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CURED IN PLACE LINER DEFECTS- THREE STUDIES OF INSTALLED LINER PERFORMANCE QUALITY

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ABSTRACT: Over the last 6 years, Malcolm Pirnie has conducted a monitoring program of cured in place mainline liners and lateral liners to assess the affect of various variables on long term liner quality, especially with regard to liner porosity/pinhole leakage, which we have determined to be a common, significant, and under reported defect characteristic of all varieties of cured in place liners we have installed. We have tracked the progression of liner defects over time for a variety of resin-tube combinations; we have tracked the differences in defect types between hot water, steam, and UV cured liners; and we have conducted an analysis of the effect of heat up and cool down rates on liner quality. This paper presents the data and findings of these three studies, including statistics on defect findings, potential root cause conjecture, and potential corrective measures based on our various trials.

1. INTRODUCTION

In the role of Design Engineer or Program Manager for a number of sewer rehabilitation programs, Malcolm Pirnie has implemented construction specification requirements for mainline and lateral lining projects that require both post-rehabilitation **and** warranty inspection requirements. These requirements began in 2005, and the period between installation and post construction inspection varied based on our observations of the behavior of defects over time. As the defects matured, so did our reaction and knowledge.

During this time period, Malcolm Pirnie has observed the installation and reviewed the post-rehabilitation and warranty inspection videos for approximately 50 miles of mainline liners, varying in diameter from 8” to 42”, and for approximately 1200 lateral liners. We have additionally reviewed about 5 miles of liners installed under other programs of an earlier vintage (5-15 years). These liners have been installed by a variety of contractors using a variety of material suppliers for resins and fabrics/tubes in a variety of states from Pennsylvania to Florida. These liners have been constructed using a variety of silicate, epoxy, and polyester resins, on a substrate of a variety of non-woven polyester, woven polyester, and fiberglass fabrics, using a variety of inner and outer coatings (PU, PE, PVC, and PP), and installed and cured using all commonly used methods (i.e., hot water, steam, UV, pull-in, and inverted).

What has become evident is that **all makes and models** of the small diameter cured in place liners that we have examined under these post-installation inspections suffer from pinhole, seam, and coating defects whose extent has been previously under-reported. This paper provides examples of these defects, how their extent and significance increases as the liner ages, hypothesizes on their causes, and presents steps we have taken to try to minimize their occurrence and significance.

2. POST-INSTALLATION INSPECTION PROGRAM

Beginning in 2004 with post-installation inspection requirements, and evolving in 2006 to include warranty inspections, Malcolm Pirnie has conducted inspections of mainline and lateral liners after installation. These inspections fall into three time categories.

The first category is the Immediately-After-Install Inspection. This inspection takes place within hours of the liner installation, often within minutes of liner cool down following curing, and typically before sewage is allowed into the liner. The images resulting from these inspections are typically what you see when viewing lining vendor's websites or visiting their booths and seeing samples, and reflects what most owners and engineers have been led to expect in a cured in place liner: gleaming, smooth, and defect free liners. In most utility inspection/acceptance programs, this post-installation submittal constitutes the sole basis of recommendation for payment and acceptance.

Figure 1. Immediately After Installation Inspection

The second category of inspection is the Post-Rehabilitation Inspection. Originally implemented as an Immediately-After-Install Inspection, as larger jobs or delays in full tap reinstatement caused contractors to lag behind in conducting post-installation inspections. These delayed inspections yeilded significantly more defects we had seen in Immediately-After Inspections. This was most evident in the SP24 mainline lining project, which had zero defects at its Immediately-After-Install Inspection , but had 57% of its segments show defects 2 years later at its Warranty Inspection. This recognition led to a change in specifications, first to a "conduct all post-rehabilitation inspection **after** all liners are installed", then to a set requirement of inspection at least 60, and now 120 days, after liner installation.

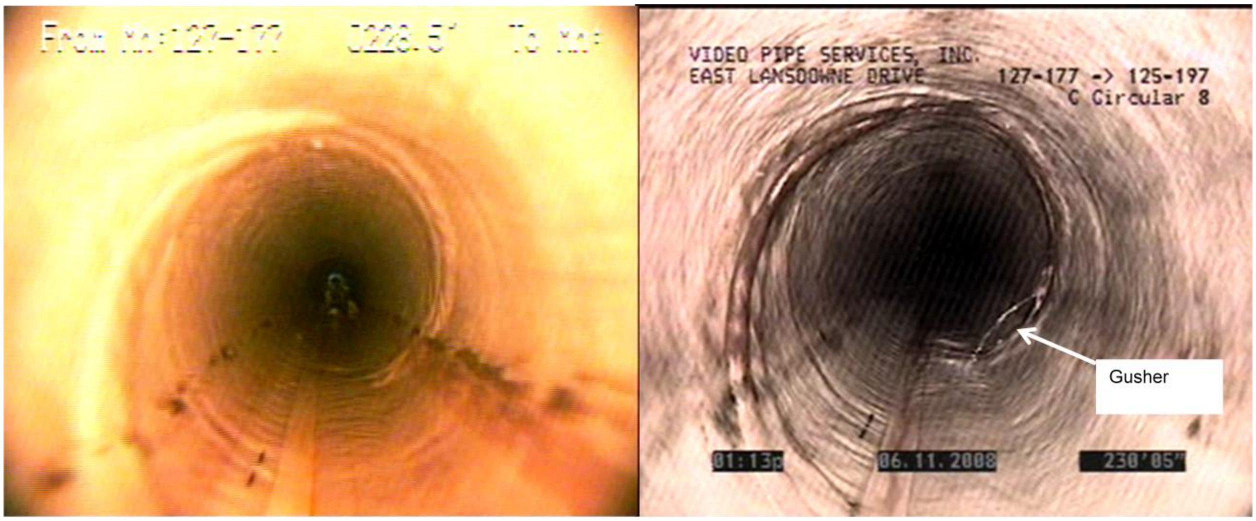
The third category is the Warranty Inspection. Originally intended as a catch-all for missed or poorly conducted/presented Post-Rehabilitation Inspections (a prevalent problem early in the program when inspections were conducted by the contractor rather than by independent inspections controlled by either the utility or the Engineer) and in response to contractor and vendor assertions that observed leakage would "self-seal" once mineral deposits built up, the Warranty Inspection has evolved into the final standard of liner quality and determination of deductions for defects, and our current point of departure for long-term quality of installed liners. Warranty Inspections were initially conducted 12-18 months after installation. Delays by contractors to conduct some of these Warranty Inspections yielded inspections even later after installation. These revealed additional defects in the liners that developed after the Post-Rehabilitation Inspection, or worsening of defects first seen at the Post-Rehabilitation Inspection. The Warranty Inspection has graduated to a planned 18-24 months after Post-Rehabilitation Inspection (2-3 years after installation).

Many of these liners have been installed under programs with a contractor's guarantee on materials and craftsmanship 10 years after the Warranty Inspection. It is intended that a fourth inspection will be conducted at that time, but none of the projects included in this study have yet reached that point in their life cycle.

3. FINDINGS

The three phase inspection program has revealed the following primary type of defects.

Pinhole Defects – The most prevalent defects found at Post-Rehabilitation Inspection are pinhole leaks in the body of the liner. These pinholes are most typically expressed as orange or red staining; as most inspections are not conducted during rain events nor during the seasonally high groundwater periods, active leakage is not typically photographed, although we do have enough instances of inspections during wet weather/high groundwater showing the same pinhole alternately actively leaking and showing only DAE to confirm that these pinholes do indeed leak during wet conditions. (It is important when evaluating pinhole leakage not to misrepresent black or brown stains as leakage, as these are typically bacterial growths blossoming under the inner coating or on the follicles of the exposed resin-tube following film removal (in the case of PU or PP film erosion/dissolving) or calibration tube removal (in the case of liners without integral interior films). As most of these projects are I&I reduction driven, and these sewers were lined to eliminate leakage long term, the presence of leakage through the body of the liner only weeks after installation is especially disconcerting, and begs the question of what will the leakage characteristics be near the end of the liner's life (typically 50-100 years, depending on the design requirements of the project/utility).



Post-Construction Inspection

Warranty Inspection

Figure 2. Time/Season dependent evidence of leakage

Our data show that 41% of the mainline liners installed suffer from pinhole leaks in the body of the liner at the Post-Rehabilitation Inspection. Disconcertingly, the percentage of pinhole leaks in the body of the liner increases to 52% at the Warranty Inspection, and the degree of leakage at previously evident pinholes has generally increased. Similar results were obtained for lateral liners, with 13% of the lateral liners installed suffering from pinhole leaks in the body of the liner at the Post-Rehabilitation Inspection, and 25% at the Warranty Inspection. Again, the degree of leakage at previously evident pinholes often increased.

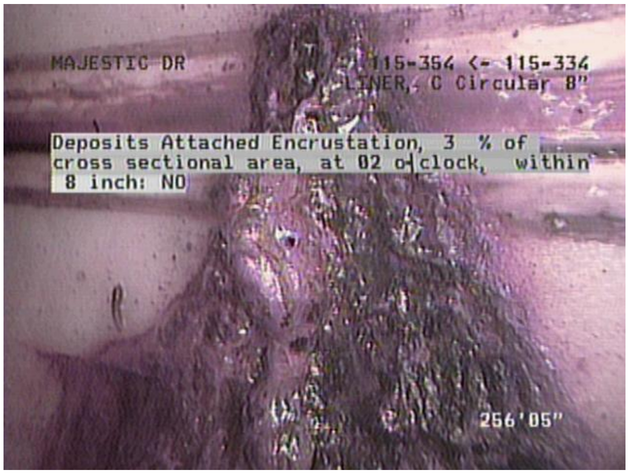


Figure 3. Pinhole Leakage on mainline liner

There appears to be no differentiator between materials, manufacturer, contractor, or installation method when considering these defects. The only liners without significant pinhole leaks appear to be the thicker liners installed in larger diameter pipe. Our data are currently insufficient to determine the breakpoint in the pinhole:thickness relationship.

The presence of an outer coating or pre-liner should reduce the presence of pinhole leaks, but we have not yet conducted enough analysis of these defects and the outer film to accurately assess the effect of this variable.

Seam Defects – Seam defects occur primarily along the longitudinal seams of non-woven felt liners. These defects are most typically expressed similar to pinhole leakage, with the exception that the leakage is usually linear rather than points. The problem is often exacerbated when the inner white strip commonly installed on non-woven liners begins to break free.

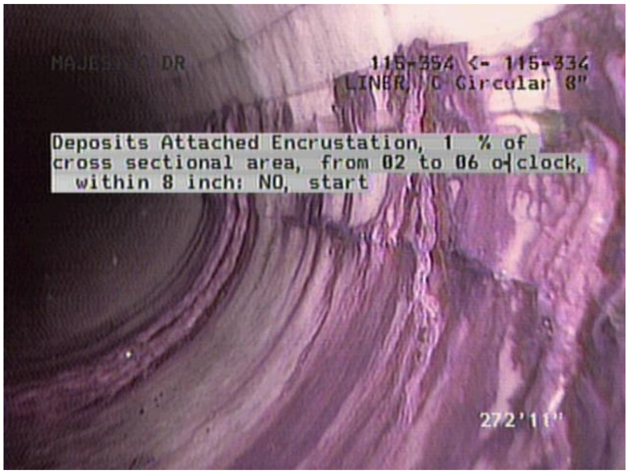
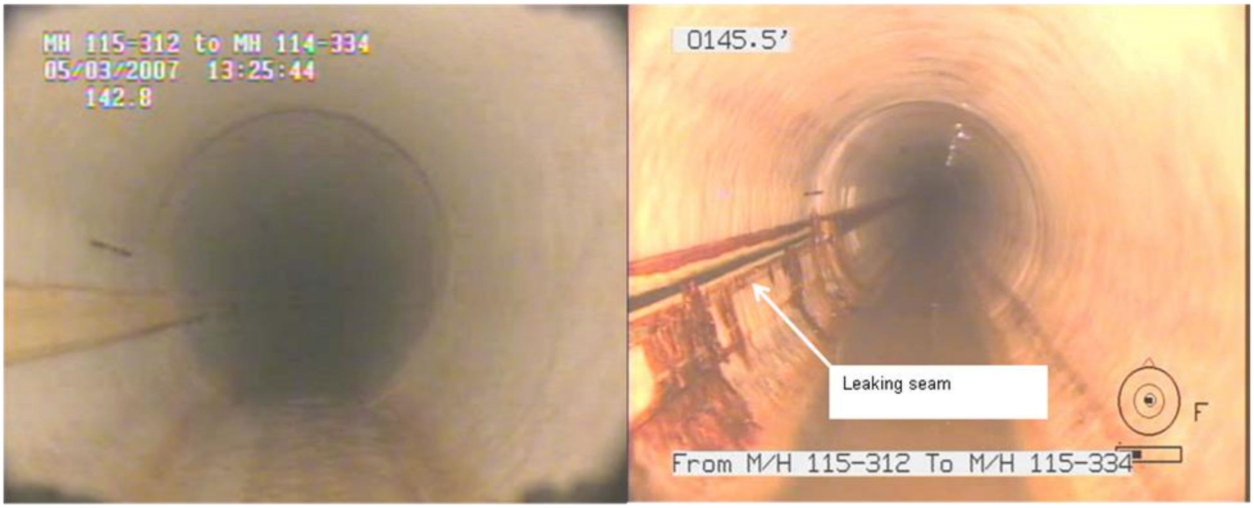


Figure 4. Seam Leakage on mainline liner

Figure 5. Seam Leakage on lateral liner



Post-Construction Inspection

Warranty Inspection

Figure 6. Seam Leakage evident over time

The data show that 0.3% of the mainline liners installed suffer from seam leaks at the Post-Rehabilitation Inspection. Disconcertingly, the percentage of seam leaks increases to 24% at the Warranty Inspection, and the degree of leakage at previously evident seam leaks has generally increased. Similar results were obtained for lateral liners, with 8% of the lateral liners installed suffering from seam leaks at the Post-Rehabilitation Inspection, and 13% at the Warranty Inspection. Again, the degree of leakage at previously evident seam leaks often increased.

Seam defects seem to be related to longitudinal seams are tightly stitched, are butt-seamed (i.e., non-overlapped), and/or have inner or outer seal tapes that are applied using flame bonding or chemical bonding in such a way that decreases the ability of the felt to retain resin in/near the seam. We have not yet conducted enough analysis of these defects and the specific stitching and seal tape bonding to accurately assess the effect of these variables. The only liners examined that did not suffer from seam leakage are those that are thick liners installed in larger diameter pipe, or do not have seams (i.e., some ultraviolet-cured pull-in liners; however, we have seen that these liners suffer a significantly higher percentage of pinhole leaks).

Coating Fraying – Most cured in place liners utilize a coating, typically polyurethane or polypropylene, that serves as the outer seal during vacuum impregnation, the resin sleeve when transporting, and which become the inner coating upon inversion. Post-installation inspection has traditionally focused on blistering and the related loss of this coating as a significant defect (see PACP code LFDL). However, vendors and knowledgeable engineers and contractors have understood that this coating is temporary and will dissolve and erode over time. What has gone unstated is that this coating is often the primary reason cured in place liners pass vacuum/pressure tests, do not leak immediately upon installation, and provide most of the C Factor improvement promoted by lining manufacturers (and often counted on by engineers when calculating the effect on pipe capacity after lining, especially for larger diameter pipes). Also unstated and undocumented is the period of time until dissolution/erosion begins, and ends, and the subsequent effect on liner leakage and blockages. The loss of inner coating also promotes the release of the inner white tape strip and the seal tape commonly installed over the seam of non-woven liners, which increases potential for blockage formation.

Initially thought of as dissolution or erosion of the film coating, we are beginning to appreciate that in some cases the loss of the coating is more like delamination than eroding or dissolving. This delamination presents itself in three formats:

- Piecemeal loss of coating with no appreciable blockage of flow but with the attendant increase in liner body leakage and the roughening of the flow surface. This is the normally anticipated deterioration of the coating;
- Sheet delamination, often with significant bubbling underneath the coating and the formation of pipe blocking lifts, the potential significant blockage caused when the sheet releases partially or fully, and the roughening of the flow surface when the delamination is complete;
- Strip delamination or erosion, with a significant increase in debris, rag, and grease accumulation caused by the greatly increased surface area in the flow path, followed by the roughening of the flow surface when the delamination is complete.

Figure 7. Lateral liner coating delamination

The typical first visual evidence of decoating is the dropping down of the white tape strip at the seam, although bubbling of the coating is also frequently seen as another indicator of coating loss.

Coating loss is not typically evident 0-6 months after installation unless some other aspect of the coating manufacturing or installation process has damaged the coating, such as overheating that result in immediate bubbling of the coating. The most common format of decoating at the Post-Rehabilitation Inspection is sheet delamination. The data show that 7% of the mainline liners installed suffer from coating sheet delamination in the body of the liner at the Post-Rehabilitation Inspection; this percentage increases at the Warranty Inspection to 14%. For lateral liners, 4% of the lateral liners installed suffering from sheet delamination in the body of the liner at the Post-Rehabilitation Inspection, and 11% at the Warranty Inspection.

Strip delamination has not been evidenced in any Post-Rehabilitation Inspection. However, at the Warranty Inspection, strip delamination is evident is a small percentage (0.5%) of the mainline liners and the lateral liner (0.7%).

Below is a summary graph of the CIPPL defect findings.

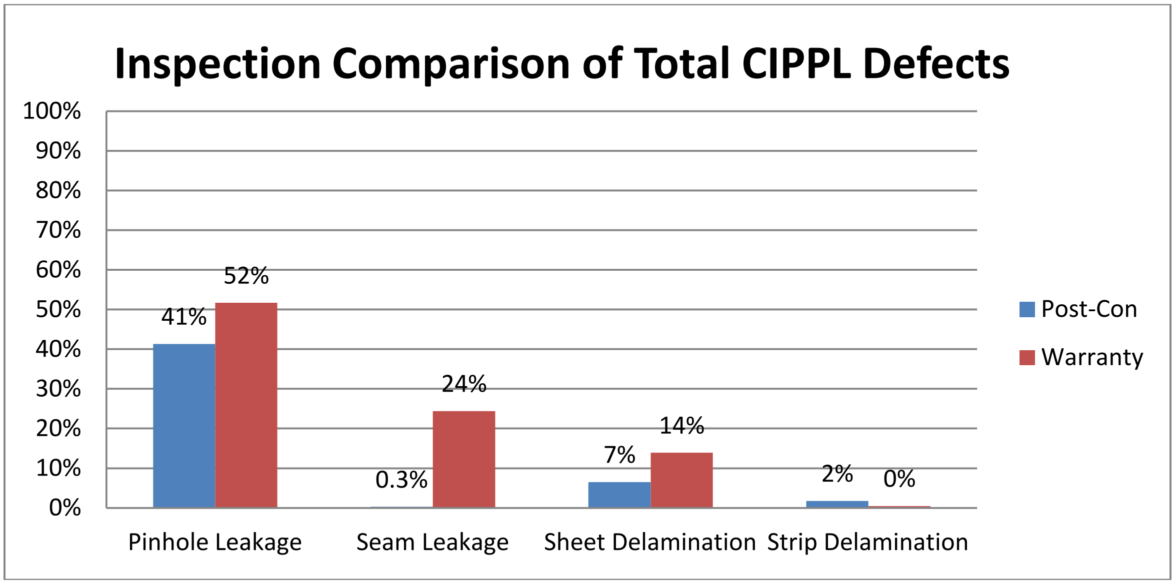


Figure 8. CIPPL defects

Below is a summary graph of the CIPLL defect findings.

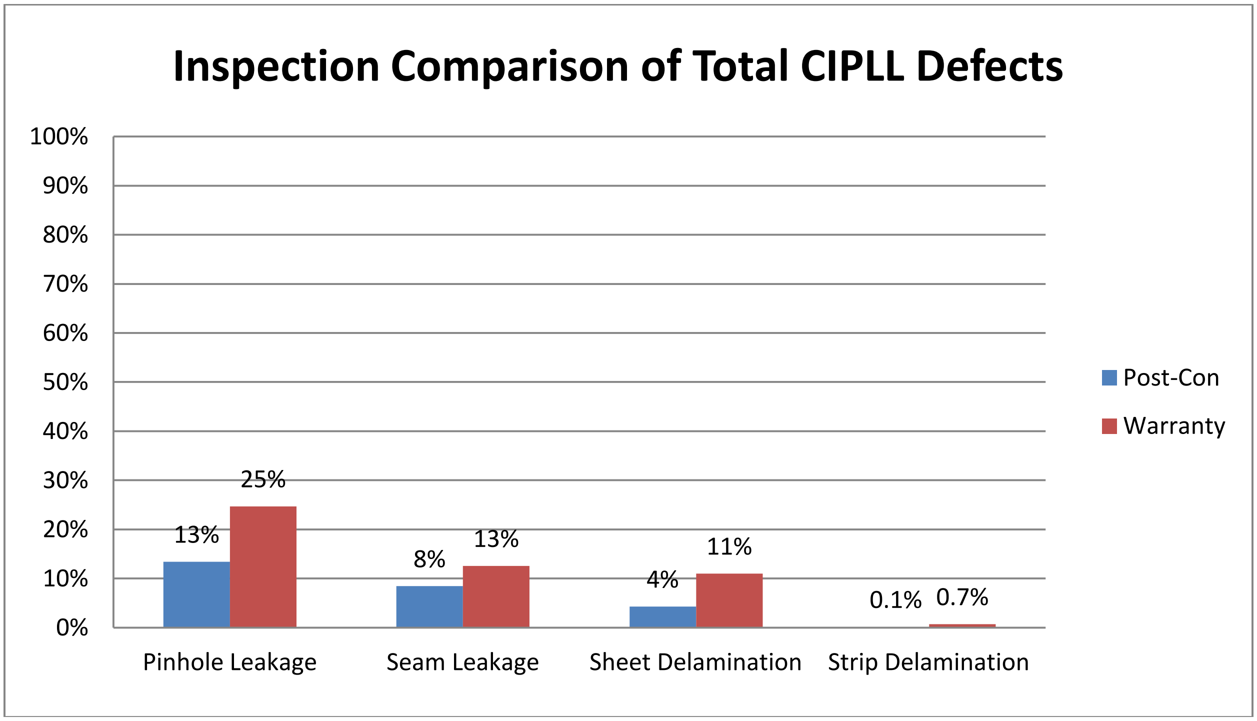


Figure 9. CIPLL defects

4. HYPOTHESES FOR DEFECT ROOT CAUSE

To evaluate the causes of these three defects, we have interviewed a number of fabric manufacturers, tube fabricators, resin manufacturers, wet out facility managers, contractors, and engineers, as well as visited a number of manufacturing facilities. There is no unanimous opinion as to the cause of these defects, and each manufacturing, installation, and curing process has its own idiosyncrasies that affect the potential cause of the defects, but the likely reasons have been narrowed down to a combination of the below explanations.

Water droplet explosion – For standard non-UV cured liners (i.e., liners that are not encased in plastic casings inside and out), as the liner is inserted, some portion of the water/moisture in the host pipe is either pressed into the resin of the liner or trapped against the host pipe. As the resin begins to cure, it releases heat. The resulting temperature approaches or exceeds the flash point of water. When water droplets flash from liquid to vapor, the vapor pressure and volume increase must be equalized. If there is a defect in the pipe wall or joint that is not filled with resin, this gas displaces outward and away from the liner and its inversion pressure. However, if these release sites are not proximate, the vapor pressure and volume increase displace resin in the liner, creating very small resin-lean or resin-free pockets in the liner.

This condition appears to be exacerbated in liner cures where the curing is conducted at an accelerated pace (e.g., uncontrolled steam curing), although we currently have insufficient data on thin walled water cured liners. Under these conditions, there is appears to be little time for the expanding vapor move away from the liner interface and seep out into non-liner spaces.

Inherent porosity of liner – Regardless of how a liner is wet out, some amount of air remains entrained in the fabric webbing of the tube. This is true for vacuum impregnation of non-woven liners, and for dipped and wound fiberglass liners. As with the water droplet explosion theory, residual air will pressurize and expand as the liner cure develops heat (a by-product of all forms of CIPP, including ambient curing). The resulting voids (porosity) are present in all liners. The greater or less extent and proximity of these air pockets in the cured liner contribute to the progression from porosity to pinhole leakage. For thinner liners, it is more likely that a small air bubble could breach the liner wall and create a pinhole leak.

Inner film pinhole with follow-on blowout of resin – The coating on all heat cured liners is very thin (8-15 mils). Various manufacturers apply this coating in a variety of ways and test the liner for holidays before shipping for tube fabrication. This testing confirms coverage, but not necessarily minimum thickness. Then during tube manufacture and wet out, this coating undergoes a variety of stresses, some common to all products, some unique to the manufacturing process. Non-woven felts are all sewn together, creating thousands of small punctures intentionally, and unaccounted unintentional pricks. During wet out, holes are intentionally punctured into the coating for vacuum impregnation; these are subsequently sealed, but have the inherent potential weakness of any human applied patch.

Post-Construction Inspection

Warranty Inspection

Figure 10. Detached Factory Patch Found at Warranty Inspection

The wet out liner is then loaded into a reefer truck whose surfaces are not Teflon smooth, transported to the site, and slid out of the reefer box to the inversion pot or tower, all movement which present the potential for small pricks in the coating.

UV cured liners have internal calibration tubes that are installed in the liner bag in the factory. The light train runs inside this bag. Any sharp edges to the wheel carriage or train can prick the calibration tube.

As steam, hot water, or air are pushed into the liner, any prick in the inner coating allows water, steam, or hot air, all of which are under pressure, to push into the uncured resin/tube. This jet of fluid displaces resin and leave behind small pinholes or increases porosity of the cured liner.

Over-pressurization and resin loss at seam or through the body – Pressure from the steam, hot water, or air push out liner tubes to meet the interior wall of the host pipe.

If the liner tube is slightly undersized, which is typically the condition when post-installation video reveal a perfectly smooth liner, the sewn seam edges of butt seamed tubes begins to pull away from each other, thinning out the resin at this point, leading to seam leakage. In spiral wound UV cured liners, this slight over-expansion of the tube can lead to pinholing at the seam.

Even if the liner is properly sized or slightly oversized, over-pressurization can drive resin from the body of the tube into surrounding joints, taps, and defects. While most liners are specified or manufactured with excess resin (typically 2-5%) to account for this resin loss, this "squeezing the sponge" effect can result in greater losses than can be accommodated by the excess resin impregnated into the tube at wetout, resulting in pinholes.

Seam construction – Non-woven tubes are constructed in a variety of manners, each of which contributes to varying degrees to an inherent weakness in sewn tube liners. Liners with butt edge seams, as described above, allow resin to migrate readily into the seam, but thin out upon inversion (even without over-pressurization) and become a source of seam leakage and, potentially, structural weakness. Liners with overlapped edges are typically tightly sewn together, squeezing the fabric before the resin is even introduced, resulting in potential for lean resin issues, even without over-pressurization. Liners with heat or chemical bonding at the seam, either for the primary tube connection or for the seam covering tapes, degrade the "sponge-worthiness" (not to be confused with Elaine Bennis's definition of the concept …..) of the liner, resulting in less than desired resin impregnation (again not to be confused with the Seinfeldian use of the term ….). Finally, the loss of covering tape, either through adhesive breakdown or through the dissolution of its substrate—the coating—while not thought to be a source of leakage, could potentially lead to blockages.

Differential shrinkage of the coating vs. cured liner – Delamination of the coating is caused by differential shrinkage between the coating and the cured liner. As the cured polyester liner shrinks, the coating buckles at weak spots in its connection to the liner. This release, coupled with the expected dissolution of the coating, creates the noted sheet and strip delamination issues documented.

5. POTENTIAL CORRECTIVE MEASURES AND APPARENT EFFECTIVENESS

To date, we have attempted a number of corrective measures. The effectiveness of these measures is largely still under assessment.

To address **water droplet explosion** and **inherent porosity of the liner**, specifications have been rewritten to require the contractor to regulate the heating up of the liner, promoting a longer warm-up period to allow air bubbles more time to migrate from the bag, water droplets more chance to find an outlet outside the liner, and water vapor bubbles a chance to migrate from the liner before resin hardening. Specifications currently being used state:

> "After insertion is completed, apply a suitable recirculation system capable of delivering air, steam, or water at various temperatures throughout the section to achieve a consistent cure of the resin *while allowing any moisture to migrate from the liner. Maximum temperature increase rate between ambient to 140°F shall be 1°F per minute*. Maintain the curing temperature or exposure times as recommended by the liner system manufacturer."

To address **water droplet explosion**, we have begun installing preliners much more often. Any leakage that continues to enter the host pipe after grouting, or if there are any sags in the host pipe containing water that cannot be removed readily, a preliner is installed. Specifications currently being used state:

> "For pipe segments found to have any actively leaking defects that would be categorized as Runners or Gushers by the PACP Defect Rating Codes, grout every joint on said pipe segment if instructed by the ENGINEER. When so instructed, render the pipe free of Runners or Gushers. *If a line segment has Runners or Gushers through non-groutable defects or if installation of a pre-liner is shown or specified for the line segment, or if any pockets of water remain in the line that cannot be readily removed, install a pre-*

> *liner* if instructed by the ENGINEER. If the cured-in-place liner has an integral exterior tube that seals the liner from the leaking water, a pre-liner will not be required."

To address **water droplet explosion**, **inherent porosity of the liner, and inner film pinhole with follow-on blowout of resin,** specifications have been changed to require thicker than F1216-required liners. When the F1216 calculations for liner thickness for:

- 8" and 10" pipes yield liners 6mm or thinner on for non-woven liners, specifications now *require a 7.5 mm minimum thick liner*.
- 8" and 10" pipes yield liners 3.2mm or thinner on for fiberglass reinforced UV cured liners, specifications now *require a 4.8 mm minimum thick liner*.

Lateral liners for 4" and 6" pipes are typically installed at around 4mm for non-woven liners. We would like to require these be installed with thicker liners, but are not convinced these thicker liners can be reliably installed in laterals.

To address **over-pressurization and resin loss at seam or through the body**, specifications require each host pipe's diameter be accurately measured before liner tube fabrication. This is especially important in older clay pipe and in concrete pipe subject to sulfide attack. Specifications have also been relaxed regarding fins and wrinkles, and regarding thicker than specified liners, with the current thinking being that a perfectly smooth liner is probably undersized and potentially subject to overpressurization, resin loss, and seam thinning. Specifications also stipulate a 5-10% minimum amount of excess resin, intended to ensure there is maximum available resin without incurring undo risk of resin slugs under the bag, resin slugs agglomerating at tap connection, or resin slugs at the house end for lateral lining. Specifications currently being used state:

> "CIPPL installations that result in thicknesses *that exceed the design thickness by the greater of 2mm or 15%* may be considered non-compliant if, in the judgment of the ENGINEER, will impede O&M and future work. CIPPL with thicknesses less than 95% of design thickness will be non-compliant. The liner shall be fabricated to a size that when cured will tightly fit the sewer being rehabilitated. Field verify all dimensions prior to delivery of the liner. *Size the liner so that fins and wrinkles are minimized while ensuring maximum practical contact with the host pipe*. The contact tolerance for pipe with a conic section is 2.0 mm; in these cases where any space or gap between the outside surface of the liner and the inside surface of the existing pipe exceeds 2.0 mm, the liner fit will be deemed deficient and corrective action will be required.
> Thoroughly saturate flexible tube prior to installation. For tubes with exposed resin faces, *add five to ten percent excess resin* to account for resin migration in pipe defects and joints and resin loss through the ends of the liner. Adjust roller gap setting so that the excess resin is uniformly distributed throughout the length of the liner.
> Provide a finished CIPPL that is free as commercially practicable from wrinkles *totaling more than 5% of host pipe inside diameter, or 1/2", whichever is greater*.

To address **coating delamination**, both thinner and thicker coatings are being field trialed. The thought is that thinner coatings will dissolve more quickly and cause fewer potential O&M issues, and that thicker coatings might not delaminate via buckling failure from differential shrinkage, but might more evenly dissolve.

To address **coating delamination, inherent porosity, and other pinhole causing issues**, we are investigating non-water soluble coatings. This will be a radical shift in liner approach, especially for I&I driven programs that have traditionally used mainline and lateral lining to eliminate leakage. Instead of relying on the liner for leakage control, the liner will only provide structural strength (which the presence of pinhole does not seem to greatly affect, assuming high performing resins that are not subject to groundwater softening are use) while *the coating will provide the long term leakage control*.

To address **over-pressurization and resin loss at seam or through the body**, specifications have been modified to require the liner manufacturer provide data on the maximum installation pressure the liner can experience before excess compression of the tube occurs, and monitor the installation for compliance with these pressures. Specifications currently being used state:

> “Provide data from the tube-resin fabricator demonstrating the maximum installation *pressure the liner can experience before excess compression of the tube resulting in loss of all excess resin occurs*.
>
> Monitor pressures during inversion and curing of the liner to determine compliance with minimum and maximum inflation pressures.”

To address the **dangling white tape and seam tape** issues, we are <u>investigating the use of alternative materials and bonding methods</u>.

To address **Differential shrinkage of the coating vs. cured liner**, specifications have been rewritten to require the contractor to <u>regulate the cool down of his liner</u>, promoting a longer tempering/acclimization period. Specifications currently being used state:

> “Initiate a controlled cool-down to cool the hardened liner to a temperature below 110°F, in accordance with the cure schedule. For pipe liners less than 21 mm thick, *maximum cool down rate shall be 0.5°F per minute*. For pipe liners greater than 21 mm thick, maximum cool down rate shall be 0.3°F per minute. ”