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Water Quality Implications of Culvert Repair Options: Vinyl Ester Based and Ultraviolet Cured-in-Place Pipe Liners

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Specifications of the Virginia Department of Transportation (VDOT) allow for the use of several "trenchless" pipe or culvert repair technologies whereby existing underground culverts are repaired in place rather than by the use of the conventional method of unearthing and replacing damaged sections. However, water quality implications of these trenchless alternatives are not completely understood. A previous evaluation found water quality impacts from installations of conventional cured-in-place pipe (CIPP). This trenchless rehabilitation technology includes saturating a flexible liner with a styrene-based resin and curing the liner onsite with steam or hot water. VDOT subsequently implemented new specifications for styrene-based CIPP to prevent water quality impacts from its installation or use. The current study included an environmental evaluation of two unconventional CIPP technologies available for use by VDOT: vinyl ester based (styrene-free) CIPP and styrene-based ultraviolet (UV) CIPP.

To evaluate the potential for vinyl ester based and UV CIPP technologies to impact water quality, water samples were collected from field installations and simulations for up to 120 days. Samples were analyzed for product constituents listed in material safety data sheets. Results were then compared with established regulatory standards and published toxicity criteria for aquatic species.

For the vinyl ester based CIPP liner evaluated, concentrations of the primary resin constituent exceeded toxicity thresholds for aquatic species in six subsequent water sampling events. Adherence to VDOT's CIPP specifications for styrene-based liners is expected to minimize contaminant leaching from the installation and use of this product. Following UV CIPP installations, no water quality impacts were documented from culvert outlets with water flow but styrene concentrations following one of the installations exceeded toxicity thresholds for aquatic species in standing water.

The study recommends that VDOT consider revising its current CIPP specifications such that styrene-based CIPP requirements also apply to non–styrene-based CIPP installations. Because the water quality evaluations conducted in this study could not capture the range of potential field scenarios and installation variables, the VDOT specification that requires the collection and analyses of water and soil samples following CIPP installations would provide VDOT with additional sampling results from liners installed in varying field conditions and help ensure that VDOT is using this lining technology with appropriate environmental safeguards.

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FINAL REPORT

WATER QUALITY IMPLICATIONS OF CULVERT REPAIR OPTIONS: VINYL ESTER BASED AND ULTRAVIOLET CURED-IN-PLACE PIPE LINERS

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In Cooperation with the U.S. Department of Transportation
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(A partnership of the Virginia Department of Transportation
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ABSTRACT

Specifications of the Virginia Department of Transportation (VDOT) allow for the use of several "trenchless" pipe or culvert repair technologies whereby existing underground culverts are repaired in place rather than by the use of the conventional method of unearthing and replacing damaged sections. However, water quality implications of these trenchless alternatives are not completely understood. A previous evaluation found water quality impacts from installations of conventional cured-in-place pipe (CIPP). This trenchless rehabilitation technology includes saturating a flexible liner with a styrene-based resin and curing the liner onsite with steam or hot water. VDOT subsequently implemented new specifications for styrene-based CIPP to prevent water quality impacts from its installation or use. The current study included an environmental evaluation of two unconventional CIPP technologies available for use by VDOT: vinyl ester based (styrene-free) CIPP and styrene-based ultraviolet (UV) CIPP.

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FINAL REPORT

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INTRODUCTION

Background

Trenchless pipe rehabilitation is a non-intrusive construction method commonly used by municipalities, utilities, and transportation agencies for repairing damaged pipes. For decades, various trenchless technologies have been applied as a means of repairing wastewater, drinking water, and stormwater infrastructure. New technologies continue to emerge as aging and failing pipes have become a significant maintenance concern in the United States (U.S. Environmental Protection Agency [EPA], 2002). However, few studies have been conducted that quantify any impact these technologies may have on the environment.

Many stormwater pipes (hereinafter "culverts") installed and maintained by the Virginia Department of Transportation (VDOT) have reached the end of their service life or have otherwise become damaged. VDOT specifications allow for the use of certain trenchless culvert repair technologies (VDOT, 2008a), but there is insufficient information for some of these technologies with regard to potential risks to water quality. A previous culvert repair evaluation conducted by Donaldson and Baker (2008) documented that one of these methods, cured-in-place pipe (CIPP) rehabilitation, had the potential to contaminate downstream water, particularly when certain installation variables (e.g., resin and cure water containments) were not properly controlled. After further analyses of CIPP technology, VDOT created specifications for styrene-based CIPP installations (VDOT, 2008b). VDOT also requested that the Virginia Transportation Research Council (now the Virginia Center for Transportation Innovation and Research) review other culvert rehabilitation products and processes used by VDOT. A second study was then conducted through a contract with the University of Virginia whereby an additional method of culvert rehabilitation (fold and form) was analyzed (Ren and Smith, 2010). Limited availability of field installations at the time limited the scope of that work to only laboratory leaching testing. Laboratory experiments and analyses suggested that fold and form liners are not expected to have any significant adverse environmental impact in field applications (Ren and Smith, 2010).

Types of CIPP Technologies

CIPP technology was introduced 40 years ago and has developed into a billion dollar industry (Griffin, 2011). CIPP repair dominates the underground pipe industry (Hoffstadt, 2000) and is also used to repair culverts maintained by U.S. transportation agencies nationwide

(Insituform, 2011). For the purposes of this study, CIPP technology is separated into three general technologies:

1. *Conventional CIPP*, which entails the insertion of a felt liner into the damaged host culvert. The liner is saturated with a styrene-monomer–based resin that polymerizes (i.e., "cures") as a result of hours of steam or hot water recirculation.

2. *Vinyl ester based CIPP*, which uses lining materials and curing methods similar to those of conventional CIPP but uses a styrene-free resin.

3. *CIPP that uses a styrene-based resin as in conventional CIPP but different liner materials than with conventional and vinyl ester based methods and cures with ultraviolet (UV) light rather than steam or hot water.* This type was relatively recently introduced in the United States.

Conventional CIPP methods are more widely used because of their long history of use in the CIPP industry (Najafi, 2004). However, there have been numerous anecdotal reports of damage to aquatic habitat and treatment processes at wastewater treatment facilities from their use (Whelton et al., 2012). The use of unconventional vinyl ester based and UV CIPP technologies is expanding, and these technologies are often marketed for their environmental benefits over traditional CIPP. No studies, however, have characterized the potential water quality impacts of the installation of vinyl ester based or UV CIPP in stormwater culverts.

VDOT's CIPP specifications (VDOT, 2008b) were largely based on the water quality evaluations of conventional CIPP (i.e., styrene-based and cured by steam or hot water). The requirements are specific to "styrene-based cured-in-place liner systems" (VDOT, 2008b). A few of these specifications include the following:

- the placement of an impermeable sheet immediately upstream and downstream of the host pipe to capture any raw resin spillage during installation

- the capture and proper disposal of any cure water or steam condensate

- a thorough rinsing of the cured pipe and capture and proper disposal of the rinse water

- the collection of water and soil samples before and after installation.

Problem Statement

Unconventional CIPP technologies (i.e., UV and vinyl ester based) were introduced to VDOT after the development of the conventional CIPP specifications. Thus, they do not apply to styrene-based repair methods (e.g., vinyl ester based CIPP) and were written without an evaluation of either of these unconventional CIPP technologies. A determination of the potential water quality implications of unconventional CIPP technologies is needed to ensure that VDOT is continuing to be a responsible user of all CIPP technologies with respect to environmental factors.

PURPOSE AND SCOPE

The purpose of this study was to evaluate two unconventional CIPP rehabilitation technologies, i.e., vinyl ester based CIPP liners and UV CIPP liners, for their potential impacts on water quality. The objectives were to provide VDOT with information on each technology regarding (1) its potential to contaminate water to a degree that exceeds the toxicity thresholds for aquatic species, and (2) whether adherence to or modification of VDOT's existing styrene-based CIPP specifications would be expected to mitigate any adverse impacts on water quality.

The scope was limited to three culvert liner evaluations that included water quality analyses up to 120 days following field installations and comparisons of the findings with toxicity thresholds for aquatic species. These evaluations can serve as a starting point for understanding water quality risks from the use of these repair technologies. A study of the water quality analyses of spray-on liners has also been completed (Donaldson and Whelton, 2012).

METHODS

Four tasks were conducted to achieve the study objectives.

1. Conduct a literature review of information regarding the material and installation procedures and relevant water quality standards and toxicity studies of aquatic species for the chemicals that comprise each of the two technologies, i.e., vinyl ester based CIPP and UV CIPP.

2. Observe one vinyl ester based and two UV CIPP installations and document methods or incidents that might pertain to water quality.

3. Conduct water quality tests and compare results with the toxicity thresholds for aquatic species.

4. Evaluate the results of the first three tasks to determine whether adherence to or modification of VDOT's current styrene-based CIPP specifications would be expected to mitigate any adverse impacts to water quality.

Literature Review

A search of the literature and sources of product information was conducted to determine (1) the methods and materials used for each evaluated technology, (2) federal and state environmental standards relevant to the product constituents, and (3) the toxicity thresholds for aquatic species with regard to the resin constituents. Information regarding standards and toxicity studies for the resin constituents was obtained from the websites of the American Society for Testing and Materials (ASTM), the U.S. EPA, the Virginia Department of Environmental Quality, and online databases such as Biological Sciences, Environmental Sciences and Pollution Management, and WorldCat. Product information was also collected directly from vinyl ester based and UV CIPP vendors. Findings documented from the literature review on installation procedures were intended to provide an overview rather than a comprehensive description.

Observations of Field Installations

Three installations of two CIPP technologies were observed (Table 1). Observations of methods or incidents during and after installations that might pertain to water quality were documented. Projects included field installations, where liners were installed in corrugated metal culverts that conveyed a stream or stormwater, and a demonstration installation. A lack of suitable options for repairing true culverts within the study timeline required that Company A's liners be installed in a hard fabric designed to simulate a host culvert.

Table 1. Descriptions of Monitored Culvert Rehabilitation Technologies in Virginia

Lining Technology	Culvert Size		Test Condition
	Diameter (in)	Length (ft)	
Vinyl ester based CIPP	15	100	Field installation. Conveys stormwater only during storm events. Drains into riprap/earthen ditch.
UV CIPP (Company A)	18 18	35 32	Demonstration installation (two liners).
UV CIPP (Company B)	30	20	Field installation. Conveys Stony Creek.

CIPP = cured-in-place pipe; UV = ultraviolet.

Water Quality Tests and Comparison With Toxicity Thresholds

Unlike tests for potable water pipes, there are no standard methods for testing the water quality implications of stormwater repair products. Table 2 lists the water quality test(s) conducted for the particular installation, including flowing water and immersion tests, and Figure 1 illustrates the tests conducted. Because of constraints unique to the vinyl ester based CIPP installation, an immersion test was not conducted for this technology.

Product material safety data sheets (MSDSs) were used to determine constituents to analyze in water samples (Table 2). The chemicals that comprise the vinyl ester resin evaluated in this study included a vinylic monomer and an acrylate monomer. Because these products are composed of proprietary chemical ingredients (which were disclosed to the author for this evaluation), references and specific chemical names are not disclosed in this report.

Table 2. Tests Conducted and Water Sampling Frequency After CIPP Installations

Tests Conducted	Water Sample Analyses and Sampling Frequency		
		Ultraviolet	
	Vinyl Ester	Company A	Company B
Flowing water test (Field installation)	Analyses: Vinylic monomer, acrylate monomer Sampling frequency: Rinse water, 30 min after installation; Days 7, 14, 21 60, 90, 120	Analysis: Styrene Sampling frequency: Rinse water, 30 min after installation; Days 2,3	Analysis: Styrene Sampling frequency: Rinse water, 30 min after installation; Days 1,2,3,7,14,21
Immersion test of liner section (Field simulation)	-	Days 1, 3	Days 1,2,7,14,21,35,49

CIPP = cured-in-place pipe.

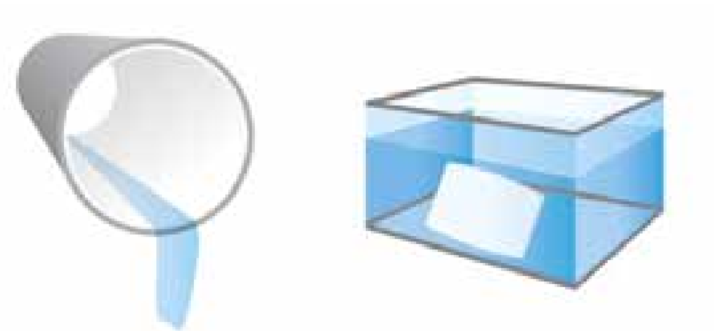

Figure 1. Illustrations of Water Quality Testing on Newly Installed Liners. *Left,* flowing water test; *right,* immersion test.

Samples were collected until the chemical concentrations were near or below the laboratory reporting limits or the toxicity thresholds for aquatic species. The number of days and sampling events before concentrations decreased below these limits or thresholds was highly variable among the tested liners (3 to 120 days following installations). Samples were packed on ice, sent to a laboratory via an overnight courier service, and analyzed for constituents identified from product MSDSs. Test results were compared with water quality standards and the toxicity thresholds for aquatic species identified from the literature review.

Flowing Water Test

Sampling techniques for the flowing water test were designed to accommodate the available flow conditions (or lack thereof) at each culvert (as described in Table 3).

The UV CIPP site of Company B was the only site that continually conveyed a stream. At the other sites, stream flow or precipitation in the form of rain did not occur over the duration of the sampling period. For these installations, a rain event was simulated each sampling period (Table 3) through the pouring of tap water slowly into the culvert inlet such that only a single stream (approximately 2 in wide) contacted the bottom of the culvert liner. Pouring was stopped once the water began flowing out of the outlet. For the longer culvert lined with vinyl ester

Table 3. Flowing Water Sampling Conditions and Analyses

Technology	Culvert Size		Water Flow at Time of Sampling	Sampling Method
	Diameter (in)	Length (in)		
Vinyl ester based CIPP	15	100	Simulated low flow	10.5 gal[a] water poured through liner. Samples captured at outlet.
UV CIPP, Company A	18 18	35 32	Simulated low flow	5 gal [a] water poured through each liner. Samples captured at outlet.
UV CIPP, Company B	30	20	Continual natural stream flow (low to heavy)	Stream water samples captured at outlet and 10 m (33 ft) downstream.

CIPP = cured-in-place pipe; UV = ultraviolet.
[a]Culvert length determined the water volume poured through the liners for sampling.

based CIPP, a greater volume of water was required (Table 3). The water was captured in 40-ml sampling vials as it flowed out of the outlet. These simulations were designed to replicate a worst case field scenario with low water flow with little dilution potential. For Company B's UV CIPP installation in a culvert with natural stream flow, water flow varied from low to heavy.

Control samples were also collected at each sampling event. Control samples at the installation with continual stream flow (UV CIPP, Company B) were taken at the outlet of the host culvert prior to liner installation and just upstream from the inlet following installation. Control samples at installations with simulated water flow were taken from the same water source that was used to flush the culvert for the purpose of water sampling.

Immersion Test

Because relatively high contaminant concentrations have been detected in pools of standing water at culvert outlets following CIPP installations (Donaldson, 2009), an immersion test was conducted on each UV CIPP liner to simulate a standing water scenario as a comparison with the flowing water test. Similar to the water flow test, this test was designed to simulate field conditions with little dilution potential and thereby represents a worst case field scenario in terms of detectable adverse impacts on water quality from contaminant leaching. For each tested liner, an open 5-gal glass tank was filled with 2 gal of tap water. A control sample was collected from each tank into 40-ml vials. Within 2 hr following installation of the Company A and Company B liners, a cut section of liner (12 by 7 by 0.25 in) was immersed in the tank. Each sampling day (listed in Table 2), water samples were collected from the tank into 40-ml vials. Fresh water with an equivalent volume to that removed for sampling was then poured into the tank with the remaining water and the liner section.

Evaluation of Findings Relative to VDOT's Styrene-Based CIPP Specifications

For each of the evaluated unconventional CIPP technologies, results of the literature review, field installations, and water quality tests were used to determine whether adherence to or modification of VDOT's existing styrene-based CIPP specifications would be expected to mitigate any adverse impacts on water quality.

RESULTS

Vinyl Ester Based CIPP

Literature Review

Materials and Installation Procedures

Installation methods for vinyl ester based CIPP are similar to those for conventional (styrene-based) CIPP, which are described in more detail in Donaldson and Baker (2008). Typical CIPP operations begin with the project setup, which includes measures to prevent water flow through the damaged host culvert. Any water normally conveyed by the culvert is dammed or diverted to a downstream point. Rocks and debris are then removed from the culvert. The resin-saturated liner is inserted into the host culvert. Three types of resins are used in CIPP applications: unsaturated polyester resins, vinyl ester based resins, and epoxies (Najafi, 2004). Unsaturated polyester resin contains styrene and is the most common resin used in CIPP installations (Najafi, 2004). Vinyl ester based resin, including that evaluated in this study, does not. The lining material used in conventional and vinyl ester based CIPP operations is composed of absorbent non-woven felt fabric that is pre-saturated (at the manufacturing facility) with a thermosetting resin.

Depending on the company, the liner is either pulled or inverted through the host culvert. Inversion is accomplished by forcing air into one end of the liner, causing the liner to turn inside-out as it travels the length of the host culvert. The liner is expanded to conform to the inner dimensions of the culvert and is subsequently cured. Typical curing is achieved by circulating heated water or steam through the culvert to polymerize the resin material. The curing process takes up to several hours, depending on the culvert size. Typically, the liner tube has a membrane coating to protect and contain the resin; the membrane is generally a flexible thermoplastic, such as polyethylene or polyurethane (Hoffstadt, 2000). This coating is normally only on the inner surface of the finished product. This allows the resin on the outer surface of the liner to migrate into any voids in the host culvert such as joints or cracks prior to curing. The curing process and subsequent cool-down period can generate spent process water or steam condensate. Following the cool-down period, the closed ends of the cured liner are cut open and generally a video camera is inserted into the culvert for a final inspection. The final thickness of the liner is approximately 0.25 to 1.0 in.

Standards and Toxicity Studies

The installation procedures for all methods of CIPP are specified by standards published by ASTM International (2003, 2007). These standards do not specifically include measures to prevent or minimize potential adverse impacts to waterways or wastewater treatment facilities. Current standards recommend that during the liner cool-down period, hot water or steam effluent should be drained through a small hole in the downstream end of the culvert and replaced with the introduction of cool water.

The vinylic monomer, one of the two predominant chemicals in the vinyl ester based resin, is on the U.S Environmental Protection Agency's list of Hazardous Substances (40 CFR 302.4). This substance therefore falls under reporting requirements for any release or leaching into the environment, although no reportable quantity is assigned to this class of chemicals (U.S. EPA, 2011). The discharge of pollutants (which includes chemical wastes) to waters of the United States is also regulated under the Clean Water Act (U.S. EPA, 2011) and in Virginia requires a permit under the National Pollutant Discharge Elimination System (NPDES) or state equivalent (Virginia Department of Environmental Quality, undated).

Table 4 provides the results of published acute toxicity studies with regard to the impacts of the chemicals on aquatic indicator species. Indicator species are sensitive to pollutants, and their disappearance from a body of water can be indicative of contamination.

Table 4. Vinyl Ester Based CIPP Proprietary Ingredient Toxicities for Various Freshwater Indicator Species

	Vinylic Monomer [a]		**Acrylate Monomer [a]**
Aquatic (Freshwater) Species	**Test Duration and LC_{50} or EC_{50} [b] Value (mg/L)**	**NOEC [c] (mg/L)**	**Test Duration and LC_{50} or EC_{50} [b] Value (mg/L)**
Freshwater green algae (*Scenedesmus subspicatus)*	48 hr: 11 72 hr: 5.5	NA	
Microalgae (*Pseudokirchneriella subcapitata)*			96 hr: 2.7
Water flea (*Daphnia magna*)	24 hr: 26	3.2	48 hr: 1.1
Golden orfe fish (*Leuciscus idus*)	48 hr: 0.4	NA	
Zebra fish (*Brachydanio rerio*)			96 hr: 1.8

CIPP = cured-in-place pipe.
[a] In order to maintain the confidentiality of the proprietary product ingredients, references for the toxicity studies are not disclosed.
[b] Lethal concentration (LC_{50}) and effective concentration (EC_{50}), or the concentration required to kill (LC_{50}) or have a defined effect on (EC_{50}) 50% of the test population after a given number of hours of exposure in that concentration.
[c] No Observable Effect Concentration or the highest limit at which no mortalities or abnormalities were observed.

Installation Observations

The observed installation was in a 100-ft-long stormwater culvert with a 15-in diameter. Observed installation procedures were generally similar to those documented for conventional CIPP (Donaldson and Baker, 2008) whereby a flexible resin-saturated liner was pulled through the host culvert and subsequently inflated and cured with steam to form a rigid lining (see Figure 2). One notable difference between this installation and those from a previous study (Donaldson and Baker, 2008) was the effective release of steam during the curing process, evident by the low volume of steam condensate following the cool-down period. The installation resulted in less than 300 ml of steam condensate, which was discharged onto the dry riprap/earthen ditch. Cutting of the ends of the new liner following the cool-down period resulted in a heavy scattering of liner shavings around the inlet and outlet. At some point during the installation process, numerous small globules (0.5 in or less) of uncured resin residue waste were discharged on leaf debris immediately outside the culvert outlet and were present up to 60 days following installation. A sample of this pure (uncured) resin left in the stream bed at Site 1 (collected 1 day after installation) had a vinylic monomer concentration of 11,818 mg/L.

Figure 2. Curing Process During Vinyl Ester Based CIPP Installation

Water Sampling Results

Table 5 provides water sampling results from the flowing water test, noting the contaminant concentrations that exceeded the toxicity thresholds for the specified species. The footnotes to the table include qualitative descriptions of the water flow during the flowing water test and the resulting anticipated levels of chemical dilution. These descriptions are intended to only generally capture dilution levels and provide a context for the sampling results. Contaminant concentrations in all control samples taken were below laboratory detection levels (<0.001 mg/L). Contaminant concentrations in all control samples were < 0.001 mg/L.

Table 5. Vinyl Ester Based CIPP Contaminant Concentrations in Water Samples Collected During and After Installation With 15-in-Diameter Stormwater Conveyance

	Vinylic Monomer Concentration (mg/L)	Acrylate Monomer Concentration (mg/L)
Time (after installation)	**Flowing Water**	**Flowing Water**
30 min	76 [a,b]	0.09
14 days	87[a,b]	0.03
21 days	79[a,b]	0.04
28 days	58[a,b]	<0.03
Day 60	19[a]	0.06
Day 90	3[a]	0.08
Day 120	<0.001	<0.001

CIPP = cured-in-place pipe.
All sampling was conducted under conditions that replicated low water flow and low dilution of chemicals.
[a]Above 48-hr LC_{50} or EC_{50} for golden orfe fish (0.4 mg/L).
[b]Above 24-hr LC_{50} or EC_{50} for water flea (26 mg/L).

The maximum concentration of the vinylic monomer was 87 mg/L, which is up to 200 times greater than the toxicity thresholds for the golden orfe fish (a common indicator species). Toxicity thresholds of this contaminant were exceeded for six subsequent sampling events. Acrylate monomer concentrations did not exceed toxicity thresholds.

Evaluation of Findings Relative to VDOT's Styrene-Based CIPP Specifications

The magnitude of the water contamination from the vinyl ester based liner installation is similar to that found with styrene in a previous conventional CIPP study (Donaldson and Baker, 2008). As noted previously, vinyl ester based installations are currently not required to comply with VDOT's styrene-based CIPP specifications. One of VDOT's CIPP specifications requires that for styrene-based CIPP installations, the contractor must place an impermeable sheet immediately upstream and downstream of the host culvert prior to liner insertion and properly dispose of any waste materials (VDOT, 2008b). Another specification requires that the liner be rinsed following installation and that the rinse water be properly disposed of (VDOT, 2008b). Although these specifications are not in place for vinyl ester based CIPP and neither rinsing nor the placement of an impermeable sheet was conducted during the observed installation, adherence to these procedures may have prevented the high contaminant concentrations found in water samples. Placement of an impermeable sheet would have captured some of the escaped uncured resin observed at the installation. Thoroughly rinsing the liner prior to reinstatement of water flow is also expected to reduce any adverse impacts on water quality, given that the sampling results indicated a decrease in contaminant concentrations with each subsequent pouring of water through the culvert.

Finally, one of VDOT's styrene-based CIPP specifications requires the contractor to employ the services of a qualified independent environmental services laboratory or environmental consultant to collect and analyze water and soil samples following the installation (VDOT, 2008b). Given the variety of potential field scenarios and installation variables, it is difficult to capture the range of water sampling results that may be found from a field evaluation of an installation. Adherence to this specification would provide VDOT with additional sampling results and ensure that VDOT is using this lining technology with appropriate environmental safeguards.

UV CIPP

Literature Review

Materials and Installation Procedures

Although UV CIPP materials and installation methods have many similarities to those of conventional and vinyl ester based CIPP, there are notable differences. The first difference is the standard installation of a slip sheet through the host culvert to prevent damage to the liner during insertion (Figure 3A). The second major difference involves the materials. As with conventional CIPP, the resin used for UV CIPP installations contains styrene, but according to a vendor, the resin is one-third the volume of that used in other CIPP methods. This resin is

A **B** **C**

Figure 3. ***A:*** **Installation of UV CIPP Liner, Illustrating Slipsheet Insertion;** ***B:*** **UV Light Train Prior to Insertion in Liner;** ***C:*** **Liner Inflation During UV Cure.**

encapsulated within a fiberglass liner rather than a permeable felt liner, presumably preventing resin and styrene from extruding or leaching. The fiberglass material is enclosed within impermeable outer and inner foils. A UV light train is used to cure the resin. A UV light train is inserted into the liner while the liner is inflated with air pressure (Figure 3B and 3C), and is generally pulled with a rope at approximately 1 ft per minute (depending on culvert diameter). The resin contains a photo-initiator that reacts to the UV light to cure the resin.

The final thickness of the liner is approximately 0.25 to 0.75 in. A camera attached to the end of the light train allows video inspection of the liner during the cure. The light train also houses a temperature sensor. This allows crews to monitor and adjust the degree of heat generated from the UV light to prevent damage to the inner foil. Cooling occurs continuously as the UV lights gradually pass through the culvert. Unlike conventional and vinyl ester based CIPP, the use of UV light rather than steam or hot water does not result in spent cure water and associated issues with its release or disposal. As with other CIPP installation procedures, liners are typically not rinsed or flushed before water flow is reinstated.

Standards and Toxicity Studies

As previously noted, the installation procedures for all methods of CIPP are specified by standards published by ASTM International (2003, 2007). The resin in UV CIPP liners contains styrene, an important industrial chemical used in the synthesis and manufacture of polystyrene and hundreds of different copolymers as well as numerous other industrial resins (Guest, 1997). In June 2011, styrene was listed on the National Toxicology Program's Twelfth Report on Carcinogens (a congressionally mandated document) and was described as being "reasonably anticipated to be a human carcinogen" (National Toxicology Program, 2011). The U.S. EPA (2009) drinking water standard lists the maximum contaminant level (MCL) for styrene as 0.1 mg/L (0.1 parts per million [ppm]). The Clean Water Act requires dischargers to obtain a permit, issued by the U.S. EPA or its designee, for the discharge of any pollutant in a water body (U.S. EPA, 2011).

As reported in Donaldson (2009), numerous acute toxicity studies have documented the impacts of styrene on aquatic organisms. Table 6 provides a summary of published values of acute styrene toxicity studies for several aquatic indicator species that are found in freshwater habitats throughout the United States.

Table 6. Styrene Toxicity Thresholds for Various Freshwater Indicator Species

Aquatic Species	Test Duration and LC_{50} or EC_{50}[a] (mg/L)	NOEC[b] (mg/L)	Reference
Water flea (*Daphnia magna*)	48-hr EC_{50}: 4.7	1.9	Cushman et al., 1997
	48-hr EC_{50}: 1.3	0.81	Baer et al., 2002
Amphipod (*Hyalella azteca*)	96-hr LC_{50}: 9.5	4.1	Cushman et al., 1997
Fathead minnow (*Pimephales promelas*)	96-hr LC_{50}: 5.2	2.6	Baer et al., 2002
	96-hr LC_{50}: 10	4	Machado, 1995
Rainbow trout (*Oncorhynchus mykiss*)	96-hr LC_{50}: 2.5	NA	Qureshi et al., 1982
Freshwater green algae (*Selenastrum capricornutum*)	96-hr EC_{50}: 0.72	0.063	Cushman et al., 1997
	72-hr EC_{50}: 2.3	0.53	Baer et al., 2002

[a]Lethal concentration (LC_{50}) and effective concentration (EC_{50}), or the concentration required to kill (LC_{50}) or have a defined effect on (EC_{50}) 50% of the test population after a given number of hours of exposure in that concentration.
[b]No Observable Effect Concentration, or the highest limit at which no mortalities or abnormalities were observed.

There have been numerous anecdotal reports of damage to aquatic habitat and treatment processes at wastewater treatment facilities from certain repair technologies (Whelton et al., 2012). In 2011, a moratorium on CIPP was enacted in Ontario, Canada, in response to a fish kill (McLuckie, 2011). Reports on few of these types of incidents have been published or have resulted in new standards or procedures, with the exception of those of three transportation agencies (to date): VDOT, the New York State Department of Transportation (DOT), and the California DOT. Styrene concentrations following steam and hot water CIPP installations on road culverts in Virginia (Donaldson, 2009) and New York (New York State DOT, 2008) were up to 2 and 3 orders of magnitude greater (respectively) than the LC_{50} or EC_{50}[a] values listed in Table 2. As a result, new specifications for CIPP repair were developed by VDOT, the New York State DOT (2011), and the California DOT (2011). These specifications were primarily developed to ensure the proper capture and disposal of spent process water and to minimize leaching of unpolymerized styrene or other resin constituents.

Installation Observations

Because Company A’s installations served as a demonstration project that was not installed in a VDOT culvert, installations followed the company’s standard procedures rather than VDOT’s CIPP specifications. Company B’s liner was installed in a VDOT culvert in compliance with VDOT specifications.

For Company A and Company B installations, cutting of the ends of the new liners following the curing period resulted in a heavy scattering of liner shavings around the inlet and outlet. There was no visible uncured resin residue waste during or following either installation.

Water Sampling Results

Tables 7 and 8 list the water sampling results from the flowing water and immersion tests for Company A and Company B, respectively. Both tables include qualitative descriptions of

Table 7. UV CIPP Styrene Concentrations in Water Samples Collected After Installation (2 18-in-Diameter Liners), Company A

Time (after installation)	Styrene Concentration (mg/L)		
	Liner 1: Flowing Water Test	Liner 2: Flowing Water Test	Liners 1 and 2: Immersion Test
End of installation (rinse water)	<0.001	<0.001	
30 min	<0.001	<0.001	
1 day	<0.001	<0.001	<0.001
3 days	<0.001	<0.001	<0.001

UV CIPP = ultraviolet cured-in-place pipe.
All sampling was conducted under conditions that replicated low water flow and low dilution of chemicals.

Table 8. UV CIPP Styrene Concentrations Including Chemical Dilution Descriptions in Water Samples Collected After Installation (30-in-Diameter Surface Water Conveyance), Company B

Time (after installation)	Styrene Concentration (mg/L) and Dilution Description		
	Flowing Water Test	Flowing Water Test	Immersion Test
End of installation (rinse water)	0.091[a]		
30 min	0.335[a] (H)	0.007 (H)	
1 day	0.014 (H)	0.001 (H)	0.53[a]
2 days	0.022 (H)	0.004 (H)	9.04[a,b,c]
3 days	0.008 (H)	0.002 (H)	
7 days	0.001 (M)	<0.001 (M)	12.90[a,b,c]
14 days	0.006 (L)		12.60[a,b,c]
21 days	0.002 (L)		10.30[a,b,c]
35 days			7.13[a,b,c]
49 days			0.58[a]

(H) = high; (M) = medium; (L) = low.
[a]Above maximum contaminant level for drinking water (0.1 mg/L).
[b]Above 96-hr LC_{50} for rainbow trout (2.5 mg/L).
[c]Above 48-hr EC_{50} for water flea (4.7 mg/L).

water flow and resulting anticipated levels of chemical dilution. These descriptions are intended to capture dilution levels only generally and provide a context for the sampling results. Styrene concentrations in all control samples from the flowing water tests and from the immersion tests were below laboratory detection levels (<0.001 mg/L).

Styrene concentrations in all water samples taken following Company A's two liner installations were below 0.001 mg/L. Following Company B's installation, although styrene was detected in samples of flowing water, styrene concentrations did not exceed the toxicity thresholds for aquatic species in any of the eight samples collected at the outlet from the flowing water test. These thresholds were exceeded in five subsequent samples of standing water from the immersion test, with a maximum styrene concentration of 12.9 mg/L. These results indicate that styrene leaching from the liner was mitigated by water flow.

Evaluation of Findings Relative to VDOT's Styrene-Based CIPP Specifications

Because Company B's liner was installed in a VDOT culvert, VDOT's existing styrene-based CIPP specifications were followed. Styrene concentrations following both Company A and Company B's installations were low in samples collected from flowing water but exceeded toxicity thresholds in the immersion test of Company B's liner. As was the case with Company B's installation, some degree of leaching from the liner is mitigated by water flow and is therefore safe for aquatic species, but further analyses would be necessary to determine acceptable levels of leaching for given conditions (i.e., flow regularity and water volume conveyed by culvert). Adherence to VDOT's specification that requires the collection and analyses of water and soil samples following CIPP installations (VDOT, 2008b) would provide VDOT with additional sampling results from liners installed in varying field conditions and ensure that VDOT's CIPP specifications are sufficient for mitigating risks to water quality.

DISCUSSION

Vinyl Ester Based CIPP

Although the vinyl ester based resin used in this method of CIPP repair does not contain styrene, the primary chemicals in the resin can also be toxic if released or leached into surface water. Concentrations of a vinylic monomer in the water that flowed through the liner were above the toxicity thresholds for aquatic species up to 90 days following installation, or six subsequent sampling events (for a maximum concentration of 87 mg/L). Water samples were collected under test conditions that simulated a worst case scenario with low water flow and low dilution potential. Higher flow volumes may have resulted in lower contaminant concentrations.

The elevated contaminant levels could have resulted from (1) contact of the sampled water with uncured resin that escaped from the liner during installation or following installation; (2) insufficient curing of the resin-saturated liner; and/or (3) some degree of permeability in the lining material. The degree to which the vinylic monomer contaminant exceeded toxicity thresholds was similar to that found with styrene in a previous conventional CIPP study (Donaldson and Baker, 2008) prior to the development of VDOT's CIPP specification. Adherence to VDOT's existing styrene-based requirements (with slight modifications to the styrene testing requirement) is expected to minimize contaminant concentrations.

UV CIPP

Styrene concentrations in all flowing water samples from the UV CIPP installations were below toxicity thresholds for aquatic species. Specifically, flowing water styrene concentrations were below detection levels following Company A's installations of two liners and were a maximum of 0.335 mg/L following Company B's installation. Although this concentration was above the MCL of drinking water, it was below toxicity thresholds for aquatic species and 1 to 2 orders of magnitude lower than maximum concentrations found following conventional CIPP installations (Donaldson, 2009; New York State DOT, 2008). It is important to note that the differences in styrene concentrations in water samples collected following Company A's installations and those following Company B's installation may be attributed to the types of demonstration installations rather than differences in materials or installation procedures between the companies. Unlike Company B, Company A provided an above-ground demonstration installation. Because this liner was not designed to meet specified load requirements, the liner comprised less material and resin than those required for Company B's liner.

Although styrene levels were below toxicity thresholds for aquatic species in all samples taken from the culvert outlet (where water flow was continual) following both companies' liner installations, concentrations were elevated in the immersion test of Company B's liner. Styrene leaching from the liner was likely a result of insufficient curing of the resin and/or some degree of permeability in the lining material. No escaped uncured resin was observed during or following installations. For Company B's installation, the contrast between styrene concentrations in samples collected from the flowing water versus those from the standing water in the immersion test underscored the effect of water flow on chemical residence time and dilution. Despite styrene's high rate of volatilization (Alexander, 1997), styrene accumulated in the standing water as it leached from the liner. The peak concentration of 12.9 mg/L occurred 7 days following immersion, followed by a gradual reduction in concentration as a result of the depletion of unpolymerized styrene from the liner. Concentrations were above toxicity thresholds for a minimum of 35 days following immersion. Given these results, it is expected that in road culverts where standing water exists at the outlets, any residual styrene may first accumulate before concentrations decrease as a result of volatilization and being diluted to some extent in a subsequent water flow event. Additional field evaluations that capture a range of field scenarios (e.g., flow volumes and regularity, culvert slope, etc.) would be necessary to allow a better understanding of the acceptable levels of leaching for given conditions.

Factors That Affect Leaching From CIPP Liners

After examination of the sampling results in the context of the installation observations and literature review in this study and those from the previous conventional CIPP evaluation (Donaldson and Baker, 2008), several factors appeared to affect the degree to which chemicals leach from a CIPP liner. One of these was the flow and associated dilution of water conveyed by the culvert. Following a UV CIPP installation, styrene concentrations in water samples collected from standing water were greater than those collected from a culvert outlet with water flow.

Other factors that affected contaminant leaching were associated with the material and installation procedures, as reflected by the different contaminant concentrations of water samples collected following UV CIPP installations and those following vinyl ester based and conventional CIPP (Donaldson and Baker, 2008). These included the following:

- *Lining material*. Conventional and vinyl ester based CIPP technologies typically use felt liners that do not encapsulate the resin. These materials have some degree of permeability and allow for the transfer of resin into cracks and holes in the host culvert, where the resin is further from the high temperatures during the curing process. Incompletely cured resin is one likely cause of the high contaminant concentrations found in water following CIPP installations (Donaldson and Baker, 2008). UV CIPP liners comprise a layer of fiberglass embedded between two foils that minimize the transfer of resin into cracks or holes and the escape of raw resin from the ends of the liner. No extruded resin was visible in the UV CIPP installations monitored, whereas extruded resin was noted during the vinyl ester based CIPP installation and previously monitored conventional CIPP installations (Donaldson and Baker, 2008; New York State DOT, 2008).

- *Resin volumes*. UV CIPP vendors maintain that their technology uses two-thirds less volume than conventional and vinyl ester based CIPP while providing the same degree of structural strength. Resin volume varies by the number of layers (or mat thickness) used, which is project dependent. A greater volume of resin used may increase the likelihood of raw resin spilling or seeping from the liner ends during installation. Samples of raw resin that escaped during conventional CIPP and vinyl ester based CIPP liner installations had extremely high contaminant concentrations (580 mg/L of styrene and 11,818 mg/L of vinylic monomer, respectively [Donaldson and Baker, 2008]).

- *Curing method*. Conventional and vinyl ester based CIPP installations use hot water or steam to cure the resin, which requires the capture of effluent to avoid contamination of receiving waters. UV CIPP uses UV light rather than hot water or steam and therefore produces no effluent. The highest contaminant concentrations occurred during the release of curing effluent in previously monitored installations (Donaldson and Baker, 2008), although VDOT specifications now require the capture and proper disposal of cure water.

CONCLUSIONS

- *Concentrations of a vinylic monomer in water samples collected following the installation of a vinyl ester based CIPP liner exceeded the toxicity thresholds for aquatic species.* Concentrations of this resin constituent were above the toxicity thresholds in water flushed through the liner for up to 90 days following installation, or six subsequent sampling events.

- *Adherence to VDOT's CIPP specifications (which are currently limited to styrene-based installations) is expected to reduce the high contaminant concentrations found following installation of a vinyl ester based CIPP liner*. A modification to the specification's sampling requirement that is specific to vinyl ester based liners (i.e., the type of chemical required for sample analysis) would be necessary to ensure that samples are analyzed for the appropriate chemical.

- *Styrene concentrations in water samples collected following UV CIPP installations exceeded the toxicity thresholds for aquatic species in standing water but were below toxicity thresholds in flowing water*. Styrene concentrations in water samples collected from flowing water tests and standing water tests of Company A's liner were below 0.001 mg/L. In water samples collected following Company B's liner installation, residual styrene accumulated in standing water (up to 12.9 mg/L), but concentrations in all eight water samples (collected up to 21 days following installation) at a culvert with water flow were below the toxicity thresholds for aquatic species.

- *Adherence to VDOT's existing CIPP specifications is expected to mitigate any adverse impacts on water quality from UV CIPP installations.*
- *For both styrene-based and styrene-free CIPP installations, adherence to VDOT's CIPP specification that requires the collection and analyses of water and soil samples following installation would (1) provide VDOT with additional sampling results from liners installed in varying field conditions, and (2) help ensure that VDOT's CIPP specifications sufficiently mitigate risks to water quality.*

RECOMMENDATION

1. *VDOT's Materials Division in consultation with VDOT's Scheduling and Contracts Division, Location and Design Division, and Environmental Division should revise the current CIPP specifications listed in VDOT's Special Provision for Pipe Culvert Replacement or Rehabilitation (VDOT, 2008b) as follows:*
    - Remove the word "styrene-based" such that the CIPP requirements also apply to vinyl ester based and other forms of styrene-free CIPP installations.
    - Add a water sampling requirement specific to vinyl ester based CIPP that requires the analyses of water samples for diallyl phthalate. The existing styrene water testing requirement for styrene-based CIPP should remain.

BENEFITS AND IMPLEMENTATION PROSPECTS

Based on industry estimates, CIPP liners are expected to add 40 to 45 years of additional service life to the pipe (Cooney et al., 2011). Because the service life of unconventional CIPP liners has not been evaluated in field installations, actual life cycle costs are difficult to estimate. Cooney et al. (2011) provided information on the per linear foot costs. According to a 2004 study by Snyder (cited in Cooney et al., 2011), an average cost estimate for a CIPP liner with a 0.25 in minimum wall thickness was $150 per linear foot for a pipe 8 inches in diameter. Costs increase with diameter as a result of higher material weight and associated installation challenges (Synder, 2004, cited in Cooney et al., 2011).

Increased regulatory scrutiny of stormwater culverts has recently increased pressure on VDOT to find environmentally sound methods of culvert repair. A public notice issued in March

2010 by the U.S. Army Corps of Engineers regarding stormwater culvert permitting requirements resulted in a change to VDOT's culvert repair selection process. Prior to the public notice, application of pneumatically applied concrete (also known as "shotcrete") over damaged culvert floors was an affordable and common method of culvert repair in some VDOT districts. Because these applications result in raised culvert bottom elevations, concerns by the U.S. Army Corps of Engineers regarding their effect on stream dynamics and passage by aquatic organisms resulted in a recent increase in the enforcement of VDOT's permitting requirements (U.S. Army Corps of Engineers, 2010). The consequent added labor, costs, and project delay to VDOT has decreased the number of culverts repaired with concrete. Because the use of CIPP liners results in a nominal increase in bottom elevation (0.25 to 1.0 in), their availability as options for culvert repair provides VDOT with greater flexibility and efficiency in repairing damaged culverts.

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