-	-
6	7.30	-	-

5.2.7 Wastewater Analysis. Retrieved wastewater samples were tested by American Analytical Laboratories, Inc., on April 14, 2010, in accordance with EPA Test Methods. EPA Method 150.1 was used to determine pH of samples. EPA Method 8015 was used to determine DRO and GRO to test for the presence of petroleum hydrocarbons. The results are shown in Table 5-5.

Table 5-5. Results of Wastewater Analysis (Columbus 8-in. Site)

Sample ID	pH	DRO (mg/L)	GRO (mg/L)
Richards-8	7.49	1.55	36.8
Richards-8D	7.44	1.81	31.3

Note: Richards-8 and Richards-8D are two samples taken from the same location and tested for QA purposes.

This data was selected to gauge the chemical characteristics of the wastewater in order to compare it to the chemical resistance test solution specified under ASTM D5813. Under ASTM D5813, CIPP materials are subjected to very low pH solutions (1% nitric acid and 5% sulfuric acid) and a petroleum hydrocarbon fuel. The pH of the wastewater was slightly basic at 7.44 to 7.49. The TPH content (DRO plus GRO) at 33 to 38 mg/L was within the range expected for normal sewage, which is less than 100 mg/L for total oil and grease (from synthetic sources such as petroleum products and animal/vegetable sources combined). Under ASTM D5813, CIPP is exposed to 100% Fuel C. The "C" refers to the vapor pressure and distillation class under ASTM D4814. ASTM Fuel C represents a typical gasoline with high aromatic content (50% toluene/50% iso-octane).

5.2.8 Annular Gap. The gap between the CIPP liner and the host pipe was measured at 45 degree increments around the circumference of the liner at both ends of the exhumed sample, as well as exposed ends of the remaining pipe sections. In the laboratory, nine separate measurements were made at each of the eight circumferential locations and averaged for the value at that location. The CIPP liner was found to tightly fit with the inner wall of the host pipe, with the average and standard deviation for the gap being 0.35±0.26 mm. The measurements are summarized in Table 5-6 and Figure 5-7.

Table 5-6. Annular Gap Measurements (Columbus 8-in. Liner)

Location	North End of Specimens (mm)	South End of Specimens (mm)	North End of Remaining Pipe (mm)	South End of Remaining Pipe (mm)
Crown	0.30	0.39	0.41	0.51
45° between crown and right spring line	0.16	0.27	0.23	0.53
Right spring line	1.27	0.30	1.14	0.33
Right haunch	0.10	0.49	0.20	0.43
Invert	0.12	0.36	0.18	0.10
Left haunch	0.39	0.10	0.43	0.13
Left spring line	0.34	0.30	0.28	0.20
45° between crown and left spring line	0.37	0.18	0.41	0.36

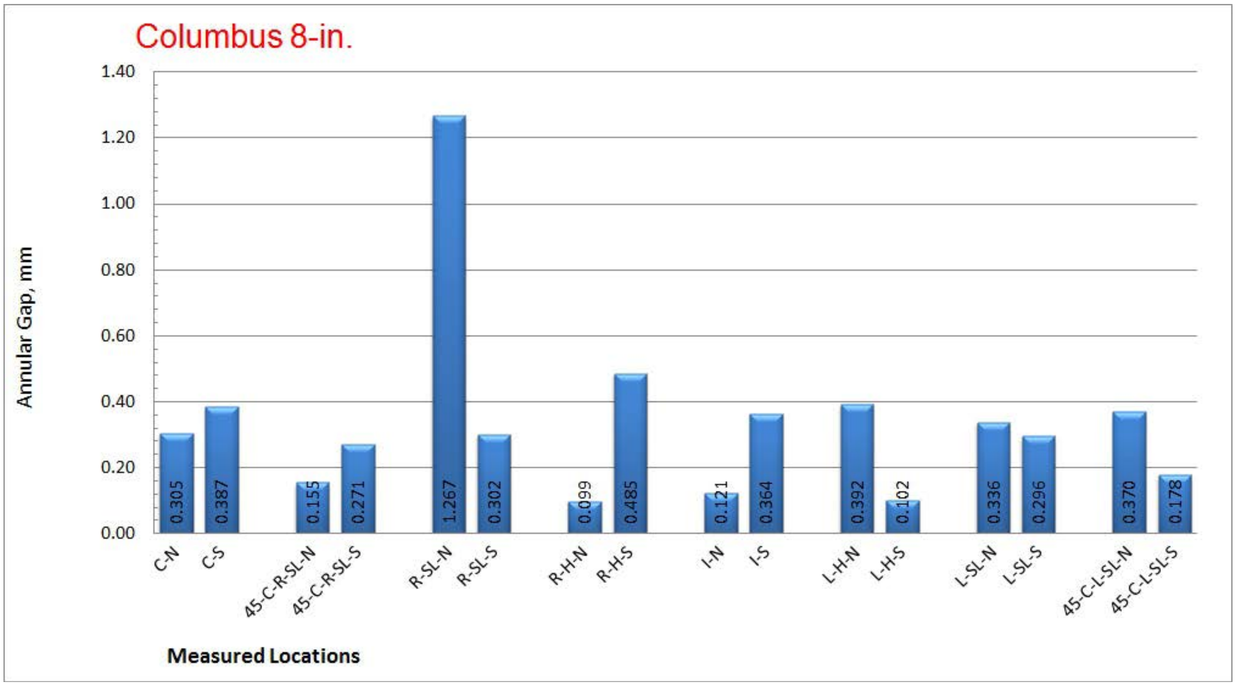


Figure 5-7. Histogram of Annular Gap Measurements (Columbus 8-in. Liner)

5.2.9 Liner Thickness. A total of 320 readings were taken to measure the liner thickness at different locations around the pipe circumference. These readings were taken using a micrometer with a resolution of ±0.0001 in.

The average thickness of the liner at different locations is shown in Figure 5-8. The thickness at the crown (5.7 mm) was found to be similar in thickness to the other locations (invert and spring line) around the circumference of the liner. The average liner thickness for each location is slightly less than the as-specified liner thickness of 6.0 mm. Additional discussion of the data measured at the time of installation with the current data is given in Section 5.2.14.

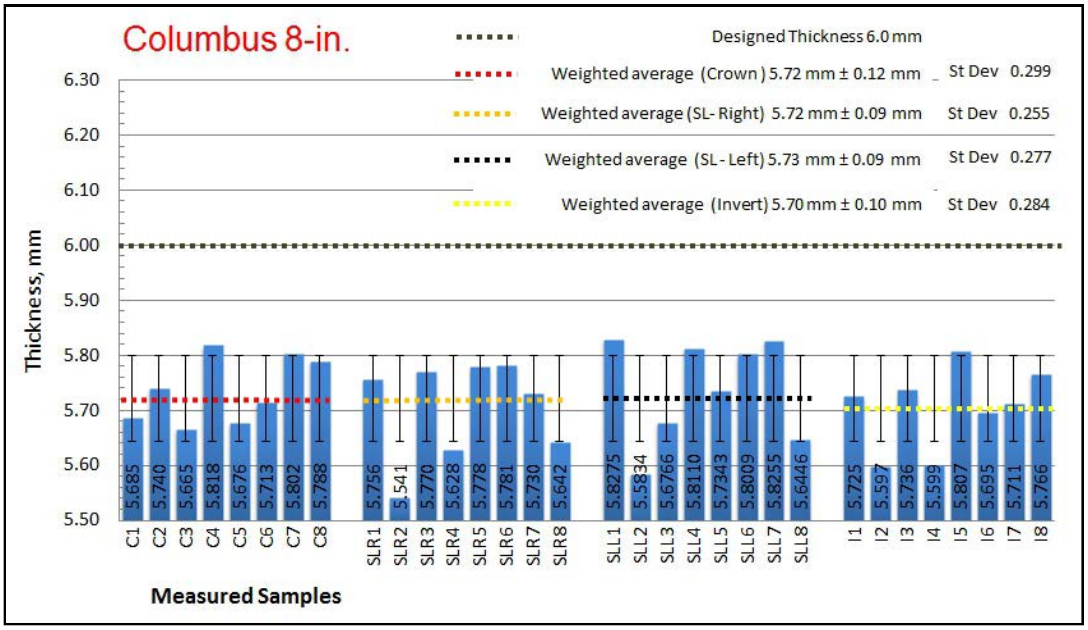


Figure 5-8. Average Thickness at Different Locations (Columbus 8-in. Liner)

5.2.10 Specific Gravity and Porosity. Measurements of density and porosity of a sample from this liner specimen were made by TTC and by Micrometrics Analytical Services. The TTC result for specific gravity (based on testing of 7 samples) was 1.11 ± 0.94. In the Micrometrics testing (using mercury penetration for the porosity determination), the bulk density (at 0.54 psia) was 1.1739 g/mL, the apparent (skeletal) density was 1.2782 g/mL, and the porosity was 8.163%. The full test report is provided in Appendix C and the specific gravity results across all samples are compared and discussed in Section 6.

5.2.11 Ovality. A profile plotter (Figure 5-9) developed at TTC was used to obtain a profile of the interior of the liner to be tested for buckling under external pressure. This profiling system is equipped with an LVDT rotating a full circle in one and one-half minutes. The voltage reading changes as the tip of the LVDT moves axially and those readings were collected using an HP 34970A DAQ. Later, the data was processed to obtain the actual profile of the liner's inside circumference. Before profiling, the pipe and profile plotter were positioned horizontally (Figure 5-10) and aligned. Figure 5-11 shows the plotted circumferential profile of the liner.

Figure 5-9. Electronic Level Used to Position Horizontally the Pipe (Left) and the Profile Plotter (Right)

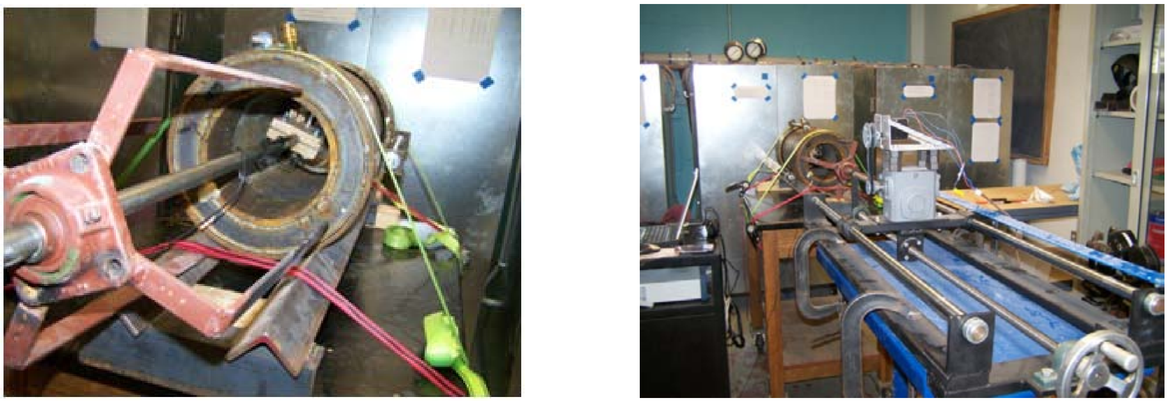


Figure 5-10. Profile Plotting with LVDT Rotating on the Inner Circumference: Close Up (Left) and Complete View (Right)

Profiling was performed before and after the buckling test. The profile plotter was not used during the test due to the risk of water leakage and/or sudden failure that might damage the LVDT.

Figure 5-11 compares the pre-buckling and post-buckling profile plots. From the pre-buckling profile plot, it can be seen that the liner did not follow a perfect circular shape. The liner had several irregularities that probably matched irregularities in the original host pipe with the largest excursion (nearly a quarter inch outwards) from a circular shape occurring at the invert of the liner. The ovality of the liner calculated in accordance with ASTM F1216 was 7.4%. It should be noted that for the buckling test (described in Section 5.1.15), the liner was inserted and sealed within a circular steel pipe.

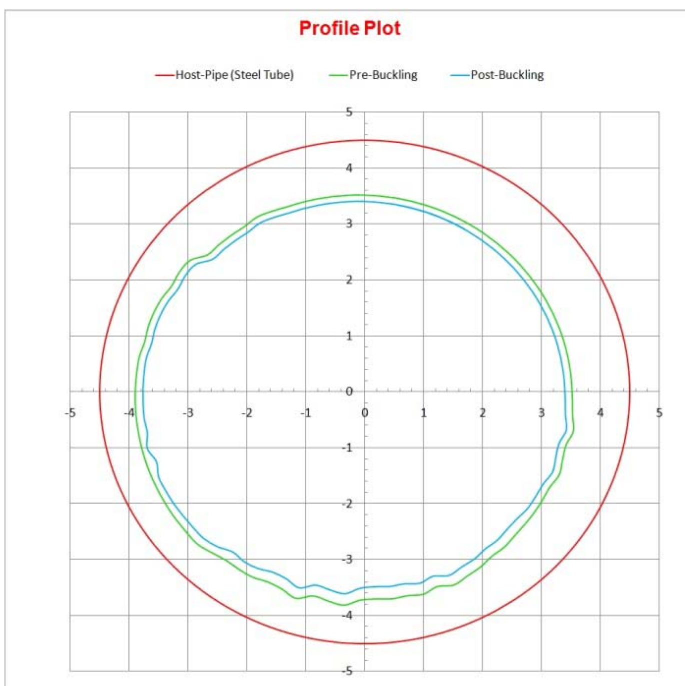


Figure 5-11. Profile Plot of Steel Host Pipe and Liner Before and After the Buckling Test (Columbus 8-in. Liner)

5.2.12 Flexural Testing. Specimens with a geometry described in ASTM D790 were cut from the crown, spring line, and invert of the retrieved CIPP liner for measuring the liner's flexural strength and flexural modulus elasticity. A total of 15 specimens were prepared and tested (five from each location). The sides of specimens were smoothed using a grinder and a table router. The water jet cutter normally used for specimen preparation could not be used in this case as the dimensions of the liner cutouts were too small to hold inside the cutting board. The specimens were marked as shown in Figure 5-12. Testing was performed using an ADMET eXpart 2611 machine (Figure 5-13). Table 5-7 lists the dimensions and moment of inertia for each of the 15 specimens.

Using the information in Table 5-7, the following flexural stress and strain graphs for crown samples, spring line samples, and invert samples were drawn and are shown in Figure 5-14.

Peak load, bending stresses, and deflections were obtained from the calculated data while the software 'MtestW' was used to calculate the peak shear stress and bending modulus of elasticity values for the different specimens. These values are given in Table 5-8.

Figure 5-12. Flexural Test Specimens (ASTM D790): Before Test (Left) and After Test (Right)

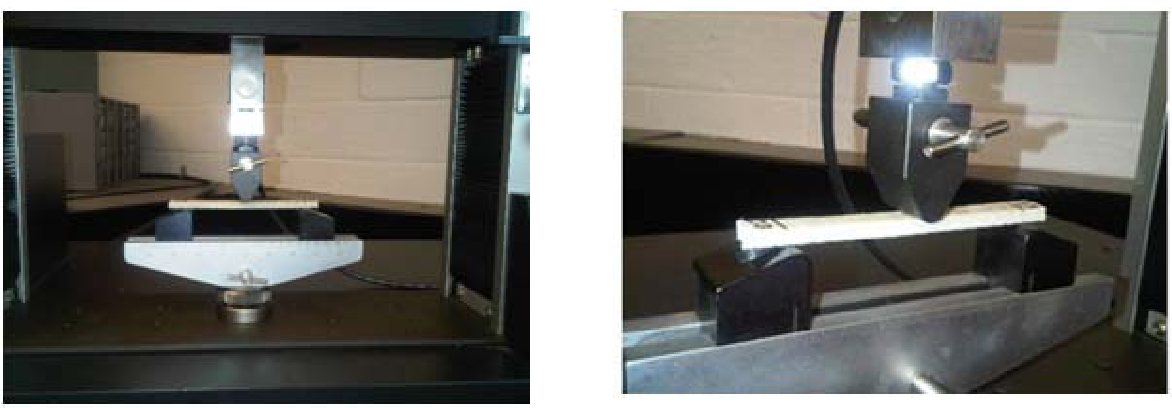


Figure 5-13. Flexural Testing in Accordance with ASTM D790

Table 5-7. Geometric Data for Flexural Test Specimens for Columbus 8-in. Liner

Location on Pipe	Span (in.)	Dimension		Moment of Inertia (in.^{4})
		W (in.)	D (in.)	
Crown 1	4	0.429	0.244	0.0005193
Crown 2	4	0.5043	0.2117	0.0003987
Crown 3	4	0.525	0.222	0.0004787
Crown 4	4	0.4777	0.2147	0.0003940
Crown 5	4	0.4337	0.2067	0.0003192
Spring line 1	4	0.506	0.2117	0.0004001
Spring line 2	4	0.527	0.2763	0.0009263
Spring line 3	4	0.5147	0.27	0.0008442
Spring line 4	4	0.4933	0.219	0.0004318
Spring line 5	4	0.5057	0.212	0.0004015
Invert 1	4	0.4723	0.2177	0.0004061
Invert 2	4	0.441	0.2173	0.0003771
Invert 3	4	0.462	0.2167	0.0003918
Invert 4	4	0.4437	0.2197	0.0003921
Invert 5	4	0.4747	0.224	0.0004446

Table 5-8. Flexural Test Results for Columbus 8-in. Liner

Location on Pipe	Peak load (lb)	Peak Bending Stress (psi)	Peak Shear Stress (psi)	Flexural Modulus (psi)
Crown 1	23.69	9,019	213	403,627
Crown 2	22.41	8,815	207	388,943
Crown 3	26.89	8,432	247	397,758
Crown 4	23.2	5,509	222	331,615
Crown 5	18.5	4,218	180	310,870
Average	-	**7,199±2190**	**214±24**	**366,563±42,340**
SL 1	21.63	7,284	122	311,381
SL 2	38.93	8,224	251	345,226
SL 3	36.01	8,769	247	417,900
SL 4	22.18	3,759	205	266,013
SL 5	23.22	4,074	217	300,069
Average	-	**6,422±2351**	**208±52**	**328,118±57,614**
Invert 1	23.93	6,702	220	355,290
Invert 2	21.17	6,575	168	375,527
Invert 3	18.78	7,106	190	403,380
Invert 4	20.45	4,273	199	304,084
Invert 5	23.49	3,478	235	279,070
Average	-	**5,627±1635**	**202±26**	**343,470±51,125**
Overall average	-	**6,416±2038**	**208±34**	**346,050±49,748**

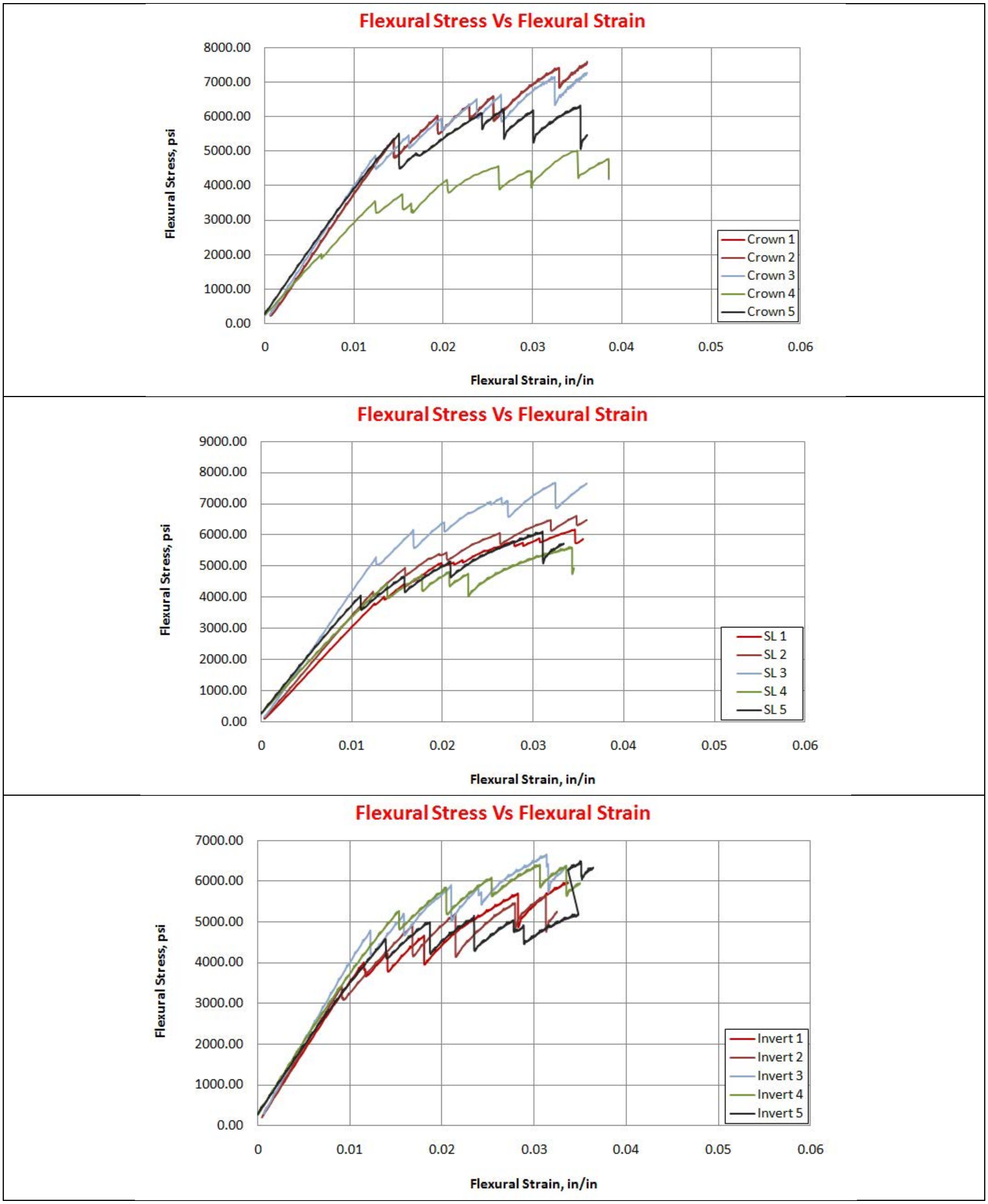


Figure 5-14. Flexural Stress-Strain Curves for Crown, Spring Line, and Invert Samples (Columbus 8-in. Liner)

5.2.13 Tensile Testing. Specimens with dimensions consistent with the values provided by ASTM D638 were cut from the crown, spring line, and invert of the exhumed CIPP liner as shown in Figure 5-15. A total of 15 specimens were prepared and tested (five from each location).

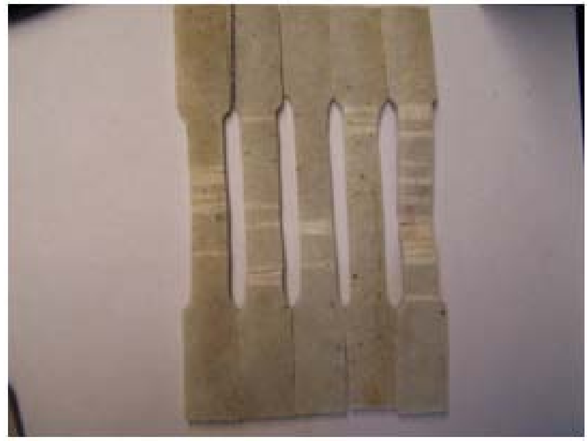


Figure 5-15. Tensile Specimens for Columbus 8-in. Liner: Before the Test (Left) and Following the Test (Right)

Using the information given in Table 5-9, the following figures were drawn: Stress-strain curves for crown samples, spring line samples, and invert samples (Figure 5-16).

Table 5-9. Summary of Results from Tensile Testing for Columbus 8-in. Liner

Location on Pipe	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Mod. E (psi)
Crown 1	0.1309	580	4,430	414,243
Crown 2	0.1462	545	3,730	341,317
Crown 3	0.1258	544	4,325	432,060
Crown 4	0.1346	497	3,694	465,690
Crown 5	0.1338	525	3,920	369,896
Average	-	-	**4,020±340**	**404,641±49,467**
Spring Line 1	0.1401	459	3,274	327,792
Spring Line 2	0.1720	644	3,747	348,035
Spring Line 3	0.1651	763	4,619	362,158
Spring Line 4	0.1612	581	3,607	328,744
Spring Line 5	0.1753	567	3,233	327,516
Average	-	-	**3,696±560**	**338,849±15,656**
Invert 1	0.1273	516	4,051	341,223
Invert 2	0.1318	474	3,597	301,994
Invert 3	0.1352	556	4,114	353,743
Invert 4	0.1346	455	3,383	359,622
Invert 5	0.1318	563	4,265	364,794
Average	-	-	**3,882±374**	**344,275±25,215**
Overall average	-	-	**3,866±426**	**362,588±43,629**

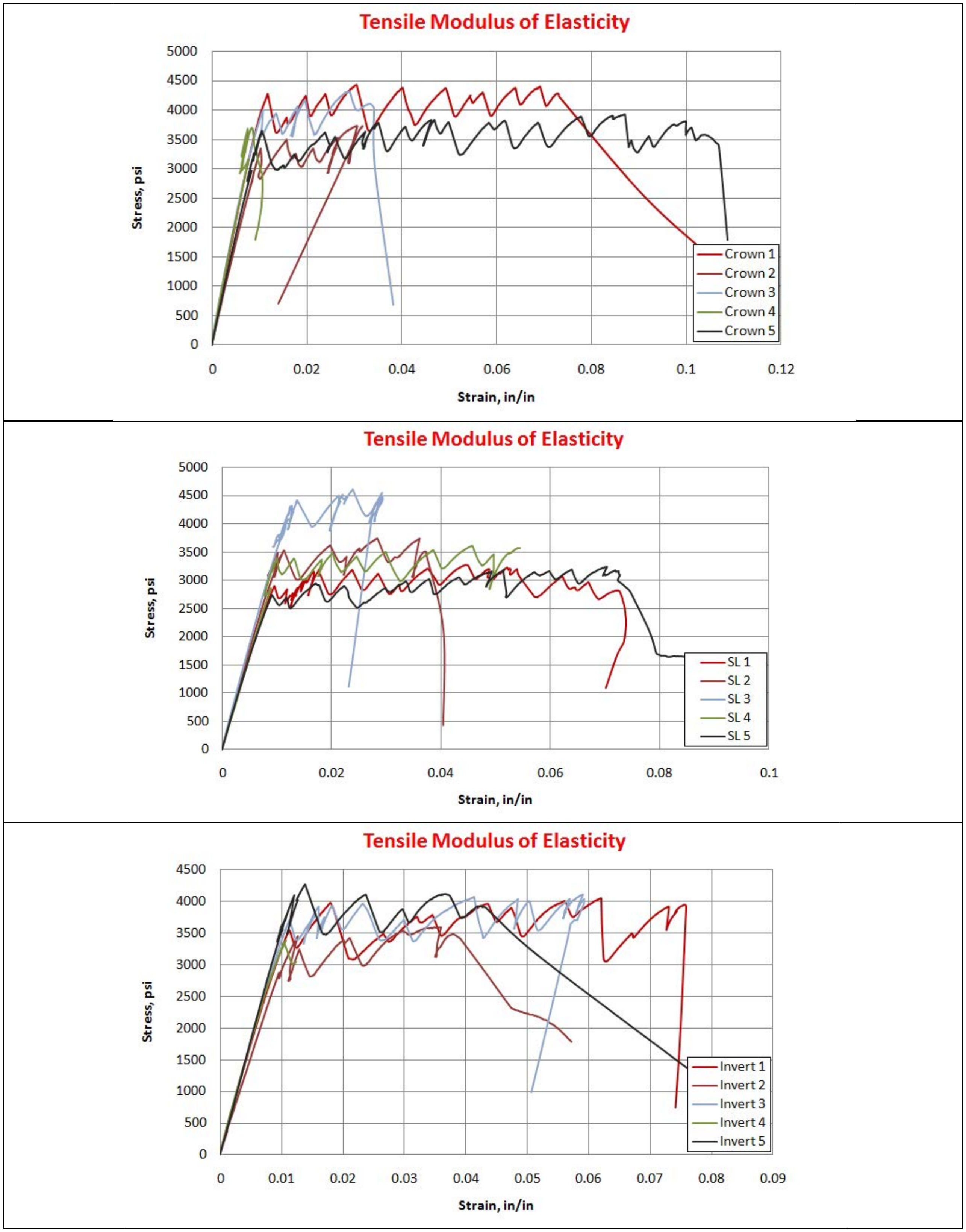


Figure 5-16. Tensile Stress-Strain Curves for Crown, Spring Line and Invert (Columbus 8-in.)

5.2.14 Comparison of Measured Values and QC Sample/Design Values. Table 5-10 presents the results for ASTM D790 and ASTM 638 testing of the 8 in. Columbus CIPP liner performed immediately following the installation (5 years earlier) by DLZ Ohio, Inc. The QA sample showed a finished thickness of 7.5 mm, compared with an average of 5.72 mm measured in this study and a design value of 6.0 mm. One possible explanation for the difference between the two measurements is that the original QA sample was taken at the upstream end of a long CIPP run, while the exhumed section came from the downstream end on a relatively steep slope (approximately 8%), which could result in stretching and subsequent thinning of the liner. Another potential explanation is that the QA sample is typically prepared by curing an extension of the liner within the manhole. This does not have the same installation and curing conditions as within the sewer line itself and such samples are generally expected to have higher test results than coupons cut from within the sewer.

Table 5-11 presents the results for ASTM D790 and ASTM D638 testing of the exhumed section of the same liner measured by TTC. The overall flexural strength of the liner (6,416 ± 2,038 psi) was found to be well above the design value of 4,500 psi, but lower than the value reported by DLZ in 2005 (7,264 ± 500 psi). The modulus of elasticity of the specimens taken from the exhumed liner was found in all cases to exceed the design value of 250,000 psi by a significant margin (see Table 5-11) with an average modulus of 346,050 ± 49,748 psi. The flexural strength and the flexural modulus of the specimens taken from the spring line and invert of the liner were found to be below the respective values at the crown. The flexural strength of the exhumed liner is 12% below the value reported for the as-installed liner. Likewise, the flexural modulus of the exhumed liner is 25% below the value reported for the as-installed liner. These values may be expected to have some differences because the as-installed samples are not taken from the liner run itself, but rather from an extended portion of the liner within a manhole. The variation of data across all the retrospective specimens is examined further in Section 6.

Table 5-10. Test Data from 2005 CIPP (as-installed) Sample (Columbus 8-in. Liner)

Property	No. of Samples	Test Standard	Test Value Mean +/- Std Dev.	Minimum Specification
Flexural Strength	5	ASTM D790	7,264+/- 500 psi	4,500 psi
Flexural Modulus of Elasticity	5	ASTM D638	464,652 +/- 30,000 psi	250,000 psi

Table 5-11. Summary of 2010 Retrospective Data (Columbus 8-in. Liner)

Location	Property	No. of Samples	Test Standard	Test Value Mean +/- Std Dev.
Crown	Flexural strength	5	ASTM D790	7,199 ± 2,190
	Modulus of elasticity	5	ASTM D638	366,563 ± 42,340
Spring line	Flexural strength	5	ASTM D790	6,422 ± 2,351
	Modulus of elasticity	5	ASTM D638	328,118 ± 57,614
Invert	Flexural strength	5	ASTM D790	5,627 ± 1,635
	Modulus of elasticity	5	ASTM D638	343,470 ± 51,125
Overall average	Flexural strength	15	ASTM D790	6,416 ± 2,038
	Modulus of elasticity	15	ASTM D638	346,050 ± 49,748

5.2.15 Buckling Test. A mechanical steel tube served as the host pipe for the exhumed liner. The tube was 2 ft long and 9.0 in. inner diameter (ID), to accommodate the ovality and curvature of the liner. Two 3/8 in. threaded holes were made on the opposite sides of the mechanical tube, and quick connectors were fixed to the pipe through the holes to allow attaching the pressure system. Two specially designed, open-ended, conical steel caps (Figure 5-17) were fabricated to keep the annular space between the inner wall of the pipe and the outer wall of the liner uniform and sealed. Effective sealing of the annulus under elevated internal annular pressure was essential during the test while the interior of the liner was frequently accessed for observation of liner deformation.

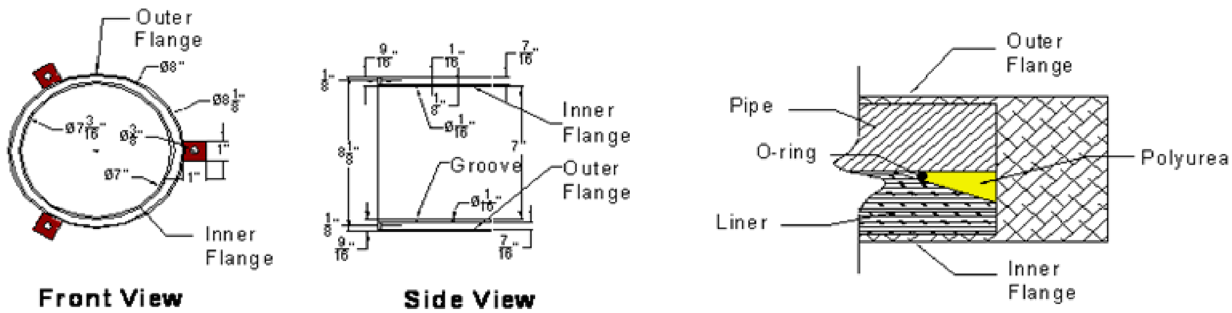


Figure 5-17. Drawing of the Pressure Cap Used

The liner was centered inside the tube and a special sealant was poured between the host pipe and cap (Figure 5-18). The caps were pressed against each end of the pipe specimen using three threaded rods (Figure 5-19).

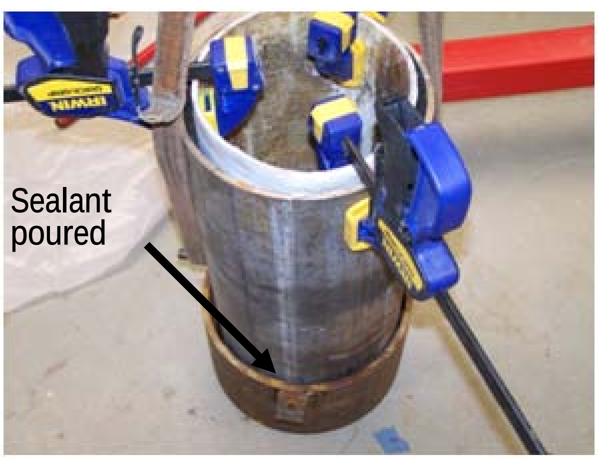


Figure 5-18. Placement of Liner Inside the Host Pipe

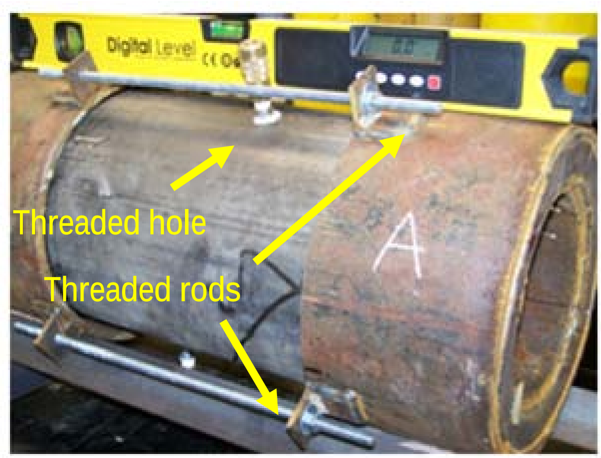


Figure 5-19. Experimental Setup

A high pressure pump system (Figure 5-20) was used to generate the needed water pressure, which was applied through a quick connector. A second quick connector was used as an access port for the gauges utilized for monitoring the pressure in the annulus during the test (Figure 5-21).

Once the setup was completed, the buckling test commenced (Figure 5-22). The liner held a pressure of over 50 psi (corresponding to around 115 ft depth of immersion in water) for nearly 15 minutes (Figure 5-23). Leakage of water was observed through the liner material on the inner wall of the CIPP liner. These leaks suggest the presence of some migration paths though the resin matrix (Figure 5-24) at this elevated pressure. The cross-sectional profile of the liner before and after buckling is shown in Figure 5-11.

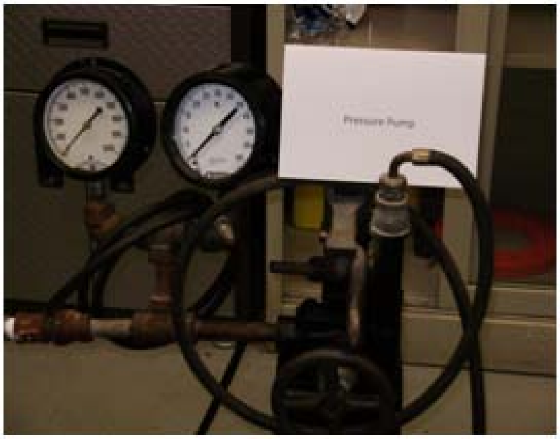


Figure 5-20. High Pressure Pump

Figure 5-21. Pressure Gauges Connected on the Tube

Figure 5-22. Pressure on the Liner During Buckling Test

Figure 5-23. Pressure Gauge Showing Pressure of 40 psi Applied on the Liner

Figure 5-24. Localized Leak on the Liner – Green Spots Due to Green Food Color

5.2.16 Shore D Hardness. The Durometer (Shore D) hardness test (ASTM D2240) 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. Specimens measuring approximately 1 in. × 1 in. were cut from the crown, spring line, and invert of the retrieved CIPP liner using a band saw. A total of 24 specimens were prepared and tested (eight from each location).

All tests were performed using the Shore D hardness scale, which utilizes a weight of 10 lb (4,536 g) and a tip diameter of 0.1 mm. Tests were conducted on the inner and outer surfaces and a total of 1,440 readings were performed on samples taken from all of the locations. The recorded values are shown in Figure 5-25. As was noted in the Denver studies, it can be seen that the inner surface readings are approximately 23% softer (63.3, 62.3, and 62.4) compared with outer surfaces of the liner (79.5, 81.7, and 83.0). However, it is difficult to separate any effects of exposure to the waste stream from differences due to the presence of the interior surface coating.

5.2.17 Barcol Hardness. Specimens were also subjected to the Barcol hardness test (ASTM D2583) as described for the Denver samples in Section 4. The results of the Barcol hardness testing for this liner are shown in Figure 5-26. The values (average of 6.77 for the inner surface and 13.76 for the outer surface) are much lower than for the equivalent testing for the Denver samples. For the inner surface, this may be a result of the different coating material used in recent liners than was used in the earlier liners retrieved from the Denver sites. Differences of similar magnitude are not seen in the Shore D hardness values between the Columbus and Denver 8-in. liners. While there is no correlation between these two hardness measurements methods, Barcol hardness is the more commonly utilized method in the CIPP industry. The Barcol hardness values for the 5-year old Columbus 8-in. liner show little difference between the inner and outer surfaces or between the invert readings and the crown readings. This may be due to the relatively short exposure of the liner to service conditions.

Figure 5-25. Shore D Hardness Readings on Inner and Outer Surfaces (Columbus 8-in. Liner)

Figure 5-26. Barcol Hardness Readings on Inner and Outer Surfaces (Columbus 8-in. Liner)

5.2.18 Raman Spectroscopy. The Raman spectroscopy plots for the Columbus 8-in. liner sample are shown in Figure 5-27. Plots are shown for the virgin resin, and several locations on the inside and outside liner surfaces. There is one clear difference in the presence of peaks between the base resin samples and the exhumed specimens, which was not seen in the Denver samples. A discussion of the possibilities for using Raman spectroscopy for liner evaluation is given in Section 6.

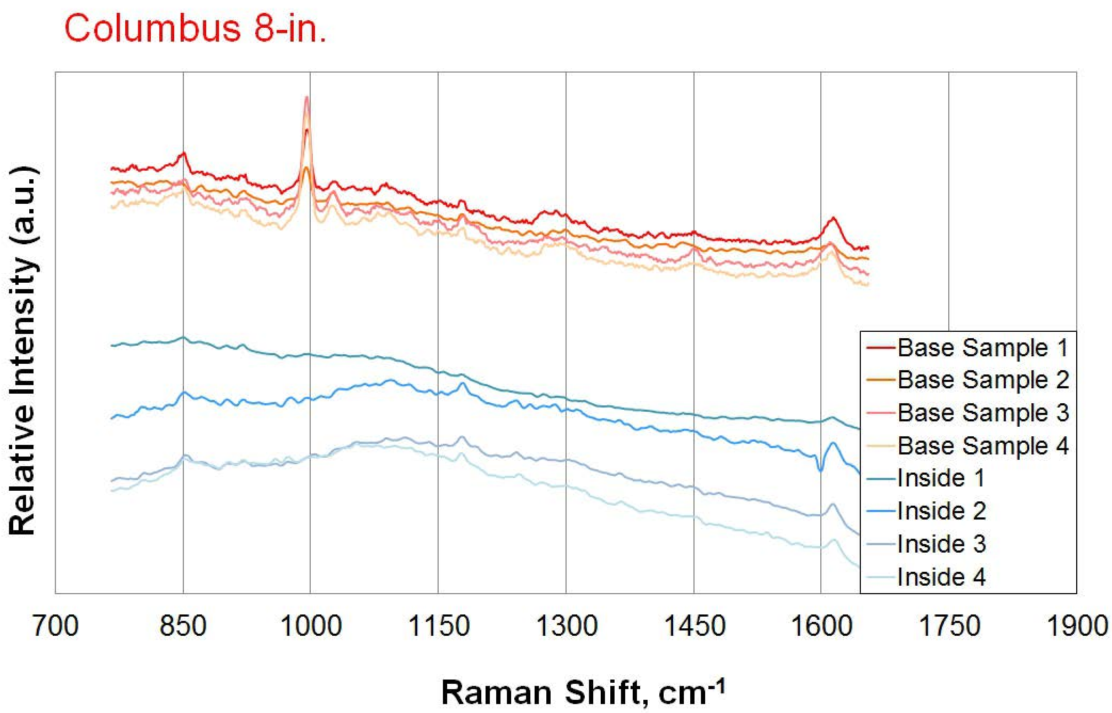


Figure 5-27. Raman Spectra for the Columbus 8-in. Liner

5.3 Site 2: 36-in. Brick Sewer

5.3.1 Host Pipe and Liner Information. The CIPP liner sample tested was exhumed from a 36-in. brick sewer pipe in Columbus, OH, which was installed in 1868 and relined with a CIPP liner in 1989 under an emergency modification to Project No. 710404.2 carried out by the City of Columbus, Department of Public Utilities, Division of Sewerage and Drainage. The original contract work involved 227 ft of CIPP lining of an adjacent 24 in. diameter pipeline 14.5 ft deep with 15 mm thick Insitutube. The emergency modification included the installation of 98 ft of inversion-installed polyester resin lining in the sewer at Gay Street. The liner thickness was unknown, but it was assumed to be similar to the adjacent 24 in. project. The CIPP-repaired section lies under a two-way, two lane road; it is a curved section that extends from the south side of Gay Street and turns north on Pearl Street. The contractor for the CIPP repair was Insituform East. No material testing was specified in the original contract or in the emergency modification.

5.3.2 Sample Recovery. On-site personnel were present from the City of Columbus, Battelle, Jason Consulting, and Reynolds Inliner, Inc. The Reynolds personnel entered the pipeline, cut out a 52 in. × 24 in. rectangular sample (Figure 5-28) and prepared it for shipment. The sample was collected from approximately 2 ft upstream (south) of the access manhole (MH 0003C0008) at the 1 to 4 o'clock position approximately 2 in. above the flow line.

5.3.3 Visual Inspection of Liner. Images of the recovered specimen are shown in Figures 5-29 and 5-30. A visual inspection found the CIPP liner to be in good condition. The polymeric film (polyurethane) was essentially hydrolyzed except for the area where the seam was sealed. This is expected as the polyurethane was added as a sacrificial layer for confining the resin during the installation and curing process. The surface when rubbed clean of debris had a "fibrous finish". This also is to be expected as the polyester fibers that were formerly embedded in the polyurethane are now exposed.

Figure 5-28. Cutting Out the Columbus 36-in. Liner Sample

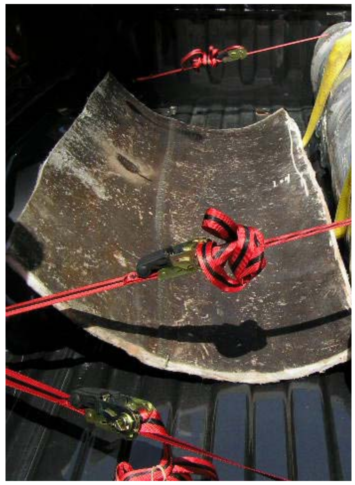


Figure 5-29. The Exhumed Sample, 24-in. × 52-in. (Columbus 36-in. Liner)

Figure 5-30. Images of the Recovered Columbus 36-in. Specimen

The outer surface of extracted sample mirrored the surface of the brick sewer in which it was installed. After removing the sample, some evidence of resin migration into the mortar joints was noticed. The CIPP did not appear to be chemically bonded to the sewer wall; in fact, a portion of the sample area had a compressed "clay-like" material on its surface, which would have prevented any such bonding. The mechanical bonding, however, was very good. The liner appeared to be positioned tight against the host pipe up to approximately the 11:00 o'clock position where an annulus began forming. Sounding the top of the CIPP indicated that this annulus continued around to the 1:00 o'clock position. This could be possibly attributable to an inadequate amount of head applied during the inversion process or inadequate cooling of the liner.

5.3.4 Wastewater Analysis. Retrieved wastewater samples were tested by American Analytical Laboratories, Inc., on April 14, 2010, in accordance with EPA Test Methods. EPA Method 150.1 was used to determine the pH of the samples. EPA Method 8015 was used to determine the DRO and GRO concentrations to test for the presence of petroleum hydrocarbons. The results are listed in Table 5-12. The pH value measured (7.54) is indicative of typical residential sewage. The wastewater analysis suggests that the wastewater stream has characteristics typical to residential areas, and no abnormal pH value or hydrocarbon concentrations were measured.

Table 5-12. Results of Wastewater Analysis for Columbus 36-in. Liner

Sample ID	pH	DRO (mg/L)	GRO (mg/L)
Pearl 36	7.54	1.99	34.3

5.3.5 Annular Gap. A feeler gauge was used to measure the annular space around the perimeter where the sample was removed. The liner appeared to be very tight along the sides and bottom of the sample and a spacing greater than 0.127 mm was measured at only three locations (see Figure 5-31) – all along the top side of the sample removal area (see note on crown annulus gap in Section 5.3.3). The end measurements shown in Figure 5-31 were taken at approximately 4 in. from each end of the cutout and the middle measurement was taken at its center. Since the liner sample was removed from the host pipe, no laboratory annular space measurements were possible.

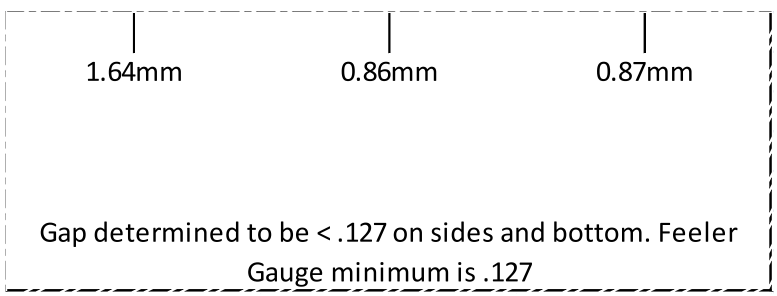


Figure 5-31. Annular Space Measurements Around the Sample Removal Area (Columbus 36-in. Liner)

5.3.6 Liner Thickness

5.3.6.1 Ultrasound Testing. An ultrasonic meter (Olympus 37DL Plus) with a 2.25 MHz contact transducer was utilized in the field in an attempt to measure the thickness of the CIPP liner (Figure 5-32). However, the ultrasound testing for thickness did not produce any readings (apparently due to the thickness of this liner). This issue is discussed further in Section 6.

5.3.6.2 Field Measurements. Caliper measurements of the exhumed liner thickness were recorded around the edges of the extracted sample in the field as shown in Figure 5-33. The liner thickness measurements taken in the field are shown in Figure 5-34. The average thickness for the sample was calculated to be 14.2 mm and standard deviation was 1.5 mm. The original design thickness was not known, but it was assumed to be 15 mm (i.e., the same as the liner used for the adjacent line).

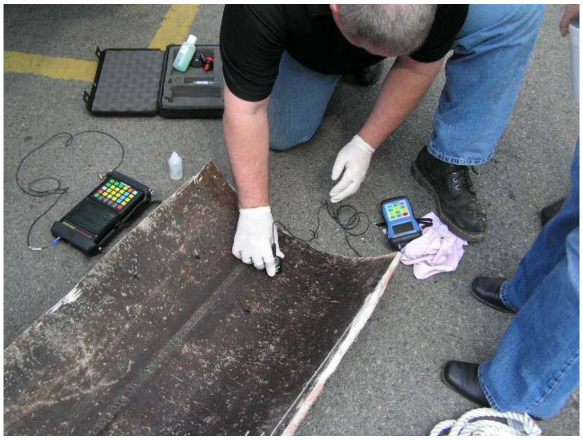


Figure 5-32. Ultrasonic Testing for Measuring Liner Thickness in the Field

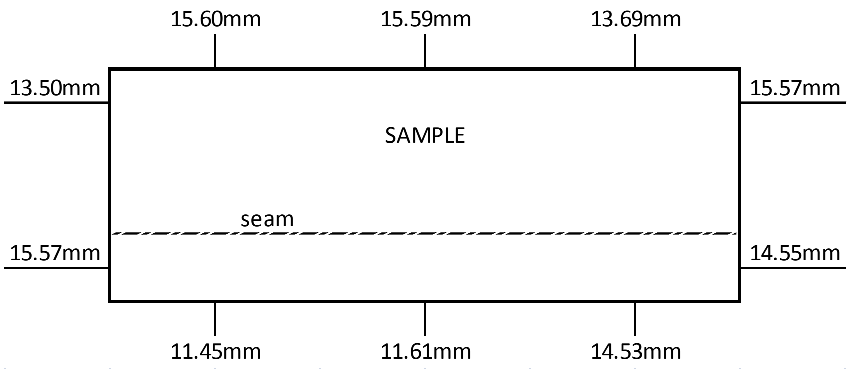


Figure 5-33. Caliper Measurements of Columbus 36-in. Sample

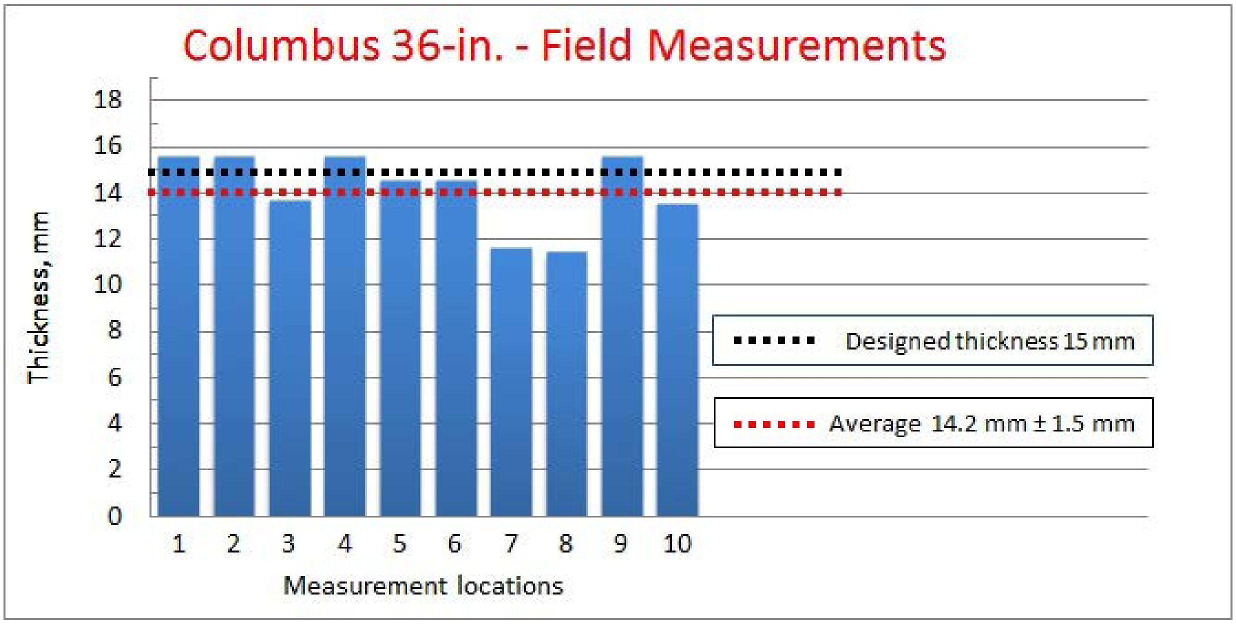


Figure 5-34. Field Measurements of Thickness for Columbus 36-in. Liner

5.3.6.3 Laboratory Measurements. For determining the liner thickness in the laboratory, specimens cut out from the liner sample for the ASTM tensile and flexural tests were used. Six specimens were used and five readings were taken for each of the specimens using a micrometer. The average calculated values and their standard deviations are shown in Figure 5-35. The original design thickness stated in the figure was not known, but it was assumed to be 15 mm based on the thickness used for the adjacent liner. The weighted average for the sample thickness measurements was calculated to be 11.9 mm and the weighted error ±0.3 mm. The laboratory measured values were 16% lower than the field measured values.

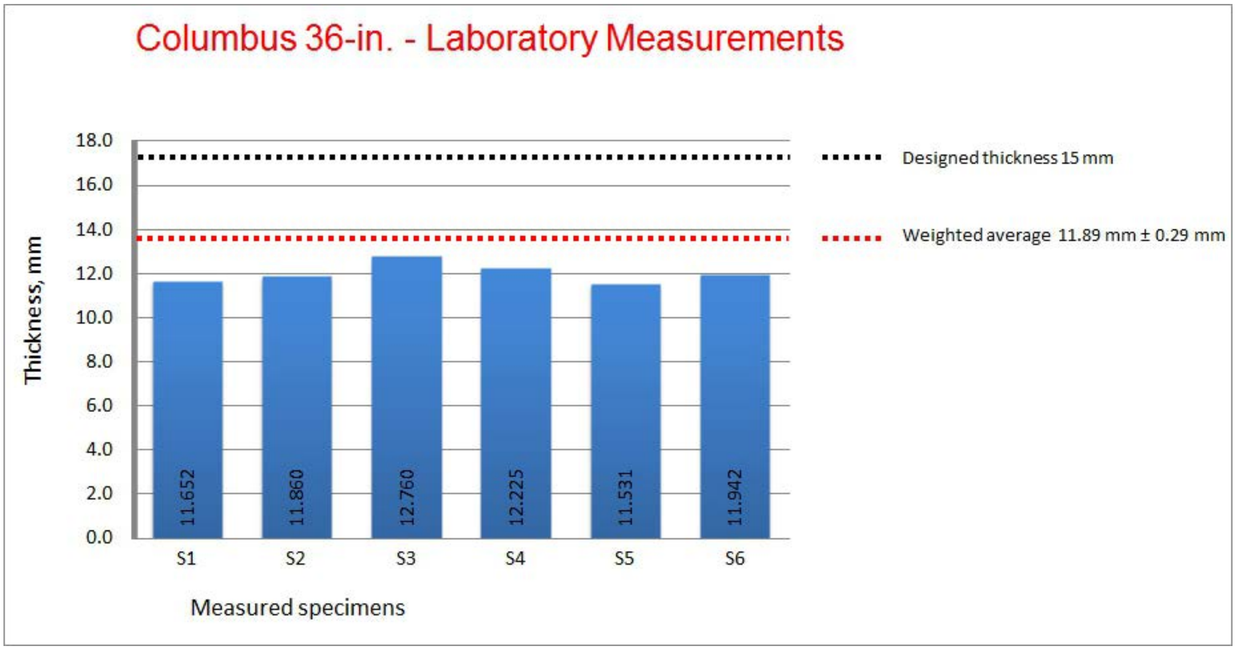


Figure 5-35. Laboratory Measurements of Thickness for the Columbus 36-in. Liner

5.3.7 Specific Gravity and Porosity. Seven specimens from the downstream sample were used to determine the specific gravity of the liner. The average specific gravity for the sample was calculated to be 1.17 with a standard deviation of 0.06.

Measurements of density and porosity of a sample from this liner specimen were made by Micrometrics Analytical Services. In their testing (using mercury penetration for the porosity determination), the bulk density (at 0.54 psia) was 1.0884 g/mL, the apparent (skeletal) density was 1.3233 g/mL, and the porosity was 17.752%. The full test report is provided in Appendix C and a discussion of the specific gravity across all the retrospective site samples is provided in Section 6.

5.3.8 Flexural Testing. Specimen cutting and preparation for testing in accordance with ASTM D790 follows the procedures described for the other liner specimens. Table 5-13 shows the dimensions and moment of inertia for the specimens.

Using the information in Table 5-13, the flexural stress and strain data for all samples was drawn (Figure 5-36). Peak load, peak shear stress, and flexural modulus values for each specimen, obtained using the software ‘MtestW’, are listed in Table 5-14.

Table 5-13. Geometric Data for Flexural Test Specimens for Columbus 36-in. Liner

Sample ID	Span (in.)	Dimension		Moment of inertia of Area (in.^{4})
		W (in.)	D (in.)	
1	4	0.542	0.504	0.005782
2	4	0.527	0.518	0.005262
3	4	0.506	0.518	0.005861
4	4	0.489	0.519	0.005697
5	4	0.486	0.530	0.006030

Table 5-14. Flexural Test Results for Columbus 36-in. Liner

Sample	Peak load (lb)	Peak bending stress (psi)	Peak shear stress (psi)	Flexural modulus (psi)
1	136.59	5,965	500	204,315
2	127.88	6,004	492	202,844
3	124.63	5,515	475	169,527
4	133.84	6,084	527	206,182
5	151.07	6,626	587	251,159
Average	**-**	**6,039±396**	**516±43**	**206,805±29,065**

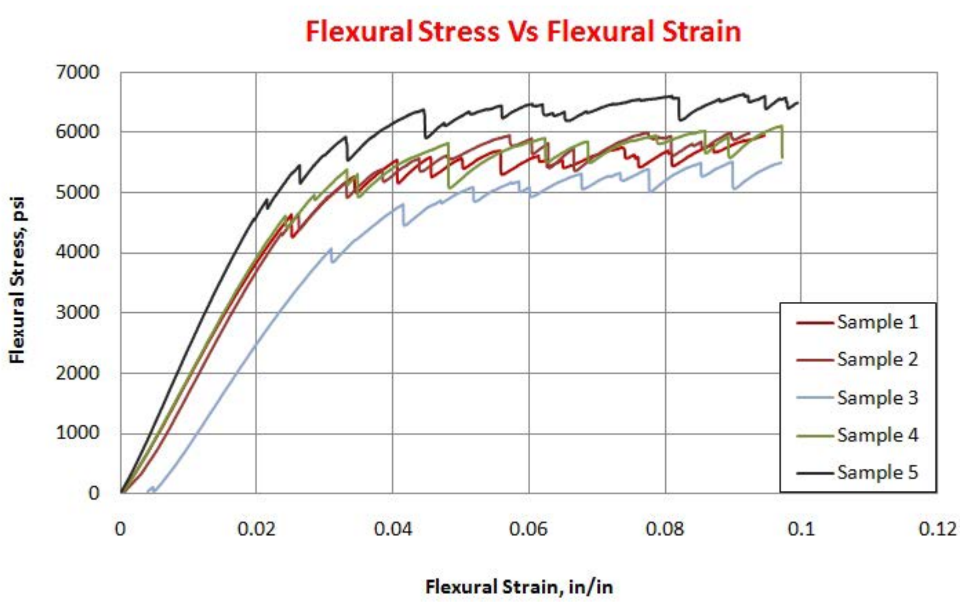


Figure 5-36. Flexural Stress-Strain Curves (Columbus 8-in. Liner)

5.3.9 Tensile Testing. Specimen cutting and preparation for testing in accordance with ASTM D638 followed the procedures described earlier for the other retrospective samples. Table 5-15 provides the results from tensile testing. Using the information given in Table 5-15, the tensile stress-strain curves for all samples were developed and are presented in Figure 5-37.

Table 5-15. Tensile Test Results for Columbus 36-in. Liner

Location on Pipe	Area ($in.^2$)	Peak Load (lb)	Peak Stress (psi)	Mod. E (psi)
1	0.3001	971.06	3,236	324,878
2	0.3043	948.33	3,116	301,645
3	0.3745	964.13	2,574	293,714
4	0.2808	814.85	2,902	375,324
5	0.3198	946.61	2,960	280734
Average	**-**	**-**	**2,958±251**	**315,259±42,504**

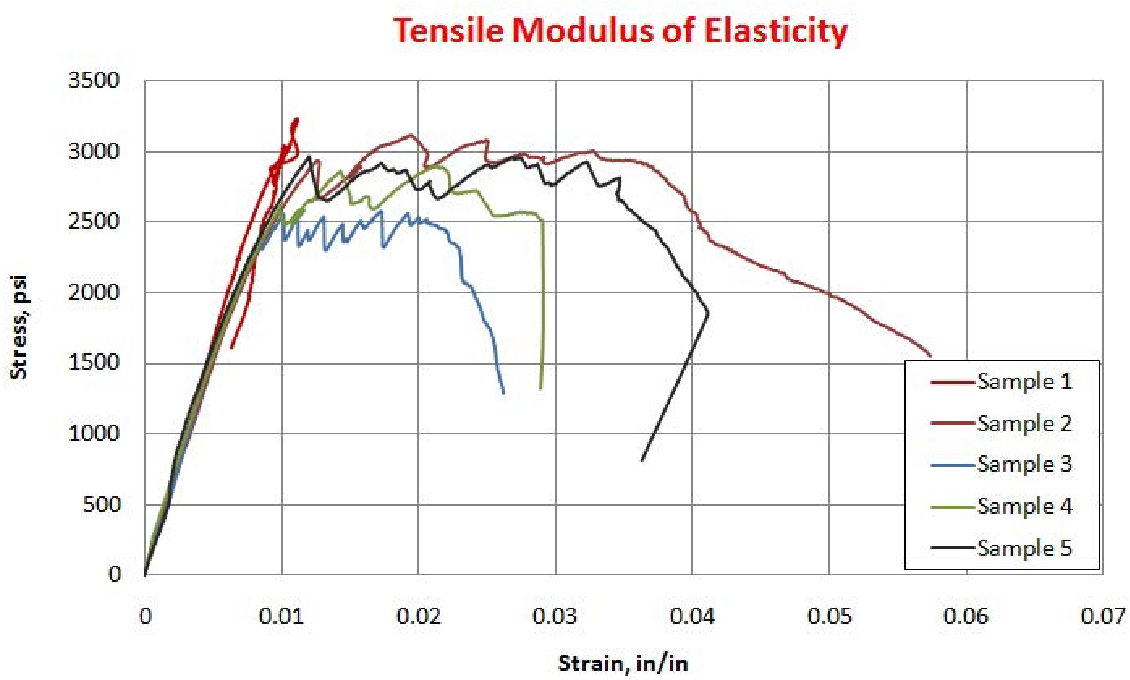


Figure 5-37. Tensile Stress-Strain Curves (Columbus 36-in. Liner)

5.3.10 Shore D Hardness. A total of six specimens measuring approximately 1 in. × 1 in. were prepared and tested using the Shore D hardness test. A total of 36 tests were conducted on each sample: 18 tests on the inner surfaces and 18 tests on the outer surfaces. The average calculated values and their standard deviations are shown in Figure 5-38. The weighted average of Shore D hardness for the sample inner surface was calculated to be 66±4, and for the outer surface 79±2.

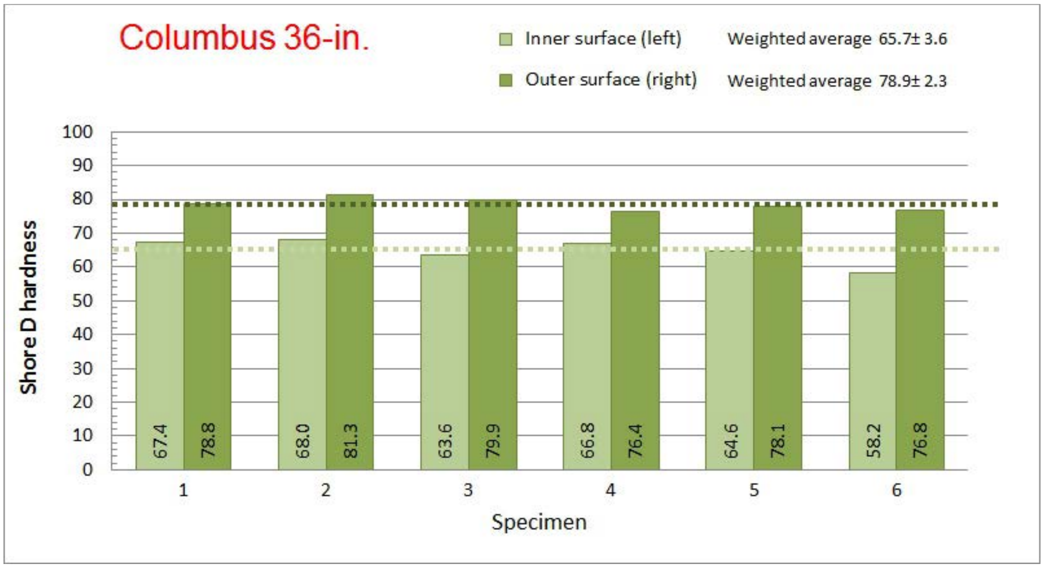


Figure 5-38. Shore D Hardness of Columbus 36-in. Liner Sample

The liner hardness was found to be medium to high on the Shore D hardness scale. For the Shore D test on this sample, the inner surface has an average hardness approximately 17% less than the outer liner surface.

5.3.11 Barcol Hardness. For each of 10 specimens, a total of 36 readings of Barcol hardness were taken: 18 on the outer surface and 18 on the inner surface. The average calculated values and their standard deviations are shown in Figure 5-39. The weighted average of Barcol hardness for the sample inner surface was calculated to be 18.9±2.2 and for the outer surface 22.3 ±2.0. As for most of the liners tested, the outer surface hardness is higher than for the inner surface. For the Barcol test on this sample, the inner surface has an average harness approximately 15% less than the outer surface.

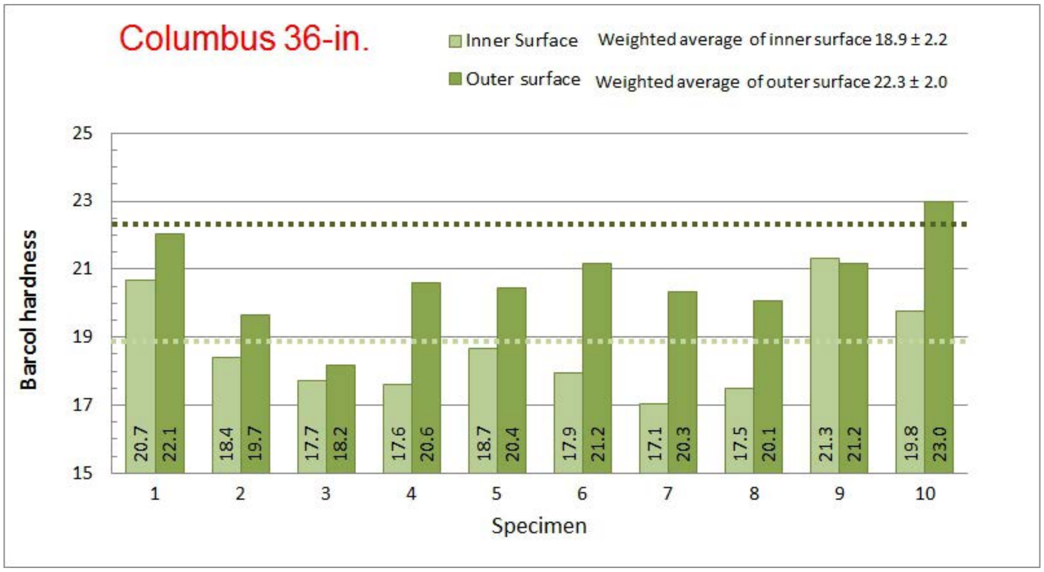


Figure 5-39. Barcol Hardness Readings on Inner and Outer Surfaces (Columbus 36-in. Liner)

5.3.12 Raman Spectroscopy. The Raman spectroscopy plots for the Columbus 36-in. liner sample are shown in Figure 5-40. Plots are shown for the virgin resin, and several locations on the inside and outside liner surfaces. There are no clear differences in the shapes of the curves or the presence of peaks between the base resin samples and the exhumed specimens. This is similar to the results from most of the retrospective liner samples. A discussion of the possibilities for using Raman spectroscopy for liner evaluation is given in Section 6.

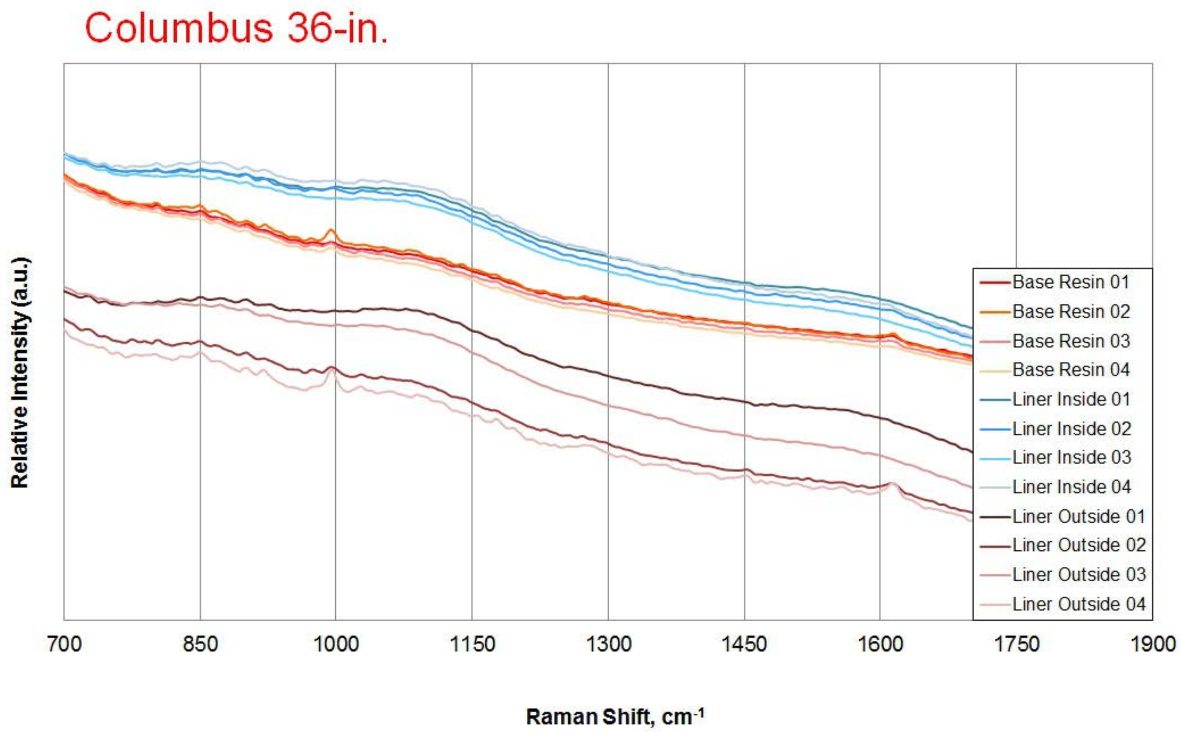


Figure 5-40. Raman Spectroscopy Plots (Columbus 36-in. Liner)

6.0: REVIEW AND COMPARISON ACROSS THE FOUR SITES

6.1 Introduction

This section reviews the series of tests that were carried out on the CIPP liners retrieved from the City of Denver and City of Columbus and compares the results across all four sites. This comparison allows observations to be made regarding the relative usefulness of the data in assessing the CIPP liner condition.

6.2 Summary for City of Denver Evaluations

Two significantly different CIPP liner installations were reviewed as part of this initial retrospective evaluation effort for the City of Denver. The sites were chosen for the detailed study on the basis of the age of the respective liners and to minimize the cost and disruption that would be incurred in retrieving physical samples.

For the 8-in. clay pipe in a residential area, the location was chosen to be able to sample a 25-year old CIPP liner and also to coincide with an alley pavement slab that needed to be replaced. The condition of the CIPP liner was found to be excellent with a minimal annular gap and excellent visual condition. The type of polyurethane inner layer used in early CIPP installations was found to have been hydrolyzed and eroded away in the invert and spring line areas of the liner but no significant additional erosion of the resin layer appeared to have occurred. CCTV inspection of the neighboring sewer lines that had been CIPP-lined during the same original project also revealed an overall excellent condition of the lining after 25 years in service. A modest number of defects were noted in the nearly 5,800 ft of sewer that was inspected. Most of the defects appeared to relate to poor restoration of lateral services or partial misalignment of the lateral opening with the lateral itself. Only two local defects were clearly not connected to lateral connection issues: a local liner bulge and a detachment of the liner from the wall of the host pipe.

The flexural and tensile test results on the 8-in. liner yielded values higher than the minimum values required at the time of installation 25 years earlier. In the TTC testing, the average flexural modulus was 335,340±18,186 psi, the average flexural strength 6,756±546 psi, and the average tensile strength 3,029±179 psi. These results are compared in Table 4-9 with similar testing carried out on the 2010 samples by Insituform, installer of the original liner. Some variations in measured values were presented, but all of the test results were satisfactory.

Although the short-term buckling test on a section of the retrieved liner had to be placed inside a surrogate host pipe for testing purposes and was shorter than desired to minimize end restraint effects during the testing, it did provide an excellent result. Despite some obvious distress to the liner at the high test pressures, the liner resisted 45 psi external pressure without buckling failure despite having a much larger annular space during the buckling test than existed in the field.

For the 48-in. brick sewer in a more commercial neighborhood, the retrieved samples were also in excellent condition. Samples had previously been retrieved from this same location in 1995 after 8 years of service and were tested again in this project after 23 years of service. The comparison was complicated by the fact that the two samples retrieved in 2010 came from each side of the manhole, in separate liner installations, whereas the single 1995 sample came only from one side of the manhole. Table 4-20 presented the comparison of test results for the three samples. The 1995 results show a flexural strength of 6,900±400 psi and tensile strength of 2,300±170 psi. The tests performed by TTC on the 2010 specimens reveal differences in the flexural strength (5,032±652, 6,117±888, and 7,031± 346 psi) and tensile strength (2,995±227psi and 3,208±222 psi) but quite acceptable values. The flexural strength in all three samples was above the ASTM value of 4,500 psi and the tensile strengths measured in 2010 were higher than those measured in 1995. However, the modulus of elasticity showed a wide variation among the three samples: 490,000±40,000 psi in 2005, 182,622±23,126 psi and 263,707±70,398 in the two sets of tests for one sample in 2010, and 302,960±24,303 psi from the other 2010 sample. All except the one set of tests are above the ASTM F1216 specified minimum value of 250,000 psi. Further discussion and comparisons among the different tested parameters are explored in Section 6.3.5.

For both CIPP liners, surface hardness measurements made on the internal and external surfaces of the CIPP liner did show some significant differences between the inner surfaces exposed to sewage flow (the invert and spring line areas) and the inner surface at the crown of the pipe and all the external locations tested. The differences were more noticeable in the Shore D hardness testing. It is difficult at this point to separate the effects of the loss of the sealing layer from any changes in the base resin but it is hoped that such surface hardness testing may represent a useful non-destructive means of assessing material changes in a CIPP liner. A next step would be to investigate changes in hardness with depth on the inner surface of CIPP liners of different ages and condition of exposure.

Overall, the liner samples tested from the City of Denver indicated that the liners are holding up well. One set of tests for one sample provided a low test value for the flexural modulus but the overall condition of the sample did not indicate that any particular distress was occurring and a repeated set of tests using different coupons cut from the same sample gave significantly higher results. Further interpretation of the liner test results across all the retrospective sites follows in Sections 6.3 and 6.4.

6.3 Summary for City of Columbus Evaluations

The City of Columbus also provided a large contrast in rehabilitation projects for evaluation. One site provided a 5-year old, 8-in. diameter CIPP liner for which a section of liner and host pipe could be retrieved easily due to existing plans for upsizing the line. The other site provided the opportunity to sample a 21-year old, 36-in. liner installed in a brick sewer dating from 1868.

The visual evaluations of both liners were excellent. For the older 36-in. liner, the inner coating layer was mostly hydrolyzed as in the Denver liners of similar age. For the 5-year old, 8-in. liner, the coating layer of PE was still intact and in good condition. The annular gaps measured were mostly very small but the 36-in. liner was found to have a larger annular gap at the crown although the width of this gap could not be measured. For both liners, the average liner thickness measured during this study was less than the design thickness. For the 8-in. liner, the liner thickness was found to vary slightly around the pipe cross-section.

The porosity of the 5-year old, 8-in. liner was significantly lower than that of the 21-year old, 36-in. liner and the variations of porosity and density across all sites is discussed in Section 6.4.4. The Raman spectroscopy data did not show any particular evidence of resin deterioration for the liners. Similar to the Denver liners, some differences in surface hardness between the inner and outer surface of both liners were noted, but it is not possible yet to separate out what impact the presence and/or impact of the surface layer has on this difference.

With regard to the flexural and tensile testing, the 8-in. liner met the original specifications for flexural strength and modulus, whereas the 36-in. liner met the strength but not the flexural modulus value. The correlations of liner properties among the various tests are explored in Section 6.3.5. Following similar test procedures as for the Denver 8-in. liner, the Columbus 8-in. liner also stood up very well in the buckling test carried out. It carried 50 psi (equivalent to 115 ft head of water) for 15 minutes without buckling although some leakage through the liner was noted during the test.

Overall, the liners appear to be holding up well despite the shortfall in thickness over the design thickness. The flexural modulus value for the 36-in. liner after 21 years of service was below the ASTM F1216 requirement for the original installation, but no visible signs of liner distress were observed.

6.4 Summary of Data and Observations for All Sites

6.4.1 Visual Observations. The observed visual condition of all of the liners retrieved was excellent. In the older liners, the older type of polyurethane coating (sealing layer) for the felt was eroded or missing in those areas regularly exposed to sewage flow. For the newer liner with a PE layer, this coating layer was still intact. The older form of coating was considered a sacrificial layer, but it has now been replaced by the major felt manufacturers with either a PE layer or a more durable form of polyurethane layer.

6.4.2 Annular Gap. Annular gap measurements were made with a feeler gauge for the Denver 8-in. liner, the Columbus 8-in. liner, and the Columbus 36-in. liner. Across all the sites, the annular gaps measured ranged between less than 0.13 mm and a maximum of 3.31 mm. For the Denver 8-in. liner, the average gap measurement was 0.9 mm. For the Columbus 8-in. liner, the gap measurements were well distributed in value and varied from 0.10 mm to 3.31 mm with an average value of 0.35 mm. For the Columbus 36-in. liner, the readings were mostly less than 0.127 mm, but with a maximum value of 1.64 mm. Sounding of the crown of the liner in situ in the Columbus 36-in. liner indicated that an annular gap did exist in this liner from around the 11 o'clock position to the 1 o'clock position. In general, the liners were still effectively tight against the host pipe. There was evidence of good mechanical interlock in the large diameter liners installed in the brick sewers, but there was no evidence of significant adhesion of the liner to the host pipe.

6.4.3 Liner Thickness. The liner thickness was measured at a large number of locations for all of the liners sampled. Measurements were carried out using a caliper, micrometer, and an ultrasonic thickness tester. The caliper and micrometer measurements are the main measurements discussed in this section and are provided in Table 6-1. The ultrasonic testing equipment did not work well on the liner field samples and testing into the cause of this issue is discussed in Appendix B.

Table 6-1. Summary of Thickness Measurements for All Samples

Measurement Set	Location	Caliper/ Micrometer Values (mm)	Values Measured by Others	Design Thickness (mm)
Denver 8-in.	Crown	5.98±0.07	-	6
	Spring line	5.93±0.11	-	
	Invert	5.91±0.09	-	
Denver 48-in. downstream	Crown	13.9±0.3	-	13.5
Denver 48-in. upstream	Crown	14.2±0.2	18	18
Columbus 8-in.	Crown	5.72±0.12	7.5	6
	Spring line	5.73±0.09		
	Invert	5.70±0.10		
Columbus 36-in. (field measurement)	Upper haunch	14.2±1.5	-	15*
Columbus 36-in. (laboratory measurement)		11.9±0.3	-	

*Original design thickness not known; assumed to be the same as the liner used for the adjacent line.

For the 8-in. liners, a small difference in thickness (1.2% variation) was measured between the crown and the invert in Denver and essentially no difference in thickness was measured in Columbus. The higher liner thicknesses occurred in the crown of the liner. This difference was interpreted to be due in large part to the loss of the polyurethane sealing layer (0.38 mm original thickness) in the lower portion of the Denver 8-in. liner, which if present, would have made the invert of the liner thicker than the crown. The average thickness value for the Denver 8-in. liner matched very closely to the design value even with the partial loss of the sealing layer. For the Columbus 8-in. sample, the average liner thickness (5.72 mm) measured during this study was approximately 4.6% less than the design thickness of 6.0 mm, but significantly less than the QA value of 7.5 mm measured during installation at the other end of the liner. In this case, since it was a relatively new liner, it had a PE inner layer that was still intact.

For the large diameter liners, the Denver 48-in. downstream sample exceeded the design thickness, but the Denver 48-in. upstream sample and the Columbus 36-in. sample both had thickness less than the recorded design value. There were also differences for the Columbus 36-in. liner between the values measured in the field with a caliper and the values measured later in the laboratory with a micrometer. A large number of separate readings were taken for each sample (see Sections 4 and 5 for the details).

The fact that 4 out of the 5 liners sampled did not meet the design thickness originally specified points to the need for good QA/QC procedures in preparations for CIPP lining and in the field procedures. A liner can become thinner than intended as a result of insufficient fabric thickness, insufficient resin, and inaccurate calibration of thickness during impregnation, higher than intended pressures during installation prior to curing, and/or stretching of the fabric at steep downhill sections of the host pipe.

6.4.4 Specific Gravity and Porosity. Table 6-2 compiles the density/specific gravity and porosity measurements carried out on the retrospective samples at the Micrometrics Laboratory using mercury vapor penetration for the porosity measurements.

Table 6-2. Compilation of Porosity Test Results (Micrometrics Data)

Location	CIPP Identification	Resin Type	Felt	Exhumed Year	Installed Year	Age Year	Porosity (%)	Bulk Density at 0.54psia (g/mL)	Apparent Density (g/mL)
Denver	8-in.	Reichhold 33060	Unwoven	2009	1984	25	15.9149	1.0731	1.2762
Denver	Downstream 48-in.	Reichhold 33060	Unwoven	2010	1987	23	11.262	1.1645	1.3123
Denver	Upstream 48-in.	Reichhold 33060	Unwoven	2010	1987	23	10.1707	1.1618	1.2933
Columbus	8-in.	ARPOL MR 12018*	Unwoven	2010	2005	5	8.1629	1.1739	1.2782
Columbus	36-in.	Reichhold 33420	Unwoven	2010	1989	21	17.7519	1.0884	1.3233

* Aropol MR 12018 (unsaturated polyester orthophthalic resin), Ashland Chemicals.

In both Denver and Columbus, the older liners have a higher porosity and lower bulk density than the younger liners. The 8-in. liner and both of the 48-in. liners in Denver used the same resin and felt, but the age difference between the liners is quite small (23 years versus 26 years). The Columbus 8-in. liner at only 5 years old has a significantly lower porosity and higher bulk density than all of the other liners which are over 20 years old. Such a change in density and porosity could be due to aging of the resin in the presence of various environmental conditions, but may also result from installation differences.

As shown in Table 6-3, for bulk density/specific gravity values, a variation of 1 to 8% was found between the TTC measured values and the values that were measured during the mercury penetration porosity testing. The values obtained during the mercury penetration testing resulted from the intrusion of mercury vapor under very high vapor pressures. The differences in values obtained by different testing methods, though relatively small; do point out the difficulty in measuring performance trends over time that may also result in only small differences in the parameters used to track the deterioration. These issues will be discussed further in Section 6.5.4.

Table 6-3. Comparison of Density Data

Identification/Measurements/Values						Theoretical Calculations		
Sample or Theoretical	**Location**	**Bulk Density M-metrics* (g/mL)**	**Bulk Density TTC** (g/mL)**	**Deviation (%)**	**Porosity (%)**	**With Talc Filler (g/mL)**	**With ATH Filler (g/mL)**	**With No Filler (g/mL)**
Field Samples	Denver 8-in.	1.073	1.160	8.1	15.915	1.144	1.112	1.006
	Denver US 48-in.	1.165	1.098	5.7	11.262	1.207	1.173	1.060
	Denver DS 48-in.	1.162	1.078	7.2	10.171	1.222	1.187	1.073
	Columbus 8-in.	1.174	1.114	5.1	8.163	1.249	1.214	1.096
	Columbus 36-in.	1.088	1.073	1.4	17.752	1.119	1.088	0.985
Theoretical Porosities					0.000	1.360	1.321	1.191
					5.000	1.292	1.255	1.133
					10.000	1.224	1.190	1.075
					15.000	1.157	1.124	1.017
					20.000	1.089	1.059	0.959

* Internal Micrometrics standard procedure
** As per ASTM D792

It is also worthwhile to compare the measured densities with theoretical calculations of bulk density when the densities of the component materials are combined in typical proportions. These calculations are also shown in Table 6-3 using information on proportions and component densities provided by Insituform. The calculations assume that the felt fibers occupy 14% of the final resin volume. The remaining volume is occupied by resin, any filler that is used, and air (the result of porosity in the liner). The amount of filler within the resin is assumed to be 12% by volume. The component densities used in the calculations are neat resin density 1.16 g/mL, fibers 1.38 g/mL, talc filler 2.80 g/mL, and ATH filler 2.42 g/mL. Both the Micrometrics and the TTC bulk densities fall within the ranges calculated depending on the type and extent of any filler used in the actual liners. Close attention to the bulk density of the final CIPP liner could provide a worthwhile quality control parameter – but only if the constituent materials and proportions are accurately known.

6.4.5 Strength and Flexural Modulus. The flexural strength and flexural modulus are the most often tested structural parameters for a CIPP lining, not least because minimum values are given for only these two structural parameters in the ASTM F1216 standard. A compilation and comparison of the available data from this study on these flexural test parameters and tensile test parameters is provided in Table 6-4.

For flexural strength, no values measured fall below the ASTM minimum of 4,500 psi. The measured values range from 5,032 psi to 7,264 psi with quite small standard deviations for each set of measured values. Excluding one of the 2010 Denver 48-in. sample set values of 5,032 psi, the remaining tensile strength values fall into quite a narrow range of 5,808 psi to 7,264 psi.

Table 6-4. Comparison of Strength, Modulus and Elongation Values for All Liner Samples

Liner	Age	Location	Flexural Strength (psi)	Flexural Modulus (psi)	Tensile Strength (psi)	Tensile Modulus (psi)	Tensile Elongation at Peak Stress (%)	Tensile Elongation at Break (%)[a]
ASTM F1216 min. value	0	N/A	4,500	250,000	N/A	N/A	N/A	N/A
Denver 8-in.	25	Crown	6,454 ±228	329,768 ±18,429	3,047 ±235	411,789 ±64,990	1.2 – 2.5	2.0-4.5
		Spring line	6,712 ±571	340,044 ±18,381	2,990 ±205	401,069 ±262	1.45-1.65	1.5-3.5
		Invert	7,103 ±702	336,209 ±23,759	3,051 ±167	422,006 ±44,988	2.25-2.4	1.5-4.5
Denver 48-in. DS	23	Crown	7,031 ±346	302,960 ±24,303	2,995 ±227	382,420 ±60,141	1.5-2.5	2.5-9.0
Denver 48-in. US (Set 1)	23	Crown	5,032 ±652	182,622 ±23,126	3,208 ±222	426,787 ±58,396	1.9-2.5	1.5-5.5
Denver 48-in. US (Set 2)			6,117 ±888	263,707 ±70,398				
Denver 48-in. (Insituform)	8	Crown	6,900 ±400	490,000 ±40,000	2,300 ±170	N/A	N/A	1.5-2.0
Columbus 8-in.	5	Crown	7,199 ±2190	366,563 ±42,340	4,020 ±340	404,641 ±49,467	1.5 – 2.5	1.0-11.0
		Spring line	6,422 ±2351	328,118 ±57,614	3,696 ±560	338,849 ±15,656	1.75-2.4	2.5-9.0
		Invert	5,627 ±1635	343,470 ±51,125	3,882 ±374	344,275 ±25,215	1.0-1.5	5.0-8.0
Columbus 8-in. (QA)	0	N/A	7,264 ± 500	464,652 ±30,000	N/A	N/A	N/A	N/A
Columbus 36-in.	21	Upper haunch	6,039 ±396	206,805 ±29,065	2,958 ±251	315,259 ±42,504	1.0-1.2	2.5-6.0

Note: (a) Tensile elongation at break is not a standardized test; no claims are made herein regarding the repeatability of these measurements or their exact engineering meaning. It is a performance indicator which is believed by some to be linked to the uniformity of the resin saturation within the felt.

For flexural modulus, only two average values fall below the minimum of 250,000 psi given in the ASTM F1216 standard. These are for the 2010 Denver 48-in. upstream liner sample with an average flexural modulus of 182,622±23,126 (Set 1) and for the Columbus 36-in. liner sample with an average flexural modulus of 206,805±29,065. Retesting with five new coupons cut from the Denver 48-in. upstream liner sample (Set 2) gave higher results that exceeded the ASTM minimum modulus value.

Looking for correlations to the low modulus value, it can be noted that the flexural strength recorded for Set 1 of the Denver 48-in. upstream liner was also the lowest value measured. However, the tensile test data (representing different coupons from the same sample) were at the upper end of the range of the remaining results. For the Columbus 36-in. liner with the low flexural modulus value (which was installed as an emergency change order to an existing contract), the flexural strength and tensile strength were all near the bottom of the range for all the liner samples, but were not the lowest values. However, the tensile modulus for the Columbus 36-in. liner was the lowest value recorded.

The 1995 sample of the Denver 48-in. liner was measured with an average flexural modulus of 490,000 psi, which was the highest value recorded in the data included in this study. The remaining modulus values measured in this study (excluding the Denver 48-in. upstream liner and the Columbus 36-in. liner) range from 263,707 psi to 366,563 psi. An additional flexural modulus value of 464,652 psi was a recorded value from the QA/QC testing during installation of the Columbus 8-in. liner.

Hence, the two flexural modulus values measured by other laboratories (464,652 and 490,000 psi) are significantly higher than the TTC measured values (182,622 to 340,044 psi). This introduces the possibility that some differences in modulus may occur through variations in sample creation, preparation, testing procedures, and/or interpretation. In particular, for the Columbus 8-in. QA/QC sample, the sample is usually prepared by curing an extension of the liner within the manhole. This does not have the same installation and curing conditions as within the sewer line itself and such samples are generally expected to have higher test results than coupons cut from within the sewer.

For tensile strength, the average values range between 2,300 psi and 4,020 psi. The Columbus 8-in. liner tended to exhibit high tensile strengths (3,696 psi to 4,020 psi) and the Denver 48-in. liner tested by Insituform had a low tensile strength of 2,300 psi. The remaining tensile strengths were all grouped in a close range between 2,990 psi and 3,208 psi. There is no minimum value for tensile strength provided in the ASTM F1216 standard.

For tensile modulus, the average values range between 315,259 psi and 426,787 psi. There is no minimum value for tensile modulus provided in the ASTM F1216 standard and it does not appear to be a commonly recorded test value.

Tensile elongation at break is sometimes used within the industry to help identify issues relating to liner composition, but it is reported to be an imprecise measure due to the effect of surface irregularities in the sample on the elongation at break. A high elongation at break may point to a lower degree of resin saturation in the liner, but good records of liner wet out and examination of specific gravity data are considered more reliable. For the test results reported in this study, the tensile elongation (strain) at break ranges from 1% to around 11%. In this study, the high elongations at break were observed for the Columbus 8-in. liner samples, but this did not appear to correlate well with poor performance in the other test values. The most common range for tensile elongation at break for the samples tested ranged from around 1.5% to around 6%.

The flexural and tensile testing results raise issues about the variability of samples within the same liner and potential variability in test results among different laboratories. However, some level of correlation between test results is observed for some of the parameters measured. As the research progresses to other sites, it will be important to find out which of the parameters are the most sensitive to deterioration of the liner structural condition and performance, as well as which are the most cost-effective and reliable to measure.

Most of the liner samples met the original specifications for structural performance in flexure. Even the two samples that were below the originally specified flexural modulus values appeared to be in good condition with no signs of structural distress. For one of these samples, retesting five additional coupons provided results that did meet the ASTM minimum value. It is considered likely that poorer liners will have more spatial variability in structural parameters and hence the test results may depend on the chance of where the coupons are taken. Higher quality liners are more likely to have full resin impregnation and even curing and should provide more consistent test results.

6.4.6 Buckling Tests. Sections of the two 8-in. liners that were recovered together with the host pipe were removed from the existing clay pipe and installed in a surrogate steel host pipe for external pressure testing. The 2-ft length that was available for testing was shorter than would be necessary to avoid end effects that tend to provide higher buckling pressures. However, the annular gap around the liner in the surrogate pipe was much higher than that in the site condition, which would tend to lower the buckling resistance. The Denver liner held 40 to 45 psi (equivalent to 96 to 102 ft head of water) for nearly an hour without buckling. The Columbus liner held 50 psi (equivalent to 115 ft head of water) for 15 minutes without buckling. In both cases, the level of applied external pressure did cause some leakage through the liner.

The depth (from the surface to the crown of the pipe) of the Denver pipe was 5 ft and the depth of the Columbus pipe was 6 ft. Thus, the short-term buckling pressures applied to the specimens were 15 to 20 times the maximum water pressure that would be applied if the groundwater table was at the ground surface.

6.4.7 Surface Hardness Tests. Surface hardness tests were performed following ASTM D2240 (Durometer Shore D) and ASTM D2583 (Barcol hardness) and the results are tabulated in Table 6-5.

Table 6-5. Summary of Hardness Values

Measurement Set	Age of Liner	Location	TTC Shore D Values		TTC Barcol Values		Insituform Barcol Values
			Interior	Exterior	Interior	Exterior	
Denver 8-in.	25	Crown	62.8±3.3	77.5±3.1	43.2±1.5	45.9±1.2	38±3
		Spring line	58.9±3.0	79.6±1.4	38.5±0.9	39.4±1.2	-
		Invert	56.4±2.3	74.3±1.7	38.9±1.3	42.3±0.8	-
Denver 48-in. downstream (2010)	23	Crown	65.2±3.4	78.9±1.6	16.5±1.5	29.3±1.3	-
Denver 48-in. upstream (2010)	23	Crown	46.6±2.3	62.7±3.1	14.9±1.8	18.5±2.4	-
Columbus 8-in.	5	Crown	63.3±0.8	83.0±1.8	7.0±0.8	14.3±1.7	-
		Spring line	62.3±0.8	81.7±1.8	6.5±0.8	14.0±1.6	-
		Invert	62.4±2.2	79.5±0.9	6.8±0.8	13.0±1.7	-
Columbus 36-in.	21	Upper haunch	65.7±3.6	78.9±2.3	18.9±2.2	22.3±2.0	-

The measurements for the exterior surface of the liner gave significantly higher readings than those for the inner surface of the liner when using the Shore D hardness test. On the Shore D scale, average inner surface values ranged from 46.6 to 65.7 and exterior surface values ranged from 62.7 to just over 83. In the Barcol hardness measurements, the differences in hardness of the inner surface compared to the exterior surface values varied significantly. In some cases, the values were quite similar and in others the exterior values were around double the interior values. It is not clear at present how much of these differences are due to the presence of and/or degradation of the inner surface layer and how much they may represent deterioration due to exposure to the waste stream.

A significantly lower range of Shore D hardness values (less than 50) were measured for the inner surface of the Denver 8-in. liner where the original surface coating had partly or fully degraded and for the interior of the 2010 Denver 48-in. upstream liner sample – perhaps correlating to the lower flexural modulus seen for this sample. All of the exterior Shore D hardness values were very close to 80 except for the 2010 Denver 48-in. upstream sample which measured 62.7 (over 20 percent less). This low exterior value may also be connected to the low flexural test results.

The surface hardness tests are easy to carry out, could be adapted to provide an in-situ non-destructive test and may offer promise for being able to track aspects of liner performance such as variability within a liner or changes of a liner over time. However, it is believed that testing of a wider range of liners using different surface preparation protocols would be needed to develop the most consistent test results for field installed liners.

6.4.8 Raman Spectroscopy and Other Polymer Testing. Raman spectroscopy tests were run on all the liner samples and these results compared to tests conducted on newly prepared samples of the base resin. With minor differences, the results for the field samples were quite similar to those for the base resins. These similar results in terms of the shape of the curves and the locations and magnitude of the peaks suggested that little chemical deterioration of the resin material had occurred. The applicability of this test to monitoring subtle issues of deterioration depends on scanning many different points on a resin surface to provide representative results. Thus, the few scans provided for each sample in this project can only be considered as indicative of a lack of significant changes in the resin properties.

DSC was also used on some samples to explore the potential of the method to track liner deterioration. No significant difference was noted in the Tg values between the virgin resin material and aged CIPP samples from the field, suggesting a similar level of curing and little to no measurable material degradation.

6.5 Current Findings

The specific findings of the current pilot study with reference to the expected service life of CIPP liners are necessarily limited by the small number of samples and the various possibilities for low physical test measurements that can be postulated. However, the study does provide an important starting point for a broader study of the performance of CIPP liners and other pipe rehabilitation technologies. An important aspect of the pilot study has been to identify where performance issues or questions exist and to suggest what forms of testing are the most useful, cost-effective, and reliable in tracking liner performance over time.

6.5.1 Material Degradation. The liners all appeared to be aging well and most of the liners' physical test properties appeared quite satisfactory after years in service ranging up to 25 years – half the originally expected service life. One sample out of five had a flexural modulus value that was lower than the originally specified value. Another had two sets of test results - one that was higher and one lower than the ASTM specified value. These results, however, cannot be tied directly to deterioration of the liner over time. In the case of the Denver 48-in. upstream liner, it appears likely that the poor physical test properties may have resulted from variability within the liner rather than a change over time.

6.5.2 Conformance of Sampled Liners to Original Specifications. The retrospective evaluation has also pointed to the fact that some aspects of the liners probably did not fully meet the original specifications at the time of installation. This is most clear in the case of the liner thickness measurements, but also is suspected in the case of the Denver 48-in. upstream liner in terms of a local variation in liner properties. For liner thickness, only one of the five samples retrieved had a thickness higher than the value specified at the time of its installation.

6.5.3 Prognosis for Remaining Life. At the end of the initial phase of the retrospective testing program, the inspection of the condition of the retrieved liners and the physical testing results do provide an expectation that all of the liners sampled would reach their planned 50-year lifetime under similar continued service conditions. The lower than specified physical properties (principally thickness and elastic modulus) measured in some samples did not appear to be causing distress to those liners and may have been present in the liner at the time of installation. None of the service conditions for the liners examined in the pilot study would be considered at all severe. The water tables appeared to be low for the excavated liners and the service conditions in terms of pH and chemical exposure were mild. The expansion of this pilot study to a wider range of service conditions would help answer the broad issues concerning expected service life of CIPP liners and its potential variability in connection with issues such as service conditions and QA/QC during installation.

6.5.4 Testing Issues. A variety of test methodologies were tried in this pilot study, ranging from the basic data for the thickness of the liner, its specific gravity and its annular gap to structural material properties such as strength, modulus, and surface hardness. It was noted that significant differences existed in data reported from QA/QC testing at the time of installation and data from tests conducted by different laboratories. This suggests that more attention needs to be placed on documenting and reducing the variability of test results derived from sample recovery procedures and in tests from different laboratories.

The shortfall in thickness measured for most of the liners coupled with the differences in results from QA/QC samples taken within a manhole points to the urgent need to develop better non-destructive means of assessing the acceptability of a newly installed CIPP liner and then tracking its deterioration over time. It was disappointing to find that commercially available ultrasonic thickness gauges did not work adequately on field CIPP samples even though they gave good results on laboratory prepared samples of moderate thickness. Appendix B describes the issue encountered with the use of the ultrasonic thickness probe with the field samples. The inability of commercially available tools to measure the thickness of large diameter CIPP liners from the inner surface only (an important QA issue because large diameters are prone to thickness variation around the circumference) is a clear call for the need for the development of new technologies for accomplishing this task in a cost-effective and reliable manner.

Raman spectroscopy and DSC tests did not produce any evidence of significant material degradation in the pilot study. This may be due to the fact that little deterioration was seen in the CIPP liners (a good finding), but the effort to find or use appropriate chemical testing to monitor liner deterioration is important to continue.

So far, from the variety of tests conducted, the conventional structural testing (especially flexural modulus) seems to clearly identify liners with suspected poorer quality with surface hardness and specific gravity also providing interesting insights. The potential non-destructive nature of surface hardness testing deployed within lined sewers makes this an interesting avenue to explore. Minimally destructive sampling and testing might also be reasonably acceptable. For instance, a small diameter core of a liner might be retrieved and used for thickness measurements, specific gravity measurements, chemical scanning, and some form of structural testing while allowing a simple robotically applied sealing of the sample location.

7.0: RECOMMENDED TEST PROTOCOL FOR FUTURE USE

7.1 Overview of Protocol Implications

The experience in working with the cities of Denver and Columbus on the pilot studies in terms of retrospective evaluation of CIPP liners was very useful. The research team found that there was strong interest by the city engineers to participate, especially when sample retrieval could be combined with other activities that the city needed to undertake. In this section, the cost implications of the study for the utility participants are discussed. The field and laboratory experiences and the usefulness of the test results in terms of understanding the expected life of CIPP pipe rehabilitation are summarized. This information is then used to discuss the technical feasibility of a broader national program for the retrospective evaluation of CIPP liners, as well as similar programs for other rehabilitation technologies.

7.2 Fieldwork Costs

Each of the cities that participated in the pilot program contributed much or all of the costs for the fieldwork in retrieving either CIPP liner samples alone (from larger diameter pipes) or a full sample of CIPP liner including the host pipe (in both cases these were from 8-in. diameter pipes). The costs incurred for the fieldwork are provided below. These costs do not include the planning and coordination costs for the city engineers and other staff that were involved in the discussions regarding participation in the study and the set up of the field tests.

Based on the experiences to date, the direct costs to a municipality to retrieve an approximately 6-ft long sample of 8-in. diameter lined pipe in a relatively low traffic area can be in the range of $10,000 to $25,000 when combined with other activities at the same site (e.g., sewer line replacement or pavement replacement at the site). Costs for person entry into a larger diameter sewer and retrieval of a sample of the liner only were much less expensive in terms of direct cost, amounting to approximately $1,600 to $3,500 in the pilot studies. These are preliminary estimates since actual costs will vary with many factors including: cost profile of city and of location within the city (e.g., downtown, suburban, etc.), depth and diameter of line evaluated, ease of access, and combination of evaluation with other planned work.

7.2.1 City of Denver Costs. The City of Denver was the first city that the research team approached. In order to explain what was being proposed, a preliminary draft of the expected evaluation activities and protocol was prepared for use in the discussion with the city engineers (see Section 2). After exchanging information by phone and e-mail, a one-half day meeting was held in Denver with the city engineering team (Wayne Querry and Randy Schnicker) after a suitable site for a retrieval of a liner plus host pipe segment had been identified. The main determinants for site selection for the sample retrieval were that the CIPP liner should be one of the oldest liners in the City and that the pavement above the pipe should be in need of replacement (so that it could be paid for by agreement with the City department responsible for paving). Following the meeting, the City collected the background information on the proposed site and made arrangements for field work for the 8-in. host pipe and liner retrieval. Since the sample to be retrieved was in an alley, there were no special costs for traffic control.

The second sample location was chosen because it was an old CIPP liner and because a sample had previously been removed from the same site for an evaluation in 1995. Dig-up was not considered feasible for the evaluation because of the cost and disruption in a busy city location and because of the need for bypassing of the line. Instead, an active local CIPP contractor was identified that would enter the sewer line to retrieve the liner sample. Because of their interest in the findings, the contractor did the work at a below-market rate.

The direct costs for the city preparation activities and the contractor site work for the two retrospective evaluations in Denver are approximately identified as indicated in Table 7-1.

Table 7-1. Field Work Costs for Sample Retrieval in Denver

Site/Cost Item	Cost
Cost for Excavation and Removal of 8-in. Clay Sewer Pipe at 1st Ave. and Monroe Alley	$ 22,800
Cost for Sample Retrieval and Patching for 48 in. brick sewer	$ 1,600
Total Cost	$ 24,400

7.2.2 City of Columbus Costs. The discussions with the City of Columbus began with an expression of interest by the City at the TTC Industry Advisory Board meeting in October 2009. Follow-up discussions were held by phone and email in the winter 2009-2010 and a planning meeting was held in Columbus on February 16, 2010. The sites were chosen to select a 36-in. diameter, 21-year old lined pipe for CIPP sample retrieval only and to retrieve a host pipe plus CIPP liner from a 5-year old, 8-in. sewer line that was being replaced because the line needed to be upsized. The principal reason for selecting a relatively newly relined pipe for inclusion was that the city could not absorb the cost of a separate dig-up and replace just for the retrospective study. The direct costs for the city for the two retrospective evaluations in Columbus are shown in Table 7-2.

Table 7-2. City of Columbus Costs

Site / Cost Item	Cost
Pay item for Richards Rd – Open Cut Open Cut Point Repair, 8 in.-12 in. Depth <12 ft, up to length ≤10 ft	$9,680
Gay St. – Reynolds Inliner force account for Gay St.	$3,520
Total Cost	$13,200

7.3 Developing an Extended Program for Retrospective Evaluation

The purpose of this section is to evaluate the mix of retrospective evaluation activities that might be employed in a broader program.

For individual cities, it is probably unrealistic to expect a large number of excavations to retrieve samples for evaluation even though checking on the continued performance of relining work is a very worthy goal. The purpose of the destructive sample retrieval is to build a detailed evaluation of selected liner sites. These are not likely to be selected at random for cost and accessibility reasons and hence with a small number of non-random sites within a city. Therefore, the value of the destructive liner sample retrieval is in the detailed evaluation of liner properties that can be carried out and in the correlation of those properties with other parameters concerning liner/site characteristics, liner age, etc., together with the information that can be gained from CCTV inspections and other NDT evaluations.

Many cities are already doing periodic CCTV inspections and also have mechanisms for keeping track of specific problems that occur in lined and unlined pipe. Thus, significant value can be added by combining this broadly available information with additional detailed evaluations of selected liners. It should be noted in this regard that selecting liners with more severe exposure conditions or other circumstances likely to cause an accelerated deterioration may provide a greater understanding about deterioration mechanisms, but may not be representative of the deterioration of liners in general use.

To get the best value from retrospective evaluation activities, it is recommended that a dual track be followed in which aggregated experiential and condition assessment information on lined pipes be collected from cities that are willing to participate together with continued intensive evaluation of liners that have seen a variety of service conditions.

Municipalities have shown great interest in having better nationwide information on the experience with the rehabilitation technologies that they are using or considering. It also appears from the discussions with municipalities regarding the pilot studies described here that municipalities would be willing to participate in providing data about their own experiences in return for being able to access the nationally aggregated information. Some municipalities may have limited resources to assist in the dig up and retrieval of host pipe samples or even liner coupons (from larger diameter pipes). As mentioned earlier, being able to combine the sample retrieval with other needed work – either on the sewer, on neighboring utilities, or on the pavement above the sewer – significantly eases the decision of the municipality to participate.

7.4 Aggregating National Data on Liner Performance

Since the ultimate goal of carrying out retrospective evaluations is to be able to provide better guidance to municipalities on the long-term performance of the various rehabilitation technologies available to them, it is worth looking ahead as to how that data might be collected into a national database.

Table 7-3 provides a summary of an overall structure that could be used for such a database. The agency or municipality will be the key provider of the information and the agency name, contact information for the person providing the data, system size, and current extent of rehabilitation should be recorded.

Various agencies would have differences in the types of technologies used and the specifics of those technology applications. It is suggested that the categorization of the city experiences be able to be as detailed as the city data would allow, but would also allow information capture at a broader level when only that level of information was available. For example, Agency A may be able to break down their experiences with CIPP installations by whether they were hot-water or steam-cured, which type of resin was used, etc. Agency B may only have retained sufficient records to be able to provide information on the length of lines rehabilitated with CIPP and their general experiences with CIPP. The database should be able to focus on or exclude specific variants if desired or to analyze all of the CIPP data in aggregate.

As discussed in Section 7.3, broad interpreted data from agency records, CCTV inspections, and condition assessment databases needs to be able to be accessed in the database in addition to well characterized, quantitative data from retrospective liner testing or the use of specific NDT approaches to liner evaluation.

It is not intended that the database proposed would attempt to include all of the individual CCTV or condition assessment data that cities are collecting. Rather, the database proposed would contain the interpreted results from agencies of the performance of rehabilitation technologies plus specific physical or NDT that addresses liner performance or degradation. The aggregation of all inspection and condition assessment information would provide additional opportunities for understanding liner performance, but is an effort that would require a larger level of resources to accomplish.

Table 7-3. Overall Structure for a National Retrospective Evaluation Database

Utility Information	
Agency	Name, City, State (Province)
Primary Contact	Name, Position, Phone, Email
System Type	Wastewater, Storm, Combined, Water (for future retrospectives)
System Size	Miles of Mains, Miles of Laterals, Number of Manholes
Rehabilitation Program Overview	Miles per Year Rehabilitated, Miles per Year Replaced
Technology Used	Sliplining **CIPP** Close-fit linings Grout-in-place linings Spiral-wound linings Panel linings Spray/spin-cast linings Grouting Other [user specified]
CIPP Experience Overview	
CIPP Usage Data	Year CIPP First Used; Total CIPP Length Installed, CIPP Miles per Year
CIPP Technology Type	Full length [ft]; Patch repairs [ft]; Lateral lining [ft]; Tees/top hats [no]
CIPP Installation Methods	Air inversion [%]; Water inversion [%]; Pull-in and inflate [%]
CIPP Curing Methods	Ambient [%]; Steam [%]; Hot Water [%]; UV Light [%]
CIPP Retrospective Case Study - Pipe Data Table	
Host Pipe Location	Street Name, City, State
Host Pipe Installation Date	Year
Host Pipe Material	Ductile iron; Cast iron; Steel; Reinforced Concrete Pipe; Prestressed Concrete Cylinder Pipe; Brick; VCP; PVC; PE, Other
Host Pipe Shape	Circle; Egg-Shaped; Box-Shaped; Other [User-Specified]
Host Pipe Diameter	in.
Host Pipe Rehab Length	ft
Host Pipe Burial Depth	ft below ground surface
Water Table Depth	ft below ground surface
Soil Conditions	Soft Clay; Firm Clay; Stiff Hard Clay; Loose Sand; Medium Sand; Dense Sand; Cobble/Boulder; Bedrock; Gravel; Other
Condition Assessment of Host Pipe	Infiltration/Exfiltration Testing [Dates/Results] CCTV [Dates/Results] Visual [Dates/Results] NDT Evaluation [Dates/Results] Coupons [Dates/Results]
Problem in the Host Pipe	Structural Failure, Insufficient Hydraulic Capacity, Inflow & Infiltration, etc.
CIPP Retrospective Case Study – Technology Background Data Table	
CIPP Type	Full length; Patch repair; Lateral lining; Tee/top hat
Date Installed	Year
Liner Design Diameter	in.
Liner Design Thickness	mm
Length Rehabilitated	ft
Installation Method	Air inversion; Water inversion; Pull-in and inflate
Curing Method	Ambient; Steam; Hot Water; UV-Light; Electricity
Liner Installer	Name, City, State (Province)
Tube Manufacturer	Name, City, State (Province)

Table 7-3. Overall Structure for a National Retrospective Evaluation Database (Continued)

CIPP Retrospective Case Study – Technology Background Data Table (Continued)	
Tube Material Type	Polyester; fiberglass; other
Tube Material Construction	Needled; woven; fiber-reinforced
Sealing Layer Type	Polyethylene; polyurethane; other
Sealing Layer Thickness	mm
Resin Supplier	Name, City, State (Province)
Resin Type	Polyester; Vinyl Ester; Epoxy; Other [User Specified]
Resin Trade Name	User-Specified
Primary Catalyst	User-Specified
Secondary Catalyst	User-Specified
CIPP Retrospective Case Study – Technology Post-Installation Data Table	
Design Spec: Tensile Strength	psi
Design Spec: Flexural Strength	psi
Design Spec: Ovality	%
Post-Install: Tensile Strength	psi
Post-Install: Flexural Strength	psi
Post-Install: Ovality	%
Post-Install: Liner Thickness	mm
Defects Noted via Visual Inspection	Wrinkling; Buckling; Blisters; Lateral Opening Issues; Discoloration; Other [User-Specified]
QA/QC Inspection of Rehabilitated Pipe	Infiltration/Exfiltration Testing [Dates/Results] CCTV [Dates/Results] Visual Assessment [Dates/Results] NDT Evaluation [Dates/Results] Coupons [Dates/Results]
Other QA/QC Data Collected	User-Specified
CIPP Retrospective Case Study – Technology Retrospective Data Table	
Date of Testing	Year
Performance Study Duration	Years [Date of Testing – Date Installed]
Soil Classification	Gravel; Fine Gravel; Coarse Gravel; Sand; Fine Sand; Medium Sand Coarse Sand; Clay; Silt
Soil Specific Gravity	Dimensionless
Soil Moisture Content	%
Soil pH	Dimensionless
Annular Gap	Measure at 8 locations (mm)
Liner Thickness	Measure at 8 locations (mm)
Liner bulk density	g/mL
Liner porosity	%
Retrospective: Tensile Strength	psi
Retrospective: Flexural Strength	psi
Retrospective: Ovality	%
Hardness	Shore D Hardness scale; Barcol Hardness scale
Raman Spectroscopy	User-Specified; Comparison of Aged to Virgin Resin
Visual Inspection	User-Specified
CIPP Lessons Learned	
Construction Problems	User-Specified
Technology Performance Problems	User-Specified
Adjustments Made	User-Specified
Continued Use of the Technology	Yes/No plus User-Specified Explanation

8.0: REPORT ON INTERNATIONAL SCAN ACTIVITIES AND FINDINGS

8.1 Introduction

An international review was undertaken to better understand the experiences of a wide range of utilities that have embarked on significant CIPP rehabilitation programs over past decades. The purpose was to assess internationally-based utilities' views on the effectiveness of CIPP rehabilitation and to document any efforts to evaluate and/or monitor the installed quality of their CIPP installations over the long term.

Face-to-face interviews were held with nine wastewater utilities located in the U.K., France, Germany, Singapore, and Australia as shown in Table 8-1. The interviews were conducted between March and October 2010. Appendix C contains a detailed interview report for each utility based upon their experience with the performance of CIPP installations. In addition, the research team collected information on CIPP use and quality control in Japan and contacted the Centre d'Expertise et de Recherche en Infrastructures Urbaines (CERIU) in Montréal regarding a retrospective evaluation effort that was underway for prior rehabilitation efforts in the Montréal region. These are discussed separately in Sections 8.7 and 8.8.

Table 8-1. Utilities or Organizations Participating in this Review

Utility/Organization	Country	First use of CIPP	Total Network Length (km)
Thames Water	U.K.	1971	69,600
Severn Trent Water	U.K.	1975	54,045
Agglomeration de Chartres	France	2000	325
Agglomeration des Hauts-de-Bièvre	France	1996	450
Göttingen Stadtentwässerung	Germany	1992	375
Technische Betriebe der Stadt Leverkusen	Germany	1994	660
Public Utilities Board Singapore	Singapore	1997	3,660
Queensland Urban Utilities	Australia	1979	6,844
Sydney Water	Australia	1986	22,000
Japan Pipe Rehabilitation Quality Assurance Association	Japan	1986	380,000
CERIU	Canada	N/A	N/A

8.2 Rehabilitation Experience

Three of the participants first used CIPP in the 1970s, and may be considered early adopters of the technology. The first CIPP was installed in London in 1971 for the Greater London Council's Metropolitan Water Board, now Thames Water Utilities, Ltd. A 70-m (230 ft) length of the Brick Lane Sewer, a century old brick 1,170 × 850 mm (46 × 33 in.) egg shaped sewer located at Riverside Close, Hackney, was lined with a 6 mm (0.24 in.) thick liner. Many of the first CIPP contracts in the U.K. were undertaken for Thames Water and its agent authorities and by 1981 over a hundred successful installations had been undertaken in the U.K. in sizes from 4 to 108 in. (200 to 2,740 mm). Much of the early experience with CIPP was in Europe as Insituform, then the only player in the market, expanded its coverage from the U.K. by licensing the technology to independent contractors. The Public Utilities Board (PUB) Singapore did not use CIPP until 1994, but since then has been the biggest user among the participants. Most of the participants also use other rehabilitation methods. Table 8-2 shows the relative use of different methods at each utility.

Table 8-2. CIPP and Other Rehabilitation Methods

Utility	City	Total CIPP Installed (km)	Total Other Rehabilitation Methods (km)
Thames Water	London & region	4 – 500	Not known
Severn Trent Water	Midlands region	700	<50
Agglomeration de Chartres	Chartres	4	0
Agglomeration des Hauts-de-Bièvre	SW Paris	30	<5
Göttingen Stadtentwässerung	Göttingen	42	24
Technische Betriebe der Stadt Leverkusen	Leverkusen	50	1
Public Utilities Board Singapore	Singapore	900	180
Queensland Urban Utilities	Brisbane	45	64
Sydney Water	Sydney	200	800

The data in this table reflect the different markets in different regions of the world. Europe is dominated by CIPP, and Singapore has adopted this as its main method too. Australia, by contrast, developed its own method, spiral winding with PVC and PE and makes substantial use of fold-and-form pipe lining, and, as a result, CIPP has never been the dominant method there. Nevertheless, CIPP is the most widely used method of sewer rehabilitation worldwide and has the longest track record of the currently used methods. It represents approximately 68% of the rehabilitation work undertaken by the participating utilities.

Current usage of the range of rehabilitation methods is similar to the historical pattern. This is shown in Table 8-3. The exception is Göttingen, which has switched recently to greater usage of PE-based methods.

Table 8-3. Current Usage of Rehabilitation Methods

Utility	CIPP Installed last year (km)	Other Rehabilitation Methods installed last year (km)
Thames Water	20	Not known
Severn Trent Water	9	Not known
Agglomeration de Chartres	0.5	0
Agglomeration des Hauts-de-Bièvre	3	1
Göttingen Stadtentwässerung	1	7
Technische Betriebe der Stadt Leverkusen	5	0
Public Utilities Board Singapore	≈200	≈20
Queensland Urban Utilities	1.7	4.7
Sydney Water	20	50

The utilities report a clear trend in the quality of CIPP work. Early installations did suffer from problems such as wrinkling, blistering, and poor reopening of lateral connections, but these issues have been reduced as installers gain experience. The need for trained and experienced installers and for clear and proven installation procedures properly followed was mentioned by several utilities as being key to successful installation.

The French and German utilities interviewed have switched in recent years to almost exclusive use of UV-cured CIPP methods. These are considered to be better controlled and to benefit from factory impregnation, which is more readily supervised than site impregnation. Monitoring of the installation is also considered to be easier and more thorough. They also tend to let term contracts to single contractors who can meet specific experience criteria, rather than going to open competitive tender for each project. The UV-cured methods have taken a dominant share of the CIPP market in Germany, which are both the largest market in Europe and the technology leader.

The U.K. utilities interviewed also place contracts for a five-year Asset Management Period (AMP) with a single or small number of selected contractors. This is intended to ensure that better quality installation is achieved.

In Singapore, there has been relatively little usage of UV-cured methods; air inversion and steam curing appears to dominate. Epoxy resins are also used for all rehabilitation at diameters up to and including 225 mm (9 in.) despite its contractors experiencing difficulties in controlling the mixed resin in a tropical climate. Thames Water is the other utility that has selectively specified epoxy resin systems, with polyester resin continuing to be the dominant resin used. Brisbane Water (now Queensland Urban Utilities) is the only other utility surveyed in a tropical or semi-tropical region, and makes only limited use of CIPP because of the difficulty of controlling the curing of the resins used.

Experience of using short liners, top hats or similar for connections, and lateral lining is shown in Table 8-4.

Table 8-4. Usage of Other CIPP Materials

Utility	Short Liners	Top Hats or Similar	Lateral Lining
Thames Water	Some	Few	Little
Severn Trent Water	Not known	Not known	Not known
Agglomeration de Chartres	No	No	No
Agglomeration des Hauts-de-Bièvre	Tried, no longer used	Tried, no longer used	4 – 5km
Göttingen Stadtentwässerung	Tried, no longer used	Tried, no longer used	6km
Technische Betriebe der Stadt Leverkusen	Tried, no longer used	Tried, no longer used	No
Public Utilities Board Singapore	No	9,000 km	No
Queensland Urban Utilities	660 km	120 km	330 km
Sydney Water	200 km	No	No

Many utilities state that they no longer use either short liners or top hats, based on negative experience with them. Short liners need to adhere to the host pipe and not shrink, so epoxy resins are used. Nevertheless utilities have experienced problems with the short liners being damaged by high pressure water jetting.

8.3 Specifications and Design

The use of specifications by the participating utilities is shown in Table 8-5.

Table 8-5. Rehabilitation Specifications

Utility	Specification
Thames Water	BS13566 Part 4
Severn Trent Water	Not known. Design to Water Industry Specifications (WIS) 4-34-04 and Water Research Centre (WRc) Sewer Rehabilitation Manual (SRM)
Agglomeration de Chartres	Own performance specification
Agglomeration des Hauts-de-Bièvre	None. Design to Association Scientifique et Technique pour l'Eau et l'Environnement (ASTEE) method.
Göttingen Stadtentwässerung	Own specification
Technische Betriebe der Stadt Leverkusen	Own specification
Public Utilities Board Singapore	Own specification based on WIS 4-34-04
Queensland Urban Utilities	EN13566 Part 4
Sydney Water	EPS 01 – Small sewers based on AS 2566 and ASTM F1216 EPS 03 – Large sewers based on AS 2566 and ASTM F1216F EPS 09 – Oviform sewers based on WRc Manual

Among the utilities with their own specifications, there are significant differences in the characteristics specified for type testing. Table 8-6 shows the type tests specified.

Table 8-6. Type Testing Required in Specifications

Utility	Characteristics for Type Testing
Thames Water	Per BS EN 13566. 10,000 hour creep, strain corrosion, Thames' own infiltration test
Severn Trent Water	Not known.
Agglomeration de Chartres	Not known
Agglomeration des Hauts-de-Bièvre	None. Design verification only
Göttingen Stadtentwässerung	Creep resistance, tensile modulus, bending modulus. Minimum wall thickness is 6mm irrespective of design requirements
Technische Betriebe der Stadt Leverkusen	Creep resistance, tensile modulus, bending modulus. Minimum wall thickness is 5mm irrespective of design requirements
Public Utilities Board Singapore	Flexural strength, tensile strength, compressive strength, shear strength, density, Barcol hardness
Queensland Urban Utilities	ISO 175; Darmstadt Abrasion Test; DIN 19253; Jetting Resistance Test; EN 1542; EN1055.
Sydney Water	Long term flexural modulus –manufacturers' data

Structural design of CIPP liners is most commonly undertaken by the contractor. Thames Water performs random in-house design checks, as does Sydney Water. Queensland Urban Utilities and PUB Singapore do some design in house and have some done by the contractors, and Göttingen has all design done by an independent consulting engineer. All the others have design undertaken by the installing contractor.

8.4 Preparation and Supervision

All of the utilities interviewed agreed that preparation and supervision are critical elements in achieving a successful installation. Their importance had generally been learned through bad experiences when either or both had been inadequate. Table 8-7 shows the different approaches to preparation and supervision.

Table 8-7. Preparation and Supervision of CIPP Works

Utility	Preparation	Supervision
Thames Water	Jetting	Contractor self-certifies to own method statement
Severn Trent Water	Not known	Contractor self-certifies to specification. Some audit by Severn Trent Water.
Agglomeration de Chartres	Jetting and root cutting	Third party project manager
Agglomeration des Hauts-de-Bièvre	Jetting and joint sealing	Contractor self-certifies under own QA scheme
Göttingen Stadtentwässerung	Jetting	Third party consulting engineer
Technische Betriebe der Stadt Leverkusen	Jetting	Third party consulting engineer and Leverkusen
Public Utilities Board Singapore	Jetting and joint sealing	PUB supervisor
Queensland Urban Utilities	Not known	Contractor self-certifies under own QA scheme
Sydney Water	Jetting, joint sealing, and rebar trimming	Sydney Water supervisor

The utilities commented that the curing and cooling cycle is the element of the process that requires closest supervision and monitoring. This is because contractors try to save time in this stage, and this can result in inadequate curing, leading to problems of service life.

8.5 Verification and Testing

Table 8-8 shows the required frequency of post-installation CCTV surveys, as well as those utilities utilizing an I/I test for in-situ performance testing. The performance test is generally an in-situ watertightness test to look for exfiltration. However, only two utilities appear to have established a clear pass/fail criterion for this characteristic. Table 8-9 sets out the mechanical characteristics of the installation that are tested. Most, but not all of the utilities, take samples from the installed liners for testing to verify that the installation meets the specification requirements.

Table 8-8. Post-Works Inspection and In-Situ Testing

Utility	CCTV Survey	I/I Test	Pass/Fail Criterion
Thames Water	✓	Own test	✓
Severn Trent Water	-	-	-
Agglomeration de Chartres	✓ & after 1 year	-	-
Agglomeration des Hauts-de-Bièvre	✓	✓	-
Göttingen Stadtentwässerung	-	-	-
Technische Betriebe der Stadt Leverkusen	✓ & after 4 years	-	-
Public Utilities Board Singapore	✓ & after 2 and 5 years	✓	-
Queensland Urban Utilities	✓	Pressure test	✓
Sydney Water	✓ & after 1 year	-	-

Table 8-9. Process Verification Testing Undertaken

Utility	Third party Laboratory	Flexural Strength	Flexural Modulus	Tensile Strength	Tensile Modulus	Watertightness	Hardness[4]	Thickness
Thames Water	✓	✓	✓	-	-	-	-	✓
Severn Trent Water[1]	-	-	-	-	-	-	-	-
Agglomeration de Chartres[2]	-	-	-	-	-	-	-	-
Agglomeration des Hauts-de-Bièvre	✓	-	✓	-	-	-	-	✓
Göttingen Stadtentwässerung	✓	-	✓	-	✓	-	-	✓
Technische Betriebe der Stadt Leverkusen[3]	✓	✓	-	-	✓	✓	-	✓
Public Utilities Board Singapore	✓	✓	✓	✓	✓	-	✓	✓
Queensland Urban Utilities	✓	-	-	-	✓	✓	-	✓
Sydney Water	✓	✓	-	✓	✓	-	✓	✓

(1) No information on Severn Trent
(2) Chartres does not undertake process verification, but is considering adding it to the specification.
(3) Leverkusen also has creep resistance measured.
(4) Public Utilities Board Singapore uses Barcol, Sydney Water uses Shore method.

In addition to the process verification and post-works inspections, there is generally a contractual requirement that the contractor provide a warranty for the works. The term of the warranty varies by utility, and, in France and Germany, there are legal limits on warranty periods enshrined in national law. Table 8-10 shows the warranty periods of the utilities interviewed.

Table 8-10. Warranty Periods on Rehabilitation Works

Utility	Warranty Period
Thames Water	Framework contractor does all remediation under his contract during its term
Severn Trent Water	Framework contractor does all remediation under his contract during and after its term
Agglomeration de Chartres	1 year (statutory in French law)
Agglomeration des Hauts-de-Bièvre	1 year (statutory in French law)
Göttingen Stadtentwässerung	4 years (statutory in German VOB contract law)
Technische Betriebe der Stadt Leverkusen	4 years (statutory in German VOB contract law)
Public Utilities Board Singapore	2 years
Queensland Urban Utilities	1 year. Approx. 3% of installation needs remediation
Sydney Water	2 years. Approx. 1% of installation needs remediation

8.6 Utilities' Views on Effectiveness of Sewer Rehabilitation

8.6.1 Based on Long-Term Samples. Of the utilities interviewed, four have taken samples for testing from CIPP installations after a period in service: Thames Water; Göttingen, Public Utilities Board Singapore; and Queensland Urban Utilities/Brisbane. In addition, Leverkusen has undertaken CCTV surveys after 10 and 15 years in service and Sydney Water has done so after 12 years of service in one line.

Thames Water: The original Insituform liner installed in the Brick Lane Sewer was examined in June 1991. Two panels were cut from the sidewall of liner along the spring line of the sewer about 3 ft from an access manhole. The location was revisited in October 2001 and two sample panels about 1 foot square were removed from an area of the sidewall about 4 ft into the sewer. In each instance, test pieces were machined from the test panels and tested in accordance with the relevant testing specifications: BS2782 Part 3 Method 335A:1978 in 1991 and U.K.WIS 4-34-04/BS EN ISO 178 in 2001. The results are provided in Table 8-11.

Table 8-11. Test Results from First CIPP Installation

	Sample Mean		Industry Standard	
Flexural Property	**20 Year**	**30 Year**	**WIS4-34-04**	**ASTM F1216**
Modulus MPa	2900	3300	2200	
Modulus psi	420,000	480,000		250,000
Strength MPa	46	43	25	
Strength psi	6,700	6,200		4,500

It is anticipated that Insituform Technologies Ltd. will seek the agreement of Thames Water to sample this unique installation again in 2011.

Göttingen Stadtentwässerung: Göttingen has taken samples of CIPP lining after 5 and 10 years in service, and some after 12 years. Pieces roughly the size of a sheet of letter paper were removed in sewers 250 to 600 mm (10 to 24 in.) in diameter. A total of 50 samples were tested by the Institute for Underground Infrastructure (Institut für Unterirdische Infrastruktur gGmbH [IKT]) for: elastic modulus; bending stiffness; thickness; and watertightness. No results were made available but, on the basis of the results, Göttingen considers CIPP to have an effective service life of 50 years.

Public Utilities Board Singapore: They have carried out inspections of historic rehabilitation projects, typically after about 10 years in service. The findings are shown in Table 8-12.

Table 8-12. Findings from Retrospective Samples of CIPP in Singapore

Location and Date Installed	Date Inspected	Diameter	Thickness	Length	Data Collected
Upper Paya Lebar Rd (1998)	10/30/2008	225 mm	NA	15.4 m	Good condition (no defect)
Kim Seng Rd (2000)	08/26/2009	225 mm	NA	34.3 m	Good condition (no defect)
Bishan Street 13 (1998)	05/29/2009	300 mm	NA	43.5 m	Good condition (no defect)
Ubi Ave 1 btw blk 338/339 (1999)	02/09/2009	150 mm	NA	64 m	Bulging liner
Geylang Rd (1999)	05/30/2009	300 mm	NA	37.8 m	Longitudinal wrinkle

NA = not available

Queensland Urban Utilities - Brisbane: An installation from 1985 comprising 1.9 km of 12 mm thick 750 mm and 825 mm diameter lining was inspected in 2002, i.e., after 17 years of service. The inspection was by CCTV only and no defects were noted. Since then several further inspections by CCTV and man entry have been undertaken of this same line, and coupons taken. No defects were noted in the inspection. Coupons have been retrieved from certain pipes when pieces have been dislodged by high pressure jetting done for cleaning purposes, but have not been tested to establish their properties. This has raised concerns over jetting for cleaning in CIPP-lined pipes.

8.6.2 Based on CCTV Inspections. Sydney undertook CCTV inspection of approximately 100 m of 990 × 660 mm ovoid CIPP lining after 15 years of service. No significant defects were noted. Leverkusen has undertaken CCTV inspections after 10 and 15 years in pipes from 250 to 1,200 mm diameter and has not identified any specific problems that raise concern over the general performance of CIPP liners. They also inspect liners as part of routine maintenance of their network. They plan to start taking coupons and testing them in the future now that they have a larger program of CIPP works.

In general, the findings from these investigations after a period in service indicate that there is no serious deterioration in performance of the CIPP linings. None of the findings has raised concerns over the service life, and those defects found are often considered to be installation issues rather than inherent weaknesses of the products themselves. The only exception to this is QUU's concern over resistance to jetting. This was also raised in Germany, where jetting is considered to be the reason for the general failure of short liners.

8.6.3 Based on General Experience. Two of the utilities interviewed, Göttingen and PUB Singapore, have a policy of trying to achieve a watertight sewerage system. Göttingen is more concerned with infiltration, whereas the driver in Singapore is to eliminate exfiltration. Whereas both use CIPP, they have different views on its application and effectiveness.

Singapore makes extensive use of CIPP, alongside PVC spiral lining and PE fold and form lining. It has stipulated epoxy-based CIPP for its smaller sewers and for laterals. More than 80% of the lining undertaken to date is CIPP and this is expected to continue to be the case in current and future phases of work. The specifics of the methods used have evolved to meet the needs of a tropical climate and the rigorous performance requirements of PUB. As a result, PUB considers CIPP to be a viable, long-lasting means of achieving a watertight sewerage system.

Göttingen's city council decided in 1990 to make serious investments in the wastewater system with the aim of achieving a watertight and maintenance-free system by 2035, including the privately-owned laterals. Göttingen's aim is a watertight system and, after 15 years of using CIPP, and some 15,000 watertightness tests, they consider that it is an excellent long-term repair method but will not provide a permanent watertight system. This is due to problems of sealing ends at manholes and of sealing the openings at lateral connections. CIPP can give a watertight pipe but not a watertight system. Göttingen has switched its strategy to achieve complete system watertightness to aiming for a 100% PE system, with welded joints throughout. When installing new pipe, only materials approved by the German Technical and Scientific Association for Gas and Water (Deutscher Verein des Gas- und Wasserfaches e.V. - Technisch-wissenschaftlicher Verein [DVGW]) for gas use are allowed to be installed. This is the reason that since 2006, PE rehabilitation technologies have replaced CIPP at Göttingen.

Of the 36 km (22 mi) of CIPP installed in main sewers in Göttingen, 7 km (4.4 mi) has already been replaced with PE and eventually all but approximately 10 km (6.2 mi) will be replaced. Taking the DVGW approach means that the system is effectively being redesigned as a pressure-capable system based on zero infiltration or exfiltration. As stated above, Göttingen now considers CIPP to be an excellent long-term repair technology with a service life of 50 years and that can make individual pipes watertight. But it does not meet their requirement of achieving a permanent, watertight network.

Thames Water is satisfied that its established system, using preferred contractors, delivers value for money. This experience is considered important in eliminating installation defects which are the main source of performance problems later on. Thames Water believes that in its geology the use of leaktight systems is important to minimizing infiltration and accordingly epoxy resin linings may be required for small diameters prone to leakage. It does not plan to change its policy on the use of CIPP.

The experience of Severn Trent Water has been generally good. They report some problems with liner stretch, missed connections, and some wrinkling. They have also experienced problems in re-rounding severely deteriorated pipe prior to lining. As with Thames Water, they do not plan to change their policy on the use of CIPP.

The Agglomeration de Chartres uses CIPP to reinforce sewers where there is high risk of root penetration. For structural problems, and even I/I, open cut replacement with ductile iron pipe is preferred. The condition of lateral connections and frequent displaced pipes means that CIPP is considered ineffective in combating I/I. CIPP is considered a maintenance activity rather than capital expenditure/asset renewal. Nevertheless, Chartres expects to increase its usage of CIPP in the coming years, and to increase rehabilitation at the expense of replacement in order to improve the network within its limited budget.

The Agglomeration des Hauts-de-Bièvre considers CIPP to be a reliable method that will remain the main one used for sewer rehabilitation works. Good planning and pipe preparation are essential and nothing should be left to chance. Experienced and knowledgeable consultants and contractors are also necessary for successful installations. They now enter into annual contracts with one contractor only to ensure experience and quality, and do not use a competitive tender for each project. While recognizing that they could save money, they consider the risk of problems due to inexperience and insufficient money to be too high. In 14 years of CIPP usage, only two projects were considered to have failed: a 200 m (656 ft) installation at a very difficult location could not be completed; and a 500 m (1,640 ft) installation was taken out because of poor installation and curing control. This represents approximately 2% of the total length installed to date.

Leverkusen has concerns over the resistance of CIPP to water jetting used for cleaning. Their cleaning uses water jetting at 20 bar (290 psi) pressure, and they report some damage to liners from cleaning. Nevertheless they continue to use CIPP. Their view is that quality of installation has improved significantly since the 1990s, especially in areas such as reopening of laterals. Testing has also improved so the overall standard has improved dramatically. They believe that the owner needs to take responsibility for QA/QC and for supervision and monitoring during installation. Even with experienced and trusted contractors the correct procedures are not always followed. For example, Leverkusen is considering introducing infrared spectroscopy to its type testing to ensure that the correct resins are used. This suggests that the level of trust between owner and installer remains low.

In Australia, the situation is different because of the predominance of PE and PVC fold-and-form and spirally-wound linings. Sydney Water has used such plastic liners for rehabilitation for over 25 years. In its reticulation sewers, fold-and-form and spirally-wound liners account for the great majority of work undertaken. Use of CIPP has been limited mainly to patches, private sewers and laterals, and more recently, junctions.

Queensland Urban Utilities in Brisbane also makes greater use of PVC and PE-based lining systems than of CIPP. It shares the concerns of the other utilities over jetting for cleaning in CIPP-lined pipes. Queensland Urban Utilities has addressed this through changing its operational procedures for jetting by limiting pressure and using specific designs of nozzle. They consider that CIPP is a valuable technology when the right product is used in the right conditions, but that it is important to understand its limitations and risks. The nature of sub-tropical regions is such that it may not be well suited to work in such locations. Also the experience, capability, and commitment of the installer are considered paramount. The combination of an inexperienced client and an inexperienced installer will lead to problems.

8.7 CIPP Use and Testing in Japan

Japan has a land area of 145,883 square miles, extending about 2,000 miles north to south on four main islands; Honshu, Hokkaido, Shikoku, and Kyushu. Its population of 128 million is 79% urban, living on just 3% of the land area. The capital and largest city is Tokyo with a population of about 8.5 million (25% of the nation lives in Greater Tokyo). There are 11 other cities with populations ranging from 1 to 3.6 million. Japan is subject to extensive tropical storms and some 1,500 earthquakes each year with a significant impact on pipeline performance issues. Climate varies from temperate in the north to subtropical in the south with implications for H_2S attack in concrete sewers.

Through the last three decades, the government has pumped significant amount of money into the economy by investment in public projects including provision of water and sewerage services, roads, rail, airports, and other urban infrastructure. However, in difficult economic times, the government has embarked on restructuring programs and has begun to cut back on investment in infrastructure projects. In 2001, the government announced a cut in expenditure of $10.3 billion, targeting areas such as social security, public works, defense, and education. The impact fell heavily on the construction sector where a 3 to 6% cut in public works has been experienced each year since 2001.

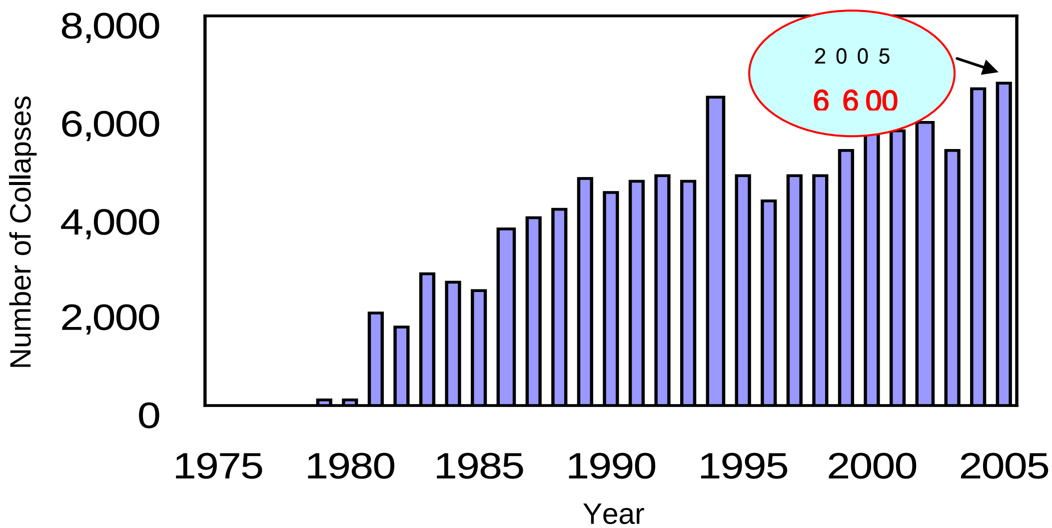
The water and sewer utilities are managed on a municipality basis, i.e., the local town or city government takes responsibility for the sewers and water mains. It has recourse to the prefecture and to the central government to obtain funds to supplement locally raised revenue for capital expenditure, but it funds maintenance work from its own budgets. With the economy at a low ebb, tax revenues which fund this expenditure are stressed, and this is in part responsible for the downturn in pipeline construction and maintenance.

The development of a piped sewer system in Japan commenced in the latter half of the 19th century – prompted by major cholera outbreaks in Nagasaki and Yokohama in 1877. Piped sewers were constructed in the foreigners' settlements in Yokohama and Kobe. Tokyo Metropolitan Government began public sewer construction in 1884. Thereafter, other major cities began sewer construction, but the pace of development lagged somewhat behind Europe and the United States. Sewerage was generally managed with an efficient system of collection and transportation of night soil for disposal as agricultural fertilizer. The system collapsed during World War II due to fuel shortages caused by the Allied blockade of shipping. The development of a modern sewerage system was a priority in post-war recovery and sewer construction became an important source of employment for unskilled labor.

However, network growth was slow and sewerage services were only available to 7% of the population in 1963, until it was accelerated by a series of Five Year Plans for Sewerage Construction. Thereafter, a network of public sewers was rapidly developed to collect and deliver sewage to treatment facilities. Sewer pipe construction peaked at 68,000 km per annum in 1986. As of 2007, 72% of the population had connected to the public sewer system and construction continues at about 10,000 km per annum. The traditional night soil collection system was progressively abandoned, but is still practiced for about 25 million people living in small towns and in country districts. In those communities with fewer than 50,000 population, the connection rate to a public sewer is still only about 29%. Over time, the night soil collectors have evolved into small local sewer construction and maintenance contractors and some have entered the growing rehabilitation business to exploit their important connections with local government. The Japanese sewer network currently comprises about 380,000 km of pipeline. It is funded by a combination of local and central government support in equal measure at a cost of about ¥ 2,392 billion (U.S. $29.17 billion) per annum. The Tokyo Metropolitan budget is ¥ 120 billion (U.S. $1.46 billion) to provide for repair, rehabilitation, and new construction of its 15,000 km network and treatment facilities. At the present time, this work involves rehabilitation of about 80 km of sewer per annum.

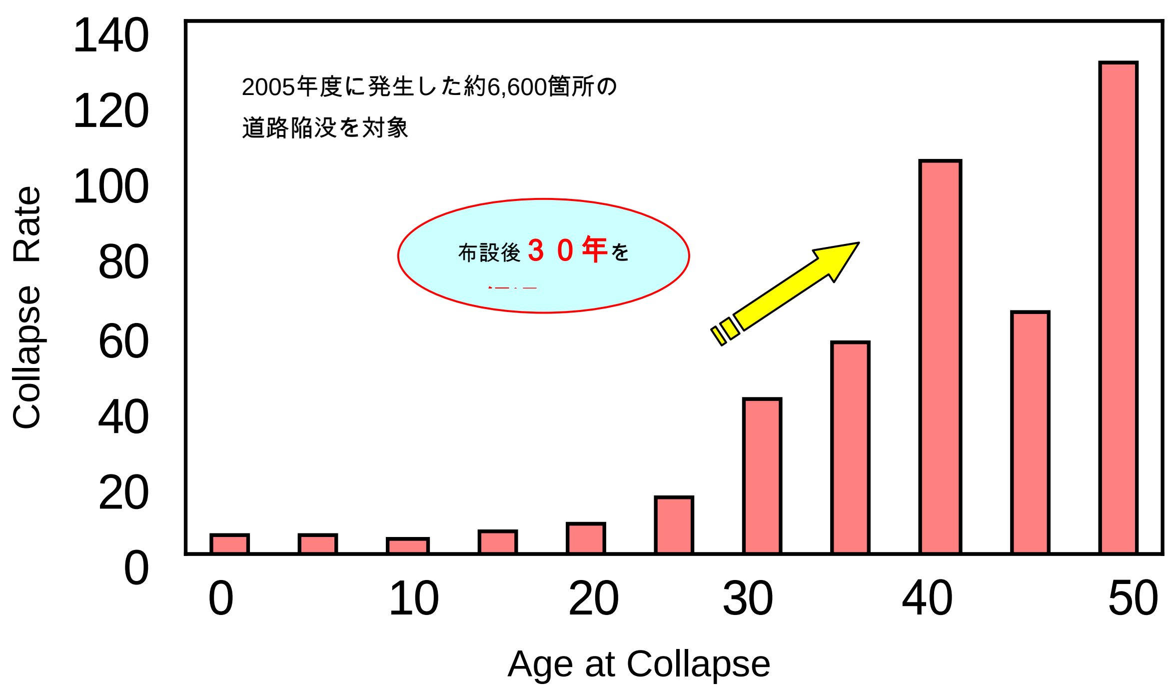
In common with many countries, the life of a sewer pipe in Japan is designated as 50 years. However, in contrast to other countries where the actual life is often substantially longer, the life cycle of pipes installed in Japan is often compromised by a combination of aggressive corrosion and frequent earthquakes. Whilst European and U.S. cities benefit from a legacy of soundly built 19th century underground infrastructure, much of Japan's sewer network was built in a post-war boom by day labor using basic pipe products. Much of the network is reinforced concrete pipeline constructed until the mid 1980s from plain ended (Type A) centrifugally spun concrete pipe with cement mortar joints.

According to the Japan Sewerage Works Agency (JSWA), sewer pipe reconstruction commenced around 1946 and continued through the 1970s by open cut methods at a rate of 15 to 40 km per annum. From about 1975, the rate of replacement increased steadily from 40 to 90 km per annum. The Agency has analyzed the age of pipe at reconstruction finding two peaks of activity, 10 to 20 and 50 to 60 years after installation. The Agency has concluded that the first major peak (at 10 to 20 years) is associated with construction faults and that the latter peak is associated with aging of the fabric of the pipe. JSWA estimates that 6,000 km of the network is more than 50 years old and 50,000 km is over 30 years old. For these reasons, Japan experiences an unusually high and increasing level of sewer collapse. In 2005, there were 6,600 collapses (see Figure 8-1). Thirty-year-old pipes are exhibiting about 40 collapses per 1,000 km of pipe and 50-year-old pipes are collapsing at the rate of about 130 collapses per annum per 1,000 km of pipe (see Figure 8-2).



Source: Nematsu Journal of Japan Sewage Works Association Vol. 44, No 538

Figure 8-1. Total Number of Sewer Collapses per Annum



Source: Nematsu, Journal of Japan Sewage Works Agency Vol. 44, No 538

Figure 8-2. Rate of Collapses by Pipe Age

Condition assessment using CCTV was established in the 13 major cities in 1988, examining 1 to 2% of the pipe stock per annum. The condition is assessed in accordance with the Ministry of Land, Infrastructure and Construction (MLIT) Manual for Construction and Repair of Sewerage Facilities.

The manual prescribes a formal assessment system based on points assigned to defects which is outlined in Tables 8-13 and 8-14, providing a means of ranking the urgency of rehabilitation. In analyzing various sewer lengths, the total points score per span gives rise to a ranking from C to AAA, which determines the action to be taken. Recommended action may require point repair or rehabilitation of the full span. It is usual to rehabilitate the whole span in the event of more than four defects in a single span. Short length rehabilitation or repair may be considered for one to four defects per span.

Table 8-13. JSWA Condition Assessment Method

Type	Symptom	Severity	Pts	Severity	Pts	Severity	Pts
1	Corrosion	Exposed Rebar	20	Exposed Aggregate	15	Other Corrosion	8
1	Pipe Broken	Fracture Collapse	20	Thru-wall crack	16	Other breakage	10
1	Joint Displacement	Withdrawn offset	18	Partial withdrawal	15	Joint gap	3
1	Root intrusion	40% block	20	10-40% block	10	<10% block	5
1	Mortar Adhesion	>33% dia.	20	10-33% dia	15	< 10%	8
2	Cracks	> 5mm	15	2-5mm	10	<2mm	5
2	Protruding laterals	50% of dia.	15	25-50% dia.	5	<25% dia.	1
2	Infiltration	Running	12	Trickling	2	Soaking	1
3	Settlement	75% dia.	10	50-75% dia.	8	<50%	5
3	Displaced Seals	> 50% Circ	4	> 25%Circ	3	<25% Circ	2
	Fat	>33% dia	20	10-33% dia	15	<10% dia	8
	Sediment	20xDepth ratio					

Type 1 – seriously affects pipe function, Type 2 – affects pipe function, Type 3 – slightly affects pipe function.

Table 8-14. JSWA Ranking System

Rank	Points per span	Priority
AAA	70+	Extremely Urgent
AA	40-69	Urgent
A	20-39	Urgent
BBB	15-19	Repair needed
BB	10-14	Repair needed
B	5-9	Repair needed
CCC	3-4	No action required
CC	2	No action required
C	0-1	No action required

Rehabilitation methods are classified as standalone, two layered, or complex pipe. The standalone pipe (similar to the ASTM fully deteriorated category) presumes no residual strength in the existing pipe and the liner is designed for soil, hydrostatic, and traffic loads. The two layered structure contemplates a degree of support from the existing pipe (similar to the ASTM partially deteriorated category) and the liner is designed to support the hydrostatic load only. The complex pipe is that in which the liner is integrated into the fabric of the pipe (similar to the Water Research Centre [WRc] Type 1). The design methods are detailed in the Guide to Pipeline Rehabilitation developed by the Japan Institute of Wastewater Technology (JIWET), published by JSWA in English and Japanese in June 2001. The guide has just been revised and expanded by JIWET to include site management and quality assurance measures. It was published in Japanese only by JSWA in June 2007.

In the period 1988-2006, renovation by repair using resin injection and rehabilitation using hose lining, fold-and-form, and spiral pipe renewal (SPR) methods grew rapidly (see Figure 8-3). Sewer maintenance is funded solely from local government funds. Network rehabilitation has been growing steadily since 1986 and is currently undertaken at a rate of almost 500 km per annum. Information obtained from the Japan Pipe Rehabilitation Quality Assurance Association (JPRQAA) is indicated below for the period 1986 to 2009. Almost 4,800 km of sewer have been renovated by inversion (1,994 km), pull-in-and-inflate (2,051 km), and spiral wound methods (745 km). The figures for the pull-in-and-inflate method include both UV and steam cured CIPP and fold-and-form methods (ExPipe and Omega Pipe).

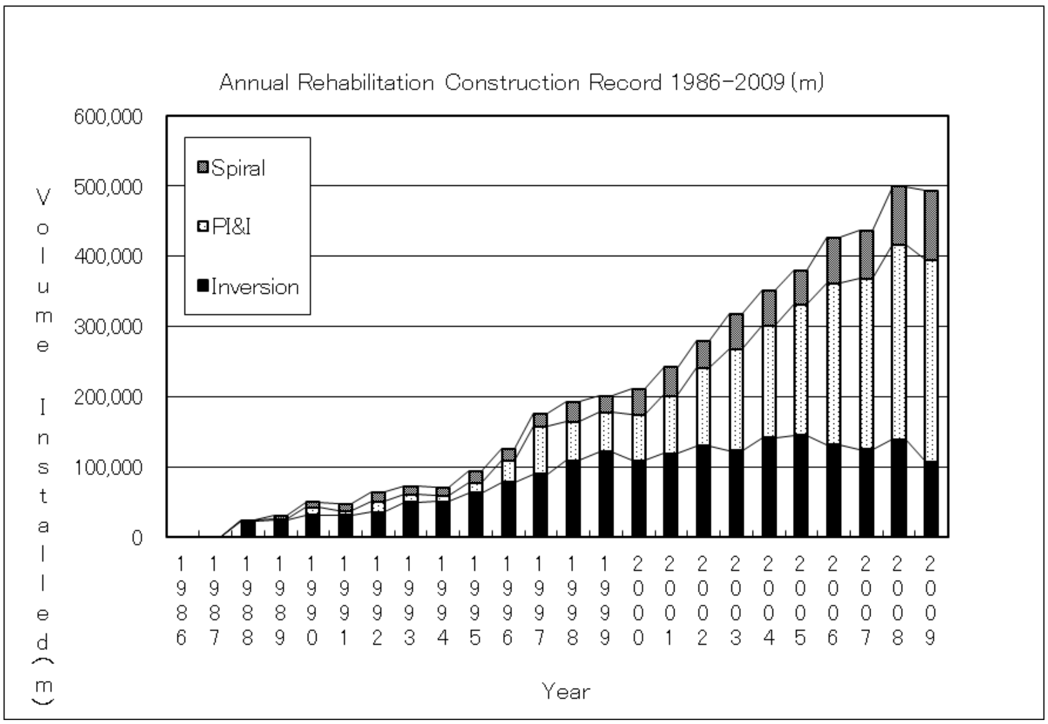


Figure 8-3. Annual Rehabilitation Construction 1986-2009

CIPP was introduced into Japan by Insituform under license to line H_2S corroded sewers under the New Tokyo International Airport in 1986. Hose lining systems, Paltem and Phoenix developed in Japan for gas pipe rehabilitation were applied to sewer rehabilitation in 1988 and spiral wound pipe was imported from Australia and adopted by Sekisui in 1989. The Omega fold-and-form system developed by Sekisui was launched in 2009 and the InPipe UV light curing CIPP was adopted in 1991. The annual rehabilitation volume grew rapidly from 50 km/year in 1991 to 200 km/year in 1999. In the early years, the preferred method was CIPP installed by inversion but, by 2005, installation by pull-in-and-inflate methods (both CIPP and fold-and-form) took 50% of the market and these are now being used for 60% of rehabilitation works. Currently, spiral wound pipe takes 20% of the market with 60% of that volume in diameters over 800 mm. In 2009, the methods used were broken down by method and diameter as shown in Figure 8-4.

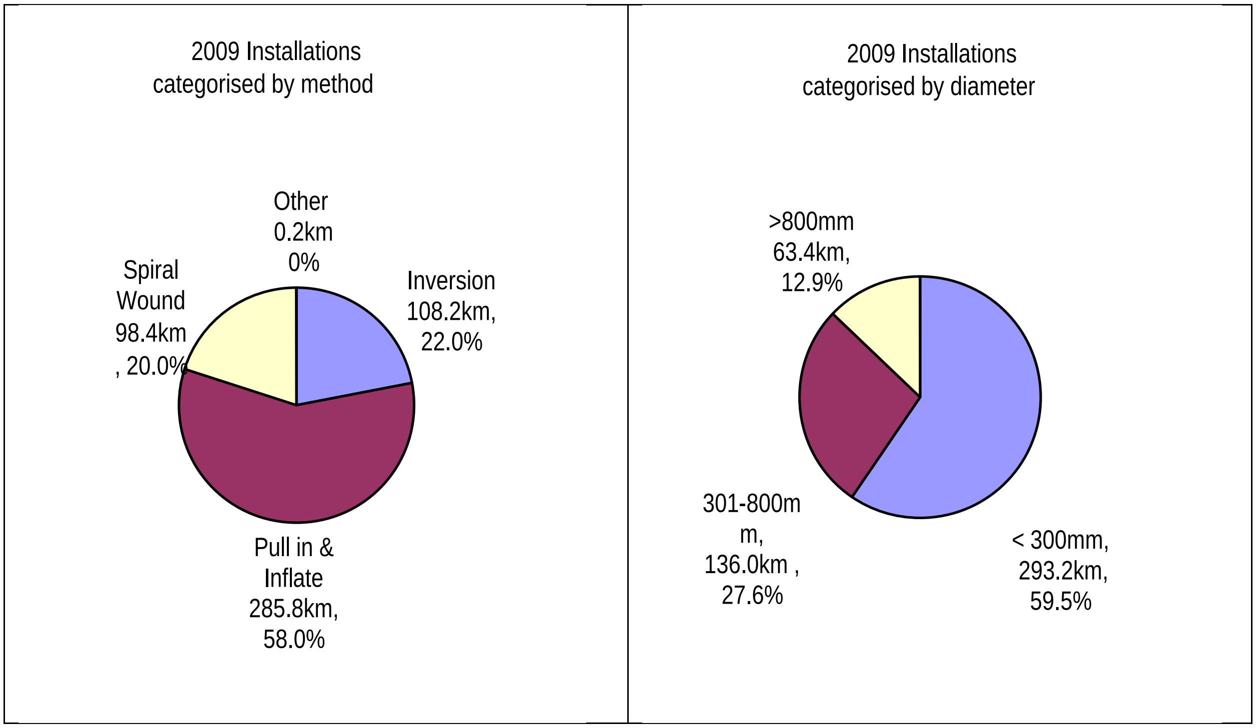


Figure 8-4. Installations Categorized by Method and Diameter for 2009

The rehabilitation systems available in Japan are licensed to contractors by domestic and international system developers. Groups of licensees, installers, and companies in the materials supply chain for given systems are usually organized together as rehabilitation system associations. Such associations in Japan may have as many as 500 members and contractors may belong to a number of associations depending on the systems they offer. The associations provide a platform for technical and commercial activity for the members who may be relatively small local companies providing sewer maintenance capability to their municipalities.

The JIWET was established by the Ministry of Construction in 1992 to undertake the research and development for new sewer construction and rehabilitation technologies and sewage treatment. It has had a particularly important role in evaluating and certifying technologies in the rehabilitation field. JIWET provides teams of engineers to undertake the investigative work and organizes committees for evaluation of new construction and rehabilitation under the chairmanship of leading academics. Activity has grown substantially. In 2009, JIWET certified or renewed 52 new or improved technologies, including eight for pipe and manhole rehabilitation and three for pipe repair methods. Products and processes are re-evaluated and certified after five years, subject to performance in use.

The JPRQAA was launched in August 2006 and represents the interest of the system providers and associations in connection with a variety of government agencies to have rehabilitation recognized as equivalent to replacement. The organization collects data on the activities of the system associations and is a technical resource for monitoring industry quality and performance

The Japan Sewer Collection Maintenance Association (JASCOMA) was set up in 1987 as an organization of 467 firms and 24 associations involved in sewer cleaning, assessment, and rehabilitation. It has provided examination and certification for technicians involved in pipe maintenance since 1998 and, in 2003, it set up a scheme to inspect and certify contractors.

The business of pipeline rehabilitation in Japan is rigorously organized by these and other organizations such as the Japan Sewage Works Association, which regulates the design process and works closely with the Japan Industrial Standards Organization. Japan currently provides the Chairman and Secretariat for the International Standards Organization Technical Committees and Working Groups in the field of water and wastewater pipe rehabilitation. At a site level, CCTV examination, measurement and sampling, and testing are required on all installations in accordance with JSWA regulations and many sites are re-examined after one year.

Regarding quality controlled testing of liner materials after curing, most municipalities are requesting a test of the actual cured liner. However, their requirement varies municipality by municipality. In the case of Osaka City, they require all installers to conduct a QC test of each span of the project. However, conduct of the testing is not limited to authorized laboratories and a test by the supplier is acceptable. In other cities, such as Tokyo, the independent laboratory is utilized, but one sample from each project is sufficient.

8.8 Approach to Retrospective Evaluation in Quebec

As a complement to the international scan information collected and described above, the research team also contacted the Centre de Recherche des Infrastructures Urbains (CERIU) in Montreal, Canada (www.ceriu.qc.ca) to gather information about a retrospective evaluation study that was underway in the Province of Quebec. This summary has been prepared on the basis of discussions with Isabel Tardiff, Technologies Director at CERIU on January 5, 2010. The purpose of the discussions was to establish the type of retrospective evaluation that was underway in Quebec, how far it had progressed, and to share information on the types of evaluation procedures that were being used in Quebec and in the EPA study.

The Quebec study is looking at the entire spectrum of rehabilitation efforts in the province including water main rehabilitation (which has been active since 2001) and sewer main rehabilitation (which has been active for significantly longer). The purpose of the study is to see how the prior rehabilitation work is holding up now and to see if the information will allow the rate of degradation to be assessed. The project is being managed through the municipal entities in the Province with CERIU as a consultant to the study. A study group involving the interested cities, CERIU, and others was formed, but does not involve many small cities since they are not much involved in rehabilitation efforts yet. Target cities for the retrospective evaluation effort were identified. The management of the project has a "Director" committee composed only of municipal members plus two other committees covering potable water and sewers/manholes. Contractors and consultants are not involved in the Director committee, but are involved as appropriate on the other committees. The universities of Concordia (sewer rehabilitation) and Ecole Polytechnique (water) are supporting the study.

The City of Montreal has been doing water rehabilitation since 2001. In total, 10 municipalities were named for the study and key participants and volunteers had been identified at the time of the conference call. It had been important to orient everyone as to the goals and scope of the study and to clarify the types of deliverables anticipated. Risks affecting the outcome of the study were considered to include: non-participation by cities and inadequate administrative support or manpower to collect and analyze the required data. Senior city administrators were called if necessary to bolster support for the study and a communication plan was prepared – laying out when data would be released, etc. Budget aspects of the study were further explored to establish the practical extent of in-service testing and the costs of specific tests that might be used. Milestones for the project were established and the specific team members that would do the analyses had been identified. The Directors committee was active in encouraging the participating municipalities to contribute in-kind help to the data collection and study efforts.

The benefits of the Quebec study were seen to be that rumors about rehabilitation performance can be addressed and that information critical to life cycle analysis of rehabilitation efforts could be collected.

A strategic decision was made in the study to cover as much of the rehabilitation work as possible so that the general condition of rehabilitated lines and any visible defects could be identified. This led to the broad use of CCTV for the assessment work. Specific samples were to be collected for quantitative analysis based on a review of the CCTV data and the available budget. A survey was sent out to the municipal participants to establish how many meters of rehabilitation had been accomplished in each municipality. The survey was also sent to contractors with the promise to keep the data as confidential as possible.

On the water rehabilitation side, the collection of data on rehabilitated lines had been relatively simple since there were only two contractors doing the water rehabilitation work. On the sewer side, the situation was more complex. The contractors had changed over time and there was a need to provide even representation in the study.

Some cities had already conducted a 10-year evaluation of their own rehabilitation program, e.g., Quebec City for CIPP relining. CERIU had conducted a review of 12 techniques for manhole rehabilitation in 1999 and had followed up with further evaluation in 2004 and 2009. The evaluation techniques used were visual inspection plus hammer tapping to identify liner defects. The results of the inspection were good and a report was to be released soon.

The universities participating in the current retrospective evaluation were focused on physical sampling for CIPP and pull-in-place liners, etc., but the budget was very limited. The committees for the project were making decisions about what should take precedence: inspection, sampling, or testing.

Many cities have done prior CCTV inspection. Montreal has 20-year old grouting rehabilitation of manholes and mainlines that was recently been reinspected by CCTV in October 2009.

Physical samples for sewer lines were planned to be retrieved principally from person-accessible locations (adjacent to manholes, person-entry diameter pipes, etc.). Concordia University was to do the testing and analysis. Both destructive and NDT methods were to be used. Some of the test parameters were to include: Manning's coefficient, liner/sample dimensions, ease of repair, permeability at connections, flow, and pressure. Most municipalities have before and after CCTV scans for the rehabilitation. Some municipalities have follow-up CCTV one and five years later.

Some of the municipalities involved in the Province study have mostly done grouting work and some mostly CIPP. Two pipe groups were anticipated for sample retrieval for water mains: 6 in. diameter and less and greater than 6 in. diameter. One meter long samples were expected in a full pipe sample retrieval. Studies of grouting effectiveness were planned to be done by internal pressure testing. Where the section would not pass, excavation was planned to see if a grout ball exists outside the pipe at this location.

Testing specifics anticipated were:

- Evidence of water leakage
- General state
- Hazen-Williams coefficient data (static and dynamic testing)
- Water connection integrity
- Pressure and flow data

- Destructive testing (but will not carry out toxicity testing)
- Thickness of liner
- Internal pressure testing
- Verification of resin penetration at connections
- Three-point bending tests to rupture
- Live loading assessment
- Peel resistance for coatings
- Conformance of liner fracture to pipe fracture

In summary, the Province of Quebec is undertaking a broad retrospective evaluation of rehabilitation technologies used for sewer collection pipes, manholes, and water distribution pipes with activities that are very complementary to the work described in this report.

9.0: SUMMARY AND RECOMMENDATIONS

9.1 Summary

9.1.1 Tasks to Date. This retrospective evaluation pilot study grew out of discussions among the research team during the early stages of the overall project, Rehabilitation of Wastewater Collection and Water Distribution Systems, which was to perform a comprehensive review and evaluation of existing and emerging rehabilitation/ repair technologies for wastewater collection and water distribution systems and to conduct demonstrations of innovative sewer and water rehabilitation technologies. The need for such information was reinforced by the participants at an international technology forum held as part of the project activities in September 2008.

The initial effort in terms of retrospective evaluation was planned as a pilot study. It targeted CIPP installations only, concentrated on quantitative testing of the CIPP liners, and used samples from both large and small diameter sewers in two cities, Denver and Columbus. For the small diameter (8 in.) sewers in each city, a 6-ft section of pipe and liner was exhumed from a convenient site. For the larger diameter sewers (36 to 48 in. diameter), CIPP liner samples were cut out from the interior of the pipe and the liner patched in-situ.

Testing on the liners included: thickness, annular gap, ovality, density, specific gravity, porosity, flexural strength, flexural modulus, tensile strength, tensile modulus, surface hardness, glass transition temperature, and Raman spectroscopy. In addition, environmental data was gathered as appropriate to each retrieval process including: external soil conditions and pH, and internal waste stream pH. The findings from the testing conducted so far are summarized in the following subsections.

As a companion to the pilot studies in Denver and Columbus, an international scan was made of the approaches used by sewer agencies overseas to oversee their CIPP rehabilitation activities and to track the subsequent performance of installed liners. A variety of approaches are used – more in the area of QA/QC at the time of installation than a planned program of follow up to track deterioration of rehabilitation technologies over time.

Given the insights provided by the pilot studies in Denver and Columbus and the international scan, recommendations are made for an expansion of the retrospective evaluation study to create a broader national database that would help to define the expected life of sewer rehabilitation technologies.

9.1.2 CIPP Liner Condition Findings to Date. All of the samples retrieved from the four locations (five individual liners) involved in the pilot study testing were in excellent condition after being in use for 25 years, 23 years, 21 years, and 5 years. Four of these liners had already been in service for approximately half of their originally expected service life of 50 years. Two sets of coupons out of six sets from five sites had a flexural modulus value that was lower than the originally specified value, but this cannot be tied directly to deterioration of the liner over time. In the case of the Denver 48-in. upstream liner, in particular, it appears likely that the poor physical test properties may have resulted from variability within the liner rather than a change over time since the second set of coupons tested produced much higher test values. Some indication of a softening of the interior surface of the liner that was exposed most to the waste stream (interior invert and spring lines) relative to the interior crown location and that of the exterior surface of the liner was noted in much of the surface hardness testing. However, it is not yet possible to isolate any effect on the resin liner itself from the hydrolysis of the handling layer that was originally present on the inside surface of the CIPP liner. For newer CIPP liners, a different handling/inner layer is used with greater durability.

In Denver, in CCTV inspections of nearly 5,800 ft of CIPP liners installed at the same time as the retrieved sample, a few specific defects were noted at different locations. Most of these appeared to relate to poor practices in cutting or reinstating lateral connections and only three appeared potentially unrelated to lateral reinstatement issues. These were a local liner bulge, a separation of the liner from the wall of the pipe, and a local tear in the liner.

Overall, there is no reason to anticipate that the liners evaluated in this pilot study will not last for their intended lifetime of 50 years and perhaps well beyond.

9.1.3 Initial Findings on Value of Various Physical Testing Approaches. The testing carried out on the CIPP liners and the data collected about the site and environment in which they were used was intended to try to capture any evidence of liner deterioration and possible reasons for such deterioration. The potential value of each type of testing to broader retrospective evaluation studies is briefly identified below.

9.1.3.1 Soil Conditions. Soil testing, including soil type, gradation, density, moisture content, pH, etc., would only be available during a dig-up of a pipe or liner sample. The data could help to identify if the host pipe had uniform soil support or was developing external voids due to leakage into the pipe. The data also can provide a background on external conditions that may relate to corrosion/deterioration of the liner and/or the host pipe. For example, for steel, cast iron, and ductile iron pipes, a number of tests (e.g., soil resistivity, pH, redox potential, presence of sulphates and chlorides, etc.) have been proposed for determining the expected rate of external corrosion of uncoated pipelines. The data is not difficult to collect when an excavation is made and provides a basis to answer questions about external pipe conditions if such questions arise. Soil samples taken during excavation, but not tested unless needed could also provide important backup for later testing as needed, but moisture content and pH at a minimum should be determined when soil sampling is conducted.

9.1.3.2 Visual Inspection. A thorough visual inspection is important to provide the overall appearance of the liner and any evidence of surface changes such as the deterioration or loss of the internal sealing layer, evidence of leakage (e.g., discoloration), or porosity. As with any visual condition assessment using a standard protocol for recording the findings is important to create useful results in a broad database.

9.1.3.3 Thickness and Annular Gap. The thickness of the liner is a critical parameter for the resistance of the liner against a variety of potential failure modes. In particular, it indicates (in conjunction with other physical liner properties) whether the liner currently meets the requirements of ASTM F1216 in terms of its resistance to external buckling. Annular gap measurements provide information about potential shrinkage or displacement of the liner away from the host pipe. A significant annular gap may allow longitudinal movement of the liner in the pipe and increase the possibility of liner buckling under external pressure. A significant annular gap also increases the potential for water migration between the host pipe and the liner. If lateral connections and/or liner terminations at manholes are not sealed, then infiltration into the sewer system can occur.

Annular gap can be measured easily and effectively with feeler gauges. Thickness can be measured using calipers within the area of a sample or a ruler at the edge of the sample. Ultrasonic measurements can also be made when only one side of the sample is available and are potentially very useful both for retrospective evaluations and for QA/QC of new installations. In this pilot study, poor success was experienced with the ultrasonic measurements. They correlated with physical measurements on laboratory-prepared thinner liner samples, but did not return useful results on the field-installed or thicker liners. The problem is thought to be related to the dissipation of the acoustic signal in the resin-fiber composite. More research on identifying or developing a better NDT method or equipment for in-situ liner thickness measurement is recommended.

9.1.3.4 Flexural and Tensile Testing. The testing of flexural specimens for the structural performance represented by the flexural strength and flexural modulus is often carried out since it can be compared with the specified values in the ASTM F1216 standard. Tensile strength and tensile elongation at break also have been measured values when structural liner performance is investigated. In this study, other parameters such as the tensile modulus were also recorded. From the testing conducted so far, the flexural modulus tests provided the most useful values for interpretation but, of course, that may not be the case for all types of liner issues. The tensile elongation at break varied over a wide range in the tests conducted. Typically, when flexural and tensile testing is carried out, all the parameters mentioned above are easily measured and recorded and could prove useful in a larger data set for establishing correlations among types of liner defects and the test values for each parameter.

9.1.3.5 Surface Hardness Testing. Surface hardness testing was found to reveal differences between the hardness of the inner surface of a CIPP liner and its external surface and to reflect the low flexural modulus value and the variability of the tensile elongation at break value of the Denver 48-in. upstream liner sample. While few conclusions can be drawn from the surface hardness data collected to date, this type of testing appears to hold promise for evaluation of liner properties – either as-installed or their degradation over time. As a non-destructive test that could potentially be deployed in pipelines of 8-in. diameter (and larger), such a test could provide a quantitative non-destructive measure of great value and it is recommended that further investigations of data correlations and test adaptations to in-pipe measurements should be pursued.

9.1.3.6 Material Composition Testing. It is considered very important in the assessment of liner deterioration to find a test or set of tests that will shed light on chemical or physical changes occurring in the liner material over time. Tracking the rate of such deterioration (in conjunction with other liner and site characteristics) would provide important information in projecting the lifetime of a liner. In the pilot study, no evidence of liner deterioration was seen in the Raman spectroscopy and differential DSC testing that was carried out. This is either due to the lack of deterioration in the samples tested compared to the virgin resins tested or because the test is not sensitive to any type of deterioration that may, in fact, be occurring. It is recommended that these tests and/or similar forms of material testing be applied to deliberately aged liner specimens to establish the signatures of particular forms of deterioration before they be applied in a wider context for tracking liner performance in the field.

9.1.4 Recommendations for National Data Compilation and Management. The ultimate goal of carrying out retrospective evaluations is to be able to provide better guidance to municipalities on the long-term performance of the various rehabilitation technologies available to them. Table 7-3 provided a summary of an overall structure that could be used for a database to accommodate the differences in the types of technologies used and the specifics of those technology applications. It is suggested that the categorization of the city experiences be able to be as detailed as the city data would allow, but would also allow information capture at a broader level when only that level of information was available. As discussed in Section 7.3, broad interpreted data from agency records, CCTV inspections, and condition assessment databases need to be accessed in addition to well characterized, quantitative data from retrospective liner testing or the use of specific NDT approaches to liner evaluation. However, it is not intended that the database would attempt to include all of the individual CCTV or condition assessment data that cities are collecting. Rather, the database proposed would contain the interpreted results from agencies of the performance of rehabilitation technologies plus specific physical or NDT that addresses liner performance or degradation.

9.2 Recommendations for Future Work

9.2.1 Recommendations for Continued Retrospective Evaluations on Retrieved Samples. The expected life of rehabilitated sewers is critical to the effective asset management of sewer systems and yet very little quantitative study has been made to determine the performance and/or degradation of rehabilitation technologies with time. This pilot project examined five CIPP liners at four sites in two cities. The results are very promising for a life of CIPP liners that will meet or exceed the 50 years which has been taken as the nominal life expectancy for such liners. The results, however, cannot be taken as representative of the tens of thousands of miles of rehabilitated sewers that have already been installed using many variations of CIPP and other rehabilitation technologies. It is recommended that the pilot studies and retrospective evaluation program be extended to cover the following activities:

- Additional CIPP sample retrieval in other cities with a wider variety of site and sewage flow characteristics.
- Pilot studies of other sewer rehabilitation technologies – focusing initially on those with the greatest number of years of service. As with the current CIPP study, the pilot study would seek to identify the most useful quantitative tests that could be used to evaluate performance, degradation, and expected remaining life.
- A broader survey to capture the locally interpreted data from a wide range of cities on their experiences with rehabilitation technologies.
- An effort to encourage sewer agencies to keep as-installed material test data for later comparison with follow-up testing. This should include working with the most widely used database and asset management systems to make sure that such information can readily be incorporated and identified using their software.
- Additional research on root cause analysis of CIPP failures.

9.2.2 Recommendations for Development and Calibration of NDT Protocols. The alternative to obtaining large physical samples for quantitative testing is to use NDT to obtain meaningful data, which was also recommended by the utilities participating in this study, and/or to test small physical samples that are easily retrieved robotically from inside the pipe and easily repaired. This project has tested several quantitative liner characterization tests that could be expected to be developed for robotic deployment within sewer mainlines of 8-in. diameter and larger. It is recommended that additional research be carried out to develop and characterize the most promising NDT protocols.

10.0: REFERENCES

Akinci, A., A. Gulec and F. Yilmaz. 2010. "The Applicability of GRP and NRP composites in Rehabilitation of Unpressurized Pipes," *Advanced Materials Research*, Vol. 83-86, pp. 563-570.

Araujo, T., S. Sabeshan and B. Yao. 2009. "Factors Affecting the Quality of Flexural Properties from CIPP Field Samples," *Proc. Intl. No-Dig 2009*, NASTT/ISTT, Toronto, Mar 29-Apr 3.

Bakeer, R., L. Guice, V.F. Sever, and G.R. Boyd. 2005. "Fluid Migration into Lined Pipelines." *Tunneling and Underground Space Technology*, Vol. 20 No. 5, pp. 452-462.

Bakeer, R. and F. Sever. 2008. "Quantification of Annular Flow in Lined Pipelines," *Tunneling and Underground Space Technology*, Vol. 23, No. 6, pp. 727-733.

Barsoom, J. 1993. "Denver's Experience in Trenchless Technology," *Proc. Trenchless Technology: An Advanced Technical Seminar for Trenchless Pipeline Rehabilitation, Horizontal Directional Drilling and Microtunneling*, Jan 26-30, 1993, Vicksburg MS, pp. 45-52.

Bennett, R.D., L.K. Guice, S. Khan, and K. Staheli. 1995. *Guidelines for Trenchless Technology: Cured-in-Place (CIPP), Fold-and-Formed Pipe (FFP), Mini-Horizontal Directional Drilling (Mini-HDD), and Microtunneling*, Technical Report CPAR-GL-95-2, Construction Productivity Advancement Research (CPAR) Program, U.S. Army Corps of Engineers, September.

Bonanotte, R. and E. Kampbell 2004. "Chicago Cures Ailing 100-year-old Sewers," *Public Works*, Vol. 135 No. 5, pp. 130-131.

Brand, M., D. Krywiak and D. Willems. 2009. "Butterfield Storm Sewer CIPP Rehabilitation," *Proc. Intl. No-Dig 2009*, NASTT/ISTT, Toronto, Mar 29-Apr 3.

Bruzzone, A., P. Lonardo, and G. Diverio. 2008. "Experimental characterization of ." *Proc. Intl. No-Dig*, Rome, Italy, Paper S3-08.

Dawson, D. 2008. "CIPP Lights Way in Buried Pipe Repair," *Composites Technology*, April.

Donaldson, B.M. 2009. "The Environmental Implications of Cured-in-Place Pipe Rehabilitation Technology," *Proc. TRB Annual Meeting, Jan 2009 (CDROM)*. Transportation Research Board, Washington, D.C.

Downey, D. 2010. "The Story Behind the Pipe: an Inside Look at CIPP," *Trenchless International*, Issue 9, Oct. 2010, pp. 28-29.

Downey, D. 2011. Personal communication, Jan. 14.

Driver, F.T. and M.R. Olson. 1983. *Demonstration of Sewer Relining by the Insituform Process, Northbrook, Illinois*, U.S. Environmental Protection Agency, Report No. EPA-600/S2-83-064, September.

El-Sawy, K. and I.D. Moore 1998. "Stability of Loosely Fitted Liners Used to Rehabilitate Rigid Pipes," *Journal of Structural Engineering*, ASCE, Vol. 124, No. 11, November, pp. 1350-1357.

Falter, B. 1996. “Structural Analysis of Sewer Linings,” *Tunneling and Underground Space Technology*, Vol. 11, Supplement 2, pp. 27-41.

Falter, B., 2004. “Lining Stability: an Analysis of Damaged Sewers,” *Proc. No Dig 2004*, New Orleans, March.

Falter, B. 2008. “New Developments in Liner Design to ATV-M 127-2,” *Proc. NASTT No-Dig Conf.*, Dallas, Apr 27-May 2.

Guice, L.K., C. Norris, D.T., Iseley, and M. Najafi. 1993. “Description of Long-Term Hydrostatic Pressure Testing of Pipeline Rehabilitation Materials,” *Proc. Water Environment Federation Conference on Collection Systems: Operation and Maintenance*, June.

Guice, L.K., W.T. Straughan, C.R. Norris, and R.D., Bennett. 1994. *Long-Term Structural Behavior of Pipeline Rehabilitation Systems*, Task Report for the Construction Productivity Advancement Research (CPAR) Project, U.S. Army Engineers and Trenchless Technology Center, August.

Gumbel, J. 2009. "Recent International Developments in Testing of CIPP (United Kingdom)," *International NO-DIG 2009*, NASTT/ISTT, Toronto, Ontario, Canada, Mar 29-Apr 3.

Hahn, D. 2007. “Risk Mitigation of Large-Diameter, Cured-in-Place Pipe Rehabilitation Work Utilizing Fiber-Reinforced Composite Sandwich Technology, *Composites in Manufacturing*, Vol. 23, No. 4.

Hall, D. and J. Matthews. 2004. "Fluid Migration in the Annular Space of Rehabilitated Pipelines: A Comparison of Insituform’s Inverted and ILS Products," Trenchless Technology Center Report, August.

Hall, D.E. and M. Zhu. 2000. "Recent Findings and Ongoing Liner Buckling Research at the Trenchless Technology Center," *Proc. North American No Dig 2000*, Anaheim, California, April. pp. 77-84.

Hannan, P.M. 1990. “Cured-in-Place Pipe: An End User Assessment.” *Buried Plastic Pipe Technology*, ASTM Special Technical Publication 1093, Buczala, G.S. and M.J. Cassady, eds., ASTM, Philadelphia.

Hansen, B. 2005. “Newark’s Brick Sewers Reinforced with Cured-in-Place Pipe,” *Civil Engineering*—ASCE, Vol. 75, No. 6, pp. 27-28.

Hayden, M. 2004. “Comparison of filled vs. neat resins for CIPP.” *NASTT No-Dig*, New Orleans, LA, Paper E-3-03.

Herzog, D.J., A.J. Bennett, K. Rahaim, J.D. Schiro and R.E. Hudson. 2007. “A Comparison of Cured-In-Place-Pipe (CIPP) Mechanical Properties - Laboratory vs. Field,” *Composites & Polycon 2007*, October 17-19, Tampa, FL, American Composites Manufacturers Association.

Hudson, R.E. 1993. “Houston Experience: Rehabilitation Costs,” *Proc. Trenchless Technology: An Advanced Technical Seminar for Trenchless Pipeline Rehabilitation, Horizontal Directional Drilling and Microtunneling*, Jan 26-30, Vicksburg MS, pp. 53-65, Trenchless Technology Center, Louisiana Tech University, Ruston LA.

Hutchinson, M.W. 1998. “Lessons Learned about Cured-in-Place Pipe During Construction,” *Pipelines in the Constructed Environment*, Proc. Pipeline Division Conference, San Diego, CA, Aug 23-27, pp. 752-762, ASCE, Reston VA.

Iseley, D.T. 2011. Personal communication, Feb. 4.

Khan, S.A. 2005. “Trouble Shooting for Liner Installation: Observations and Recommendations based on Field Experiences,” *Proc. NASTT No-Dig Conf.*, Orlando FL, Apr 24-27.

Kahn, S. and C. Dobson 2007. “Just Like New,” *Water Environment & Technology*, Vol. 19 No. 3, pp. 52-57.

Kampbell, E. 2009. *Guideline for the Use and Handling of Styrenated Resins in Cured-in-Place Pipe*, NASSCO, 13 pp. Available at http://nassco.org/publications/misc/styrene_report_8-09.pdf

Kampbell, E., D. Downey and W. Condit. 2011. *Quality Assurance and Quality Control Practices for Rehabilitation of Sewer and Water Mains.* EPA/600/R-11/017. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Edison NJ. www.epa.gov/nrmrl/pubs/600r11017/600r11017.pdf

Kapasi, S. and D. Hall. 2002. "Monitoring Deflections of Pipe Liners Under External Water Pressure During Liner Buckling Experiments," *Proc. North American NO-DIG 2002*, NASTT, Montreal, Canada, April 28-30.

Kleweno, D. 1994. “Physical properties and chemical resistance of selected resin for CIPP rehabilitation.” *Buried Plastic Pipe Technology*, 2nd Vol., ASTM, Philadelphia, PA.

Knight, M. and K. Sarrami. 2009. “Testing of CIPP Resins used within the City of Toronto Sewers,” *Proc. NASTT No-Dig Conf*., San Diego, Apr 16-19.

Kurz, G.E., G.A. Ballard and L.B. Scott. 2009. “Nashville Project Shows Long-Term Effectiveness of Sewer Rehabilitation for Infiltration Reduction,” *Proc. Intl. No-Dig 2009*, NASTT/ISTT, Toronto, Mar 29-Apr 3.

Law, T.C.M., and I.D. Moore. 2007. “Numerical Modeling of Tight Fitting Flexible Liner in Damaged Sewer under Earth Loads,” *Tunneling and Underground Space Technology*, Vol. 22, pp. 655-665.

Llagas, M.P. and D. Cook. 2004. “Pipeline Rehabilitation in the R.O.W. and Easements - Phase A,” *Proc. ASCE Pipeline Division Specialty Congress - Pipelines 2004 - What's on the Horizon*, pp. 139-149, Am. Soc. Civil Engrs., Reston VA.

Larsen, J.P., J.N. Struve, F. Bloetscher and D. McLaughlin. 1997. “After Rehabilitation, Then What?,” *Water Environment & Technology*, April, pp. 45-49.

Lee, R.K. 2008. “Risks Associated with CIPP Lining of Storm Water Pipes and the Release of Styrene,” *Proc. NASTT No-Dig Conf*., Dallas, Apr 27-May 2.

Lee, R.K. and S. Ferry. 2007. “Long-Term CIPP Performance and its Design Implications,” *Proc. NASTT No-Dig Conf*., San Diego, Apr 16-19.

Lehmann, M.A, J.P. Schroeder and C.M. Saunders. 2009. "Challenges and Lessons Learned using Air Inversion and Steam Cure for CIPP Sewer Rehabilitation."*Proc. Intl. No-Dig 2009*, NASTT/ISTT, Toronto, Mar 29 - Apr 3.

Li, J.Y., and L.K. Guice. 1995. "Buckling of an Encased Elliptic Thin Ring," *ASCE Journal of Engineering Mechanics*, December.

Lindsey, S.E. 2007. "What Every System Owner Should Know about CIPP," *Water Environment & Technology*, Vol. 19 No. 1, January, pp. 59-62.

Martin, S. 2007. "Crescent City Rebirth includes CIPP," *JEC Composites Magazine,* Vol. 44, No. 33, pp. 37-38.

Matthews, J., W. Condit and R. McKim. 2011. *Decision Support for Renewal of Wastewater Collection and Water Distribution Systems*, Report to EPA under Contract No. EP-C-05-057. Task Order No. 58, National Risk Management Research Laboratory, in press.

Moore, I. 2008. "Assessment of Damage to Rigid Sewer Pipes and Erosion Voids in the Soil, and Implications for Design of Liners," *Proc. NASTT No-Dig*, Dallas, Texas, April 27–May 2.

Nelson, K., T. Tekippe, R. Matheson, R. Ohlemutz and B. Pomeroy, 2005. "Case Study: Large Diameter Cured-in-Place Plastic Pipe," *Proc. NASTT No-Dig*, Orlando, FL, Apr. 24-27.

Omara, A.A., L.K. Guice, W.T., Straughan, and F.A. Akl. 1997. "Buckling Models of Thin Circular Pipes Encased in Rigid Cavity," *ASCE Journal of Engineering Mechanics*, December.

Osborn, L. 2011. Personal communication February 2.

Pang, X., L. Goodrich, and S. Ahmed. 1995. "Testing Quality Assurance in CIPP Systems," *Pipeline Digest*, November, pp. 19-21.

Pennington, R.A., K.A. Gersley, A.L. Zach, and J.T. George. 2005. "Brick Sewer Evaluation and Rehabilitation Program in Newark, New Jersey," *Proc. NASTT No-Dig*, Orlando, FL, Apr. 24-27.

Potvin, D., E. Waite, and B. St. Aubin. 2008. "Assessment of CIPP Liner Performance in Contaminated Soils," *Proc. NASTT No-Dig*, Dallas, Apr 27-May 2.

Rahaim, K. 2009. "Cured-in-Place Pipe: Past, Present and Future," *Trenchless International*, July, Great Southern Press, Sydney, Australia. Available at http://trenchlessinternational.com/news/cured-in-place_pipe_past_present_and_future/000863/

Roeling, M. 2009. "UV-Light Curing of Cured-in-Place Pipes with LEDs," *Proc. Intl. No-Dig 2009*, NASTT/ISTT, Toronto, Mar 29-Apr 3.

Rose, J.J. and L.X. Jin. 2006. "Resin Choices for Cured-in-Place Pipe (CIPP) Applications," *Proc. COMPOSITES 2006 Convention and Trade Show,* October 18-20. St. Louis, MO, American Composites Manufacturers Association, Arlington VA.

Schwarz, W. 2007. "Sewer Rehabilitation: Integral Component of an Infrastructure Rehabilitation Program in Fort Lauderdale, FL– Part II, Implementation and Results," *Proc. NASTT No-Dig Conf., San Diego,* Apr 16-19.

Sever, V., G. Boyd, and R. Bakeer. 2005. “Oxidative Chemical Effects on CIPP Liners,” *Proc. NASTT No-Dig Conf.*, Orlando FL, Apr 24-27.

Spasojevic, A., R. Mair and J. Gumbel 2004. “Experimental studies of soil load transfer to flexible sewer liners: Latest results and implications for design,” *ASCE Pipeline Division Specialty Congress - Pipelines 2004 - What's on the Horizon*, pp. 417-427, Am. Soc. Civil Engrs., Reston VA.

Spasojevic, A., R. Mair and J. Gumbel. 2007. “Centrifuge Modeling of the Effects of Soil Loading on Flexible Sewer Liners,” *Geotechnique*, Vol. 57, No. 4, pp. 331-34, Thomas Telford Serv., UK.

Sterling, R., J. Simicevic, E. Allouche, W. Condit, and L. Wang, 2010. *State of Technology for Rehabilitation of Wastewater Collection Systems*. EPA/600/R-10/078. U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory - Water Supply and Water Resources Division, Edison NJ. July. www.epa.gov/nrmrl/pubs/600r10078/600r10078.pdf

Sterling, R., L. Wang, and R. Morrison. 2009. *Rehabilitation of Wastewater Collection and Water Distribution Systems - State of Technology Review Report*. EPA/600/R-09/048. U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory - Water Supply and Water Resources Division, Edison NJ. May. www.epa.gov/nrmrl/pubs/600r09048/600r09048.pdf

Straughan, W. T., L.K. Guice, and C., Mal-Duraipandian. 1995. "Long-Term Structural Behavior of Pipeline Rehabilitation Systems," *ASCE Journal of Infrastructure Systems*, December.

Straughan, W.T., N. Tantirungrojchai, L.K. Guice, and H. Lin. 1998. “Creep Test of Cured-in-Place Pipe Material Under Tension, Compression and Bending, *J. Test. and Eval.*, Vol. 26, No. 6, Nov.

Thépot, O. 2003. “The Design of Non-Circular Linings,” *Proc. Pipeline Engineering and Construction Conf.*, Jul 13-16, pp. 1059-1068, Am. Soc. Civil Engrs., Reston VA.

U.S. Environmental Protection Agency (EPA). 2002. *The Clean Water and Drinking Water Infrastructure Gap Analysis*, Office of Water. EPA-816-R-02-020. September.

Yoshimura, H., J. Tohda, Y. Inoue and A. Ohsugi. 2006. “Response of Sewer Concrete Pipes Rehabilitated by CIPP through Two-Edge Loading Tests,” *Proc. 6th Intl. Conf. on Physical Modeling in Geotechnics*, Vol. 2, pp. 1587-1592.

Zhao, Q., R. Nassar, and D.E. Hall. 2001. "Numerical Simulation of Creep-Induced Buckling of Thin Walled Pipe Liners," *Journal of Pressure Vessel Technology*, Vol. 123, August, pp. 373-380.

Zhao, W., R. Nassar, R. and D.E. Hall. 2005. "Design and Reliability of Pipeline Rehabilitation Liners," *Tunneling and Underground Space Technology*, Vol. 20, pp. 203-212.

Zhao, W. and G. Whittle. 2008. “Liner Long-Term Performance Life Prediction using Critical Buckling Strain,” *Proc. NASTT No-Dig Conf.*, Dallas, Apr 27-May 2.

Zhu, M. and D.E. Hall. 2001. "Creep Induced Contact and Stress Evolution in Thin-Walled Pipe Liners," *Thin Walled Structures*, Vol. 39, pp. 939-959.

APPENDIX A

LIST OF TEST STANDARDS REFERENCED

The following table lists ASTM standards that are referenced in this report.

Standard	Description
ASTM C128	Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate
ASTM C136	Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates
ASTM D638	Standard Test Method for Tensile Properties of Plastics
ASTM D790	Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
ASTM D792	Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement
ASTM D2216	Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
ASTM D2240	Standard Test Method for Rubber Property—Durometer Hardness
ASTM D2583	Standard Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor
ASTM D5813	Standard Specification for Cured-in-Place Thermosetting Resin Sewer Piping Systems
ASTM E96	Standard Test Methods for Water Vapor Transmission of Materials
ASTM E797	Standard Practice for Measuring Thickness by Manual Ultrasonic Pulse-Echo Contact Method
ASTM E1356	Standard Test Method for Assignment of the Glass Transition Temperatures by Differential Scanning Calorimetry
ASTM E2602	Standard Test Method for the Assignment of the Glass Transition Temperature by Modulated Temperature Differential Scanning Calorimetry
ASTM F1216	Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube
ASTM F1743	Standard Practice for Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Cured-in-Place Thermosetting Resin Pipe (CIPP)
ASTM F2019	Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Pulled in Place Installation of Glass Reinforced Plastic (GRP) Cured-in-Place Thermosetting Resin Pipe (CIPP)
ASTM F2599	Standard Practice for The Sectional Repair of Damaged Pipe by Means of an Inverted Cured-in-Place Liner

The following table lists the non-ASTM standards, guidelines, and manual of practice listed in this report. Contact information is provided for the organization.

ASTEE - Association Scientifique et Technique pour l'Eau et l'Environnement	www.astee.org/
Council of the Standards Association of Australia • AS2566 Plastics Pipelaying Design	www.standards.org.au/
British Standards Institute • BS 2782-10 Methods of testing plastics. Glass reinforced plastics. Measurement of hardness by means of a Barcol impressor. • BS EN 1055:1996 Plastics piping systems. Thermoplastics piping systems for soil and waste discharge inside buildings. Test method for resistance to elevated temperature cycling. • BS EN 1542:1999 Products and systems for the protection and repair of concrete structures. Test methods. Measurement of bond strength by pull-off • BS EN 13566-4:2002 Plastics piping systems for renovation of underground non-pressure drainage and sewerage networks.	www.standardsuk.com/shop/
Darmstad Rocker Test Method (abrasion) • See DIN 19565	
DIN (Deutsches Institut für Normung e.V.) • DIN 19565 (P1) Centrifugally cast and filled polyester resin glass fibre reinforced (up-gf) pipes and fittings for buried drains and sewers.	www.normas.com/DIN/pages/Translations.html or http://global.ihs.com/
EN Standards (CEN - European Committee for Standardization) • BS EN 1055:1996 Plastics piping systems. Thermoplastics piping systems for soil and waste discharge inside buildings. Test method for resistance to elevated temperature cycling. • BS EN 1542:1999 Products and systems for the protection and repair of concrete structures. Test methods. Measurement of bond strength by pull-off • BS EN 13566-4:2002 Plastics piping systems for renovation of underground non-pressure drainage and sewerage networks. Lining with cured-in-place pipes	www.standardsdirect.org/standards/
ISO (International Standards Organization) • ISO 175:1999 Plastics -- Methods of test for the determination of the effects of immersion in liquid chemicals • ISO 178:2010 Plastics -- Determination of flexural properties	www.iso.org/
WIS (Water Industry Standard) • WIS 4-34-04 Specification for renovation of gravity sewers by lining with cured-in-place pipes.	www.water.org.uk/
WRc (Water Research Center UK) • WRc SRM (Sewer Rehabilitation Manual)	www.wrcplc.co.uk/

APPENDIX B

INVESTIGATION OF ULTRASONIC MEASUREMENTS FOR CIPP THICKNESS

B.1 Introduction

This study was conducted using an ultrasonic thickness gauge probe (Olympus 37DL utilizing a 5.0 MHz transducer). The research team was unable to obtain any reading when attempting to obtain thickness measurements on the five CIPP liners recovered during the retrospective study (from both Columbus and Denver). In order to determine the cause for this inability of the equipment to perform as expected, the TTC undertook a study utilizing homogenous materials and CIPP liners with a range of resin types and resin saturation levels. A list of the materials used in the evaluation program of the Olympus 37DL is given in Table B-1. The results of this study are discussed here for future consideration of the utility of ultrasonic measurements in similar field studies.

Table B-1. List of the Material Used for Measuring Thickness

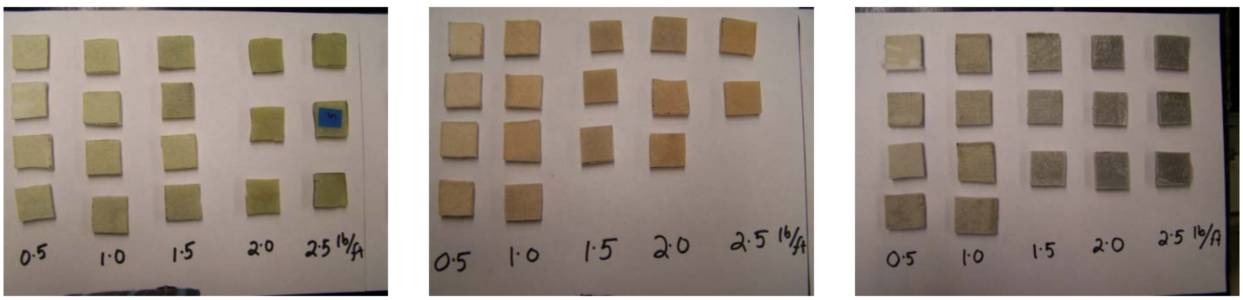
Material	Sound Velocity (in./μsec)	Remarks
CIPP made with Quik POX resin	0.1043	Approximately 6.5 mm (0.25-in.) thick control specimens with a known range of resin content (0.5, 1.0., 1.5, 2.0, and 2.5, lb/l.f. for a 7.5-in. dia. liner)
CIPP made with Quik PE resin	0.1043	
CIPP made with Reichhold resin	0.1043	
CIPP sample (Marked as Ultra Sonic 1)	0.05 – 0.15	Approx. 6.5mm (0.25-in.) liner; this sample was not properly impregnated. The instrument was ineligible to read thickness for a sound velocity ranging from 0.05 to 0.15 in. / μsec.
CIPP Sample (Marked as Ultra Sonic 2)	0.101	Approx. 6.5 mm (0.25-in.) thick, well impregnated and cured CIPP sample
CIPP Sample (Marked as Ultra Sonic 3)	0.101	Approx. 6.5 mm (0.25-in.) thick, well impregnated and cured CIPP sample
PVC Pipe SDR 35	0.0945	N/A
Polyurea/polyurethane hybrid		3.5 mm (0.14-in.) coupon; the instrument was unable to provide a reading for sound velocity ranging from 0.05 to 0.15 in. / μsec.
CIPP felt	0.001 – 0.15	No readings
Steel	0.2643	N/A

Note: N/A = not available

B.2 Preparation of Controlled Specimens

The TTC developed control specimens using three different resin types and five resin concentrations (specified as lb of resin per linear foot of 7.5-in. diameter felt). These samples were prepared in a controlled lab setting. A 6-in. x 6-in. felt panel was impregnated with resin using a roller system and cured in the microprocessor controlled oven as shown in Figure B-1. The resins used for preparing the samples were QuikPOX, Quik PE and Reichhold. Following the curing process the 6-in. square panels were cut to prepare 1-in. x 1-in. specimens, as shown in Figure B-2. The thickness of each specimen was measured using a slide caliper. Next, the ultrasonic device (Olympus 37DL fitted with a 5.0 MHz transducer) was used to measure the thickness of each specimen, as shown in Figure B-3.

Figure B-1. CIPP Roller System (left), Oven (middle), and a Batch of Controlled Specimen after Curing (right)



Quik POX Quik PE Reichhold

Figure B-2. Three Different Types of Resin Used for CIPP Saturation

Figure B-3. Measuring with Slide Calipers (left) and Olympus 37DL (right)

Mean thickness values for each control specimen are shown in Table B-2. From the data, it can be seen that the ultrasonic gauge works well when the specimen is well impregnated in resin (2.0 lb/ft or higher resin content), but does not provide a reading when the resin content falls to 1.5 lb/ft.

Table B-2: Measured Thickness of the Controlled Specimens

Resin Content lb/ft	Quik POX		Quik PE		Reichhold	
	Slide Calipers (in.)	Ultrasonic (in.)	Slide Calipers (in.)	Ultrasonic (in.)	Slide Calipers (in.)	Ultrasonic (in.)
2.50	0.234	0.234	0.269	0.268	0.228	0.229
2.00	0.242	0.241	0.240	0.237	0.201	0.198
1.50	0.217	N/A	0.239	N/A	0.196	N/A

N/A = Reading not available

B.3 Other Specimens

The ultrasonic gauge did not provide readings when used on a felt sample. This is attributed to the absorption of acoustic energy by the material. The device also did not provide a reading when used on an improperly cured liner, as shown in Figure B-4.

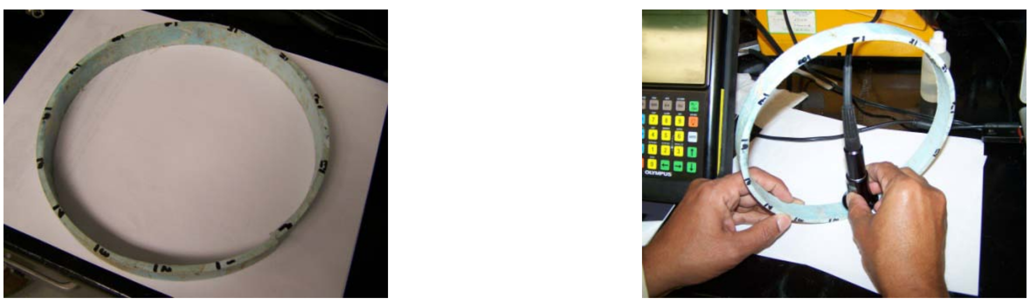


Figure B-4. Ultrasonic Thickness Measurements on Improperly Cured Liner

The device worked well in the case of a PVC liner. A SDR35 PVC pipe was used. When measured with a slide calipers, average thickness value was 0.187". Using the ultrasonic device, the thickness found was 0.182-in. to 0.183-in., as shown in Figure B-5.

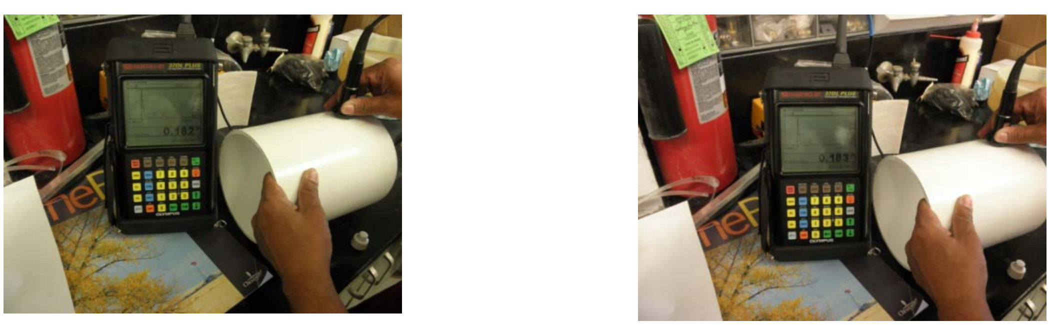


Figure B-5. Ultrasonic Instrument Used to Measure Thickness of PVC Pipe

When utilized for measuring the thickness of a 6.5 mm, well-impregnated and cured CIPP liner, the discrepancy between thickness values measured using slide calipers and the ultrasonic probe were on the order of 1% (see Figure B-6).

Figure B-6. Ultrasonic Instrument Used to Measure Well Cured Liner - MTC (left) and Insituform (right)

A summary of the measured average thicknesses for all sample specimens is given in Table B-3.

Table B-3. Comparison of Thickness Measured using the Slide Calipers and the Ultrasonic Device

Sample Specimens	Measured Thickness		Remarks
	Slide Calipers (in.)	Ultrasonic Device (in.)	
Improperly cured CIPP liner (Ultra Sonic 1)	0.203	N.A.	Improperly impregnated sample
Properly cured CIPP liner (Ultra Sonic 2)	0.280	0.281	None.
Properly cured CIPP liner (Ultra Sonic 3)	0.270	0.271	None.
Properly cured CIPP Liner Ultra Sonic 4)	0.268	0.267	None.
PVC Pipe SDR 35	0.187	0.183	None.
Polyurea/polyurethane hybrid	0.127	N/A	None.
White Felt	0.112	N/A	None.
Steel	0.187	0.188	None.

N/A = Reading not available

B.4 References

01. http://www.bamr.co.za/velocity%20of%20materials.shtml
02. Olympus 37DL – Manual

APPENDIX C

INTERNATIONAL STUDY INTERVIEW REPORTS

INTERNATIONAL STUDY INTERVIEW REPORTS

The interview reports from international utilities are provided in this appendix including: Thames Water (TW), Severn Trent Water (STW), Communauté d'Agglomeration de Chartres (CAC), Communauté d'Agglomeration Les Hauts-de-Bièvre (CAHB), Göttingen Stadtentwässerung (GS), Technische Betriebe der Stadt Leverkusen (TBL), Public Utilities Board (PUB) Singapore, Brisbane Water (BW), and Sydney Water (SW).

C.1 Thames Water (TW)

In 1973, the U.K. Department of the Environment established 10 regional water authorities including Thames Water Authority (TWA) to manage water resources and the supply of water and sewerage services on a fully integrated basis. Prior to this reorganization, there were more than 1,000 bodies involved in the supply of water and around 1,400 bodies responsible for sewerage and sewage disposal. In 1989, under the terms of the Water Act, these authorities were privatized as water and wastewater service companies and TWA became Thames Water Utilities, Ltd., the largest water and wastewater service company in the U.K. Within the southeast region of the U.K., there are also a number of small water service only providers.

TW has an extraordinary heritage including the construction of the New River in 1613, an artificial water course built by Sir Hugh Myddleton that brings fresh water from the River Lee and Amwell Springs to the City of London. TW also inherited the vast interceptor sewers commissioned by Prime Minister Disraeli's government in the 1860s and built by Sir Joseph Bazalgette to restore the Thames River. TW was acquired in 2001 by RWE, a German Utility Company and is presently owned by Kemble Water, Ltd., a consortium owned by Macquarie Group, Ltd., an Australian investment bank.

TW employs 5,000 staff and spends U.S. $1.5 billion a year to maintain its water and sewer network, which includes over 20,000 miles of water mains (about 30% of which is over 150 years old), 100 water treatment plants, 288 pumping stations, 265 reservoirs, 43,500 miles (70,000 km) of sewer, 800,000 manholes, 2,530 pumping stations and 349 sewage treatment plants (STPs) including Beckton, Europe's largest sewage treatment plant. It is the utility responsible for water supply, wastewater collection, and treatment in parts of Greater London, Surrey, Gloucestershire, Wiltshire, Kent and the Thames Valley in the U.K. Each day, it supplies 686 million gallons of tap water to 8.5 million customers across London and the Thames Valley and collects and treats 740 million gallons of sewage for an area of South England covering 13.6 million customers. Standards of service are set for TW by three regulatory bodies responsible to the Department of the Environment, Food and Rural Affairs (DEFRA). These are the Office of Water Services (OFWAT) responsible for service quality and efficiency; the Environment Agency (EA) responsible for rivers and other water sources, pollution and flooding; and the Drinking Water Inspectorate (DWI) responsible for drinking water quality.

TW has for many years been at the center of the development and usage of techniques for sewer rehabilitation. The first CIPP was installed in the Brick Lane Sewer, a century old brick, egg-shaped sewer located at Riverside Close, Hackney in 1971 and many of the first CIPP contracts in the U.K. were undertaken for TW and its agent authorities. TW Manager, Graham Cox, made the case for trenchless rehabilitation at the Institution of Civil Engineers Conference 'Restoration of Sewerage Systems' held in London in 1981, emphasizing that inversion lining was established as a well tried and proven method of making full use of the cross-sectional area of the existing pipe. Cox identified that by 1981 over a hundred successful installations had been undertaken in the U.K. in sizes from 4 to 108 in. (100 to 2,740 mm).

The original Insituform liner installed in the Brick Lane Sewer was examined in June 1991 and two sample panels were removed from the lining by Insituform Permaline, Ltd., and placed in the custody of MTS Pendar, Ltd., under the scrutiny of TW. The panels were cut from the sidewall of the liner along the spring line of the sewer about 3 ft (900 mm) from the access manhole located in Riverside Close. The location was revisited in October 2001 and two sample panels about 1 foot (300 mm) square were removed from an area of the sidewall about 6 ft (1.83 m) into the sewer (Figure C-1). The second set of samples was placed in the custody of Bodycote Materials Testing, Ltd. (owners of MTS Pendar). In each instance, test pieces were machined from the test panels and tested for flexural strength and modulus in accordance with the relevant testing specifications: BS 2782 Part 3 Method 335A:1978 in 1991 and U.K.WIS 4-34-04/BS EN ISO 178 in 2001. The results of this retrospective evaluation spanning 20 to 30 years after the original CIPP installation are summarized in Table C-1.

Figure C-1. Sample Retrieval at the Brick Lane Sewer CIPP Project in Hackney, U.K.

Table C-1. Results of Brick Lane Sewer CIPP Retrospective Testing

Flexural Property	Sample Mean		Industry Standard	
	20 Year	30 Year	WIS4-34-04	ASTM F1216
Modulus, MPa	2,900	3,300	2,200	-
Modulus, psi	420,000	480,000	-	250,000
Strength, MPa	46	43	25	-
Strength, psi	6,700	6,200	-	4,500

It is anticipated that Insituform Technologies, Ltd., will seek the agreement of TW to sample this unique installation again in 2011. There is no data from the original installation which predates the formation of the Permaline Division of Edmund Nuttall, Ltd., (now Insituform Technologies, Ltd.), nor similar data from other installations.

Today, TW is headquartered in Reading with operational centers based on major treatment plants at Mogden, Cross Ness, Sandford and Beckton. These operations centers use preferred contractors to undertake emergency works which investigate flooding incidents and other system failures, its crews identify lining needs which are passed to a lining manager based at Reading and sanctioned for implementation, mainly using the preferred contractor Onsite Central. Other specialist contractors such as Waterflow and Insituform can be used. Larger projects classed as capital works will be undertaken by any of four major framework contractors appointed for the current asset management period (AMP) 5. These contractors are B&V, Optimise, MGJV, or GBM and they are expected to utilize the preferred specialist subcontractors.

Lining volumes are not centrally recorded, so it is difficult to estimate how much CIPP and other lining methods have been installed. TW and its antecedents, the city and municipalities of the region have been undertaking this type of work since before formation of TWA in 1973 and it is thought that lining volumes have fluctuated widely from 6 to 60 km/year. Policy changes in the four five-year AMPs since privatization have ensured that there has been no continuity of lining work. According to TW, the work currently undertaken is customer focused on solving problems and not asset focused. In England and Wales, according to the U.K. Water Regulator OFWAT, over this asset management period, the proportion of sewers in condition grade 3 to 5 (the poorest conditions) has increased from 20 to 30% of the network.

According to OFWAT, TW has renovated 408 km (254 miles) and replaced 264 km (164 miles) of critical sewer since 1990-91. Critical sewers, in the U.K. perspective, are sewers identified for proactive maintenance. These may be located under major roads, highways, rail tracks or in other sensitive locations and serve critical facilities such as hospitals, major business or population centers where the consequences of failure are major. It is thought that critical sewers make up some 20% of the network. OFWAT has published data on renovation and replacement for non-critical sewers since 2000-01; nationwide annual rates of rehabilitation for non-critical sewers of 87 to 91 km (54 to 57 mi)/year are marginally lower than for critical sewers 83 to 110 km (52 to 68 mi)/year. It seems reasonable to assume that TW may have renovated about 800 to 900 km (500 to 560 mi) of all sewers, perhaps 45 km (28 mi) per year since 1990. Table C-2 summarizes sewer renovation data from TW and for all U.K. utilities.

Table C-2. TW and U.K. Sewer Renovation Rates for 1990 to 2010

	Thames Water		All U.K. Water Companies		
Asset Management Period	**Critical Sewers Renovated km**	**Non-Critical Sewers Renovated**	**Critical Sewers Renovated km**	**Non-Critical Sewers Renovated**	**Water Mains Relined km**
AMP1 90-95	113	N/A	509	N/A	10,639
AMP2 95-00	36	N/A	711	N/A	9,670
AMP3 00-05	47.1	102	505.4	350.5	9,255
AMP4 05-10	231.7	118.8	1,162.5	1,356.7	6,238
Subtotal	427.8	>220.8	2,887.9	>1,707.2	35,802
Proposed AMP5 10-05	79.5	184	769.4	3,358.9	1,126

However, the figures published by OFWAT cannot be taken at face value in terms of total rehabilitation effort since they refer to rehabilitation activity in terms of structural enhancement. For example, a length of condition Grade 4 or 5 sewer lined to improve condition to Grade 3 or better is deemed a valid rehabilitation output and may be included in the volume of activity, whereas a joint sealing by CIPP in a Grade 1 or 2 sewer may improve serviceability, but not structure and accordingly will not be counted. The length reported may also refer to the whole section of sewer, whereas the repair may be a simple CIPP patch repair. So the volumes of work reported as undertaken by OFWAT may be at variance with actual lengths of lining installed by preferred contractors. The CIPP contractors themselves were contacted for estimates of work done for TW and, on this basis, from equally fragile data, it seems more likely that the actual volumes of CIPP undertaken for TW annually may be only about 25 to 30 km (16 to 19 mi) over the period since privatization.

The bulk of TW's experience since 1971 has been with polyester resin and felt lining, inverted with water and hot water cured. Currently, TW's preferred lining methods include traditional polyester resin and felt for structural improvement, epoxy resin and felt for leak tight lining (mainly for pipes 150 mm in diameter), woven hose lining (Brawoliner) for small diameter pipes with multiple bends and UV cured glass reinforced polyester linings for critical locations such as adjacent to rail tracks where time pressures require rapid installations.

TW confines its work to experienced contractors, particularly Onsite and Waterflow, having had unsatisfactory work completed by small contractors. In its experience, construction defects, if present, become apparent within 1 to 2 years of installation. Its experience overall has been good, though some deficiencies in older works have been identified through routine and emergency CCTV surveys where local municipalities acting as TW agents may not have been as informed on acceptance standards and where acceptance criteria have been improved over the years in the transition from WRc IGN 4.34.04 Issue 1 (April 1986) to the current BS12566 Part 4:2002 (see Table C-3).

Table C-3. TW Sewer Renovation Acceptance Criteria and Relevant Standards

Criterion	WRc IGN 4-34-04 Issue 1 1986	WRc IGN 4.34.04 Issue 2 1995	BS EN 13566 Part 4:2002
Appearance	Smooth, generally free from wrinkles, degree of wrinkles may be agreed by purchaser and manufacturer	Surface irregularities less than 6mm or tabulated value, % of diameter, normally longitudinal 2% in the invert and 5% above the flowline, circumferential 2% anywhere	Surface irregularities not more than 2% of diameter or 6 mm
Thickness	Minimum specified and up to 15% thicker. May be greater where felt layers overlap	Minimum specified and up to 15% thicker	Mean thickness not less than design thickness and minimum not less than 80% of design thickness or 3 mm
Tensile Strength/ Modulus/ Elongation	Not less than 25 MPa 1,700 MPa 1.5%	NA	Not less than Declared value < 15 MPa N/A Declared value < 0.5%
Flexural Strength/ Modulus/ Elongation	Not less than 50 MPa 2, 600 MPa 1-2.5%	Not less than Declared value < 25 MPa Declared value Declared value < 0.75%	Not less than Declared value < 25 MPa Declared value < 1,500 MPa Declared value < 0.75%

The main defects noted during inspections after 1 to 2 years are bulges and deformations caused by buckling failure of poorly impregnated or cured sections and delamination of coatings.

TW operates a Dynamic Asset Condition Model based on the performance of a group of sewers initially inspected around 1989 and reinspected periodically. Most sewers in the model focus have been inspected at least three times since inception. The rate of deterioration is described as not significantly different from the rate of error in identification in the survey. Over the course of the exercise, terminologies and classification software have changed. TW used an internal classification scheme SRS2 at the outset and moved to Examiner software and is currently transitioning towards Infonet. It is hoped that some historic data can be reclassified using the improved system. Generally, the financing method discourages capital maintenance, concentrating on investment in new works which enhance profitability, pipe lining is undertaken on an as-needed basis, particularly where assets are identified as at risk of collapse within five years.

TW has proposed a type test for CIPP systems that is applied to demonstrate water tightness (see Figure C-2). CIPP systems satisfying this test may be selected for small diameter sewers, up to 375 mm (14.8 in.) exhibiting serious infiltration. The test (developed by WRc as a collaborative project CP308 - infiltration reduction properties of CIPP linings) involves setting up an array of five 1 m (3.28 ft) long, plain ended clay pipes such that the gradient is not more than 50 mm (2 in.) over the length of the test line. The central pipe is fitted with a lateral connection through which the line may be filled to test infiltration through the liner wall. The pipes are jointed using mechanical couplings with joint gaps set at 3 and 25 mm (0.12 and 0.98 in.). Each coupling is fitted with top and horizontal ferrule connectors. The top ferrule connectors are fed from a header tank so as to provide a 5 m (16.4 ft) water head, the test line is plugged and restrained before pressure testing for leakage under the 5 m head for 15 minutes.

Figure C-2. Setup for CIPP Water Tightness Test Used by TW

The lining is installed under a 3 m (9.84 ft) inversion or inflation head and cured in accordance with manufacturers recommendations. Mechanical or hydrophilic seals which are deemed part of the system may be fitted. The lined pipe is subjected to an external head of 5 m (16.4 ft) for 30 minutes using the horizontal and top ferrule connections as valves in combination to simulate various conditions of exfiltration and infiltration. Any water running through the annulus between liner and test line or through the liner wall is captured and measured. The acceptance levels for various configurations are based upon the acceptable infiltration in new pipelines (i.e., 500 ml/m diameter/m length [1.2 gal/ft diameter/100 ft length] over a 30 minute period at 5 m (16.4 ft) hydrostatic pressure), which is based upon BS EN 1610 "Construction and testing of drains and sewers." Epoxy resin systems (such as Epros and Brawoliner) exhibit lower volume shrinkage and are more successful in this battery of tests than traditional polyester resins. The UV light cure system, BKP Berolina fitted with hydrophilic end seals, has also passed the test.

Lining thicknesses are determined by the preferred contractor using the procedures outlined in the Water Research Centre (WRc) Sewer Rehabilitation Manual (SRM), the German Wastewater Technical Association (Abwassertechnische Vereinigung [ATV]) method, or the ASTM method for fully-deteriorated pipe. Preferred contractors submit a table of thicknesses with their price schedule based on these design methods taking into account ovality and the declared physical properties of their lining systems. Contractors also provide a quality manual covering their system and are QA tracked for compliance to check that they are following the due procedures. Their records may be checked at random and, early in their relationship as suppliers, there are random site visits to monitor performance. There is no formal training for site supervision but TW's Technical Consultant (Sewerage) Don Ridgers provides an overview of supervision and inspection. Type testing and process verification in accordance with BS EN 13566 Part 4 is mandatory. Leak testing according to the WRc CP308 protocol is included for the leak tight resin systems. After lining, all installations are surveyed in accordance with BS EN 13508. CCTV information is archived, but not yet recorded on geographic information system (GIS) records. It is expected that the Infonet data system will facilitate enhanced data storage and recovery. Where patch repair and top hats are employed, these are inspected by CCTV for leakage and may be subject to vacuum or air testing.

TW is very active in the process of establishing standard specifications in the U.K. and Europe for new construction and rehabilitation; Technical Consultant (Sewerage) Don Ridgers is active as the U.K. representative in a number of European Committee for Standardization (Comité Européen de Normalisation [CEN]) working groups and mirror committees, (Working Groups 12, 13 and 22) and is at the center of an initiative to revise design methods.

Overall, TW is satisfied that its time-established system, using preferred contractors, delivers value for the money. TW believes that, in its geology, the use of leaktight systems is important to minimizing infiltration and, accordingly, epoxy resin linings are used for small diameter pipes prone to leakage.

C.2 Severn Trent Water (STW)

The Severn Trent Water Authority along with Thames and the other catchment-based regional water authorities was formed in 1974 under the Water Act to supply water and wastewater services to some 7.4 million customers distributed across a large geographical area of the U.K., known as the Midlands, which includes major cities such as Birmingham, Gloucester, Coventry, Leicester, Nottingham, Stoke, Stafford, Wolverhampton and parts of Wales. Its regional coverage includes two major river systems, the Severn and the Trent from which it takes its name. It is believed to be the world's fourth largest privately owned water company and the second largest in the U.K.

Privatized in 1989, STW employs 5,686 staff and generates a turnover of U.S. $2.2 billion to maintain its facilities, which include 28,546 miles (45,940 km) of water mains, 20 water treament works, 33,778 miles (54,360 km) of sewers, and 1,000 sewer treatment plants. Historically, STW has played an important role in the development of the sewer rehabilitation business in the U.K. It took a pioneering role in the assessment of sewer condition and its staff made numerous contributions to developing knowledge at water industry conferences. A senior STW manager, George Hedley, chaired the Department of the Environment's Committee responsible for materials used in sewer and water mains networks. In 1980, it conducted a survey of sewers in 240 locations distributed across its territory from Shrewsbury in the west to Scunthorpe in the east and Cheltenham in the south. The resulting analysis relating age, size, construction material, depth and condition led to a comprehensive estimate of rehabilitation needs and costs which had an influence on the National Water Council and the Department of the Environment and the direction of its Water Research Centre in developing sewer rehabilitation strategies.

The reputation developed by STW in the 1980s for its expertise in the practice of rehabilitation was such that it became respected consultants providing engineers and managers to guide overseas water agencies such as the Delhi Jal Board and the Bombay Municipal Corporation in sewer cleaning and maintenance, condition assessment and rehabilitation. The expertise continued after privatization when STW purchased Haswell and Partners, a specialist consultant firm, and transfered operations engineers and managers into the consultancy firm during a period of reorganization. Haswell Consulting Engineers ceased to trade in 2005 and residual staff were transfered back to Severn Trent, some finding opportunities in Severn Trent Services, Severn Trent Water's sister company.

STW has experienced significant difficulties with flooding. In 2007, flooding cost the company U.S. $50 million and affected more than 140,000 customers in and around the Gloucestershire city of Tewkesbury. It is involved in extensive network monitoring and drainage studies, which will have future network maintenance implications.

In the period since privatization, AMP1 through AMP4 (1991-2010), Severn Trent undertook a significant program of sewer renewal (Table C-4). According to OFWAT statistics, it renovated 630 km (391 mi) of critical sewer and replaced 414 km (247 mi). OFWAT commenced reporting volumes of renovation work on non-critical sewers in 2001. Recorded volumes of non-critical sewer work within STW are surprisingly low, a little over 25 km (16 mi). Follow-up discussions with contractors suggest that more work has been undertaken in this area and so, as discussed in the Thames Water report, the under and over reporting to OFWAT may be misleading and it may be reasonable to suppose that the overall volumes of non-critical sewers lined may be similar to the volumes of critical sewers lined. Conflicting reports were received from STW about its rehabiliation and replacment volumes in AMP4, which perhaps confirms the difficulties of classification and interpretation described earlier. According to STW, in AMP4 it rehabilitated 31 km (19.3 mi) of critical sewer and 10 km (6.2 mi) of non-critical sewer; it replaced 25 km (15.5 mi) of critical sewer and 97 km (60.3 mi) of non-critical sewer.

Table C-4. STW and U.K. Sewer Renovation Rates for 1990 to 2010

Asset Management Period	Severn Trent Water		All U.K. Water Companies		
	Critical Sewers Renovated km	Non-Critical Sewers Renovated	Critical Sewers Renovated km	Non-Critical Sewers Renovated	Water Mains Relined km
AMP1 90-95	79	NA	509	NA	10,639
AMP2 95-00	221	NA	711	NA	9,670
AMP3 00-05	63	13	505.4	350.5	9,255
AMP4 05-10	271	11	1162.5	1356.7	6,238
Sub Total	634	>24	2887.9	>1707.2	35,802
Proposed AMP5 10-05	96.1	161	769.4	3358.9	1,126

STW uses CIPP for virtually all of its sewer renovation works and more than 90% is undertaken by the traditional water inversion and hot water cure method. There have been air inversion and steam curing trial projects and demonstrations of the Omega fold-and-form lining method. Some Thermopipe inflated hose has been used for raw water and force main renovation.

The company's design and procurement procedures have changed over time as the company has evolved through privatization. Initially, work was scoped and managed by the 2,000 agencies under STW direction; this work was later undertaken by wholly-owned consultants Haswells and, following the closure of the consulting firm, the work was absorbed into the regional offices. In AMP4, the regional offices undertook feasibility studies and let work out as design-and-build projects to nominated contractors selected by the regional engineers. Much responsibilty is placed on the design-and-build contractors who work from the CCTV tapes and design rehabilitation works according to WIS 4-34-04 and the WRc SRM. (STW carries out a considerable amount of CCTV work – in AMP4, 1,024 km [636 mi] of critical sewer and 5,947 km [3,695 mi] of non-critical sewer were surveyed).

In AMP4, STW staff functioned as resident engineers and provided oversight on contract execution and installation works. This will change in AMP5 when the contractors take full responsibility for their design-and-build works. The contractors will self certify their works for compliance with the STW specifications and STW will audit a sample of works and supervise any remedial activities required. Overall, STW staff report that their experience has been generally good. The company reports some problems with liner stretch, missed connections, and some wrinkling. STW has also experienced problems rerounding severely deteriorated pipe prior to lining. Works undertaken for STW are subject to a one-year materials and installation warranty and, where necessary, defects may be cut out and replaced. STW places great reliance on its contractors who are appointed for each AMP period. Performance is a key factor in contract renewal, so STW is able to call on contractors to undertake remedial works long after the notional warranty period. STW has reported increasing problems with complaints from the public about styrene odors.

C.3 Communauté d'Agglomeration de Chartres (CAC)

CAC was interviewed in Chartres on October 29, 2010. The interview was conducted in French with the head of the water and wastewater service. CAC provides municipal services to the cathedral city of Chartres and six neighboring communities. The population served is approximately 90,000. The collection system is both separate and combined, with a total mains length of 325 km (202 mi) and approximately 29,500 lateral connections. Operation of the collection network is under a 10-year concession contract from 2004 to 2014 with la Compagnie des Eaux et d'Ozone, a Veolia subsidiary.

CAC first used CIPP in 2000. Total installation since then is approximately 3 to 4 km (2 to 2.5 mi) in diameters up to 400 mm (16 in.). Current installation is approximately 0.5 km (0.3 mi) per year, and this level is expected to increase slightly in the coming years. Typically, just one or two projects are undertaken each year. CAC has also used grout injection in the past, but this was not successful. All renovation is now either open trench replacement or CIPP. All of the CIPP installed is full length from manhole to manhole. CAC has not used short patch liners, lateral liners, or top hats at connections. CAC inspects some 15 km (9.3 mi) of sewers per year with CCTV and finds lots of defects, but does not have the budget to rehabilitate them all. Rehabilitation and replacement runs at approximately 2.7 km (1.7 mi) per year, so open cut replacement is the dominant method. CAC considers this to be more cost-effective over the long-term service life than relining. Current CIPP installation is exclusively with UV-cured methods.

CAC has not taken samples of CIPP lining after a period in service. It has undertaken just one inspection after a period in service in response to a problem and found both I/I and blockage because of a partially collapsed liner after 8 years in service. Further rehabilitation was undertaken to rectify the problem.

CAC has its own specification for CIPP works. This was developed in house based on one used by another municipality and amended to suit the needs of CAC. This is a performance specification that sets material and performance standards while leaving the method itself to the contractor to decide. Design is undertaken by contractors to meet the specification. Data sheets and test certificates of materials used are submitted by the contractor and must include all QA certification. These must show conformance with the specification. Pipe preparation consists of cleaning by jetting, a CCTV survey, and root removal if necessary. This is done by the contractor under the rehabilitation contract and is considered essential to ensure a good quality installation. Site supervision consists of monitoring of installation, the curing/cooling cycle and any reinstatement works and is undertaken by a third party project manager. Copies of all control documents are obtained as part of the QA process. No process verification test samples are taken. CAC is considering adding this to the specification so that mechanical testing is undertaken. A post-installation CCTV survey is required and is required to be repeated after one year at the end of the warranty period, but this second inspection is not often done.

Few problems are encountered. The main ones concern poor reopening of lateral connections. Occasional partial collapse of liners has also occurred. Lack of adhesion to the host pipe, especially at manholes is a common problem, and grout injection is used to rectify this.

CAC uses CIPP to reinforce sewers where there is high risk of root penetration. For structural problems, and even I/I, open cut replacement with ductile iron pipe is preferred. The condition of lateral connections and frequent displaced pipes means that CIPP is considered ineffective in combating I/I. CIPP is considered a maintenance activity rather than capital expenditure/asset renewal. Nevertheless CAC expects to increase its usage of CIPP in the coming years, and to increase rehabilitation at the expense of replacement in order to improve the network within its limited budget.

C.4 Communauté d'Agglomeration Les Hauts-de-Bièvre (CAHB)

CAHB was interviewed in Paris on October 19, 2010. The interview was conducted in French with the head of the water and wastewater service. CAHB combines several local authorities in the southwestern suburbs of Paris, including Versailles. The population served is approximately 100,000. The collection system is both separate and combined, with a total mains length of 450 km (280 mi) and approximately 25,000 lateral connections.

CAHB first used CIPP in 1996 when Insituform was used. The total installation since then is approximately 30 km (18.6 mi) in diameters from 200 to 500 mm (8 to 20 in.). Current installation is approximately 3 km (1.9 mi) per year, and this level is expected to remain unchanged in the coming years. Most projects are quite small, less than 200 m (656 ft) in length, and there are up to 20 such installations per year. Other rehabilitation methods used are open cut replacement, pipe bursting and replacement with PVC when upsizing is necessary, and robotic local repairs at junctions with lateral connections. Almost all of the CIPP installed is full length from manhole to manhole. CAHB has used short patch liners but experience was poor and they are no longer used. No specific technical reason was given, but funding may be a reason. The Agences d’Eau (government water agencies) that are the source of funds for local operators do not fund short liner works as they are considered to be repairs and not renovation. For renovation, they will fund up to 40% of the cost.

Some 3 to 5 km (1.9 to 3.1 mi) of lateral lining has been used, all installed from man-entry size sewers rather than remotely. This is considered successful and CAHB expects to increase its usage of this method. Top hat repairs to junctions were trialed, but are not used. CAHB finds robotic repair to be more cost-effective.

Current CIPP installation is almost exclusively with UV-cured methods. In the past, CAHB used hot water-cured methods, but experience has been that UV-cured methods provide better quality and cost-effectiveness.

CAHB has not taken samples of CIPP lining after a period in service. It has undertaken approximately 4 km (2.5 mi) of CCTV inspections after 5 and 10 years in pipes from 250 to 500 mm (10 to 20 in.) diameter and have not identified any specific problems that raise concern over the general performance of CIPP liners. Any anomalies or defects found are considered to be due to installation problems rather than indicative of systemic or materials problems. Nothing that indicated any deterioration over time was identified in the inspections.

CAHB does not have its own specification for CIPP works. Design is undertaken by contractors to a national design method developed by Association Scientifique et Technique pour l'Eau et l'Environnement (ASTEE). This defines the required thickness and is checked by the consulting engineer and project manager for conformity to the ASTEE method. No specific type testing is required, merely verification of the design.

Pipe preparation consists of cleaning by jetting and joint sealing where necessary. Good cleaning is considered to be important in paving the way for a successful lining, since there are fewer wrinkles and blisters in well-cleaned lines. Also, good measurement is essential. CAHB requires the surveyor, engineer, and contractor all to inspect and measure the line independently in advance of the work to ensure that the correct diameter liner is used.

Contractors are required to have QA systems that conform to ISO9001, and this is considered adequate to ensure quality. Site supervision consists of monitoring of installation and the curing/cooling cycle. Copies of all control documents are obtained as part of the QA process.

Process verification test samples are taken from all projects and tested by a third party laboratory. The characteristics tested are thickness and flexural modulus. Failures are rare. A post-installation CCTV survey is also required. Watertightness testing in situ is undertaken before laterals are reopened so that the liner itself is tested.

Few problems are encountered. The main ones concern poor reopening of lateral connections. In early installations it was not uncommon for cutting to be in the wrong places. Also, in the early installations, wrinkling of the liner was a common problem. Both these have now been solved.

In 14 years of CIPP usage, only two projects were considered to have failed. A 200 m (656 ft) installation at a very difficult location could not be completed, and a 500 m (1,640 ft) installation was taken out because of poor installation and curing control. This represents approximately 2% of the total length installed.

CAHB considers CIPP to be a reliable method that will remain the main one used for sewer rehabilitation works. Good planning and pipe preparation are essential and nothing should be left to chance. Experienced and knowledgeable consultants and contractors are also necessary for successful installations. CAHB now enters into annual contracts with one contractor only in order to ensure experience and quality, and does not use competitive tender for each project. While recognizing that it could save money, CAHB considers the risk of problems due to inexperience and insufficient money to be too high.

C.5 Göttingen Stadtentwässerung (GS)

GS was interviewed in Göttingen on November 3, 2010. The interview was conducted in German. GS is the drainage and wastewater service of the City of Göttingen, Germany. The population served is 130,000. The collection system is a separate system with each of the sanitary and stormwater systems having a mains length of 375 km (233 mi) and a publicly-owned length of laterals of 300 km (186 mi). The laterals are owned by the city as far as the property boundary.

The city council decided in 1990 to make serious investments in the wastewater system with the aim of achieving a watertight and maintenance-free system by 2035, including the privately-owned laterals. The annual budget is € 25 million (U.S. $33 million), all from local taxes, and GS considers that it receives this to do the job properly and solve the problem, and not to fiddle about with minor maintenance to keep the system going. This 45-year timeframe is exceptional and was driven by political pressure. A national newspaper article in 1988 had been critical of the city for the state of its underground infrastructure as a result of several large collapses, and the council in 1990 had a strong Green Party representation. As a result of this policy and its implementation, GS is seen as a leader in wastewater system rehabilitation in Germany.

GS was an early user of CIPP. Its first use was in 1992. Total installation of all rehabilitation methods is shown in Table C-5.

Table C-5. Use of Rehabilitation Methods in Göttingen Stadtentwässerung, Germany

Method	First Use	Total Installed (km)	Length in past year (km)
CIPP	1992	42	1
Pipe bursting (replace with PE)	2006	24 incl. methods below	7 incl. methods below
PE Sliplining	2006	Incl. in above	Incl. in above
PE fold & form	2006	Incl. in above	Incl. in above

The total of the CIPP above that is lateral lining is approximately 6 km (3.7 mi). Of the CIPP installed, 7 km (4.4 mi) has already been replaced. In the longer term, all but about 10 km (6.2 mi) is expected to be replaced. GS trialed short liners, but experience was poor and all were removed. The main problem was poor resistance to water jetting during routine cleaning operations. GS also tried steel short liners, but considered them not to be cost-effective. Similarly, GS has trialed top hats for rehabilitation of the junction between main sewers and laterals, but again had poor experience and has ceased their use.

GS has taken samples of CIPP lining after 5 and 10 years in service, and some after 12 years. Pieces roughly the size of a sheet of letter paper were removed in sewers 250 to 600 mm (10 to 24 in.) in diameter. A total of 50 samples were tested by the Institut für Unterirdische Infrastruktur gGmbH (Institute for Underground Infrastructure [IKT]) for: E modulus; bending stiffness; thickness; and watertightness. No results were made available, but on the basis of the results, GS considers CIPP to have an effective service life of 50 years. GS has not confirmed the methodology for reaching this conclusion, and review of related published reports by IKT does not provide any information that might indicate how it was calculated.

Current CIPP installation uses UV-cured methods only. GS had a major contractual disagreement with the leading heat-cured system supplier and switched its specification to UV-cured and has found better quality and fewer site problems with this technology. In its specification, GS requires type testing of materials including creep resistance and tensile and bending modulus. Minimum wall thickness is 6 mm (0.24 in.) irrespective of design requirements.

All design and construction supervision is undertaken by external consulting engineers. GS considers its role to be one of owner and facilitator, with expertise – it directs and delegates, but doesn't do the work itself. Supervisors are required to be certified PE welders and to monitor critical site activities at any time of day or night. Monitoring of the cooling phase (of CIPP and fold-and-form) is considered especially important as this is where contractors cut corners to save time.

The problems encountered relate to watertightness. GS's aim is a watertight system, and after 15 years of using CIPP, and some 15,000 watertightness tests, determined that it is an excellent long-term repair method, but will not provide a permanently watertight system. This is due to problems of sealing ends at manholes and of sealing the openings at lateral connections. CIPP can give a watertight pipe, but not a watertight system. GS has switched its strategy to achieve complete system watertightness to aiming for a 100% PE system, with welded joints throughout. When installing new pipe, only materials approved by DVGW for gas use are allowed to be installed. This is the reason that, since 2006, PE rehabilitation technologies have replaced CIPP at GS.

Nevertheless, it continues to use CIPP where extension of service life until PE replacement or lining is undertaken is needed. GS's view is that quality of installation has improved significantly since the 1990s, especially in areas such as reopening of laterals. Testing has also improved so the overall QA/QC approach is now credible and CIPP is considered to be a reliable repair method. In order to ensure the quality of CIPP installation, GS requires that installers have a QA manual covering all processes and submit it to GS in advance of undertaking any work. The supervising engineer is expected to monitor adherence to the QA procedures set out in the manual and to prevent the contractor from cutting corners with curing cycles, etc., in order to work more quickly. GS has noticed a reduction in prices of CIPP in recent years and considers that this represents increased risk as contractors have to work more quickly in order to make money, and this leads to cutting corners. GS would prefer to pay more and take less risk of poor installation.

GS also has a policy of not rehabilitating pipe in condition class 2 or worse (Germany has five condition classes, 0 to 4, of which 4 is the best and 0 the worst). Any sewer in classes 0 to 2 is replaced with open cut. Rehabilitation with CIPP is only used for class 3 and 4 pipes. This is despite CIPP costing typically one sixth to one quarter of the open cut price. Also, when CIPP is used in collectors with few lateral connections, the lateral connections are diverted to manholes and old openings are lined over to avoid problems of watertightness around the lateral connection junction. Manhole rehabilitation is also undertaken, under a separate contract.

GS is a special case because of its watertight network policy. However, it was a leading adopter of CIPP in Germany and is considered by its peers to be an expert client at a technical level, despite any misgivings about the underlying policy. Therefore, its adoption of CIPP and its switch to PE is of interest. As stated above, it now considers CIPP to be an excellent long-term repair technology with a service life of 50 years and that can make individual pipes watertight. But it does not meet its requirement of achieving a permanent, watertight network.

C.6 Technische Betriebe der Stadt Leverkusen (TBL)

TBL was interviewed in Leverkusen on November 2, 2010. The interview was conducted in German. TBL is the technical service of the City of Leverkusen, Germany. The population served is 150,000. The collection system is both separate and combined, with a total mains length of 660 km (410 mi) and approximately 90,000 lateral connections.

TBL first used CIPP in 1994. The total installation of all rehabilitation methods is shown in Table C-6. The diameter range of CIPP undertaken is 250 to 1,200 mm (10 to 48 in.). Since 2005, its emphasis has been on rehabilitation instead of replacement.

Table C-6. Use of Rehabilitation Methods in Technische Betriebe der Stadt Leverkusen, Germany

Method	First Use	Total Installed (km)	Length in past year (km)
CIPP	1994	50	5
PE fold-and-form	1998	1	0

All of the CIPP installed is full length from manhole to manhole. TBL trialed short liners, but they were easily damaged by water jetting during routine cleaning operations. TBL also trialed top hats for rehabilitation of the junction between main sewers and laterals, but again had poor experience and has ceased their use. The problem was inability to install consistently, leaving wrinkles in the top hat, which led to blockages in the lateral. Where repair of the junction is necessary, TBL uses grouting and Ka-Te robotic repair methods. Where there is severe localized pipe damage, it uses mortar grouting and then lines over the repair. Any lateral lining has been in the private part of the lateral and undertaken by the property owners.

CIPP is now the only rehabilitation method used by TBL. The experience with PE fold-and-form was poor. In the second project undertaken, all of the lateral re-openings were found after some months to have moved longitudinally by approximately 150 mm (6 in.) and all laterals were blocked. This is thought to be due to overheating in the reversion stage of the process resulting in stress relaxation over a long period and movement of the liner. As a result, the method is no longer used.

Current CIPP installation uses UV-cured methods only. In the past, TBL used hot water curing, but has concerns over the styrenes in the resin so it has switched its specification to UV-cured and has found better quality and fewer site problems with this technology.

TBL has not taken samples of CIPP lining after a period in service. It has undertaken CCTV inspections after 10 and 15 years in pipes from 250 to 1,200 mm (10 to 48 in.) diameter and has not identified any specific problems that raise concern over the general performance of CIPP liners. It also inspects liners as part of routine maintenance of its network. It plans to start taking coupons and testing them in the future now that it has a larger program of CIPP works.

In its specification, TBL requires type testing of materials including creep resistance and tensile and bending modulus. Minimum wall thickness is 5 mm (0.2 in.), irrespective of design requirements. It is considering adding chemical resistance testing because of the large volume of industrial effluent in the system. The largest industrial installation feeding into the system is Bayer, the pharmaceutical company and inventor of aspirin. Structural design of liners is undertaken by the contractor and submitted for approval to TBL. Construction supervision is undertaken partly by TBL and partly by external consulting engineers. TBL consider this to be a critical aspect – all contractors need close supervision to ensure that they do indeed follow the correct and agreed procedures. It has experienced contractors leaving the site before curing is complete. All materials used must have approval from DIBt (Deutsches Institut für Bautechnik), but installation remains the weak area for CIPP. TBL considers that UV-cured systems have less scope for installation errors, which is one reason for switching to this method.

Process verification test samples are taken from all projects and sent to IKT for testing. The characteristics tested are: watertightness; elastic modulus; bending strength; creep resistance; and thickness. Failures of watertightness are not uncommon, whereas failures of the other properties are rare.

The problems encountered relate to watertightness. Re-survey by CCTV is undertaken after 4 years, which is the limit of the warranty period under the German standard construction contract conditions. TBL has undertaken watertightness tests in lined pipes up to 4 years after installation, as part of this inspection, and several have failed. Therefore, it considers CIPP to be an adequate technology for reduction of I/I, but that it does not lead to a watertight system. TBL also has concerns over its resistance to water jetting used for cleaning. Its cleaning uses water jetting at 20 bar (290 psi) pressure, and TBL reports some damage to liners from cleaning.

Nevertheless TBL continues to use CIPP. Its view is that quality of installation has improved significantly since the 1990s, especially in areas such as reopening of laterals. Testing has also improved so the overall standard has improved dramatically. TBL believes that the owner needs to take responsibility for QA/QC and for supervision and monitoring during installation. Even with experienced and trusted contractors the correct procedures are not always followed. For example, TBL is considering introducing spectroscopy to its type testing to ensure that the correct resins are used. This suggests that the level of trust between owner and installer remains low.

C.7 Public Utilities Board (PUB) Singapore

Singapore is a small (272 km^2 [105 mi^2]), but densely populated (5 million population) city state located off the southernmost tip of Malaysia just 137 miles (220 km) north of the equator. PUB Singapore is the National Water Agency responsible for collection, production, distribution, and reclamation of water. PUB relies heavily on Malaysia for water, importing around 50% of its water demand and over time has been developing infrastructure to reduce reliance on its neighbor. Under its ‘Four Taps Strategy,’ PUB operates 15 reservoirs for collection of rainwater, four NEWater (advanced membrane and UV disinfection) plants, one desalination plant, and a number of undersea pipelines crossing the Straights. It is understood that from 2011 Singapore will not seek a new water supply arrangement with Malaysia. The drive to self-sufficiency has shaped water policy since independence and this has also impacted the collection and processing of wastewater. Singapore invests heavily in its water industry (approximately U.S. $3 billion since 1996).

PUB operates a very modern sewerage system, comprising six wastewater treatment plants, 130 pumping stations, 3,400 km (2,113 mi) of gravity sewers, and 260 km (162 mi) of force mains. It has recently constructed a world-class Deep Tunnel Sewerage System and has taken significant steps to limit infiltration and exfiltration, so as to improve the efficiency of its wastewater collection, treatment, and re-use processes. Construction of the sewer network in Singapore commenced around 1910 with the building of three sewers; a network of around 700 km (435 mi) existed in 1970 and thereafter the network was expanded at a rate of about 70 km (43 mi) per annum to its present size.

In 1993, PUB dispatched a team of its engineers to the U.K. to meet with WRc and study emerging rehabilitation methods. It appointed Montgomery Watson (now MWH) as its rehabilitation consultant and embarked on a major rehabilitation project (U.S. $6 million) to upgrade one of the older catchments at Paya Lebar. The work was undertaken by a local contractor using the Formapipe CIPP system. In 1995, MOE embarked its second project (U.S. $7 million) at Pulau Saigon, lining approximately 4 km (2.5 mi) of 150 to 600 mm (6 to 24 in.) sewer; the project again planned to used Formapipe, but the system was acquired by Insituform and the project handed over to local licensee IPCO Insituform SE Asia Pte (IPCO).

Encouraged by its success in these two pilot schemes, PUB put out to tender the first of its two major schemes to renovate the bulk of Singapore's older sewers in six subsidiary projects. Phase 1 (valued at U.S. $105 million) involved 420 km (261 mi) of sewer and was shared by three contractors: IPCO, Johnson Pacific using InLiner, and L&M using Permaline.

The scale of the Phase 1 project established the three companies and encouraged new competitors to target the Phase 2 released for tender from 2001. Phase 2, nearing completion and valued at U.S. $73 million involved 350 km (217 mi) of sewer and was shared by the three contractors from Phase 1 together with new players PRS (now Sekisui) and Jetscan, who utilized the Multiliner system. The PUB sewer renovation program from 1993 to 2005 involved an investment of almost U.S. $200 million and addressed problems in 800 km (497 mi) of sewers. It commenced with two small-scale projects, initially managed with outside expert experience and concluded with two substantial schemes that established a pool of expert contractors. The issue of contracts on this scale had a major impact on unit length pricing. The average pricing fell from S $550/m to S $205/m (U.S. $128 to U.S. $48 per ft) in the 10-year period since 1993. There were many technical developments employed in the period, including the use of pressure inversion vessels, resin extenders, fast cure catalysts, fiber reinforcements, and innovative scheduling to achieve product quality and cost reduction.

In 2006, Phase 3 was released and will continue until 2012. It involves sewers and private drain lines in the Marina Barrage Catchment. As part of the Four Taps strategy, PUB has constructed a barrage across the mouth of the Singapore River. This U.S. $226 million dam constructed across the mouth of the river created Singapore's 15th reservoir in 2008. It took the top prize awarded in 2009 by the American Academy of Environmental Engineers. The Marina Reservoir is used for flood control, water storage and recreational facilities such as boating. It is important that is not polluted by sewage and PUB has conducted a major investigation to identify sources of exfiltration and groundwater pollution. Phase 3 will address issues identified in 600 km (373 mi) of the public sewer and private drain line network in the Marina area. Investment is expected to be in excess of U.S. $100 million.

Phase 4, which involves 1130 km (702 mi) of sewer, is also now under way and is expected to cost a further U.S. $100 million. It is hoped that Phase 4 will be completed in 2012. The PUB Web site currently lists 1,264 individual projects scheduled for 2010 to 2012 and the majority involve sewer rehabilitation. In addition to gravity sewers, PUB has relined a significant amount of sewer force mains using Sekisui's Nordipipe product, and products from Insituform including the Kevlar reinforced liners, InsituMain® Pressure Liner and InsituMain® Reinforced Pressure Pipe.

At the present time, PUB estimates that it has lined in excess of 1,100 km (684 mi) of the 3,400 km (2,113 mi) network, i.e., about 30% of the wastewater collection system. In addition to CIPP (900 km (560 mi), it has used some 120 km (75 mi) of spiral wound pipe and about 60 km (37 mi) of fold-and-form (mainly Ex-Pipe from Australian contractor Kembla Construction). About 150 km (93 mi) of private sewers have been lined and some 9,000 top hats installed at private sewer connections.

PUB has carried out inspections of historic rehabilitation projects, typically after about 10 years in service. Early installations at Paya Lebar, Kim Seng Road, and Bishan Street were found to be in generally good condition with no major defects. However, some defects have been identified, for example, a collapsed liner in Ubi Avenue and serious longitudinal wrinkling in Geylang Road.

Much of the early work tendered by PUB was water inversion and hot water cure; however, in recent years, some steam curing has been undertaken and it is estimated that this method amounts to about 50% of current work. Much of the air inversion steam curing is carried out on the private drain lines in the Marina Catchment. UV curing has also been undertaken on one project to date. Design work is undertaken by PUB staff and by independent consultants – particularly CPG Consultants, a local consultant born out of the corporatization of the Public Works Department and acquired by the Australian Downer group in 2003. Designs make reference to the tender documents and a PUB Sewerage Rehabilitation Manual, which draws heavily on U.K. and U.S. practice and references the WRc, WIS, and ASTM standards. PUB is rigorous on sampling and testing from installed liners and uses its engineering staff to supervise works. However, the scale of current works is so substantial that staff are very stretched to cover all the installation activities. Works are routinely CCTV surveyed after two years in service (i.e., on completion of the warranty period), and problems encountered include wrinkling, coating defects such as blistering, and poor quality lateral reinstatement. Contractors are required to remedy defects.

The emphasis in Phases 3 and 4 on private drain lines and exfiltration has encouraged the PUB to trial various proprietary lateral lining and top hat connection systems and this has encouraged a number of epoxy resin system developers such as Epros, RS Lining, and MC Bauchemie to concentrate on the Singapore market. At the present time, PUB has specified that all sewers up to 225 mm (9 in.) shall be lined with epoxy-resin-based systems. This practice, implemented to avoid shrinkage associated with polyester use, is not without problems because of the tropical climate experienced in Singapore. Mixing two-component epoxy systems can give rise to difficulties with premature curing in high ambient temperatures and when large batches are mixed. Experienced contractors such as OLiner Pte Ltd. have equipped themselves with static mixer equipment and limited batch sizes to minimize installation risks. Other less experienced contractors have not always been so fortunate and there is an undercurrent of rumors about site problems. Some system providers (Epros, MC) have established local depots providing technical support, central mixing and impregnation facilities to service less experienced contractors and this has helped to minimize difficulties. Some system providers have also introduced resins formulated for warmer climates.

In a recent development, the principal CIPP contractors and PUB have established, in June 2009, a Singapore Society for Trenchless Technology (SgSTT). This body will work with PUB to establish a good practice consensus and revise the local Sewer Rehabilitation Manual. PUB is keen to work with its contractors to establish training and certification schemes so that all parties involved in sewer rehabilitation can attain minimum standards. SgSTT affiliated with ISTT in November 2010 prior to the International No Dig Conference and Exhibition to improve access to international experience and raise standards. Current initiatives are focused on provision of CCTV and CIPP training.

PUB Consultants Private Limited (PUBC) is the commercial arm of PUB and plays strategic and active facilitative roles in assisting PUB to achieve its goal in developing the Singapore Water industry. PUBC harnesses PUB’s operational experience and resources to support the Singapore-based water companies in their overseas ventures in projects relating to infrastructure development and operation and maintenance of municipal systems in water supply, used water treatment and disposal in the key markets of the Middle East, North Africa, China, Southeast Asia, Australia and India water reclamation and recycling. It can be expected that PUB’s substantial experience in managing sewer rehabilitation projects will play a role in PUBC activities in Southeast Asia in future years.

C.8 Brisbane Water (BW)

BW was interviewed in Brisbane on April 19, 2010. BW distributes water and collects wastewater in the City of Brisbane, Australia. It is Australia’s second largest water and wastewater utility. In July 2010, it merged with four adjacent utilities to form Queensland Urban Utilities (QUU). QUU is jointly owned by the five local authorities and operates as a statutory authority. QUU is one of the largest water retail distributors in Australia, providing service to more than 1.3 million residents. This report focuses on the experience of BW rather than that of QUU as a whole, since the adjacent utilities have minimal experience of sewer rehabilitation. BW operates a sewer network of 6,844 km (4,253 mi) with an additional 740 km (460 mi) of laterals. BW was the first user of CIPP for sewer rehabilitation in

Australia; its first installation was in 1979. BW had already used sliplining for some 10 years prior to the first use of CIPP.

The technologies used for sewer rehabilitation by BW are shown in Table C-7.

Table C-7. Use of Rehabilitation Methods in Brisbane, Australia

Method	First Use	Total Installed (km)	Length in past year (km)
CIPP	1979	45 (main sewers); 330 (laterals)	1.7
Spiral lining	1985	25.5	2.5
Sliplining	1968	9.5	Minimal
PVC fold & form	1985	28.9	2.2

In addition to the main sewer and lateral lining, BW has installed 660 patch repairs and 120 tees/top hats using CIPP technology. Between 1979 and 1985, it used CIPP almost exclusively for its sewer rehabilitation requirements. At that time there was no viable alternative to CIPP, so BW continued to use it despite several problems. The problems encountered were:

- Where there was a high head of groundwater over the pipe, there was leakage into the pipe during the installation. This caused holidays and areas of uncured resin. At that time, unsaturated polyester resin was exclusively used.
- Poor bond of resin to concrete pipe. This led to risk of collapse. Liners shrunk away from the host pipe leaving an annular space. In deep sewers this was under high pressure. One installation was undertaken at 116 ft (35 m) deep.
- Tendency of the ends of the CIPP to contract back into the pipe when cut, leaving a length of unlined sewer adjacent to manholes.
- Operational risk. Brisbane has a sub-tropical climate and is subject to sudden and severe rainfall events at certain times of the year. When one of these occurs, the sewer system quickly becomes surcharged and it is necessary to stop all works in the system. If using CIPP, this results in a major problem as the liner is left partially cured and has to be painstakingly removed and the work repeated.
- Installation risk. BW had one experience where an installation of 100 m (328 ft) length of 675 mm (27 in.) diameter CIPP was lost. The end plug holding the curing water blew out and all the curing water was lost. The sewer was 10 m (32.8 ft) deep and it was not possible to retrieve the partially cured liner, so it continued to cure, but slowly and not sufficiently to provide the necessary rehabilitation. It had to be cut into small pieces and extracted; this work took several months.

As a result of these problems and also due to the problems of ensuring that the line was sufficiently dry for CIPP to cure, BW considers CIPP to be risky in sub-tropical climates and was open to alternatives. When spiral lining and PVC fold-and-form became available in 1985, BW tested them and switched to spiral lining as its main rehabilitation method. The more recent use of CIPP has been mainly in laterals.

Spiral lining has two practical advantages for BW:

- It can be undertaken with some flow in the pipe.
- If there is a sudden rainfall event, it can easily be removed and the work repeated.

BW continues to use CIPP, mainly in laterals. The current methods used are:

- Installation: air inversion 80%; water inversion 15%; and pull-in and inflate 5%
- Curing: steam 80%; hot water 15%; and UV 5%

Recently, BW experienced a problem with a UV-cured installation. A liner failed to cure properly for unknown reasons, but BW suspects that it was due to contractor inexperience or equipment failure. The liner was removed by cutting it into small pieces, and successfully replaced with a similar UV-cured liner. However, BW considers that such failures are a rarity and that the systems are generally reliable; the technology is adequate, but that the problems occur with installers. A committed and experienced installing contractor is necessary.

In order to ensure the quality of CIPP installation, BW has developed a specification based around the following standards:

- EN13566-1:2002: plastics piping systems for renovation of underground non-pressure drainage and sewerage networks - General.
- EN13566-4:2002: plastics piping systems for renovation of underground non-pressure drainage and sewerage networks - Lining with CIPP.
- ISO175:1999: plastics - methods of test for the determination of the effects of immersion in liquid chemicals.
- EN1542:1999: products and systems for the protection and repair of concrete structures. Test methods.
- A jetting resistance test developed by BW.
- The Darmstadt abrasion resistance test.

Type testing is required for all materials used. Tests stipulated are: strain corrosion, creep, and chemical resistance. Samples from the installation are taken and tested in a third party laboratory for thickness, tensile modulus and watertightness. Post-installation CCTV survey is also required; it is linked to GIS data and the data is archived for future reference. Liners are also pressure tested where their location is considered critical, for example under embankments where the consequence of failure is high.

The above items are QA/QC data required from the contractor, but BW is moving to a system of performance specification and requiring a guarantee from the manufacturers of proprietary products that this can be met. Products will be allowed based on such guarantees and the performance risk placed on the vendor.

BW has undertaken inspection of CIPP installations after a period in service. An installation from 1985 comprising 1.9 km (1.18 mi) of 12 mm (0.47 in.) thick 750 mm (30 in.) and 825 mm (32.5 in.) diameter lining was inspected in 2002, i.e., after 17 years of service. The inspection was by CCTV only and no defects were noted. Since then, several further inspections by CCTV and man entry have been undertaken of this same line, and coupons taken. No defects were noted in the inspection.

Coupons have been retrieved from certain pipes when pieces have been dislodged by high pressure jetting done for cleaning purposes, but have not been tested to establish their properties. This has raised concerns over jetting for cleaning in CIPP-lined pipes. BW has addressed this through changing its operational procedures for jetting by limiting pressure and using specific designs of nozzle.

BW considers that CIPP is a valuable technology when the right product is used in the right conditions, but that it is important to understand its limitations and risks. The nature of sub-tropical regions is such that it may not be well suited to work in such locations. Also the experience, capability and commitment of the installer are considered paramount. The combination of an inexperienced client and an inexperienced installer will lead to problems. The move to requiring guarantees from system vendors is intended to overcome this risk.

C.9 Sydney Water (SW)

Sydney was declared the first city in Australia in 1842. By 1857, the City Council had commissioned five sewer outfalls discharging into the harbor. A Board of Water Supply and Sewerage was established in 1880 and Botany Sewage treatment farm was opened in 1888. Sewer collection systems were built to serve the north, west and south of the city starting in 1898. Four major sea outfalls were built between 1916 and 1936. Inland treatment facilities were built at Fairfield and Campbelltown in 1938 and collection systems were built at Cronulla and Port Kembla starting in 1958. The Metropolitan Water Supply and Sewerage Board became the Sydney Water Board in 1987 and Sydney Water Corporation in 1994.

SW serves the city and suburbs, an area of some 12,700 km^2 (4,900 mi^2) housing a population of 4.5 million. It collects and treats 1.2 billion liters of wastewater daily. The three largest of 29 plants, located at Malabar, North Head and Bondi, treat about 75% of the volume collected. Recycling and desalination are major initiatives to improve water provision and it is hoped to recycle about 12% of wastewater by 2015. The wastewater collection system involves about 24,000 km (14,900 mi) of pipes, 5,500 km (3,418 mi) of laterals and 674 pumping stations. In addition, there are 443 km (275 mi) of stormwater channels and pipes. As expected in a city of such history, the system is mature and maintenance and restoration programs are ongoing.

SW operates a number of major pipe maintenance programs. These include: the A $560 million (U.S. $552 million) four-year Sewerfix plan due for completion in 2012; the Northern Suburbs Ocean Outfall System project, to clean and repair large diameter tunnels and pipes; and the targeted A$80 million (U.S. $79 million) Wastewater System Rehabilitation Project.

SW has had a long involvement in the development and use of sewer rehabilitation methods. Rocla Monier was among the first overseas companies to adopt the Insituform system in 1978. Sydney is thought to be the first city in Australia to use the Insituform method. In 1992, the Insituform license was taken over by East Coast Underground, a company which also offered the Nupipe PVC fold-and-form system. The license was withdrawn after 3 to 4 years and Insituform contracted works directly from the U.K. from time to time until a local operation (Insituform Pacific Pty) was established in 2007. Some 200 km (124 mi) of CIPP has been installed by SW since 1978 and currently a number of contractors including Insituform, Kembla and Veolia offer CIPP. Water inversion and hot water cure is the preferred installation method but air inversion and steam are in the process of introduction and some UV light curing has been used. The Berolina and Brandenburger systems have been tried. Overall, approximately 20 km (12.5 mi) of sewer was lined with CIPP in 2009.

SW also supported the development of local technology and has been a major user of the Ribloc Spiral Wound PVC method. It is estimated that 800 km (497 mi) of spiral wound (Ribloc and Danby) and fold-and-form (EX Pipe) systems have been used in Sydney. Spiral wound pipes are popular in Australia. The principal system installer is InterFlow Pty, Ltd., which holds the Ribloc license from Sekisui SPR. This technology was developed in Australia in 1983 as a means of casting pipe in remote locations. By 1986, it had been employed for sewer lining and was taken up by Sekisui and developed in joint venture with the Tokyo Metropolitan Government in Japan. The technology has been well utilized in the Middle

East, but has not yet had marked success in Europe or North America. Since the worldwide licensed business was acquired by Sekisui Corporation, significant marketing effort has been applied and a range of new spiral wound products including Rib Steel and Rib Line are making some headway. In addition to Ribloc, the Danby system was also invented in Australia and its Panel Lok is available for man-entry sewers.

Since 1992, some 1,200 km (746 mi) of fold-and-form pipe has been installed throughout Australia; the folded pipe material is manufactured by Vinidex. In 2009, SW lined approximately 50 km (31 mi) of sewer with spiral wound and fold-and-form products.

For some years, SW's rehabilitation programs have been driven by inflow and infiltration reduction and the organization has focused on both sewer mains and laterals. Generally, the private lateral is considered as the pipe from the boundary trap to the household. In the 1990s, there was a considerable focus on lateral lining and grouting with the Logiball system and a number of lateral lining systems have been employed. The current policy on laterals is to line the connection with the main and some 300 to 400 mm (12 to16 in.) of the sewer lateral using a top hat system such as Kembla's Tiger T or Interflow's Interfit connection seal. From 1997, SW trialed a number of different lining systems and now concentrates its programs around CIPP, fold-and-form systems and EX Pipe for lines up to 300 mm (12 in.). SW has recently moved away from its focus on I/I due to a prolonged drought affecting its catchments.

Currently, SW aims to undertake 400-500 km (250-310 mi) of CCTV work and anticipates that this will yield a lining program covering 10-15% of pipe surveyed. The reasons for remedial work are predominantly associated with workmanship issues arising from original construction and root intrusion. Liner designs are undertaken as partially or fully deteriorated using ASTM F1216 for partially deteriorated pipe and AS2566 Plastic Pipe-laying Design for fully deteriorated pipe. In this latter local standard, the liner is designed as a new pipe. Egg shapes are designed in accordance with the WRc Sewer Rehabilitation Manual.

The long-term flexural modulus values selected for design adopted by SW are generally those provided by the local manufacturer or overseas system provider. Liners are predominantly resin and felt and there is little experience of strain corrosion or chemical resistance testing. For process verification of installed liners, restrained samples are generally taken from the liner in the manholes; one from each four to five installations is transferred into safe custody and tested by a third-party laboratory. Usually parallel plate testing of pipe samples is preferred to flat plate or prepared coupon samples. SW also specifies that Shore hardness testing is undertaken for CIPP installations as a simple indicator of satisfactory curing and impregnation. A Shore D hardness value of 60-70 is considered acceptable. The Shore hardness durometer with its round tipped indentor is preferred to the flat tipped Barcol device and can deal with curved surfaces.

SW inspects installed liners at the end of two years in service; problems are rarely experienced because its shortlisted framework contractors, Interflow, Kembla Watertech and Insituform Pacific are all substantially experienced. The main defect experienced with CIPP liners are reported to be poorly reinstated connections. Wrinkling greater than 1% and ovality greater than 5% are regarded as defects. SW's construction supervisors are trained in house and on the job; construction activity is monitored, but resin mixing and impregnation are deemed to be the contractor's competency.

SW has more than 30 years of experience with CIPP and other rehabilitation methods and is involved in a wide range of rehabilitation activity from service connections to large outfall sewers. Major programs are ongoing.

APPENDIX D

MERCURY PENETRATION POROSITY TEST REPORTS

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09	Serial: 1011	Port: 2/1	Page 1

Sample: Denver Upstream-48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007920.SMP

LP Analysis Time:	1/7/2011 3:26:05PM	Sample Weight:	2.9639 g
HP Analysis Time:	1/7/2011 4:39:09PM	Correction Type:	None
Report Time:	1/14/2011 2:35:46PM	Show Neg. Int:	No

Summary Report

Penetrometer parameters

Penetrometer:	374 - (01) 15 Bulb, 0.392 Stem, Solid		
Pen. Constant:	11.007 μL/pF	Pen. Weight:	71.1760 g
Stem Volume:	0.3920 mL	Max. Head Pressure:	4.4500 psia
Pen. Volume:	15.1835 mL	Assembly Weight:	245.1800 g

Hg Parameters

Adv. Contact Angle:	130.000 degrees	Rec. Contact Angle:	130.000 degrees
Hg Surface Tension:	485.000 dynes/cm	Hg Density:	13.5335 g/mL

Low Pressure:

Evacuation Pressure:	50 μmHg
Evacuation Time:	5 mins
Mercury Filling Pressure:	0.54 psia
Equilibration Time:	10 secs

High Pressure:

Equilibration Time:	10 secs

No Blank Correction

Intrusion Data Summary

Total Intrusion Volume =	0.0967 mL/g
Total Pore Area =	31.968 m²/g
Median Pore Diameter (Volume) =	0.0286 μm
Median Pore Diameter (Area) =	0.0048 μm
Average Pore Diameter (4V/A) =	0.0121 μm
Bulk Density at 0.54 psia =	1.1645 g/mL
Apparent (skeletal) Density =	1.3123 g/mL
Porosity =	11.2620 %
Stem Volume Used =	73 %

Micromeritics Instrument Corporation

Sample: Denver Upstream-48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007920.SMP

LP Analysis Time: 1/7/2011 3:26:05PM
HP Analysis Time: 1/7/2011 4:39:09PM
Report Time: 1/14/2011 2:35:46PM

Sample Weight: 2.9639 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (µm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m²/g)	Incremental Pore Area (m²/g)
0.54	332.8265	0.0000	0.0000	0.000	0.000
0.77	236.3104	0.0042	0.0042	0.000	0.000
1.01	178.7894	0.0061	0.0019	0.000	0.000
2.02	89.5715	0.0201	0.0140	0.001	0.000
3.01	60.1294	0.0287	0.0086	0.001	0.000
4.01	45.1181	0.0308	0.0021	0.001	0.000
5.50	32.8603	0.0327	0.0019	0.001	0.000
7.00	25.8231	0.0333	0.0006	0.001	0.000
8.50	21.2743	0.0339	0.0006	0.002	0.000
10.50	17.2325	0.0342	0.0003	0.002	0.000
12.99	13.9282	0.0345	0.0003	0.002	0.000
15.98	11.3175	0.0348	0.0003	0.002	0.000
19.96	9.0632	0.0352	0.0003	0.002	0.000
22.95	7.8802	0.0354	0.0002	0.002	0.000
25.02	7.2287	0.0355	0.0002	0.002	0.000
29.99	6.0314	0.0359	0.0003	0.002	0.000
36.75	4.9218	0.0360	0.0001	0.002	0.000
46.64	3.8781	0.0361	0.0001	0.002	0.000
55.91	3.2348	0.0362	0.0001	0.003	0.000
71.26	2.5382	0.0363	0.0001	0.003	0.000
86.40	2.0934	0.0364	0.0001	0.003	0.000
112.35	1.6098	0.0379	0.0015	0.006	0.003
136.89	1.3212	0.0383	0.0004	0.007	0.001
172.00	1.0516	0.0385	0.0002	0.008	0.001
216.55	0.8352	0.0386	0.0001	0.008	0.001
266.75	0.6780	0.0388	0.0002	0.009	0.001
326.80	0.5534	0.0390	0.0002	0.011	0.001
416.49	0.4343	0.0393	0.0003	0.013	0.002
516.92	0.3499	0.0395	0.0003	0.015	0.003
637.69	0.2836	0.0398	0.0003	0.018	0.003
697.19	0.2594	0.0399	0.0002	0.021	0.002
797.45	0.2268	0.0403	0.0004	0.027	0.006
987.87	0.1831	0.0406	0.0003	0.033	0.007
1197.43	0.1510	0.0409	0.0003	0.041	0.008
1297.67	0.1394	0.0411	0.0002	0.046	0.005
1396.71	0.1295	0.0413	0.0002	0.050	0.005
1497.27	0.1208	0.0414	0.0002	0.055	0.005
1596.95	0.1133	0.0416	0.0001	0.060	0.005
1696.21	0.1066	0.0417	0.0002	0.066	0.006
1895.77	0.0954	0.0420	0.0003	0.077	0.011
2045.35	0.0884	0.0422	0.0002	0.086	0.009

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 2/1 Page 3

Sample: Denver Upstream-48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007920.SMP

LP Analysis Time: 1/7/2011 3:26:05PM
HP Analysis Time: 1/7/2011 4:39:09PM
Report Time: 1/14/2011 2:35:46PM

Sample Weight: 2.9639 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (μm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m^2/g)	Incremental Pore Area (m^2/g)
2195.38	0.0824	0.0424	0.0002	0.095	0.010
2345.25	0.0771	0.0426	0.0002	0.106	0.011
2494.90	0.0725	0.0428	0.0002	0.117	0.011
2644.26	0.0684	0.0430	0.0002	0.129	0.012
2694.72	0.0671	0.0431	0.0001	0.135	0.006
2843.76	0.0636	0.0433	0.0002	0.147	0.013
2994.37	0.0604	0.0435	0.0002	0.161	0.013
3242.63	0.0558	0.0439	0.0003	0.182	0.022
3492.02	0.0518	0.0442	0.0003	0.208	0.025
3741.92	0.0483	0.0445	0.0003	0.234	0.026
3991.68	0.0453	0.0449	0.0003	0.262	0.029
4241.14	0.0426	0.0454	0.0006	0.314	0.052
4486.29	0.0403	0.0457	0.0003	0.344	0.030
4725.91	0.0383	0.0461	0.0004	0.383	0.039
4984.93	0.0363	0.0466	0.0005	0.433	0.050
5282.52	0.0342	0.0471	0.0005	0.488	0.055
5481.05	0.0330	0.0474	0.0003	0.525	0.037
5731.50	0.0316	0.0477	0.0003	0.562	0.037
5978.42	0.0303	0.0480	0.0003	0.600	0.038
6224.62	0.0291	0.0483	0.0003	0.639	0.039
6474.14	0.0279	0.0485	0.0003	0.678	0.039
6723.87	0.0269	0.0488	0.0003	0.721	0.043
6972.33	0.0259	0.0491	0.0003	0.764	0.044
7475.55	0.0242	0.0497	0.0005	0.851	0.087
7974.62	0.0227	0.0502	0.0005	0.943	0.092
8476.29	0.0213	0.0507	0.0005	1.040	0.096
8975.63	0.0202	0.0513	0.0005	1.143	0.103
9271.17	0.0195	0.0516	0.0003	1.208	0.065
9569.83	0.0189	0.0520	0.0004	1.296	0.088
10024.73	0.0180	0.0525	0.0005	1.411	0.115
10470.36	0.0173	0.0531	0.0006	1.545	0.135
10972.28	0.0165	0.0537	0.0006	1.684	0.138
11472.64	0.0158	0.0543	0.0005	1.817	0.134
11969.80	0.0151	0.0548	0.0005	1.958	0.141
12575.52	0.0144	0.0556	0.0008	2.182	0.224
13075.16	0.0138	0.0562	0.0005	2.332	0.150
13623.25	0.0133	0.0567	0.0006	2.501	0.169
13969.03	0.0129	0.0571	0.0004	2.616	0.115
14308.11	0.0126	0.0575	0.0004	2.734	0.119
14564.80	0.0124	0.0578	0.0003	2.832	0.098
14969.20	0.0121	0.0582	0.0004	2.976	0.144

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 2/1 Page 4

Sample: Denver Upstream-48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007920.SMP

LP Analysis Time: 1/7/2011 3:26:05PM
HP Analysis Time: 1/7/2011 4:39:09PM
Report Time: 1/14/2011 2:35:46PM

Sample Weight: 2.9639 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (μm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m²/g)	Incremental Pore Area (m²/g)
15420.78	0.0117	0.0588	0.0006	3.176	0.200
15766.99	0.0115	0.0592	0.0004	3.314	0.138
16171.48	0.0112	0.0597	0.0005	3.476	0.162
16620.37	0.0109	0.0602	0.0005	3.649	0.174
16969.08	0.0107	0.0605	0.0004	3.788	0.139
17313.23	0.0104	0.0609	0.0004	3.932	0.143
17668.07	0.0102	0.0613	0.0004	4.086	0.155
18069.68	0.0100	0.0618	0.0005	4.287	0.200
18418.26	0.0098	0.0622	0.0004	4.457	0.171
18765.49	0.0096	0.0626	0.0004	4.620	0.163
19164.20	0.0094	0.0631	0.0004	4.796	0.176
19771.59	0.0091	0.0637	0.0007	5.079	0.283
20272.19	0.0089	0.0644	0.0007	5.397	0.318
20778.76	0.0087	0.0651	0.0006	5.682	0.285
21181.29	0.0085	0.0657	0.0007	5.988	0.306
21633.64	0.0084	0.0662	0.0005	6.230	0.242
22031.44	0.0082	0.0675	0.0012	6.820	0.590
22637.16	0.0080	0.0681	0.0006	7.118	0.298
23187.58	0.0078	0.0686	0.0005	7.380	0.263
23738.37	0.0076	0.0691	0.0005	7.657	0.277
24089.02	0.0075	0.0695	0.0004	7.845	0.189
24639.09	0.0073	0.0700	0.0005	8.121	0.276
25040.53	0.0072	0.0704	0.0004	8.334	0.213
25440.46	0.0071	0.0708	0.0004	8.551	0.217
25891.56	0.0070	0.0716	0.0008	9.026	0.476
26441.46	0.0068	0.0722	0.0006	9.361	0.335
26941.94	0.0067	0.0727	0.0005	9.653	0.292
27391.92	0.0066	0.0732	0.0005	9.974	0.321
27792.81	0.0065	0.0736	0.0004	10.212	0.238
28242.91	0.0064	0.0740	0.0004	10.470	0.258
28993.84	0.0062	0.0746	0.0006	10.860	0.391
29493.05	0.0061	0.0751	0.0004	11.147	0.287
29994.09	0.0060	0.0755	0.0004	11.435	0.288
30444.07	0.0059	0.0759	0.0004	11.700	0.265
30893.78	0.0059	0.0764	0.0005	12.010	0.310
31294.74	0.0058	0.0767	0.0004	12.254	0.244
31794.42	0.0057	0.0771	0.0004	12.560	0.306
32344.31	0.0056	0.0776	0.0005	12.894	0.334
32894.51	0.0055	0.0781	0.0005	13.225	0.331
33495.02	0.0054	0.0786	0.0005	13.591	0.365
33994.86	0.0053	0.0790	0.0004	13.909	0.318

Micromeritics Instrument Corporation

Sample: Denver Upstream-48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007920.SMP

LP Analysis Time: 1/7/2011 3:26:05PM
HP Analysis Time: 1/7/2011 4:39:09PM
Report Time: 1/14/2011 2:35:46PM

Sample Weight: 2.9639 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (μm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m²/g)	Incremental Pore Area (m²/g)
34644.05	0.0052	0.0795	0.0005	14.306	0.397
35495.53	0.0051	0.0803	0.0008	14.890	0.585
36194.58	0.0050	0.0808	0.0005	15.268	0.378
36993.98	0.0049	0.0814	0.0006	15.769	0.500
37645.64	0.0048	0.0819	0.0005	16.205	0.436
38444.59	0.0047	0.0825	0.0006	16.737	0.532
39194.91	0.0046	0.0831	0.0006	17.234	0.498
39993.93	0.0045	0.0837	0.0006	17.761	0.527
40494.13	0.0045	0.0841	0.0004	18.127	0.366
40994.47	0.0044	0.0845	0.0004	18.493	0.366
42494.84	0.0043	0.0856	0.0011	19.501	1.008
43342.89	0.0042	0.0862	0.0006	20.083	0.583
43991.40	0.0041	0.0868	0.0005	20.584	0.501
44992.86	0.0040	0.0875	0.0007	21.313	0.728
46493.57	0.0039	0.0885	0.0010	22.304	0.991
47990.06	0.0038	0.0894	0.0010	23.304	1.000
49486.39	0.0037	0.0904	0.0010	24.344	1.040
50182.66	0.0036	0.0909	0.0005	24.872	0.528
52972.13	0.0034	0.0925	0.0017	26.757	1.886
54469.81	0.0033	0.0935	0.0009	27.851	1.094
55968.54	0.0032	0.0944	0.0009	28.950	1.099
57966.30	0.0031	0.0955	0.0012	30.447	1.497
59964.98	0.0030	0.0967	0.0012	31.968	1.521

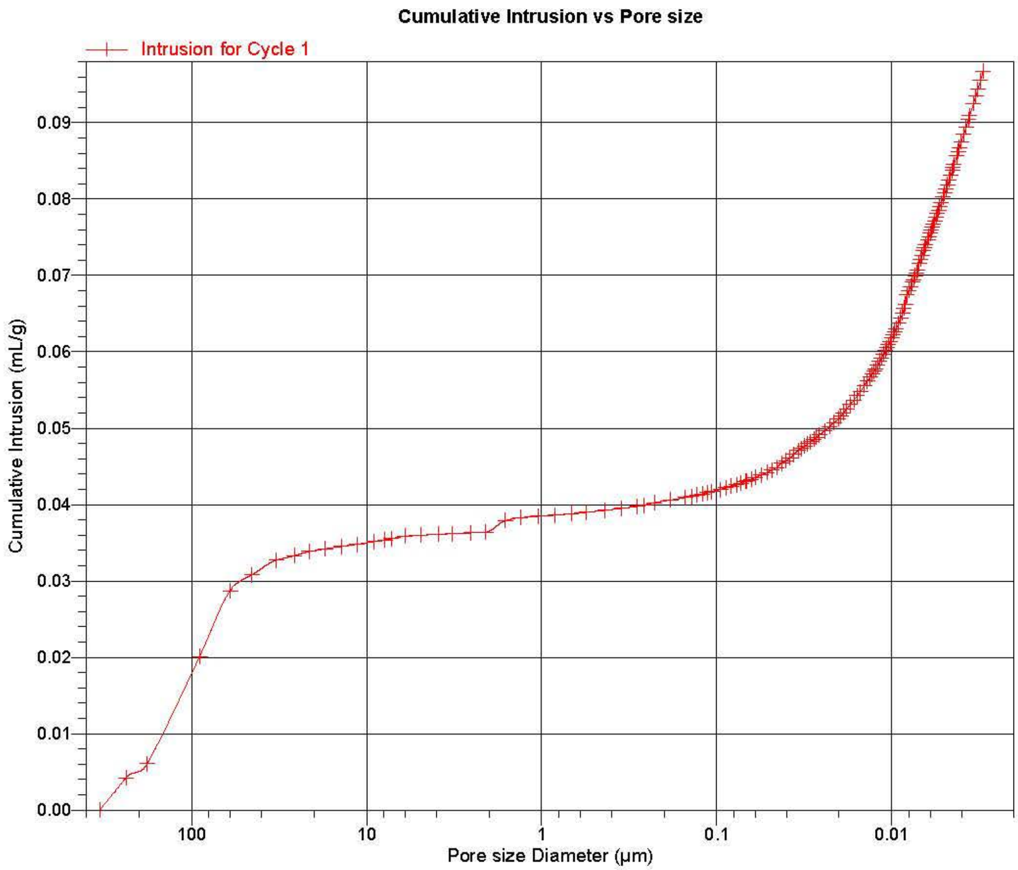
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 2/1 Page 6

Sample: Denver Upstream-48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007920.SMP

LP Analysis Time: 1/7/2011 3:26:05PM
HP Analysis Time: 1/7/2011 4:39:09PM
Report Time: 1/14/2011 2:35:46PM

Sample Weight: 2.9639 g
Correction Type: None
Show Neg. Int: No

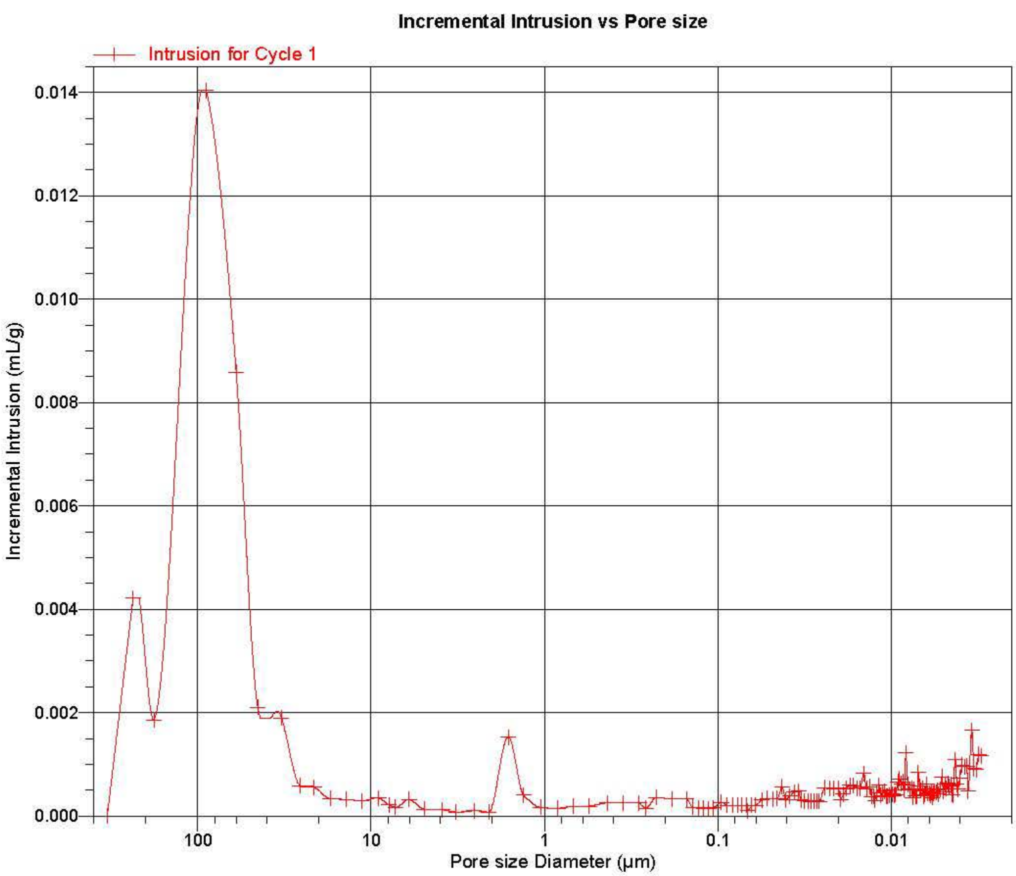


Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09	Serial: 1011	Port: 2/1	Page 7

Sample: Denver Upstream-48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007920.SMP

LP Analysis Time:	1/7/2011 3:26:05PM	Sample Weight:	2.9639 g
HP Analysis Time:	1/7/2011 4:39:09PM	Correction Type:	None
Report Time:	1/14/2011 2:35:46PM	Show Neg. Int:	No



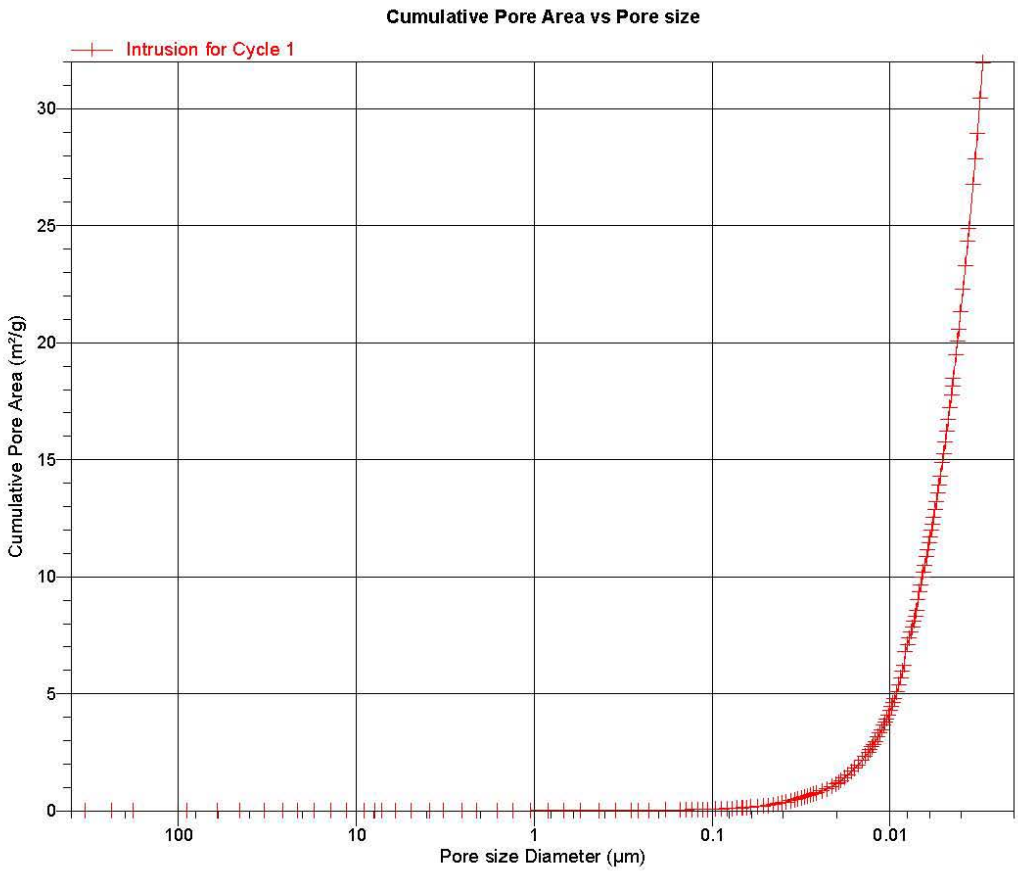
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 2/1 Page 8

Sample: Denver Upstream-48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007920.SMP

LP Analysis Time: 1/7/2011 3:26:05PM
HP Analysis Time: 1/7/2011 4:39:09PM
Report Time: 1/14/2011 2:35:46PM

Sample Weight: 2.9639 g
Correction Type: None
Show Neg. Int: No



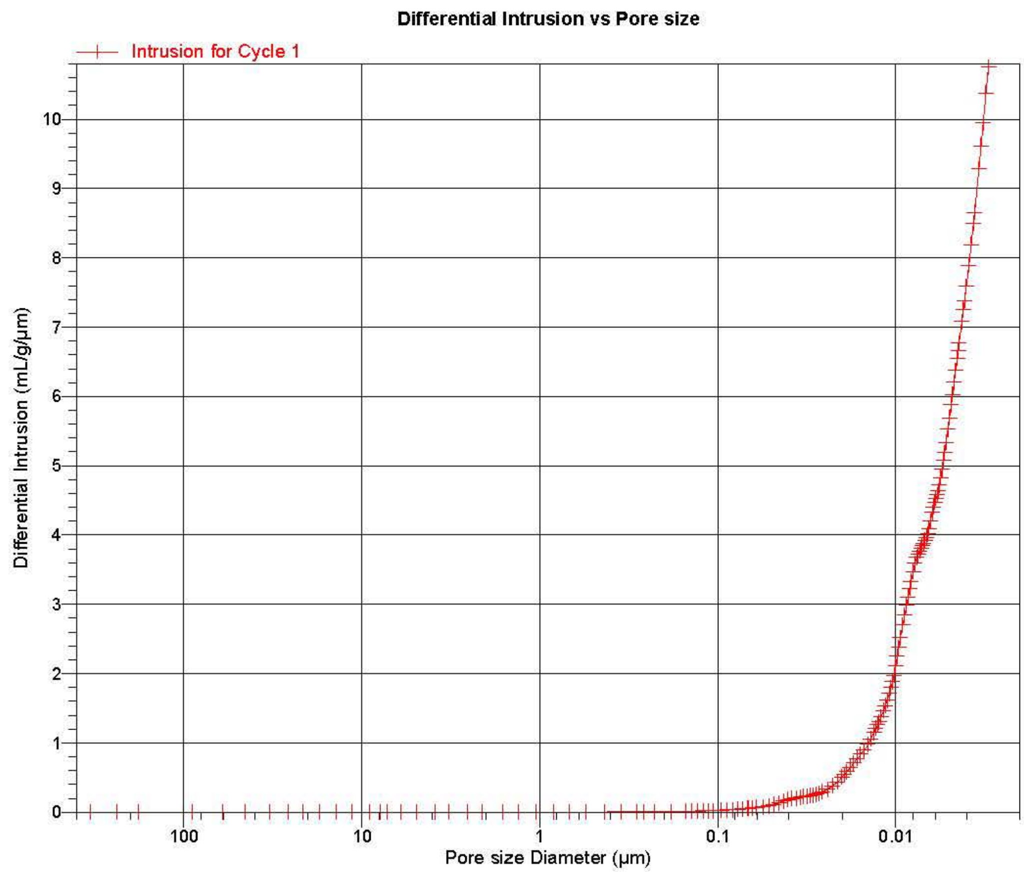
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 | Serial: 1011 | Port: 2/1 | Page 9

Sample: Denver Upstream-48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007920.SMP

LP Analysis Time: 1/7/2011 3:26:05PM
HP Analysis Time: 1/7/2011 4:39:09PM
Report Time: 1/14/2011 2:35:46PM

Sample Weight: 2.9639 g
Correction Type: None
Show Neg. Int: No



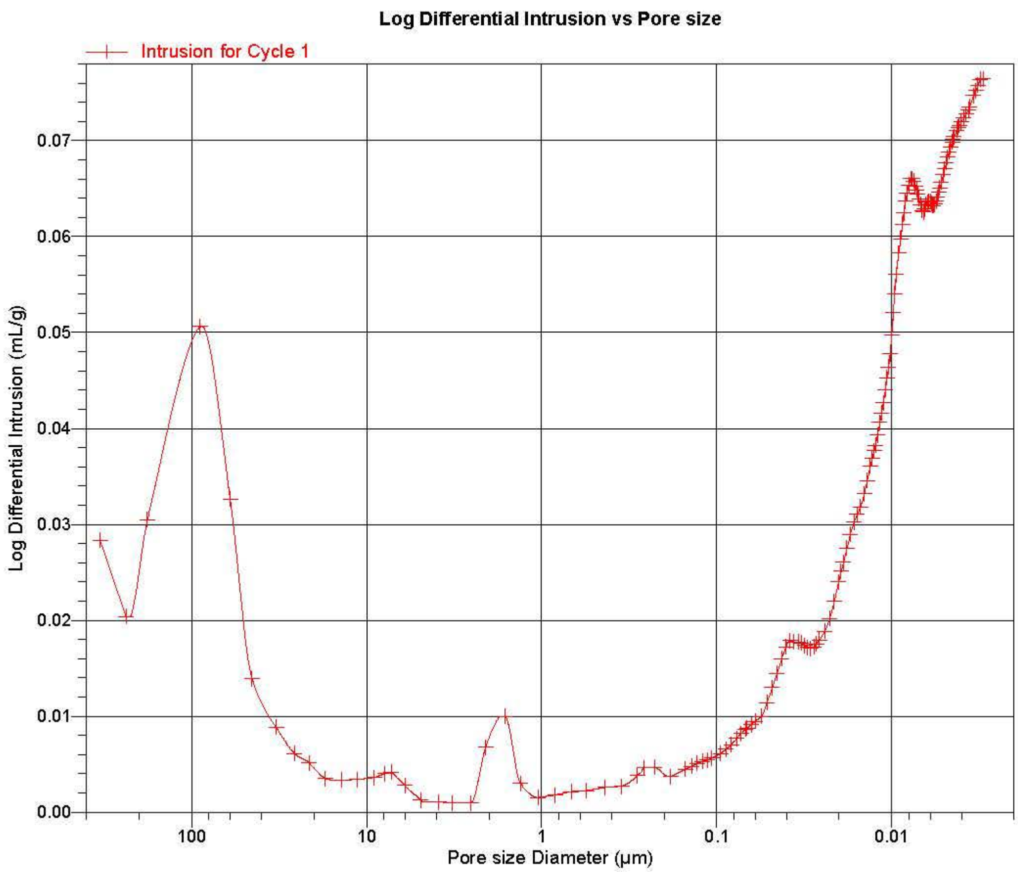
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 2/1 Page 10

Sample: Denver Upstream-48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007920.SMP

LP Analysis Time: 1/7/2011 3:26:05PM
HP Analysis Time: 1/7/2011 4:39:09PM
Report Time: 1/14/2011 2:35:46PM

Sample Weight: 2.9639 g
Correction Type: None
Show Neg. Int: No



Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 1/1 Page 1

Sample: Denver 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007921.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 2.2503 g
Correction Type: None
Show Neg. Int: No

Summary Report

Penetrometer parameters

Penetrometer: 705 - (02) 15 Bulb, 0.392 Stem, Powder

Pen. Constant:	11.117 µL/pF	Pen. Weight:	73.2081 g
Stem Volume:	0.3920 mL	Max. Head Pressure:	4.4500 psia
Pen. Volume:	14.2463 mL	Assembly Weight:	239.8797 g

Hg Parameters

Adv. Contact Angle:	130.000 degrees	Rec. Contact Angle:	130.000 degrees
Hg Surface Tension:	485.000 dynes/cm	Hg Density:	13.5335 g/mL

Low Pressure:

Evacuation Pressure:	50 µmHg
Evacuation Time:	5 mins
Mercury Filling Pressure:	0.54 psia
Equilibration Time:	10 secs

High Pressure:

Equilibration Time:	10 secs

No Blank Correction

Intrusion Data Summary

Total Intrusion Volume =	0.1483 mL/g
Total Pore Area =	39.720 m²/g
Median Pore Diameter (Volume) =	0.2983 µm
Median Pore Diameter (Area) =	0.0051 µm
Average Pore Diameter (4V/A) =	0.0149 µm
Bulk Density at 0.54 psia =	1.0731 g/mL
Apparent (skeletal) Density =	1.2762 g/mL
Porosity =	15.9149 %
Stem Volume Used =	85 %

Micromeritics Instrument Corporation

Sample: Denver 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007921.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 2.2503 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (μm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m^2/g)	Incremental Pore Area (m^2/g)
0.54	335.7452	0.0000	0.0000	0.000	0.000
0.76	237.9319	0.0020	0.0020	0.000	0.000
1.01	179.6617	0.0038	0.0019	0.000	0.000
2.02	89.5844	0.0295	0.0257	0.001	0.001
3.01	60.1207	0.0446	0.0152	0.002	0.001
4.01	45.1217	0.0478	0.0032	0.002	0.000
5.51	32.8460	0.0499	0.0021	0.002	0.000
7.00	25.8338	0.0514	0.0015	0.002	0.000
8.50	21.2717	0.0537	0.0024	0.003	0.000
10.49	17.2375	0.0558	0.0021	0.003	0.000
12.99	13.9219	0.0586	0.0028	0.004	0.001
15.98	11.3189	0.0608	0.0021	0.005	0.001
19.96	9.0628	0.0627	0.0019	0.005	0.001
23.01	7.8594	0.0639	0.0012	0.006	0.001
25.02	7.2288	0.0644	0.0005	0.006	0.000
29.99	6.0317	0.0658	0.0013	0.007	0.001
36.82	4.9123	0.0663	0.0005	0.007	0.000
46.29	3.9072	0.0669	0.0006	0.008	0.001
55.80	3.2411	0.0673	0.0005	0.008	0.001
71.57	2.5271	0.0682	0.0008	0.009	0.001
86.75	2.0850	0.0685	0.0004	0.010	0.001
111.45	1.6228	0.0690	0.0005	0.011	0.001
136.04	1.3295	0.0693	0.0003	0.012	0.001
171.86	1.0524	0.0701	0.0007	0.014	0.002
216.81	0.8342	0.0710	0.0009	0.018	0.004
266.99	0.6774	0.0721	0.0011	0.024	0.006
326.85	0.5534	0.0727	0.0005	0.028	0.004
417.10	0.4336	0.0732	0.0006	0.032	0.005
516.99	0.3498	0.0737	0.0005	0.038	0.005
636.72	0.2841	0.0743	0.0006	0.045	0.007
697.38	0.2593	0.0745	0.0002	0.048	0.003
797.94	0.2267	0.0748	0.0003	0.053	0.005
987.62	0.1831	0.0753	0.0005	0.063	0.010
1198.11	0.1510	0.0758	0.0005	0.074	0.011
1297.40	0.1394	0.0760	0.0002	0.081	0.007
1397.88	0.1294	0.0763	0.0003	0.089	0.008
1497.41	0.1208	0.0765	0.0002	0.096	0.008
1596.22	0.1133	0.0768	0.0002	0.104	0.007
1696.00	0.1066	0.0770	0.0002	0.112	0.009
1896.12	0.0954	0.0774	0.0004	0.128	0.016
2046.05	0.0884	0.0777	0.0003	0.142	0.014

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 | Serial: 1011 | Port: 1/1 | Page 3

Sample: Denver 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007921.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 2.2503 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (μm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m^2/g)	Incremental Pore Area (m^2/g)
2195.52	0.0824	0.0781	0.0004	0.160	0.018
2345.47	0.0771	0.0784	0.0003	0.173	0.013
2494.76	0.0725	0.0789	0.0005	0.202	0.028
2645.49	0.0684	0.0792	0.0003	0.218	0.017
2694.23	0.0671	0.0793	0.0001	0.226	0.007
2844.00	0.0636	0.0796	0.0003	0.242	0.016
2994.37	0.0604	0.0798	0.0003	0.259	0.017
3243.83	0.0558	0.0802	0.0004	0.287	0.028
3492.37	0.0518	0.0807	0.0004	0.320	0.033
3742.71	0.0483	0.0811	0.0004	0.353	0.033
3991.99	0.0453	0.0815	0.0004	0.389	0.036
4240.43	0.0427	0.0820	0.0004	0.430	0.041
4484.77	0.0403	0.0824	0.0004	0.467	0.038
4724.61	0.0383	0.0828	0.0004	0.513	0.046
4982.60	0.0363	0.0833	0.0005	0.562	0.049
5283.24	0.0342	0.0840	0.0007	0.647	0.085
5482.35	0.0330	0.0844	0.0003	0.687	0.040
5730.31	0.0316	0.0848	0.0005	0.745	0.057
5976.53	0.0303	0.0853	0.0005	0.804	0.059
6225.27	0.0291	0.0856	0.0004	0.854	0.051
6472.55	0.0279	0.0860	0.0003	0.902	0.047
6725.79	0.0269	0.0865	0.0005	0.979	0.078
6971.92	0.0259	0.0871	0.0006	1.074	0.094
7474.30	0.0242	0.0880	0.0008	1.208	0.134
7974.95	0.0227	0.0887	0.0007	1.334	0.126
8476.51	0.0213	0.0894	0.0007	1.457	0.123
8975.22	0.0202	0.0902	0.0008	1.604	0.147
9269.96	0.0195	0.0906	0.0004	1.691	0.087
9568.27	0.0189	0.0910	0.0004	1.773	0.082
10023.06	0.0180	0.0916	0.0006	1.902	0.129
10468.24	0.0173	0.0922	0.0006	2.043	0.141
10972.38	0.0165	0.0929	0.0007	2.220	0.177
11472.17	0.0158	0.0938	0.0008	2.427	0.207
11972.62	0.0151	0.0948	0.0010	2.680	0.253
12576.36	0.0144	0.0958	0.0011	2.966	0.286
13070.78	0.0138	0.0967	0.0009	3.218	0.251
13622.13	0.0133	0.0979	0.0012	3.561	0.343
13969.93	0.0129	0.0985	0.0006	3.747	0.185
14308.38	0.0126	0.0990	0.0006	3.924	0.177
14567.04	0.0124	0.0996	0.0005	4.099	0.176
14971.25	0.0121	0.1003	0.0007	4.328	0.229

MICROMERITICS ANALYTICAL SERVICES The Particle Testing Authority

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 1/1

Sample: Denver 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007921.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 2.2503 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (µm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m^2/g)	Incremental Pore Area (m^2/g)
15420.59	0.0117	0.1009	0.0006	4.541	0.213
15768.42	0.0115	0.1015	0.0005	4.724	0.183
16166.40	0.0112	0.1023	0.0009	5.040	0.316
16617.40	0.0109	0.1030	0.0006	5.271	0.231
16963.14	0.0107	0.1035	0.0005	5.472	0.201
17319.47	0.0104	0.1042	0.0007	5.719	0.248
17667.82	0.0102	0.1047	0.0006	5.937	0.218
18067.91	0.0100	0.1053	0.0006	6.157	0.220
18416.13	0.0098	0.1059	0.0006	6.385	0.228
18765.64	0.0096	0.1064	0.0005	6.611	0.226
19164.96	0.0094	0.1070	0.0006	6.877	0.265
19764.62	0.0092	0.1082	0.0012	7.385	0.509
20273.28	0.0089	0.1090	0.0008	7.745	0.359
20777.43	0.0087	0.1097	0.0007	8.063	0.318
21179.38	0.0085	0.1104	0.0007	8.369	0.305
21631.86	0.0084	0.1111	0.0007	8.695	0.326
22033.96	0.0082	0.1122	0.0011	9.231	0.537
22636.97	0.0080	0.1130	0.0008	9.609	0.377
23186.88	0.0078	0.1138	0.0008	10.035	0.427
23738.84	0.0076	0.1146	0.0008	10.430	0.395
24088.76	0.0075	0.1151	0.0005	10.711	0.281
24640.45	0.0073	0.1159	0.0008	11.122	0.411
25039.78	0.0072	0.1164	0.0005	11.395	0.272
25440.51	0.0071	0.1169	0.0005	11.699	0.304
25891.81	0.0070	0.1175	0.0006	12.051	0.352
26441.73	0.0068	0.1183	0.0007	12.485	0.433
26942.16	0.0067	0.1191	0.0008	12.951	0.466
27391.61	0.0066	0.1197	0.0006	13.331	0.380
27792.91	0.0065	0.1202	0.0005	13.654	0.323
28242.99	0.0064	0.1210	0.0008	14.127	0.473
28993.45	0.0062	0.1219	0.0009	14.678	0.551
29493.95	0.0061	0.1225	0.0006	15.062	0.384
29993.17	0.0060	0.1230	0.0005	15.410	0.349
30443.60	0.0059	0.1235	0.0005	15.773	0.363
30893.57	0.0059	0.1241	0.0006	16.165	0.391
31293.66	0.0058	0.1246	0.0005	16.488	0.323
31793.27	0.0057	0.1252	0.0006	16.892	0.404
32344.46	0.0056	0.1257	0.0006	17.308	0.416
32895.03	0.0055	0.1263	0.0006	17.739	0.431
33495.38	0.0054	0.1270	0.0006	18.203	0.463
33995.14	0.0053	0.1275	0.0005	18.611	0.409

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 1/1 Page 5

Sample: Denver 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007921.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 2.2503 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (µm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m^2/g)	Incremental Pore Area (m^2/g)
34644.78	0.0052	0.1282	0.0006	19.104	0.493
35495.32	0.0051	0.1289	0.0008	19.702	0.598
36195.81	0.0050	0.1296	0.0007	20.247	0.545
36994.26	0.0049	0.1304	0.0007	20.849	0.601
37645.13	0.0048	0.1311	0.0007	21.425	0.576
38444.51	0.0047	0.1318	0.0008	22.081	0.656
39194.77	0.0046	0.1325	0.0007	22.683	0.602
39994.93	0.0045	0.1333	0.0007	23.317	0.634
40493.52	0.0045	0.1338	0.0006	23.830	0.513
40994.74	0.0044	0.1344	0.0005	24.295	0.465
42493.72	0.0043	0.1356	0.0012	25.405	1.110
43344.34	0.0042	0.1363	0.0007	26.082	0.678
43993.54	0.0041	0.1368	0.0006	26.625	0.543
44991.98	0.0040	0.1378	0.0009	27.524	0.898
46493.72	0.0039	0.1389	0.0011	28.643	1.119
47988.28	0.0038	0.1400	0.0012	29.877	1.234
49483.07	0.0037	0.1411	0.0011	31.050	1.174
50183.38	0.0036	0.1418	0.0006	31.740	0.689
52971.26	0.0034	0.1436	0.0018	33.837	2.097
54469.30	0.0033	0.1446	0.0010	35.081	1.244
55967.23	0.0032	0.1457	0.0010	36.340	1.259
57967.82	0.0031	0.1470	0.0013	37.995	1.656
59964.80	0.0030	0.1483	0.0013	39.720	1.725

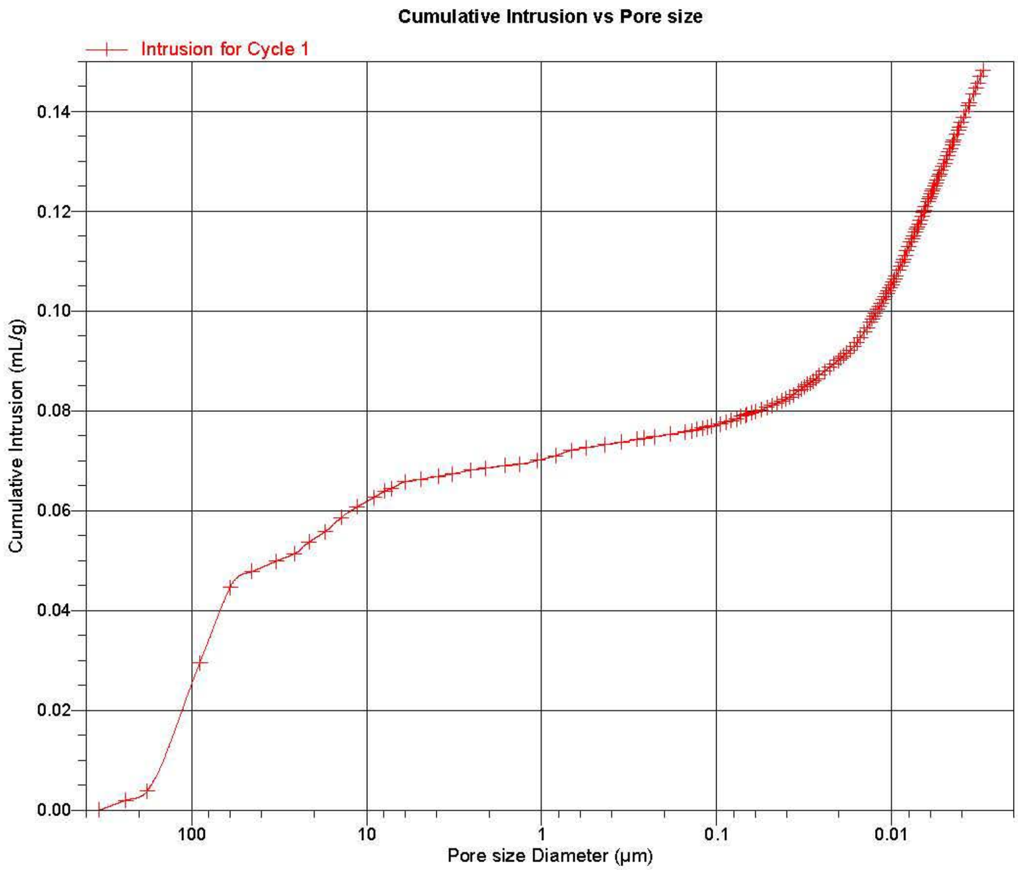
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 1/1

Sample: Denver 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007921.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 2.2503 g
Correction Type: None
Show Neg. Int: No



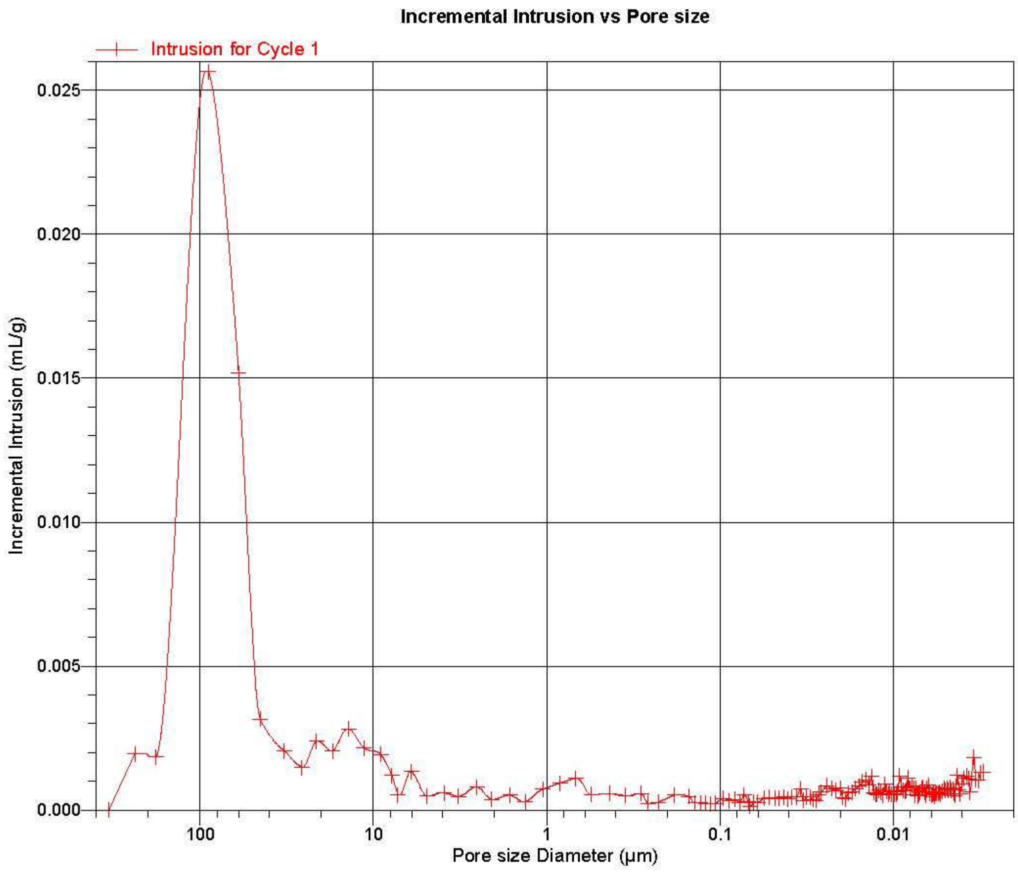
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 1/1 Page 7

Sample: Denver 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007921.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 2.2503 g
Correction Type: None
Show Neg. Int: No



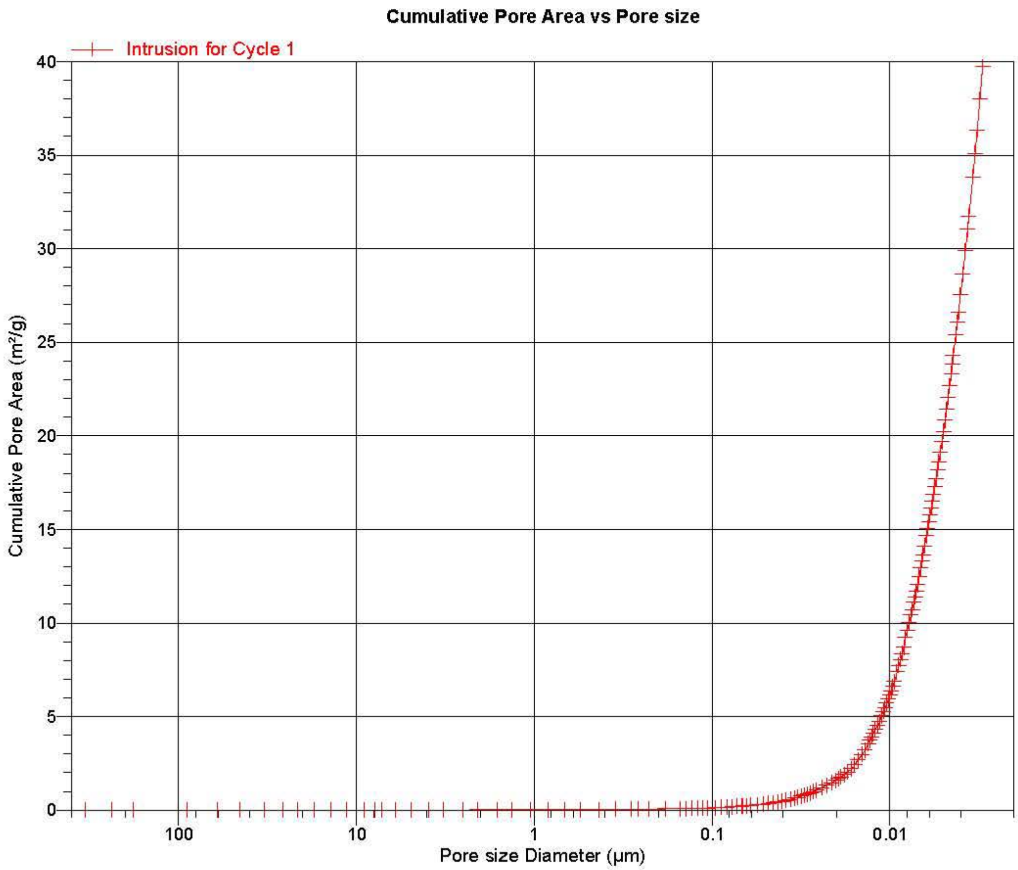
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 1/1 Page 8

Sample: Denver 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007921.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 2.2503 g
Correction Type: None
Show Neg. Int: No



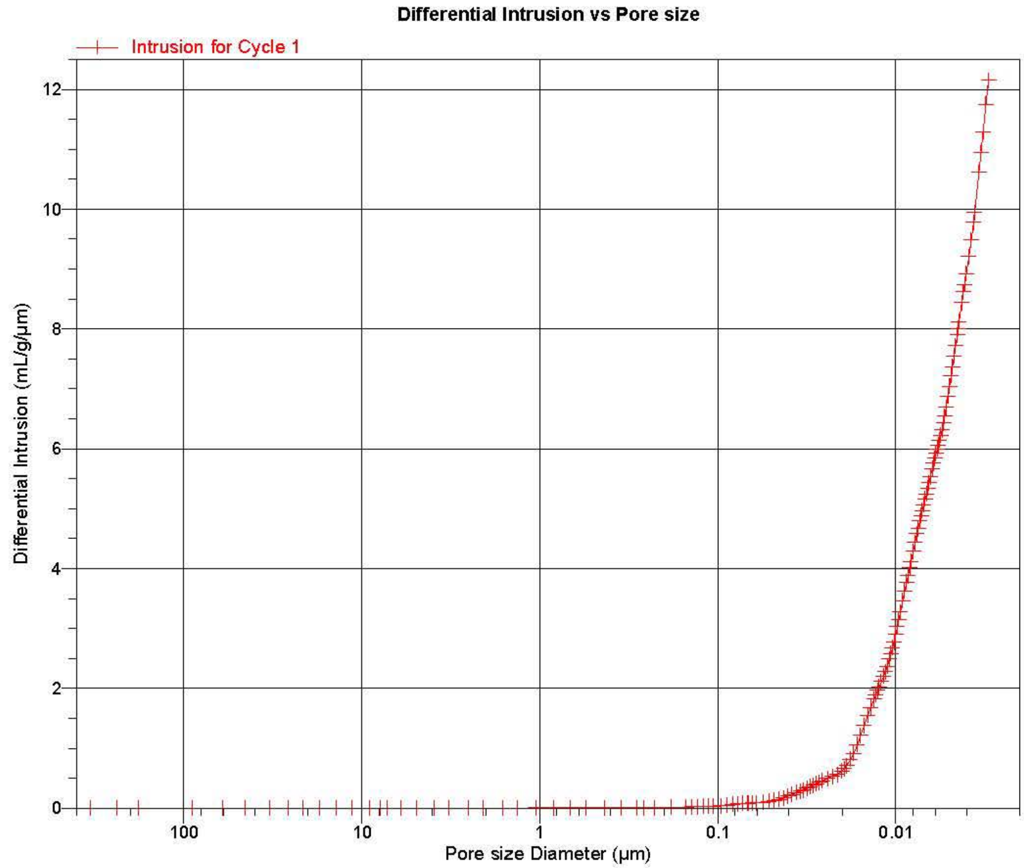
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 1/1 Page 9

Sample: Denver 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007921.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 2.2503 g
Correction Type: None
Show Neg. Int: No



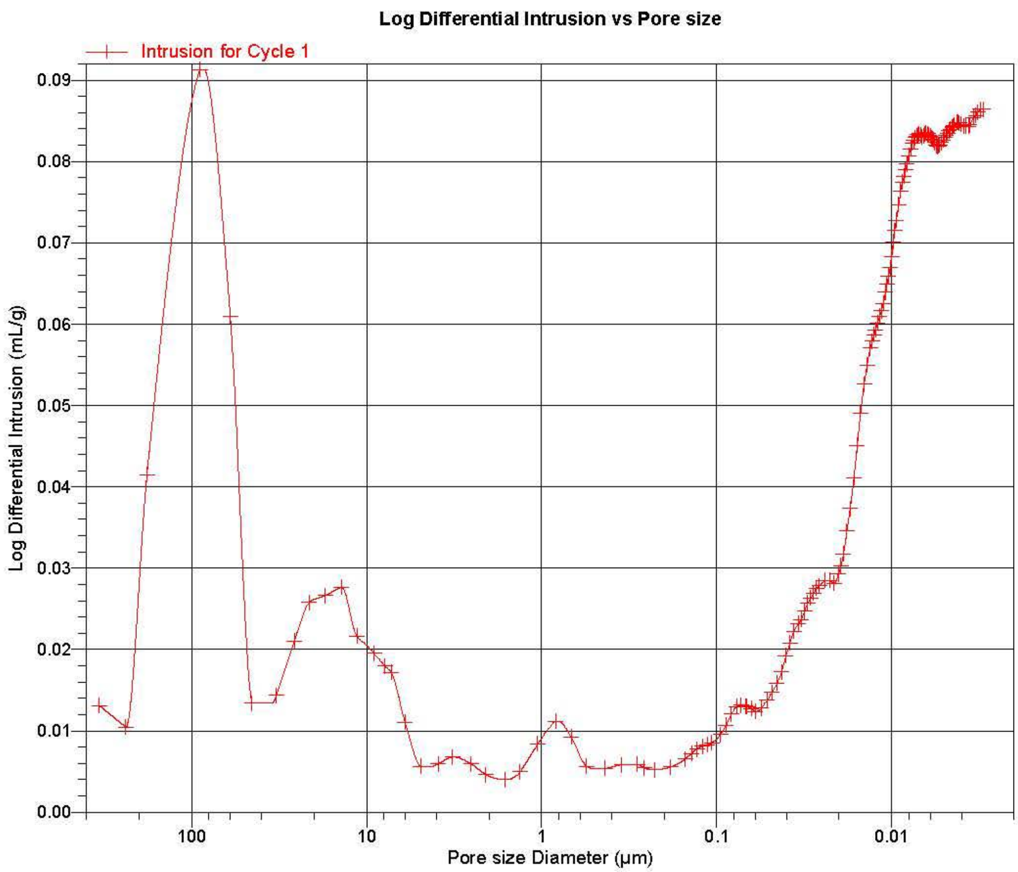
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 | Serial: 1011 | Port: 1/1 | Page 10

Sample: Denver 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007921.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 2.2503 g
Correction Type: None
Show Neg. Int: No



Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 | Serial: 1011 | Port: 2/2 | Page 1

Sample: Denver Downstream 48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007922.SMP

LP Analysis Time:	1/7/2011 5:32:42PM	Sample Weight:	5.4169 g
HP Analysis Time:	1/13/2011 1:21:30PM	Correction Type:	None
Report Time:	1/13/2011 1:21:31PM	Show Neg. Int:	No

Summary Report

Penetrometer parameters

Penetrometer: 640 - (03) 15 Bulb, 1.131 Stem, Solid

Pen. Constant:	21.416 µL/pF	Pen. Weight:	69.1016 g
Stem Volume:	1.1310 mL	Max. Head Pressure:	4.4500 psia
Pen. Volume:	15.8168 mL	Assembly Weight:	225.4733 g

Hg Parameters

Adv. Contact Angle:	130.000 degrees	Rec. Contact Angle:	130.000 degrees
Hg Surface Tension:	485.000 dynes/cm	Hg Density:	13.5335 g/mL

Low Pressure:

Evacuation Pressure:	50 µmHg
Evacuation Time:	5 mins
Mercury Filling Pressure:	0.54 psia
Equilibration Time:	10 secs

High Pressure:

Equilibration Time:	10 secs

No Blank Correction

Intrusion Data Summary

Total Intrusion Volume =	0.0875 mL/g
Total Pore Area =	27.578 m²/g
Median Pore Diameter (Volume) =	0.0357 µm
Median Pore Diameter (Area) =	0.0048 µm
Average Pore Diameter (4V/A) =	0.0127 µm
Bulk Density at 0.54 psia =	1.1618 g/mL
Apparent (skeletal) Density =	1.2933 g/mL
Porosity =	10.1707 %
Stem Volume Used =	42 %

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 2/2 Page 2

Sample: Denver Downstream 48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007922.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 5.4169 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (µm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m²/g)	Incremental Pore Area (m²/g)
0.54	335.7452	0.0000	0.0000	0.000	0.000
0.76	237.9319	0.0037	0.0037	0.000	0.000
1.01	179.6617	0.0051	0.0014	0.000	0.000
2.02	89.5844	0.0104	0.0053	0.000	0.000
3.01	60.1207	0.0152	0.0048	0.000	0.000
4.01	45.1217	0.0167	0.0014	0.001	0.000
5.51	32.8460	0.0198	0.0031	0.001	0.000
7.00	25.8338	0.0205	0.0007	0.001	0.000
8.50	21.2717	0.0211	0.0006	0.001	0.000
10.49	17.2375	0.0216	0.0005	0.001	0.000
12.99	13.9219	0.0222	0.0006	0.001	0.000
15.98	11.3189	0.0226	0.0005	0.002	0.000
19.96	9.0628	0.0231	0.0005	0.002	0.000
23.01	7.8594	0.0234	0.0003	0.002	0.000
25.02	7.2288	0.0235	0.0001	0.002	0.000
29.99	6.0317	0.0239	0.0004	0.002	0.000
38.00	4.7599	0.0241	0.0002	0.002	0.000
47.48	3.8093	0.0243	0.0002	0.003	0.000
57.00	3.1732	0.0247	0.0004	0.003	0.000
72.78	2.4852	0.0251	0.0004	0.003	0.001
87.96	2.0563	0.0254	0.0003	0.004	0.000
112.67	1.6053	0.0258	0.0005	0.005	0.001
137.26	1.3177	0.0260	0.0002	0.006	0.001
173.09	1.0449	0.0263	0.0003	0.006	0.001
218.06	0.8294	0.0265	0.0002	0.007	0.001
268.26	0.6742	0.0267	0.0002	0.008	0.001
328.13	0.5512	0.0270	0.0003	0.010	0.002
418.31	0.4324	0.0309	0.0039	0.042	0.032
517.92	0.3492	0.0315	0.0006	0.048	0.006
637.92	0.2835	0.0326	0.0010	0.062	0.013
698.59	0.2589	0.0327	0.0002	0.064	0.003
799.15	0.2263	0.0330	0.0003	0.069	0.005
988.83	0.1829	0.0334	0.0004	0.076	0.007
1199.32	0.1508	0.0340	0.0007	0.092	0.016
1298.56	0.1393	0.0368	0.0028	0.168	0.077
1399.04	0.1293	0.0373	0.0005	0.183	0.014
1498.57	0.1207	0.0375	0.0002	0.188	0.006
1597.38	0.1132	0.0377	0.0002	0.194	0.006
1697.16	0.1066	0.0378	0.0002	0.200	0.006
1897.28	0.0953	0.0382	0.0004	0.217	0.017
2047.22	0.0883	0.0385	0.0002	0.227	0.010

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 2/2 Page 3

Sample: Denver Downstream 48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007922.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 5.4169 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (μm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m^2/g)	Incremental Pore Area (m^2/g)
2196.69	0.0823	0.0387	0.0003	0.240	0.013
2346.64	0.0771	0.0392	0.0005	0.263	0.023
2495.94	0.0725	0.0395	0.0002	0.276	0.013
2646.66	0.0683	0.0397	0.0003	0.293	0.017
2695.41	0.0671	0.0399	0.0001	0.301	0.008
2845.17	0.0636	0.0402	0.0003	0.317	0.016
2995.55	0.0604	0.0404	0.0002	0.332	0.015
3245.01	0.0557	0.0407	0.0004	0.356	0.024
3493.56	0.0518	0.0411	0.0004	0.387	0.031
3743.89	0.0483	0.0415	0.0004	0.417	0.030
3993.18	0.0453	0.0421	0.0006	0.466	0.049
4241.62	0.0426	0.0425	0.0004	0.499	0.032
4486.05	0.0403	0.0429	0.0005	0.545	0.047
4725.81	0.0383	0.0433	0.0003	0.579	0.034
4983.80	0.0363	0.0437	0.0004	0.621	0.042
5284.45	0.0342	0.0441	0.0004	0.671	0.050
5483.55	0.0330	0.0445	0.0004	0.714	0.043
5731.52	0.0316	0.0448	0.0003	0.753	0.040
5977.74	0.0303	0.0451	0.0004	0.799	0.045
6226.48	0.0290	0.0456	0.0005	0.866	0.067
6473.77	0.0279	0.0459	0.0003	0.911	0.045
6727.02	0.0269	0.0463	0.0003	0.962	0.051
6973.15	0.0259	0.0467	0.0004	1.017	0.055
7475.54	0.0242	0.0474	0.0007	1.132	0.115
7976.19	0.0227	0.0482	0.0008	1.275	0.143
8477.75	0.0213	0.0489	0.0007	1.399	0.124
8976.47	0.0201	0.0495	0.0006	1.522	0.123
9271.21	0.0195	0.0499	0.0003	1.592	0.070
9569.52	0.0189	0.0502	0.0003	1.662	0.070
10024.32	0.0180	0.0507	0.0005	1.763	0.101
10469.51	0.0173	0.0512	0.0005	1.868	0.105
10973.66	0.0165	0.0517	0.0005	1.994	0.126
11473.45	0.0158	0.0522	0.0005	2.124	0.130
11973.92	0.0151	0.0527	0.0005	2.255	0.131
12577.67	0.0144	0.0533	0.0006	2.419	0.164
13072.10	0.0138	0.0538	0.0005	2.564	0.144
13623.47	0.0133	0.0544	0.0006	2.731	0.167
13971.28	0.0129	0.0548	0.0004	2.849	0.118
14309.74	0.0126	0.0551	0.0004	2.961	0.113
14568.40	0.0124	0.0554	0.0003	3.048	0.087
14972.62	0.0121	0.0558	0.0004	3.180	0.132

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 | Serial: 1011 | Port: 2/2 | Page 4

Sample: Denver Downstream 48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007922.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 5.4169 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (μm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m²/g)	Incremental Pore Area (m²/g)
15421.97	0.0117	0.0563	0.0004	3.326	0.146
15769.81	0.0115	0.0566	0.0004	3.448	0.122
16167.80	0.0112	0.0570	0.0004	3.588	0.140
16618.81	0.0109	0.0574	0.0004	3.749	0.161
16964.56	0.0107	0.0579	0.0004	3.909	0.160
17320.89	0.0104	0.0583	0.0004	4.056	0.148
17669.25	0.0102	0.0586	0.0004	4.200	0.143
18069.34	0.0100	0.0590	0.0004	4.349	0.149
18417.56	0.0098	0.0594	0.0004	4.491	0.142
18767.09	0.0096	0.0597	0.0003	4.628	0.137
19166.42	0.0094	0.0601	0.0004	4.793	0.166
19766.10	0.0092	0.0606	0.0005	5.016	0.223
20274.77	0.0089	0.0611	0.0005	5.217	0.201
20778.93	0.0087	0.0615	0.0004	5.419	0.201
21180.88	0.0085	0.0619	0.0004	5.593	0.174
21633.37	0.0084	0.0623	0.0004	5.776	0.184
22035.49	0.0082	0.0626	0.0003	5.945	0.168
22638.51	0.0080	0.0631	0.0005	6.193	0.248
23188.43	0.0078	0.0636	0.0005	6.422	0.229
23740.40	0.0076	0.0640	0.0005	6.662	0.240
24090.33	0.0075	0.0644	0.0003	6.835	0.173
24642.03	0.0073	0.0648	0.0005	7.083	0.248
25041.36	0.0072	0.0652	0.0004	7.286	0.203
25442.10	0.0071	0.0655	0.0003	7.477	0.191
25893.41	0.0070	0.0659	0.0004	7.696	0.219
26443.34	0.0068	0.0663	0.0004	7.942	0.246
26943.78	0.0067	0.0667	0.0004	8.173	0.231
27393.24	0.0066	0.0671	0.0004	8.386	0.213
27794.54	0.0065	0.0674	0.0003	8.598	0.211
28244.64	0.0064	0.0678	0.0004	8.830	0.232
28995.11	0.0062	0.0684	0.0006	9.178	0.348
29495.62	0.0061	0.0688	0.0004	9.431	0.253
29994.83	0.0060	0.0691	0.0004	9.684	0.253
30445.28	0.0059	0.0695	0.0004	9.929	0.246
30895.25	0.0059	0.0698	0.0003	10.160	0.230
31295.34	0.0058	0.0702	0.0003	10.379	0.219
31794.96	0.0057	0.0705	0.0004	10.636	0.257
32346.16	0.0056	0.0709	0.0004	10.919	0.283
32896.73	0.0055	0.0713	0.0004	11.210	0.291
33497.09	0.0054	0.0718	0.0004	11.529	0.319
33996.86	0.0053	0.0721	0.0004	11.801	0.273

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 2/2 Page 5

Sample: Denver Downstream 48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007922.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 5.4169 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (μm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m^2/g)	Incremental Pore Area (m^2/g)
34646.50	0.0052	0.0726	0.0005	12.150	0.349
35497.05	0.0051	0.0732	0.0006	12.595	0.444
36197.55	0.0050	0.0736	0.0005	12.965	0.371
36996.01	0.0049	0.0742	0.0005	13.397	0.432
37646.89	0.0048	0.0746	0.0004	13.767	0.369
38446.28	0.0047	0.0751	0.0005	14.210	0.443
39196.54	0.0046	0.0756	0.0005	14.633	0.424
39996.71	0.0045	0.0762	0.0005	15.088	0.455
40495.30	0.0045	0.0765	0.0004	15.403	0.315
40996.54	0.0044	0.0769	0.0003	15.708	0.306
42495.53	0.0043	0.0778	0.0009	16.542	0.834
43346.16	0.0042	0.0783	0.0005	17.044	0.502
43995.36	0.0041	0.0787	0.0004	17.453	0.408
44993.81	0.0040	0.0793	0.0006	18.053	0.601
46495.56	0.0039	0.0802	0.0009	18.925	0.872
47990.13	0.0038	0.0810	0.0008	19.801	0.877
49484.93	0.0037	0.0819	0.0008	20.706	0.904
50185.25	0.0036	0.0823	0.0004	21.187	0.481
52973.14	0.0034	0.0838	0.0015	22.897	1.710
54471.19	0.0033	0.0846	0.0008	23.868	0.971
55969.13	0.0032	0.0854	0.0008	24.878	1.010
57969.73	0.0031	0.0865	0.0010	26.193	1.315
59966.72	0.0030	0.0875	0.0011	27.578	1.386

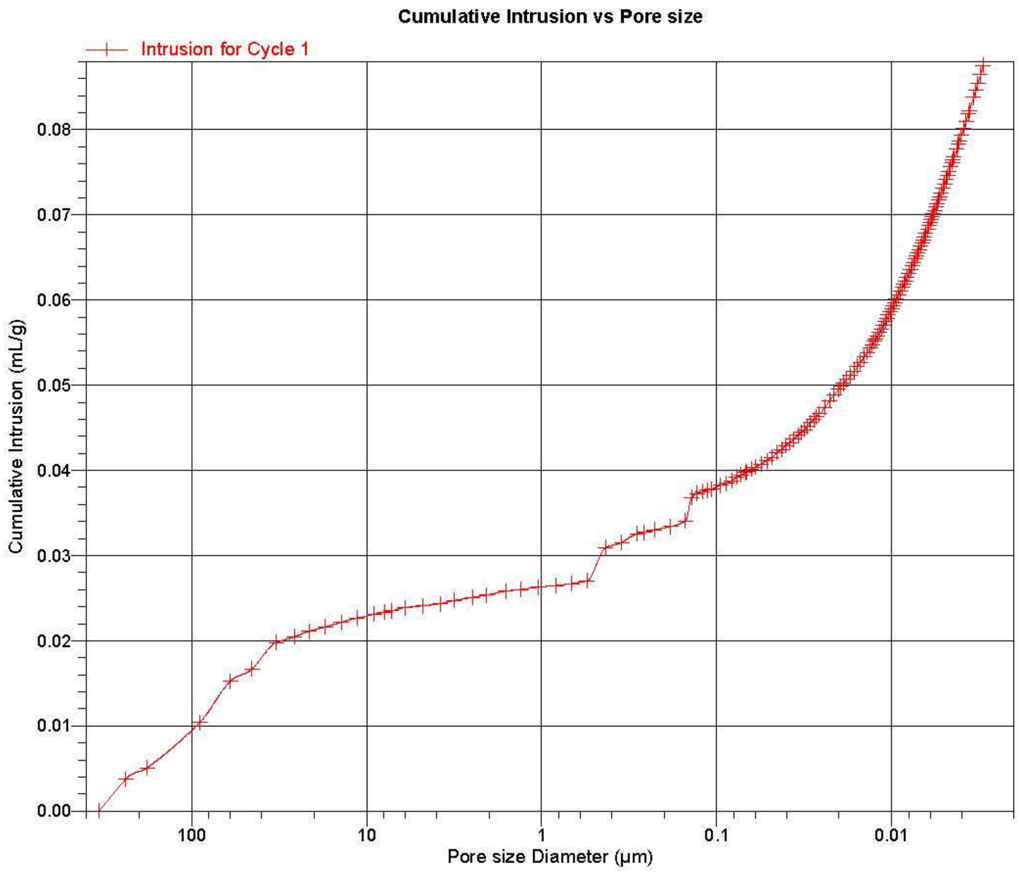
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011 Port: 2/2 Page 6

Sample: Denver Downstream 48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007922.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 5.4169 g
Correction Type: None
Show Neg. Int: No



Micromeritics Instrument Corporation

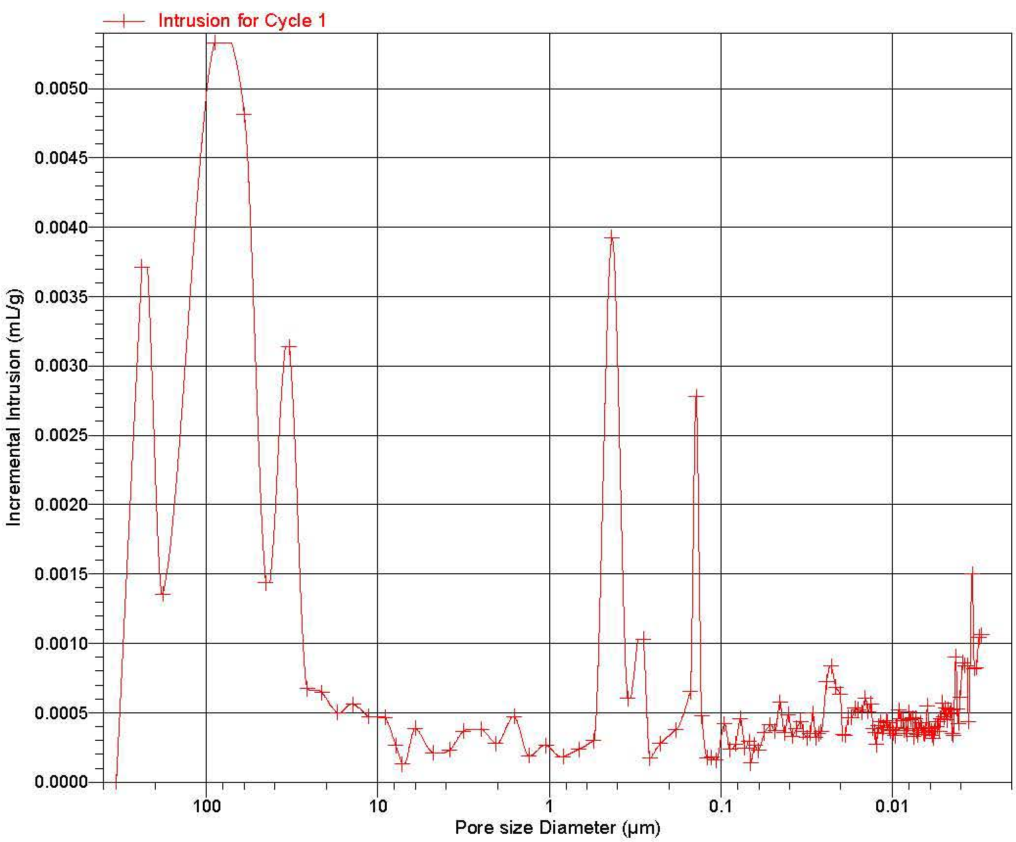
AutoPore IV 9500 V1.09 | Serial: 1011 | Port: 2/2 | Page 7

Sample: Denver Downstream 48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007922.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 5.4169 g
Correction Type: None
Show Neg. Int: No

Incremental Intrusion vs Pore size



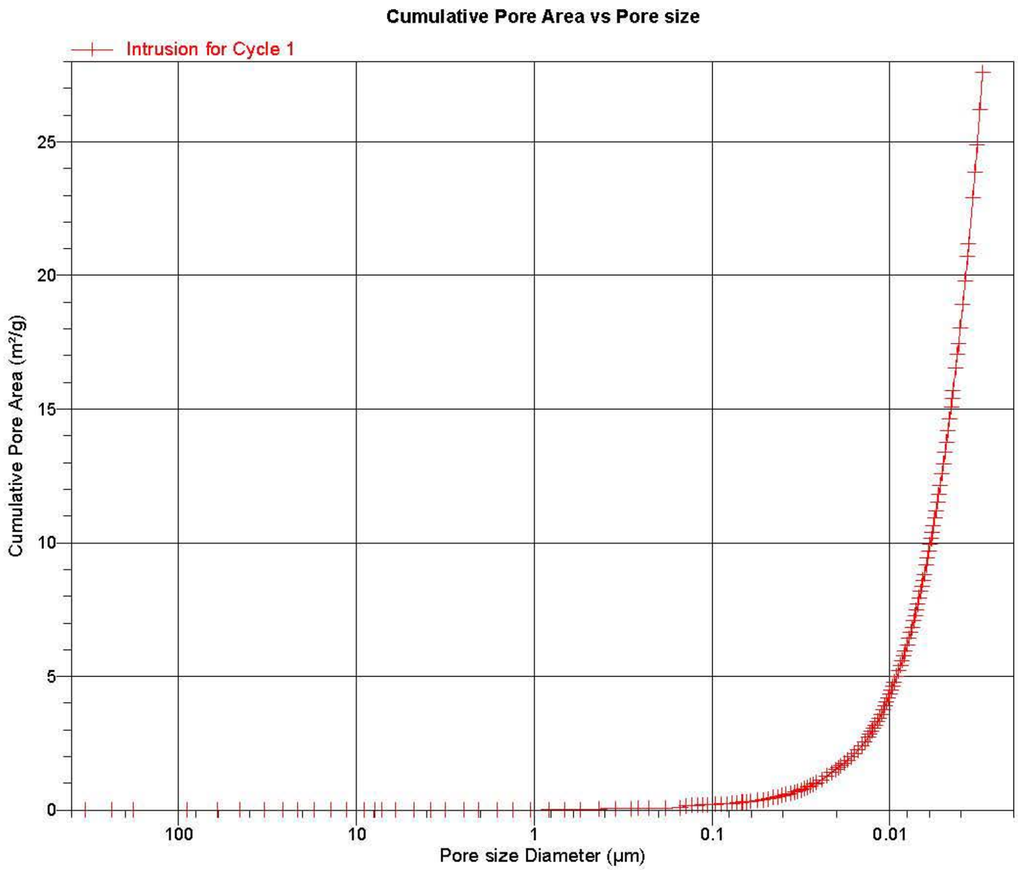
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 | Serial: 1011 | Port: 2/2 | Page 8

Sample: Denver Downstream 48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007922.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 5.4169 g
Correction Type: None
Show Neg. Int: No



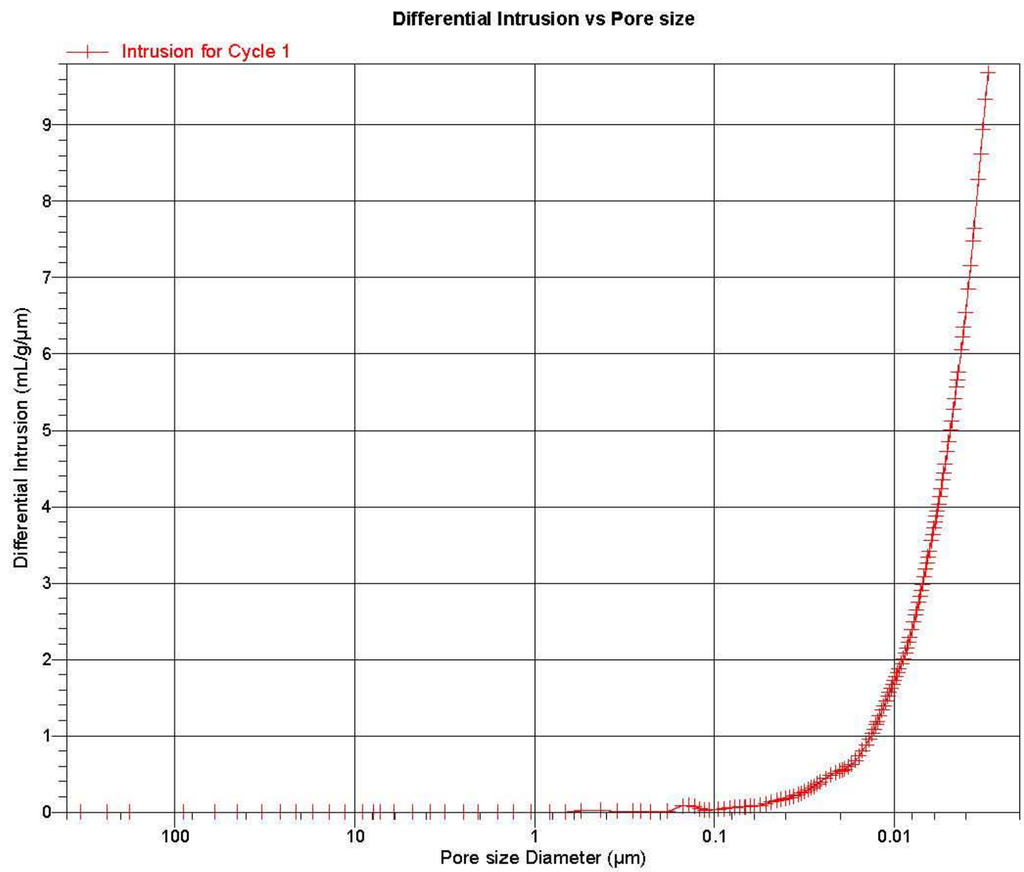
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 | Serial: 1011 | Port: 2/2 | Page 9

Sample: Denver Downstream 48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007922.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:21:30PM
Report Time: 1/13/2011 1:21:31PM

Sample Weight: 5.4169 g
Correction Type: None
Show Neg. Int: No



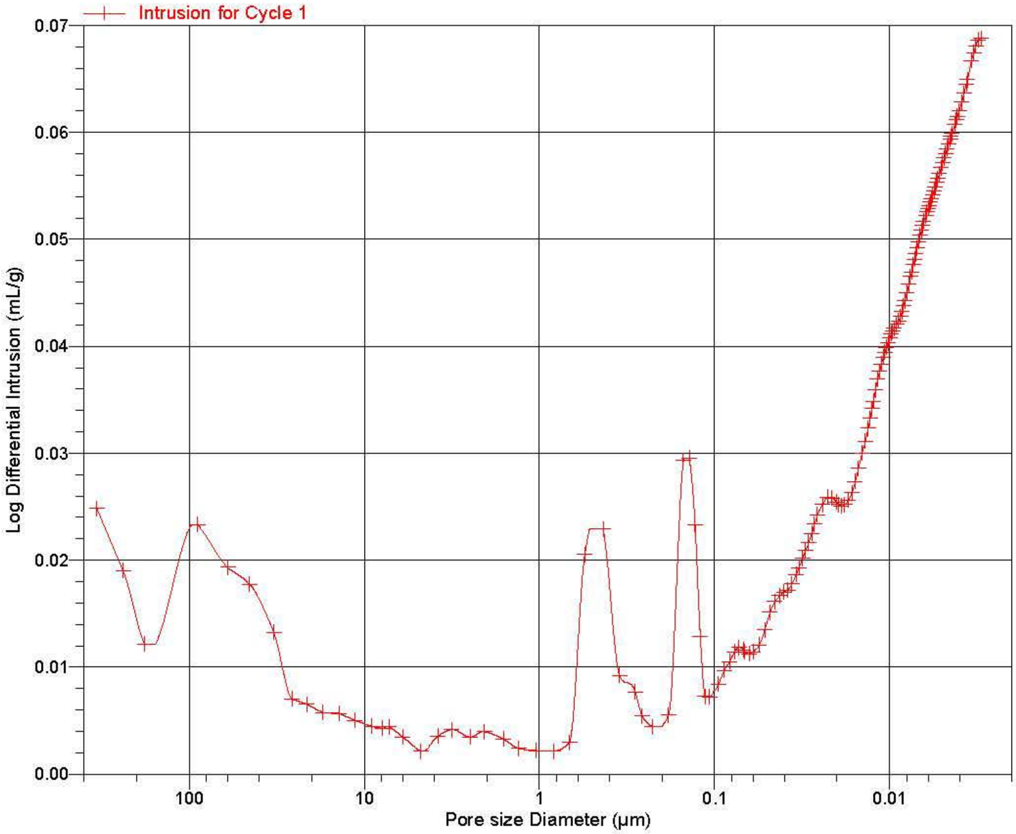
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09	Serial: 1011	Port: 2/2	Page 10

Sample: Denver Downstream 48"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007922.SMP

LP Analysis Time:	1/7/2011 5:32:42PM	Sample Weight:	5.4169 g
HP Analysis Time:	1/13/2011 1:21:30PM	Correction Type:	None
Report Time:	1/13/2011 1:21:31PM	Show Neg. Int:	No

Log Differential Intrusion vs Pore size



Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09	Serial: 1011/886	Port: 3/1	Page 1

Sample: Columbus 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007923.SMP

LP Analysis Time:	1/7/2011 5:32:42PM	Sample Weight:	2.6206 g
HP Analysis Time:	1/13/2011 1:34:06PM	Correction Type:	None
Report Time:	1/14/2011 2:36:35PM	Show Neg. Int:	No

Summary Report

Penetrometer parameters

Penetrometer: 707 - (02) 15 Bulb, 0.392 Stem, Powder

Pen. Constant:	11.007 µL/pF	Pen. Weight:	73.8245 g
Stem Volume:	0.3920 mL	Max. Head Pressure:	4.4500 psia
Pen. Volume:	14.1733 mL	Assembly Weight:	238.0465 g

Hg Parameters

Adv. Contact Angle:	130.000 degrees	Rec. Contact Angle:	130.000 degrees
Hg Surface Tension:	485.000 dynes/cm	Hg Density:	13.5335 g/mL

Low Pressure:

Evacuation Pressure:	50 µmHg
Evacuation Time:	5 mins
Mercury Filling Pressure:	0.54 psia
Equilibration Time:	10 secs

High Pressure:

Equilibration Time:	10 secs

No Blank Correction

Intrusion Data Summary

Total Intrusion Volume =	0.0695 mL/g
Total Pore Area =	27.968 m²/g
Median Pore Diameter (Volume) =	0.0138 µm
Median Pore Diameter (Area) =	0.0047 µm
Average Pore Diameter (4V/A) =	0.0099 µm
Bulk Density at 0.54 psia =	1.1739 g/mL
Apparent (skeletal) Density =	1.2782 g/mL
Porosity =	8.1629 %
Stem Volume Used =	46 %

Micromeritics Instrument Corporation

Sample: Columbus 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007923.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/14/2011 2:36:35PM

Sample Weight: 2.6206 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (μm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m²/g)	Incremental Pore Area (m²/g)
0.54	335.7452	0.0000	0.0000	0.000	0.000
0.76	237.9319	0.0016	0.0016	0.000	0.000
1.01	179.6617	0.0025	0.0009	0.000	0.000
2.02	89.5844	0.0068	0.0043	0.000	0.000
3.01	60.1207	0.0089	0.0021	0.000	0.000
4.01	45.1217	0.0094	0.0006	0.000	0.000
5.51	32.8460	0.0100	0.0006	0.000	0.000
7.00	25.8338	0.0106	0.0006	0.000	0.000
8.50	21.2717	0.0111	0.0005	0.001	0.000
10.49	17.2375	0.0118	0.0007	0.001	0.000
12.99	13.9219	0.0126	0.0008	0.001	0.000
15.98	11.3189	0.0143	0.0017	0.001	0.001
19.96	9.0628	0.0165	0.0023	0.002	0.001
23.01	7.8594	0.0175	0.0010	0.003	0.000
25.02	7.2288	0.0179	0.0004	0.003	0.000
29.99	6.0317	0.0186	0.0007	0.003	0.000
36.64	4.9368	0.0188	0.0002	0.004	0.000
46.53	3.8866	0.0191	0.0004	0.004	0.000
56.57	3.1970	0.0194	0.0003	0.004	0.000
71.07	2.5448	0.0197	0.0003	0.005	0.000
86.14	2.0996	0.0199	0.0002	0.005	0.000
111.66	1.6198	0.0202	0.0002	0.005	0.001
136.49	1.3251	0.0203	0.0002	0.006	0.000
171.07	1.0572	0.0205	0.0001	0.006	0.000
216.87	0.8340	0.0206	0.0002	0.007	0.001
267.27	0.6767	0.0208	0.0001	0.008	0.001
326.24	0.5544	0.0209	0.0001	0.009	0.001
416.96	0.4338	0.0211	0.0002	0.010	0.001
516.59	0.3501	0.0212	0.0002	0.012	0.002
636.23	0.2843	0.0214	0.0002	0.014	0.002
697.57	0.2593	0.0216	0.0001	0.016	0.002
798.04	0.2266	0.0217	0.0002	0.018	0.003
987.61	0.1831	0.0220	0.0003	0.024	0.005
1195.62	0.1513	0.0223	0.0003	0.030	0.007
1297.35	0.1394	0.0224	0.0001	0.034	0.004
1396.17	0.1295	0.0225	0.0001	0.038	0.004
1493.66	0.1211	0.0227	0.0001	0.042	0.004
1594.81	0.1134	0.0228	0.0001	0.047	0.004
1696.41	0.1066	0.0229	0.0001	0.052	0.005
1893.81	0.0955	0.0232	0.0002	0.061	0.009
2045.53	0.0884	0.0233	0.0002	0.068	0.008

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 | Serial: 1011/886 | Port: 3/1 |

Sample: Columbus 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007923.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/14/2011 2:36:35PM

Sample Weight: 2.6206 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (μm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m^2/g)	Incremental Pore Area (m^2/g)
2195.55	0.0824	0.0235	0.0002	0.076	0.008
2344.40	0.0771	0.0236	0.0002	0.084	0.008
2493.66	0.0725	0.0238	0.0002	0.094	0.010
2644.42	0.0684	0.0240	0.0002	0.104	0.010
2693.29	0.0672	0.0241	0.0001	0.108	0.004
2844.32	0.0636	0.0243	0.0002	0.118	0.011
2995.52	0.0604	0.0244	0.0002	0.130	0.011
3244.44	0.0557	0.0247	0.0003	0.148	0.018
3493.68	0.0518	0.0249	0.0003	0.167	0.019
3743.33	0.0483	0.0252	0.0003	0.188	0.021
3992.11	0.0453	0.0255	0.0003	0.210	0.022
4240.83	0.0426	0.0257	0.0003	0.233	0.023
4486.94	0.0403	0.0261	0.0003	0.266	0.033
4726.09	0.0383	0.0263	0.0003	0.292	0.026
4984.19	0.0363	0.0266	0.0003	0.323	0.031
5283.58	0.0342	0.0269	0.0003	0.359	0.036
5481.82	0.0330	0.0272	0.0002	0.386	0.027
5733.11	0.0315	0.0274	0.0003	0.420	0.034
5978.96	0.0302	0.0277	0.0003	0.453	0.033
6229.66	0.0290	0.0280	0.0003	0.491	0.038
6479.13	0.0279	0.0282	0.0003	0.528	0.037
6727.29	0.0269	0.0285	0.0003	0.567	0.039
6977.00	0.0259	0.0288	0.0003	0.609	0.041
7477.26	0.0242	0.0292	0.0005	0.684	0.075
7974.45	0.0227	0.0297	0.0005	0.771	0.087
8474.48	0.0213	0.0302	0.0005	0.859	0.088
8974.24	0.0202	0.0307	0.0005	0.953	0.095
9270.13	0.0195	0.0310	0.0003	1.010	0.056
9570.45	0.0189	0.0313	0.0003	1.076	0.066
10020.53	0.0180	0.0318	0.0005	1.173	0.098
10473.12	0.0173	0.0322	0.0005	1.279	0.106
10970.08	0.0165	0.0327	0.0004	1.380	0.101
11472.44	0.0158	0.0332	0.0005	1.510	0.130
11969.78	0.0151	0.0337	0.0005	1.637	0.127
12571.86	0.0144	0.0343	0.0006	1.795	0.158
13066.47	0.0138	0.0348	0.0005	1.941	0.146
13618.66	0.0133	0.0353	0.0005	2.098	0.156
13968.93	0.0129	0.0357	0.0004	2.212	0.114
14303.98	0.0126	0.0361	0.0004	2.329	0.118
14562.73	0.0124	0.0362	0.0002	2.382	0.053
14958.84	0.0121	0.0367	0.0005	2.536	0.154

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011/886 Port: 3/1

Sample: Columbus 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007923.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/14/2011 2:36:35PM

Sample Weight: 2.6206 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (μm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m²/g)	Incremental Pore Area (m²/g)
15413.88	0.0117	0.0371	0.0004	2.683	0.147
15766.83	0.0115	0.0375	0.0004	2.810	0.127
16165.42	0.0112	0.0379	0.0004	2.952	0.142
16614.87	0.0109	0.0383	0.0004	3.113	0.161
16965.68	0.0107	0.0387	0.0004	3.247	0.134
17314.12	0.0104	0.0391	0.0004	3.386	0.139
17654.82	0.0102	0.0394	0.0003	3.521	0.135
18067.87	0.0100	0.0398	0.0004	3.675	0.154
18414.94	0.0098	0.0402	0.0004	3.839	0.163
18760.10	0.0096	0.0404	0.0002	3.908	0.070
19161.77	0.0094	0.0408	0.0005	4.102	0.193
19765.62	0.0092	0.0414	0.0006	4.359	0.257
20266.23	0.0089	0.0419	0.0004	4.551	0.192
20772.99	0.0087	0.0423	0.0005	4.763	0.212
21174.21	0.0085	0.0427	0.0003	4.924	0.161
21628.20	0.0084	0.0431	0.0004	5.134	0.210
22031.46	0.0082	0.0435	0.0004	5.306	0.172
22633.96	0.0080	0.0440	0.0005	5.564	0.258
23184.30	0.0078	0.0445	0.0005	5.812	0.248
23735.30	0.0076	0.0451	0.0006	6.118	0.306
24085.35	0.0075	0.0451	0.0000	6.118	0.000
24636.08	0.0073	0.0457	0.0006	6.449	0.331
25037.47	0.0072	0.0461	0.0004	6.644	0.194
25437.17	0.0071	0.0464	0.0004	6.839	0.196
25887.75	0.0070	0.0468	0.0004	7.060	0.221
26438.43	0.0068	0.0473	0.0004	7.318	0.257
26938.92	0.0067	0.0477	0.0004	7.569	0.252
27388.66	0.0066	0.0480	0.0003	7.778	0.209
27789.53	0.0065	0.0484	0.0003	7.991	0.213
28239.83	0.0064	0.0487	0.0004	8.220	0.229
28989.15	0.0062	0.0493	0.0006	8.569	0.350
29488.39	0.0061	0.0497	0.0004	8.827	0.258
29977.85	0.0060	0.0501	0.0004	9.100	0.273
30439.00	0.0059	0.0505	0.0004	9.370	0.270
30887.07	0.0059	0.0508	0.0003	9.584	0.214
31282.47	0.0058	0.0512	0.0003	9.808	0.224
31786.99	0.0057	0.0516	0.0004	10.088	0.280
32330.73	0.0056	0.0520	0.0004	10.385	0.297
32867.55	0.0055	0.0524	0.0004	10.697	0.313
33457.40	0.0054	0.0528	0.0004	11.020	0.323
33947.88	0.0053	0.0532	0.0004	11.313	0.293

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011/886 Port: 3/1 Page 5

Sample: Columbus 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007923.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/14/2011 2:36:35PM

Sample Weight: 2.6206 g
Correction Type: None
Show Neg. Int: No

Tabular Report

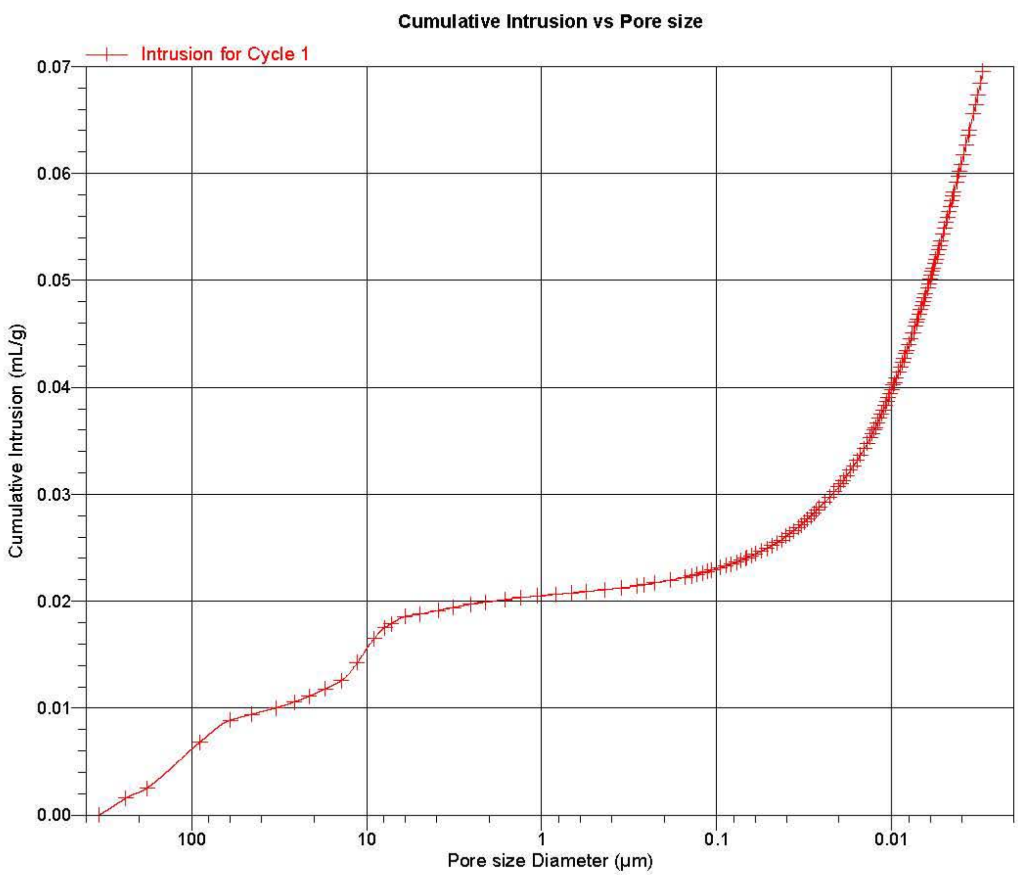
Pressure (psia)	Pore Diameter (µm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m²/g)	Incremental Pore Area (m²/g)
34598.98	0.0052	0.0537	0.0004	11.653	0.340
35444.09	0.0051	0.0543	0.0006	12.154	0.500
36143.39	0.0050	0.0549	0.0005	12.568	0.415
36942.55	0.0049	0.0554	0.0006	13.040	0.472
37593.96	0.0048	0.0559	0.0004	13.393	0.353
38396.88	0.0047	0.0564	0.0006	13.866	0.473
39145.35	0.0046	0.0569	0.0005	14.298	0.432
39943.96	0.0045	0.0575	0.0006	14.787	0.488
40446.18	0.0045	0.0579	0.0004	15.125	0.338
40944.14	0.0044	0.0583	0.0004	15.461	0.336
42445.48	0.0043	0.0592	0.0010	16.340	0.879
43295.18	0.0042	0.0598	0.0006	16.877	0.538
43942.78	0.0041	0.0602	0.0004	17.309	0.431
44944.67	0.0040	0.0609	0.0006	17.947	0.639
46446.68	0.0039	0.0618	0.0009	18.866	0.919
47947.35	0.0038	0.0627	0.0009	19.821	0.955
49448.08	0.0037	0.0636	0.0009	20.800	0.979
50146.62	0.0036	0.0641	0.0005	21.311	0.511
52949.35	0.0034	0.0656	0.0016	23.078	1.767
54446.35	0.0033	0.0665	0.0009	24.089	1.011
55945.20	0.0032	0.0673	0.0009	25.139	1.050
57941.40	0.0031	0.0685	0.0011	26.577	1.438
59925.91	0.0030	0.0695	0.0011	27.968	1.390

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09	Serial: 1011/886	Port: 3/1	Page 6

Sample: Columbus 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007923.SMP

LP Analysis Time:	1/7/2011 5:32:42PM	Sample Weight:	2.6206 g
HP Analysis Time:	1/13/2011 1:34:06PM	Correction Type:	None
Report Time:	1/14/2011 2:36:35PM	Show Neg. Int:	No



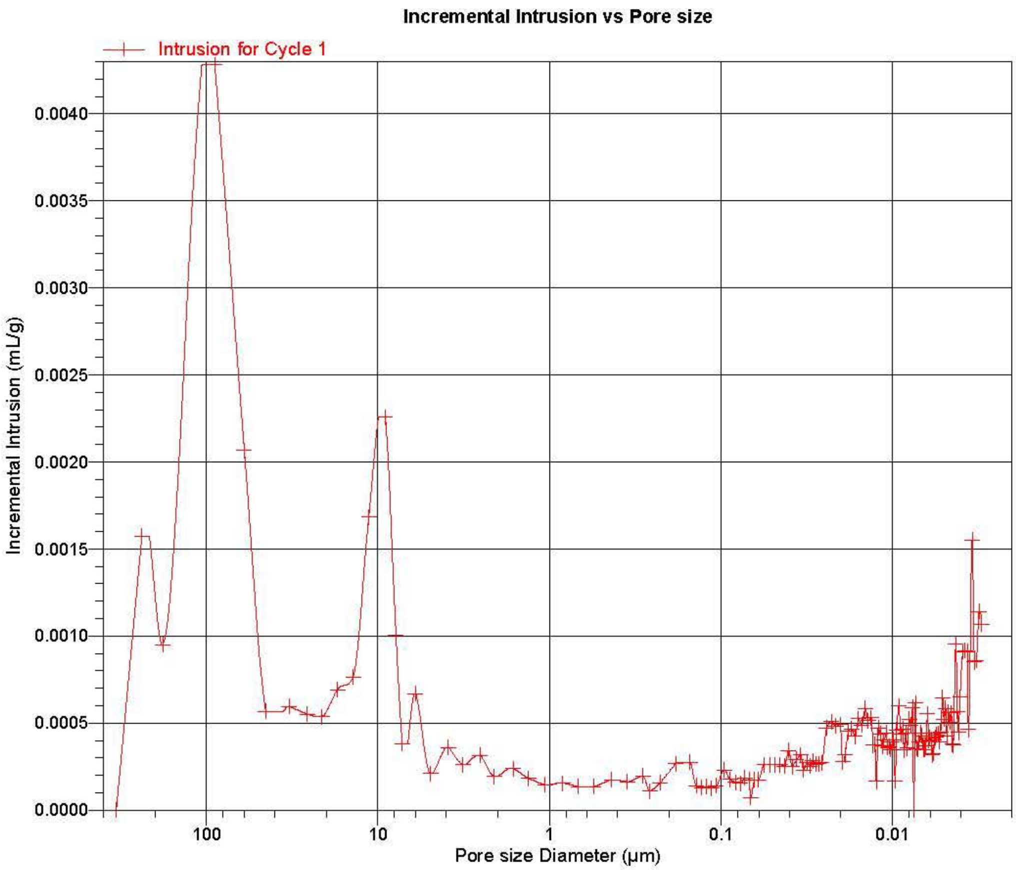
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 | Serial: 1011/886 | Port: 3/1 | Page 7

Sample: Columbus 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007923.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/14/2011 2:36:35PM

Sample Weight: 2.6206 g
Correction Type: None
Show Neg. Int: No



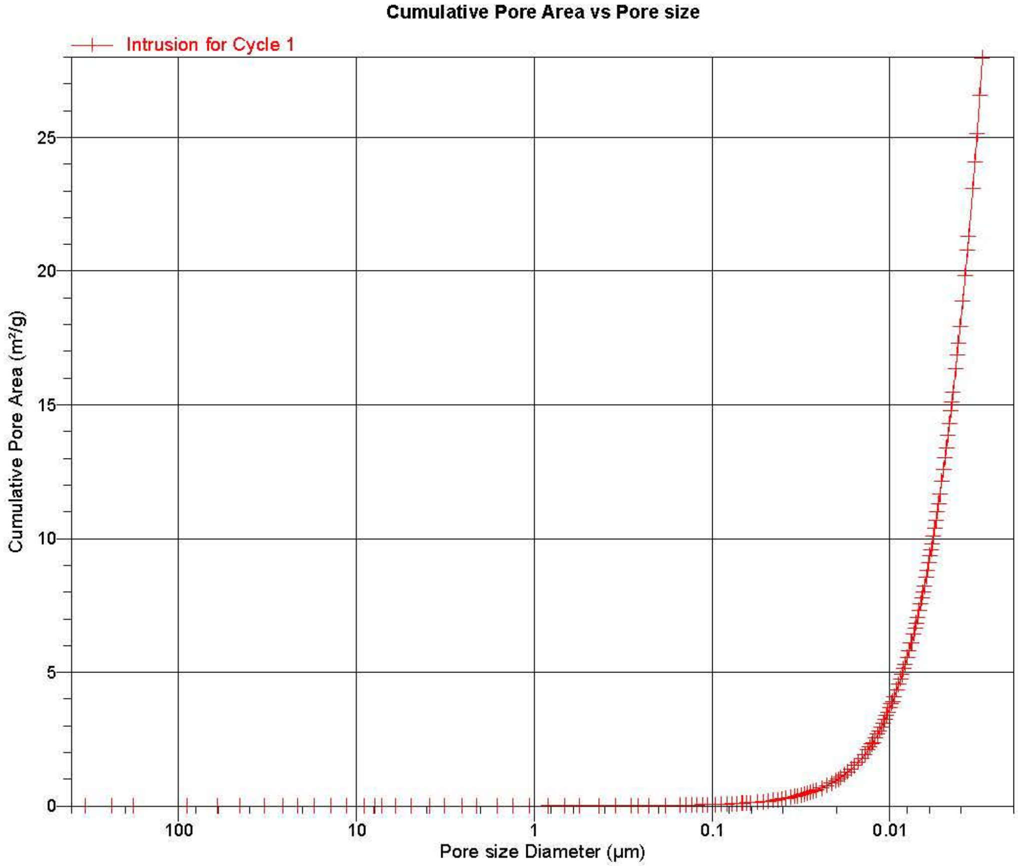
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011/886 Port: 3/1 Page 8

Sample: Columbus 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007923.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/14/2011 2:36:35PM

Sample Weight: 2.6206 g
Correction Type: None
Show Neg. Int: No



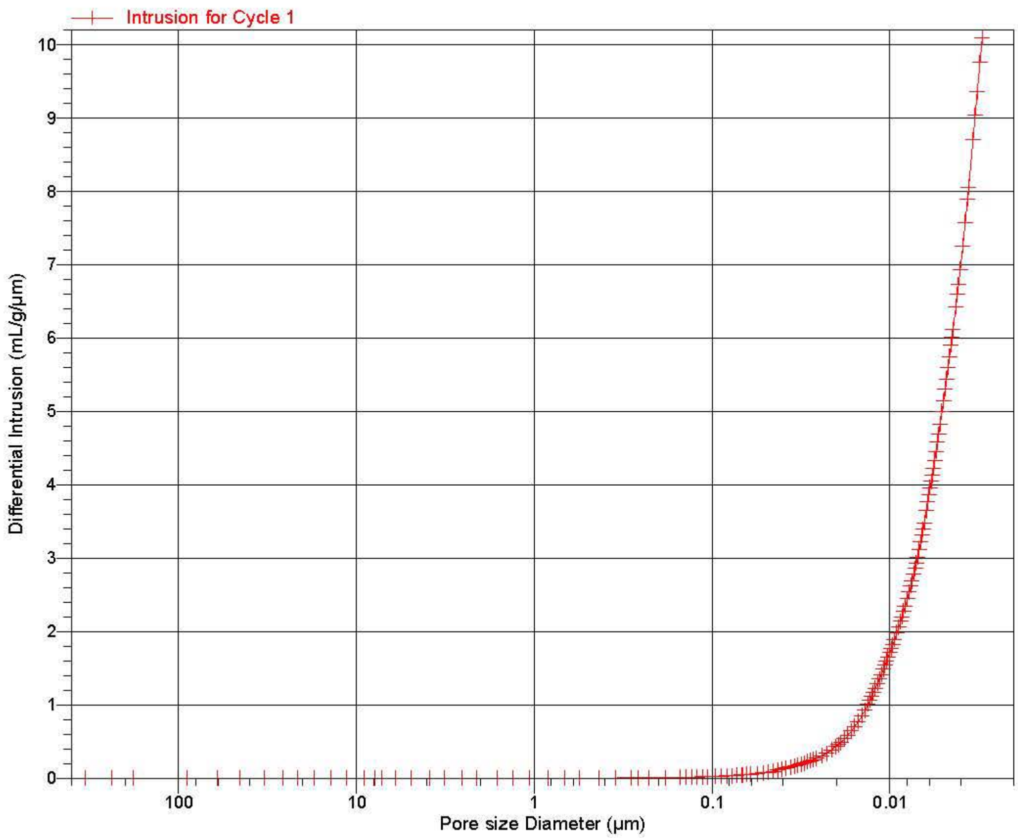
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09	Serial: 1011/886	Port: 3/1	Page 9

Sample: Columbus 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007923.SMP

LP Analysis Time:	1/7/2011 5:32:42PM	Sample Weight:	2.6206 g
HP Analysis Time:	1/13/2011 1:34:06PM	Correction Type:	None
Report Time:	1/14/2011 2:36:35PM	Show Neg. Int:	No

Differential Intrusion vs Pore size



Micromeritics Instrument Corporation

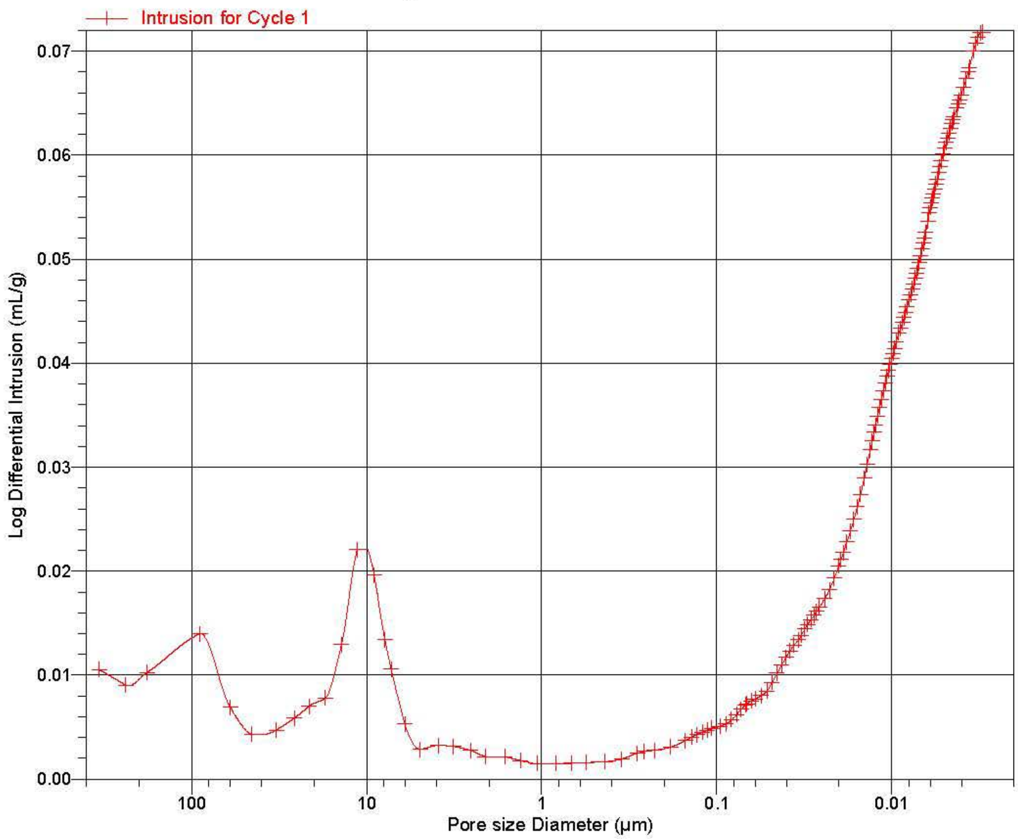
AutoPore IV 9500 V1.09 Serial: 1011/886 Port: 3/1

Sample: Columbus 8"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007923.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/14/2011 2:36:35PM

Sample Weight: 2.6206 g
Correction Type: None
Show Neg. Int: No

Log Differential Intrusion vs Pore size



Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09	Serial: 1011/886	Port: 4/2	Page 1

Sample: Columbus 36"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007924.SMP

LP Analysis Time:	1/7/2011 5:32:42PM	Sample Weight:	4.6449 g
HP Analysis Time:	1/13/2011 1:34:06PM	Correction Type:	None
Report Time:	1/13/2011 1:34:07PM	Show Neg. Int:	No

Summary Report

Penetrometer parameters

Penetrometer: 751 - (03) 15 Bulb, 1.131 Stem, Solid

Pen. Constant:	22.065 µL/pF	Pen. Weight:	68.5930 g
Stem Volume:	1.1310 mL	Max. Head Pressure:	4.4500 psia
Pen. Volume:	16.3057 mL	Assembly Weight:	236.1535 g

Hg Parameters

Adv. Contact Angle:	130.000 degrees	Rec. Contact Angle:	130.000 degrees
Hg Surface Tension:	485.000 dynes/cm	Hg Density:	13.5335 g/mL

Low Pressure:

Evacuation Pressure:	50 µmHg
Evacuation Time:	5 mins
Mercury Filling Pressure:	0.54 psia
Equilibration Time:	10 secs

High Pressure:

Equilibration Time:	10 secs

No Blank Correction

Intrusion Data Summary

Total Intrusion Volume =	0.1631 mL/g
Total Pore Area =	31.836 m²/g
Median Pore Diameter (Volume) =	6.4576 µm
Median Pore Diameter (Area) =	0.0049 µm
Average Pore Diameter (4V/A) =	0.0205 µm
Bulk Density at 0.54 psia =	1.0884 g/mL
Apparent (skeletal) Density =	1.3233 g/mL
Porosity =	17.7519 %
Stem Volume Used =	67 %

MICROMERITICS ANALYTICAL SERVICES The Particle Testing Authority

Micromeritics Instrument Corporation

Sample: Columbus 36"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007924.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/13/2011 1:34:07PM

Sample Weight: 4.6449 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (μm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m^2/g)	Incremental Pore Area (m^2/g)
0.54	335.7452	0.0000	0.0000	0.000	0.000
0.76	237.9319	0.0026	0.0026	0.000	0.000
1.01	179.6617	0.0053	0.0027	0.000	0.000
2.02	89.5844	0.0222	0.0169	0.001	0.001
3.01	60.1207	0.0355	0.0134	0.001	0.001
4.01	45.1217	0.0474	0.0119	0.002	0.001
5.51	32.8460	0.0567	0.0093	0.003	0.001
7.00	25.8338	0.0607	0.0040	0.004	0.001
8.50	21.2717	0.0628	0.0022	0.004	0.000
10.49	17.2375	0.0681	0.0053	0.005	0.001
12.99	13.9219	0.0706	0.0025	0.006	0.001
15.98	11.3189	0.0751	0.0045	0.007	0.001
19.96	9.0628	0.0770	0.0019	0.008	0.001
23.01	7.8594	0.0791	0.0021	0.009	0.001
25.02	7.2288	0.0798	0.0007	0.009	0.000
29.99	6.0317	0.0825	0.0027	0.011	0.002
35.68	5.0695	0.0831	0.0006	0.011	0.000
45.55	3.9709	0.0852	0.0021	0.013	0.002
55.57	3.2549	0.0867	0.0015	0.015	0.002
70.03	2.5827	0.0892	0.0024	0.018	0.003
85.06	2.1262	0.0914	0.0022	0.022	0.004
110.53	1.6363	0.0945	0.0031	0.029	0.007
135.34	1.3364	0.0961	0.0017	0.033	0.004
169.90	1.0645	0.0973	0.0011	0.037	0.004
215.68	0.8386	0.0987	0.0014	0.043	0.006
266.06	0.6798	0.0999	0.0012	0.049	0.007
325.02	0.5565	0.1008	0.0010	0.055	0.006
415.73	0.4350	0.1018	0.0009	0.063	0.008
515.35	0.3510	0.1023	0.0005	0.068	0.005
634.97	0.2848	0.1043	0.0019	0.093	0.024
696.29	0.2598	0.1047	0.0004	0.099	0.006
796.77	0.2270	0.1052	0.0005	0.107	0.008
986.33	0.1834	0.1057	0.0005	0.117	0.010
1193.98	0.1515	0.1061	0.0004	0.127	0.010
1296.08	0.1395	0.1063	0.0002	0.133	0.006
1394.89	0.1297	0.1065	0.0002	0.139	0.006
1492.38	0.1212	0.1067	0.0002	0.146	0.007
1593.53	0.1135	0.1070	0.0002	0.153	0.008
1695.13	0.1067	0.1072	0.0002	0.162	0.008
1892.53	0.0956	0.1076	0.0004	0.177	0.015
2044.26	0.0885	0.1079	0.0003	0.189	0.013

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 | Serial: 1011/886 | Port: 4/2 | Page 3

Sample: Columbus 36"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007924.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/13/2011 1:34:07PM

Sample Weight: 4.6449 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (μm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m^2/g)	Incremental Pore Area (m^2/g)
2194.28	0.0824	0.1081	0.0002	0.201	0.011
2343.12	0.0772	0.1084	0.0003	0.214	0.013
2492.38	0.0726	0.1087	0.0003	0.230	0.016
2643.14	0.0684	0.1090	0.0003	0.248	0.018
2692.02	0.0672	0.1091	0.0001	0.257	0.009
2843.04	0.0636	0.1093	0.0002	0.269	0.013
2994.25	0.0604	0.1095	0.0002	0.283	0.014
3243.17	0.0558	0.1099	0.0003	0.305	0.021
3492.41	0.0518	0.1101	0.0003	0.327	0.022
3742.06	0.0483	0.1104	0.0003	0.349	0.023
3990.84	0.0453	0.1107	0.0003	0.376	0.027
4239.57	0.0427	0.1111	0.0004	0.408	0.032
4485.68	0.0403	0.1115	0.0004	0.445	0.037
4724.82	0.0383	0.1118	0.0004	0.481	0.036
4982.93	0.0363	0.1122	0.0003	0.515	0.034
5282.32	0.0342	0.1126	0.0004	0.566	0.051
5480.57	0.0330	0.1129	0.0003	0.599	0.033
5731.86	0.0316	0.1132	0.0004	0.643	0.044
5977.71	0.0303	0.1137	0.0005	0.707	0.064
6228.41	0.0290	0.1142	0.0005	0.773	0.066
6477.88	0.0279	0.1148	0.0006	0.855	0.082
6726.03	0.0269	0.1152	0.0004	0.914	0.059
6975.75	0.0259	0.1155	0.0003	0.963	0.050
7476.01	0.0242	0.1161	0.0006	1.062	0.098
7973.21	0.0227	0.1167	0.0005	1.152	0.090
8473.23	0.0213	0.1172	0.0005	1.249	0.097
8973.00	0.0202	0.1178	0.0006	1.356	0.107
9268.90	0.0195	0.1181	0.0003	1.421	0.065
9569.22	0.0189	0.1184	0.0003	1.493	0.072
10019.30	0.0181	0.1190	0.0005	1.607	0.114
10471.89	0.0173	0.1197	0.0008	1.784	0.177
10968.85	0.0165	0.1203	0.0005	1.912	0.129
11471.22	0.0158	0.1208	0.0006	2.049	0.137
11968.56	0.0151	0.1214	0.0005	2.183	0.134
12570.65	0.0144	0.1220	0.0007	2.364	0.181
13065.27	0.0138	0.1226	0.0005	2.516	0.152
13617.45	0.0133	0.1233	0.0008	2.748	0.232
13967.73	0.0129	0.1238	0.0004	2.877	0.129
14302.79	0.0126	0.1242	0.0005	3.022	0.145
14561.53	0.0124	0.1246	0.0003	3.132	0.110
14957.65	0.0121	0.1251	0.0005	3.301	0.169

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011/886 Port: 4/2 Page 4

Sample: Columbus 36"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007924.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/13/2011 1:34:07PM

Sample Weight: 4.6449 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (μm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m^2/g)	Incremental Pore Area (m^2/g)
15412.68	0.0117	0.1258	0.0007	3.535	0.234
15765.63	0.0115	0.1264	0.0006	3.732	0.197
16164.22	0.0112	0.1270	0.0007	3.963	0.231
16613.68	0.0109	0.1276	0.0006	4.163	0.200
16964.49	0.0107	0.1280	0.0004	4.311	0.147
17312.93	0.0104	0.1284	0.0005	4.484	0.174
17653.64	0.0102	0.1288	0.0004	4.631	0.146
18066.69	0.0100	0.1292	0.0004	4.807	0.177
18413.77	0.0098	0.1296	0.0004	4.959	0.152
18758.92	0.0096	0.1300	0.0004	5.105	0.146
19160.60	0.0094	0.1304	0.0004	5.275	0.170
19764.46	0.0092	0.1310	0.0006	5.531	0.256
20265.07	0.0089	0.1315	0.0006	5.781	0.250
20771.84	0.0087	0.1321	0.0006	6.034	0.253
21173.05	0.0085	0.1327	0.0005	6.288	0.253
21627.05	0.0084	0.1331	0.0005	6.518	0.230
22030.31	0.0082	0.1336	0.0004	6.730	0.213
22632.82	0.0080	0.1343	0.0007	7.064	0.333
23183.16	0.0078	0.1348	0.0006	7.366	0.302
23734.17	0.0076	0.1354	0.0006	7.677	0.311
24084.21	0.0075	0.1359	0.0004	7.898	0.221
24634.95	0.0073	0.1364	0.0005	8.193	0.296
25036.34	0.0072	0.1369	0.0005	8.449	0.255
25436.04	0.0071	0.1373	0.0004	8.683	0.235
25886.63	0.0070	0.1378	0.0005	8.966	0.283
26437.31	0.0068	0.1383	0.0006	9.285	0.319
26937.80	0.0067	0.1389	0.0006	9.620	0.335
27387.54	0.0066	0.1394	0.0005	9.924	0.304
27788.41	0.0065	0.1399	0.0004	10.188	0.264
28238.72	0.0064	0.1403	0.0004	10.451	0.263
28988.04	0.0062	0.1409	0.0006	10.857	0.406
29487.28	0.0061	0.1414	0.0005	11.167	0.310
29976.75	0.0060	0.1419	0.0005	11.470	0.303
30437.91	0.0059	0.1423	0.0004	11.750	0.280
30885.98	0.0059	0.1427	0.0004	12.052	0.302
31281.38	0.0058	0.1431	0.0004	12.316	0.264
31785.90	0.0057	0.1436	0.0005	12.639	0.324
32329.64	0.0056	0.1441	0.0005	13.012	0.372
32866.47	0.0055	0.1446	0.0005	13.380	0.368
33456.32	0.0054	0.1451	0.0005	13.766	0.386
33946.80	0.0053	0.1456	0.0005	14.147	0.381

Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011/886 Port: 4/2 Page 5

Sample: Columbus 36"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007924.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/13/2011 1:34:07PM

Sample Weight: 4.6449 g
Correction Type: None
Show Neg. Int: No

Tabular Report

Pressure (psia)	Pore Diameter (µm)	Cumulative Pore Volume (mL/g)	Incremental Pore Volume (mL/g)	Cumulative Pore Area (m^2/g)	Incremental Pore Area (m^2/g)
34597.91	0.0052	0.1462	0.0006	14.567	0.421
35443.03	0.0051	0.1469	0.0007	15.071	0.504
36142.33	0.0050	0.1474	0.0006	15.538	0.466
36941.50	0.0049	0.1481	0.0006	16.046	0.508
37592.91	0.0048	0.1486	0.0006	16.511	0.465
38395.83	0.0047	0.1493	0.0006	17.044	0.534
39144.31	0.0046	0.1499	0.0006	17.573	0.529
39942.93	0.0045	0.1505	0.0007	18.143	0.570
40445.14	0.0045	0.1510	0.0004	18.510	0.368
40943.10	0.0044	0.1514	0.0005	18.939	0.429
42444.46	0.0043	0.1525	0.0011	19.925	0.986
43294.16	0.0042	0.1531	0.0006	20.489	0.564
43941.76	0.0041	0.1536	0.0005	20.946	0.457
44943.66	0.0040	0.1543	0.0007	21.618	0.672
46445.68	0.0039	0.1552	0.0010	22.591	0.973
47946.36	0.0038	0.1561	0.0009	23.553	0.962
49447.10	0.0037	0.1571	0.0009	24.552	1.000
50145.64	0.0036	0.1576	0.0005	25.099	0.547
52948.39	0.0034	0.1592	0.0016	26.921	1.823
54445.40	0.0033	0.1601	0.0010	28.075	1.153
55944.26	0.0032	0.1609	0.0008	29.035	0.960
57940.48	0.0031	0.1620	0.0011	30.433	1.398
59925.00	0.0030	0.1631	0.0011	31.836	1.403

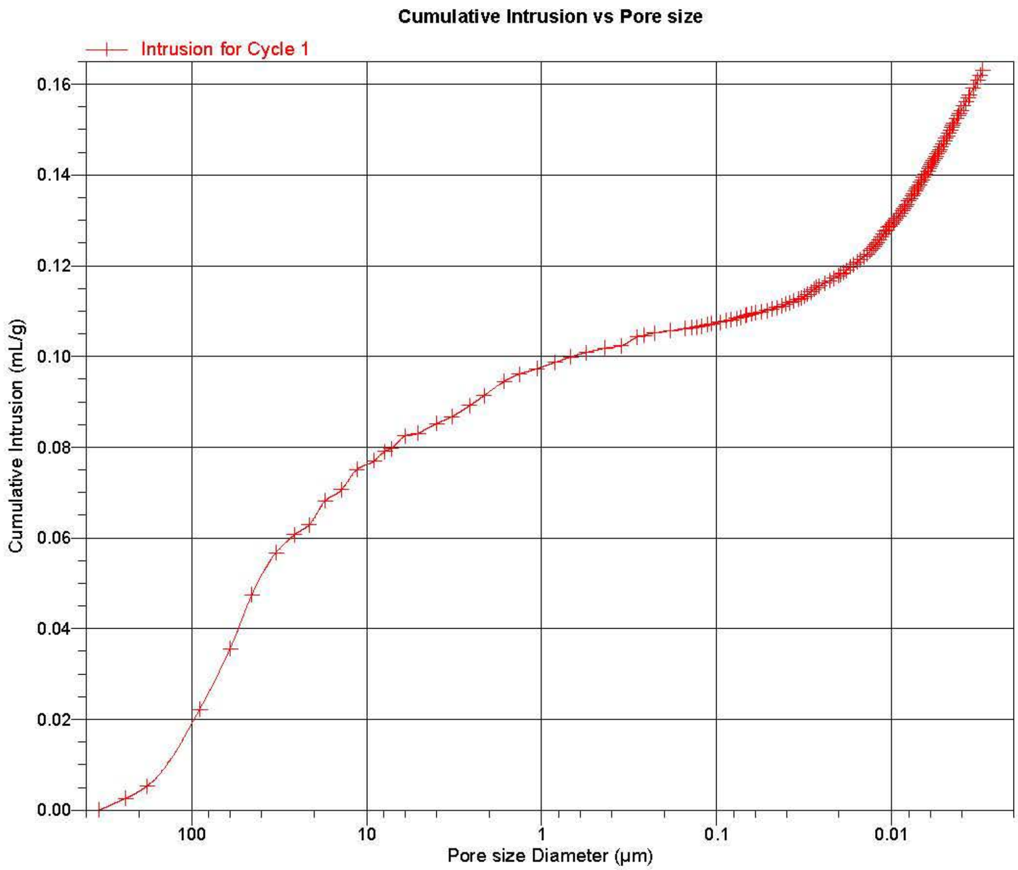
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 Serial: 1011/886 Port: 4/2 Page 6

Sample: Columbus 36"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007924.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/13/2011 1:34:07PM

Sample Weight: 4.6449 g
Correction Type: None
Show Neg. Int: No



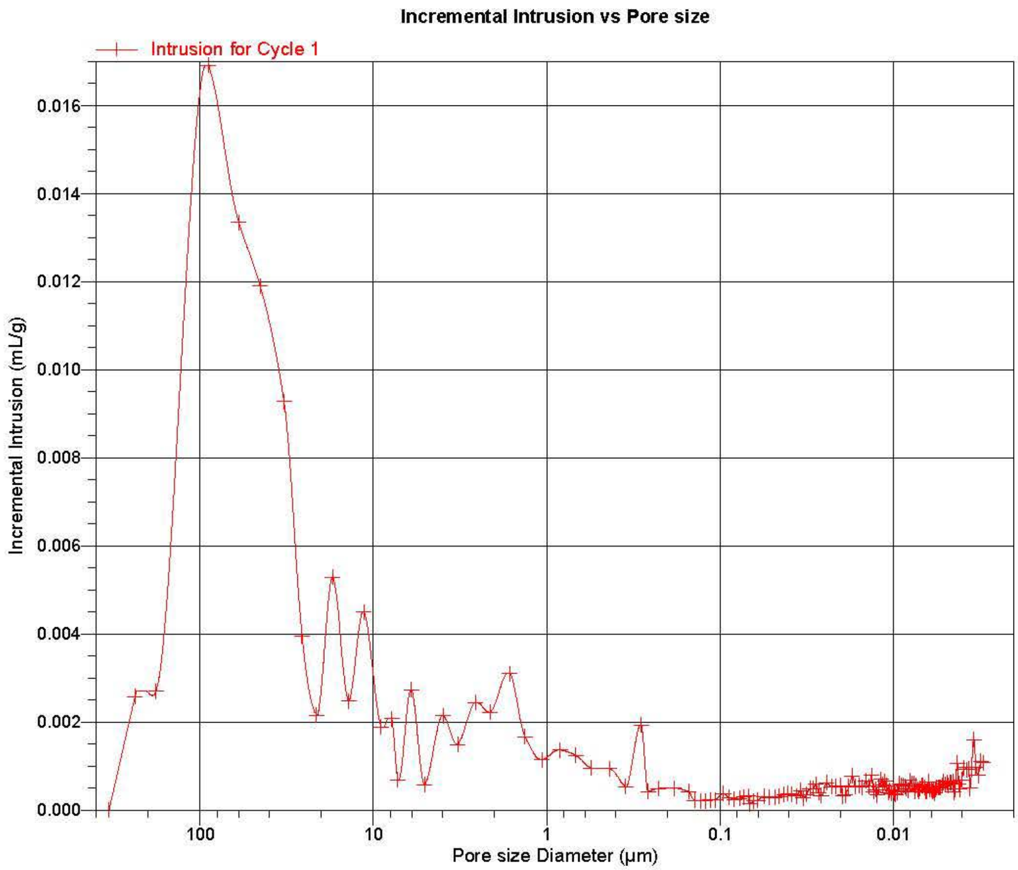
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 | Serial: 1011/886 | Port: 4/2 | Page 7

Sample: Columbus 36"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007924.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/13/2011 1:34:07PM

Sample Weight: 4.6449 g
Correction Type: None
Show Neg. Int: No



Micromeritics Instrument Corporation

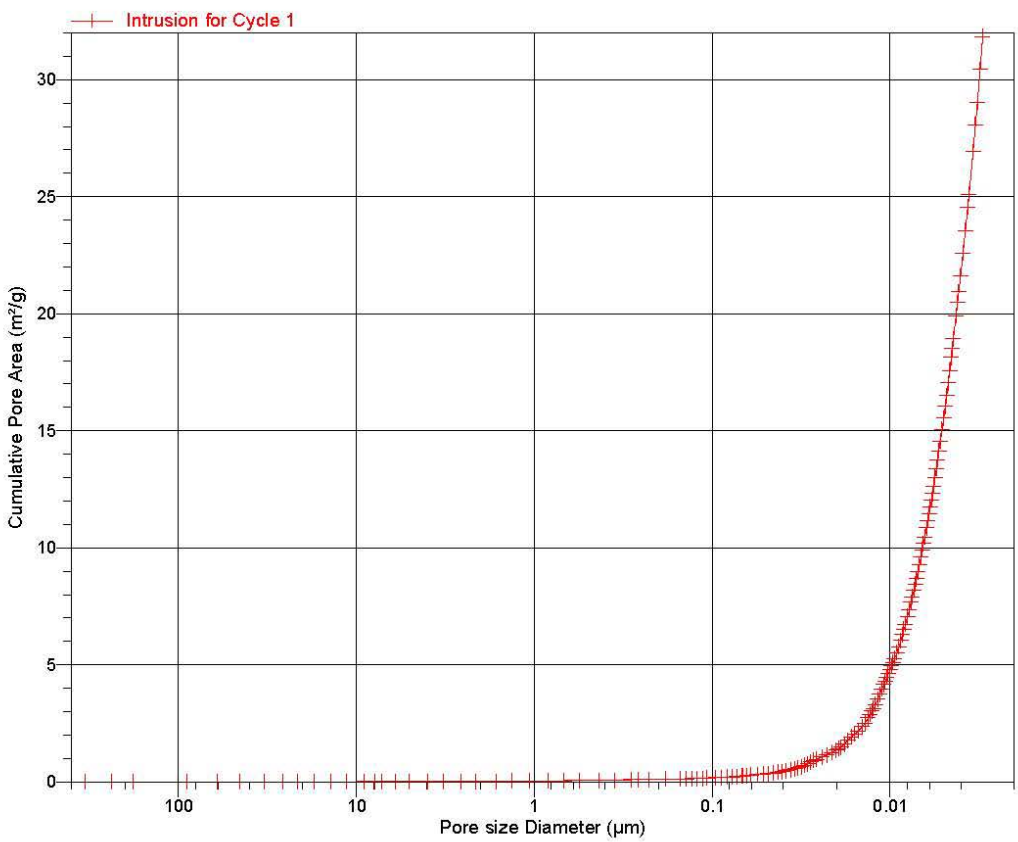
AutoPore IV 9500 V1.09 Serial: 1011/886 Port: 4/2

Sample: Columbus 36"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007924.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/13/2011 1:34:07PM

Sample Weight: 4.6449 g
Correction Type: None
Show Neg. Int: No

Cumulative Pore Area vs Pore size



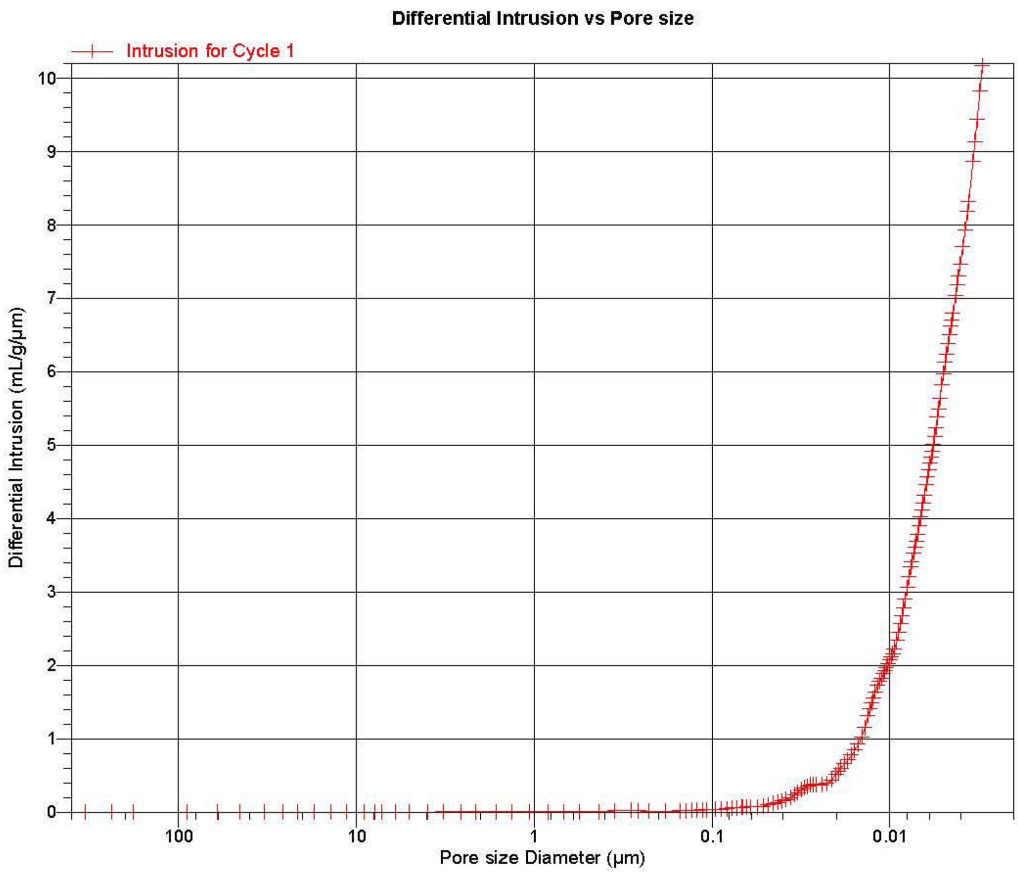
Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09 | Serial: 1011/886 | Port: 4/2 | Page 9

Sample: Columbus 36"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007924.SMP

LP Analysis Time: 1/7/2011 5:32:42PM
HP Analysis Time: 1/13/2011 1:34:06PM
Report Time: 1/13/2011 1:34:07PM

Sample Weight: 4.6449 g
Correction Type: None
Show Neg. Int: No



Micromeritics Instrument Corporation

AutoPore IV 9500 V1.09	Serial: 1011/886	Port: 4/2	Page 10

Sample: Columbus 36"
Operator: CB
Submitter: Louisiana Tech University
File: C:\9500\DATA\2011\01JAN\1007924.SMP

LP Analysis Time:	1/7/2011 5:32:42PM	Sample Weight:	4.6449 g
HP Analysis Time:	1/13/2011 1:34:06PM	Correction Type:	None
Report Time:	1/13/2011 1:34:07PM	Show Neg. Int:	No