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Alternative Approach for Assessment of Hydraulic Design Basis for Pressure Pipe Liners

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ALTERNATIVE APPROACH FOR ASSESSMENT OF HYDRAULIC DESIGN BASIS FOR PRESSURE PIPE LINERS

by

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ABSTRACT

New product development requires stringent testing to ensure that strength and safety standards are met by the innovative materials. When developing a new pipe material, several factors have to be tested for. In addition to normal material characteristics such as elastic modulus of pipe materials, long-term hydrostatic strength (LTHS) and hydrostatic design basis (HDB) are needed. Tests for typical material characteristics are commonplace and can certainly be conducted in most lab facilities. In contrast, LTHS and HDB as described in ASTM D2992 are two tests that can prove very challenging to conduct. The current method requires a minimum of 18 full pipe specimen be placed under hydrostatic test at various stress levels to produce required failures. Successfully generating these failures can be very hard to achieve with a relatively unfamiliar material. This work suggests a modified method drawing from years of successful ASTM D2990 testing. This method will combine the loading apparatus used for ASTM D2990 creep testing, strain gauges and a new relationship between strain and the typical ductile failures seen in D2992 testing. It is also possible, with existing long-term data, to model the material behavior and reduce time further. The goal of this approach is to increase the volume of testing in order to ensure a higher level of confidence for designers and owners and save clients research funding as well.

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DEDICATION

This work is dedicated to my co-advisors who made this possible and to my family and many friends who have been a part of it.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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I would like to express my gratitude to my co-advisors Dr. John Matthews and Dr. Shaurav Alam, for their support and guidance throughout this project. I would also like to thank the remainder of my advisory committee Dr. Jay Wang, Dr. David Hall, and Dr. Elizabeth Matthews for their professional advice and guidance whenever it was needed. I would also like to thank TTC shop crew past and present who have helped me out through the years of work. And my family who have put up with this adventure and supported me when I needed them. And all of the many friends that I have made throughout my many years at Louisiana Tech.

CHAPTER 1

INTRODUCTION

1.1 Background

Before installing a pipe or any material, it is common practice for a design review to be performed. When it comes to pressure pipes and pipe systems, one important value is the Hydraulic design basis or HDB. There are two standards used to determine this value that are similar but vary slightly by what material is being tested and the data tables used for selecting the HDB range. The first standard is ASTM D2992 Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings. The second standard is ASTM D2837 Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials or Pressure Design Basis for Thermoplastic Pipe Products. The first standard ASTM D2992 was tested by the Trenchless Technology Center (TTC) for a client in 2017 with very little success due to lack of specifics given in the standard.

To elaborate, the test failed because the sample failures required by the standard were not met. This requirement made the standard difficult to meet in a cost-effective manner. Instead, an alternative method was then developed in which the samples that had been tested for 10,000 hours could be used in a similar long-term test. The other long-term test in question is ASTM D2990 Standard Test Methods for Tensile, Compressive, and Flexural Creep-Rupture of Plastics. This method does not produce any sort of HDB value for the end user but does provide the user with an estimate of long-term creep effects on the strength retention of the material over time. Of the 36 total samples used in the D2992 test only 18 were equipped with strain gauges and only 12 of these samples were found to be useful for this new analysis method.

However difficult to perform the test the HDB value of a material is still required for structural design. The continued interest in testing of either D2992 and D2837 has spurred the development of an alternative method for determining this HDB value, which is the focus of this dissertation.

1.2 Objective

The objective of this research is to create a testing method that will enable pipe and liner material manufacturers or testing labs to more easily and cost-effectively determine the HDB of a pipe or liner material. This newly proposed method would reduce the lab testing area required by the long-term samples drastically and reduce the labor hours to run the test and the difficulty that is required to construct the traditional samples that are used during ASTM D2992 testing. These traditional samples are fully formed pipe samples under constant and/or dynamic internal pressure for up to 10,000 hours. The possibility of predicting the time to failure by modeling the creep behavior will also be explored. The ability to accurately model the creep behavior will depend on the available long-term creep data for the pipe or liner material.

1.3 Dissertation Organization

This dissertation is organized into seven chapters: (1) Introduction; (2) Review of Relevant Literature; (3) Experimental Setup; (4) Strain Based HDB; (5) Control Data; (6) Modelled Results of HDB; and (7) Conclusion and Future Direction.

Chapter 2 presents an overview of trenchless technology and a research project that unfortunately highlighted the difficulties discovered when performing an ASTM D2992 test.

Chapter 3 presents an altered modified method to find HDB using a different procedure and the steps that have been taken to prepare the systems required for the test. The dimensions and sample preparation required is also reviewed.

Chapter 4 presents the theory behind the alternative method and how it will corelate to existing data acquired by the existing method.

Chapter 5 presents the control data provided by an outside material manufacturer who has performed extensive testing of their product.

Chapter 6 presents the results discovered through modeling the proposed test method at stress levels representative of those tested by the supplier of the control data.

Chapter 7 presents concluding remarks on the research to date, limitations that are currently at hand and directions for future study.

1.4 Key Contributions

The main contributions of this work are detailed below:

1. The development of a method to recover creep retention data from unfailed and otherwise unused ASTM D2992 test samples.

2. The development of modernized methods for gathering data for ASTM D2990 test and a modified testing method to gather ASTM D2992 data using a strain method.

3. The development of a model to predict failure time for materials using elastic and creep strain limits.

4. The development of a most cost effective method for determining HDB in pressure pipe and liners.

CHAPTER 2

REVIEW OF RELEVANT LITERATURE

2.1 Trenchless Technology†

2.1.1 Introduction

Out of all of mankind's inventions very few if any have ever lasted forever. At some point in the service life or design life of a system it will have to be repaired, rebuilt, or replaced entirely. This can be said for mechanical systems and static systems. These systems have vastly different design lives ranging from hours, miles, or years of service in the case of infrastructure. Infrastructure is much more than just roads and bridges, however. These infrastructure systems include but are not limited to water, sewer, gas, power, and telecommunication. This chapter will detail how the service or design life of some of these systems can be extended with minimal social and economic impact to the communities above; and how these methods can benefit countries like Bangladesh.

2.1.2 Technology Categories

It is important to fully understand the needs of the utility before any recommendations can be made. Not all failures are a sign that the system as a whole has failed and needs to be replaced. There are three Technology Categories to consider while

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† Portions of this chapter have been published previously as part of *Proceedings of the 5th Annual Paper Meet and 2nd Civil Engineering Congress*, Dhaka, Bangladesh, Kraft, J.J., et al., *Trenchless Technology - Bangladesh Aspect: Part I-III*. July 2022: (2022) The current version has been formatted for this dissertation.

selecting a Trenchless method. The categories are typically defined as (Matthews et al. 2013, and Morrison et al. 2012):

- Repair: These techniques are used when the host pipe is structurally sound short of the limited section that may require the repair.
- Rehabilitation: These techniques are typically more extensive and are used to extend the life of the entire host pipe. In many cases pipes that need rehabilitation have lost considerable amounts of hydraulic or structural capacity.
- Replacement: These technologies are used when the structural deterioration is too severe, or the service capacity of the pipe needs to be increased beyond the capacity of rehabilitation methods. This paper does not focus on these methods.

These repair or rehabilitation concepts can be collectively referred to as renewal. Renewal methods can vary dependent on the size of the pipe. Pipes with diameters measuring 16 in (400 mm) or less are considered small diameter while pipes measuring greater are considered large diameter (Matthews et al. 2013). Similar to how renewal method selection can vary by size, the media that is transported by the pipeline system must also be considered. A method that would be suitable for sanitary sewer or stormwater systems may not meet the stringent requirements that a waterline system would require (AWWA 2005).

2.1.3 Repair

While the repair of short utility segments or point repairs is not the focus of this paper, it is important to note that there are Trenchless methods readily available for these applications. Typically, these repairs are done on an as-needed basis when problems arise. Many municipalities and owners have crews that are trained and capable of carrying out these methods on staff (Matthews et al. 2013). While there are certainly more methods available, this paper will refer to well established methods that also have established good practice guidelines. These methods are as follows (Potvin et al. 2018):

- Cured-in-Place Pipe (CIPP)
- Mechanical Repair Sleeves
- Internal Joint Seals
- Fiber reinforced Polymers
- Chemical Grouting

Cured-in-Place Pipe (CIPP)

CIPP, while typically used for gravity sewers, can also be used for water and gas applications. Lengths of these short applications can typically range between 3-8 feet (Potvin et al. 2018). Do to the construction of CIPP liners being flexible and adjustable based on the application this method offers the flexibility of fitting a wide variety of diameters and structural requirements, ranging from non-structural to structural. A unique benefit that CIPP offers is the ability to be used in almost any host material while offering minimal disruption to the host pipe surface (Matthews et al. 2013, Potvin et al. 2018). Figure 2-1 depicts a common CIPP point repair application.

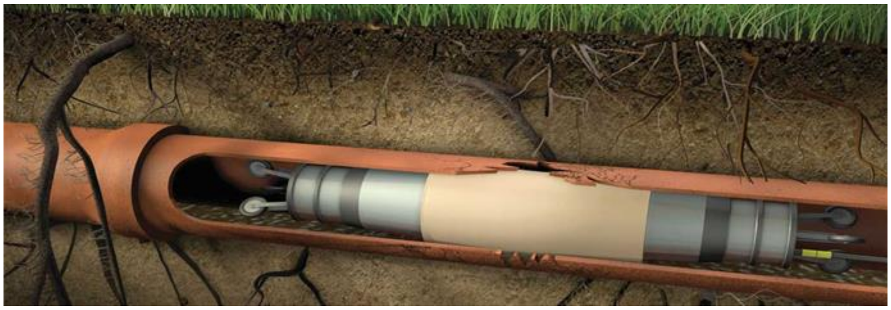

Figure 2-1: CIPP Point Repair – Courtesy of Trenchless Technology Magazine

Mechanical Repair Sleeves

Mechanical repair sleeves come in multiple different sizes and material compositions. The ring materials are most commonly constructed of stainless steel in sizes up to 54 in diameter but can be constructed out of PVC for larger diameters and irregularly shaped sewer mains up to 108 in diameter. Depending on the ring used, there are also multiple gaskets and resin combinations available ranging from rubber to absorbent foam saturated with resin sealant (Potvin et al 2018). These seals have proven especially successful at sealing joints in watermains and isolating lead in joints and preventing any leaching in CI water mains (Cost-Mattos et al. 2008). While these repairs also provide limited disruption to the host pipe diameter, the relative short lengths of 4 ft and inability to be used in corrugated metal piping limit the use of this technology. Figure 2-2 shows a common repair application.

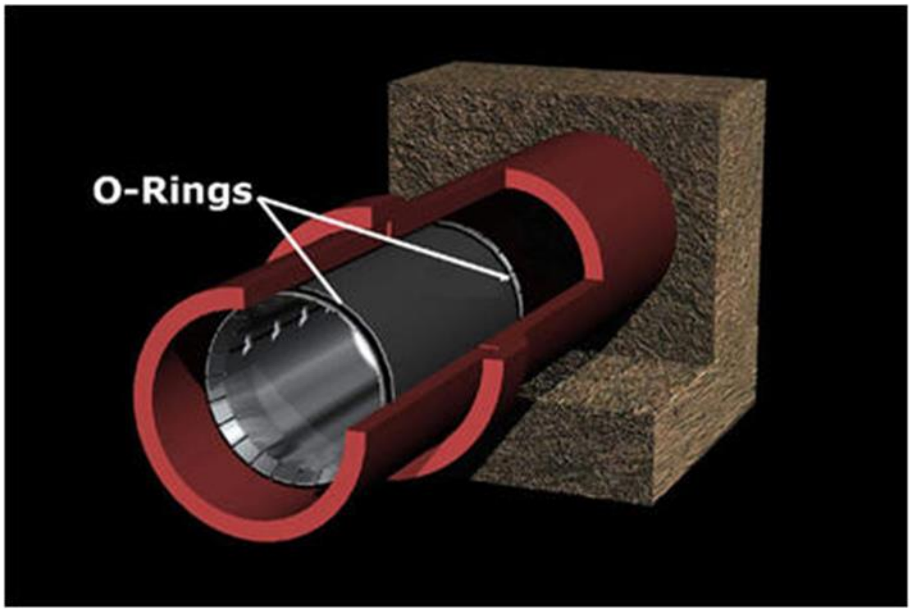

Figure 2-2: Mechanical repair sleeve - Courtesy FDOT

Internal Joint Seals

The third trenchless repair method we will discuss is the Internal Joint Seal. These seals consist of an elastomer ring with stainless steel rings that lock the seal in place. These seals were initially designed to seal joints, radial cracks, or interfaces where materials change. In Figure 2-3 an internal joint seal is used to seal the joint between two sections of concrete pipe. These seals can also be used to seal holes and other issues in host pipes, but this is typically reserved for pipes that can be man-entered to clean and ensure a good surface is available for the elastomer to seal. To use these seals in sanitary sewer applications it is important to specify that a higher grade of stainless steel be used. These seals come in larger diameters of up to 216 in While this is a larger diameter than Mechanical Repair Sleeves, they do not offer any structural abilities and are also limited to short lengths of 3 ft and a smooth pipe surface, so they are not suitable for corrugated metal pipe (Potvin et al. 2018).

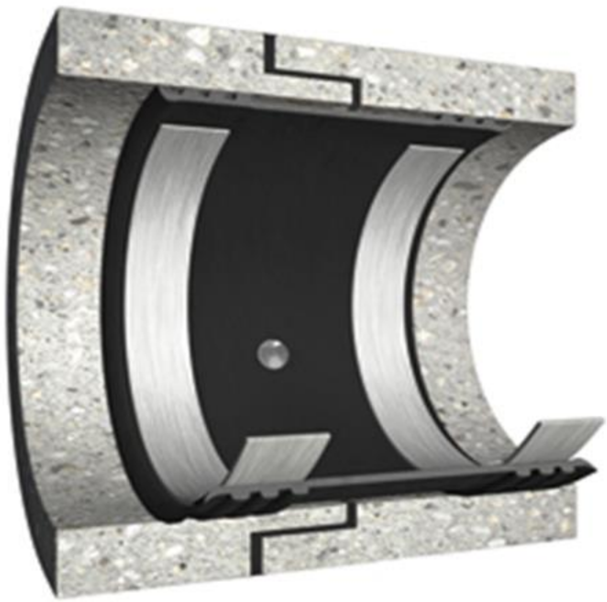

Figure 2-3: Internal joint seal - courtesy of Water & Wastes Digest

Fiber Reinforced Polymers

The use of Fiber Reinforced Polymer (FRP) has a long-standing history of repairing different infrastructure systems ranging from pipelines, bridges, and even buildings. Carbon Fiber Reinforced Polymer (CFRP) has become a viable and widely accepted method to rehabilitate deteriorating pipelines. CFRP has been used to strengthen and reinforce PCCP externally since the 1990s (Gipsov 2012). FRP is a relatively simple system consisting of at a minimum a reinforced polymer of some make and a complementary resin. Depending on the material and the application the polymer and the resin can be designed to meet the criteria required for the project. This material versatility allows FRP to be compatible with a large selection of pipe materials and sizes regularly up to 12 ft (Potvin et al. 2018). Two workers can be seen applying FRP by hand in Figure 2-4.

Figure 2-4: Manual application of FRP Liner - Courtesy Water News Network

Chemical Grouting

Chemical Grouting can be used in a number of cases from addressing leaking joints, cracks, fractures, and even settlement during other trenchless installation methods. Chemical grout can also boast that it was the first trenchless rehabilitation method. It was first Introduced in 1955 and was first installed on a job in 1962 in Oaklawn, Kansas. In the same year, other projects were performed in both Michigan and Wisconsin (Romans 2001). A trait that makes chemical grouting so versatile is the fact that when the two-part system is mixed it has the same viscosity as water. Meaning that any crack or void that water could seep through or penetrate the grout can also. When the grout is installed, it is done using an inflatable packer. Typically, in the range of 6 in and up in size. The packer is placed in position with the help of CCTV and inflated sealing off the area where the grout will be installed. The grout is then mixed and pumped into the application area. The back pressure is monitored to determine when the proper amount of grout has been pumped into the application (Potvin et al. 2018). In Figure 2-5, the packer has been moved slightly out of position after the grout has been cured for a post installation CCTV inspection.

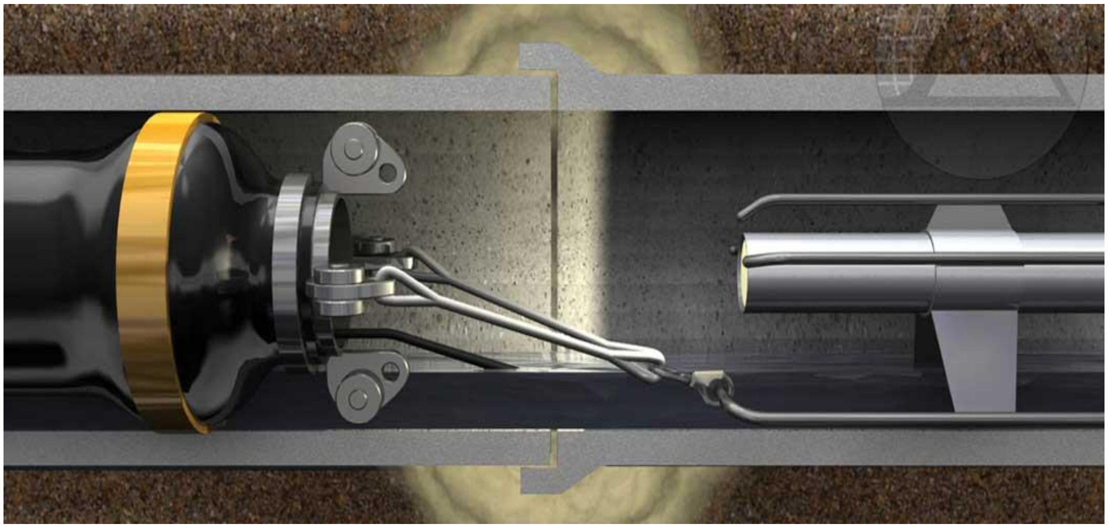

Figure 2-5: Post installation inspection of chemical grout installation – courtesy Avanti and Trenchless Technology Magazine.

2.1.4 Rehabilitation

In this context, rehabilitation will refer to methods that address the entire length of a system. In gravity applications, this will be from manhole to manhole while in pressure this will mean from access to access. These access points can vary depending on the location of the system in relation to any surrounding structures. All of the methods discussed today fall into four classifications based on the AWWA M28 Manual (AWWA 2001b):

- Class I: These are linings that provide no structural value and at only as corrosion inhibitors.
- Class II: These linings go further and have the ability to span holes but require structural support from the host pipe. These linings are known as semi structural.

- Class III: These linings are designed with sufficient thickness to resist external loads from hydrostatic loads but also internal vacuum conditions.
- Class IV: These systems are completely self-supporting and only use the existing pipe as a conduit during installation.

Cured-in-Place Pipe (CIPP)

Full length CIPP is very similar to CIPP used for point repair applications. In many applications, it is the same liner and resin being used for both applications. The major difference is the installation and curing methods used for each application. In the case of CIPP rehabilitation, there are three methods typically used, Air inversion, water inversion, or simply pulled into place and inflated against the host pipe with air or water pressure. Once the liner has been positioned the resin in the liner is cured at ambient or raised temperature using hot water or steam. More recently, with a rise in possible environmental-concerns, UV curing has been introduced. This paper will not discuss the possible environmental or health impacts because they have been found to be low risk or avoidable (Howell et al. 2020). The differences aside, CIPP has been successfully installed in gravity, low-pressure wastewater, and stormwater applications in the mid-1970s some pressure applications began. Initial pressure applications included industrial process pipes and raw water. Through research and development there are now several pressure pipe lining products that meet NSF/ANSI Standard 61 (NSF/ANSI 1988; Heavens and Gumbel 2004). The two major applications for CIPP that are worth reviewing are Water Main Applications and Wastewater Applications.

Water Main Applications (Pressure)

Pressure liner applications for CIPP will typically include seven steps. A temporary water supply installation, access pit excavation, clean and prep host pipe, wet out liner, installation, curing, and service reinstatement. Similar to a sewer bypass that is sometimes required in sanitary sewer applications, a temporary water supply is provided to ensure that no customers are without service for extended periods of time. Excavation of access pits is an added burden on pressure applications that are not typically associated with gravity due to the availability of manholes. Because of this, access pits for pressure are often placed based on the locations of appurtenances (tees, crosses, hydrants, valves, etc.) or as far apart as material limitations will allow. Cleaning for pressure applications is also more involved. Large amounts of tuberculation can accumulate in water mains and any such contaminants need to be removed before lining. Cleaning can not be too rough or damage to the service connections could prevent proper plugging and could require manual reconnection by digging. However, if the cleaning process is performed without issue the services can be plugged and the liner installed with no issue. After the liner has been cured, the service connections, if there were any, are reconnected using a robotic cutter and CCTV. The plugs used before installing the liner typically cause a dimple to appear in the liner and aid in service connection. It is important to record or map the location of services in the preinstallation inspections. If no issues are located in the post curing inspection the line is ready to be reinstated following any other test or requirements that may take precedent in that region (Potvin 2018).

These applications are typically limited to 4 ft diameter by the availability of the specialty liners that have to be used for the application. Lengths of 500 feet are typically considered standard but larger spans can be completed. Bends of up to 45 degrees are also considered to be the maximum for these applications. The resin used for these applications is typically epoxy and must adhere to NSF/ ANSI Standard 61 requirements for potable water (Potvin 2018; NSF/ANSI 1988). Figure 2-6 shows what a severely tuberculated pipe before cleaning and a cleaned and lined pipe look like.

Figure 2-6: Water line repaired using CIPP - Courtesy Aquazen Services

Wastewater Applications (Gravity)

For gravity applications the first step of the process remains the same; the flow must be stopped. Depending on the location and size of the line, the flow could be capped or will need to be bypassed. With the flow removed the line will need to be cleaned. Many of the same technologies utilized in cleaning of pressure pipes are also used in gravity pipes. Care should be taken so as to not cause excessive damage to the host pipe. Once the pipe is cleaned, end seals, if called for, can be installed prior to the liner. In gravity application service connections do not need to be plugged prior to lining. After installation and curing, the excess liner is removed from both ends, and service connections are once again reconnected robotically. Before and after installation of a CIPP liner can be seen in Figure 2-7.

Figure 2-7: Sewer application of CIPP – Courtesy of Lining Pro

During the curing process regardless of method used it is important to ensure that quality control processes are adhered to. There are multiple methods and sensors available to help ensure a quality cure (Potvin 2018).

Unlike pressure applications, gravity applications are not limited by material sizes but more by the weight of the saturated liner. Once liners begin to exceed the 4 ft mark, the weight becomes a larger issue than any other. The increased weight will cause a need for more pressure during installation and curing. The weight becomes such an issue that the wet out, which is typically performed at controlled sites, will have to be performed on the job site so as to not exceed over the road weight limits during shipping. It is not uncommon to have liners installed from 6 in up to 105 in diameter and lengths of 1500 ft and greater are also achievable (Matthews et al. 2013; Potvin 2018).

Sliplining

Sliplining is a well-established rehabilitation technique that can trace its origins back to the 1940s. A long track life combined with a very straight forward installation method makes sliplining a viable option for many situations (Sullivan 2018). Technology and design have come a long way from the first applications of sliplining, but the concept remains the same. While sliplining can be used in both pressure and gravity applications it is important to consider the loss of capacity from the reduction of pipe volume even more than with methods such as CIPP. When slip lining space is lost, more space called annular space is also lost to allow for the new pipe to fit inside of the old host pipe. If hydraulic requirements are still met after checking these calculations, sliplining could go ahead as a possibility. There are two typical installation methods used for sliplining. The first method known as continuous slipping requires large amounts of layout space in order to build the pipe string above ground. Because the purpose of this paper is to discuss techniques to limit disruption this method will not be discussed. The second method is segmental sliplining which is what it sounds like, piece by piece.

Installation Method

As with other rehab methods the flow will need to be bypassed in order to begin the project. The exception to this is gravity applications without excessive flow. Cleaning needs to take place but not with the same vigor as a product that needs to adhere to a host pipe surface. Depending on the application, the new pipe can be inserted through the existing manhole or for larger pipe sizes a pit will need to be excavated to allow the pipe to be inserted. Figure 8 shows the pit created to slipline a large pipe without bypass pumping. The pipe material used will typically be of a bell and spigot design. As one joint is inserted the next is lowered, connected in the previous and then pushed forward just like the previous until the new pipe reaches the exit pit. After the liner has been placed it is common to grout the annular space to secure the new system and protect the pipe from any possible point loads that could be applied by the failing host pipe (Potvin 2018).

Some of the more common materials for sliplining are PVC, HDPE, or PE. The most common choice is PE (Sullivan 2018). However, most common pipe materials can be used for sliplining applications; this helps to make the method versatile. The most common application for the sliplining process is for old reinforced concrete pipe (RCP) sewer applications. Concrete pipes corrode rapidly in concentrated sewer gas environments, and this has led to many municipalities proactively lining existing concrete mains with more resistant fiberglass pipe materials. It was for this reason that the County Sanitation Districts of Los Angeles County selected sliplining for nearly 30,000 ft of 60 in RCP in the 1980s and early 1990s when all of the existing RCP had considerable corrosion of ¾ in and exposed rebar throughout the system (Sung and Anktell 1996). While a design life of 50 years is typically considered standard, the city of Denver was able to achieve a 500-year service life by rehabilitating their sewers using fiberglass reinforced polymer mortar pipe manufactured by Hobas (Khamanian and Rocco 2018). Even though there have been great results using sliplining it is important to remember any product's limitations. Sliplining is best used in straight shots, but some curves have been completed successfully. Reinstating service connections can be difficult and, in many cases, require digging to reinstate (Potvin 2018).

Figure 2-8: Sliplining with flow – Courtesy mclewis888

Panel Liners

Panel lining is similar to sliplining with one major difference being that panel lining can only be performed in lines large enough for man entry. While this is a downfall of the system, there are other attributes that should be considered. Panel liners are constructed using Glass Reinforced Plastic (GRP) this allows for the panels to be constructed to fit in almost any host pipe shape. Some profiles that will allow for GRP panels include round, egg-shaped, square, rectangular, symmetrical, and non-symmetrical. Figure 2-9 shows the installation of GRP panels in a rectangular sewer. Lengths of sections can also be custom made ranging from 3.5 – 26 ft but can be built in partial sections if the job requires it. Bends can even be navigated through the fabrication of custom panels. Like in slip lining, services have to be extended out and connected to the new liner before grouting can take place. There are two design methodologies that could be used when designing panel liners. One methodology relies on the strength and bond of the grout to support the system while the other simply calls for thicker panels and does not rely on grout strength (Potvin 2018)

Figure 2-9: GRP lining in rectangular sewer- Courtesy Trenchless Technology Magazine

Close Fitting Liners

Close fitting liners while consisting of either two materials polyethylene (PE) or polyvinyl chloride (PVC) can be separated into four categories:

- Compression
- Tension
- Fold and Form
- PVC liner expansion

The downfall of all of these methods requires that large strings of pipe be constructed above ground before installation. Caution must be exercised when cleaning the host pipe to ensure all debris is removed and a CCTV inspection must be performed to ensure the host pipe is clean (Norman and Simicevic 2021; Potvin 2018).

Compression

The compression method begins with PE pipe that is slightly larger than the inside diameter of the host pipe that is run through compressive rollers to reduce the outside diameter by approximately 20% but may relax to approximately 10%. After this the liner is installed using normal slipping methods. Once the new close-fitting liner is in place hydraulic pressure is used to expand the pipe until a close fit is achieved and mechanical restraints should be used to prevent any future movement. This installation can be fully structural and a range of 4 to 20 in in diameter (Norman and Simicevic 2021; Potvin 2018). A large HDPE compression installation can be seen in Figure 2-10.

Figure 2-10: Installation of HDPE liner – Courtesy Trenchless Technology Magazine

Tension

In the tension method, the PE pipe is continuously pulled through a swaging die that reduces the diameter by approximately 10%. This tensile force must be held continuously in order for the pipe to be installed. In some instances, heat is also applied to reduce the tensile forces required to insert the liner. The tension is gradually reduced once the liner is installed to allow the PE to return to its original diameter and a close fit. This installation can be structural and range in size from 3 up to 48 in diameter (Norman and Simicevic 2021; Potvin 2018).

Fold and Form

HDPE and PVC are both commonly used for fold and form applications with PE being reserved for larger applications. In the process the pipe is deformed into a ‘C’ or ‘U’ shape with smaller diameters requiring heat to help the process. The diameters that require heat will hold the deformed shape throughout installation, while larger liners will require sacrificial banding temporarily. A 40% reduction in cross sectional area can be expected when using this process, making for an easy slip lining application. However, this method is typically thought of as a thin-walled partial pressure liner not a fully structural liner. Therefore, the pressure rating of this system may rely heavily on the remaining strength of the host pipe. This method allows for installation of liners from 3 to 63 in diameter (Norman and Simicevic 2021; Potvin 2018).

Figure 2-11: Fold and Form install and inflation – Courtesy Olimb

PVC Liner Expansion

In this method the liner is not deformed before installation. The PVC is slightly smaller than the host pipe and installed using regular sliplining methods. Once the liner is installed heat and pressure are applied to create the close fit condition. This method is typically suited for much shorter lengths than other close fit liners and should only be used to travers long radius bends. This system can provide a fully structural solution for pipes 4 to 16 in diameter.

Pipe Bursting

Pipe bursting is a unique method on this list of rehabilitation methods. Pipe bursting is the only method listed that allows for the retention of the same diameter or for an increase in diameter. The most basic explanation of pipe bursting is that a pulling head is attached to a new section of pipe the same diameter or larger than your existing pipe. The head is attached to a large winch unit at the other end of the existing line and pulled through the old pipe leaving a new pipe in its place. The major drawback to this system is that any service connections must be dug and disconnected and then reconnected once the new pipe is in place. However, when the capacity must be increased, pipe bursting is a viable option. It is routine to increase pipe size by 25%, between 25-50% is said to be challenging. Upsizing by 50-125% is very challenging but has been completed successfully (Ambler et al. 2019; Potvin 2018).

Installation and Consideration

In order to allow for these upsizes updated pulling heads were developed. The Static head was the original design; it was just pulled through the existing pipe. In order to increase capabilities Pneumatic and Hydraulic heads were developed that included cylinders inside of the heads that pulse and help break the existing pipe and reduce the pulling forces required. These methods are still only suitable for some existing pipe materials. For traditional pipe bursting the host pipe must be brittle in order to shatter or break when the head is pulled. Asbestos cement, non-reinforced concrete, and cast iron would all make good candidates for pipe bursting. Malleable materials such as ductile iron, PVC, PE, and steel all require a simple modification to be made to the cutter head. Sometimes referred to as a separate method Pipe Splitting can only be used with static pipe bursting equipment. In this method, specialty design cutting wheels are mounted on a static pull head and cut the host pipe in a number of sections allowing the new pipe to be pulled into place (Ambler et al. 2019; Potvin 2018). Figure 12 depicts the pipe bursting with a modified pull head.

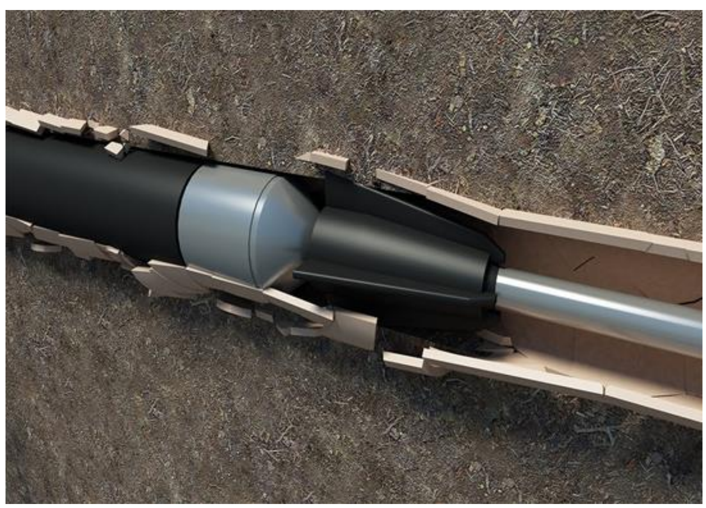

Figure 2-12: Pipe bursting with a modified pulling head – Courtesy of Trenchless Solution

Soil Conditions

It is highly recommended that a geotechnical survey be performed of the proposed project before selecting slip lining as the installation method. Easily compatible soils such as expandable clay and loose cobble are recommended but densely compacted clay and sandstone are not. It is also not recommended to attempt pipe bursting below the water table. It is also not recommended to attempt pipe bursting very soft and loose soils as they can flow and fill the annular space created by the head causing excessive friction values that could exceed the design of the project (Ambler et al. 2019; Potvin 2018).

Spiral Wound Liners

Similarly, to other liners we have discussed, Spiral Wound liners can be designed as semi-structural solutions or fully structural solutions. The ability for the liner to be constructed as a fully structural solution will depend on several values. The soil conditions and methods used when burying the original host pipe must be known in order to truly say that the system is completely structural (Tomes 2022). Work performed by the trenchless technology center seems to confirm some of these concerns. A 24 in lined section of corrugated metal pipe experienced tensile failure due to soil cover and bedding conditions (Alam 2014).

There are two primary methods for applying spiral wound liners: Robotic winding and manual hand winding. Even further distinctions can be made between small-diameter and large-diameter robotic installations. Installations of 60 in and smaller are installed directly on the host pipe without the need for any grouting. Some robotic equipment is capable of installing steel reinforcing strips, welding seams, and applying sealant and adhesive. Manual winding is reserved for larger man entry lines and irregularly shaped sewers. A rectangular sewer is repaired using this method in Figure 2-13. All service laterals have to be manually reconnected and extended to the new liner before grouting the liner in place. Man (crew) entry lines can be connected from inside the lines while smaller lines have to be dug and extended externally. Winding installations can be performed during low flow conditions, but all flow must be removed before grouting operations commence (Potvin 2018).

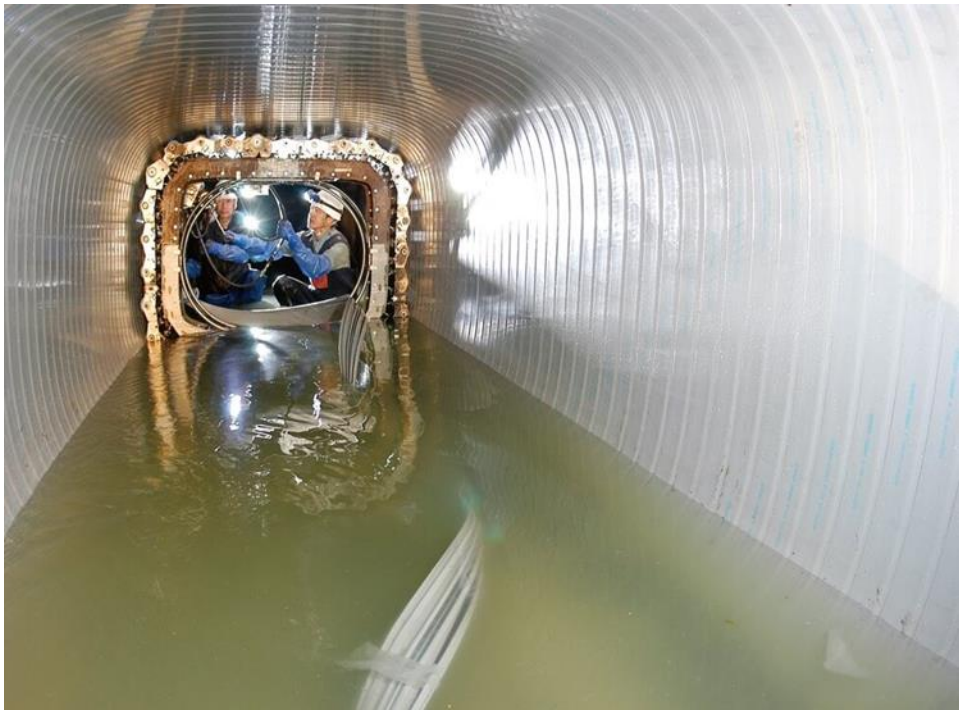

Figure 2-13: Installation of spiral wound liner in rectangular sewer – Courtesy Trenchlesspedia

Spray on Lining

The final rehabilitation technique discussed here will be Spray on Lining. There are several different suitable materials available for spray-on applications the most common and longest used technique, with 80 years of installation history, is cement mortar lining. Initially, this technology could only be applied by hand in large tunnels. Technological advances have led to robotic installation technologies and spin casting for pipes as small as four inches. Just as installation methods have improved, some new lining materials have been developed. Epoxy resins and polyurethane have been around for nearly 30 years while polyurea has been available for approximately 15 years (Potvin 2018).

While these methods can be structural, they are more commonly not structural or applied in semi structural applications in smaller pipes. This is because the resultant increase in thickness that would be required to reach a structural classification would reduce the capacity of the pipes to greatly. Each material does deserve to be reviewed independently.

Cement Mortar Lining

The most common application of cement mortar lining is a thin corrosion barrier in small pipes. The high alkaline nature of these liners makes them highly successful at mitigating sulfate attack of the host pipe. In larger applications structural capabilities are possible. In these cases, reinforcement materials such as polymers, steel fibers and reinforcing fabric can be applied by technicians (Potvin 2018).

A similar technology was introduced by Milliken Infrastructure Solutions, LLC. Their product known as GeoSpray utilizes geopolymer technology and offers increased benefits over current cement liners. The benefits include usage of over 60% post-industrial waste, reduced water usage, and 80-90% less CO2 emissions (Royer and Henning 2015). In Figure 14 a pipeline with GeoSpray is inspected.

Figure 2-14: Geospray geopolymer liner post installation – Courtesy ClockSpring NRI

Epoxy Lining

Epoxy liners are usually not structural but are the most forgiving of the polymer lining technologies because they can be applied during slightly damp conditions. Semi-structural thicker applications are possible but high cost and long curing times usually prevent this application. This application can be seen in Figure 15.

Figure 2-15: Epoxy pipe lining – Courtesy Trenchless Pipe Lining

Polyurethane Lining

Polyurethane coatings offer a quicker cure time than epoxy but require a perfectly clean and dry surface to achieve adhesion. Polyurethane is not typically applied in high build semi structural applications however it is possible to do so.

Polyurea Lining

Polyurea liners have the fastest curing times of any spray on liners. A cure of 80% is achievable in approximately five minutes. Because of this quick cure time, high build structural applications are possible. Figure 16 demonstrates what a typical polyurea application process may look like.

Figure 2-16: Centrifugal spray applying polyurea – Courtesy Trenchless Technology Magazine

Conclusion

Bangladesh is a developing nation with steady growth in the GDP. The traditional open cut method can easily disrupt such economic development in a densely populated area by causing more time spent on the street for daily business, thus raising the business's cost and impacting the socio-economic life. This section contains a summary of different repair and rehabilitation technologies, which has the potential for use in Bangladesh and help the economy run better.

Repair Technologies

Each of the repair solutions presented here have a particular instance where they excel. There is no one size fits all solution when it comes to infrastructure repair. In each case the full picture of the situation needs to be examined before planning and decision making. All aspects should be reviewed such as size of the pipeline, effluent or media, type of damage or failure, location, or access to the failure, expected life of the repair, and available budget. Table 2-1. summarizes some of the attributes of each of these technologies. Maximum pressure will vary for materials in the same category.

Table 2-1: Summary of different repair methods

Technology	Diameter (in)	Max. Pressure (psi)	Length of Repair (ft)	Host Pipe Cleaning Require	Structural Class	Relative Service Life	Relative Cost
CIPP (when used as a spot repair)	4 to 48 and above	Up to 250	3 – 8	H	FS	M	M
Mechanical Repair Sleeve	Up to 108	Up to 150	Up to 4	M	FS	M	M
Internal Joint Seals	Up to 216	Up to 300	Up to 3	M	NS	M	L
Fiber Reinforced Polymers	24 and up	Up to 500	As required	H	FS	M	H
Chemical Grouting	6 and up	Not for pressure application	As required	M	NS	M	L
FS: Fully Structural, **NS:** Non-structural, **H:** High, **M:** Medium, **L:** Low, **Ln:** Long							

Rehabilitation Technologies

Each of the rehabilitation methods mentioned here have intended applications where they excel. There are no one size fits all solutions when it comes to infrastructure rehabilitation but there are many options and combinations of techniques that when utilized correctly can lead to a very successful project. In each case the full picture of the situation needs to be examined before planning and decision making. All aspects should be reviewed such as size of the pipeline, effluent or media, type of damage or failure, location, or access to the failure, expected life of the repair, and available budget. Table 2-2. summarizes some of the attributes of each of these technologies, where the maximum pressure will vary for materials in the same category.

Table 2-2: Summary of different rehabilitation methods

Technology	Diameter (in)	Max. Pressure (psi)	Length of Repair (ft)	Host Pipe Cleaning Require	AWWA Structural Class	Relative Service Life	Relative Cost
CIPP	4 to 48 and above	Up to 250	1500 or more possible	H	IV	M	M
Sliplining	6 and up	Up to 300	Up to 1000	M	IV	Ln	M
Panel Liners	Man entry	N/A	Access to access	M	IV	Ln	H
Close Fitting Liners	3 to 60	Up to 500	Up to 5000	H	II/III/IV	Ln	M
Pipe Bursting	Up to 54	Up to 300	Up to 1000	L	IV	Ln	L
Spiral Wound Liners	6 to 200	N/A	Up to 1000	H	IV	Ln	H
Spray on Liners	4 to 48	Up to 200	Only limited by equipment	H	II/III	M	L

FS: Fully Structural, **NS:** Non-structural, **H:** High, **M:** Medium, **L:** Low, **Ln:** Long

2.2 General Industry Gap

There are many forms of both repair and rehabilitation methods available to the industry. CIPP proves to be very versatile filling gaps in both the repair and rehab categories. CIPP proves to be very versatile, capable of both pressure and non-pressure applications. However, the levels of certification for products to be used can very in each application. With the highest levels of certification being required for potable water pressure liners. The specific requirements of this technology is discussed in the following work.

2.3 Conducting the ASTM D2992 – Challenges and Concerns†

2.3.1 Abstract

Deployment of newly manufactured materials first requires extensive evaluation through rigorous testing. One of these newer materials is a lightweight fiberglass reinforced CIPP that includes both glass-fiber-reinforced thermosetting-resin pipe (RTRP) and glass-fiber-reinforced polymer-mortar pipe (RPMP). One such testing standard suitable for obtaining the hydrostatic or pressure design basis of these materials is ASTM D2992. The standard evaluates the strength-regression data derived from the liners, fittings or both subjected to two test procedures, A (cyclic) and B (static) through Hydrostatic Design Basis (HDB) or Pressure Design Basis (PDB). The constraints and limitations of the test include the dimension ratio for HDB determination, complex stress scenarios possibly inhibiting PDB calculation, and types of either restrained or free end closures. For this material, Procedure B (static) was used, and performing the test following the standard proved to be more complex than anticipated, as the standard was found non-specific at several different steps and during data analysis. At several points in the ASTM, scopes of the steps are left for the tester to interpret and determine the intention of the standard. This can result in inconsistent outcomes depending on the perspective of the tester and potentially lead to reporting an unrealistic performance on the product. This paper contains a detailed description of the HDB testing approach that was used and includes recommendations for how the standard could be improved. The authors hope the knowledge gained from this

† Section 2.3 of this chapter has been published previously as part of *Proceedings of the North American Society for Trenchless Technology's 2019 No-Dig Show*, Under the designation TA-TE-01. Kraft J., et al., *Creep Evaluation of GFRP Pressurized Pipe Materials.* 2019: p.1-10.. (2019), The current version has been formatted for this dissertation.

project will help improve this test and standard in the future and thus help the trenchless industry.

2.3.2 Introduction

Testing new innovative materials using available standards can be difficult. Conducting testing of specimens made of those materials against a standard that is less than familiar can add another level of difficulty. However, this is the exact scenario with which the research team at the TTC met. When contracted to perform testing of a liner material the staff performed its due diligence in preparing a proposal of work to be completed. Due to there being little to no existing published data on the ASTM D2992 several assumptions were made in the planning and scheduling process. Once the plans are made and proposals got accepted the testing must take place and continue until completion regardless of the outcomes and setbacks.

In the D2992 standard minimum requirements are set for the data. One of the minimums is that a certain number of test specimens must fail within particular hour ranges. See Table 1 below for failure distribution requirements.

Table 2-3: Desired test failure points according to ASTM D2992 standard.

Hours to Failure	Failure Points
10 to 1000	At least 4
1000 to 6000	At least 3
After 6000	At least 3
After 10000	At least 1
Total	At least 18

This requirement proved to be an issue for the team during the testing. The standard does not provide any guidance on how to select the test pressures to use. The trick is selecting pressures high enough to cause an early failure but some pressures low enough to last for the full ten thousand hours and the Table 2 shown below contains the collected failure points.

Table 2-4: Failure distribution from the actual test performed.

Hours to Failure	Failure Points
10 to 1000	3 Samples
1000 to 6000	0 Samples
After 6000	0 Samples
After 10000	9 Samples
Total	12 Samples

It was agreed upon in the original contract documents that 18 samples would be tested. Due to material quality issues in the samples only 15 samples could be pressurized and tested. Due to the cost of manufacturing test samples and the time involved no more samples were made to replace the initially discarded samples. Once the testing had begun there was also equipment issues with some of the pressure transducers not reading and effectively making the strain data of three more samples useless. How to make the most out of the data that we were able to collect using the twelve samples and what to do differently to avoid this issue in the future is the goal of this paper.

2.3.3 Sample Preparation

Fiberglass reinforced CIPP liner specimens each 48 in long were prepared. Steel rings each 6 in deep were cut from a 12 in ductile iron pipe (DIP) and the inner grout layer from the DIP were removed using a chisel. Next, one end of the specimen was positioned inside the ring and the annular space between the inner surface of the ring and the outer surface of the liner was filled with epoxy resin and was cured for minimum 4(four) hours. Following the similar procedure another DIP ring was attached to the other end of the liner (see Figure 2-17). This mechanism ceased the radial expansion of the liner at both ends while assisted with the sealing of the samples.

Figure 2-17: Pouring resin in annular space (top left), prepared specimen (top right), and close up of resin after curing (bottom)

Next, the MJ caps, one on each end were attached to the DIP pipes using 8 – 5/8 in diameter high strength Grade 8 threaded rod. As the rods were tightened in an inward direction, the rubber seal inside the MJ caps were pressing against the DIP's outer surface wall creating the seal. Inlet and outlet tap connections were made on each MJ cap to let the water in and bleed out the inside air. Later, pressure gauges and pressure transducer were attached to the outlet connection. Axial movement of the caps was restricted by two structurally strengthened I-beams positioned on both ends and secured firmly using 4 - 1in diameter high strength threaded rods. Preparation for the test is shown in Figure 2-18.

Next, the specimens were filled with water and pressure was applied using the TTC's Elevated Pressure Application Device (EPAD). In the EPAD, the elevated pressure is generated using a system equipped with a pressure-washer that apply the internal pressure on the liner (see Figure 2-19).

Figure 2-18: Specimen w/MJ caps before attaching threaded rod (left) and liner positioned inside I-beam reinforcement for short term burst (right)

Figure 2-19: Test setup producing ASTM D2992 data (left) and EPAD Equipped with pressure washer (right)

2.4 Methods

2.4.1 <u>ASTM D2992 Analysis procedure</u>

The standard list two methods of testing that could be used to obtain a hydrostatic design basis (HDB). There is a cyclic method and a static method. Our design team ultimately chose to go with the static method for simplicity. This method is not however perfect. The standard does not explicitly state how to select the points at which to test the pipes, how to maintain these pressures, or how to repressurize the pipes if pressure is lost but the pipes have not yet completely failed. We would discover the roles that each of these issues would play.

Testing proceeded for the prescribed 10,000 hours and all test had passed the ten-thousand-hour mark by October of 2018. Preliminary analysis performed throughout testing confirmed known facts about the material being tested such as the Poisons Ratio and the Elastic Modulus. The first calculation needed for analysis of samples is the hoop stress in each sample. Eq. 2-1 can be used to calculate this value.

$$S = \frac{P(D - t_r)}{2t_r} \qquad \textbf{Eq. 2-1}$$

where:

S = hoop stress, psi

D = average reinforced outside diameter, in

P = internal pressure, psig

t_r = minimum reinforced wall thickness, in

The standard specifies that the researchers use a linear functional relationship analysis to find the required data. The required data in accordance with ASTM D2992 are:

- Slope of the line, b
- Y axis intercept, a
- The coefficient of correlation, r
- Prediction mean
- Prediction interval and lower 95% prediction interval.

To calculate these points for our data, the failure points of our samples are plotted. The X-axis is the $log_{10}t$, and the Y-axis as $log_{10}V$. The X-axis is the time at which the sample failed. The Y-axis in our case is the strain at the time of failure of the sample.

Other necessary symbols and steps that are needed to complete the analysis will be provided at this time.

n = number of data points

y_i = log_{10} of V_i, where V_i is the strain at failure of sample i; i = 1 to n,

x_i = log_{10} of t_i, where t_i is the time to failure of sample i; i = 1 to n,

$\bar{y}$ = arithmetic mean of all y_i values.

$\bar{x}$ = arithmetic mean of all y_i values.

$$\bar{y} = \frac{1}{n}\sum y_i \qquad \text{Eq. 2-2}$$

$$\bar{x} = \frac{1}{n}\sum x_i \qquad \text{Eq. 2-3}$$

At this time the sum-of-squares and cross products can be calculated.

$$S_{xy} = \frac{1}{n}\sum (x_i - \bar{x})(y_i - \bar{y}) \qquad \text{Eq. 2-4}$$

Once the S_{xy} has been calculated it must be found that it is greater than zero otherwise this analysis would not be appropriate. If this check passes, then proceed by calculating S_{xx} and S_{yy} as shown in Eq. 2-5 and 2-6.

$$S_{xx} = \frac{1}{n}\sum (x_i - \bar{x})^2 \qquad \text{Eq. 2-5}$$

$$S_{yy} = \frac{1}{n}\sum (y_i - \bar{y})^2 \qquad \text{Eq. 2-6}$$

With sums-of-squares and cross-products calculated and checked the coefficient of correlation or r value can be calculated and checked. But, first the r^2 value is calculated and then the r value is the result of taking the root of that value.

$$r^2 = \frac{(S_{xy})^2}{(S_{xx} \times S_{yy})} \qquad \text{Eq. 2-7}$$

$$r = \sqrt{r^2} \qquad \text{Eq. 2-8}$$

The r value can be checked against the minimum allowable value specified in Table A1.1 from ASTM D2992. If the value of r is less than specified in the table this method of analysis is considered inappropriate.

Table 2-5: Minimum value for the coefficient of Correlation, *r*, for acceptable records from *n* pairs of data.

(n-2)	r minimum	(n-2)	r minimum
11	0.6835	25	0.4869
12	0.6614	30	0.4487
13	0.6411	35	0.4182
14	0.6226	40	0.3932
15	0.6055	45	0.3721
16	0.5897	50	0.3541
17	0.5751	60	0.3248
18	0.5614	70	0.3017
19	0.5487	80	0.2830
20	0.5386	90	0.2673
21	0.5252	100	0.2540
22	0.5145	…	…
23	0.5043	…	…
24	0.4952	…	…

The values for a and b for the relationship line of our data can be calculated easily at this point. First λ can be found using the cross-products. With λ, b can be found, once b is known it can be used for finding the a.

$$\lambda = \frac{S_{yy}}{S_{xx}}$$ Eq. 2-9

$$b = \sqrt{\lambda}$$ Eq. 2-10

$$a = \bar{y} - b\bar{x}$$ Eq. 2-11

Once a and b have been solved for the remaining variance values can be calculated and found in accordance with the standard. At this point for i = 1 to n, the following variances can be determined. The best fit for true x(ξ_i), the best fit for true y(Y_i), and the error variance for x(σ_{δ}^2) using the following equations.

$$\xi_i = \frac{\lambda x_i + (y_i - a)b}{2\lambda}$$ Eq. 2-12

$$Y_i = a + b\xi_i$$ Eq. 2-13

$$\sigma_6^2 = \frac{\sum(y_i - Y_i)^2 + \lambda\sum(x_i - \xi_i)^2}{\lambda(n-2)}$$ Eq. 2-14

Furthermore, the variance *C*, of *b* can be calculated by finding the following values.

$$\tau = \frac{b\sigma_6^2}{2S_{xy}}$$ Eq. 2-15

$$D = \frac{2\lambda b\sigma_6^2}{nS_{xy}}$$ Eq. 2-16

$$B = -D\bar{x}(1+\tau)$$ Eq. 2-17

$$C = D(1+\tau)$$ Eq. 2-18

The variance of a (*A*):

$$A = D\{\bar{x}^2(1+\tau) + \frac{S_{xy}}{b}$$ Eq. 2-19

The variance of the fitted line(σ_n^2) at x_L:

$$\sigma_n^2 = A + 2Bx_L + Cx_L^2$$ Eq. 2-20

The error variance (σ_ϵ^2) of *y*:

$$\sigma_\epsilon^2 = \lambda\sigma_6^2$$ Eq. 2-21

The total variance (σ_y^2) for future values:

$$\sigma_y^2 = \sigma_n^2 + \sigma_\epsilon^2$$ Eq. 2-22

Calculate the standard deviation (σ^2) of predicted values:

$$\sigma_y = (\sigma_n^2 + \sigma_\epsilon^2)^2$$ Eq. 2-23

Calculating the prediction values(y_L) for *y* at x_L using the following relationship. Where, *a* and *b* were calculated previously:

$$y_L = a + bx_L$$ Eq. 2-24

At this time in the calculations the lower 95% confidence interval ($y_{L0.95}$) can be calculated using the following equation:

$$y_{L0.95} = y_L - t_v \sigma_y$$ Eq. 2-25

The corresponding lower 95% prediction interval for V can be found using:

$$V_{L0.95} = 10^{Y_{L0.95}}$$ Eq. 2-26

The Prediction mean value of V at time t_L is given (V_L):

$$V_L = 10^{Y_L}$$ Eq. 2-27

The final value needed, the confidence interval, can be found by setting $\sigma_y^2 = \sigma_n^2$ in Eq. 2-22. The results generated by the above data analysis method specified in the standard are shown below in Figure 2-20 that shows the Test Sample Failure Point Data (Our Data), Mean data, Lower Confidence Interval and Lower Prediction Interval.

In accordance with the standard, the Mean, the Lower Confidence Interval (LCI), and the Lower Prediction Interval (LPI) were developed. Next, the strain data was evaluated using a linear regression suggested in the standard. Strain data in the Hoop and Longitudinal direction were both analyzed. Due to the pipe samples being restrained in the longitudinal direction little information was drawn from this data and not included in this paper. Let it be noted however, that the initial resistance readings in the longitudinal direction were higher than the final indicating shrinking of the samples, which also means expansion in the radial direction.

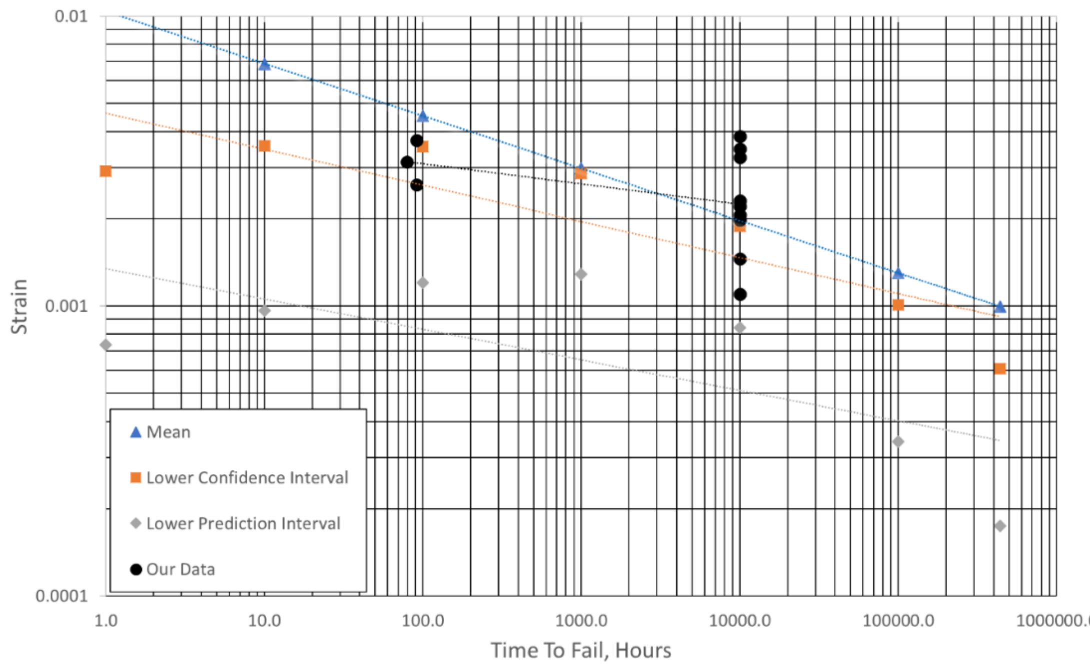

Figure 2-20: Strain base data analysis in accordance with the ASTM D2992

The proposed pressure range was found not adequate to cause failure and meet the failure criteria, and distribution of failure points as suggested in the standard. Due to this issue, the percent retention using the ASTM D2992 results has the potential to produce a misleading fifty years of retention result. At this time, it became clear that the requirements for the ASTM D2992 standard had not been met with our test data. The testing team began considering multiple options for what the logical next step would be. It was decided while the data was not suitable for the D2992 test it could still possibly be used.

2.4.2 <u>ASTM D2990 Analysis Procedure</u>

This unique situation directed the analysis methods towards the ASTM D2990, which suggests tensile, flexure, or compression creep testing of the samples and does not directly correlate with the analysis found in ASTM D2992. In accordance with the D2990 standard we converted strain values into creep modulus values. The values collected by the data logger is resistance values in ohms. These resistance values can be converted to hoop strain by using the Eq. 2-28. The Elastic hoop strain, $\mathcal{E}_{E.H.}$, in each sample can be calculated using Eq. 2-29. The only remaining equation is that for Creep modulus (E_{creep}) and the Eq. 2-30 depicts this calculation.

$$\varepsilon = \frac{\Omega_i - \Omega_0}{\Omega_0 \times G.F.} \qquad \text{Eq. 2-28}$$

where:

$\mathcal{E}$ = Hoop strain

Ω_i = Any value of resistance after the initial value

Ω_0 = The initial value of resistance

$G.F.$ = The gauge factor used to convert the engineering strain values to true strain

$$\varepsilon_{E.H.} = \frac{\sigma_{hoop}}{E_{hoop}} \qquad \text{Eq. 2-29}$$

where:

σ_{hoop} = hoop stress

E_{hoop} = hoop modulus

$$E_{creep} = \frac{\sigma_{hoop}}{\varepsilon + \varepsilon_{E.H.}} \qquad \text{Eq. 2-30}$$

Therefore, the material's percent retention was determined by combining the aspects of both standards ASTM D2992 and ASTM D2990. Percentage of retention creep modulus for hoop stress at 50 yrs (438,000 hrs) was calculated using the power equations obtained from the trend line drawn in Figure 2-20. Equations 2-31 and 2-32 below are used to predict percent retention. Here, x = 438,000 hrs while A and B are constants. The E50 value in this equation is the predicted creep modulus at 50 years. By taking the predicted modulus value and dividing it by the initial modulus the percent retention of the sample is calculated. The hoop stress creep retention factor was found around 52%.

$$E_{50} = Ax^B \quad \text{Eq. 2-31}$$

$$P_r = \frac{E_{50}}{E_i} \quad \text{Eq. 2-32}$$

where:

P_r = Sample percent retention

E_{50} = Predicted value for modulus at 50 years

E_i = Value of the initial modulus

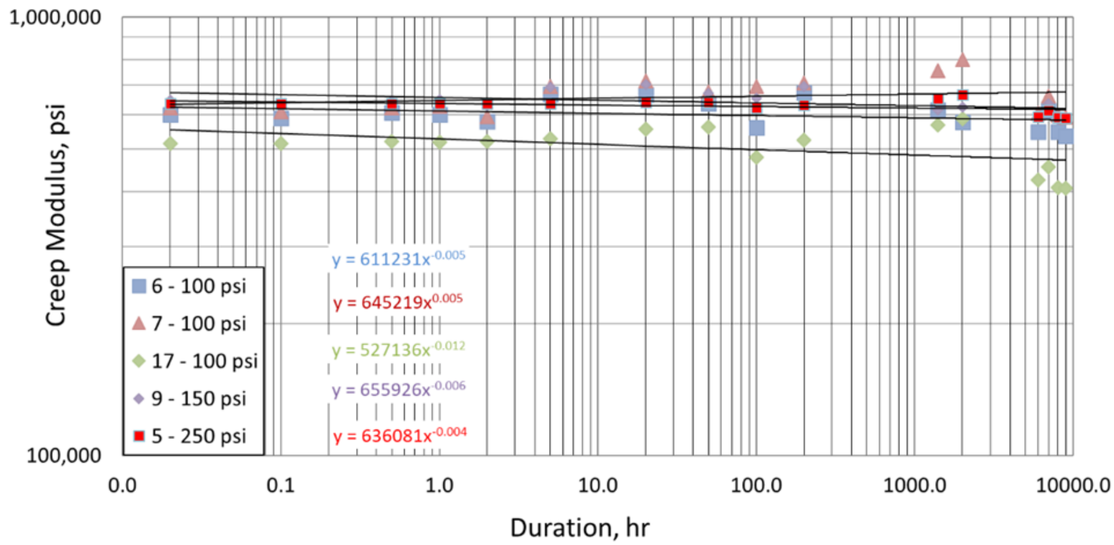

Figure 2-21: Analysis of strain data following ASTM D2990 in the hoop direction.

2.5 Results

The status and measurements of the samples tested are presented below in Table 4. In the status section of the table there are multiple abbreviations that the reader needs to be aware of. The Done abbreviations distinguish that the sample was tested to the 10,000 hours' point. The UTT (Unable to Test) designation means that this sample had quality issues and could not hold water before testing was initiated. The designation of Malfunction is in reference to an equipment malfunction that took place after testing was initiated and does not refer to material quality. Failure and an hour value means just that, the sample failed at that point in time.

Table 2-6: Specimen parameters and final condition.

Test Pressure, psi	Sample ID	Minimum Thickness, in	Average OD, in	Hoop stress, psi	Status
100	6	0.36	11.87	1599	Done
100	7	0.38	11.81	1504	Done
100	17	0.44	11.93	1306	Done
150	9	0.36	11.95	2415	Done
150	12	0.35	11.75	2443	Malfunction
150	13	0.38	11.76	2246	Malfunction
200	1	0.45	11.87	2538	Done
200	2	0.42	11.75	2698	Done
200	16	0.35	11.81	3274	Done
250	3	0.39	11.81	3660	Fail, 91 hours
250	4	0.38	11.75	3740	Done
250	5	0.34	11.9	4250	Done
350	8	0.42	11.92	4792	Fail, 91 hours
350	14	0.37	11.86	5434	Fail, 79.4 hours
350	15	0.41	11.81	4866	Malfunction
NA	10	0.35	11.93	NA	UTT
NA	11	0.33	11.81	NA	UTT
NA	18	0.35	11.83	NA	UTT

Table 2-7: Poisons Ration calculations performed during testing that proved to be close to other data.

Pressure, psi	Longitudinal Stress, psi	Hoop stress, psi	Strain		Poisson's Ratio N
			Longitudinal Direction, L_ε	Hoop Direction, H_ε	$\frac{L_\varepsilon}{H_\varepsilon}$
100	722	1599	1E-04	0.0010	0.10
100	722	1504	2E-04	0.0008	0.27
100	722	1306	5E-04	0.0012	0.44
150	1083	2415	4E-04	0.0012	0.29
200	1444	2538	6E-04	0.0014	0.45
200	1444	2698	6E-04	0.0016	0.39
200	1444	3274	1E-03	0.0022	0.55
250	1804	3660	1E-03	0.0028	0.49
250	1804	3740	1E-03	0.0026	0.43
250	1804	4250	8E-04	0.0028	0.28
350	2526	5434	1E-03	0.0031	0.42
350	2526	4792	1E-03	0.0037	0.35
				average	0.37

The Poisson's ratio calculations presented above were performed for the first time during the D2992 testing and are based on the average diameter and thickness of the sample. The value calculated was close to that determined by other means and sources. This test gave a good indication that good test data was being acquired.

Table 2-8: Values of Percent Retention determined by the equation generated by sample data.

Sample ID	A	B	E_0	Hours in 50 Years	E_{50}	Percent Retention, E50/E0 x 100
6	611,231	-0.005	1,092,000	438,000	572,793	52
7	645,219	0.005			688,517	63
17	527,136	-0.012			451,050	41
9	655,926	-0.006			606,745	56
5	636,081	-0.004			603,874	55
1	576,163	-0.006			532,962	49
2	580,906	-0.019			453,856	42
16	617,870	0.003			638,265	58
4	606,821	-0.006			561,322	51
					Average	51.99

This value does not reflect the impacts (either beneficial or detrimental) of corrosion, hazardous fluid flow, pressure surges, physically damaged liners, quality of installation, and age-related stiffness changes.

2.6 Discussion and Conclusion

We believe that we have discovered a solution for our issue. Others who might also have ran into the same issue and could not use their data may be able to salvage the data by following the method described here. In order to avoid the issue in the future it is clear that higher pressures must be chosen. The pressures chosen for this testing were too low to cause failure in a realistic amount of time. The ASTM D2992 does not provide any guidance in the selection of these pressures, but that is understandable considering the large variation in materials presumably being tested with the standard. Further testing and comparison between like materials that are tested using both ASTM D2992 and D2990 will be needed to determine the overall validity of our test data.

2.7 Acknowledgement

The authors acknowledge kind support of the various research team members – Ben Curry, Chris Bartlett, Chris Morgan, Dr. Erez Allouche, Lane Elien, Sarkar Sayem, and Tylor Baus for their support over the duration of the project. The authors also acknowledge the patience and financial support of the client, without which the project goals could not have been met.

2.8 Further Identification of Research Gap

These difficulties seen by Trenchless Technology Center team members while performing The ASTM D2992 test indicates that further work is needed to develop a more user friendly and repeatable test method. Other researchers who may have had similar issues are also working on alternative and modified methods for performing D2292 testing and analysis(Nassar and Yousef, 2002, Granderson 2016, 2017, and Krishnan 2018). The work performed by the TTC in order to use the data that was available at the completion of this HDB test has formed the basis for this continuation of work.

CHAPTER 3

EXPERIMENTAL SETUP

3.1 Background

This chapter will discuss the preexisting experimental setups and the changes that will be implemented for the new analysis method.

3.2 Method

The experimental setups required by the ASTM D2992 standard have proven to be a major driver for this research. The traditional standard requires the samples to be four times their diameter in length. In the case in question the sample diameters were approximately 11 inches which required specimen lengths to be 4 feet.

The standard proposes two methods for determining hydrostatic strength and hydrostatic design basis (HDB). The procedures are procedure A and B with A being a cyclic loading and B a static loading. Both methods use the same failure criteria and differ primarily on how the failures are initiated. Each method would also require similar amounts of space with procedure A also requiring additional systems to generate the up to 15 million pressure cycles to failure. The less complicated nature of procedure B led to its selection for the study performed by the Trenchless Technology Center (TTC). Some other researchers have found recent success by following this methodology (Dai et al.,2022, Mahdavi et al., 2019, Chen et al., 2018, and Napiah et al., 2017). Far fewer yet have been able to perform procedure A successfully (Tarakcioglu et al., 2005; Kara and Kirici, 2017; and Sepetcioglu et al., 2022).

The area required by Procedure B can be seen in Figure 3-1 below. Because of the sensitive nature of these tests, they must be stored in temperature-controlled environments and spaces like these are limited. Performing the same test at this time would not be possible due to the lack of any suitable location being available. The alternative testing frames based on the tensile method of ASTM D2990 reduces the space required by the samples by more than half. The space required by samples following a method such as ASTM D2990 can be seen in Figure 3-2. In the most recent iterations of the setups used for this testing strain data is collected directly from the samples through strain gauges. This made it possible to rule out any error due to relaxation of material in the points of contact between the sample and the apparatus. The strain gauges also helped to streamline the analysis method be removing multiple calculations and the possibility of human error by transcribing the data. The Agilent data logger system used to record the strain data and a screen capture of the user interface (Benchlink Data Logger Pro) of the software used are in Figures 3-3 and 3-4.

Figure 3-1: Static samples used for ASTM D2992 testing.

Figure 3-2: Tensile setup commonly used in ASTM D2990 testing.

Figure 3-3: Data Logger used for strain data collection.

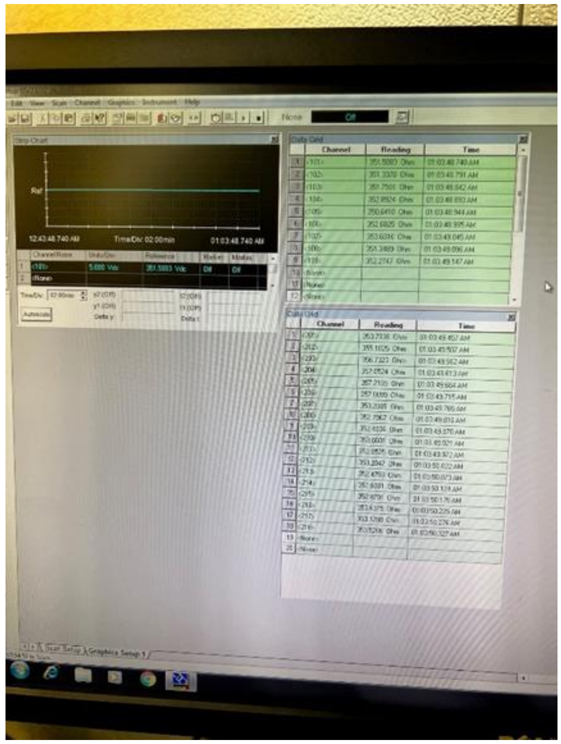

Figure 3-4: Data Logger Pro software interface.

The culmination of this alternative method would not make any further modifications to the existing equipment. This method should make use of the existing ASTM D2990 setups while only changing the interpretation of the data collected. With the setups and data acquisition methods for the new method determined, the remaining factor is to determine what would signify a failure, such as strain level, with the absence of water under pressure like in the ASTM D2992 testing.

3.3 Sample Preparation

Samples used in the new experimental setups will be the same size used in ASTM D2990 testing. To model these dimensions, one will need to look back to ASTM D638 Standard Test Method for Tensile Properties of Plastics. Samples with the approximate thickness of 0.28 inches or less need to follow Type 1 sizing (ASTM D638). Figure 3-5 and Table 3-1 depict the proper sizing.

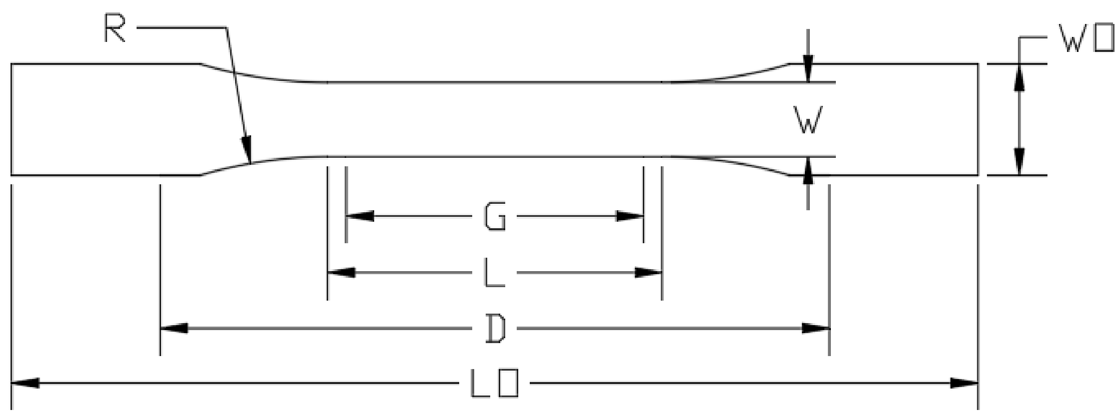

Figure 3-5: Dog Bone sample with segment designations.

Table 3-1: Dimensions specified in ASTM D638 for dog bone samples.

Dimensions (see drawing)	Type 1 (inches)
W - Width of narrow section	0.5
L - Length of narrow section	2.25
WO - Width overall	0.75
LO - Length overall	6.5
G - Gauge length	2.0
D - Distance between grips	4.5
R - Radius of fillet	3.0

After determining proper dimensions for the tested material, the sample needs to be sketched in an available CAD software. For anyone not familiar, there are thousands of examples of use online to help. Figure 4-2 depicts a 3-D sketch of a dog bone. For this purpose, a 2-D model would also work. While in the modeling software the file needs to be saved as a .dxf file. This type of file is required by the OMAX water jet that is available for sample preparation at Louisiana Tech.

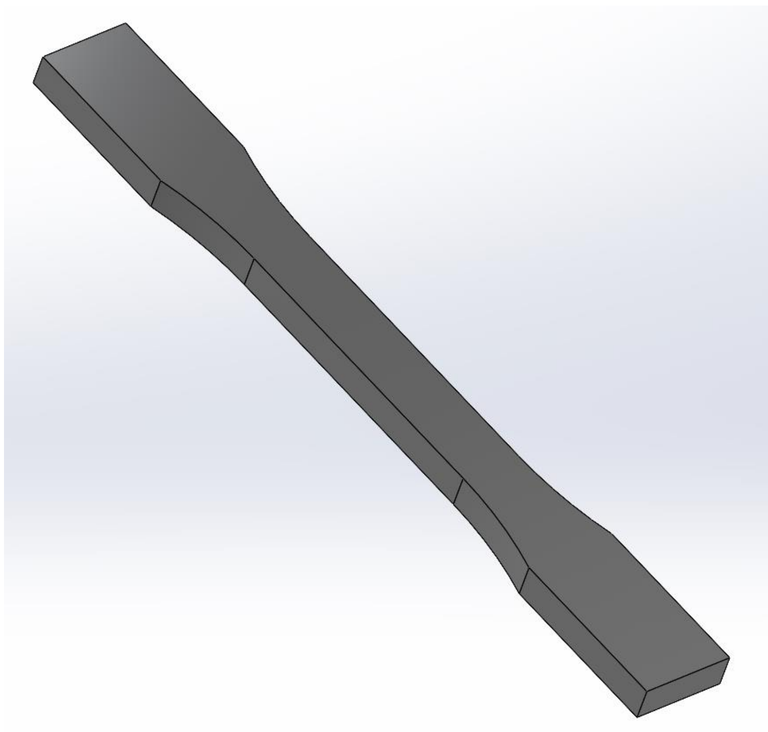

Figure 3-6: 3-D SolidWorks rendering of dog bone sample.

CHAPTER 4

STRAIN BASED HDB

4.1 Introduction

In the initial study performed at the TTC, data was used from a failed ASTM D2992 test attempt to calculate a material's long-term retention value. These results are typically found by following a separate standard, via ASTM D2990. That standard uses a different testing method and different apparatuses. However, if testing samples following the ASTM D2992 method can use the data for the ASTM D2990 analysis, why couldn't the same be done in reverse. Both standard methods use strain in their analysis methods with the difference being the ASTM D2992 needs to use failures in its analysis and the ASTM D2990 method does not use failures. To explore this idea further two steps needed to be performed:

- Determine how to model creep strain
- Determine representative load cases and calculate the associated strain values

4.2 Modeling Creep

Dassault Systems, the publisher of SolidWorks, prepared a guide for modeling creep in their software (Creep Model, 2023). The software uses the Bailey-Norton Classical Power Law for Creep based on an "Equation of State" approach. The law defines creep strain in terms of stress and time. While they intended this guide to be used in conjunction with their FEA modeling capabilities it will also serve the purpose of the analytical model herein. The law is presented in Eq. 4-1 below.

$$\varepsilon^{c} = C_{o}\sigma^{(C_1)}t^{(C_2)}e^{(\frac{-C_T}{T})} C_1 > 1\ and\ 0 < C_2 \leq 1 \qquad \text{Eq. 4-1}$$

where:

T = Element temperature (Kelvin).

C_T = A material constant defining the creep temperature-dependency.

C_0 = is the Creep Constant 1 used in calculations.

C_1 = is Creep constant 2.

C_2 = is Creep constant 3.

t = is current real time.

σ = total uniaxial stress at the time t.

This law represents primary and secondary creep regimes in one formula. The tertiary regime is not considered (Shannon 2022).

The publisher also provides an example for determining creep constants from reference data. This information has proven crucial as finding creep constant data for the PVC material provided with a known HDB value has proven difficult (Brathe and Josefson, 2013). In the example provided, the creep strain is given at a time t, when temperature change is not considered (Creep Model, 2023). In order to derive the creep constants from the reference data available, a simplified version of the equation was used. In the simplified Eq. 4-2 the consideration for temperature variation is dropped.

$$\varepsilon^c = C_o \sigma^{(C_1)} t^{(C_2)} \quad \text{Eq. 4-2}$$

It is assumed that the reference data was acquired at approximately 73 °F or 295 K. The stress and time data are presented in Table 4-1.

Table 4-1: Reference data used to calculate creep constants.

Temperature (K)	Stress (MPa) time = 10,000 hr	Stress (MPa) time = 100,000 hr
295	32	28.7

It can be assumed that $C_2 = 1$. From the initial creep state equation, you find two equations for two unknowns.

$$0.01 = C_0 \cdot 32C_1 \cdot 10{,}000 \quad \text{Eq. 4-3}$$

$$0.01 = C_0 \cdot 28.7C_1 \cdot 100{,}000 \quad \text{Eq. 4-4}$$

Rewrite the two equations and solve for C_1.

$$C_1 \cdot \log(32) = C_1 \cdot \log(28.7) + 1 \quad \text{Eq. 4-5}$$

By solving Eq. 4-5, one finds that C_1 equals 20.83. Either Eq. 4-3 or Eq. 4-4 can now be used to find C_0. By inputting the values into Eq. 4-4 we find the final creep constant creating Eq. 4-6.

$$C_0 = \frac{0.01}{28.7^{21.15} \cdot 100{,}000} = 1.224 \cdot 10^{-166} \quad \text{Eq. 4-6}$$

Once the three creep constants have been determined they can be used in conjunction with Eq. 4-2 to determine the control materials creep behavior over time.

Sensitivity analysis revealed that the C_0 value was the most sensitive. While C_1 was less sensitive but remained more sensitive than C_2.

4.3 Modeling Creep Behavior

In order to use the Bailey-Norton law for this testing purpose a creep strain limit needs to be established (Sattar et al.,2020). The stress values in this case needs to match the stress values used in the control data. The time variable in the equation can be changed to solve for the required creep strain limit. In this case, short term tensile testing on an identical material is available along with existing HDB data. It is assumed that by reviewing these data sets a reasonable strain limit may be determined. The strain values found during short term testing are presented in Table 4-2. The elastic and creep strain calculated for the HDB data sets are presented in Table 4-3.

Table 4-2: Tensile Strain seen at failure during testing.

Tensile Strain
0.021
0.021
0.020
0.020
0.020

Table 4-3: Strain data for existing HDB data.

Hoop Stress (psi)	Time to Rupture (hr)	Elastic Strain	Creep Strain	Sum
6000	42	0.0150	0.0085	0.0235
6000	91	0.0150	0.0184	0.0334
5800	119	0.0145	0.0119	0.0264
5800	72	0.0145	0.0072	0.0217
5800	153	0.0145	0.0153	0.0298
5600	142	0.0140	0.0068	0.0208
5600	231	0.0140	0.0111	0.0251
5600	402	0.0140	0.0193	0.0333
5400	248	0.0135	0.0056	0.0191
5400	1103	0.0135	0.0249	0.0384
5200	1012	0.0130	0.0104	0.0234
5000	1409	0.0125	0.0064	0.0189
5000	1998	0.0125	0.0091	0.0216
5000	3010	0.0125	0.0137	0.0262
4800	4970	0.0120	0.0096	0.0216
4800	3521	0.0120	0.0068	0.0188
4800	5009	0.0120	0.0097	0.0217
4600	14981	0.0115	0.0120	0.0235
4600	19298	0.0115	0.0154	0.0269
4600	8995	0.0115	0.0072	0.0187
			Average	0.0246

Based on the short-term data and a review of the long-term data a maximum combined strain limit will be set at 0.02 for this phase of the testing. Some of the long-term samples seemed to withstand a greater amount of strain while some handled less. By selecting this maximum point for failure, it can be assumed that with over 95% confidence that the actual failure point would exceed this strain value. Without more knowledge on the testing conditions this is the best assumption that can be made at this time.

To speed up the testing process, a Mathcad and Excel solver will be used for the computations. The full solvers are available in Appendix B and C. Hooke's law will be used to calculate the theoretical elastic strain and followed by the theoretical creep strain being calculated with the Simplified Bailey-Norton Power equation already provided. See Eq. 4-7 for elastic strain (Allen 2011).

$$\varepsilon_E = \frac{\sigma}{E} \qquad \text{Eq. 4-7}$$

where:

ε_E= Elastic strain

σ= The applied stress

E= Modulus of elasticity

For each case, the elastic strain will be calculated and subtracted from the allowable strain limit of 0.02. The time variable of the power equation is then manipulated using a goal seek function or solver function to find the amount of time required for the creep strain to reach the threshold for failure.

Once failure times have been calculated for the selected stress levels the data can be plotted and a trendline created. As per the usual data analysis for ASTM D2992 or similar the regression line and equation are used to determine what stress would cause a failure at 100,000 hours. This point is known as the long-term hydrostatic strength or LTHS. The LTHS is compared to the provided HDB pressure and classification tables and the process is completed.

CHAPTER 5

CONTROL DATA

5.1 Introduction

When considering a control material to be used for the verification of this testing hypothesis several factors were considered. The leading cause for using PVC for this test was the availability of IPEX's (a TTC Industry Advisory Board member) actual ASTM D2992 data. Considering that PVC was discovered by accident in 1926 it was also reasonable to assume that there would be ample published materials on its performance. This also proved to be a factor in the decision to move forward with this testing (Semon et. al.1981).

Several authors have pursued other methods for long-term testing of PVC products (Read et al., 1991; Castiglioni et al., 1999; Brostow et al., 2015; Brostow et al., 2022; Arbeiter et al., 2015; Chaallal et al., 2016; Hsieh et al.,2010; Carpentier et al, 2021; and Shi and Jar, 2022). While these methods were not directly applicable, reviewing this work helped eliminate methods that might not serve this purpose. Nearly as numerable as the methods that have been implemented, were tests that raise concerns for long-term performance and the need for further long-term testing of PVC and an improved method for testing plastic pipes all together (Makris, et al., 2020; Makris et al., 2022; Ariaratnam, et al., 2003; Anton-Prinet et al., 1999; Bauer, 1990; Zha et al., 2022; Zha et al., 2023; and Manu, 2022)

5.2 Introduction to IPEX Data

It is worth noting that the hydrostatic strength of viscio-elastic materials like PVC can be described using a stress regression (SR) line, but this is not the case for linear elastic materials such as metals. Before developing an SR line, there are key relationships to note. The relationships between internal pressure and hoop stress are detailed in Figure 5-1 and Eq. 5-1.

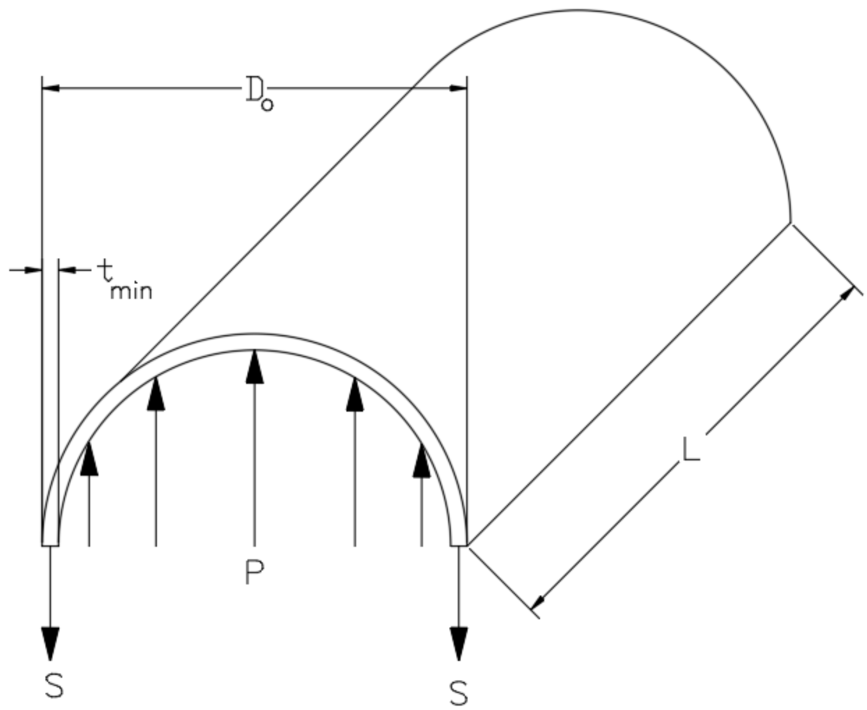

Figure 5-1: Stress regression curve for PVC pressure pipe.

$$S = \frac{P(D_o - t_{min})}{2t_{min}}$$ **Eq. 5-1**

where:

S = hoop stress, psi

T_{min} = minimum wall thickness, in

P = internal pressure, psi

D_o = pipe outside diameter, in

When working with PVC pipe for pressure applications the term dimension ratio is used (DR). The DR is a dimensionless ratio based on the outside diameter of the sample divided by the minimum wall thickness. DR is defined in Eq. 5-2.

$$DR = \frac{D_o}{T_{min}} \qquad \textbf{Eq. 5-2}$$

where:

DR = dimensional ratio, dimensionless

There are four important points to remember about the *DR* of PVC pipe (IPEX):

- Thicker pipe wall results in lower *DR* number.
- Regardless of diameter pressure capacity of particular *DR* is constant.
- Regardless of diameter structural strength of particular *DR* is the constant.
- Higher the *DR* pipe has lower pressure rating, low *DR* pipe has higher pressure rating.

5.3 IPEX Data

Assumptions can be made and calculations performed, but without checking data derived by the alternative method against true ASTM D2992 data, researchers can-not verify the data from the modified method. ASTM D2992 results data for PVC material class 12454 was provided by (IPEX). Table 5-1 includes the requirements for a material of this cell class.

Table 5-1: The minimum property values by cell class, courtesy (IPEX)

Designation Order No.	Property and Unit	Cell Limits						
		0	1	2	3	4	5	6
1	Base resin	unspecified	poly(vinyl chloride) homo-polymer	chlorinated poly (vinyl chloride)	vinyl co-polymer			
2	Impact Resistance (Izod). Min: J/m of notch ft-lb/in of notch	unspecified	<34.7 <.65	34.7 0.65	80.1 1.5	266.9 5.0	533.8 10.0	800.7 15.0
3	Tensile Strength, min: MPa psi	unspecified	<34.5 <5000	34.5 5000	41.4 6000	48.3 7000	55.2 8000	
4	Modulus of elasticity in tension, min: MPa psi	unspecified	<1930 <290000	1930 320000	2206 320000	2482 360000	2758 400000	3034 440000
5	Deflection temperature under load, min, 1.82 MPa [264 psi]: C F	unspecified	<55 <131	55 131	60 140	70 158	80 176	90 194

It was found that flat panels of PVC are not referred to by their cell class, but rather a type designation. It was determined that Type 1 PVC meets the cell class requirements of class 12454 (Material Spec Guide, 2018). For proof of concept testing, Type 1 panels should be used for dog bone sample preparation.

In the ASTM D2992 study performed by IPEX, 20 individual samples were tested at eight separate pressure ranges to induce the required failures at separate times. Table 5-2 includes the test pressures that the samples experienced while Table 5-3 includes the rupture failure distributions.

Table 5-2: Sample pressure distributions

Number of samples	Hydrostatic Pressure, psi	Hoop stress, psi
2	706	6000
3	685	5800
3	659	5600
2	635	5400
1	612	5200
3	588	5000
3	565	4800
3	541	4600

Table 5-3: Time to rupture distribution for IPEX test data

Sample number	Hoop stress, psi	Time to rupture, hr
1	6000	42
2	6000	91
3	5800	119
4	5800	72
5	5800	153
6	5600	142
7	5600	231
8	5600	402
9	5400	248
10	5400	1103
11	5200	1012
12	5000	1409
13	5000	1998
14	5000	3010
15	4800	4970
16	4800	3521
17	4800	5009
18	4600	14981
19	4600	19298
20	4600	8995

In accordance with the ASTM D2992 standard, the stress and time to failure should then be plotted to create a regression cure. However this data is not preferred for further analysis. It is appropriate to convert this plot to a log-log plot. When this change is made to the plot the data, there appears to be in a straight line and without much scatter. This data is more desirable for the next phase of the analysis. The regression curve created first and the regression line created after altering the plot can be seen in the figures 5-2 and 5-3 below.

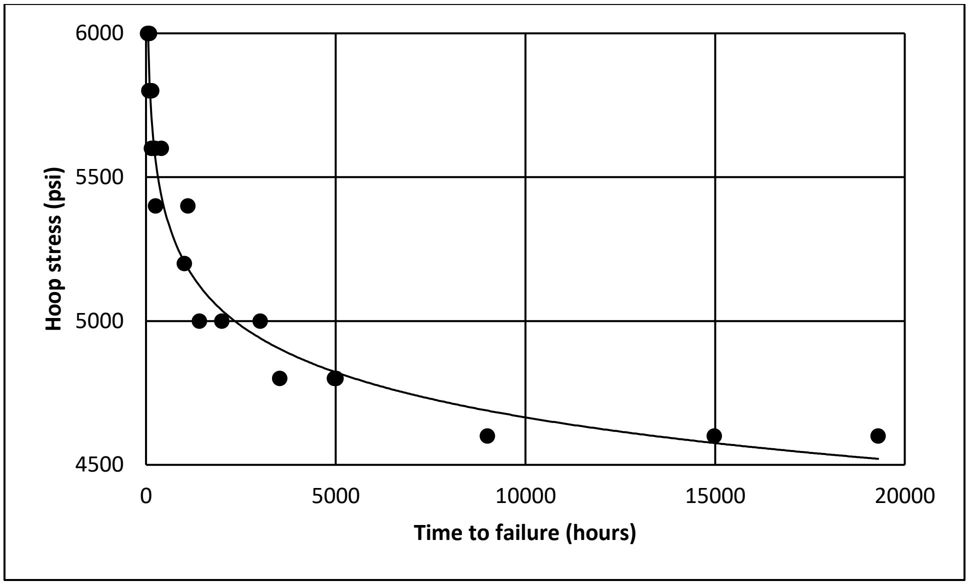

Figure 5-2: Stress regression curve for PVC pressure pipe.

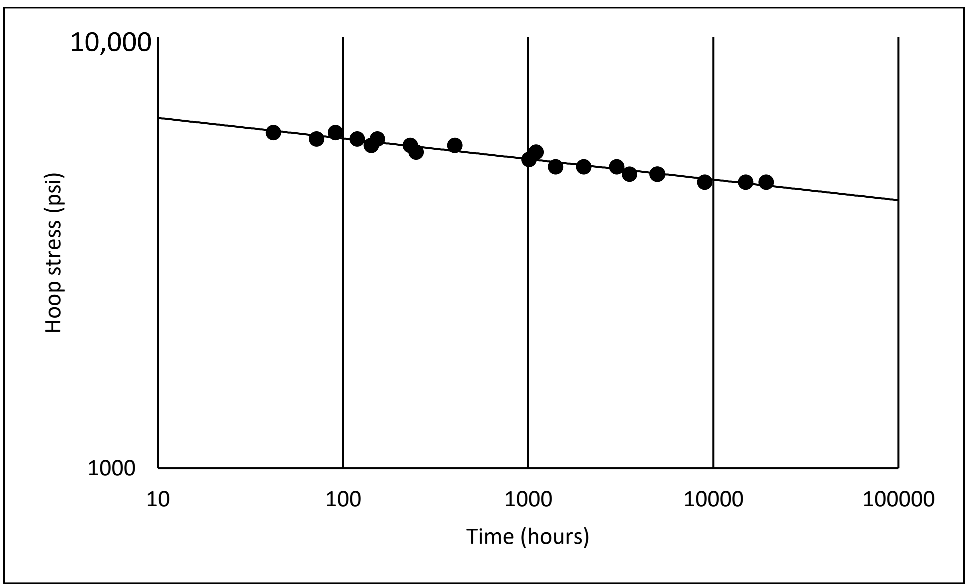

Figure 5-3: Stress regression line for PVC pressure pipe (log-log).

Once the stress regression line has been determined for the given material, the final phase of analysis can begin. The LTHS can now be found by using the regression line. Determining where the trendline of the data crosses the 100,000-hour threshold and the corresponding value on the Y-axis will determine the HDB value. Figure 5-4 includes annotations to aid in determining the classification.

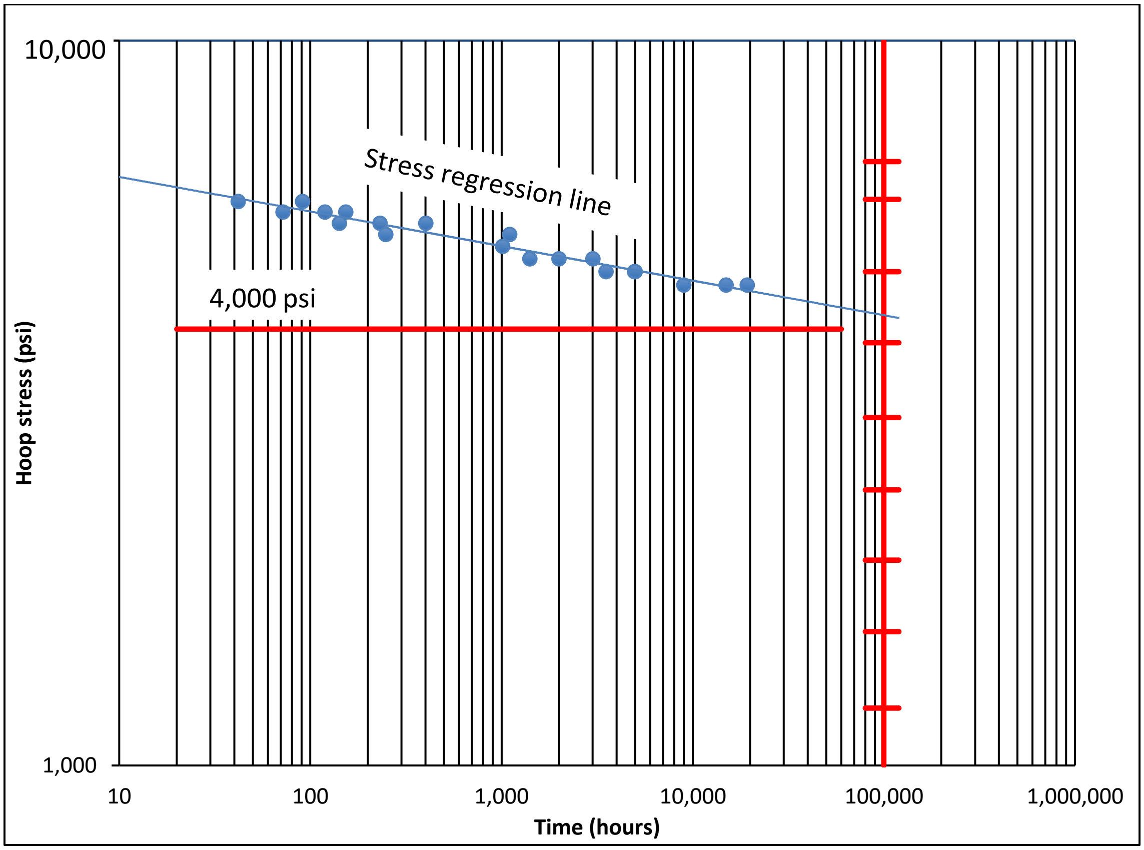

Figure 5-4: Stress regression line for PVC pressure pipe.

After reviewing the chart without calculating an exact LTHS value the value visually crosses above 3,830 psi and below 4,800 psi. Values that fall within this range meet the requirements of 4,000 psi HDB class materials. After this determination, the analysis is complete and the relevant information would be made available to designers.

CHAPTER 6

MODELLED RESULTS OF HDB

6.1 Introduction

This chapter presents the data produced by using short- and long-term data to determine failure criteria and predict sample failures. The results presented were determined theoretically based on actual sample data from a PVC manufacturer (IPEX).

6.2 Elastic and Creep Results

By using Hooke's law discussed in Chapter 4 the elastic strain was determined for each stress level. The allowable creep strain was then calculated by subtracting the elastic strain values from the determined strain limit of 0.02, previously determined in Chapter 4, found by reviewing available short- and long-term data.

Table 6-1: Elastic strain and allowable creep.

Stress (psi)	Elastic Strain	Allowable Creep
4000	0.0100	0.0100
4250	0.0106	0.0094
4500	0.0113	0.0088
4750	0.0119	0.0081
5000	0.0125	0.0075
5250	0.0131	0.0069
5500	0.0138	0.0063
5750	0.0144	0.0056
6000	0.0150	0.0050

The solvers were used at this point to manipulate the time variable until a creep strain matching these limits was reached. The results of this solver are presented in Table 6-2. The Power equation uses time in seconds so attention should be paid to properly converting this time to hours of time by dividing time in seconds by 3,600 seconds/hours.

Table 6-2: Time to creep limit.

Stress (psi)	Time (sec)	Time (hrs)
4000	841000000.0	233611.1
4250	244000000.0	67777.8
4500	63308197.0	17585.6
4750	19061806.0	5294.9
5000	6044837.0	1679.1
5250	2187820.0	607.7
5500	691821.0	192.2
5750	246666.3	68.5
6000	90354.1	25.1

A regression line can be created now where the predicted failures can be plotted against the stress values. Figure 6-1 is the plot of the regression line for the theoretical results. To determine the success of the experiment the data now needs to be compared to the supplied control data.

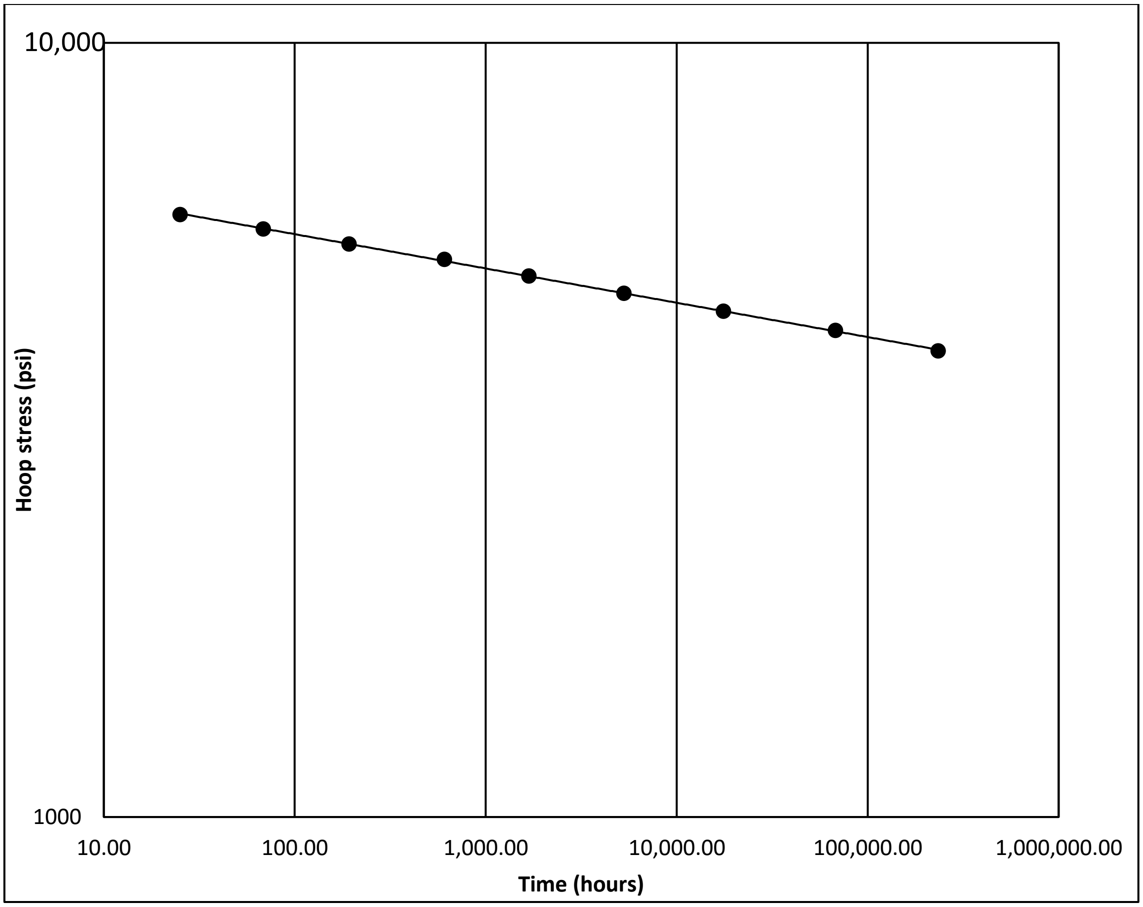

Figure 6-1: Stress regression line for theoretical data

6.3 Comparison of Theoretical and Control Data

Before directly comparing the theoretical data with the control data it can already be seen that a similar plot is created. Figure 6-2 depicts the theoretical data in black overlaid the control data in blue. In this figure, the two data sets appear to match well. To more closely compare the results, LTHS values are determined for each line and presented in Table 6-3.

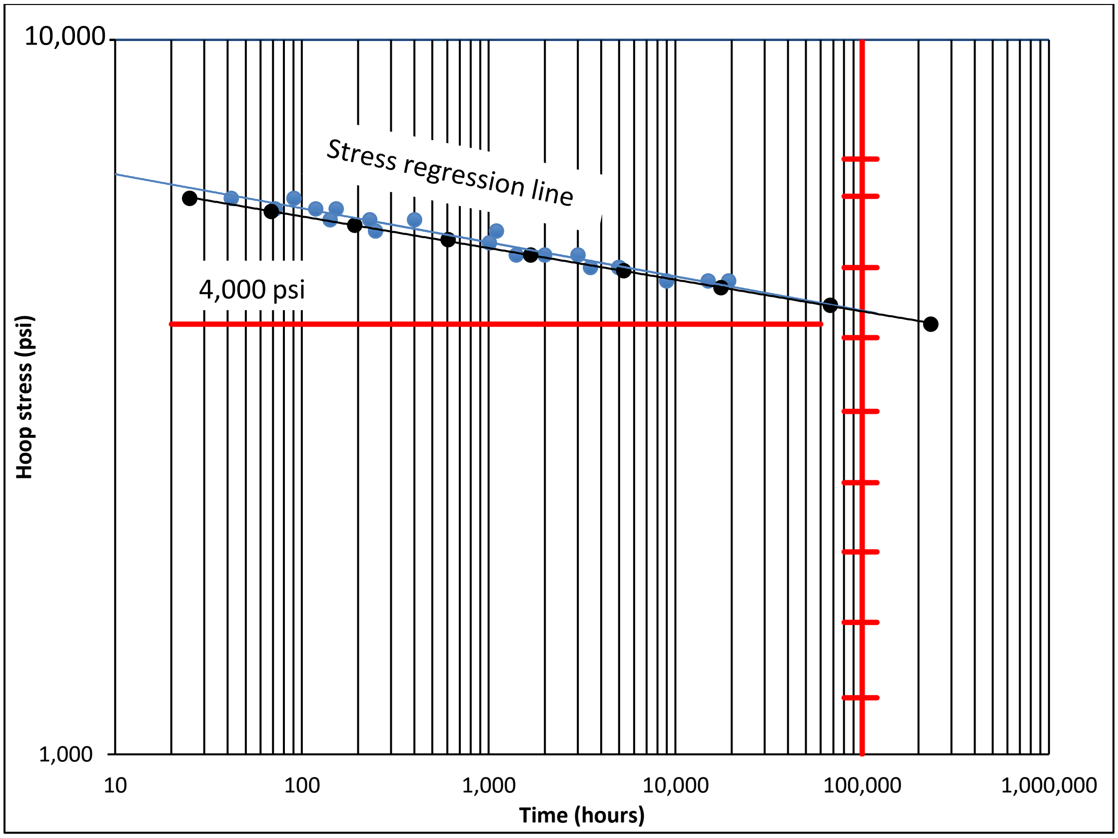

Figure 6-2: Stress regression line for theoretical data (Black) plotted with control data (Blue)

Table 6-3: LTHS and Pressure Class for Theoretical and Control Data

Sample	LTHS	Pressure Classification
Control	4,166	4,000 psi
Theoretical	4,183	4,000 psi

This data indicates just how closely the theoretical data matches the control data. Less than a 20-psi difference in the LTHS values equates to less than a 0.3 % difference.

CHAPTER 7

CONCLUSIONS AND FUTURE DIRECTION

7.1 Summary

A review of the relevant literature revealed that accurate long-term performance of pipe materials is vital. With tight budgets and growing demand engineers need to be able to rely on products and solutions they recommend and build to continue to work reliable for years and decades to come. The currently accepted method for determining the HDB for pipe liner materials is difficult and extremely costly for material manufacturers to run on their own and research centers possessing the ability to do so are limited. The ability to reduce the footprint of the test and the overall demand of the process by partially automating the process would be a game changer for the industry.

7.2 Conclusions

The following conclusions are presented from the research work of this dissertation:

1. The traditional methods detailed in ASTM D2992 and ASTM D2837 are extremely costly to perform (approximately $100,000 to $200,000 in 2023 US Dollars) and without experience in the process could result in no usable results.
2. Analyzing results from D2992 and D2837 test that did not generate failures as if they were ASTM D2990 test data could result in generating Creep retention data

for a product. While not the original intent of the test this produces valuable information.

3. Determining the LTHS and HDB of a material can be done following a strain-based approach. By analyzing the failure data of samples tested IPEX a suitable strain limit can be determined. This strain limit can then be used to determine time to failure in this case for PVC cell class 12454.
4. The failures found analytically in this case did produce values found to be very close to the actual test data provided by IPEX. These results make the method look promising for other materials.
5. The cost to run this alternative method are approximately $30,000 to $50,000 in 2023 US Dollars and the test can be completed 25% to 50% quicker that ASTM D2992 dependent on available creep constant data.

7.3 Limitations

This section presents limitations in this work:

1. One of the main limitations of this work is the lack of real-world control data. With more data sets more trials could be performed to further support the theory.
2. This method requires that some form of long-term creep data be available, or the material have known creep constant values.
3. This work was performed analytically based on simple uniaxial loading assumptions.
4. This method has only been tested on one material.
5. The method was only tested using one creep model.

7.4 Future Work

This section presents future research work that could be performed to help increase the confidence and reliability of the model:

1. Collect more real-world data from manufacturers who have successfully performed the ASTM D2992 or D2837 test on their products but not published the data publicly.
2. Perform further analysis on creep factors and implement more available creep models in addition to Bailey-Norton.
3. The ASTM D2992 and ASTM D2837 standards were not only written for strait pipe segments to be tested. Complex shapes of valve bodies and other segments were intended to be tested and certified as well. In order to do this reliably an FEA model would need to be developed for complex applications.

APPENDIX A

FLOW CHART FOR ASTM D2992 OR D2990 PROCEDURES

The following figure was created to help when following the process developed during the TTC's first ASTM D2992 test.

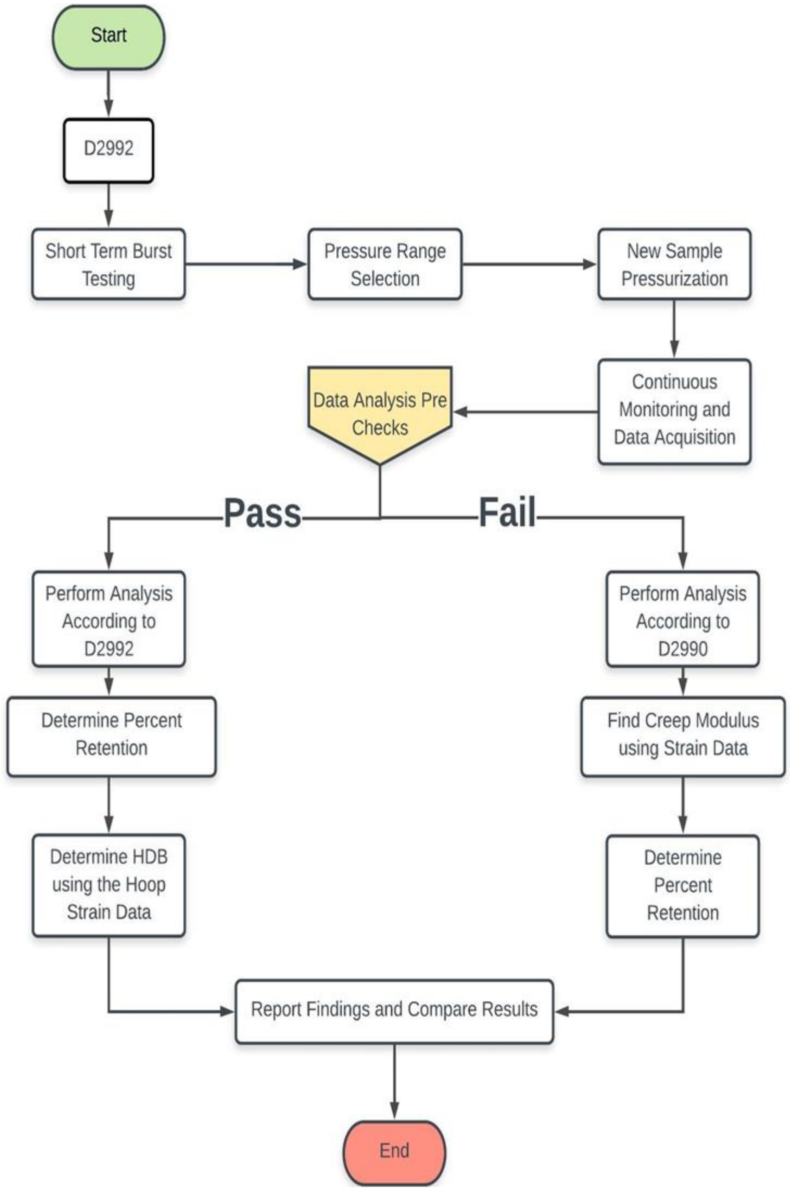

Figure A-1: Suggested flowchart providing a general guideline for conducting test.

APPENDIX B

MATHCAD SOLVER FOR ELASTIC AND CREEP STRAIN

The following Mathcad solver was useful in establishing the initial relationships and working through the trial-and-error phase of testing the hypothesis. For repetitive calculations it proved easier to implement an excel solver to solve for time.

Elastic Strain:

Given; *Find;* ε

$\sigma := 4000\ \mathbf{psi}$

$E := 400\ \mathbf{ksi}$

$$\frac{\sigma}{E} = 0.01$$

Creep Strain:

Give; *Find;* ε^c

$C_0 := 1.22 \cdot 10^{-166}$

$\sigma := 2.758 \cdot 10^7$ $4000\ \mathbf{psi} = \left(2.758 \cdot 10^7\right)\ \mathbf{Pa}$

$C_1 := 20.83$

$C_2 := 1$

$t := 841315584.23$

$$C_0 \cdot \sigma^{C_1} \cdot t^{C_2} = 0.00997$$

Figure B-1: Initial Mathcad used in first phase of testing.

APPENDIX C

EXCEL SOLVER FOR REPETETIVE CREEP CALCULATIONS

The following Excel solver was created to speed up the process after the Mathcad solver proved to be successful. Data in dark green are variables that can be changed but are set for the material being tested and should not be changed after testing on that material has been started. The light green box containing the value of stress is changed for each stress category tested. The red box is the time in seconds that is calculated using the goal seek function.

Table C-1: Excel solver used to find the time to maximum allowable creep strain.

Elastic & Creep Strain solver				
Knowns			Solve	
Stress (psi)	6,000		time to failure (sec)	
E mod (psi)	400,000		t =	90,354.13
C0	1.22E-166			
C1	20.83			
C2	1			
Failure > (strain combined)	0.02			
Elastic Strain	0.015000			
Creep Strain	0.005000			
allowable creep	0.005			

Table C-2: Excel solver results table.

Results			
Stress (psi)	Time (s)	Time (minutes)	Time (hours)
4000	841,000,000	14,016,667	233,611
4250	244,000,000	4,066,667	67,778
4500	63,308,197	1,055,137	17,586
4750	19,061,806	317,697	5,295
5000	6,044,837	100,747	1,679
5250	2,187,820	36,464	608
5500	691,821	11,530	192
5750	246,666	4,111	69
6000	90,354	1,506	25

The *t* values in seconds are added to the results tables where the values are automatically converted to time in hours. The stress column and time (hours) column are already fed to excel plot and the results can be seen immediately in Figure C-1.

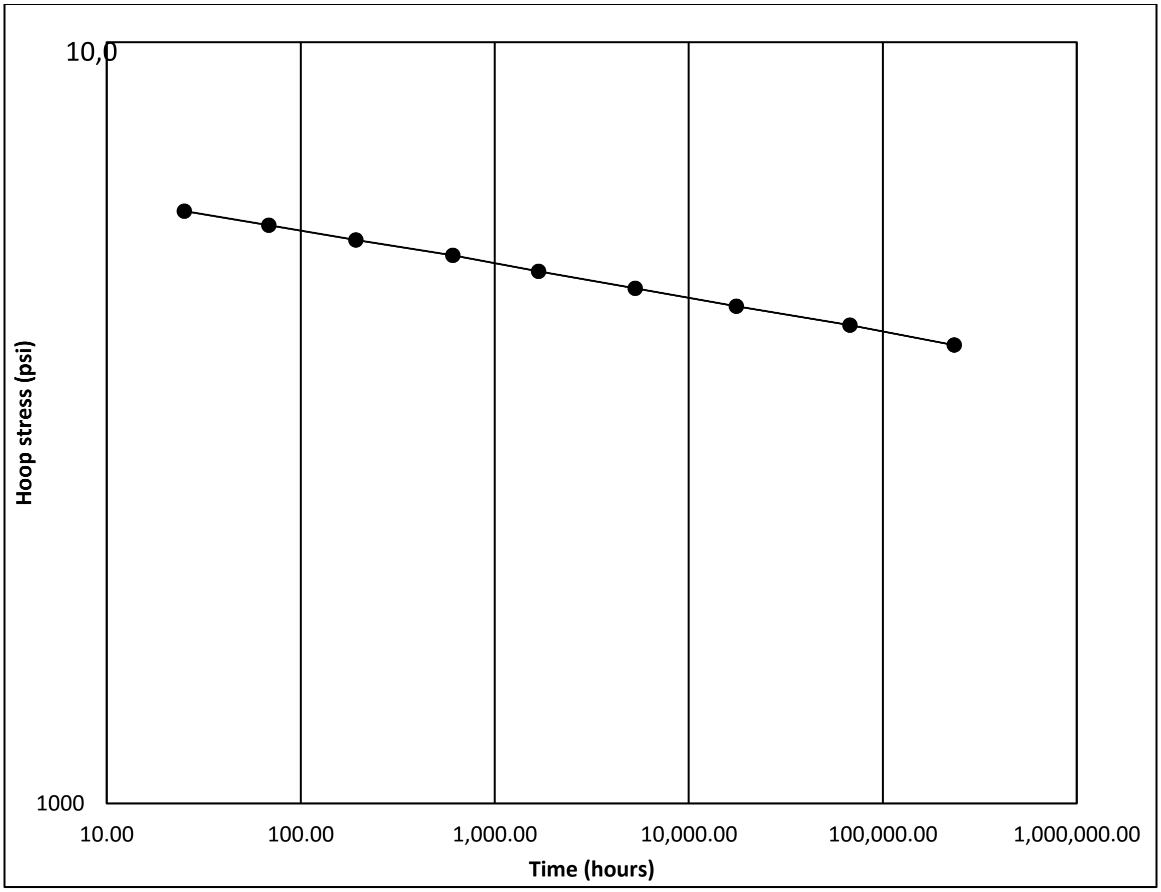

Figure C-1: Stress and time data plotted through the excel solver.

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