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Worksite Chemical Air Emissions and Worker Exposure during Sanitary Sewer and Stormwater Pipe Rehabilitation Using Cured-in-Place-Pipe (CIPP)

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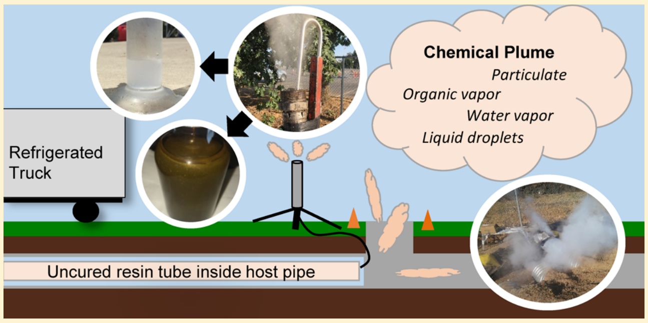
Supporting Information



ABSTRACT: Chemical emissions were characterized for steam-cured cured-in-place-pipe (CIPP) installations in Indiana (sanitary sewer) and California (stormwater). One pipe in California involved a low-volatile organic compound (VOC) non-styrene resin, while all other CIPP sites used styrene resins. In Indiana, the uncured resin contained styrene, benzaldehyde, butylated hydroxytoluene (BHT), and unidentified compounds. Materials emitted from the CIPP worksites were condensed and characterized. An emitted chemical plume in Indiana was a complex multiphase mixture of organic vapor, water vapor, particulate (condensable vapor and partially cured resin), and liquid droplets (water and organics). The condensed material contained styrene, acetone, and unidentified compounds. In California, both styrene and low-VOC resin condensates contained styrene, benzaldehyde, benzoic acid, BHT, dibutyl phthalate, and 1-tetradecanol. Phenol was detected only in the styrene resin condensate. Acetophenone, 4-*tert*-butylcyclohexanol, 4-*tert*-butylcyclohexanone, and tripropylene glycol diacrylate were detected only in the low-VOC condensate. Styrene in the low-VOC condensate was likely due to contamination of contractor equipment. Some, but not all, condensate compounds were detected in uncured resins. Two of four California styrene resin condensates were cytotoxic to mouse alveolar type II epithelial cells and macrophages. Real-time photoionization detector monitoring showed emissions varied significantly and were a function of location, wind direction, and worksite activity.

1. INTRODUCTION

Cured-in-place-pipe (CIPP) is a popular sanitary sewer, stormwater, and drinking water pipe repair technology that was invented in the 1970s.[1,2] A resin-impregnated felt tube is inserted into a damaged pipe and is cured in place with hot water, steam, and/or ultraviolet light.[3−9] In the United States, styrene-based polyester and vinyl ester resin systems are popular because they are less expensive than their alternatives.[10] Non-styrene resin systems such as epoxy are also used.[10] For non-styrene unsaturated polyester or vinyl ester resins, fatty acid-based reactive monomers are available.[11,12] Because concentrated chemicals are used and CIPP is manufactured in the field, forced air, pressurized steam, and other activities can release chemicals into the worksite, nearby pipes, and environment during site setup, installation, and cleanup (Figure 1).[13−25]

CIPP installation activities have caused ambient and indoor air contamination incidents, but the types and magnitudes of materials emitted have received little scrutiny. Air contamination has been documented inside (49) and outside (10) the United States (see Table S1 for details). Persons near CIPP installation sites have reported odors and illness symptoms (i.e., nausea, headache, vomiting, difficulty breathing, eye and nasal irritation, etc.). In some cases, buildings were evacuated and emergency services responded. During the past 16 years, only four CIPP chemical air emission studies have been conducted. A 2015 Los Angeles, CA study revealed styrene exited three sewer pipe manholes during steam curing (250−1070 ppm$_v$) and during cool down (3.6−76.7 ppm$_v$).[26] The styrene 700 ppm$_v$ immediately dangerous to life and health

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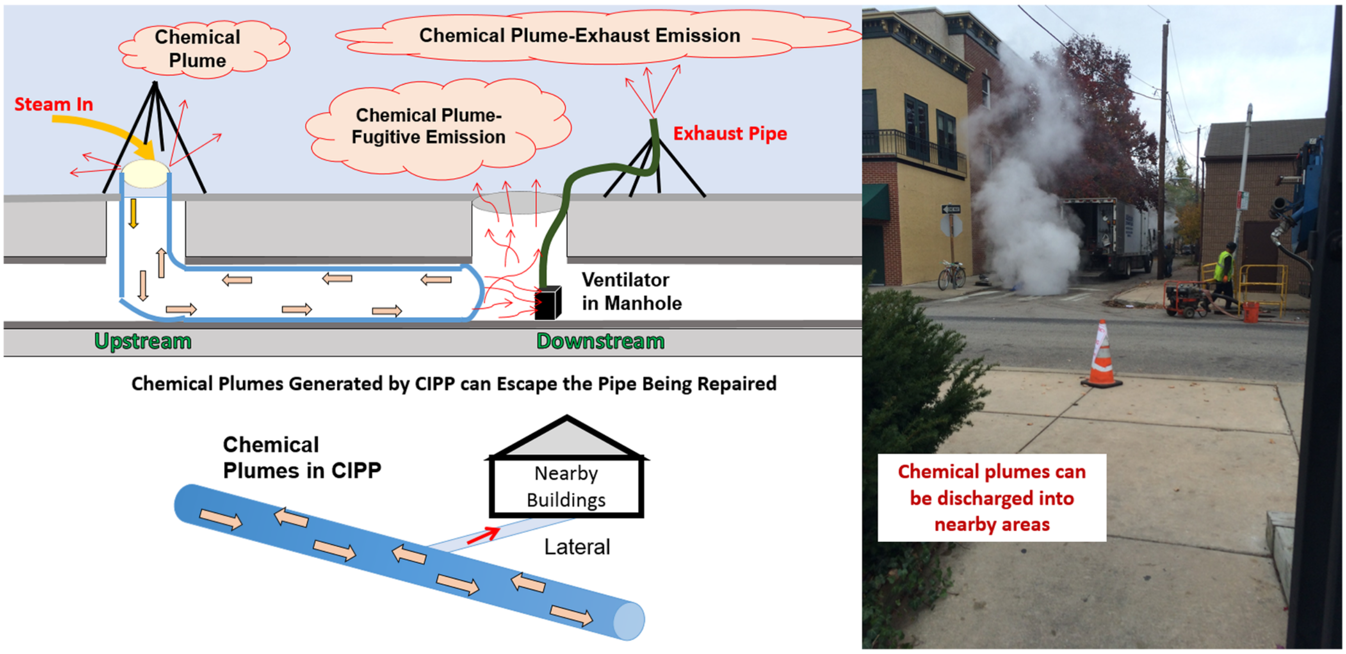

Figure 1. Diagram of emissions typical of a sewer CIPP installation. In the left diagram, steam or hot water is injected in the upstream portion of the uncured resin tube. Chemicals are emitted from the uncured resin tube into the host pipe and the annular space between the resin tube and host pipe. Some chemicals can exit buried infrastructure through nearby manholes and pipes. Sometimes contactors add excess resin, and it can be squeezed into other nearby pipes, spaces, and cracks during initial tube setup and does not remain in the resin tube. The process for installing sanitary sewer pipe CIPP is like that required for stormwater pipe CIPP, including chemical emission points. In the right photograph, a chemical plume is emitted from a downstream manhole in a residential area in Philadelphia, PA.

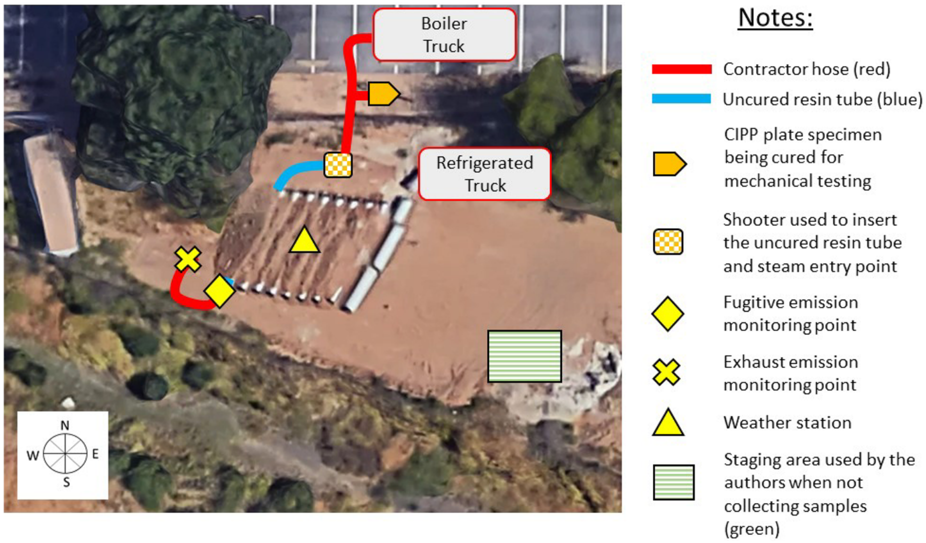

Figure 2. Plan view of the California site for a CIPP installation. After an uncured resin tube (blue) was inserted into a target pipe using the shooter, an ethylene propylene diene monomer (EPDM) contractor hose (red) was connected to the boiler truck. An EPDM contractor hose was also connected to the end of the uncured resin tube and extended to the exhaust emission pipe. The boiler truck delivered steam to the "shooter" that then entered the uncured resin tube. Each pipe was approximately 20 ft in length. A weather station was located on the top of the pipes being rehabilitated (Table S6). For each installation, contractors redirected some steam away from the first contractor hose to use for curing a separate uncured resin tube they had removed from the initial uncured resin tube. This small sample was sandwiched between two metal plates, exposed to steam, and sent to the laboratory for mechanical testing.

worker exposure limit was exceeded,[27] and styrene is expected to be carcinogenic.[28] In 2005, the U.S. Agency for Toxic Substances and Disease Registry (ATSDR)[29] concluded that a CIPP installation caused a public health hazard and contaminated an office building's indoor air. The level of styrene (0.320 ppm_v) exceeded its minimal acceptable chronic exposure level (0.060 ppm_v). A 2004 CIPP study found chemicals exited two sewer pipe manholes, and a photoionization detector (PID) reading indicated a maximal level of 110 ppm_v.[23] Steam curing lasted 24 h. Investigators speculated that styrene caused the PID response. A maximum 3.2 ppm_v styrene level (adsorption onto charcoal sorbent for 2.4 h) was found by others[30] in 2001, and buildings with dry plumbing traps were hypothesized to have styrene levels higher than those of buildings with wet traps.

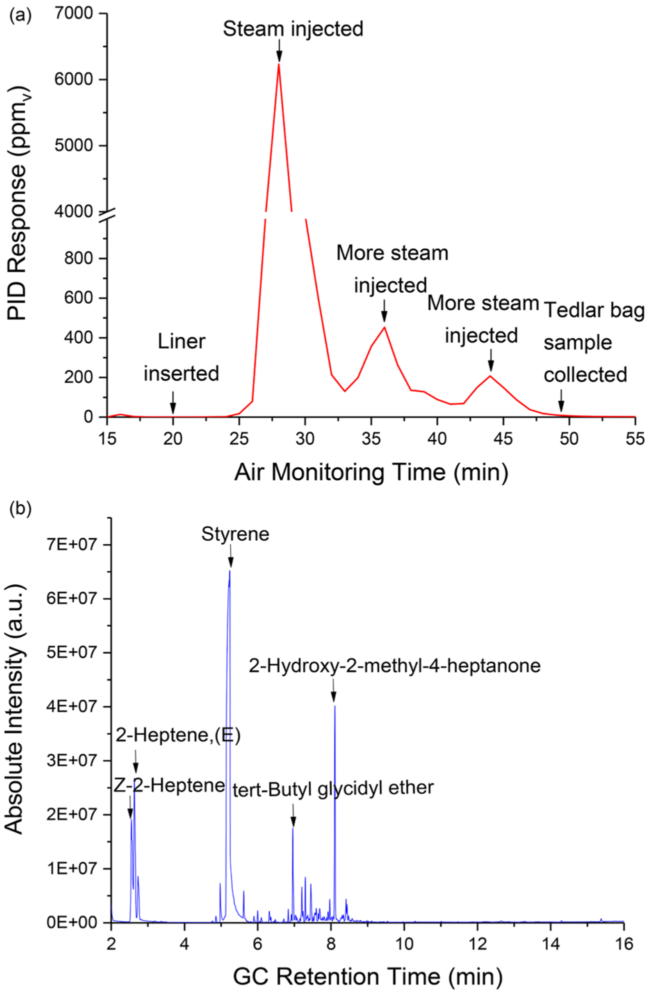

Figure 3. Exhaust emission point. (a) PID air monitoring results for Indiana site 2. (b) GC chromatogram for the Tedlar bag air sample collected at 49 min. "Liner inserted" refers to the uncured resin tube. The names of compounds with a peak area of >24000000 are shown. Styrene was confirmed with an analytical standard.

The goal of this study was to better understand the materials emitted into air during CIPP installations. Field work was conducted in Indiana at sanitary sewer sites and California at stormwater sites. Specific study objectives were (1) to conduct real-time emission monitoring using PIDs and videotaping, (2) to chemically characterize the uncured resin-impregnated tube, and (3) to examine the chemical characteristics and toxicological significance of emitted materials.

2. MATERIALS AND METHODS

Seven steam-cured CIPP installations were monitored in Indiana and California. Air sampling manifolds were installed to capture materials emitted into the air. PIDs were used for real-time emission monitoring. The condensate cytotoxicity was evaluated for styrene-based CIPP installations in California. The Supporting Information contains a detailed description of the field and laboratory methods: PID devices and calibration, analytical standards, procedures for sample preparation, methylene chloride and hexane solvent extraction for the uncured resin tubes and condensate, and gas chromatography/mass spectrometry (GC/MS) methods for uncured resin tube and condensate extracts. Condensate thermal and chemical properties were determined using thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and proton nuclear magnetic resonance (^{1}H NMR) spectroscopy. Cell cytotoxicity methods are also described.

2.1. Indiana. In July 2016, air sampling was conducted during CIPP installation for two 45.7 cm inside diameter vitrified clay sanitary sewer pipes. The manufacturer-reported resin information can be found in section S2. Chemicals in the uncured resin tube were extracted into methylene chloride and hexane to obtain resin tube extracts that were analyzed by GC/MS.

For site 1, a PID was used to monitor chemical emissions at the refrigerated truck that transported the uncured resin tube and near the upstream and downstream manholes. For site 2, the PID was used to measure chemical emissions immediately above a section of uncured resin tube cut from the main pipe segment before curing. The PID had a 1 min sampling frequency. An apparatus with a GAST vacuum pump (diaphragm type, ISSACS) was set up and drew exhaust emissions into a polytetrafluoroethylene (PTFE) (64 cm inside diameter, 0.79 cm outside diameter) and perfluoroalkoxy (PFA) (0.32 cm inside diameter, 0.64 cm outside diameter) tubing manifold under vacuum. Emissions flowed through a sealed glass filter flask immersed in an ice bath (condenser) and a vacuum flask. One Tedlar bag sample was collected at a location following the condenser. Condensate captured using the manifold was characterized by TGA and DSC, mixed with chloroform-*d*, and analyzed using ^{1}H NMR.

Air was sampled into Tedlar bags (≤75% of the total bag volume) using a bag sampler (model 1060, Xitech Instrument). The bag sample was analyzed within 24 h of collection. A CIA Advantage-Thermal Desorption Unity Series2 instrument was used with Maverick Bonanza software (version 6.1.0.A, Markes International, Inc.). The cold trap temperature was 10 °C. A GC/MS instrument was used to analyze the field and control samples. The gas chromatograph was equipped with an HP-5MS capillary column (30 m length, 0.25 mm diameter, 0.25 μm film) (Agilent Technologies, Inc.). The oven temperature program was as follows: oven temperature of 40 °C (held for 2 min) that was then ramped to 320 °C at a rate of 15 °C/min and held for 4 min using He carrier gas (5 mL/min) with a direct injector mode (held at 100 °C). The purge flow was 5.0 mL/min, and the column flow was 1.5 mL/min.

2.2. California. In August 2016, CIPPs were installed in one concrete and four corrugated metal pipes at an outdoor research site. California State University at Sacramento[12] predetermined CIPP design (Table S2) and installation conditions (Table S3). One CIPP was manufactured with a low-volatile organic compound (VOC) non-styrene resin, and four were manufactured with a styrene-based resin. Manufacturer-reported resin information can be found in section S2.

At each site, air manifolds were set up at an exhaust and fugitive emission point (Figures 2 and sections S1−S3). These stainless steel manifolds captured and condensed materials from the air. For the exhaust emission point, materials were removed from the air stream by ambient cooling and passage of the air stream through ice chest condensers and collected in Pyrex bottles. Because of equipment damage concerns at the exhaust emission point, the PID was positioned adjacent to the exhaust pipe outlet (Figure S2b). At the fugitive emission point, materials removed from the air by a condenser were collected in Pyrex bottles. Remaining emissions that continued though the manifold were monitored using a PID. A GAST vacuum pump (0.5 L/min) withdrew air into the manifold.

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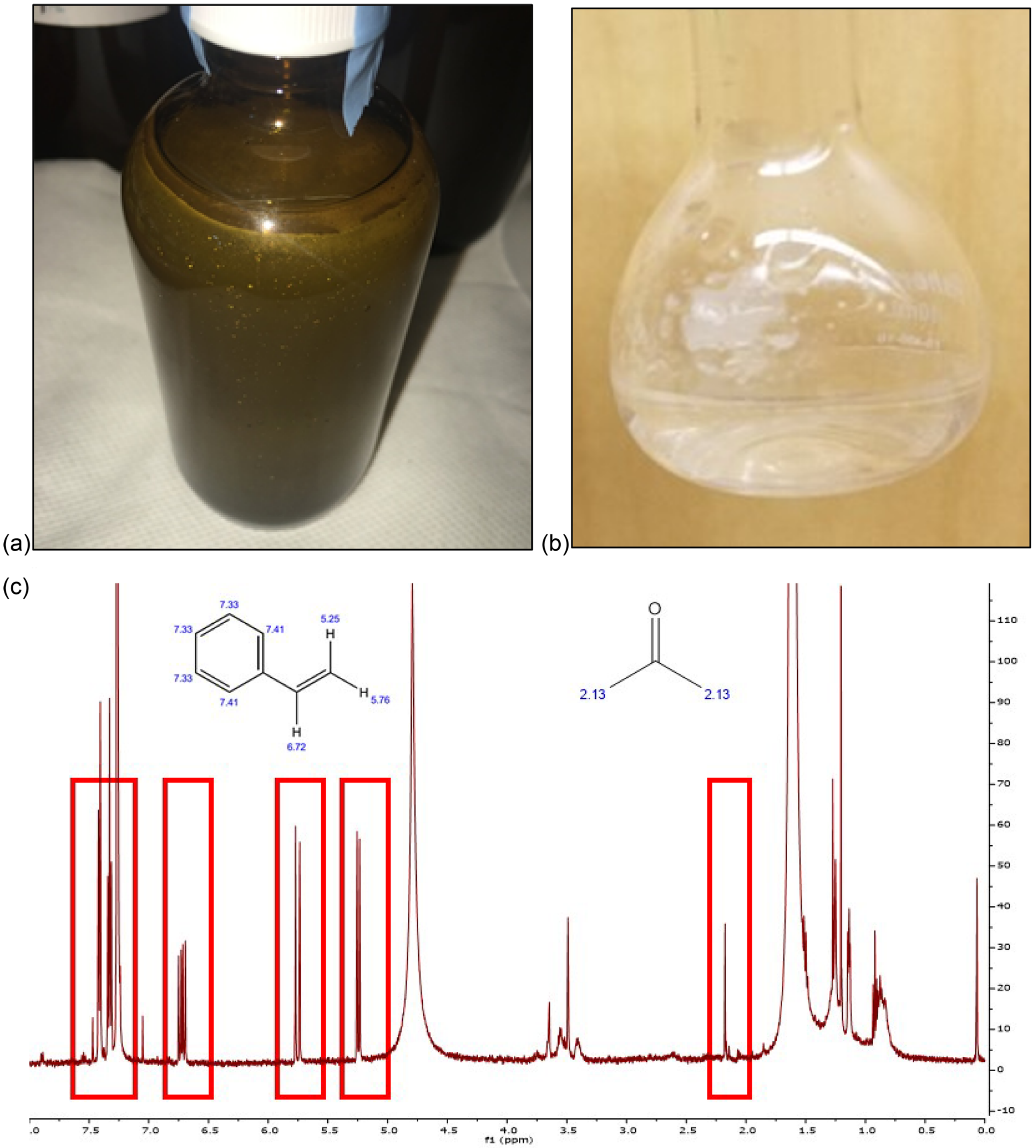

Figure 4. (a) Image of the multiphase condensate collected. (b) Image of the white waxy phase material that was separated by centrifugation from the condensate. (c) NMR spectra of particulate collected from emissions that exited the CIPP exhaust emission point at the Indiana site.

PIDs sampled the air every 2 s at each location. PFA tubing was used to reduce the potential of cross-contamination. Arcodisc filters (0.45 μm PTFE) (Pall Life Sciences) served as humidity filters for each PID and were replaced after each installation.

Captured materials underwent liquid–liquid extraction, and the chemical sampling flux was reported for condensate samples (mass of compound captured/surface area of stainless steel tube − sample collection time). In preparation for chemical analysis, condensate samples were homogenized by being vigorously shaken. A sample (15 g) was added to the separation funnel followed by 20 mL of solvent (hexane or methylene chloride). The mixture was shaken slowly and left for 10 min, and the extractant was then collected. Solvent addition and mixing were performed three times. Next, a rotary evaporator was used to reduce the volume of 60 mL of extractant to 3.7 mL. Finally, 1.5 mL of the sample containing 1 ppm of the

Table 1. Maximal Exhaust Chemical Sampling Flux for Methylene Chloride-Extracted Condensates When Two Different Resins Were Used[a]

compound	installation site (resin type) and chemical sampling flux (mg m^{-2} s^{-1})				
	1 (L713)	2 (EcoTek)	3 (L713)	4 (L713)	5 (L713)
Material Captured before the Condensers, Ambient Cooled					
acetophenone^{HAP}	–	1.65, 1.74$^{\Delta\Delta\Delta}$	–	–	–
benzaldehyde*‡	0.03, 0.04$^{\Delta}$	0.07$^{\Delta\Delta\Delta}$	0.25, 0.25$^{\Delta}$	–	–
benzoic acid†	1.12, 1.19$^{\Delta}$	1.84, 1.99$^{\Delta\Delta\Delta}$	1.59, 2.38$^{\Delta}$	0.68$^{\Delta}$	–
BHT*	–	0.08$^{\Delta\Delta\Delta}$	–	–	–
4-*tert*-BCHl	–	1.73, 2.06$^{\Delta\Delta\Delta}$	–	–	–
DBP^{†‡HAP}	0.02, 0.02$^{\Delta}$	0.13$^{\Delta\Delta\Delta}$	–	–	–
phenol^{‡HAP}	0.06, 0.09$^{\Delta}$	–	0.23, 0.23$^{\Delta}$	–	–
styrene^{*HAP}	6.17, 7.29$^{\Delta}$	0.63, 0.81 $^{\Delta\Delta\Delta}$	<MRL$^{\Delta}$	13.63, 17.4$^{\Delta}$	<MRL$^{\Delta}$
1-tetradecanol	–	0.37, 0.37$^{\Delta\Delta}$	–	–	–
Material Captured after Two Cold Condensers					
acetophenone^{HAP}	–	–	–	–	–
benzaldehyde*‡	0.26, 0.26	0.04, 0.05	1.16, 1.24	3.76, 4.33	0.56, 0.59
benzoic acid†	–	–	–	1.88, 2.59	–
BHT*	0.16, 0.18	0.07, 0.12	0.16, 0.17	–	–
4-*tert*-BCHl	–	1.96, 1.99	–	–	–
DBP^{†‡HAP}	0.03, 0.03	0.13	–	–	–
phenol^{‡HAP}	0.69, 0.76	–	0.89, 1.03	1.34, 1.7	0.63, 0.69
styrene^{*HAP}	501.4, 853.37	2.62, 2.93	497.68, 683.75	481.23, 715.73	516.75, 530.21
1-tetradecanol	0.57, 0.68	–	0.47, 0.58	0.92, 1.48	0.13

[a] Two resins were used for CIPP installations: L713-LTA (styrene-based resin) and EcoTek (non-styrene-based resin). Results represent two extractions per condensate sample collected per condensate collection period. A dash indicates no instrument response for the compound, while MRL indicates the compound was detected but was present at a concentration below the minimal calibration curve standard. A superscript triangle indicates how many total condensate samples were collected during the entire CIPP curing period at the sampling location before the cold condensers. Samples collected following the cold condensers were collected every 20 min. Condensate samples after the cold condensers reported for sites 1 and 3–5 represent the first 20 min period of CIPP curing. The condensate sample for site 2 represents the second 20 min period of CIPP curing because the level of styrene was greatest during that period for all the site 2 condensates collected. 4-*tert*-Butylcyclohexanone and TPGDA were detected only in hexane extracts. At site 2, 4-*tert*-butylcyclohexanone was present at a concentration lower than the minimal reporting level. At site 2, the TPGDA flux was 8.20 and 8.99 mg m^{-2} s^{-1}, the site 3 flux was 1.55 and 1.59 mg m^{-2} s^{-1}, and TPGDA was not detected in site 1, 4, or 5 condensate. Abbreviations: BHT, butylated hydroxytoluene; 4-*tert*-BCHl, 4-*tert*-butylcyclohexanol; DBP, dibutyl phthalate. An asterisk denotes a compound detected in the uncured resin tube. A dagger denotes CDOT (2011), and a double dagger denotes Tabor et al. detected that compound in their CIPP water impact study. HAP denotes a hazardous air pollutant.

internal standard (1,4-dichlorobenzene-d_4) was analyzed by GC/MS. LLE percent recoveries of toluene (40 ± 5.0%), naphthalene (76.4 ± 5.8%), and phenanthrene (95.9 ± 3.6%) for methylene chloride and of toluene (20.1 ± 2.4%), naphthalene (70.1 ± 5.1%), and phenanthrene (85.5 ± 3.2%) for hexane were achieved.

3. RESULTS AND DISCUSSION

3.1. Indiana Investigation of Sanitary Sewer Pipes.

Uncured resin tube samples were extracted using hexane and methylene chloride from site 2. Hexane extractions showed 67.4 ± 19.7 mg of styrene/gram of tube. Methylene chloride extractions revealed styrene (40.3 ± 8.6 mg/g), butylated hydroxytoluene (BHT) (22.8 ± 14.0 mg/g), and benzaldehyde (2.2 ± 0.7 mg/g). 1-Dodecanol was also detected but not quantified.

During CIPP installation, the authors did not see workers using PPE such as respirators and earplugs. One worker sat on a chair inside the white chemical plume emitted from the downstream manhole. This worker monitored a pressure gauge to determine when the worker at the boiler needed to inject more steam.

For the two sites, PID measurements ranged from 0 to 6231 ppm$_v$ and were a function of location, type of CIPP activity taking place (tube insertion, steam injection, curing, and venting), wind condition, and vehicle traffic (Video S1 and section S3.1). Site 1 spot PID measurements ranged from 0 to 514 ppm$_v$. At site 2, when the PID was located a few centimeters above an excess piece of uncured resin tube, a spot reading of 1361 ppm$_v$ was recorded and white material was emitted into the air (Video S2). Materials were emitted into the air while the uncured resin tube was guided into the sewer manhole (Video S3). Once the tube was inserted into the sewer pipe, the PID was fixed at the exhaust emission point. A PID response of 6231 ppm$_v$ was detected during the curing process (Figure 3). The increase in the magnitude of the PID signal corresponded to the forced introduction of air into the resin tube, before steam was introduced. A Tedlar bag air sample collected near the end of the curing period confirmed styrene and unidentified compounds were present (Table S4).

The material captured by the condenser was a complex multiphase mixture. This included organic vapor, water vapor, particulate (condensable vapor and partially cured resin), and liquid droplets (water and organics). At room temperature, the materials partially phase separated into a colorless phase (top) and dense cloudy phase (bottom). The dense cloudy phase was centrifuged (3500 rpm for 15 min) and separated into a colorless liquid phase and a white waxy phase (the top layer). TGA demonstrated that the waxy phase evaporated fully at 90 °C with volatilization occurring immediately at the onset of heating at 30 °C. DSC curves showed three characteristic endothermic peaks at 2 °C (melting), 42 °C (evaporation), and

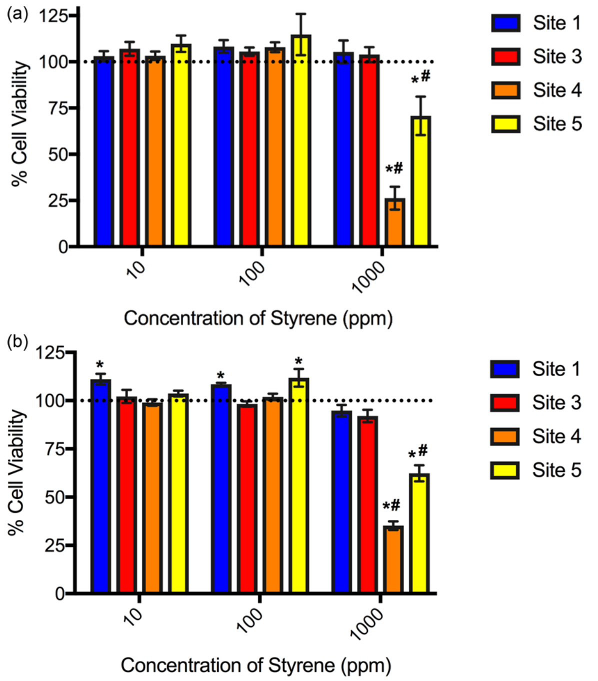

Figure 5. (a) Mouse alveolar type II epithelial cells and (b) macrophages were exposed to styrene-based CIPP condensates in serum-free medium for 24 h at a styrene concentration of 10, 100, or 1,000 ppm. Changes in viability were determined via the MTT assay comparing CIPP condensate-exposed cells to control (untreated) cells. The dotted line represents the value of control (untreated) cells. Data are presented as means ± the standard error of the mean ($n = 4$ per group). An asterisk denotes statistical significance compared to control cells, and a number sign denotes statistical significance compared to all other CIPP condensate exposures at the same concentration ($p \leq 0.05$).

77 °C (evaporation). The waxy phase was likely a mixture of low-molecular weight volatile organic material with minimal presence of water or inorganic materials. ^1H NMR revealed styrene monomer, acetone, and multiple unidentified compounds were present in the waxy phase (Figure 4).

3.2. California Investigation of Stormwater Pipes.

3.2.1. Condensate Composition. The greatest volume and mass of condensate and number of compounds detected were found at the exhaust emission point (Video S4). Styrene was found in greatest abundance compared to other compounds identified (Table 1). Some condensate compounds were detected in the uncured resin tubes (Table S5). Non-styrene compounds were likely created during curing and were unreported ingredients in the uncured resin, plastic preliner, plastic coating on the interior of the resin tube, or the polyethylene terephthalate felt.

Low-VOC condensate (site 2) contained a quantifiable amount of styrene. Because the uncured low-VOC resin did not contain styrene (Table S5) and Currier[12] found styrene leaching into simulated stormwater from this same CIPP, unintentional contamination by the contractors is suspected. The low-VOC non-styrene and styrene-based resin tubes were delivered on a refrigerated truck and inserted into the pipes by the same contractor with the same equipment.

Acetophenone, 4-*tert*-butylcyclohexanol, and 4-*tert*-butylcyclohexanone were exclusively found in the low-VOC resin condensate. Tripropylene glycol diacrylate (TPGDA) was detected in site 2 and 3 condensates. The TPGDA flux was greatest for the low-VOC resin site 2 condensate (8.20, 8.99 mg m^{-2} s^{-1}) compared to that of the styrene-based resin site 3 condensate (1.55, 1.59 mg m^{-2} s^{-1}). 4-*tert*-Butylcyclohexanone and TPGDA were detected only in hexane extracts. Other unidentified compounds were detected in extracts but were not quantified.

3.2.2. Condensate Cytotoxicity. For the styrene-based resin condensates, no cell viability changes were found for mouse alveolar type II epithelial cells or alveolar macrophages exposed to a diluted condensate with 10 and 100 ppm styrene, but changes were observed for the 1000 ppm styrene condensate (Figure 5). Differential toxicity between sites indicated toxicity due to non-styrene compounds. Site 4 demonstrated enhanced cytotoxicity compared to that of site 5. These findings support a prior observation that even a dilute condensate (styrene below its *Daphnia magna* 48 h LD_{50}) can be acutely toxic.[13]

3.2.3. Evaluation of the Magnitude and Variation of Concentration. PID readings fluctuated during each CIPP installation (Figure 6). The lowest maximal PID response was found for the low-VOC CIPP installation (9.6 ppm_v), whereas the styrene-based resin CIPP's maximal PID responses ranged from 394 to 757 ppm_v (Table 2).

For the styrene-based CIPPs, lower PID levels were likely found at the exhaust emission point than at the fugitive emission point because the exhaust emission point PID was not located directly in the air stream and greater mixing and dilution with ambient air took place (Video S3). PID readings may have been affected by the PTFE filters because of the tendency of filters to adsorb chemicals. Because materials were removed from the manifold prior to PID sampling, observed PID signals may underestimate chemical emissions.

4. IMPLICATIONS

The goal of this study was to improve our understanding of the materials emitted into air by steam-cured CIPP installation activities. The chemical plume was determined to be a multiphase chemical mixture that includes organic vapor, water vapor, particulate (condensable vapor and partially cured resin), and liquid droplets (water and organics). The nature of the partially cured resin captured in the air remains unclear because the extent of polymerization, side reactions, and role of environmental conditions upon its formation have not been studied. Compounds that were confirmed in condensates included hazardous air pollutants, a suspected carcinogen, an endocrine disruptor compound, and others that had limited toxicological data. Compounds quantified in condensates included acetone, acetophenone, benzaldehyde, benzoic acid, BHT, 4-*tert*-butylcyclohexanol, 4-*tert*-butylcyclohexanone, DBP, phenol, styrene, 1-tetradecanol, and TPGDA. Differential cytotoxicity in alveolar cells occurred even when condensate styrene levels were equivalent and indicated non-styrene compounds contributed to chemical toxicity. The emission of styrene from the non-styrene resin CIPP installation indicated that contractor equipment handling practices affected the resulting chemical emissions.

Sampling methods and approaches are needed to better characterize chemical emissions, chemical mixture exposures, and short- and long-term health impacts. The high temperature, high velocity, and multi-phase emissions posed a challenge in this study. Emission variability was evident by PID readings and video monitoring. Even when the same CIPP contractor used the same resin on the same diameter and type of pipes, the type and amount of chemicals emitted differed. To understand worker chemical exposures and the types and masses of

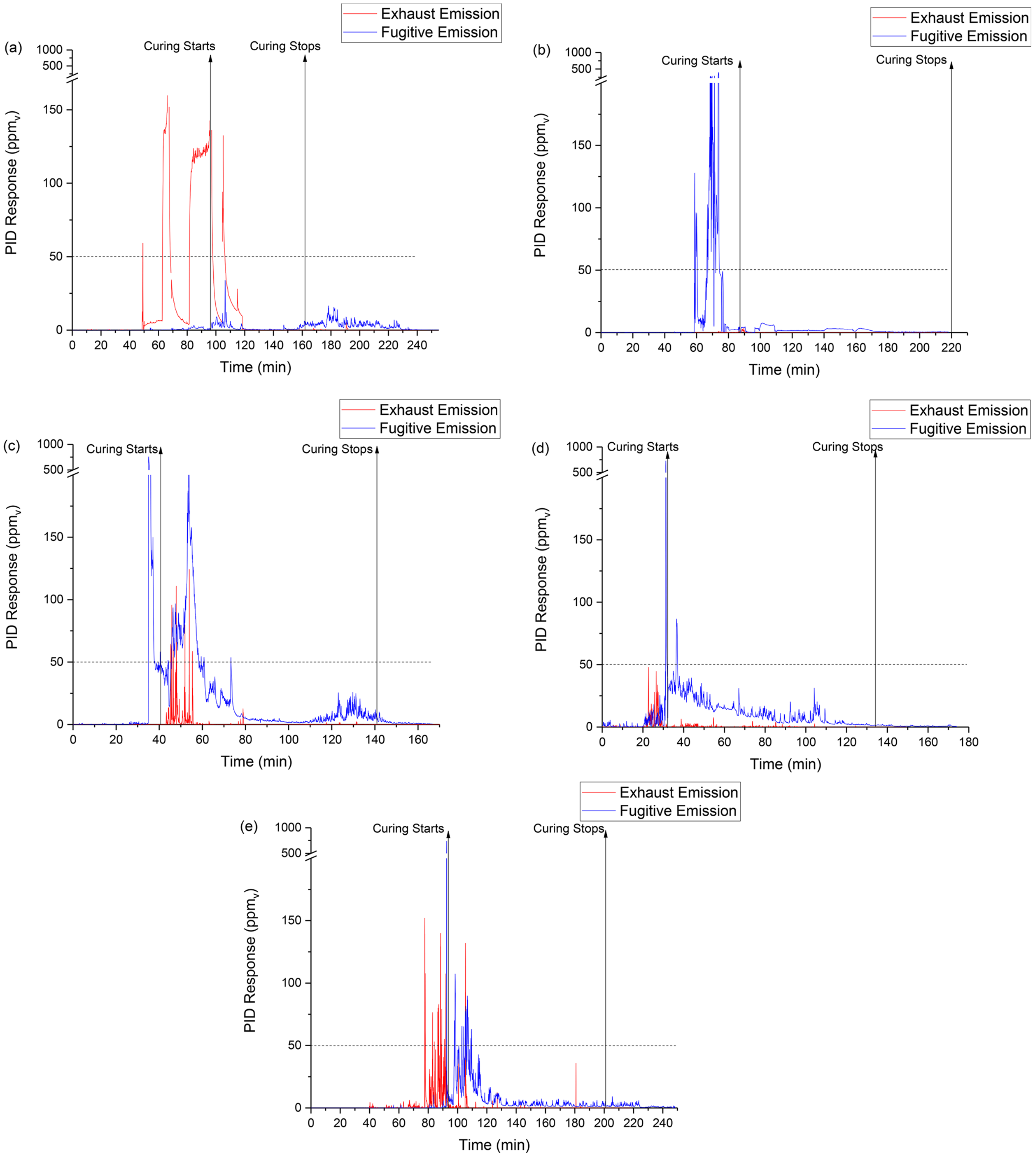

Figure 6. PID monitoring results for five CIPP installations in California where fixed PID units were located at the fugitive emission point and exhaust emission point for (a) site 1, (b) site 2 (low VOC), (c) site 3, (d) site 4, and (e) site 5. The horizontal dotted line represents 50 ppm$_v$. Several "out-of-range" events were detected when the signal exceeded 9.999 ppm$_v$, and out-of-range events are not shown in these graphs. Table 2 describes out-of-range events for each site. The PID at the exhaust emission point was located adjacent to and below the exhaust pipe outlet.

chemicals emitted, their phases and exposure duration and the mixture's toxicological impacts should be investigated.

Because there are many resins and CIPP installation variables, and because very few studies have been conducted to characterize air emissions, additional investigations are needed. Limited information exists that enables an understanding of chemical exposure risks to CIPP workers, the public, and the environment. During this investigation, CIPP workers did not use respirators and resided inside and walked through the chemical plumes (section S3) and exposures occurred even when plumes were not visible (Video S5). Contractors also sometimes handled the uncured resin tube and CIPP with their

Table 2. Maximal PID Responses at Each California CIPP Installation in ppm_v[a]

	fixed PIDs		out-of-range events	
installation number (resin type)	fugitive emission (ppm_v)	exhaust emission (ppm_v)	total number	total minutes
1 (L713)	394	159	135	4.17
2 (EcoTek)	7.7	9.6	2	0.03
3 (L713)	757	124	15	0.30
4 (L713)	724	47	0	0
5 (L713)	734	151	7	0.17

[a] Two resins were used for CIPP installations: L713-LTA (styrene-based resin) and EcoTek (non-styrene-based resin). PIDs sometimes recorded out-of-range events, and this occurred when the signal exceeded 9999 ppm_v. The PID at the exhaust emission point was located adjacent to and below the exhaust pipe outlet.

bare hands. Until more CIPP air monitoring and chemical toxicity data are available, the recommendation is that persons at or near CIPP sites (1) minimize dermal and inhalation exposures, (2) monitor emissions, (3) use appropriate personal protective equipment (section S2), and (4) capture emissions and confirm this by monitoring.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.estlett.7b00237.

A detailed description of the list of CIPP-caused air contamination incidents and field and laboratory methods, Materials and Methods, Figures S1−S3, and Tables S1−S6 (PDF)
Chemical plume movement (MP4)
Chemical emission from an uncured resin tube before curing (MP4)
Uncured resin tube guided from a truck into a sewer (MP4)
CIPP exhaust pipe emitting materials into the worksite (MP4)
Time-lapse video of movement of workers around work site (MP4)

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Wood, E. Lining of passageways. Patent US4064211, 1977.

(2) Wood, E. Method of lining a passageway with a resin absorbent tube. Patent US4135958, 1979.

(3) *Cured-In-Place Pipe (CIPP) Good Practices Guidelines*, 1st ed.; North American Society for Trenchless Technology (NASTT): Cleveland, OH, 2015.

(4) *Manual for Inspector Training and Certification Program (ITCP) for the Inspection of Cured in Place Pipe Installation*, version 3.0; National Association of Sanitary Sewer and County Officials, Inc.: Marriottsville, MD, 2011.

(5) *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)*; American Society of Testing and Materials: West Conshohocken, PA, 2011.

(6) *Standard Specification for Cured-In-Place Thermosetting Resin Sewer Piping Systems*; American Society of Testing and Materials: West Conshohocken, PA, 2012.

(7) *Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube*; American Society of Testing and Materials: West Conshohocken, PA, 2016.

(8) *Standard Practice for Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Cured-in-Place Thermosetting Resin Pipe (CIPP)*; American Society of Testing and Materials: West Conshohocken, PA, 2017.

(9) *M28 Rehabilitation of Water Mains*, 3rd ed.; American Waterworks Association: Denver, 2014.

(10) Muenchmeyer, G. NASSCO Inspector Training Course. Personal communication, 2017.

(11) Moore, W. *Non-Styrene Options for Cured in Place Pipe*; AOC, LLC: Ft. Lauderdale, FL, 2011.

(12) La Scala, J.; Sands, J. M.; Orlicki, J. A.; Robinette, E. J.; Palmese, G. R. Fatty Acid-Based Monomers as Styrene Replacements for Liquid Molding Resins. *Polymer* **2004**, *45*, 7729−7737.

(13) Currier, B. Water Quality of Flow through Cured-In-Place Pipe (CIPP), Final Report; Office of Water Programs, California State University Sacramento: Sacramento, CA, 2017 (prepared for California Department of Transportation, Sacramento, CA).

(14) Tabor, M. L.; Newman, D.; Whelton, A. J. Stormwater Chemical Contamination Caused by Cured-in-Place Pipe (CIPP) Infrastructure Rehabilitation Activities. *Environ. Sci. Technol.* **2014**, *48*, 10938−10947.

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

(16) Donaldson, B.; Whelton, A. J. Impact of Stormwater Pipe Lining Materials on Water Quality: Field Study and Resulting Specifications. *Transp. Res. Rec.* **2013**, *2362*, 49−56.

(17) Donaldson, B. M. 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, 2013.

(18) Whelton, A. J.; Salehi, M.; Tabor, M.; Donaldson, B.; Estaba, J. Impact of Infrastructure Coating Materials on Storm Water Quality: A Review and Experimental Study. *J. Environ. Eng.* **2013**, *139*, 746−756.

(19) *Environmental Effects of Cured in Place Pipe Repairs*; CTC & Associates, LLC, and Caltrans Division of Research and Investigation: Sacramento, CA, 2012 (preliminary investigation).

(20) Summary of Water Sampling, CIPP for 4 Culverts; State Department of Transportation: Binghamton, NY, 2009.

(21) Donaldson, B. M.; Baker, A. J. *Understanding the Environmental Implications of Cure-In-Place Rehabilitation Technology*; Virginia Transportation Research Council: Charlottesville, VA, 2008.

(22) Lee, R. K. Risk Associated with CIPP Lining of Stormwater Pipes and the Release of Styrene. Proceedings of the North American Society for Trenchless Technology (NASTT) NO-DIG Conference, NASTT, Dallas, TX, 2008; Paper E-1-05.

(23) Bauer, G.; McCartney, D. Odour Control-More than sewage when installing cured-in-place sewer pipe. Proceedings of the North American Society for Trenchless Technology (NASTT) NO-DIG Conference, NASTT, Liverpool, NY, 2004; Paper D-3-02.

(24) 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 SanierungsverfahrensowieallgemeingültigenAusschreibungsempfehlungen (in German); Ministry of environment and natural protection, agriculture and consumer protection (MUNLV) of the north country Rhine-Westphalia in Bielefeld: Bielefeld, Germany, 2004; pp 104.

(25) CDPHE Environmental Release and Incident System Report 2011-0066; Colorado Department of Public Health and Environment: Denver, 2011.

(26) Ajdari, E. B. Volatile Organic Compound (VOC) Emission during Cured-in-Place-Pipe (CIPP) Sewer Pipe Rehabilitation. Ph.D. Dissertation, University of New Orleans, New Orleans, 2016.

(27) Styrene, Immediately Dangerous to Life and Health (IDLH) Concentration. National Institute for Occupational Safety and Health: Atlanta, 1994 (https://www.cdc.gov/niosh/idlh/100425.html, accessed July 2, 2017).

(28) *Report on Carcinogens, Styrene*, 14th ed.; U.S. National Toxicology Program: Research Triangle Park, NC, 2011 (https://ntp.niehs.nih.gov/pubhealth/roc/index-1.html, accessed July 2, 2017).

(29) Schlitz Park Office Building, Milwakee, Milwakee County, Wisconsin; U.S. Agency for Toxic Substances and Disease Registry: Atlanta, 2005.

(30) 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, 2001.

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