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Critical Review: Surface Water and Stormwater Quality Impacts of Cured-In-Place Pipe Repairs

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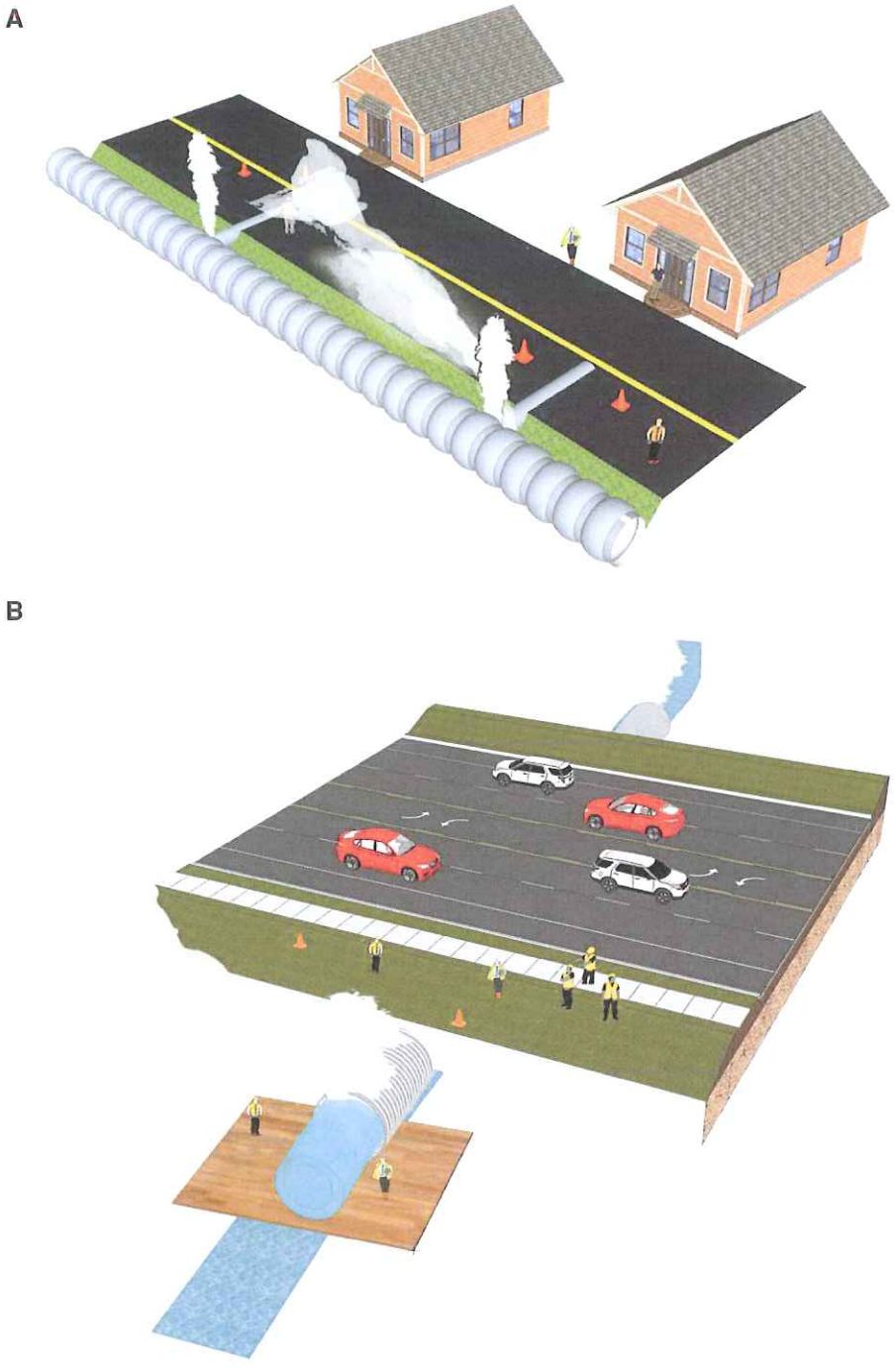
Cured-in-place pipe (CIPP) technology has been used to rehabilitate sanitary sewer, storm sewer, and drinking water pipes. However, utilities, regulators, and health officials have raised environmental, occupational, and public health concerns regarding chemical emissions into air and water. To better understand emissions into water, available literature was reviewed. Water contamination has been documented in 10 states and Canada because of the release of uncured resin, solvents, manufacturing byproducts, and wastes during and after construction. Odor, fish kill, and drinking water contamination incidents have been reported. The few field- and bench-scale studies available show that a variety of volatile organic compounds and semivolatile organic compounds have been released into water and contamination was detected for several months. CIPP waste was acutely toxic to aquatic organisms. Chemical release is likely influenced by formulation, installation, and environmental conditions. CIPP installation and inspection recommendations were suggested. Studies are needed to develop evidence-based construction and monitoring practices to minimize risks.

Keywords: *cured-in-place pipe, leaching, plastic pipe, rehabilitation*

Cured-in-place pipes (CIPPs) are increasingly being installed to repair sanitary sewer, storm sewer, and drinking water pipes (Stratview Research Inc. 2017). The CIPP installation process was invented in the 1970s (Wood 1979, 1977) and involves the chemical manufacture of a new plastic pipe inside an existing damaged pipe (Figure 1). This in situ process helps avoid open-trench excavation, damaged pipe replacement, and roadway shutdowns (Piratla & Pang 2017, Morrison et al. 2013). Because many pipes across the United States need to be repaired, CIPP technology use is expected to increase in coming years (Stratview Research Inc. 2017).

Utilities, regulators, and health officials recently have raised concerns regarding chemical emission occurring during and after CIPP installation. In July 2017, the California Department of Public Health (CDPH) issued a safety alert (Figure 2) on the basis of their own investigation of residential building chemical contamination caused by a CIPP sanitary sewer installation (CDPH 2017a). Also in July, a CIPP air testing study described 59 publicly reported, unique air contamination incidents (Teimouri et al. 2017). Some incidents involved complaints of odors, whereas others involved associated health symptoms, including incidents in which people were administered medical assistance at schools, day care centers, offices, or residences. Additional air contamination incidents were reported at elementary schools and/or residential buildings in California, Indiana, Missouri, New York, and Pennsylvania (De la Batisde 2017, Kelly 2017, Kennedy 2017, Landstra 2017, Saunders & Boone 2017, Staff 2017). In September 2017, the CDPH issued a second statement about CIPP that included "Persons who detect an odor and experience health symptoms... should contact their medical provider and local health

FIGURE 1 Generic schematic showing possible chemical emissions into the air while cured-in-place pipes are being installed for sanitary sewer pipe (A) and storm sewer pipe (B)

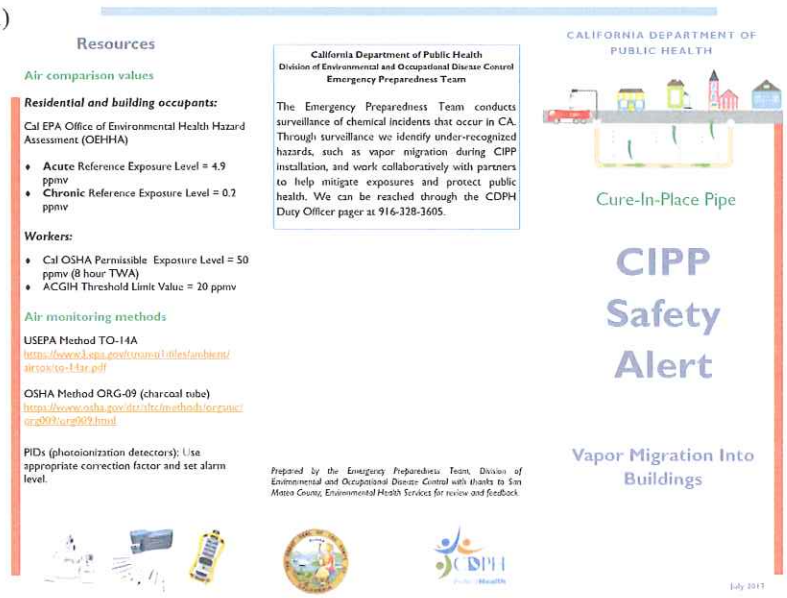


The type and magnitude of emissions may depend on the materials used, installation practices, environmental, and site conditions.

department; utilities, engineering firms, and contractors should not tell residents the exposures are safe. There is no credible testing data for all CIPP installation scenarios" (CDPH 2017b). In October, a worksite fatality during an Illinois sanitary sewer CIPP installation triggered a federal investigation (Peterson 2017). A study by Teimouri et al. (2017) revealed a lack of independent third-party, peer-reviewed data about chemical

FIGURE 2 Public statements issued by the California Department of Public Health: July 2017 (A) and September 2017 (B)

(A)



Resources

Air comparison values

Residential and building occupants:

Cal EPA Office of Environmental Health Hazard Assessment (OEHHA)

- **Acute** Reference Exposure Level = 4.9 ppmv
- **Chronic** Reference Exposure Level = 0.2 ppmv

Workers:

- Cal OSHA Permissible Exposure Level = 50 ppmv (8 hour TWA)
- ACGIH Threshold Limit Value = 20 ppmv

Air monitoring methods

USEPA Method TO-14A
https://www3.epa.gov/ttnamti1/files/ambient/airtox/to-14ar.pdf

OSHA Method ORG-09 (charcoal tube)
https://www.osha.gov/dts/sltc/methods/organic/org009/org009.html

PIDs (photoionization detectors): Use appropriate correction factor and set alarm level.

California Department of Public Health
Division of Environmental and Occupational Disease Control
Emergency Preparedness Team

The Emergency Preparedness Team conducts surveillance of chemical incidents that occur in CA. Through surveillance we identify under-recognized hazards, such as vapor migration during CIPP installation, and work collaboratively with partners to help mitigate exposures and protect public health. We can be reached through the CDPH Duty Officer pager at 916-328-3605.

Prepared by the Emergency Preparedness Team, Division of Environmental and Occupational Disease Control with thanks to San Mateo County, Environmental Health Services for review and feedback

CALIFORNIA DEPARTMENT OF PUBLIC HEALTH

Cure-In-Place Pipe

CIPP Safety Alert

Vapor Migration Into Buildings

July 2017

(B)

Cure-In-Place Pipe (CIPP) Additional Considerations for Municipalities

Background

CDPH Alert

The CDPH Cure-In-Place Pipe (CIPP) Safety Alert, issued in July 2017, is not a comprehensive engineering guide for controlling chemical releases; rather, its purpose is to raise awareness and provide some steps that should be considered by municipalities permitting CIPP projects in their jurisdiction.

Concerns

Studies of chemical releases during the installation and curing of CIPP are limited and protocols for controlling exposures have not been developed. Safety Data Sheets (SDS) do not describe all of the compounds present in the raw materials or emitted into the air during CIPP installation.

A July 2017 study conducted by Purdue University (http://pubs.acs.org/doi/10.1021/acs.estlett.7b00237) shows steam released during the installation process is made up of a complex mixture of volatile (VOC) and semi-volatile organic compounds (SVOC), including styrene, acetone, phenol, phthalates and others.

CIPP installations can emit multiple chemicals into the air, some of which may be toxic. There is no credible testing data for all CIPP installation scenarios. The odor produced by a CIPP installation may be caused by one or more compounds in the air.

The public, workers involved in CIPP installations, and first responders can be exposed to toxic vapors. The following provides additional considerations for municipalities that utilize CIPP technology in their jurisdiction.

Considerations

Health

Persons who detect an odor and experience health symptoms near CIPP installation sites should contact their medical provider and local health department.

Air monitoring

Four-gas meters, commonly used by the first responders, do not detect styrene or other chemicals emitted during the CIPP process.

Installation

Utilities, engineering firms, and CIPP contractors should not tell residents the exposures are safe.

The pressure from the CIPP process can blow water out of toilets or drains allowing vapors to enter. Filling up plumbing traps with water does not guarantee vapors will not enter through other building entry points such as cracks in foundations, doors, windows, and air intakes.

emissions into the air. In addition to Teimouri et al. (2017), only four other studies have described air monitoring (Ajdari 2016, ATSDR 2005, Bauer & McCartney 2004, AirZone Inc. 2001). More work is needed to understand the type and magnitude of emissions as well as the short- and long-term health impacts of exposure.

Chemical release into water is also a concern. Six years ago, a review of 14 state transportation agencies by the California Department of Transportation (CALTRANS) was conducted. The study indicated four states (New York, Oregon, Virginia, and Washington) reported water quality issues, and styrene release into waterways was the most reported problem (CTC & Associates LLC 2012). CIPP installations can also generate wastes, and these materials have been associated with wastewater treatment plant (WWTP) upsets (Sullo 2012, Henry 2007). At one point, some New York WWTPs banned the discharge of CIPP wastewater to the sanitary sewer (Silcuna 2010). Two organizations concluded that CIPP wastewater could be discharged to the sanitary sewer if its styrene concentration was less than 2 (Loendorf & Waters 2009) and 0.4 mg/L (MENP 2004), respectively. Styrene is a common chemical used in the manufacture of some CIPPs, is "reasonably anticipated to be a human carcinogen" (USNTP 2011), and is toxic to aquatic organisms at more than 0.072 mg/L (USEPA 2006). However, styrene is not the only chemical that can be released from CIPP installations. The type and magnitude of chemicals released is likely formulation dependent and influenced by installation and environmental conditions. While styrene-based resins are popular, nonstyrene resins also are available (Doherty et al. 2017). Concerns about chemical emission from storm sewer pipe repairs have previously prompted temporary CIPP technology bans in Virginia (Griffin 2008), California (CTC & Associates LLC 2012), and Canada (McLuckie 2011).

To understand the potential for chemical emission during and after a CIPP installation, knowledge of the installation process is needed. For CIPP installations, raw chemicals and materials are transported to the worksite. Vinyl ester and polyester resins often are used for gravity sewer CIPPs, whereas epoxy is used for force mains because of the added strength it provides (NASSCO Inc. 2011). Drinking water CIPPs have historically used epoxy resins, and manufacturers have submitted epoxy products for Standard 61 testing (Matthews et al. 2012a, 2012b). The uncured resin tubes generally are constructed of felt and/or reinforcing fiber. Sometimes these fabrics have coatings (i.e., polypropylene, polyethylene, polyvinylchloride). Thermally cured materials are also often transported in refrigerated trucks, but ultraviolet (UV)-cured materials do not have this same transportation requirement. Once onsite, the uncured resin tube is set in place by applying pressurized air inside the resin tube so that it expands and contacts the inner pipe walls. For some installations, the resin is manually inserted into the resin tube on site. A CIPP is created after the tube is hardened by either thermal (hot water or steam) or UV light-curing methods (Doherty et al. 2017). Curing facilitates resin polymerization and chemical cross-linking. Curing time is dependent on the length of the pipe, the liner thickness, the resin composition, and a variety of other factors. A plastic "preliner" can be inserted into the pipe before the uncured resin tube is inserted. This preliner reportedly reduces the amount of resin that exits the tube and reduces the amount of water that enters the tube before beginning the facilitated curing process (Najafi 2010). After the contractor stops the facilitated curing process, the liner is often cooled by forcing hot air or ambient air through the tube, and the liner ends are removed. While the liner is now "solid," the total CIPP "cure time" reportedly can take six months (ATSDR 2005). Base resins can contain different monomers (i.e., styrene or bisphenol A diglycidyl ether), stabilizers (i.e., hydroquinone, Interplastic Corporation 2016), and fillers (i.e., talc, AOC 2013; crystalline silica, AOC 2013; silica colloidal amorphous, Ashland 2011; sodium metasilicate, Interflow Pty. Ltd. 2008). Because initiators present in the resin chemically react during the creation of a new CIPP, new volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs) can be created during the curing process (Table 1; Teimouri et al. 2017, Tabor et al. 2014). Phthalates are also associated with some initiators (Table 1; ICTRD 2007). Wastewater, condensate, and rinse water can be generated during certain installation processes.

At present, limited chemical emissions data are publicly available for drinking water and sanitary sewer CIPP installations. Therefore, only bench- and field-scale chemical emissions data collected during and after storm sewer pipe CIPP installation were reviewed in this study. These data should be useful for outlining future research on storm sewer CIPP installations. Results should also be useful in outlining future research and anticipated issues with respect to sanitary sewer and drinking water CIPP installations. The study objectives were to (1) compile and review CIPP-related surface water contamination incidents from publicly reported data; (2) analyze CIPP water quality impacts; (3) evaluate current construction practices for CIPP installations as reported by US state transportation agencies; and (4) review current standards, textbooks, and guideline documents. Surface water contamination incidents were defined as those that involved pollutant discharge outside a sanctioned CIPP field study.

TABLE 1 List of degradation products reported for some initiators used for CIPP installations

Perkadox®[a]	Trigonox®[a]	Butanox®[a]	*N,N*-Dimethylaniline	Norox®[b]
Benzene[HAP,CAR,EDC] Benzoic acid 4-*tert*-Butylcyclohexanone 4-*tert*-Butylcyclohexanol Carbon dioxide Diphenyl[HAP] Phenylbenzoate Tetradecanol	Acetone Acetophenone[HAP] Benzene[CAR, EDC, HAP] Benzoic acid *tert*-Amyl alcohol *tert*-Butanol 3-*tert*-Butoxyheptane 2-*tert*-Butyloxy-2,4,4-trimethylpentane Carbon dioxide 3-(1,1,Dimethylpropoxy) heptane Ethane 2-Ethylhexanoic acid Heptane Methane 2-Phenylisopropanol 3,3,5-Trimethylcyclohexanone	Acetic acid Carbon dioxide Formic acid Propanoic acid Methyl ethyl ketone[CAR, HAP]	Aniline[HAP] Carbon oxides Nitric oxides[HAP]	No degradation products listed

CAR—suspected or confirmed carcinogen, CIPP—cured-in-place pipe, EDC—endocrine disrupting compound, HAP—hazardous air pollutant as defined by US Environmental Protection Agency

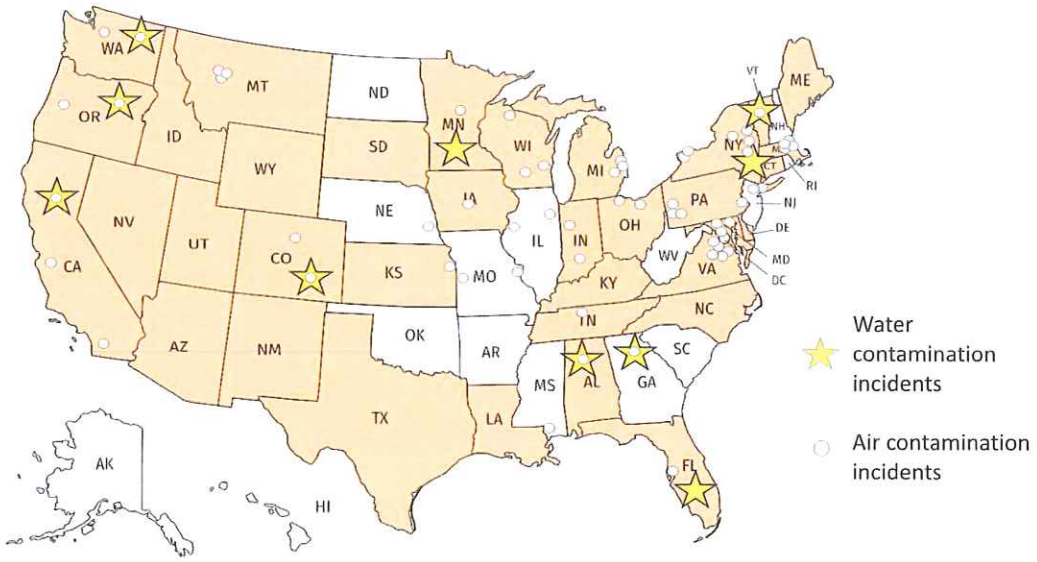
Information provided is based on a review of initiator safety data sheets found for CIPP installations; CIPPs manufactured in ambient conditions have reportedly used benzoyl peroxide initiator systems (ICTRD 2006), but decomposition products for these systems were not found in the literature search; Norox® initiators were also listed, but no decomposition products were reported (United Initiators Inc. 2017a, 2017b). Initiator information was obtained from Puritan Products Inc. (2016), United Initiators Inc. (2015, 2017a, 2017b), and Akzo Nobel (2016a, 2016b, 2015a, 2015b, 2015c, 2015d, 2015e, 2015f, 2008a, 2008b, 2008c, 2008d, 2008e). According to safety data sheets, some Perkadox® products also contained dipropylene glycol dibenzoate, water, and dicyclohexyl phthalate, and some Trigonox® products contained BBP, DBP, and dioctyl phthalate (AOC 2007). Parent initiator compounds were not included in this table. This table may not account for all initiators used, the complete composition of initiator products, or initiator degradation products. Some compounds were found because they were reported in Das (2016), Allouche et al. (2014, 2012), and other references cited in this article.

[a]AkzoNobel, Chicago, Ill.
[b]United Initiators, Inc., Elyria, Ohio

METHODS

A literature review was conducted to identify available bench- and field-scale research studies pertaining to CIPP-associated chemical emissions. Scientific databases, foundation research reports, conference proceedings, trade association literature, AWWA and ASTM standards, trenchless technology textbooks, and state transportation agency research reports were reviewed. One

FIGURE 3 Publicly reported CIPP storm sewer and sanitary sewer water and air contamination incidents found in the United States



CIPP—cured-in-place pipe

author completed a 1.5-day CIPP construction inspector training course in 2017. Thirty-five state transportation agencies were contacted as part of this study and were not randomly selected (Figure 3). Agencies were identified from their prior support, participation in, or conduct of CIPP water quality impact studies. Agencies were also selected on the basis of their prior publication of reports that evaluated the feasibility of CIPP use for culvert repair. Other agencies were contacted in which CIPP-related contamination incidents occurred. Each agency was asked for a copy of its current CIPP construction specifications, and any documented special provisions for pipe rehabilitation. In addition, literature and media reports were reviewed to identify previous surface water contamination incidents associated with CIPP installations.

RESULTS AND DISCUSSION

Water contamination incidents: Literature and media reports. Thirteen water contamination incidents were found and they occurred in 10 states (Alabama, California, Colorado, Connecticut, Florida, Georgia, Minnesota, Oregon, Vermont, Washington), an unreported location, and Canada (two incidents; Figure 3; Shearer 2016; Barker 2013; Renda 2013; VTDEC 2013; CDOT 2012; CTC & Associates LLC 2012; Marohn 2011a, 2011b, 2011c; MTO 2011; Weldon & Morton 2011; ADEM 2010; NRC 2010; WSDOE 2010; Donaldson 2009; O'Reilly 2008; Gerrits 2007; LMES 2007; GESI 2004). Eleven incidents were first identified by the detection of an odor or fish kill. Two incidents were first identified by people complaining about their drinking water, which had been contaminated by nearby CIPP stormwater pipe repair activities. In particular, chemicals were released from the CIPP stormwater pipe construction site, traveled downstream through a nearby drinking water system, and the contaminated water was provided to the affected population. A limited amount of information about each incident was reported. Often only the presence of styrene was reported when chemicals were mentioned, but a review of water testing records revealed additional CIPP-associated chemicals were sometimes present.

A commonality across most incidents was that they were caused by contractor material or waste handling (i.e., release into the environment of CIPP wastewater, uncured resin, condensate, or other materials). For example, in Georgia, 2,000–3,000 gal of CIPP wastewater was discharged into a creek. This incident was first detected by an odor complaint on a university campus (UGA 2016). Water testing was conducted about 1,000 ft downstream of the discharge point 19 h later (US Environmental Protection Agency [USEPA] Method 8260B) and revealed the presence of 1,3,5-trimethylbenzene (TMB; 1.72 µg/L), *tert*-butylbenzene (2.80 µg/L), acetone (512 µg/L), and styrene (1,300 µg/L). In response to a contamination incident in Oregon, "[T]he styrene levels were so high [the] responder had to wear a respirator to collect samples" (CTC & Associates LLC 2012). Twelve days after the incident in Connecticut, 291 µg/L styrene was found downstream (GESI 2004). Regarding the incident in Minnesota, spilled resin reportedly remained in a surface water for five months (Marohn 2011a, 2011b, 2011c).

The greatest amount of detail was found for the CIPP-related water contamination incidents in Alabama, Colorado, and Vermont. In 2010, the National Response Center (NRC) reported that a CIPP-lining contractor released about 70,000 gal of CIPP wastewater to a dry creek bed in Alabama (NRC 2010). The waste traveled downstream and contaminated a residential drinking water well. The creek-water styrene concentration was 143 mg/L, and the concentration in contaminated drinking water from a nearby well was 4 mg/L. The USEPA's styrene drinking water maximum contaminant level (MCL) is 0.1 mg/L (USEPA 1991). Alabama's environmental regulatory agency noted that the contractor violated state code with an unpermitted pollutant discharge, and that mitigative and investigative actions were required (ADEM 2010). The water testing methods, laboratory reports, and the presence of other chemicals in the contaminated waters were not found.

In 2011, CIPP wastewater was released from a storm sewer pipe repair site into Clear Creek in Colorado. Residents and employees at a nearby ski resort were the first to report the problem and complained about odor and illness symptoms caused by the drinking water (CDOT 2012, Weldon & Morton 2011). The incident prompted a response by Colorado's transportation, environmental protection, and health agencies. The response revealed that a surface water and the community's drinking water were contaminated. An alternate drinking water supply was provided to the affected community. Testing (USEPA Methods 624 and 625) indicated that the CIPP wastewater contained styrene and other VOCs, including 1,2,4-TMB, 1,3,5-TMB, acetone, benzene, ethylbenzene, isopropylbenzene, *n*-propyl benzene, *o*-chlorotoluene, *p*-isopropyltoluene, and xylenes. Some SVOCs also were detected in samples and included diethyl hexyl phthalate (DEHP), benzoic acid, isophorone, and butyl benzyl phthalate (BBP). DEHP was found at 0.0026 mg/L and exceeded the minimum Colorado groundwater and chemical standard of 0.0025 mg/L (CWQCC 2016). The federal drinking water MCL of 0.006 mg/L was not exceeded (USEPA 2009). The maximum styrene concentration was found to be 18 mg/L in water and 14 mg/kg in soil. State officials analyzed the water at the culvert's inlet and outlet for pH, total organic carbon (TOC), chemical oxygen demand (COD), total suspended solids, total dissolved solids, oil and grease, total residual chlorine, and flowmetering. Styrene and DEHP were found at the outlet of three culverts during the investigation. Styrene

was detected in surface water for 119 days. VOCs (USEPA Methods 524.2 and 624), SVOCs (USEPA Methods 525.2 and 625), compounds not expected to be associated with the CIPP installation (such as pesticides), and polychlorinated biphenyls were also analyzed with results of nondetect or below regulatory limits.

In 2013, a CIPP storm sewer pipe installation in Vermont contaminated a ½ mi creek reach and negatively impacted fish communities (Barker 2013, VTDEC 2013). The day after the installation, a resident complained that his dog became sick after drinking creek water. Emergency responders and state transportation officials investigated. Water samples were collected and analyzed for VOCs (USEPA Method 8260) the day following the CIPP installation and periodically during a 70-day period. Styrene creek levels were reported at three downstream locations the day following the CIPP installation (206, 5,160, and 770 mg/L). (Note that information described here was reported in Vermont Department of Environmental Conservation [VTDEC 2013]. Questions regarding details about this water contamination incident and the reported data may be directed to the VTDEC.) Styrene is soluble in water at 6–51°C from 0.029 to 0.045% (Lane 1946). Results suggested that styrene may have been adsorbed to colloidal resin particles, was present in stabilized droplets as a microemulsion, and/or within a separate nonaqueous liquid phase attached as droplets to resin particles. Downstream styrene levels decreased over the two-month monitoring period: measured at 16 h (3.26, 3.22, 2.36 mg/L), at 28 days (0.228, 0.160, 0.513 mg/L), and at 70 days (0.08, 0.06, 0.03 mg/L). A closer review of the laboratory water analysis reports indicated other compounds were also present: acetone (1.39, 4.88, and 1.81 mg/L), 1,2,4-TMB (<0.1, 0.49, 0.1 mg/L), 1,3,5-TMB (<0.1, 0.129, <0.1 mg/L), and *tert*-butanol (<1, 5.49, <1 mg/L; Spectrum Analytical Inc. 2013a, 2013b, 2013c, 2013d). Water quality standards were not found in Vermont for these compounds, but these compounds had water quality standards in other states that would have been exceeded. The contractor proposed removing resin from contaminated rocks with acetone, but state officials discouraged this action.

Bench- and field-scale studies: Water quality impacts. Several studies have identified construction practices that can reduce CIPP water quality impacts. The earliest study was conducted in 2008 by the Virginia Department of Transportation (VDOT). During this project, stormwater quality was monitored at seven steam-CIPP sites (Donaldson 2009). Water samples were collected before, during, and after installation. All samples were analyzed for VOCs (USEPA Method 8260B). Styrene concentrations exceeded the USEPA drinking water MCL at five of the seven study sites during and after installation. Styrene exceeded toxicity thresholds for common indicator species (i.e., the water flea [*Daphnia magna*] and the rainbow trout [*Oncorhynchus mykiss*]) at four project sites. Styrene levels differed based on sampling location, and a maximum 77 mg/L was detected. Styrene remained detectable in water up to 88 days after the installation. The presence of other VOCs and their method detection limits (minimum concentration of a substance that can be measured and reported with 99% confidence that the analyte concentration is greater than zero) were not reported. VDOT concluded that

> ...the findings resulted from one or a combination of the following: (1) installation practices that did not capture condensate containing styrene, (2) uncured resin that escaped from the liner during installation, (3) insufficient curing of the resin, and (4) some degree of permeability in the lining material.

Following these findings, VDOT suspended styrene-based CIPP until additional research was conducted to gain a better understanding of the technology and its potential impacts. VDOT also created specifications for styrene-based CIPP to reduce the potential for water quality impacts, and then permitted CIPP use.

In 2008, the New York State Department of Transportation (NYSDOT) conducted a study to investigate styrene release into a surface water by hot-water CIPP (O'Reilly 2008). Water samples before and after CIPP installations at four different culverts were characterized for VOCs (USEPA Method 8260). When the curing temperatures were reached, the investigators theorized the material that exited both ends of the culverts was "steam." The CIPP installations contributed styrene to water, and styrene was also found in the wastewater drained from the CIPP testing. Styrene was detected in all four culverts, and levels ranged from nondetect to 250 mg/L. The presence of other compounds and method detection limits were not reported. NYSDOT investigators noted that pollutant discharge to a surface water was regulated "under the Clean Water Act and by the USEPA or its designee (a state)." According to their assessment, styrene discharge from a CIPP site should not exceed 0.005 mg/L to comply with state regulation (NYSDOT 2016). This limit is lower than USEPA's 0.1 mg/L styrene MCL (USEPA 1991).

In 2013, VDOT examined water quality impacts caused by one vinyl ester-based (styrene-free) CIPP installation and two styrene-based UV-CIPP installations (Donaldson & Whelton 2013, 2012). Water was collected before or upstream of CIPP installation sites and at the outlet. Samples were characterized for VOCs (USEPA Method 8260B). For the vinyl ester-based CIPP, vinylic monomer (specific compound unreported) aqueous concentrations (USEPA Method 8310M) exceeded toxicity thresholds for aquatic species in six

subsequent water sampling events up to 120 days after CIPP installation. Concentrations were found as high as 87 mg/L (exceeding the range of aquatic species' thresholds of 0.4–26 mg/L). Acrylate monomer (specific compound not reported) was released from the installation site and detected on day 90 at 0.08 mg/L. In water samples collected following the UV-CIPP installation, styrene concentrations varied according to the degree of water flow. Styrene concentrations for water exiting the newly installed liner were 0.72–10 mg/L, but standing water contained up to 12.9 mg/L styrene. Results indicated that residual styrene was greater in standing water and could be diluted in subsequent water flow events. Styrene concentration reduction also was hypothesized to occur as a result of volatilization. Using these results, VDOT further revised its CIPP specifications to include (1) styrene-based CIPP installation requirements for nonstyrene-based CIPP installations, (2) pre- and post-installation water and soil sample analyses requirements, and (3) aqueous concentration limits for styrene and diallyl phthalate (DAP).

In 2014, researchers in Alabama monitored COD, TOC, VOC, and SVOC levels at a steam-CIPP stormwater field site for 35 days (Tabor et al. 2014, Whelton et al. 2014). At the pipe outlet and downstream from the outlet, COD levels ranged from 100 to 375 mg/L, and styrene concentrations ranged from 0.01 to 7.4 mg/L. TOC levels indicated chemical release from the installation; levels were initially 140 mg/L at the outlet and decreased with time. Although, TOC, COD, and styrene levels generally decreased with time, the greatest COD and styrene concentrations were detected 50 ft downstream of each installation site the day following CIPP installation—not at the pipe outlets. Condensate liquid-like waste was collected and tested. Although the condensate pH was close to neutral, it contained heavy metals and had a COD of approximately 36,000 mg/L (similar to some industrial wastewaters). Condensate contained a variety of carcinogens, endocrine-disrupting compounds, and other contaminants including acetone, benzene, chloroform, isopropylbenzene, methylene chloride, methyl ethyl ketone, styrene, 1,2,4-TMB, and 1,3,5-TMB. Other chlorinated compounds were also found, and their origin was not clear. The condensate (undiluted and diluted) was determined to be acutely toxic to freshwater test organisms. Undiluted condensate dissolved the test organisms (*Daphnia magna*) at room temperature within 24 h. When the condensate was diluted 10,000 times and styrene was present only in nominal concentrations, all test organisms died after a 48 h exposure time. This result indicated that other compounds, in addition to styrene, contributed to chemical toxicity. CIPP specimens removed from the field site were characterized, and VOCs and SVOCs found in the field were released also into laboratory-prepared stormwater.

The most recent water quality impact study was conducted by California State University at Sacramento for CALTRANS (Currier 2017). This research was designed to examine stormwater VOC levels caused by CIPP installations in accordance with construction specifications for 10 steam-CIPPs and 1 UV-CIPP. Both styrene and nonstyrene resins were used at these sites; three CIPPs were installed in active culverts, and eight CIPPs were installed at a controlled field research site. Sites were monitored for up to 16 days post-installation. Water samples were analyzed for VOCs (USEPA method 8260B). During water sampling, the Currier (2017) researchers wore respirators (half-facepiece drop down[1]). This decision was based on input from the organization's industrial hygienists. Results showed that styrene leached from the CIPPs into simulated stormwater that was flushed through the pipes, with styrene ranging from nondetectable to greater than 0.20 mg/L. From the installation that used nonstyrene resin, a lower level of styrene was found leaching from the CIPP. Additional testing revealed that the contractors may have contaminated the nonstyrene CIPP with styrene during installation (Teimouri et al. 2017). Currier (2017) also detected other compounds in rinse water at less than 0.1 mg/L, including acetone, isopropylbenzene, *tert*-butyl alcohol, *N*-propylbenzene, toluene, xylenes, 1,2,4-TMB, and 1,3,5-TMB. Several compounds have been associated with prior CIPP water quality impact investigations and studies. Some compounds detected by Currier (2017) were also in materials captured and condensed from the air by Teimouri et al. (2017). Respirators,[2] recommended by industrial hygienists, were worn by Teimouri et al. (2017) to protect against inhalation exposures during steam-CIPP manufacture. The Currier (2017) statement that "forced heated air after the CIPP had been installed appeared to reduce styrene levels below aquatic toxicity thresholds" indicates a relationship may exist between chemical air emissions and CIPP chemical leaching. Specifically, chemicals that volatilize from the CIPP installation in air would not subsequently leach from the installed CIPP into water. On the basis of Currier (2017), CALTRANS has been evaluating potential CIPP installation specification upgrades to limit stormwater quality impacts. Some installation conditions and chemical air emission results for five CIPPs have been published by Teimouri et al. (2017), and others are still undergoing evaluation.

Review of construction documents. Of the total 35 state transportation agencies that were contacted, 32 responded to the authors' request for CIPP construction documentation. Of these responses, 23 agencies provided construction specifications, special provisions, or other materials related to CIPP technology use (Table 2). Some agencies volunteered addendums, bid summaries, material safety data sheets, and/or construction maps. A few state agencies indicated that the

TABLE 2 Comparison of CIPP construction specifications and requirements for state transportation agencies

Requirement	Number of States of 35
No documents provided or no CIPP use[a]	9
Before construction	
Obtain and show POTW permit to the engineer	4
Install impermeable liner up and downstream	4
Conduct water testing at the site	4
Before reinstating flow	
Rinse new liner with clean water, capture, and dispose	5
Prohibit return to service before a minimum unspecified period	4
Prohibit return to service before a minimum period (two, four, or seven days)	3
General requirements	
Capture and dispose of compounds, water, and condensate	10
Conduct water testing at the site	4
Contractor is responsible for reporting any water quality alterations	3

CIPP—cured-in-place pipe, POTW—publicly owned treatment works

[a]Some state agencies provided documents that did not specify CIPP and/or the agency indicated they did not use CIPP; one state agency did not accept CIPP point repairs; one state agency no longer permitted any CIPP technology except for ultraviolet CIPP; two state agencies described plan notes for CIPP because they did not have specifications or special provisions.

materials provided to the authors originated from different offices within each state, as there were no statewide guidance documents for CIPP installation activities. One state cited the Greenbook (2015) as its CIPP specification source. During document review, two different degrees of detail were found. California, Colorado, Virginia, and Vermont documents contained the greatest amount of information related to limiting water quality impacts and monitoring.

Before construction, transportation agencies in Colorado, Pennsylvania, Vermont, and Virginia explicitly required contractors to obtain and present a permit to the engineer. This permit was to indicate that a publicly owned treatment works (POTW) permits the discharge of CIPP waste. Other states varied with regard to their specified waste-handling requirements:

- Eight states did not specify requirements for waste disposal in documents provided.
- Six states required contractors to "...remove and properly dispose of waste."
- Three states required that "...debris of culvert should be disposed of in accordance with state and local environmental regulations."
- One state required contractors to "...follow the rules and regulations for discharge of waste."
- One state required that "...a compound, process water, or condensate used during the installation or curing operation shall be contained, removed from the site and disposed of in a manner approved by the Engineer."

At the construction site, four states required the use of some type of material (i.e., liner or matting) upstream and downstream of the CIPP installation (California, Nevada, Vermont, Virginia). California had the most explicit requirements and included a plastic coating 20 ft long and 10 mils (250 μm) thick to contain resin before liner installation. The other three states did not describe liner dimensions but required "an impermeable inner and outer plastic film or plastic pre-liner immediately prior to liner installation upstream and downstream of the site." Other states that provided construction documents did not specify the type of material. No studies were found that determined the degree to which these actions limited water quality impacts.

To determine the types of chemicals emitted into the environment from CIPP installations, four of 23 states (Colorado, Nevada, Vermont, Virginia) required water testing (Table 3). One state required the installers to "flush the new pipe until styrene residual levels were below EPA and or wastewater treatment levels," but the specific levels were not mentioned. Because water analysis requires time and results are not available in real time, it was unclear how this specification requirement was followed. The water sampling strategies and testing methods varied across these states. A comparison of each agency's recommended water testing method is shown in Table 3. VDOT required styrene testing for all styrene-based CIPP installations and DAP testing for vinyl ester CIPP installations. Vermont's Agency of Transportation (VTRANS) also required water testing,

TABLE 3 Different water testing methods required or used by state transportation agencies for CIPP installations and each method's ability to detect known CIPP compounds

Name of Compound Previously Detected at a CIPP Site or Found Leaching From a CIPP During a Bench-Scale Study	Compound Class	USEPA Water Testing Method Required or Used by Certain States (State)		
		524.2 (Colorado)	8260 (Colorado, Vermont, Virginia)	8021B (Nevada)
Acetone[θ‡§Δ¶ρ]		x	x	
Benzene[θΔ¶]	CAR, EDC, HAP	x	x	x
2-Butanone (methyl ethyl ketone)[¶]	CAR, HAP	x	x	·
tert-Butyl alcohol[§]		·	x	·
tert-Butyl benzene[ρ]		x	x	x
Chloroform[¶θρ]	CAR, HAP	x	x	x
o-Chlorotoluene[θ]		x	x	x
Diallyl phthalate (DAP)[Φ]	EDC	·	·	·
Ethylbenzene[θ‡]	EDC, HAP	x	x	x
Isopropylbenzene[‡0§Δ¶Ψ]		x	x	x
p-Isopropyltoluene[θ]		x	x	x
Methylene chloride[¶Ψ]	CAR	x	x	x
N-Propylbenzene[‡§Δ¶Φ]	EDC	x	x	x
Styrene[¥†‡§0¶Δρ*]	CAR, EDC, HAP	x	x	x
Toluene[0Δ]	HAP	x	x	x
1,2,4-Trimethylbenzene[θ‡§Δ¶Ψρ]	CAR	x	x	x
1,3,5-Trimethylbenzene[θ‡§Δ¶Ψρ]	CAR	x	x	x
Xylene (total)[Δ]	EDC, HAP	x	x	x

x—detectable, [-]—not detectable, CAR—suspected or confirmed carcinogen, CIPP—cured-in-place pipe, EDC—suspected or confirmed endocrine-disrupting compound, HAP—hazardous air pollutant as defined by USEPA, USEPA—US Environmental Protection Agency, VDOT—Virginia Department of Transportation

DAP was detectable using USEPA Method 8310M specified in VDOT (2016); Compounds in table were detected by prior investigators who examined CIPP waste or water sampling; USEPA 524.2 lists purgeable organic compounds, USEPA 8260 lists volatile organic compounds, and USEPA 8021B lists aromatic and halogenated volatiles; symbols correspond to when a compound was detected at an incident during a study: [θ]Currier (2017); [‡]Teimouri et al. (2017); [§]UGA (2016); [Δ]VDOT (2016); [¶]Tabor et al. (2014); [†]Donaldson (2013); [§]Spectrum Analytical Inc. (2013a, 2013b, 2013c, 2013d); [0]CDOT (2012); [¶]Weldon & Morton (2011); [Ψ]NRC (2010); [Φ]Tentatively identified compounds in Tabor et al. (2014); Initiator degradation products from material safety data sheets listed in Table 1 were not used to create this table.

and both Vermont and Virginia specifically mentioned styrene and DAP limits that should not be exceeded: for VDOT, 2.5 mg/L styrene (USEPA Method 8260) and 0.4 mg/L DAP (USEPA Method 8310M); for VTRANS, 1.0 mg/L styrene (USEPA Method 8260) and 0.4 mg/L DAP (method not reported). VDOT styrene and DAP limits were based on the lethal concentration (LC_{50}) values for the rainbow trout (*Oncorhynchus mykiss*) and golden orfe fish (*Leuciscus idus*), respectively (Donaldson & Whelton 2012). The VTRANS styrene limit was lower than VDOT's limit because of a recommendation by the Vermont Agency of Natural Resources. The VTRANS DAP limit was adopted from a VDOT study. In addition, NYSDOT did not require water testing, but the state's allowable styrene limit would depend on the class of surface water and groundwater. A 0.005 mg/L concentration was the lowest allowable discharge limit in accordance with state code (NYSDOT 2016).

Some compounds known to be released during CIPP installation (identified in bench- and field-scale studies) were not covered by the USEPA test methods specified in the state documents (Table 4). As Tables 3 and 4 show, numerous compounds have been associated with CIPP water contamination. However, some compounds would not have been detected by the USEPA test method used, and hence not reported, by the four states that required water testing. Therefore, the USEPA methods required or suggested for use by states will not result in a complete understanding of chemical release from CIPP sites. Chemicals released from CIPP installations are likely influenced by the resin composition, the applied CIPP curing and cool-down process, and possibly other parameters (i.e., environmental conditions, preliners, cutting pieces after curing, air emissions, etc.). More work is needed to characterize which chemicals are released, are significant from an environmental impact standpoint, and that should therefore require monitoring.

TABLE 4 Compounds associated with CIPP installations that are not detectable by the USEPA water testing method required or used by certain state transportation agencies

Name of Compound	Compound Class
Acetophenone[*]	HAP
Acrylate monomer (undisclosed)[†]	
Benzaldehyde[¶*]	
Benzoic acid[Θ*]	
Benzyl alcohol[¶]	
Butylated hydroxytoluene[#]	
4-*tert*-Butylcyclohexanol[*]	
4-*tert*-Butylcyclohexanone[*]	
Dibutyl phthalate[¶§*]	EDC, HAP
Diethyl phthalate[Θ¶]	EDC
Di(2-ethylhexyl) phthalate[Θ¶§]	CAR, EDC, HAP
4-(1,1-Dimethyl) cyclohexanol[Ψ]	
4-(1,1-Dimethyl) cyclohexanone[Ψ]	
3-Heptanol[¶]	
Phenol[¶Δ*]	HAP
1-Tetradecanol[*]	
Tripropylene glycol diacrylate[*]	
Vinylic monomer (undisclosed)[‡]	CAR

CAR—suspected or confirmed carcinogen, CIPP—cured-in-place pipe, EDC—suspected or confirmed endocrine-disrupting compound, HAP—hazardous air pollutant as defined by USEPA, USEPA—US Environmental Protection Agency

Symbols correspond to when a compound was detected at an incident during a study. Multiple monomers can be present. Initiator degradation products from material safety data sheets listed in Table 1 were not used to create this table. [Δ]Currier (2017); [†]Teimouri et al. (2017); [¶]Tabor et al. (2014); [§]Whelton et al. (2014); [‡]Donaldson (2013); [#]Weldon and Morton (2011); [*]Spectrum Analytical Inc. (2013a, 2013b, 2013c, 2013d); [Ψ]Tentatively identified compounds in Tabor et al. (2014).

Some construction documents specified that the contractor must capture and dispose of CIPP wastes following the installation. Ten states explicitly mentioned the requirement to capture and dispose of wastewater. NYSDOT (2016) required contractors to utilize "a preliner bag and excavate a temporary resin control pit at the outlet 4–5 m long, twice the culvert diameter wide and 300 mm deep." The pit's purpose was to collect the "styrene" and allow the wastewater to cool. Five states required contractors to rinse the newly installed CIPP with clean water, and then capture and dispose of the rinse water. None of the construction documents indicated from where the clean water should originate or what kind of the water to use (i.e., chlorinated drinking water, creek water, etc.). Discharge of chlorinated water to surface waters may require approval from the state environmental agency in accordance with the Clean Water Act.

Three states required a certain time period before the repaired pipe was allowed to be returned to service: Virginia (seven days), California (four days), and Maine (two days). Four states required that the pipe be returned to service after "a length of time to complete the cure," but the characteristics used to determine when the "cure" was complete were not defined. By delaying the pipe's return to service, some residual chemicals are likely permitted to volatilize into the air and be less available for leaching into the stormwater.

Requirements unique to NYSDOT were that when a nonstyrene resin was used, that resin must contain less than 5% VOCs with less than 0.1% hazardous air pollutants (NYSDOT 2016). Also, "the resulting cured liner shall contain less than 0.1% of the water quality pollutants" listed in state code. According to discussions with NYSDOT, independent chemical confirmation has not been conducted to validate these requirements. Because of a lack of independent resin and CIPP chemical composition test results, it is unclear whether contractors are meeting or can meet these requirements.

Standards, textbooks, and guideline documents. Because several construction specifications cited standards related to CIPP, these standards and other related literatures were reviewed. The purpose of reviewing this information was to determine whether the standards, texts, and guideline documents contained information regarding CIPP water quality impacts and waste disposal. Several ASTM documents were mentioned in construction specifications (ASTM 2017, 2016, 2012, 2011), but none contained information about water quality impacts or waste disposal. The AWWA (2014) manual for water main cleaning and lining was mentioned in ASTM sewer-related documents, but this manual did not mention water quality impacts or waste disposal. Two trenchless technology textbooks were also reviewed. These books mentioned that hazards can exist with steam condensate and with water used during the curing process, but chemical analysis data and studies were not cited (Najafi 2010, Najafi & Gokhale 2005).

A culvert repair construction and best practices study prepared for the Minnesota Department of Transportation and two trade association documents regarding CIPP use were reviewed. Trade association documents were examined because they were cited in transportation agency reports. In the 2014 best practices document, the capture and disposal of CIPP (waste) water was recommended, but other actions implemented by some states such as upstream/downstream protection, delay in return to service, or water testing were not mentioned (Wagener & Leagjeld 2014). Wagener and Leagjeld (2014) also recommended that states hire "NASSCO-trained construction inspectors to monitor installation and curing." According to training materials issued to CIPP construction inspector trainees in 2017

(NASSCO Inc. 2011), construction inspectors were not trained on past water quality impacts, methods to detect them, or evidence-based construction practices to help avoid them. Two trade documents were also evaluated because they were referenced in reports prepared for state agencies about CIPP. The first document published by the North American Society of Trenchless Technology (NASTT) mentioned human health concerns about CIPP technology, but recommendations lacked citations necessary to understand the justification for these concerns (Doherty et al. 2017). For example, the document stated "use styrene-free resins where public waterway contamination is a concern" but did not cite evidence that indicated "styrene-free resins" would not contaminate a public waterway. A prior study found that a styrene-free resin system can contaminate water (Donaldson 2013).

A NASSCO Inc. (2009) resin handling document cited in the NASTT document was reviewed also. This resin handling document also was issued to CIPP construction inspector trainees in 2017. It contained information about styrene levels in process water and the disposal of process water and condensate into ditches and/or waterways. Specifically, the document indicated that condensate discharge into receiving waters was acceptable if the waste contained 30 mg/L styrene or less (p. 11, paragraph 2). These statements lacked citations to chemical analysis or related toxicity data. Some similar observations about information contained in this document were previously identified by O'Reilly (2008) for NYSDOT. Other than styrene, no other compounds present in CIPP wastewater or condensate were described. As mentioned previously, many VOCs and SVOCs can be present and cause aquatic toxicity. A study conducted for the Wisconsin Department of Transportation cited this document, but added that "styrene and other chemicals leach into cure water" and "wastewater should not be discharged to the environment" (Salem et al. 2008). None of the standards, textbooks, or guideline documents indicated that approval of state environmental protection officials may be required before CIPP associated chemicals could be discharged to a surface water.

The authors also reviewed a styrene resin handling document released in late 2017 that mentioned water quality impacts associated with CIPP installations (NASSCO Inc. 2017). Like the NASSCO Inc. (2009) resin handling document, content in the more recent NASSCO Inc. (2017) document focused solely on styrene. Similar to the 2009 document, some claims about styrene levels in CIPP wastewater (i.e., 20–25 mg/L) lacked supporting data. One recommendation was that steam-CIPP airflow should be maximized to minimize the amount of condensate waste generated. As hypothesized by Currier (2017), this practice may remove chemicals from the CIPP that may otherwise leach into water after the CIPP is placed into service. It is unknown whether this increased chemical emission practice increases the chemical exposure risk to workers and the nearby public. General recommendations for improved worksite safety were provided, but details and/or references to support statements were not provided. Another recommendation was that a permit or permission should be obtained from a local regulatory agency before CIPP wastewater is discharged to the environment. Clarification from state environmental agencies about organizations that permit and monitor waste discharges from CIPP manufacturing sites is needed. The authority of permitted pollutant discharges under the National Pollution Discharge Elimination System has been delegated by the USEPA to 46 states and one territory, not to local authorities (USEPA 2018). The 2017 document did not reference all available independent peer-reviewed research pertaining to CIPP emissions.

CONCLUSION

The study objectives were to (1) compile and review CIPP-related surface water contamination incidents; (2) report on and review all known CIPP water quality impact studies; (3) evaluate current construction practices for state transportation agencies; and (4) review current standards, textbooks, and guideline documents. Water contamination incidents (13) were identified that were associated with CIPP pipe rehabilitation activities. Reported incidents generally involved the discharge of uncured resin, chemicals, or other wastes (e.g., CIPP wastewater by curing) into the local surface water. Reported incidents involved fish kills, odors, and/or drinking water supply contamination. Respiratory protection was worn to collect water samples following one incident. Water testing methods differed across incidents, and some of the analytical methods used were unable to detect the presence of some compounds known to be released during CIPP installation. For one incident, styrene was detected in water for almost four months. To better design water testing strategies, more independent testing data are needed about the chemicals that are used, created, and released during and after CIPP installation.

At present, there is no master list of chemicals of concern for water testing because little is known about the array of chemicals used, created, and emitted during CIPP manufacture. Some state transportation agencies have identified a few compounds (Tables 3 and 4). Water testing challenges arise because of the high variability in CIPP installation conditions (i.e., a CIPP installation at one site may cause different chemical releases than another installation, even when the same methods are used). As found on material safety data sheets and in prior field testing, new chemicals can be created during CIPP manufacture that are not listed as

ingredients on safety data sheets. While waters can be analyzed for monomers like styrene, a prior study showed other nonstyrene compounds (from a styrene-based CIPP) can be responsible for the observed aquatic toxicity. Until more information is available, a variety of different water tests (methods) should be applied at all CIPP installation sites. The selected water tests should be based on information in this report and in consultation with environmental and public health agencies. This water sampling approach is recommended following chemical spills when the composition of materials released is unclear (Horzmann et al. 2017, Huang et al. 2017, Weidhaas et al. 2017, Whelton et al. 2017).

Bench- and field-scale CIPP water quality impact studies have been conducted and supported by transportation agencies in Alabama, California, New York, and Virginia. In one study, chemicals were detected in water for 88 days after a CIPP was installed, and concentrations exceeded aquatic species toxicity thresholds. In another study, steam-CIPP condensate waste contained a variety of carcinogenic (styrene, benzene, methyl ethyl ketone, 1,2,4-TMB, and 1,3,5-TMB) and endocrine-disrupting compounds (dibutyl phthalate [DBP] and diethyl phthalate), and was acutely toxic (i.e., 24 h, 23°C) to a freshwater organism (*Daphnia magna*). Water testing by multiple organizations has indicated that several VOCs and SVOCs can be released from CIPP sites into water. Findings indicated that the highest levels of contamination occurred closer to the date of installation and can decrease with time. Respirators were worn by researchers to collect water samples during a field water sampling study. Respirators were also worn by others who conducted air sampling during those same steam-CIPP installations. Standard USEPA water testing methods listed in the reviewed construction documents can identify and quantify some, but not all, chemicals released during CIPP installation. No long-term CIPP leaching studies were found to describe emissions as the material aged. A potential relationship was mentioned between styrene leaching from a newly installed CIPP and use of forced air during CIPP cool-down, but very limited air testing data exist, as summarized elsewhere (Teimouri et al. 2017).

CIPP construction specifications differed greatly among states. To limit chemical release from CIPP installations into the environment, four states required the temporary installation of materials (i.e., streambed liners) upstream and downstream of the CIPP installation site. However, the type and characteristics of the specific materials varied. Three states required that the pipe not be returned to service for two, four, and seven days after CIPP installation. Water testing before and after CIPP installation was required by four states. No federal or state standards, literature texts, or industry documents were found that described evidence-based practices for limiting water quality impacts, or for capturing and disposing of the waste generated as a result of CIPP manufacture.

RECOMMENDATIONS

Evidence-based construction practices are recommended that minimize water quality risks. Limited chemical testing data are available that support existing procedures and specifications. Studies are needed to document a more complete list of chemicals generated during CIPP installation and their toxicities. Without publicly available field testing data and future laboratory studies, the expected magnitude and duration of chemical emissions cannot be understood. The incidents described here may be outlier events, or they may represent the risks inherent of typical installations. Also needed are evidence-based waste handling practices and identification of the necessary time required before placing the CIPP into service to limit chemical leaching.

Organizations that contract for CIPP technology use need to be aware of the human health and environmental risks associated with the installation, as well as evidenced-based practices to mitigate these risks to their employees, the public, and the environment. People who monitor, visit, or conduct water sampling at CIPP worksites should wear appropriate personal protective equipment. This could include respirators and chemically resistant gloves, depending on the potential exposure routes (inhalation, dermal) as determined appropriate by industrial hygienists and the National Institute for Occupational Safety and Health. Additional chemical air-emission work as recommended by Teimouri et al. (2017) is needed. Evidence-based best practices should be included in construction specifications and contracts. At a minimum, construction inspectors should be trained on topics identified in this article. Future studies should be designed to evaluate different approaches to reducing chemical emission into the environment.

On the basis of the compilation of existing data, some recommendations are made. First, the local environment (sediments, soils, water) should be protected during CIPP installation. Contractors should use impermeable plastic sheets (i.e., 10 mils thick) immediately upstream and downstream of the pipe to help prevent chemicals from entering the environment. This recommendation is based on CALTRANS research. The protected area's size may depend on the pipe size and area morphology. Water flow should be diverted from the pipe until a complete cure has been established. But more information on the curing time for each type of CIPP method is needed where degree of cure can be correlated with both mechanical *and* chemical integrity of the pipe. Curing time likely is a function of resin thickness, composition, curing method, pipe conditions, and ambient temperature, so the "time to service" needs to be defined in terms of these and possibly other parameters. New

CIPPs should be rinsed after installation, and waste should be collected. CIPPs should be prohibited from service until water testing results indicate no exceedances.

Water or steam condensate used for curing or rinse water should not enter the environment (waterways, soil) and should be collected. These materials should be properly discharged to a POTW, with preapproval of the POTW, or other approved facility. In the absence of waste collection, any discharge to the environment should have preapproval by the state or federal agency responsible for environmental protection. Any accidental discharge, small or large, should be reported to state officials immediately, so actions can be taken to protect downstream water supplies, the environment, and nearby population.

On the basis of resin composition and leachate and chemical toxicity tests, analytical water testing methods selected should be capable of detecting all contaminants of concern. Testing procedures, locations, number of samples, and temporal extent (i.e., to include pre- and post-installation) need better definition. Independent organizations, properly trained on environmental sampling, should conduct testing. Results should be rapidly obtained and compared against state and federal water quality limits for allowable pollutant discharge, limits in construction specifications, and to acute and chronic toxicity limits for native aquatic species. Sampling at the pipe inlet and outlet immediately before and after the CIPP is placed in service should constitute temporal (and spatial) sampling events. This testing is required in some states but should be adopted across all storm sewer applications. As known contamination incidents and existing studies have indicated, follow-up testing for days, weeks, or months may be necessary depending on what is discovered. Testing for surrogate water quality parameters (i.e., TOC, COD) may prove to be a rapid and cost-effective way to help identify whether water contamination occurred and may decrease the amount of specific chemical sampling. Any exceedance of state water quality limits and limits set forth in specifications should trigger additional water testing, state environmental agency notification, and possibly remediation actions. Additional work is needed to determine the time required for CIPP leaching to decrease below-accepted chemical concentrations, and limits for some chemicals may differ between states.

Additional studies should examine chemical leaching from CIPPs over time, after facilitated curing (UV, steam, and/or hot water exposure) has occurred, with the rate of leaching examined as a function of facilitated curing time (and temperature, where appropriate). No data were found that described chemical leaching for the multitude of known resin compositions, curing methods, cool-down methods, and conditions. Existing studies are limited in that they may represent only the specific application, not CIPP technology across sites. Chemical extraction of the cured liner according to NYSDOT's requirement would help other transportation, state, and federal agencies understand what chemicals are used, created, and remain in the CIPP after installation.

Discussions among researchers, state transportation agency representatives, environmental protection officials, public health officials, and CIPP contractors are recommended to define "curing time" from an environmental risk perspective. The authors' discussions with state transportation agencies, consulting firms, and CIPP contractors revealed that the current definition of "cure" does not consider the amount or type of residual chemicals that remain on or inside the new CIPP. Even if the contractors do everything properly, some chemical compounds may continue to volatilize from the new CIPP or leach out into water. Further studies and information will better determine the necessary time required before returning each pipe to service to minimize contaminant release from the worksite and the CIPP. Also, further studies could elucidate the relationship between water quality impacts caused by the CIPP after installation and chemical emission into the air during CIPP manufacture. While it is likely that some recommendations mentioned previously may already be considered by some transportation agencies and CIPP contractors, it is imperative that the entire industry (infrastructure owners, environmental agencies, public health agencies, contractors) act to prevent future incidents from occurring.

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ENDNOTES

[1]6000DD with cartridge P100 3M type 60,926; 3M, Maplewood, Minn.
[2]Model 6800, North 5400 full face with organic vapor, carbon filter cartridges, 3M 6610, N75001; 3M, Maplewood, Minn.

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REFERENCES

ADEM (Alabama Department of Environmental Management), 2010. *RE: Groundwater Incident Number GW10-10-01, Styrene Release.* ADEM, Montgomery, Ala.

AirZone Inc., 2001. A Report on the Monitoring of Styrene in Toronto Homes During the Cured In Place Pipe (CIPP) Process for Sewer Pipe Rehabilitation by Insituform. Project 041-6742. AirZone, Inc., Toronto.

Ajdari, E.B., 2016. Volatile Organic Compound (VOC) Emission During Cured-In-Place-Pipe (CIPP) Sewer Pipe Rehabilitation. Doctoral dissertation, University of New Orleans, New Orleans.

Akzo Nobel, 2016a. Product Data Sheet: Butanox® M-50. www.mbfgfiles.co.uk/datasheets/m50_sds.pdf (accessed Oct. 1, 2017).

Akzo Nobel, 2016b. Product Data Sheet: Trigonox® C. www.pcpds.akzonobel.com/PolymerChemicalsPDS/showPDF.aspx?pds_id=1807 (accessed Nov. 29, 2017).

Akzo Nobel, 2015a. Product Data Sheet: Perkadox® 16. www.pcpds.akzonobel.com/PolymerChemicalsPDS/showPDF.aspx?pds_id=78 (accessed Dec. 1, 2017).

Akzo Nobel, 2015b. Product Data Sheet: Perkadox® 26. www.polymerpds.akzonobel.com/PolymerChemicalsPDS/showPDF.aspx?pds_id=1296 (accessed Dec. 1, 2017).

Akzo Nobel, 2015c. Product Data Sheet: Perkadox® CH-50. www.pcpds.akzonobel.com/PolymerChemicalsPDS/showPDF.aspx?pds_id=510 (accessed Dec. 1, 2017).

Akzo Nobel, 2015d. Product Data Sheet: Trigonox® 21-C50. www.pcpds.akzonobel.com/PolymerChemicalsPDS/showPDF.aspx?pds_id=1523 (accessed Dec. 1, 2017).

Akzo Nobel, 2015e. Product Data Sheet: Trigonox® 21S. www.polymerpds.akzonobel.com/polymerchemicalspds/showpdf.aspx?pds_id=120 (accessed Dec. 1, 2017).

Akzo Nobel, 2015f. Product Data Sheet: Trigonox® 42S. www.pcpds.akzonobel.com/PolymerChemicalsPDS/showPDF.aspx?pds_id=151 (accessed Dec. 21, 2017).

Akzo Nobel, 2008a. Product Data Sheet: Perkadox® BTW-50. www.brenntag.com/media/documents/bsi/product_data_sheets/material_science/akzo_nobel_initiators/perkadox_btw-50_pds.pdf (accessed Dec. 21, 2017).

Akzo Nobel, 2008b. Product Data Sheet: Trigonox® 121-BB75. www.brenntag.com/media/documents/bsi/product_data_sheets/material_science/akzo_nobel_initiators/trigonox_121-bb75_pds.pdf (accessed Dec. 21, 2017).

Akzo Nobel, 2008c. Product Data Sheet: Trigonox® 21-OP50. www.polymerpds.akzonobel.com/PolymerChemicalsPDS/showPDF.aspx?pds_id=938 (accessed Dec. 21, 2017).

Akzo Nobel, 2008d. Product Data Sheet: Trigonox® K90. www.auroracomposites.com/wp-content/uploads/2016/04/TRIGONOX-K-90.pdf (accessed Dec. 21, 2017).

Akzo Nobel, 2008e. Product Data Sheet: Trigonox® KSM. www.brenntag.com/media/documents/bsi/product_data_sheets/material_science/akzo_nobel_initiators/trigonox_ksm_pds.pdf (accessed Nov. 29, 2017).

Allouche, E.; Alam, S.; Simicevic, J.; Sterling, R.; Condit, W.; Matthews, J.; & Selvakumar, A., 2014. A Pilot Study for Retrospective Evaluation of Cured-In-Place Pipe (CIPP) Rehabilitation of Municipal Gravity Sewers. *Tunneling and Underground Space Technology*, 39:82. https://doi.org/10.1016/j.tust.2012.02.002.

Allouche, E.; Alam, S; Simicevic, J.; Condit, W.; Headington, B.; Matthews, J.; Kampbell, E.; Sangster, T.; & Downey, D., 2012. A Retrospective Evaluation of Cured-In-Place Pipe Used in Municipal Gravity Sewers. EPA/600/R-12/004, Prepared for Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, Water Supply and Water Resources Division.

AOC, LLC, 2013. Material Safety Data Sheet, L721-LTI-12. Collierville, Tenn.

AOC, LLC, 2007. Material Safety Data Sheet, L713-LTA-12. Collierville, Tenn.

Ashland, 2011. Safety Data Sheet, Aropol MR 12018. www.b2bcomposites.com/msds/ashland/815733.pdf (accessed Dec. 1, 2017).

ASTM, 2017. *Standard Practice for Rehabilitation of Existing Pipelines and Conduits by Pulled-In-Place Installation of Cured-In-Place Thermosetting Resin Pipe (CIPP).* F1743-17, ASTM, West Conshohocken, Pa.

ASTM, 2016. *Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube.* F1216-16, ASTM, West Conshohocken, Pa.

ASTM, 2012. *Standard Specification for Cured-In-Place Thermosetting Resin Sewer Piping Systems.* D5813-12, ASTM, West Conshohocken, Pa.

ASTM, 2011. *Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Pulled in Place Installation of Glass Reinforced Plastic (GRP) Cured-In-Place Thermosetting Resin Pipe (CIPP).* F2019-11, ASTM, West Conshohocken, Pa.

ATSDR (Agency for Toxic Substances and Disease Registry), 2005. ASTDR, Milwaukee County, Atlanta.

AWWA, 2014 (3rd ed.). Manual of Water Supply Practices, M28. *Rehabilitation of Water Mains.* Denver.

Barker, C., 2013. *Weathersfield STP 0146(11) Timeline Summary.* Vermont Agency of Transportation, Montpelier, Vt.

Bauer, G. & McCartney, D., 2004. Odour Control-More Than Sewage When Installing Cured-In-Place Sewer Pipe. Proc. North American Society for Trenchless Technology (NASTT) NO-DIG Conf., NASTT, Paper D-3-02, Liverpool, N.Y.

CDOT (Colorado Department of Transportation), 2012. *Joint Budget Committee Hearing Agenda.* FY 2012-13, Department of Transportation, Denver, Colo.

CDPH (California Department of Public Health—Division of Environmental and Occupational Disease Control), 2017a. CIPP Safety Alert. Sacramento, Calif. www.cdph.ca.gov/Programs/CCDPHP/DEODC/CDPH%20Document%20Library/CIPP%20Alert%20final.pdf (accessed Sept. 1, 2017).

CDPH, 2017b. Cure-In-Place Pipe (CIPP) Additional Considerations for Municipalities. www.cdph.ca.gov/Programs/CCDPHP/DEODC/CDPH%20Document%20Library/CIPP%20additional%20considerations.pdf#search=CIPP%20alert (accessed Nov. 1, 2017).

CTC & Associates, LLC, 2012. *Preliminary Investigation: Environmental Effects of Cured In Place Pipe Repairs.* Caltrans Division of Research and Investigation, Sacramento, Calif.

Currier, B., 2017. *Water Quality of Flow Through Cured-In-Place Pipe (CIPP).* Final Report, Office of Water Programs, California State University Sacramento, Sacramento, Calif. Prepared for California Department of Transportation, Sacramento, Calif. http://trid.trb.org/view.aspx?id=1467684 (accessed Oct. 1, 2017).

CWQCC (Colorado Water Quality Control Commission), 2016. *The Basic Standards for Ground Water, Regulation No. 41.* 5 CCR 1002-41, Colorado Water Quality Control Commission, Denver, Colo.

Das, S., 2016. Evaluation of Cured-In-Place Pipe Lining Installations. Master's thesis, University of Alberta, Edmonton, Alta.

De la Batisde, K., 2017. Sewer Work on Schedule in Anderson: $4 Million Upgrade to Aging Main Line. *The Herald Bulletin.* August 31. www.heraldbulletin.com/news/local_news/sewer-work-on-schedule-in-anderson/article_eb966c65-7872-5969-a5c8-37d8e12138aa.html (accessed Jan. 28, 2018).

Doherty, I.; Downey, D.; Macey, C.; Rahaim, K.; & Sarrami, K., 2017 (1st ed.). *NASTT's Cured-In-Place-Pipe (CIPP) Good Practices Guidelines.* North American Society for Trenchless Technology, Cleveland.

Donaldson, B.M., 2013. *Water Quality Implications of Culvert Repair Options: Vinyl Ester Based and Ultraviolet Cured-In-Place Pipe Liners.* Final Report VCTIR 13-R2, Virginia Transportation Research Council, Charlottesville, Va.

Donaldson, B.M., 2009. The Environmental Implications of Cured-In-Place Pipe Rehabilitation Technology. *Journal of the Transportation Research Board,* 2123:172. https://doi.org/10.3141/2123-19.

Donaldson, B. & Whelton, A.J., 2013. Impact of Stormwater Pipe Lining Materials on Water Quality: Field Study and Resulting Specifications. *Journal of the Transportation Research Board,* 2362:49. https://doi.org/10.3141/2362-07.

Donaldson, B.M. & Whelton, A.J., 2012. *Water Quality Implications of Culvert Repair Options: Cementitious and Polyurea Spray-On Liners.* FHWA/VCTIR 13-R3, Virginia Center for Transportation Innovation and Research, Charlottesville, Va.

Gerrits, L., 2007. Toxins Dumped in Como Creek. *Tri-CityNews.* www.tricitynews.com (accessed Oct. 1, 2011).

GESI (Groundwater and Environmental Services Inc.), 2004. *45-Day Spill Report, Mobile Service Stations.* Letter to Mr. J. Aceto, Connecticut Department of Environmental Protection, Hartford, Conn.

Greenbook, 2015. *Standard Specifications for Public Works Construction.* BNI Building News, Vista, Calif.

Griffin, J., 2008. Virginia DOT Lifts CIPP Ban. *Underground Construction,* 63:6:44.

Henry, C., 2007. Discharges From Cured In Place Pipe (CIPP) Installations, Central Contra Costa Sanitary District Experience. Presentation at the California Water Environment Association Conf., April 19, Ontario.

Horzmann, K.; de Perre, C.; Whelton, A.J.; & Freeman, J.L., 2017. Comparative Analytical and Toxicological Assessment of Methylcyclohexanemethanol (MCHM) Mixtures Associated With the Elk River Chemical Spill. *Chemosphere,* 188:599. https://doi.org/10.1016/j.chemosphere.2017.09.026.

Huang, X.; Whelton, A.J.; Andry, S.; Yapturi, J.; Kelly, D.; & Ladner, D.A., 2017. *Interaction of Fracking and Crude Oil Contaminants With Water Distribution Pipes.* Final Report 4579. Water Research Foundation, Denver.

ICTRD (Interplastic Corporation Thermoset Resins Division), 2007. *Technical Research: Optimizing Initiator Systems for Cured-In-Place Pipe Infrastructure Repair.* ICTRD, St. Paul, Minn. www.interplastic.com/UserFiles/File/T_OptInitiatorSys7_07.pdf (accessed Dec. 1, 2017).

ICTRD, 2006. *Cured-In-Place Pipe Resins: An Endless Flow of Experience and Innovation.* ICTRD, St. Paul, Minn. www.interplastic.com/UserFiles/File/M_CIPP_bro.pdf (accessed Dec. 1, 2017).

Interflow Pty Ltd, 2008. *Interfit Resin Part A & B.* MSDS ID NC317TCP Version No. 2.0. Girraween, Australia. http://gulfcoastunderground.com/wp-content/uploads/2014/04/MSDS-Resin-B-Interfit.pdf and http://gulfcoastunderground.com/wp-content/uploads/2014/04/MSDS-Resin-A-Interfit.pdf (accessed Dec. 1, 2017).

Interplastic Corporation, 2016. *CIPP COR78-AT-579 Resin.* Interplastic Corporation, St. Paul, Minn.

Kelly, M., 2017. Video: Dublin Sewer Construction Project Causes Foul Smell for Residents. *Kron4.* August 9.

Kennedy, K., 2017. South Heights Neighborhood Evacuated After Epoxy Odor Fills Homes. *The Times.* September 14. www.timesonline.com/news/local_news/south-heights-neighborhood-evacuated-after-epoxy-odor-fills-homes/article_a4fec7d8-996b-11e7-a2d5-c790031a83fc.html (accessed Oct. 5, 2017).

Landstra, M., 2017. LS Water Utilities Releases Statement on Market Street Sewer Lining Project. *Lee's summit Tribune,* August 22. http://lstribune.net/lees-summit-news/ls-water-utilities-releases-statement-on-market-street-sewer-lining-project.htm (accessed Oct. 5, 2017).

Lane, W.H., 1946. Determination of Solubility of Styrene in Water and of Water in Styrene. *Industrial and Engineering Chemistry Analytical Edition,* 18:5:295. https://doi.org/10.1021/i560153a009.

LMES (Lockheed Martin Energy Systems), 2007. *Fish Kill Resulting From Styrene Resin Spill.* Lessons Learned Database. www.hss.energy.gov/csa/analysis/ll/ (accessed Jun. 12, 2007).

Loendorf, T.; Waters, D., 2009. Styrene Removal Adds to the Challenges of Rehabilitating Sewer Pipeline in Reno, Nevada. Proc. North American Society for Trenchless Technology (NASTT) NO–DIG Conf., NASTT, Liverpool, N.Y.

Marohn, K., 2011a. Hazardous Material Sits Since October. *St. Cloud Times*, March 13, A-1.

Marohn, K., 2011b. Cleanup to Begin at Site of October Resin Accident. *St. Cloud Times*, March 31, A-1.

Marohn, K., 2011c. Cleanup Work on Months-Old Resin Spill Is Underway. *St. Cloud Times*, April 8, A-1.

Matthews, J.C.; Condit, W.; Wensink, R.; & Lewis, G., 2012a. *Performance Evaluation of Innovative Water Main Rehabilitation Cured-In-Place Pipe Lining Product in Cleveland, Ohio.* EPA/600/R-12/012. Prepared for Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, Water Supply and Water Resources Division.

Matthews, J.C.; Simicevis, J.; Kestler, M.A.; & Piehl, R., 2012b. *Decision Analysis Guide for Corrugated Metal Culvert Rehabilitation and Replacement Using Trenchless Technology.* Prepared for US Department of Agriculture Forest Service, Washington.

McLuckie, R., 2011. Personal communication. Head, Planning and Design Section, Kingston, Ont., Canada.

MENP (Ministry of Environment and Natural Protection), 2004. *Agriculture and Consumer Protection (MUNLV) of the North Country Rhine-Westphalia in Bielefeld: Bielefeld, Germany.* Final Report: Untersuchungenzu Styrol emission enbeimgro ß technischen Ein-satz von Schlauchlining verfahrenbei Kanalsanierungen, Verein-heitlichung der Probenahme und Analysemethoden, Festsetzung von Grenzwerten und Optimierung der Sanierungsverfahrensowiealigemeingültigen Ausschreibungsempfehlungen (in German), p. 104.

Morrison, R.; Sangster, T.; Downey, D.; Matthews, J.; Condit, W.; Sinha, S.; & Sterling, R., 2013. *State of Technology for Rehabilitation of Water Distribution Systems.* EPA/600/R-13/036. Prepared for Environmental Protection Agency, Office of Research and Development, National Risk Management Laboratory, Water Supply and Water Resources Division.

MTO (Ministry of Transportation of Ontario), 2011. Personal communication. Ministry of Transportation of Ontario, North York, Ont., Canada.

Najafi, M., 2010. *Trenchless Technology: Installation and Inspection.* The McGraw-Hill Companies Inc., New York.

Najafi, M. & Gokhale, S., 2005. *Trenchless Technology: Pipeline and Utility Design, Construction, and Renewal.* The McGraw-Hill Companies Inc., New York.

NASSCO Inc. (National Association of Sewer Service Companies Inc.), 2017. *Guidelines for the Safe Use and Handling of Styrene Based Resins in Cured-In-Place-Pipe.* Prepared by Pipe Rehab Committee. NASSCO, Inc., Marriottsville, Md.

NASSCO Inc., 2011. *Manual for Inspector Training and Certification Program (ITCP) for the Inspection of Cured In Place Pipe Installation*, Version 3.0. NASSCO, Inc., Marriottsville, Md.

NASSCO Inc., 2009. *Guideline for the Use and Handling of Styrenated Resins in Cured-In-Place-Pipe.* Created Sept. 2008; revised Aug. 19, 2009. Prepared by Pipe Rehab Committee, NASSCO, Inc., Marriottsville, Md.

NRC (National Response Center), 2010. *Incident Report.* 957007.

NYSDOT (New York State Department of Transportation), 2016. Chapter 8: Highway Drainage. Revision 87-Metric. *Highway Design Manual.* NYSDOT, Albany, N.Y. www.dot.ny.gov/divisions/engineering/design/dqab/hdm/hdm-repository/chapt_08_metric.pdf (accessed Oct. 3, 2017).

O'Reilly, M., 2008. *Summary of Water Sampling – CIPP for 4 Culverts.* New York State Department of Transportation, Albany, N.Y.

Peterson, E., 2017. Worker Killed in Streamwood Sewer Line. *Daily Herald.* www.dailyherald.com/news/20171025/worker-killed-in-streamwood-sewer-line (accessed Oct. 26, 2017).

Piratla, K.R. & Pang, W., 2017. *Best Practices for Assessing Culvert Health and Determining Appropriate Rehabilitation Methods.* Publication FHWA-SC-17-01. Prepared for South Carolina Department of Transportation, Columbia, S.C.

Puritan Products Inc., 2016. Safety Data Sheet: *N, N-Dimethylaniline.* www.puritanproducts.com/wp-content/uploads/2015/08/DIMETHYLANILINE-SDS.pdf (accessed Dec. 1, 2017).

Renda, M., 2013. Hazardous Spill at Hwy 49 Sinkhole. *The Union.* August 12. www.theunion.com/news/local-news/hazardous-spill-at-hwy-49-sinkhole/ (accessed Dec. 7, 2017).

Salem, O.; Najafi, M.; Salman, B.; Calderon, D.; Patil, R.; & Bhattachar, D., 2008. Use of Trenchless Technologies for a Comprehensive Asset Management of Culverts and Drainage Structures. Publication MRUTC 07-15. Prepared for Wisconsin Department of Transportation, Madison, Wis.

Saunders, M. & Boone, M., 2017. Construction Fumes Prompt Emergency Response at Bay Terraces School. *10 News.* September 21. www.10news.com/news/construction-fumes-prompt-emergency-response-at-bay-terraces-school (accessed Oct. 5, 2017).

Shearer, L., 2016. State Investigating Chemical Spill in UGA Campus Stream. http://onlineathens.com/mobile/2016-09-08/state-investigating-chemical-spill-uga-campus-stream (accessed July 14, 2017).

Silcuna, J., 2010. Personal communication. Civil engineer. New York State Department of Transportation, Albany, N.Y.

Spectrum Analytical Inc., 2013a. Laboratory Report – Project No. 08-220953.00, Weathersfield, Vt. Report Date Sept. 17, 2013, Agawam, Mass.

Spectrum Analytical Inc., 2013b. Laboratory Report – Project No. 08-220953.00, Weathersfield, Vt. Report Date Sept. 24, 2013, Agawam, Mass.

Spectrum Analytical Inc., 2013c. Laboratory Report – Project No. 08-220953.00, Weathersfield, Vt. Report Date Oct. 11, 2013, Agawam, Mass.

Spectrum Analytical Inc., 2013d. Laboratory Report – Project No. 08-220953.00, Weathersfield, Vt. Report Date Nov. 27, 2013, Agawam, Mass.

Staff, A., 2017. The Gedney Street Smell Was Sewer Stuff. *Nyack News and Views.* July 27. www.nyacknewsandviews.com/2017/07/gedney-smell-sewer-plastic (accessed Oct. 5, 2017).

Stratview Research Inc., 2017. *Global Cured-In-Place Pipe (CIPP) Market Likely to Grow at a Healthy CAGR During 2017 to 2022.* www.stratviewresearch.com/press_details.php?name_id=140 (accessed Dec. 1, 2017).

Sullo, A., 2012. King Street Sewer Rehab and Water Quality Impacts. Underground Infrastructure Research International Conf. and Trenchless Technology Road Show, Center for Advancement of Trenchless Technologies, Waterloo, Ont.

Tabor, M.L.; Newman, D.; & Whelton, A.J., 2014. Stormwater Chemical Contamination Caused by Cured-In-Place Pipe (CIPP) Infrastructure Rehabilitation Activities. *Environmental Science & Technology*, 48:18:10938. https://doi.org/10.1021/es5018637.

Teimouri, S.M.; Ra, K.; Conkling, E.N.; Boor, B.E.; Nuruddin, M.; Howarter, J.A.; Youngblood, J.P., et al., 2017. Worksite Chemical Exposure and Air Emissions during Sanitary Sewer Pipe and Stormwater Culvert Rehabilitation Using Cured-In-Place-Pipe (CIPP). *Environmental Science & Technology Letters*, 4:8:325. https://doi.org/10.1021/acs.estlett.7b00237.

UGA (University of Georgia), 2016. *Water Testing VOC Analysis for 9/16/2016 and 9/21/2016.* College of Agriculture and Environmental Services, Athens, Ga.

United Initiators Inc., 2017a. Safety Data Sheet. Norox® 600. www.united-initiators.com/files/NOROX_600/United_Initiators_NOROX+600_MSDS_GB_EN.pdf (accessed Dec. 1, 2017).

United Initiators Inc., 2017b. Safety Data Sheet. Norox® TBPB. www.united-initiators.com/files/NOROX_TBPB/United_Initiators_NOROX+TBPB_MSDS_US_EN.pdf (accessed Dec. 1, 2017).

United Initiators Inc., 2015. Safety Data Sheet. Norox® 600 (BCHPC). www.united-initiators.com/files/NOROX_600/United_Initiators_NOROX+600_MSDS_US_EN.pdf (accessed Dec. 1, 2017).

USEPA (US Environmental Protection Agency), 2018. National Pollutant Discharge Elimination System (NPDES), About NPDES. www.epa.gov/npdes/about-npdes (accessed Jan. 25, 2018).

USEPA, 2006. EPA Region III BTAG Freshwater Screening Benchmarks. www.epa.gov/sites/production/files/2015-09/documents/r3_btag_fw_benchmarks_07-06.pdf (accessed Dec. 1, 2017).

USEPA, 1991. Phase II Volatile Organic Contaminants, Final Rule. 56 FR 3526. *Federal Register*, Effective: 1992. www.gpo.gov/fdsys/pkg/CFR-2010-title40-vol22/xml/CFR-2010-title40-vol22-part141-subpartG.xml (accessed Dec. 1, 2017).

USEPA, 2009. National Primary Drinking Water Regulations, EPA 816-F-09-004. www.epa.gov/sites/production/files/2016-06/documents/npwdr_complete_table.pdf (accessed Nov. 5, 2017).

USNTP (US National Toxicology Program), 2011. Report on Carcinogens, Styrene (14th ed.). https://ntp.niehs.nih.gov/pubhealth/roc/listings/s/styrene/summary/index.html (accessed Sept. 28, 2017).

VDOT (Virginia Department of Transportation), 2016. *Special Provision for Pipe Rehabilitation.* SP302-000140-01, Richmond, Va.

VTDEC (Vermont Department of Environmental Conservation), 2013. *Memorandum.* Agency of National Resources, Burlington, Vt.

Wagener, B.D. & Leagjeld, E.E., 2014. Culvert Repair Best Practices, Specifications and Special Provisions – Best Practices Guidelines. Publication MN/RC 2014-01. Prepared for Minnesota Department of Transportation, Saint Paul, Minn.

Weidhaas, J.L.; Dietrich, A.M.; DeYonker, N.J.; Dupont, R.R.; Foreman, W.T.; Gallagher, D.; Gallagher, J.E.G.; Whelton, A.J.; & Alexander, W.A., 2017. Enabling Science Support for Better Decision-Making When Responding to Chemical Spills. *Journal of Environmental Quality*, 45:5:1490. https://doi.org/10.2134/jeq2016.03.0090.

Weldon, T. & Morton, M., 2011. *Report of CDOT I-70 Culvert Repair Project Styrene Release, Response, and Mitigation at Clear Creek County, Colorado.* Colorado Department of Transportation, Denver.

Whelton, A.J.; McMillan, L.; Novy, C.L.R.; White, K.D.; & Huang, X., 2017. Case Study: The Crude MCHM Chemical Spill. *Environmental Science: Water Research and Technology*, 3:2:312. https://doi.org/10.1039/C5EW00294J.

Whelton, A.J.; Tabor, M.L.; Boettcher, A.; White, K.D.; Newman, D.; & Steward, E.J., 2014. *Standardized Test Method to Quantify Environmental Impacts of Stormwater Pipe Rehabilitation Materials.* Final Report, VCTIR 15-R11. Prepared for Virginia Transportation Research Council, Charlottesville, Va.

Wood, E., 1979. Method of Lining a Passageway With a Resin Absorbent Tube. US Patent 4135958 A. U.S. Patent Office, Washington.

Wood, E., 1977. Lining of Passageways. US Patent 4064211 A. U.S. Patent Office, Washington.

WSDOE (Washington State Department of Ecology), 2010. Press Release: Contractor Fined for Bellevue Chemical Spill; Warning Issued to Transportation Agency. Olympia, Wash.