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Volatile Organic Compound (VOC) Emission during Cured-in-Place-Pipe (CIPP) Sewer Pipe Rehabilitation

A Dissertation

Submitted to the Graduate Faculty of the
University of New Orleans
in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy
in
Engineering and Applied Science
Environmental Engineering

by

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May, 2016

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Author's Preface and Attribution

This dissertation consists of 6 chapters involving three major industries: public health, trenchless technology, and resin and plastics. Contributing authors other than Ms. Elena Bourbour Ajdari (Doctoral Student), with brief description of their background and their contributions are included here. It is noted here that the entire manuscript has been edited by Jane Banks, Ph.D., at Editing with Care in New Orleans, Louisiana. The research described in this dissertation contains significant scientific contributions spanning multiple disciplines.

Chapters 2, 3, 4, and 5: Dr. Andrew J. Whelton, Assistant Professor of Civil Engineering and Environmental and Ecological Engineering, Purdue University, IN helped with the literature review, contributed to interpretation of lab results and conclusions, elucidated limitations and recommendations for future studies, and reviewed the manuscript before publication.

Chapter 6: Dr. Nima Taha, M.D., practitioner of Internal Medicine with a subspecialty in Eco-cardiography, at the Providence Little Company of Marry Hospital, CA provided the medical paper review and assisted in the section on the health effects of relevant pollutants exposure.

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Abstract

The maintenance or replacement of deteriorated pipes and culverts is a constant and significant concern for municipalities and transportation agencies in the United States (Donaldson and Wallingford, 2010). Trenchless technologies and especially the Cured-in-place pipe (CIPP) method have become increasingly common ways to preserve infrastructures owing to their feasibility, cost-effectiveness, and fewer social impacts (Jung and Sinha, 2007). Therefore, there is a growing need to understand the direct and indirect effects of pipeline rehabilitation activities on the environment. Nearly all past CIPP studies have focused on its mechanical properties, and its environmental impacts are poorly investigated and documented (Allouche et al. 2012). Sewer pipelines and storm-water culverts are administered by municipalities and transportation agencies who bear the responsibility for rehabilitation and renewal of these infrastructures. In consequence, they rarely allow sampling and research projects in the field due to liability issues. This is a main obstacle to conducting comprehensive, precise, and unbiased research on CIPP environmental impacts and to date, the degree of relevant health effects and related environmental impacts have remained unknown.

Numerous building indoor air contamination incidents indicate that work is needed to understand the magnitude of styrene emission from CIPP sanitary sewer repairs. The main goal of this study was to better comprehend Volatile Organic Compounds emission at three CIPP sanitary sewer installation sites in one U.S. city. Results showed that CIPP chemical emissions may be a health risk to workers and nearby building inhabitants. Additional testing and investigations regarding chemical emissions from CIPP should be commissioned to fill in the environmental and public health knowledge gaps. The acute and chronic chemical exposure risks of CIPP chemical steam constituents and styrene to sensitive populations should be further examined.

Other goals of this study were to estimate the magnitude of solid waste generated as well as the amount of certain criteria air pollutants and greenhouse gases emitted from onsite heavy equipment for both CIPP and open-cut sites in a U.S city. The results indicated that the amount of open-cut related solid waste, criteria air pollutants, and greenhouse gases were greater than those during CIPP activities. Additional work is needed to quantify pollutant emissions from CIPP and open-cut activities and consider emissions from a cradle-to-grave standpoint.

Key words: CIPP air emission; sanitary sewer pipe rehabilitation; criteria air pollutants at CIPP and open-cut sites; solid waste generation at CIPP and open-cut sites, health effects of styrene, health effects of criteria air pollutants and GHGs

Chapter 1

1. Introduction

Most sewer collection systems in the USA were built in the early 20th century and their condition is becoming a substantial maintenance concern (Tafuri et al. 2001). Replacement of crumbling sewer pipes using open-trench excavation techniques can pose public inconvenience and safety challenges especially in megacities. Instead, many cities are choosing to rehabilitate sewer pipes *in-situ* using the cured-in-place-pipe (CIPP) "trenchless" renewal technique. The CIPP renewal technique involves the installation of a resin impregnated fabric into the deteriorating pipeline. This material is then cured *in-situ* by heat (hot water or steam) or ultraviolet light. CIPP is created *in-situ* by the crosslinking of a polymer resin, such as an unsaturated polyester. Studies have shown CIPP rehabilitated sewer pipes have reduced inflow/infiltration and emergency repair costs (Najafi 2011).

While the CIPP renewal method for wastewater industry has been used in the U.S. for more than 40 years (Matthews et al. 2012), CIPP mechanical properties have been the focus of nearly all past CIPP studies, not its environmental impacts (Allouche et al. 2012). In 2011 and 2013, researchers compiled a number of environmental contamination incidents from the past 15 years associated with CIPP sanitary sewer and storm water culvert installations (Whelton et al. 2013; Tabor et al. 2014). These incidents involved the discharge of hot water and condensate from CIPP sites directly into waterways and sanitary sewer systems causing fish kills and activated sludge process inhibitions. Other incidents have involved chemical emission from nearby CIPP sanitary sewer pipes which traveled through sewer pipes and entered nearby residences through their premise plumbing. In some cases, emitted chemicals traveled above-ground and entered building ventilation systems. Emission of Volatile Organic Compounds (VOCs) into the air from CIPP operations is poorly documented and understood. Hence, the main focus of this dissertation is to characterize and quantify VOCs which are emitted from CIPP sewer pipe rehabilitation activity. Long-term VOC inhalation of workers and short-term

exposure for building residents have the potential to impact the quality of their life and may cause health effects which need to be investigated and elucidated.

1.1 Sewer System History

With a population of 35,000 in the Indus River Valley of Pakistan, Mohenjo-Daro is considered to be the birthplace of sewers. Cut stone or man-made masonry units were being used to build open-topped drains and became the prototype used throughout the ancient world (History of Sanitary Sewers, 2016).

1.1.1 Pipes

At about the same time (4,000 BCE) the first pipes made from terracotta were invented in Iraq, and the sewer pipe idea spread far into Asia, the Middle East, and Europe. Paris was among the first cities that developed a comprehensive sewer system, and a sewer was built under almost every street from the 1860's to the 1890's. The Paris sewer system included several new ideas, including devices to clean the sewers, a sidewalk area for sewer workers, and low flow channels. In the 1860's a new sewer system was built because of deplorable sanitation conditions, and egg-shaped and separate sewers were constructed in England. In Europe large sewers were usually made from cut stone or brick, and the smaller pipes were built of cast iron, clay, and wood. In the United States after the civil war, diseases such as cholera posed problems, and American civil engineers followed strategies from England and Europe to deal with the situation (History of Sanitary Sewers, 2016).

The birthplace of the first new separate sanitary sewer system was in Memphis, Tennessee. Initially, six-inch internal diameter (ID) clay pipes without maintenance holes were used for the sewer system, and afterward they were converted to eight inches ID with maintenance holes. Clay was the major material for pipe factories across the United States although other materials including wood, cast iron, and concrete were in use as well. Wood in particular was in common use due to its wide availability. However, wood

is not good for sewage because of sulfides and sulfuric acid. Salt-glazed and vitrified clay brick was used extensively and is still in effective service for sewer systems throughout the United States. Since the late 1800's, the basic sewer system design has not changed for the most part, but new pipe materials have been added to the previous selections. Steel was another option for pipe material but was less common owing to its cost. The first cast iron foundry emerged in New Jersey, and Philadelphia was the first place to utilize cast iron pipes (History of Sanitary Sewers, 2016).

1.1.2 Manholes and Lampholes

In the primary sewer collection system, a narrow hole, named lamphole, was encased for visual sewer inspections. However, it was found to be cumbersome as a maintenance access point. Because of that, manholes or maintenance holes were developed to provide access to the sewers for inspection and cleaning. People also recognized that sewers had to be ventilated, and manholes could play a major role in sewer ventilation. Originally, manhole covers were made from slabs of stone or pieces of wood, and in the 19th century modern manhole covers were built. In the United States, cast iron manhole covers were very popular and were made in various shapes, including rectangular and square, but largely round. The oldest existing foundry catalog for manhole covers was published in 1860 (History of Sanitary Sewers, 2016).

1.1.3 Flush Tanks

In the United States at the early stage of sewer system design, the necessity of sewage flushing was recognized, particularly in the areas where sewer reaches had a low slope and low tributary sewage flow. Because of this, flush tank mechanisms, commonly installed in upstream manholes, were constructed to assist the periodic flushing of downstream reaches. Both manual and automatic versions of flush tanks were used. A considerable amount of water was accumulated and released into the downstream and, generally, the water source was public potable water (History of Sanitary Sewers, 2016).

1.1.4 Combined and Separate Sewer Systems

As early as 1842 the concept of establishing separate systems for conveyance of human wastes was proposed in England by Edwin Chadwick, well-known as the "Father of Sanitation." American engineers such as Colonel George Waring pursued the British systems. In America's cities, based on precipitation volume and terrain characteristics, two different options were feasible: a combined system or a separate system. Generally, cities with heavy precipitation and flat terrain were selected for the combined system, which can flush and facilitate sewage conveyance. The separate system was used for cities with steep terrain and/or low volume of precipitation. In the late 1800's, engineers from various locations proposed comprehensive sewer systems designed to handle certain difficulties of the existing system, especially flow and odor problems. For these reasons, Shone in London, Berlier in Paris, and Liernur in Holland created pneumatic systems which were applied in several areas. American designs for similar problems were not fulfilled due to the high cost. Progress elsewhere in sewer design systems eventually made them obsolete (History of Sanitary Sewers, 2016).

1.2 Sewer System in USA

It seems, sewer systems are nothing new, and the use of sewer pipes dates from ancient times. The United States began developing its own sewer system and most of the wastewater collection mains were expanded in the early part of the last century (Tafuri and Selvakumar, 2001). One challenge to infrastructure systems is that pipeline networks require sequential inspection and maintenance which can help repair deteriorated pipes early on and save time and money.

In the U.S. most of the water and wastewater infrastructures are aging, and repair and rehabilitation of these systems are the first priority for municipalities. This exigent situation has given rise to an emerging and extensive body of research on how best to manage the situation with an engineering-based and cost-effective design, construction, and repair. The United States wastewater network, with large sections buried

underground and beneath buildings, is a complex and broad infrastructure that increases the difficulty and cost of inspection and repair. Numerous factors, including geology, climate, and topography affect the design, construction, function, and potential failure of the system. Other factors such as age, size, location, deterioration rate, management practices, financial resources, hydraulic capacity, and regulatory requirements influence the repair and rehabilitation approaches (Tafuri and Selvakumar, 2001).

In 2012 the EPA's Clean Watersheds Needs Survey (CWNS) announced that a capital investment of $271 billion is essential to meet the nation's wastewater and stormwater treatment and collection requirements for the next 20 years (2032). This includes $197.8 billion for wastewater pipes and treatment facilities, $48.0 billion for combined sewer overflow correction, $19.2 billion for stormwater management, and $6.1 billion for recycled water treatment and distribution. To meet the water quality requirements of the Clean Water Act, the CWNS is conducted every four years to evaluate the capital investment required nationwide for wastewater collection and treatment plants. Figure 1-1 illustrates the expected costs by each category (EPA, 2016).

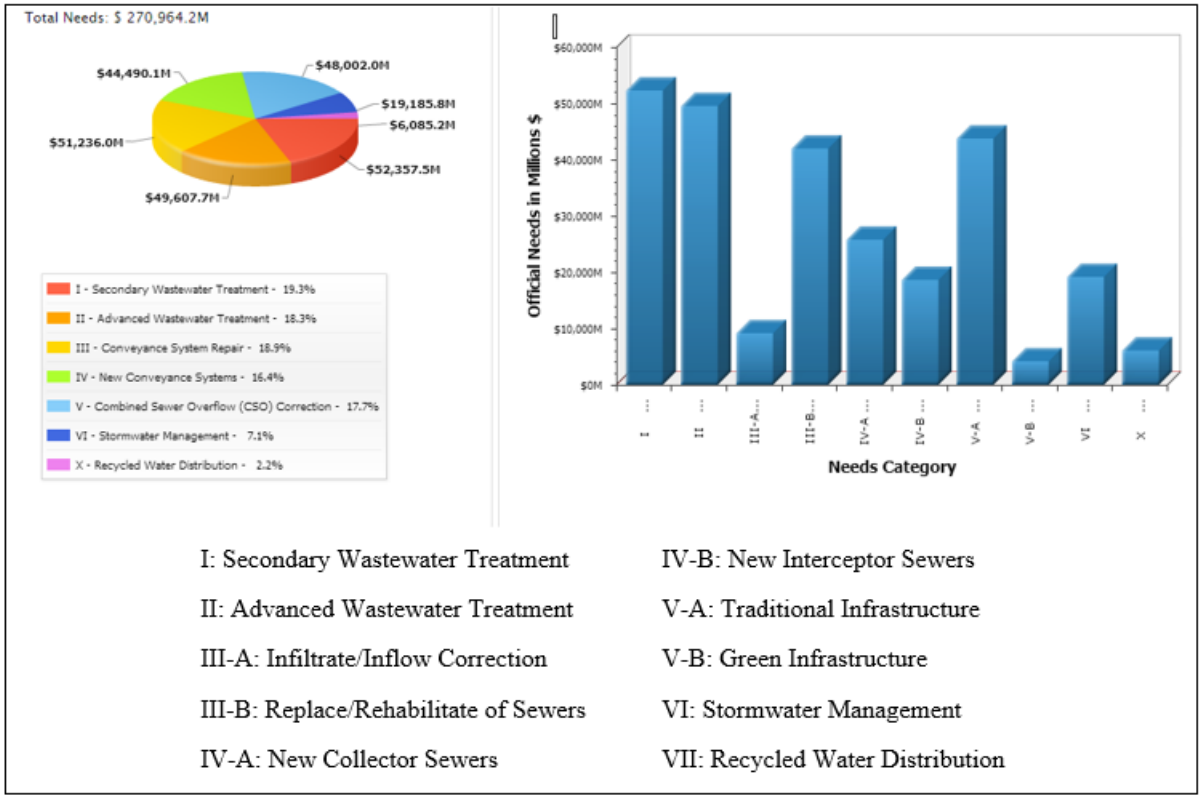


Figure 1.1: CWNS 2012, Required Capital Investment by Each Category
(Source: Clean watersheds Needs Survey, US EPA 2016)

1.3 Pipeline Deterioration

Random events may lead to pipe deterioration, and drastic defects do not always result instantly in collapse. The complicated interactions of different mechanisms that happen through and surrounding the pipeline can cause a pipe's failure. It is nearly impossible to predict the time of a pipe's collapse, but it is possible to estimate the collapse probability based on deterioration levels (Najafi, 2011).

Two main classifications apply to pipeline defects: built-in and long-term. Damages and defects, which generate within piping construction and influence the functionality of the pipe after installation, belong in the built-in category. However, long-term defects emerge from the sequence of the deterioration and disintegration process. Built-in defects consist of flattened or ovaled pipes, offsets in alignments, sags

because of soil settlement, overburdened compaction, stresses due to dynamic loadings of backfills, removal of trench sheathing, loose-fitted joints, pinching of gaskets, joints gasket misalignment, etc. Long-term disintegrations take place over long periods of time and include hydraulic overflows, infiltration and inflow, structural fractures, erosion, and sulfate corrosion. In the wastewater stream, bacteria transform sulfate to hydrogen sulfide, which is then converted to sulfuric acid by the oxidation process when it is released to the pipe's air space. The sulfuric acid causes corrosion to some pipe materials due to its reactivity, which can affect the pipe's structural integrity and accelerate the failure process (Najafi, 2011).

Pipeline defects and collapse are environmental, economic, functional, and safety matters (Najafi, 2011); thus, the constant inspection and maintenance of pipelines is necessary. Appropriate renewal techniques and/or repair methods should be fulfilled to fix the defects or extend the service life of the pipe at the lowest cost.

1.4 Pipeline Renewal Methods

Any technology which enhances the useful life of an existing, old, and defective infrastructure system is called "service life extension," and the threshold of a new service duration for a pipe is generally determined at 50 years as a default. However, in some cases a service life of up to 100 years for certain methods and pipe supplies is possible (Najafi, 2011).

In the past, the "open-cut" method, which involves the excavation of the buried pipe, was the solution for renewing or repairing pipe. Digging has to be performed with a high level of accuracy due to the existence of other utilities, such as cables, electrical power, gas pipes, water pipes, and other obstacles adjacent to the wastewater pipe, which makes the work time-consuming and difficult. Furthermore, restoring the existing surfaces, including pavement, landscaping, and sidewalks, is a lengthy and costly approach. Road or lane closure of main streets is another consequence of the conventional open-cut technique, which negatively affects the daily life and activity of

nearby residents. The resulting traffic delays can cause air pollution and other environmental impacts related to the open-cut procedure, which should also be considered. In addition, the settlement of trench backfill materials has the potential to damage other existing underground utilities (Jung and Sinha, 2007).

Since the 1980's, several methods have become available to renew and rehabilitate sewage pipes in-situ as a solution to the above mentioned problems; these methods are called "trenchless technology," which comprises the replacement or installation of a new pipe or the rehabilitation of an existing defective pipe with minimal surface disruption and excavation. Trenchless methods can minimize social and environmental costs, extend the service life of the pipe, decrease operation and maintenance (O&M) costs, increase productivity and workers' safety, and save money in repair and replacement expenses (Najafi, 2011; Jung and Sinha, 2007).

Making a decision about a pipe renewal method requires considerable technical and engineering knowledge. The age of the pipe is the most important parameter that needs to be considered, but other factors such as deterioration level and its sequel, pipe location (under a private building or easy to access, for example), environmental concerns, hydraulic capacity, pipe depth, costs, and regulatory requirements should also be weighed (Najafi, 2011).

Within the family of "trenchless technology," numerous techniques have been developed or are under progress to rehabilitate, renovate, replace, or enlarge the existing deteriorated pipe. Najafi has classified the basic trenchless renewal methods in the following categories:

1) Cured-in-place pipe (CIPP)
2) Sliplining (SL)
3) Modified sliplining (MSL)
4) In-line replacement (ILR)
5) Close-fit pipe (CFP)

6) Spray-in-place pipe (SIPP)
7) Thermoformed pipe (ThP)
8) Sewer manhole renewal (SMR).

Decision makers choose one of the renewal methods accordance with certain parameters, such as pipeline length and depth, pipe material, size, age, hydraulic capacity of the pipe, type and number of maintenance holes and service connections (laterals), level of the defect, nature of the problem, renewal method constructability, durability, and cost (Najafi, 2011).

In this dissertation research, the focus is on the environmental impacts of the first option, the cured-in-place pipe (CIPP) method, owing to its popularity globally and specifically in the United States. CIPP is by far the leading method of the trenchless family for the rehabilitation of gravity sewer pipes (EPA, 2012). Hence, the following chapter will be limited to the discussion of CIPP history and procedure.

Chapter 2

2. Scope and Objective

Numerous building indoor air contamination incidents indicate that research is needed to understand the magnitude of chemical emissions from CIPP sanitary sewer repairs. The lack of a comprehensive and non-biased study to investigate CIPP air emissions poses an environmental challenge and hinders the public and workers from truly understanding the potential and magnitude of exposures when they occur. Evidence suggests that the CIPP technique has potentially significant environmental, ecological, and health impacts that desire further study. Limited knowledge in this matter and the importance of understanding CIPP technique outcomes has clearly established a need and led to this dissertation research.

The first goal of this study was to better understand VOC emission at three CIPP sanitary sewer installation sites in one U.S. city. Specific objectives were to: (1) Characterize the steam temperature, flowrate, and velocity being emitted from CIPP installation, (2) Chemically identify and quantify VOCs emitted into air at three sites, and (3) Provide recommendations for future research.

The second goal of this study was to estimate the magnitude of solid waste generated and the contribution of criteria air pollutants (VOC, CO, SO_x, NO_x, $PM_{2.5}$, PM_{10}) and greenhouse gas (GHG) emissions from heavy equipment usage during open-cut (remove and replace) and CIPP procedures for sanitary sewer rehabilitation. Emissions were measured for both CIPP and open-cut excavation activities during 2015. Specific objectives were to: (1) Collect information regarding the CIPP installation process and open-cut excavation sites studied, (2) Document the amount of waste generated by each process, and (3) Using equipment usage data, hours of equipment operation onsite, and emission factors, calculate GHG and criteria pollutants emissions per project.

2.1 CIPP History

In 1971, a man named Eric Wood was faced with a leaky pipe under his garage in London. To avoid difficulties from excavation and pipe replacement, he came up with the idea to insert a flexible fabric tube inside the deteriorated pipe, allowing it to cure and harden. Wood titled his initiative “insituform,” which originates from the Latin meaning “form in place” (Kozman, 2013)

London was the first municipality that used Wood’s idea when they lined Marsh Lane sewer in Hackney, East London in 1971. The pipe was 100 years old, 230 feet in length, egg-shaped, and made from brick. In this procedure, the liner was pulled in and inflated inside the pipe. The work was performed by Wood himself, supported by Doug Chick and Brian Chandler. After this successful experiment, they established a company named “Insituform Pipes and Structures, Ltd.” (EPA, 2012)

In 1975, Wood applied for a patent, and in 1977 was granted a U.S. patent for his CIPP process. Insituform Technologies manufactured and developed the technology until 1994 when the patent entered the public domain, which resulted in a newly competitive market in the CIPP trenchless industry (Kozman, 2013; Heinselman, 2012).

In 1976, a 12-inch diameter pipe in Fresno, California was the first pipe in the United States that underwent a CIPP process, and Insituform was the manufacturer of the liner. Since then, Insituform contractors have installed nearly 19,000 miles of CIPP in the United States. Other municipalities which were early adopters of CIPP rehabilitation include the Washington suburban sanitary commission, Denver, St. Louis, Memphis, Indianapolis, Little Rock, Houston, and Baltimore (EPA, 2012).

2.2. CIPP Procedure

The procedure begins with a resin-impregnated fabric tube, which is inserted into the defective pipe from an upstream manhole. Water or pressurized air inversion or winching is used for tube installation and pushes forward the tube inside the host pipe. The fabric is flexible and made from polyester material, fiberglass-reinforced or similar materials. The flexibility characteristic of the resin-filled fabric helps to occupy the cracks, connect the gaps, and move through curves in the pipe. After that, hot water, hot steam, or ultraviolet (UV) light is applied for curing the resin. After curing, the fabric becomes hard in the host pipe. CIPP has been utilized for both structural and non-structural purposes (Najafi, 2011). Table 2.1 presents the major specifications of different CIPP installation methods.

Table 2.1: Major Specifications of CIPP Installation Methods

Installation method	Diameter inch (mm)	Maximum insertion feet (m)	Liner material	Applications
Inverted in place	4-108 (100-2700)	3000 (1000)	Thermoset resin/ Fabric composite	Gravity and pressure pipelines
Winched in place	4-54 (100-1500)	1000 (300)	Thermoset resin/ Fabric composite	Gravity and pressure pipelines

(Source: Pipeline Rehabilitation Systems for Service Life Extension, Najafi, 2011)

Commonly, resin impregnation of the liner (also known as “wet out”) is carried out in a factory. After the wet out process, the liner is kept in refrigerated storage or in a chilled unit to prevent premature curing of the liner. Curing characteristics such as time and temperature are key factors in properly curing of the liner. After curing, the laterals (house connections) must be reinstated by a cutting robot. Liner dimpling can assist in identifying the laterals location. However, dimpling of higher strength liners is less distinguishable (EPA, 2012).

2.3 Literature Review

Many of the reported CIPP caused air contamination incidents were detected first by building inhabitant odor reports (Whelton et al. 2013). Many of these reports included building evacuations to contain the affected schools, childcare centers, office buildings, single-family and multi-family buildings, and hospitals. Those reported to have been affected included adults, toddlers, and infants. Chemical exposure symptoms such as dizziness, eye irritation, headache, shortness of breath, confusion, and groggy feeling were reported by the people who were exposed in addition to emergency and public health officials who responded to each incident. Unfortunately, nearly all of the air contamination incident investigations anecdotally attributed the odor detected in affected buildings to styrene without any analytical confirmation. The code of Federal Regulations, Title 40 defines VOCs as follows:

"Volatile organic compounds (VOC) means any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions." This includes any such organic substances but there are several compounds which have been designated by the EPA to have negligible photochemical reactivity. These compounds are also in the VOC category (e-CFR; EPA, 2015). Volatile organic compounds quickly evaporate at room temperature, and some have perceptible odors at certain concentrations; however, other VOCs have no smell. Odor is not an indicator for the level of risk from inhalation of VOCs. The health effects of any chemical exposure varies based on chemical concentration, exposure duration, and how often a person breathes it in. Moreover, VOCs belong to a group of chemicals in which the toxicity and ability of each chemical to produce adverse health effects are different (Minnesota Department of Health).

2.3.1 Previous Studies in Air Contamination of CIPP

An investigation of a CIPP air contamination building in Milwaukee, Wisconsin by the U.S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry (ATSDR) in 2005 has been performed. A large diameter brick-made sewer pipe located beneath an old brewery building, which had been converted to an office building, went under the CIPP installation process and styrene vapor penetrated inside the building through foundation cracks. Briefly after lining initiation, the occupants started complaining about a strong odor and irritant respiratory effects which made the building nearly uninhabitable. Air sampling and testing were conducted and styrene levels above 200 ppb were detected more than one month after installation, as well as other VOCs at low concentrations. The measured styrene concentrations exceeded the acceptable ATSDR long term exposure levels on several occasions during and after the lining project and the problem solvers classified the past conditions at the site as a public health hazard. Ventilation was applied which assisted in accelerated dissipation of air borne styrene (Department of Health and Human Services, 2005).

Whelton et al. (2013) compiled numerous indoor air contamination anecdotal reports form building residents nearby the CIPP sites (Table 2.2). A major takeaway from this work was that indoor air contamination incidents have occurred, but quantitative air monitoring data is lacking.

Table 2.2: Indoor Air Contamination Incidents Compiled by Whelton et al. (2013)

Incident Location	***Styrene, ppm***	***Description of Events from Reference***
Ottawa, Canada (Bauer 2012)	Air: nr	Odors detected kilometers from worksite
Fayetteville, New York (Doran 2012)	Indoor Air: nr	Odors permeated into nearby residences; residents complained and evacuated their homes
Worcester, Massachusetts (Dayal 2011)	Indoor Air: 60-70	Fumes caused daycare center evacuation; headaches reported; emergency responders called to site
Minnesota (Marohn 2011)	Indoor Air: nr	Odor caused building evacuations
Southfield, Michigan (Banovic 2011)	Indoor Air: nr	Hazardous materials response team (HAZMAT) responded; vapors from nearby CIPP operation entered school ventilation system; building evacuated; children transported to hospital for chemical exposure symptoms
Saugus, Massachusetts (Tempesta 2011)	Indoor Air: nr	Firefighters ordered evacuation of elementary school because of strong odor; dizzy and light-headed symptoms reported
Pittsburgh, Pennsylvania (Hayes & Biedka 2011)	Indoor Air: nr	Elementary and high school students were evacuated for fear of gas leak; odors from nearby CIPP operation were the cause
Helena, Montana (Banks 2010)	Indoor Air: nr	Fire department evacuated nearby affected building because of complaints of strong odors, nausea, and headaches
Arlington, Virginia (ARLnow.com 2010)	Indoor Air: nr	Nearby CIPP installation caused odor; fire department responded
Pittsburgh, Pennsylvania (WPXI-TV 2009)	Indoor Air: nr	Firefighters evacuated nearby apartment buildings; initially suspected cyanide gas, but styrene was ultimately detected from nearby CIPP
Somerset, United Kingdom (Wills 2007)	Indoor Air: nr	Foul CIPP styrene odor permeated into residence through drain because of nearby installation
Brooklyn, New York (Lysiak 2007)	Indoor Air: nr	Foul CIPP styrene odor permeated into buildings through drain because of nearby installations

(Table Continued)		
Ottawa, Canada (Bauer & McCartney 2004)	Indoor Air: 20, 115 ppm	Venting determined to be necessary to prevent air backup into nearby residences/ buildings
Alexandria, Virginia (Gowen 2004)	Indoor Air: 500 ppm	HAZMAT team responded because of styrene vapor backup into nearby buildings; illness symptoms reported
St. Petersburg, Florida (Saewitz 2001)	Indoor Air: nr	Styrene odor detected; hospital evacuated; HAZMAT team responded

nr= not reported

As demonstrated in the table, for the limited data available, the highest indoor air styrene concentration found was 500 ppm.

Another notable CIPP air contamination study was commissioned by the City of Toronto Works and Emergency Services (2001). Researchers examined the presence of styrene and 24 other VOCs above manholes; at the breathing zone of installation personnel, and inside eight nearby buildings. The researchers detected only styrene near manholes (0.16-3.2 ppm), the personnel breathing zone (0.08-0.5 ppm), and in some, but not all, nearby residences tested (0.1-0.2 ppm). Unfortunately, it is unclear if testing was carried-out during CIPP curing, cooling, or after the cooling period. A major conclusion of this study, however, was that styrene concentrations were enhanced significantly during installation in the buildings with dry premise plumbing p-traps, and researchers recommended that p-traps include water seals to limit chemical intrusion (NASSCO, 2008). A detailed description of premise plumbing in building was not provided.

Another indoor air contamination incident occurred in Birmingham, UK and prompted the federal health agency to investigate. People living nearby CIPP rehabilitation activities complained of noxious fumes inside their homes and CIPP contractors advised some residents to evacuate their homes. Some residents, however, did not evacuate. Initial air testing by the health agency showed styrene at 15 ppm inside a home, and a 20 ppm and 100 ppm health exposure limits were deemed important

toxicological thresholds. Some residents sought medical attention for their families (children, baby) and relocated for multiple days. After odor complaints, CIPP contractors reportedly continued construction on 24-hr. shifts. Two days after the incident, the contractor notified the health agency that their own commissioned indoor air test results from a few days earlier showed 200 ppm styrene levels in a home (CRCE, 2012).

Emission of VOCs into the air from CIPP operations is poorly documented and understood. Regulatory styrene exposure levels have been developed for healthy adults primarily, although the public health exposure limits cited by the CIPP industry do not consider infants or children who would be more susceptible to chemical exposure. Styrene exposure limits for these vulnerable populations range from 20-25 ppm according to the International Toxicity Estimates for Risk (TOXNET 2015). The main route of styrene exposure for the general public is indoor air inhalation. Average levels are in the range of 0.0002 to 0.0021 ppm and is ascribed to emissions from consumer products, building materials, and tobacco smoke. Styrene also can be found in ambient air in urban areas (6.8×10^{-5} to 0.0008 ppm) and in rural locations (6.5×10^{-5} to 7.9×10^{-5} ppm) (EPA, 2000).

Numerous building indoor air contamination incidents confirmed by public health agencies and others indicate that work is needed to understand the magnitude of chemical emission, duration, and how variable emissions can be across similar CIPP installations. More specifically, the National Association of Sewer Service Companies (NASSCO) previously concluded that air emission of 0.5 ppm styrene is typical during CIPP activity and styrene emitted by the CIPP process (Salem et al. 2008). Based on the growing number of indoor air contamination incidents (Table 2.2), this conclusion is not supported.

2.3.2 Previous Studies about Other Environmental Impacts of CIPP

A separate study investigated styrene and other contaminants resulting from CIPP of stormwater culverts and characterized its generated condensate. The researchers detected endocrine disrupting chemicals, volatile and nonvolatile organic contaminants, and several carcinogens downstream from CIPP sites. Some of these contaminants were present in culvert outlets, downstream, and CIPP condensates. Room temperature condensate had a very high chemical oxygen demand (COD) of around 36,000 ppm, which is greater than those of regular landfill leachate (22,000 to 27,000 ppm). Multiple VOCs were recognized in the diluted condensate (1:10) containing methyl ethyl ketone, isopropylbenzene, n-propylbenzene, and 1,3,5-trimethylbenzene, but these chemicals were not detected in further dilution (1:100). Furthermore, the condensate contained different heavy metals with concentrations greater than those detected in stormwater. Numerous solvents such as styrene and benzene, degraded products of Perkadox®, dibutyl phthalate, and diisoocytal phthalate, known plasticizers, and endocrine disrupting compounds were recognized in condensate both in culvert outlets and downstream. The condensate totally dissolved *Daphnia magna* (the study's indicator species) over a 24-hour period, and 100% mortality happened in 48 hours. Condensate dilution by a factor of 10,000 showed styrene levels at 1.53 ppm, which implies that raw condensate had a styrene level of 15,300 ppm. In fact, the condensate expressed a complex mixture of solvents and compounds. However, in 2009, a NASSCO guideline report described that "the condensate concentration based on measurements made to date of the report, is around 30 ppm" (probably styrene; since the report did not indicate the substance directly). Also, the report mentioned the condensate may be released to the receiving waterways "once it has cooled to near ambient temperature".

Furthermore, COD and total organic carbon (TOC) was measured at the culvert outlet and downstream as well, and demonstrated that organic compounds remained in the environment at least 35 days after CIPP installation. Initially after installation, concentrations were higher at outlets but declined with time, and after seven days

concentrations downstream were greater than those at the outlet. The highest styrene concentrations were found instantly post-installation and seven days afterwards. In addition, other aliphatic and aromatic contaminants of an unknown origin were detected in the culvert outlet and downstream. While these studies are informative, important questions remain. Because of the need for comprehensive research in CIPP formulation, further experimental work is required to determine contaminants' persistence, origin, and ecological and environmental impairment (Tabor et al. 2014).

In 2012, another study was conducted to investigate the environmental impacts of Ultraliner and Troliner technologies which are applied to repair storm water pipes. Steam and grout are applied for installation of Ultraliner and Troliner technologies respectively. The liner that is used in these techniques includes three plasticizers that are believed to be of potential environmental concern: benzyl butyl phthalate (BBP), di-(2-ethyl-hexyl) phthalate (DEHP), and bisphenol A (BPA). The analytes mentioned were selected based on a review of the material safety data sheets (MSDS) of each liner product. In order to examine the release of other organic compounds, a gas chromatography and flame ionization detector (GC-FID) was utilized for samples collected at different times. The study sought to determine whether the contaminants were leaching from liners and grout into water. The result of the GC-FID scan showed that negligible trace organics penetrated from the products into water during a 48-hour incubation period. The research resulted in no detection of the three plasticizers and other organic solutes leaching from the liner materials into water. However, the possibility of leaching concentrations below the method detection limit should be noted (Ren and Smith, 2012).

Furthermore, a mathematical model was also developed to better estimate the possible range of penetration. Leaching rates of the three plasticizers were assumed to be proportional to the surface area of the material in contact with water and the duration of contact time. The results of the model revealed that the concentration of the plasticizers were meager and less than regulatory limits. Even so, the bioaccumulation of low levels of these plasticizers in aquatic organisms might be possible. Appreciable levels of BBP

and DEHP are more likely to bioconcentrate in the lipid reservoirs of aquatic organisms. BPA is least likely to bioaccumulate due to its relatively high water solubility (Ren and Smith, 2012).

In Virginia, a one-year study was performed to evaluate the environmental implications of hot-steam CIPP technology in surface water and storm water conveyances. To that end, seven styrene-based, steam-cured CIPPs were selected, and water samples were collected before and after CIPP installation at various time intervals over one year. None of the sites were directly linked to sources of drinking water. The EPA has not determined regulatory standards for ecological toxicity of styrene concentrations in waterbodies, but the EPA's maximum contaminant level (MCL) of 0.1 mg/L for styrene can be a good indicator for comparison. Styrene levels at five sites were more than 0.1 mg/L, and these concentrations were seen a minimum of 5 days to 71 days after installation. In addition, some measurements were higher than the concentration required for the mortality of 50 percent of multiple freshwater aquatic indicator species. Emergence of algal blooms were also observed at three sites within 6 to 8 days after CIPP installation with observation continuing for at least 50 to 55 days. Commonly, nitrogen or phosphorus pollution in water can lead to algal blooms, which is an indication of poor water quality and can impair ecological life. This implies that some aspects of CIPP activity could contribute to algal blooms, but the specific reason is unknown. The study proposed one or a more of the following causes for the high styrene concentrations of water samples: some amount of permeability in the lining substances, the release of uncured resin from the liner during installation, the absence of condensate capturing practices which are generated during the CIPP process, and inadequate curing of the resin (Donaldson, 2009).

Chapter 3

3. Methodology

In order to achieve the objectives discussed in Chapter 2, the following agenda was established for this research:

- Select three sites (pipes) which have been scheduled for CIPP activity during the course of a one-year study for this dissertation.
- Collect relevant data for these three sites, such as pipe age, length, depth, material, a list of the heavy equipment used, operation hours, etc.
- Devise an air monitoring procedure for different stages of the CIPP activity and performing VOC analysis for each sample for all three sites.
- Compare of laboratory analysis results with regulatory requirements for contaminant concentration limits and with the result of other studies about CIPP impacts on water bodies.
- Calculate the generated excavation waste of the open-cut method for certain pipes which have been slated for repair during the one-year study of the research.
- Collect all related data such as above-mentioned parameters for CIPP pipes and for the pipes targeted for the open-cut method.
- Calculate criteria air pollutant emissions and waste generation amount for 58 sites containing both CIPP and open-cut programs.

The first section of the methodology will describe the CIPP air emission analysis procedure. In the second section, the method for waste and criteria air pollutant calculation of CIPP and open-cut will be explained.

3.1 Case Study

In cities containing various wastewater basins which accommodate numerous sewer pipes, all the sewage from each basin heads to a particular destination. For mega cities with several wastewater treatment plants (WWTP), the destination of various basins

can be different WWTPs, but in small cities, the sewage of all basins usually flows to the same plant.

One of the basins of one U.S. city was used as a case study for this research. At the time these data were collected, this basin contained 58 pipes designed for rehabilitation and replacement between May and November 2015. Of the 58 sanitary sewer pipes identified for rehabilitation, 22 were targeted for CIPP lining, 36 were targeted for replacement, and 7 were to undergo both spot repair and CIPP lining. In total, the 58 pipes were 13,516 ft. (4,119.6 m) in length; 6,561 ft. (1,999.7 m) (48.5%) were targeted for CIPP rehabilitation, and 6,955 ft. (2,119.8 m) (51.5%) were targeted for open-cut method/replacement. Only four pipes were found to be concrete, and all others were vitrified clay. Most pipes were 8 inches in diameter; however, a few pipes were 10, 12, and 14 inches in diameter. The oldest and newest pipes were installed in 1908 and 1957, respectively. Sanitary sewer pipes were buried 7 ft. (2.1 m) to 16 ft. (4.8 m) below ground surface. Table 3.1 presents the specifications of all 58 sanitary sewer pipes.

Table 3.1: Characteristics of the Pipes in the Basin

No.	*Pipe Length (FT)*	*Pipe Size (inch)*	*Pipe Material*	*Year Built*	*Open-Cut Length (LF)*	*CIPP Length (LF)*
1	235	8	VCP	1912	35	235
2	225	8	VCP	1912	225	
3	290	8	VCP	1915	292	
4	290	8	VCP	1915	292	
5	333	10	VCP	1911	25	333
6	323	10	VCP	1911		323
7	226	8	VCP	1913		226
8	312	8	VCP	1911		312
9	368	10	VCP	1913	367	
10	397	10	VCP	1911	396	

(Table continued)						
11	336	12	VCP	1911		336
12	313	8	VCP	1912	313	
13	313	8	VCP	1912	18	
14	328	10	VCP	1913	328	
15	315	8	VCP	1912	14	
16	328	12	VCP	1913	330	
17	254	8	VCP	1910		254
18	304	12	VCP	1910		304
19	309	8	VCP	1910	16	309
20	422	8	VCP	1911		422
21	422	8	VCP	1910	20	
22	232	8	VCP	1910	16	232
23	305	8	VCP	1915		305
24	300	8	VCP	1913	300	
25	329	12	VCP	1910	33	329
26	239	8	VCP	1910	241	
27	305	8	VCP	1913	34	305
28	246	8	VCP	1910	21	
29	328	8	VCP	1910		328
30	192	8	VCP	1910		192
31	304	8	VCP	1908	306	
32	308	8	VCP	1912	310	
33	308	8	VCP	1912	310	
34	308	8	VCP	1912		308
35	247	8	VCP	1908	249	
36	304	8	VCP	1908	24	
37	293	8	VCP	1913		293
38	293	8	VCP	1913	295	
39	293	8	VCP	1913	20	

(Table Continued)						
40	293	8	VCP	1913	30	
41	326	14	VCP	1908	34	
42	304	8	VCP	1908	6	
43	304	8	VCP	1913	18	
44	296	8	VCP	1913	28	
45	93	8	VCP	1957	93	
46	304	8	VCP	1908	32	
47	342	10	VCP	1957	18	342
48	291	8	VCP	1913	6	
49	304	8	VCP	1908		304
50	143	8	VCP	1957	42	
51	292	8	VCP	1913	294	
52	245	8	VCP	1957		245
53	331	8	CON	1919	331	
54	326	8	CON	1919	326	
55	231	8	VCP	1915	231	
56	296	8	CON	1919	296	
57	341	8	CON	1919	340	
58	324	8	VCP	1911		324

3.2 Analysis of CIPP Air Emissions

3.2.1 Field Sites and CIPP Installation

Of the 22 CIPP projects, three CIPP sanitary sewer installation sites were the subject of air emission sampling. CIPP activities were conducted between September and November 2015. All three rehabilitated pipes in the present study were vitrified clay (VCP). After the sanitary sewer pipes were cleaned by high-pressure water, the fabric containing the uncured CIPP liner was inverted to the pipe by 80 psi (551.5 kPa)

pressurized air. For all pipes, CIPP was installed using hot steam curing reportedly at 60^0C, though no measurements by the author were conducted to verify this initial condition. The curing durations for each CIPP installation differed on each site. After the curing process, a cooling down period commenced for 15 minutes on all three sites. Within the cooling down course, pressurized air with no heat was blown through the pipe to complete the CIPP installation activity and to allow the temperature to decrease. During both curing and cooling procedures, air emissions were observed from two locations per site: manholes and steam hoses. At each site the steam hose was installed by the contractor during the curing and cooling down periods and connected to a ventilator located at the bottom of the maintenance hole. This unit facilitated the emission of a vapor-like substance into the ambient air. CIPP pipes were allowed to cool for 15 min. Next, contractors released the generated condensate waste into the collection system. The condensate was not characterized. It is presumed this condensate mixed with sewage and traveled to the wastewater treatment plant with 300+ million gallons per day capacity. Table 3.2 shows pipe characteristics and the condition of CIPP installations for the three sites. Figure 3.1 illustrates the profile view of the air emission pathways from CIPP installation for sanitary sewer pipes.

Table 3.2: Pipes Characteristics and CIPP Installation Conditions

Site No.	Pipe Year Built	VCP Characteristics		CIPP Installation Conditions				
		Diameter (inch , cm)	Length (ft, m)	Curing (min.)	Cooling (min.)	Date	Ambient air temp (^{0}F, ^{0}C)	wind velocity (mph , m/s)
1	1908	(8 , 20.32)	(304 , 92.6)	60	15	9/25/2016	(83.8 , 28.8)	(0.04 , 0.02)
2	1912	(8 , 20.32)	(235 , 71.6)	55	15	11/9/2016	(73.4 , 23)	(0.11 , 0.05)
3	1910	(8 , 20.32)	(309 , 94.1)	45	15	11/10/2016	(71.6 , 22)	(0.65 , 0.29)

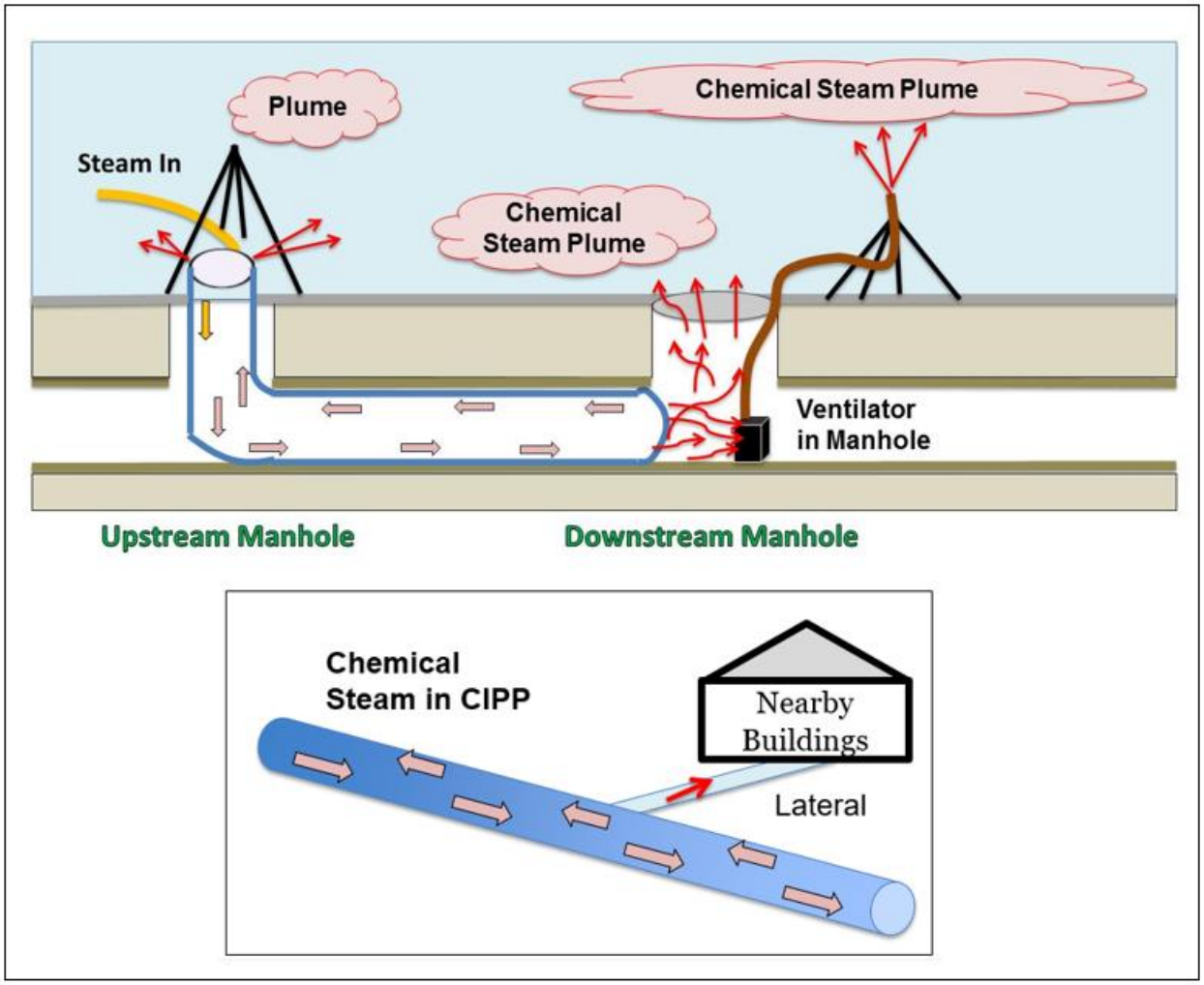


Figure 3.1: Profile View of the Air Emission Pathways from a Steam Cured-in-Place-Pipe (CIPP) Used for Sanitary Sewer Pipe Repair
(Courtesy of Dr. Andrew Whelton, Purdue University)

3.2.2 Resin Type

The resin used by the installers was Alpha Owens Corning L010-PPA-38 Vinyl Ester. The resin material safety data sheet reported 40-43% styrene, 1-5% amorphous fumed silica, and the remaining 50% unreported ingredients (AOC 2000). The resin manufacturer's product literature reported the presence of 1.0% Di-(4-tert-butyl-cyclohexyl) peroxydicarbonate and 0.5% tert-butyl peroxybenzoate (AOC 2009). A

multiple layer polyester felt liner with an “impermeable” polyurethane coating was used to limit styrene permeation.

3.2.3 Sampling Equipment

Sampler Box

Air samples were collected with a Xitech 1060H high vacuum bag sampler Manufactured by Xitech Instruments, Inc. (Placitas, NM). This device can easily collect an air sample from an air stream by applying a high vacuum to the outside of the sample bag with up to 22 inches of mercury direct vacuum force. This instrument weighs 9 pounds and is 9 inches in height, 7 inches in depth, and 10 inches in length. The instrument’s rechargeable battery can run continuously for 8 hours; a see-through window is provided to help an operator monitor the amount in the sample bag.

There is a sample inlet on the wall of the box which accepts any ¼-inch outer diameter (OD) tubing. The tubing passes through the inlet port, then one head of a tubing is attached to the 1 or 2-liter sampling bag (Tedlar bag) inside the chamber, and another end is placed to the air stream by an operator. The vacuum pump filling rate is adjustable between 1 to 6.5 L/min. The air inside the chamber evacuates by pump operation and the interior pressure drop leads to sample bag inflation. In fact, the Xitech sampler box unit generates a negative pressure to allow air to flow into the isolation unit which is connected to the Tedlar bag.

The most important feature of Xitech is its zero pump contamination design (Xitech Instrument Inc.). The air enters the bag directly without passing through the pump, which results in protection of the pump and samples from cross contamination (SKC Inc.). Figure 3.2 depicts the different sections of the Xitech 1060H sampler box. When the air sampling transits across the pump, there is a possibility for the residue of substances in the air stream to attach to the pump and affect the concentration of the pollutants in the samples being taken after the previous ones.

Calibration was performed by the rental company before each application, and calibration certificates of the devices are provided in Appendix A of this dissertation.

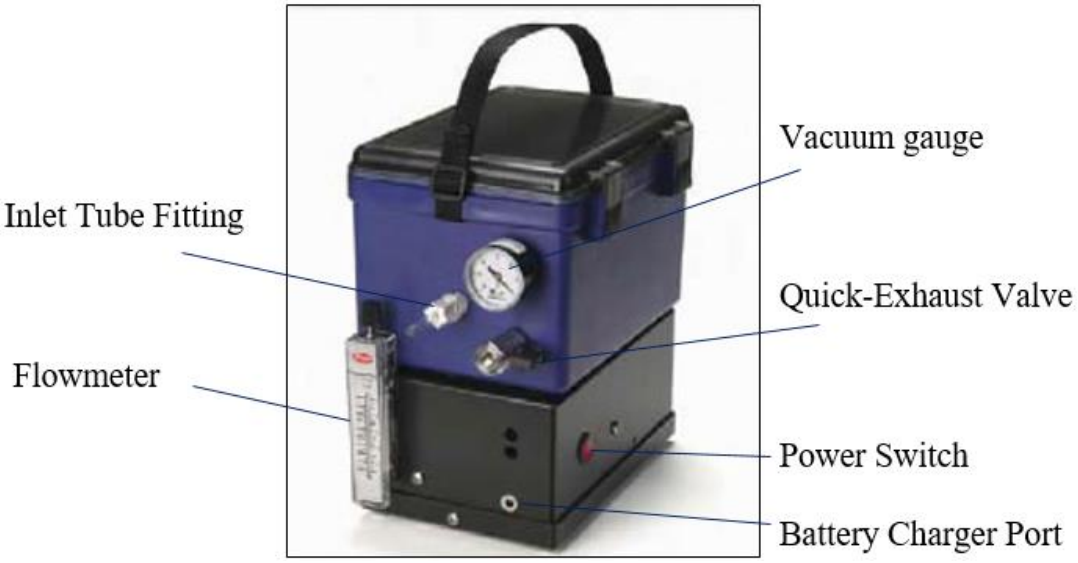


Figure 3.2: Xitech 1060H
(Source: Xitech Instrument Inc.)

Sampling Bag

A one-liter (7-inch × 7-inch) capacity Tedlar(R) T.O. Plus Air/Gas Sampling Bag w/Polypropylene 2-N-1 Combination Fitting (San Leandro, CA) manufactured by Environmental Sampling Supply, Inc. (ESS) was used for the sampling. The bag was filled up to 75% of its maximum capacity according to the manufacturer's instructions (Environmental Sampling Supply Inc., San Leandro, CA). Each Tedlar bag was filled in approximately 20 sec. and at a flowrate of 3 L/min. The bag contains a side port/stem with a 3/16-inch OD, which facilitates the filling process with tubing and pump. The top section of the valve rotates clockwise and counter clockwise for closing and opening purposes, respectively. An orifice is provided in the top of the valve for injection or extraction through a septum with a syringe (Environmental Sampling Supply Inc., San Leandro, CA). Figure 3.3 demonstrates the utilized tedlar bag and inflation.

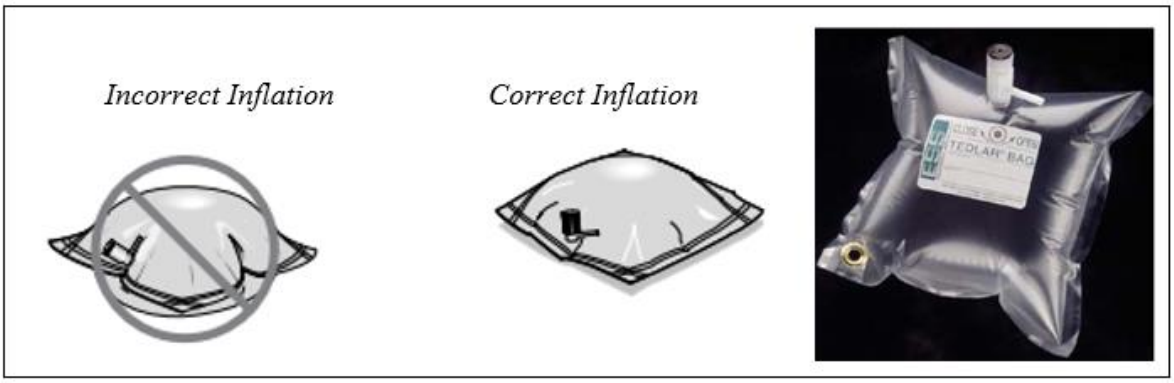


Figure 3.3: Tedlar Bag and Inflation
(Source: SKC Inc. and ESS Inc.)

Tubing

Tubing (TB10145) with a 0.17-inch ID and a 0.25-inch OD made from low-density polyethylene (LDPE) provided by Pine Environmental Services Inc. was used for sampling. LDPE is an inexpensive polymer with broadly desirable mechanical and chemical resistance attributes. It is a flexible homopolymer formed by ethylene monomers. LDPE tubing is translucent, corrosion resistant, and stable which results in wide utilization of this kind of tubing for chemicals, gasses, and water transmissions. (TBL Performance Plastics Co. New Jersey; USP United States Plastic Corp. Ohio). Figure 3.4 shows the tubing used for this study.

Figure 3.4: LDPE Tubing (TB10145)

Thermometer, Flow Rate, and Velocity Meter

In order to measure the flow rate, velocity, and temperature of the steam emitted at the sites, the VelociCalc Plus model 8384 manufactured by TSI Inc. was applied. The main compartments of the device include a keypad, a display window which shows the measurements, and an adjustable probe with a maximum length of 40 inches. The probe's base diameter is 0.395 inch with a smaller diameter at the tip (0.276 inch). The length of the probe helped the author locate the sensor in the steam with a sufficient distance to avoid steam heat and exposure. This device is powered by battery and shows temperature ranges of 0 to 200^{0}F. Figure 3.5 illustrates this instrument.

Figure 3.5: VelociCalc Plus Model 8384

Calibration of the VelociCalc Plus model 8384 was performed by the rental company before each usage, and calibration certificates of the device are provided in Appendix A of this dissertation.

3.2.4 Sampling Procedure

Air sampling was conducted at all job sites in different stages. Control air samples at each job site were also collected before construction activities began. These samples help establish the air quality of the area before work initiation, and serve as a criterion for comparison of the air quality before and after work commencement. Each Tedlar bag was filled in approximately 10 sec. at a flowrate of 3 L/min. For each air sample, a new length of tubing was used to eliminate the potential of sample cross-contamination. During the operation of Xitech, the author monitored the Tedlar bag through the transparent lid of the device, and when the inflation of the bag reached around 70-75% of the total capacity, the author turned off the instrument, opened the lid, closed the bag's valve to prevent sample loss, and detached the bag. All samples were stored out of sunlight in a cool and dry place.

During CIPP installation, the author detected a sharp odor in the surrounding area and experienced a slight burning sensation when the wind directed the plume of steam toward her location. None of the workers were seen wearing a respirator, and in most cases, no gloves. Images of air sample collection and steam plumes can be found in Figure 3.6. All activities were conducted in public spaces.

Figure 3.6: (Left) Air Sample Being Collected During the Curing Period (Site #1), (Right) Steam Being Emitted through a Hose and Downstream Manhole During the Curing Period (Site #3)
(Pictures were taken in public area)

3.2.5 Sites

Volatile Organic Compound (VOC) air sampling was conducted at three CIPP installation sites. Eleven air samples were collected during this investigation. One ambient air sample was collected at each site before construction began and was treated as a background control. Because the greatest visible amount of chemical steam was emitted through downstream manholes, not upstream manholes, only manholes downstream of each CIPP installation site were sampled for VOC testing.

Site 1 was located in Street A, and a total of five air samples were collected. Site 1 was the only site where air sampling was also carried out on a sidewalk next to a private residence. During time when the uncured fabric CIPP liner was inverted into the VCP pipe using 80 psi pressurized air (5 min.) another sample from ambient air near the job site was collected. Once curing began, two samples were collected. The first sample was collected from the downstream manhole 15 minutes after curing started, and the second sample was grabbed from ambient air next to the nearest residential building to the project site 45 minutes after curing began. CIPP cooling began after 1 hour of curing, and

a final air sample was collected from the downstream maintenance hole 10 minutes after cooling down started, with 5 minutes left before cooling was completed.

At Site 2 a total of three air samples were collected, including one control sample from ambient air before construction began. At Site 2 air sampling was conducted at a downstream manhole located in B Avenue. One air sample was collected during the curing procedure after 25 minutes from the curing start point and another during the cool down process after 10 minutes of cooling down.

For Site 3, a total of three air samples were also collected on C Avenue. One control sample was collected before construction commencement. Another air sample was collected during the curing after 20 minutes from curing initiation, and a sampling from the cool down process was taken after 10 minutes from the starting point at the downstream manhole.

In an effort to limit the potential wind or other uncontrolled environmental conditions that could affect the results, air samples were collected approximately 10 inches inside each manhole. Twenty feet of tubing was used for sampling from the manholes. This approach enabled the author to avoid exposure to this hot and potentially hazardous vapor. Also, if vapors escape into nearby sewer laterals, air results inside the sewer network would be more representative than above manhole.

The temperature, flow rate, and velocity were measured exiting the downstream manhole and hose for Sites 2 and 3 during the curing and cooling procedures. Air measurements at the manhole and hose were challenging because the displayed number on the flowrate meter was increasing very quickly. When the probe was located in the steam exiting the hose, the probe could not be maintained at the very first location of the emission due to the high energetic force of the steam. Therefore, the probe was inserted to the steam immediately above the hose in an effort to stabilize the probe inside the steam. Each reading was collected by keeping the probe in the vapor for 4 seconds, and the first number at the 4-second mark was reported. Every 5 minutes measurements were

conducted for each phase, and the average of the measurements reported as a single number for that phase.

3.2.6 Chemical Analysis

Air samples were sent to and characterized by a commercial laboratory for VOC analysis the same day that they were collected. EPA method 8260B was applied for concentrations measurement.

3.2.6.1 Method 8260B

Numerous methods have been developed by the EPA to analyze and quantify VOCs. The concept behind almost all VOC methods is to concentrate the volatiles from the sample matrix by utilizing purge and trap techniques (RESTEK Corp., 2003). Method 8260B is applicable to approximately all types of samples such as air sampling trapping media, waste solvents, surface and ground water, caustic or acid liquors, oily waste, aqueous sludge, etc. This method is appropriate for most volatile organic analytes which have boiling points below 200 °C and can determine the concentration of 108 compounds (EPA, 1996). The complete list of 108 compounds has been provided in Appendix B.

3.2.6.1.1 Gas Chromatography

Instruments utilized for the test are gas chromatography (GC) and mass spectrometry (MS) which can separate, identify, and quantify the complicated mixture of chemicals. A gas chromatograph contains an injection port located at one end of a packed metal tube column with the other end attached to the detector. An operator injects the sample into the port, and a carrier gas propels the sample down the column. The carrier gas should not react with the sample or column. Argon, helium, hydrogen, and nitrogen can be utilized for a carrier gas; however, helium is more common due to its inert nature. While the sample travels through the column, each compound in the sample interacts with the column surface and the partition itself. Substances are transported through the column at different speeds based on the mass and shape of the molecules and the

interactions between the samples' molecules and the column surface. Substances which are reluctant to attach to the column move through the column quickly, and components that stick to the column remain but finally elute from the column. A detector which is attached to the other end of the column quantifies the various compounds as they exude from the column (Douglas, 2016).

3.2.6.1.2 Mass Spectrometry

A mass spectrometer is a detector, and when connected to gas chromatography, the detection system itself is referred to as a mass selective detector or simply the mass detector (Chasteen, 2009). Mass spectrometry electrically charges the sample molecules and speeds them up through a magnetic field. Molecules are divided into charged segments, and different charges can be detected by MS. A spectral plot will be depicted by the device and presents the mass of each segment. A compound's mass spectrum helps an operator with qualitative identification. The masses of segments are like puzzle pieces to assemble together to determine the mass of the original molecule since each substance has a unique mass spectrum. A combination of gas chromatography and mass spectrometry for chemical analysis works more efficiently (Douglas, 2016). Figure 3.7 displays the main compartments of GC/MS.

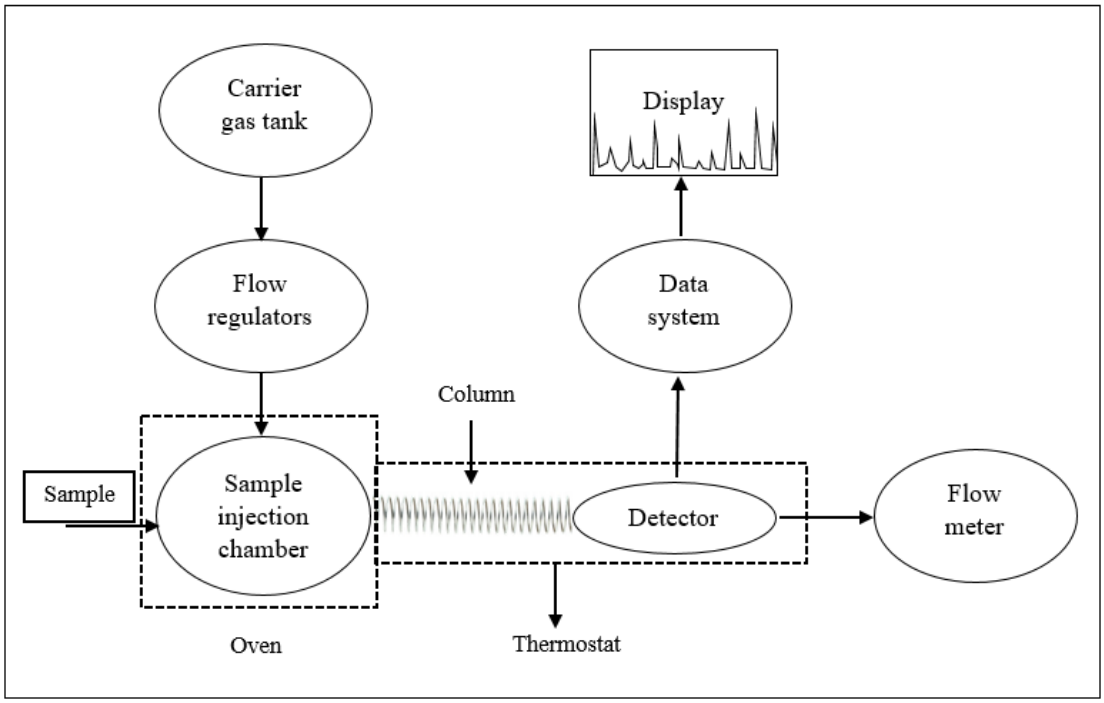


Figure 3.7: Main Compartments of GC/MS
(Source: Donald Poe, Quantitative Analysis Laboratory; University of Minnesota Duluth)

3.2.6.1.3 Internal Standards

Usually, prior to direct injection of the samples into a gas chromatography, they need to undergo preparation. Some of the reasons are as follows:

- The concentration of target analytes is very low and pre-concentration prior to analysis helps to detect them
- Samples may have an incompatible solvent such as water or a solvent which is problematic with gas chromatography, which needs to be exchanged

- Samples that are unstable and vulnerable to disintegration from exposure to gas chromatography temperature need derivatization to make them more stable

- Overcomplicated samples which cannot be analyzed swiftly (Klee, 2015).

The following errors are associated with sample preparation:

- Errors in weight or volume measurements,

- Contamination,

- Errors in transfer,

- Losses due to evaporation or container's surface (Klee, 2015).

Furthermore, other errors can be introduced from the analysis method and gas chromatography system (sample introduction to the device including injection, volatilization, and transition to the column). In an effort to compensate these potential errors and to determine the concentrations of the substances in a mixture, the Internal Standards (ISTD) method is applied. By adding a known amount of a compound (which is similar to the target analyte and is named surrogate) to the sample, the change in surrogate and the target analyte should be the same. The selection of internal standards is very important, and physical and chemical characteristics of the ISTD should be as similar as possible to the target analyte. In general, a deuterated analog of each analyte of interest is the best option for the internal standard. Generally, however, the cost and accessibility of deuterated standards hinder them from everyday use (Klee, 2015).

Owing to the broad variation in physical and chemical specifications of analytes of interest, several internal standards must be exerted. The similarity level between target substances and internal standards affects the responses of the test. If deuterated standards are applied, each compound would have its own unique internal standard. An operator

can mix stable internal standards together and keep them in sealed containers in a refrigerator or freezer. Unstable ISTDs are commonly prepared freshly before application (Klee, 2015). Figure 3.8 is one of the spectral plots produced by the gas chromatography in this dissertation research. The spectral plots for all samples are provided in Appendix C.

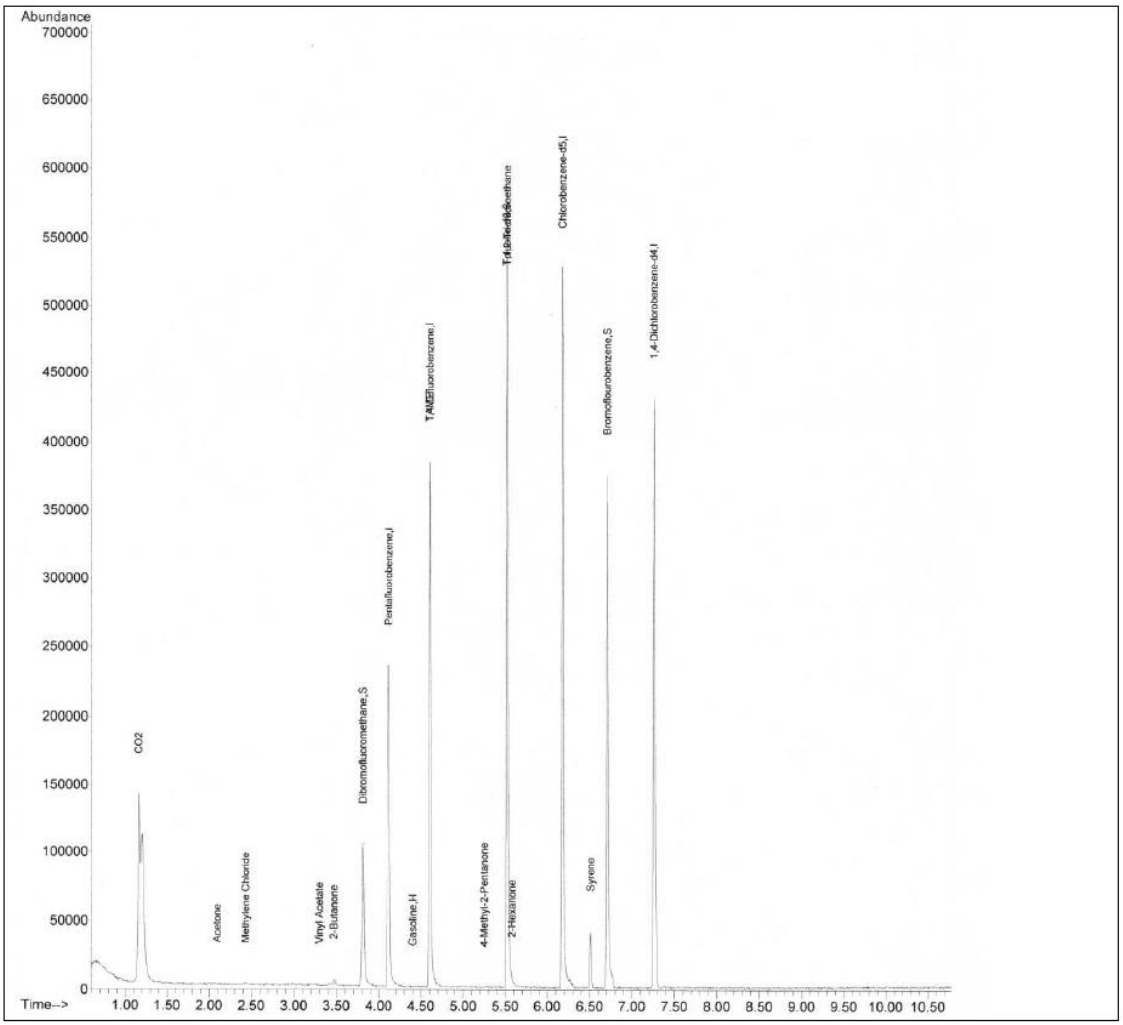


Figure 3.8: One of the Spectral Plots Produced by the Gas Chromatography

In order to calculate the concentration of certain compounds, the following steps and formulas are employed.

As discussed earlier, a known amount of internal standards and the target substances should be analyzed, and then we need to add a known amount of the internal standards to the sample which consists of compounds of unknown concentrations. From the first analysis the Internal Response Factor (IRF) can be obtained using equation 3-1 (Alltech Associates, Inc. 1998):

Equation 3-1: $$\text{IRF} = \frac{area\ (ISTD)\ \times\ amount\ (TA)}{amount\ (ISTD) \times\ area\ (TA)}$$

Where:

ISTD = Internal Standards

TA = Target Analytes

From the second analysis the amount of the unknown analyte will be calculated using equation 3-2 (Alltech Associates, Inc. 1998):

Equation 3-2: Amount of specific substance $= \frac{amount\ (ISTD) \times area\ (TA) \times IRF\ (TA)}{area\ (ISTD)}$

Where:

ISTD = Internal Standards

TA = Target Analytes

IRF = Internal Response Factor

Below is an example that demonstrates the procedure.

An operator injects a sample containing 2,000 µg/mL of toluene (as an internal standards) and 1,000 µg/mL of benzene as the analyte. The peak areas in the spectral plot are 120,000 for toluene and 67,000 for benzene.

From this analysis we can obtain the internal response factor for benzene:

$$\text{IRF} = \frac{120{,}000 \times 1{,}000}{2{,}000 \times 67{,}000} = 0.89552$$

Then, the operator injects the sample consisting of 2,000 µg/mL of toluene and an unknown amount of benzene using the same chromatography circumstances. The peak areas in the plot are 122,000 for toluene and 43,000 for benzene.

Now, from the second analysis the concentration of benzene (target analyte) can be calculated as follows (Alltech Associates Inc. 1998):

$$\text{Amount of benzene (target analyte)} = \frac{2{,}000 \times 43{,}000 \times 0.89552}{122{,}000} = 631.268\ \mu\text{g}$$

3.2.6.1.4 Tentatively Identified Compounds (TICs)

Substances which are not in the target compounds list, but appeared in the analysis are considered to be unknown compounds. They can be detected, but their identification is not confirmed until a known standard for the dubious chemical can be analyzed on the same device. The GC/MS system comprises a library of more than 250,000 compounds, and can repeatedly render a tentative identification to the unknown compounds while searching for the unknown chemical. The concentration of TIC is always an approximation when further investigation is required to corroborate the identity of the chemical. Sometimes, only a class of compounds is recognizable (e.g., alkane). When a TIC is detected, an appropriate standard can be applied and compared to the sample

outcome. If they match, the TIC can be added to the list of the target analytes in the sample (EPA, 2006).

In this research, a GC model Agilent 6890N and Network Mass Selective Detector (MS) model Agilent 5973 with 4560 OI Analytical Sample Concentrator and 4552 OI Analytical Autosampler were used to quantify VOCs. Each sample (20 mL) was injected into the GC port, and helium was the carrier gas. Oven temperature was held between 45°C to 225°C while the purge temperature was at 20°C, desorb temperature at 190°C, and bake temperature was 210°C. The GC column was Agilent J&W, and the dimension was 20.0 m × 180 µm × 1.00 µm. Chromatograms were analyzed for tentatively identified compounds in addition to internal standards, including pentaflourobenzene, 1,4-diflourobenzene, chlorobenzene–d5, and 1,4–dichlorobenzene-d4, and system monitoring compounds such as dibrompflouromethane, toluene-d8, and bromoflourobenzene. The GC/MS analysis condition is summarized in Table 3.3.

Table 3.3: GC/MS Analysis Condition in This Study

Sample Injection volume	20 mL
Carrier Gas	Helium
Oven Temperature	45 °C to 225 °C (113 °F to 437 °F)
Purge Temperature	20 °C (68 °F)
Desorb Temperature	190 °C (374 °F)
Bake Temperature	210 °C (410 °F)
Column dimension	20.0 m × 180 µm × 1.00 µm
Internal Standards	Pentaflourobenzene / 1,4-diflourobenzene chlorobenzene–d5 / 1,4–dichlorobenzene-d4

3.2.6.1.5 Method Reporting Limit (MRL) and Method Detection Limit (MDL)

There are always limitations to the sensitivity, accuracy, and precision of analytical instruments. It is essential to obtain data which is both accurate and precise. The terms "reporting limits" and "detection limits" represent the various limits that announce the lowest concentrations of compounds with a different degree of confidence. They describe the performance of a laboratory, operator, and test method. Figure 3.9 explains the concepts of accuracy and precision.

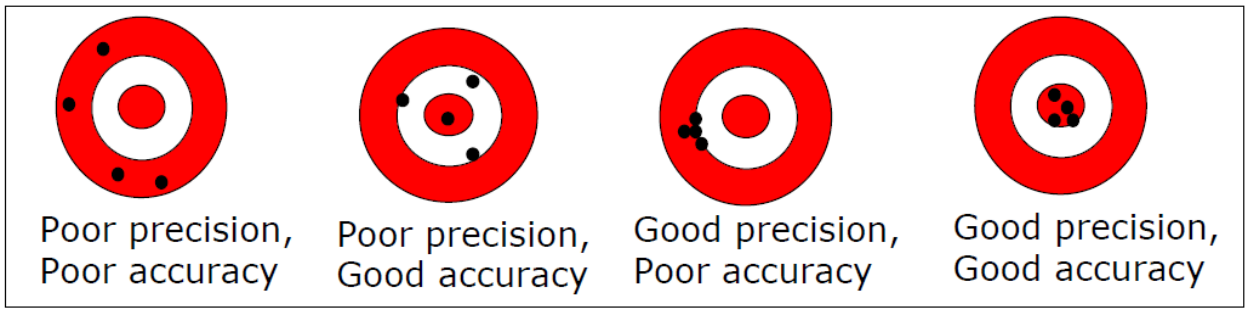


Figure 3.9: Concepts of Accuracy and Precision
(Source: Florida Department of Environmental Protection, 2009)

The method reporting limit (MRL) is the lowest amount of a chemical which can be quantitatively specified with acceptable accuracy and precision under stated analytical circumstances (ALS Environmental Lab). In fact, if a laboratory does not discover a substance in a sample, it does not indicate the absence of that substance in a sample. It only indicates that the amount of the substance is below the instrument sensitivity. Therefore, the smallest concentration of the compound which a laboratory can report is denominated MRL (LCS Laboratory Inc.). Sometimes, scientists use the phrase "Practical Quantitation Limit (PQL)" instead of MRL.

Giving an example can be useful. A water sample is tested for compound A and the regulatory limit for A is 0.5 µg/L. The method reporting limit for the laboratory is 1.0 µg/L. Then if the sample is contaminated by compound A with a concentration of 0.7

µg/L, the experiment result shows the sample as clean, even though the amount of chemical A is above the regulatory limits and can be a health risk. Hence, it is important that an investigator initially informs the laboratory what MRL (PQL) is desired for the research; in this case, the laboratory may be able to select a more suitable test method to fulfill an investigator's need (EPA, 2011).

The method detection limit (MDL) is the lowest concentration of a compound which can be quantified and reported with 99% confidence that the substance amount is greater than zero in the sample matrix (EPA, 2009). Therefore, MDL concentrations are not accurate or precise (USGS 1999). Figure 3.10 depicts the difference between MRL (PQL) and MDL.

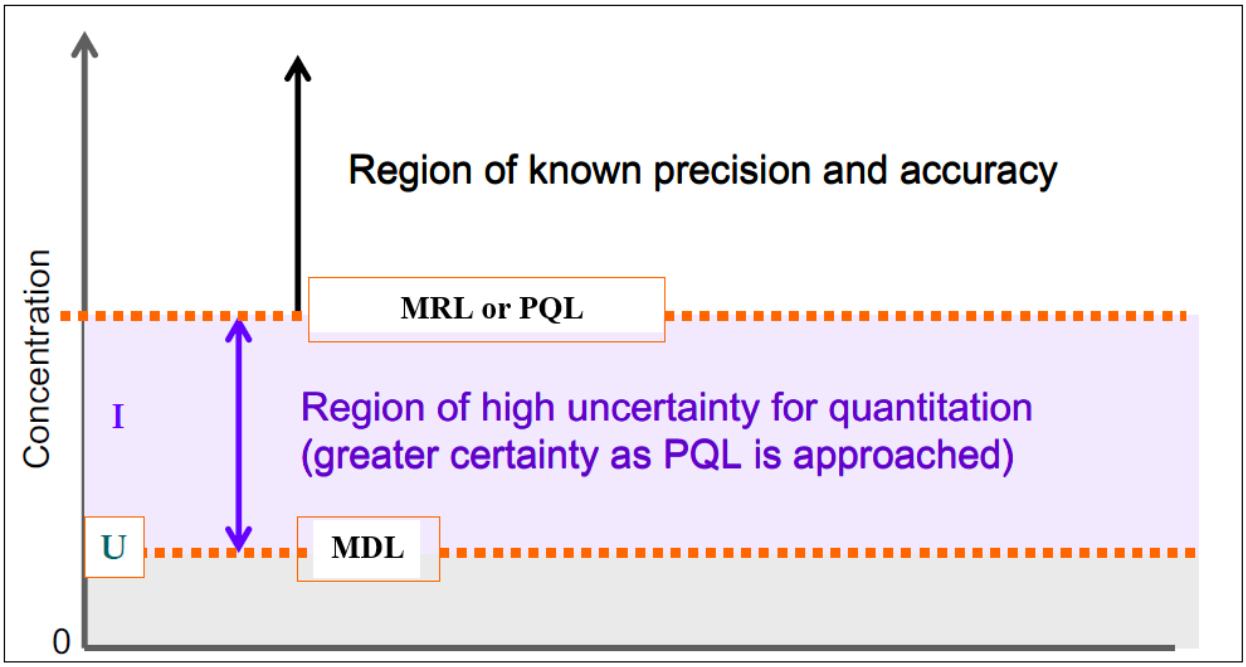


Figure 3.10: Relationship between MRL (PQL) and MDL
(Source: Florida Department of Environmental Protection, 2009)

When an analytical instrument analyzes the samples, it produces a signal even for a blank sample (matrix without analytes). This signal for a blank sample is called the

instrument background level. Measurement of the fluctuation of the background level is referred to as noise. In the background signal, fluctuation measurement can be achieved by calculating the standard deviation of successive point measurements (Wells et al., 2011). The adequate concentration of the analyte in the matrix must exist to generate an analytical signal which can be recognized from analytical noise (Shrivastava and Gupta, 2011). Indeed, in situations when noise and analyte signal are indiscernible, MDL protects against faulty reporting of the availability of the analyte at low concentrations. When the instrument reports a detection of a chemical which is absent in the matrix, it is known as a "false positive." Reporting the discovery of a compound at MDL amounts in a blank specimen or a sample which does not have the substance is rare. Thus, such a reporting is not presumably in error (USGS, 1999).

The United States EPA has developed a procedure to calculate the method detection limits. In this method, a minimum of seven replicate (*n*) spikes at low concentrations, usually 1 to 5 times the anticipated MDL, should be prepared and processed via the full analytical method (Figure 3.11) (USGS, 1999).

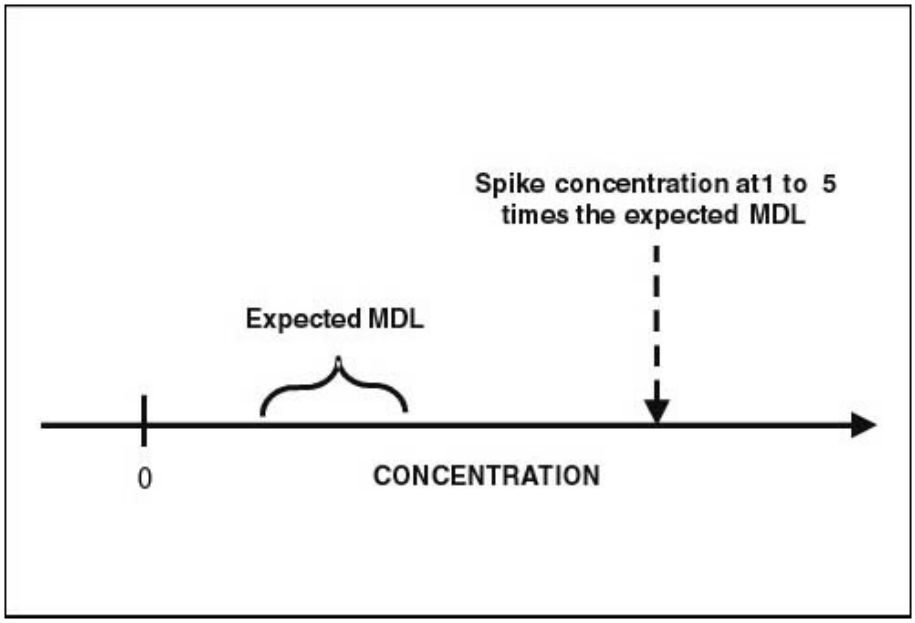


Figure 3.11: Relation between Spike Concentration and MDL
(Source: United States Geological Survey (USGS) 1999)

Analysis of the spike samples is usually performed over a few days, and reagent water is typically the spiked matrix. By gathering data points at the spike concentration, a distribution of measured concentrations will be generated. Figure 3.12 shows an example which is related to distribution of measured concentrations of chlorobenzene for 50 injections spiked at 0.05 µg/L. The EPA procedure considers this distribution to be a normal distribution and is displayed by the bell-shaped curve. (USGS, 1999)

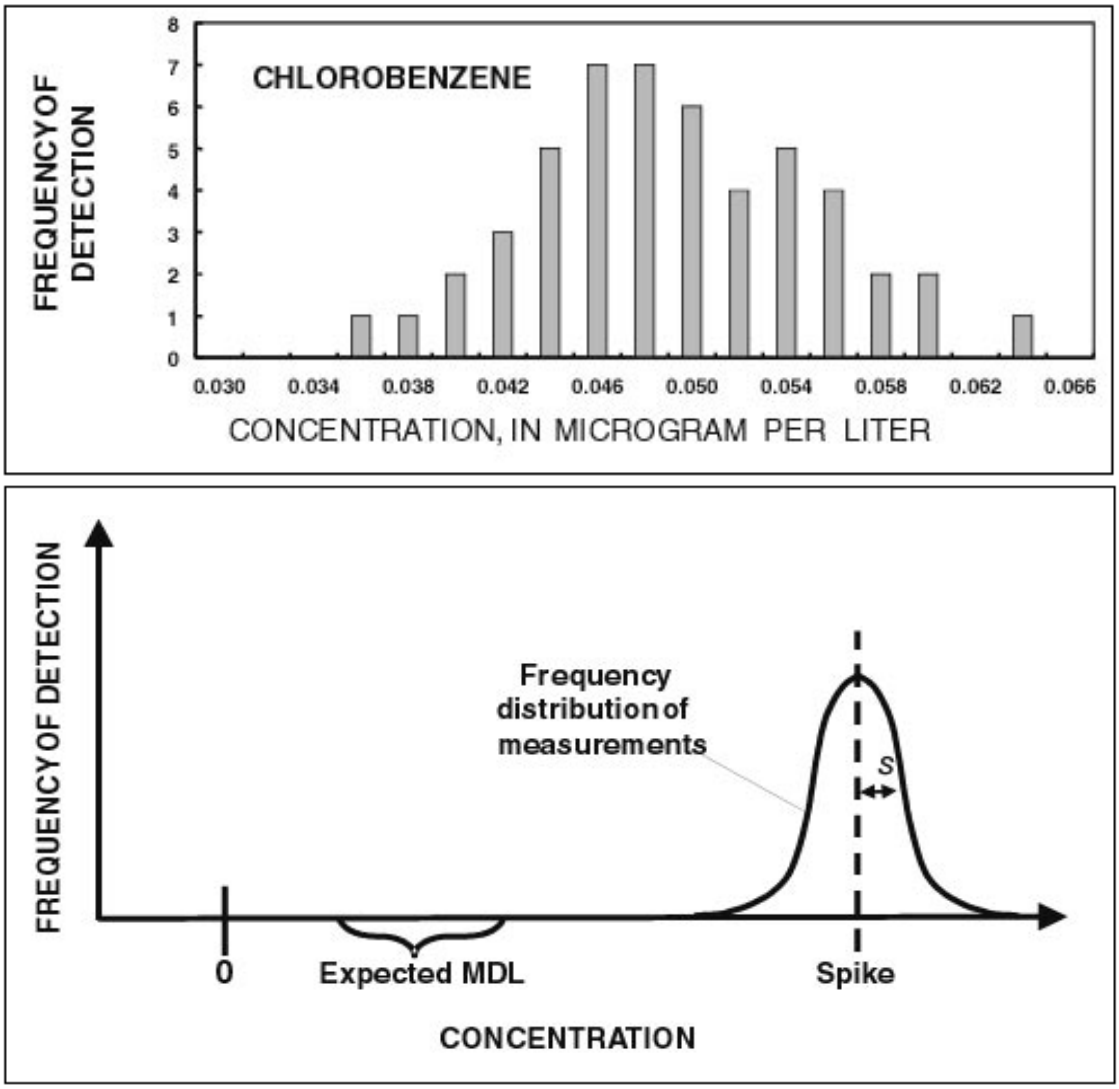


Figure 3.12: Frequency Distribution of Measured Concentrations of Chlorobenzene Spiked at 0.05 µg/L
(Source: United States Geological Survey (USGS) 1999)

It is assumed that the frequency of the distribution and, therefore, the standard deviation of the distribution will be constant at some low concentration and stays constant down to zero concentration. Figure 3.13 represents the standard deviations for various spike concentrations. The EPA method suggests an iteration approach to decrease the spike concentration to lower concentrations in order to approximate the region of constant standard deviation to MDL (USGS, 1999).

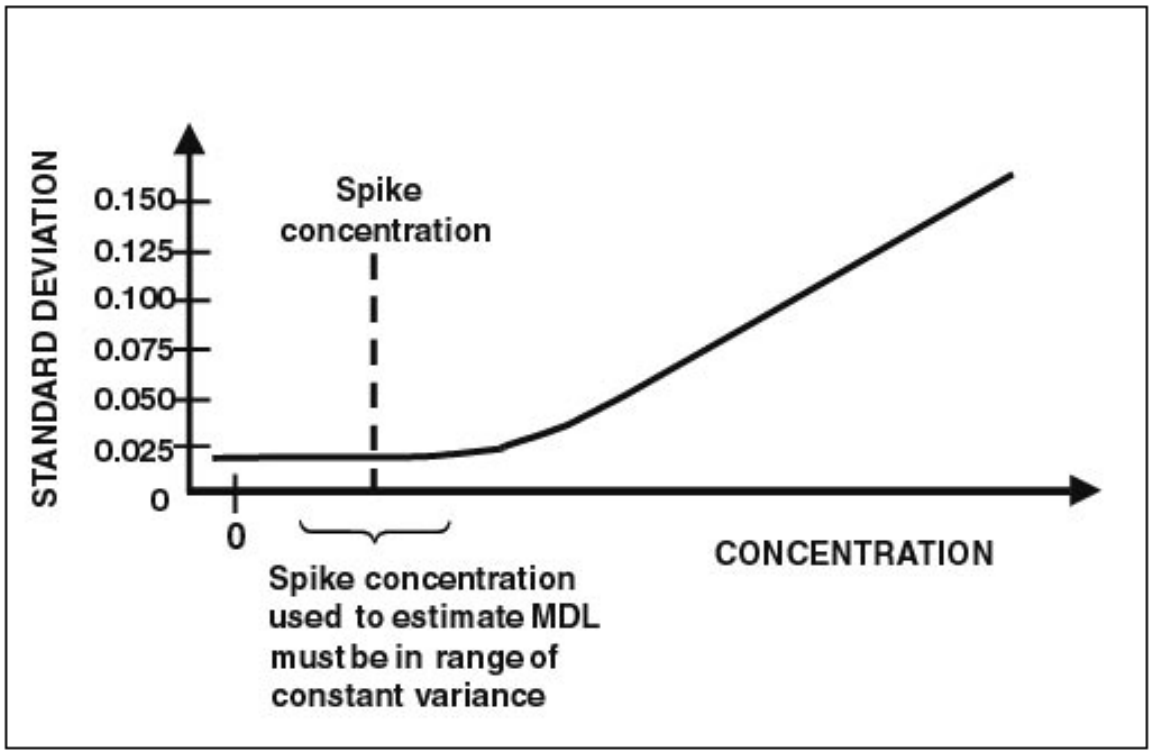


Figure 3.13: Standard Deviations for Spike Concentrations, Presenting a Zone of Constant Standard Deviation at Low Concentrations
(Source: United States Geological Survey (USGS) 1999)

It is unfeasible to measure noise signal in repetitive blank samples. In an effort to simulate the distribution of measuring the noise signal or actual unspiked analyte or both in a series of blank samples, the frequency distribution of low concentration spikes will

be centered on zero concentration and can be considered to be a hypothetical blank samples frequency distribution (Figure 3.14) (USGS, 1999).

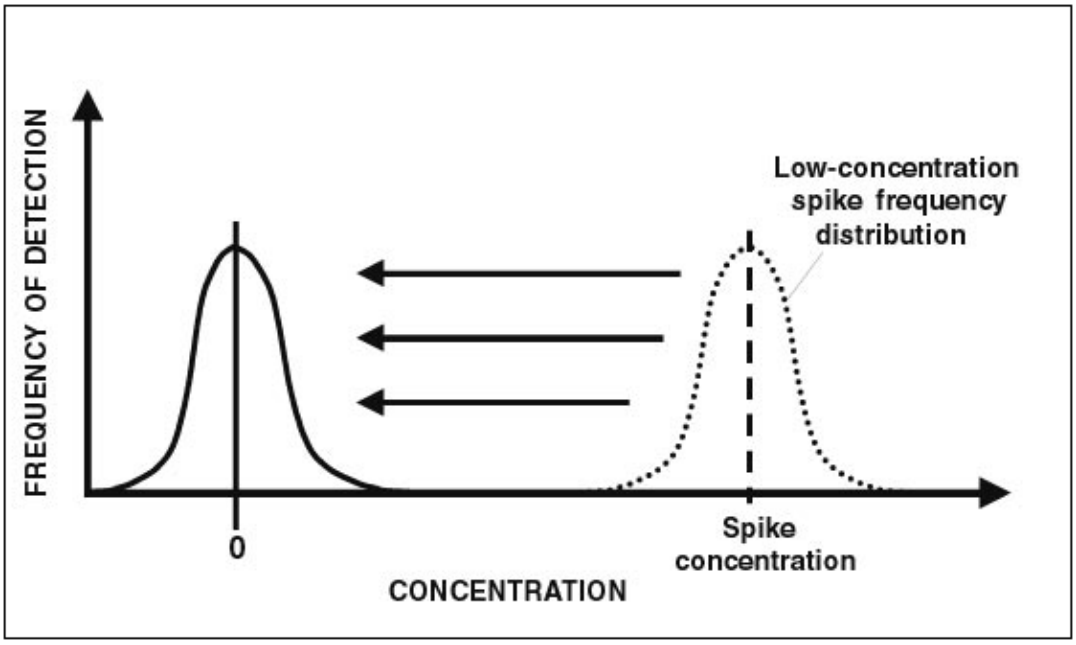


Figure 3.14: Frequency Distribution of Spike Measurements is Superimposed on Zero Concentration
(Source: United States Geological Survey (USGS) 1999)

These hypothetical blank measurements are employed to compute the concentration at which no more than 1 percent of the blank samples will result in the reporting of a false positive, and that concentration is called the MDL. Accordingly, reported detections at concentrations equal to or greater than MDL concentrations should be real detections 99 percent of the time. The following formula is used to calculate EPA MDL (USGS, 1999).

Equation 3-3: $\text{MDL} = S \times t_{(n-1, 1-\propto=0.99)}$

Where:

n = number of replicate spike (1 to 5 times the estimated MDL)

s = standard deviation of measured concentrations of n spike

t = student's t value at n-1 degrees of freedom and 1- $\propto$ (99 percent) confidence level. Student's t value can be seen at Table 3.4.

$\propto$ = level of significance

Table 3.4: Student's t Value for Different Replicates and Degrees of Freedom

Number of Replicates	Degrees of Freedom (n-1)	$t_{(n-1,0.99)}$
7	6	3.143
8	7	2.998
9	8	2.896
10	9	2.821

(Source: Environmental Protection Agency (EPA) 2009)

For this dissertation research, the method reporting limits (MRL) of each target analyte are presented in Appendix F.

3.3 Solid Waste Generation

The United States EPA (EPA 2016) has a specific definition for solid wastes, as follows (EPA, 2016):

> Any garbage or refuse, sludge from a wastewater treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semi-solid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities. Nearly everything we do leaves behind some kind of waste.

A considerable portion of solid waste is "industrial waste," even in small cities. Unlike residential waste, which is collected by municipalities, industrial waste is commonly managed by the private sector. The EPA has provided numerous topical websites which can help communities to handle their industrial waste successfully and guide them to select environmentally responsible options to better address the management of the waste (EPA, 2016).

In the 1980s, American industrial facilities including 17 various industry categories, generated and disposed of almost 7.6 billion tons of industrial waste per year. Standard Industrial Classification (SIC codes) represents these 17 industries. The SIC codes are a set of codes which are applied to categorize the economic activities of the industries or types of business formations in America's economy. The SIC classification includes 10 divisions (A to J) with multiple subdivisions. Sewer construction and sewage collection are under division C (Major Group 16) and E (Major Group 49), respectively. Plastic resins are under division D, Major Group 30 (EPA, 2016; OSHA, 2016).

3.3.1 Open-Cut or Remove and Replace Method

Construction and demolition (C&D) debris produced within the construction, reconstruction, and demolition of structures, including buildings, bridges, and roads was considered as C&D waste by the EPA. Most of C&D material is disposed in two types of landfills: 1) Municipal solid waste landfills, where household wastes are managed and

handled. 2) C&D landfills, the places which are assigned particularly for C&D materials. Combustion facilities and unpermitted landfills are other destinations for some of the C&D materials. The EPA believes that roughly 1,900 C&D landfills were established throughout the nation in 1994. The EPA regulates municipal solid waste landfills, while C&D landfills are mainly regulated by state and local governments (EPA, 2016)

Fulfilment of waste management policies such as recycling, reduction, and reusing of C&D materials can reserve landfill space, indirectly diminish methane gas emission, minimize the extraction and consumption of virgin resources, decrease environmental impacts of new material production, provide business opportunities, and save money by avoiding disposal costs (EPA, 2016).

As mentioned earlier, 36 pipes in the basin were removed and replaced, and 7 pipes had a small section of open-cut followed by CIPP (total of 43 pipes). For this purpose, the contractor excavated along the designated pipes and replaced them with new VCP pipe in the same size as the old one. The contractor completed an average of 60 - 70 linear feet for removal and replacement per day.

A variety of data was collected from each project site. Where data were not readily available, these values were estimated. Trench dimensions were used to estimate the amount of waste/material produced as a result of land disturbance during removal and replacement (R&R). Land disturbances for 43 pipe removal and replacement activities generated a large amount of dirt and crushed asphalt and road base, which is referred to as excavation waste. Since the depth of each pipe differed, trench volume varied per excavation site.

Waste management practices implemented during the project resulted in a significant reduction in the amount of waste transported to the landfill. The excavated dirt was in most cases backfilled into the trench created during excavation. According to the contractor, old pipe which was targeted for removal and replacement was crushed into small pieces approximately 4 inches in size and mixed with the dirt used to backfill the

trench. Only road base and asphalt material were considered to be generated solid waste and transported to a recycling center and landfill. Asphalt and road base thickness were roughly 8 inches, and the width of the trenches was around 2.5 feet.

All buried pipes require an appropriate bedding case which protects the pipe against loading pressures and provides rigid pipe support. In general, granular material that is uniformly compacted to an equal extent is used to build the bedding case. Sometimes for good practice, over-excavation of the trench, the substitution of a flat foundation, and the implementation of the bedding case over the foundation are employed (Gabriel, 1998). Various types of bedding cases are available based on the depth of the pipe. Each bedding case may differ in materials and dimensions. All pipes in this case study had the same bedding case, and the pipes' depth were between 7 to 16 feet below the ground surface.

3.3.2 CIPP Method

While the pipe replacement method generates some waste that must either be recycled within the site or go to the landfill, CIPP generates a different kind of waste. Commonly CIPP curing is performed by circulating hot water or steam inside the pipe to polymerize the resin material followed by a cooling down period. These two actions lead to the generation of processed water or steam condensate which contains a high concentration of chemicals. (Donaldson, 2009; Tabor et al., 2014). The processed water or condensate is considered to be liquid or semi-solid wastes which should be managed appropriately. However, a few states take active steps to handle this matter and have implemented restricted specifications to their CIPP projects (Caltrans, 2012). The liquid and semi-solid wastes were not evaluated in this study.

The CIPP activity produces some solid waste as well, such as the excess cured resin liner and other material. Some of these materials are classified in the plastic group and can be recycled. The recycling rate for various kinds of plastic varies significantly. Plastics have two major classifications: thermosets and thermoplastics. Heat stiffens a

thermoset type plastic irreversibly, and their strength and durability make them a suitable choice for application in automobiles, construction, adhesives, inks, and coatings (EPA, 2015).

In contrast, heat softens a thermoplastic which reverts to its original condition at room temperature. Because of this characteristic, thermoplastics can readily be shaped and molded and they are useful for manufacturing of products such as carpet fibers, floor covering, and credit cards (EPA, 2015).

Businesses for recycling of some kinds of plastic resins such as high density polyethylene (HDPE) are active and developing in the United States. The U.S. capacity for recycling of post-consumer plastics and the market demand for plastic resins recovery are larger than the amount of post-consumer plastics obtained from the waste stream (EPA, 2015).

3.4 Criteria Air Pollutants and Greenhouse Gases Emissions

3.4.1 Criteria Pollutants

The Clean Air Act (CAA) is the federal law that was first enacted in 1955, with major revisions in 1970 and 1977, and last amended in 1990 which established the basis for the nationwide air pollution control effort (California Environmental Protection Agency, 2015). The act requires the EPA to determine criteria for healthy ambient air quality and set emission standards for ubiquitous sources of air pollution, such as power plants and motor vehicles (McCarthy, et al., 2011).

In response, the EPA set National Ambient Air Quality Standards (NAAQS) (40 Code of Federal Regulations part 50) for management of pollutants noxious to public health and the environment. Two types of ambient air quality standards are recognized by the act: primary standards and secondary standards. Primary standards relate to human health and provide protection to public health. Secondary standards prevent damage to

the environment, such as animals, vegetation, and buildings, and provide protection to public welfare. The NAAQS was set for six common and principal air pollutants which are called “criteria pollutants.” These pollutants are listed below (EPA, 2015):

- Carbon monoxide,
- Nitrogen oxides,
- Sulfur dioxide,
- Particulate matter,
- Ozone, and
- Lead.

Human health-based and environmentally-based criteria are used to regulate mentioned pollutants, the reason for using the word “criteria” for these pollutants. Exposure to these pollutants can cause numerous human health effects containing respiratory symptoms, heart and lung diseases, asthma, chronic bronchitis, child IQ loss, hypertension, stroke, and premature death (EPA, 2015). Health effects associated with each of the criteria pollutants are discussed in Chapter 6.

Numerous monitors located across the U.S. measure the concentration of pollutants in different areas. The EPA uses these data to generate air quality trends. In 2014, air pollution emissions into the atmosphere in America were estimated near 89 million tons and these emissions played the major role in ozone and particulate formation, the deposition of acids, and visibility impairment. The effectiveness of the EPA program can be evaluated by the estimation of annual emissions. Tracking the changes in different aspects of society between 1980 until 2014 can provide a better understanding of the EPA’s endeavor. Figure 3.15 depicts the trends for different areas.

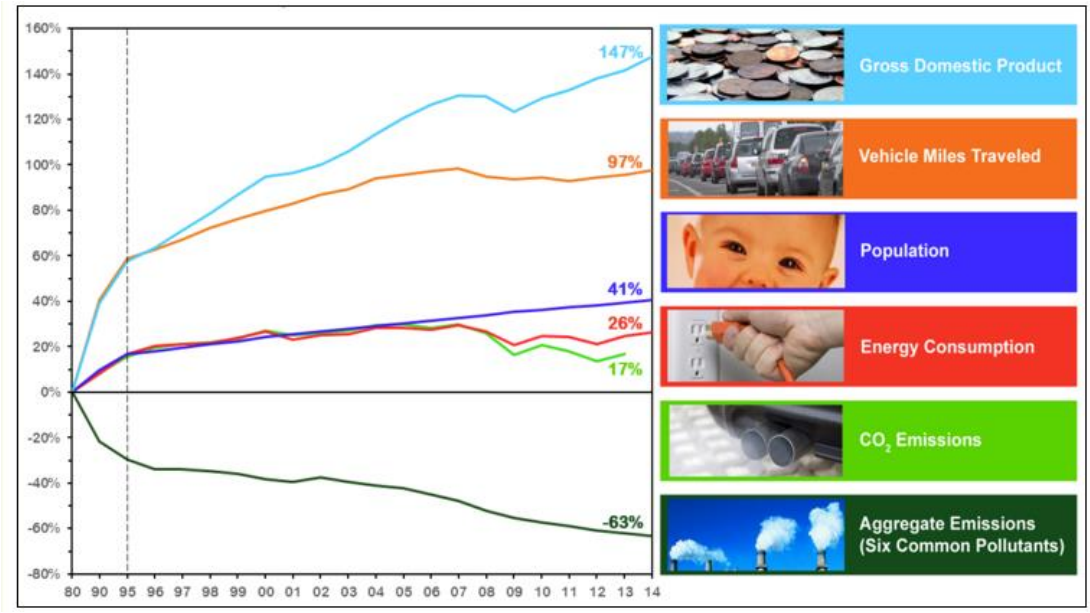


Figure 3.15: Comparison of Growth Areas and Air Pollutant Emissions (1980-2014)
(Source: EPA, 2015)

It is notable that since 1980 the gross domestic product, vehicle miles traveled, U.S. population, energy consumption, and CO_2 emissions enhanced 147, 97, 41, 26, and 17 percent, respectively, while, total emissions of criteria pollutants decreased by 63 percent. Air quality benefits will result in health improvement and enhanced quality of life. As a result of this air quality improvement, many regions in the United States meet the NAAQS requirement. For instance, 41 areas had an unhealthy concentration of carbon monoxide in 1991, and, currently, all those areas meet the standards. The main reason for this progress is the evolution of the motor vehicle fleet. The new motor vehicles are much cleaner owing to CAA standards. Airborne lead resulting from motor vehicle gasoline was another widespread health concern prior to the EPA banning the usage of lead in gasoline under the CAA authority, and now, most regions of the country meet the national standard. Also, for other pollutants dramatic amelioration is remarkable (EPA, 2015).

In contrast with such a great improvement in air quality, in 2014 around 57 million people throughout the United States were the residents of places where the pollution concentrations are above the primary NAAQS and efforts need to be continued to bring more areas under the coverage of the healthy air umbrella (EPA, 2015).

3.4.2 Greenhouse Gases (GHGs)

Gases that ensnare heat in the atmosphere and make the earth warmer are entitled greenhouse gases (EPA, 2015). These gases allow sunlight to pass through the atmosphere unimpeded and reach the earth's surface. When the sunlight warms the surface, infrared energy (heat) is emitted to the atmosphere. GHGs almost block the escape of a large section of this heat from the atmosphere and trap it in the lower atmosphere. Some GHGs occur naturally, like methane, carbon dioxide, nitrous oxide, and water vapor, whereas others are anthropogenic, including chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Because of the industrial revolution, the concentration of several important GHGs has been increased by about 25 percent over the last few centuries. Within the past 20 years, approximately three-quarters of anthropogenic carbon dioxide emissions are related to burning fossil fuels. Although carbon dioxide occurs naturally in the atmosphere, human interference with the carbon cycle led to an artificial shift of carbon from solid storage to its gaseous state and thus enhancing atmospheric concentrations (Figure 3.16) (NOAA, 2016; U.S. Energy Information Administration, 2004).

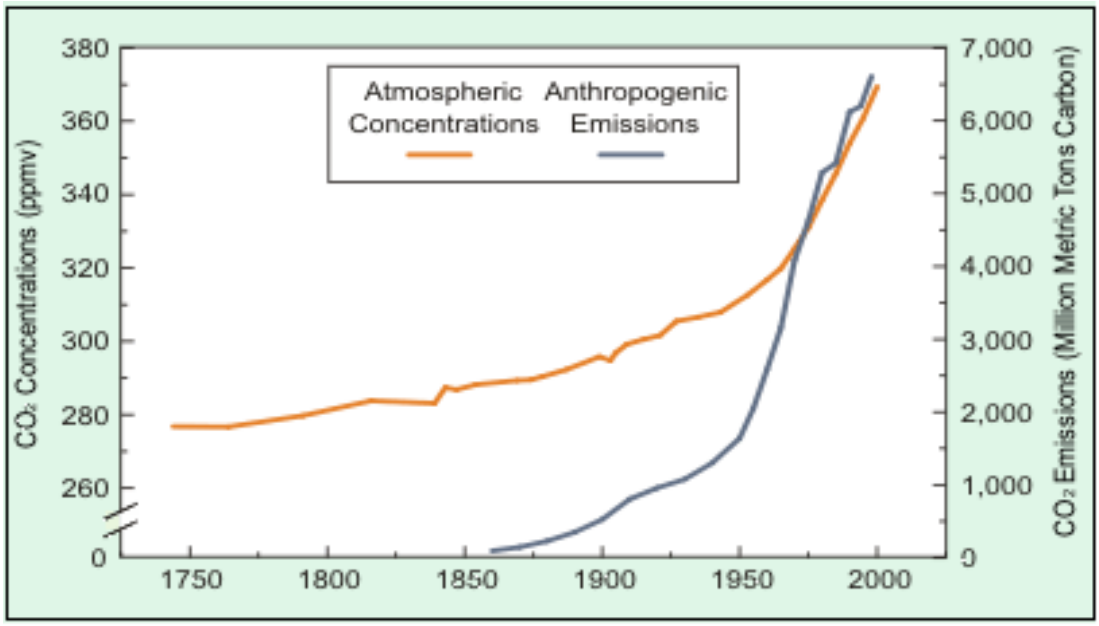


Figure 3.16: Atmospheric and Human-Made Concentrations of Carbon Dioxide Emissions
(Source: U.S. Energy Information Administration 2004)

The main sources of GHG emissions in the United States are as follows (Figure 3.17):

- Electricity generation: About 67 percent of electricity comes from fossil fuels burning, especially coal and natural gas.
- Transportation: Production of gasoline and diesel primarily depends on fossil fuel burning.
- Industry: Required energy is provided by fossil fuel burning.
- Commercial and residential: heat for homes and businesses come from fossil fuel burning and waste handling, which result in GHG emissions.
- Agriculture: emission from this source comes from livestock, including cows, rice production, and agricultural soils.
- Land use and forestry: this source can both absorb CO_2 and emit GHG. But with proper management absorbing can be higher than emission.

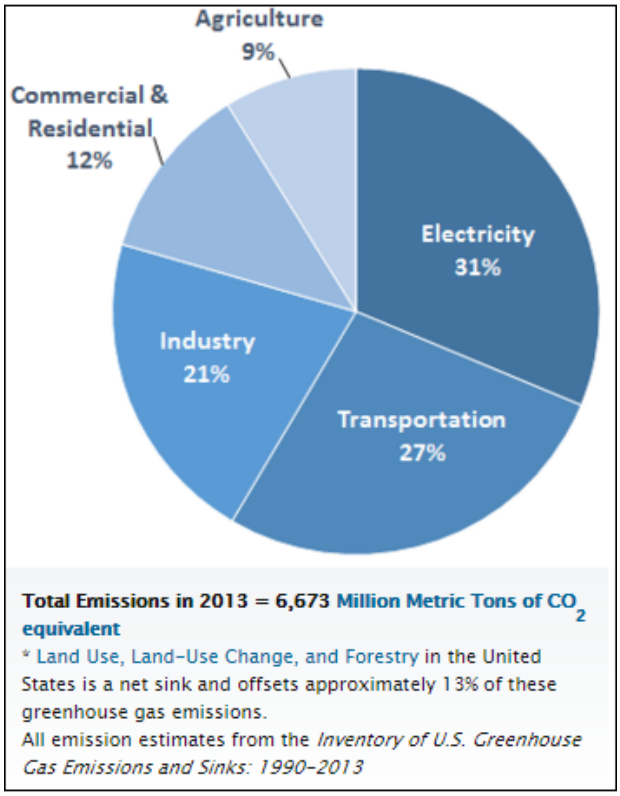


Figure 3.17: Share of Each Source in 2013 Total GHG Emissions
(Source: EPA 2015)

3.4.3 Pollutant Emissions for Open-Cut Method

Understanding the emission of criteria air pollutants and GHGs from different repair methods is helpful for environmental effects comparison. In this study, pollutants (criteria and GHG) from heavy equipment usage during installation at work sites were evaluated. Criteria air pollutants that are likely emitted by heavy equipment used for pipeline rehabilitation constriction activities include VOCs, CO, SOx, NOx, and particulate matter of 2.5 and 10-micron size ($PM_{2.5}$, PM_{10}). GHG emissions have also been the focus of several studies because GHGs have a significant contribution in global warming and climate change.

To calculate pollutant air emissions in this research, the number of onsite work days, types of heavy equipment onsite, daily hours of heavy equipment operation, and emission factors for equipment were obtained. During this project, 110 work days were

considered for R&R activities. The California Air Resources Board's emission factors were obtained to calculate the quantity of emitted pollutants (AQMD, 2015). A list of the emission factors for various equipment is provided in Appendix D.

The following equipment and vehicles were used during this process: air compressor, dump truck, utility truck, signal board, mini excavator, bypass pump, concrete saw, crushing machine, chipping gun, backhoe, roller, and paver.

3.4.4 Pollutant Emissions for CIPP Method

In order to calculate pollutant air emissions during CIPP, the same parameters for the R&R method were investigated, including the number of onsite work days, types of heavy equipment onsite, daily hours of heavy equipment operation, and emission factors for equipment.

For the CIPP process the following equipment and vehicles were used in this study: jetter (truck for cleaning the sewer line), television truck, boiler, air compressor, refrigerated truck, utility truck, diesel engine, and generator. Some equipment was turned on continuously for different purposes during the installation. The contractor installed on average 300 linear feet of CIPP liner in one day and 22 work days were considered for CIPP activities.

Chapter 4

4. Results and Discussion

4.1 CIPP Air Emission

As previously mentioned, the first part of this study focused on VOC emissions from a CIPP sanitary sewer installation, and three CIPP installation sites in one U.S. city were examined. During the CIPP curing period for all three sites, a white vapor-like substance was emitted from the hose and immediate downstream and upstream manholes (U/S MH). Emissions from the upstream manholes were apparent but much less visible than those from the downstream manholes (D/S MH). A distinct sweet chemical odor was also detected once CIPP installation activities began. During the CIPP cooling period however, no white-vapor was visible exiting the hoses and a very slight white vapor-like substance was seen exiting the manholes (Figure 4.1).

Figure 4.1: Chemical Emission from Downstream Manhole During the Cooling Period
(Picture was taken in public area)

The temperature and flowrate characteristics of the vapor-like substance, referred hereto as steam, exiting downstream manhole and the hose setup by the contractor were measured in this study. The greatest steam temperatures (43 - 64°C) and flowrates (0.05 - 0.08 m^3/s) were detected during the CIPP curing period. During the cooldown period, steam exiting the hose was substantially cooler (20 - 25°C) but had a similar flowrate (0.05 - 0.06 m^3/s); (Tables are provided in Appendix E). While the emission of white-vapor like substances from CIPP installations is commonly reported, unfortunately no other steam emission monitoring data was found in the literature for comparison. Steam was also observed by the author from upstream manholes and temperature, flowrate, and velocity characteristics of those emissions were not measured.

VOC air sampling results indicated that the CIPP activities emitted chemicals into the air during both curing and cooling periods. Styrene was the only chemical detected using EPA Method 8260b at any point during the study, although the laboratory reported MRLs were highest during curing and cooling samples. Thus, the analytical method inhibits a determination of VOCs detected in water previously by Tabor et al. (2014) in CIPP condensate. Acetone, benzene, chloroform, isopropylbenzene, methylene chloride, methyl ethyl ketone, *N*-propylbenzene, 1,2,4-trimethylbenzene (TMB), and 1,3,5-TMB were emitted during the present study. The method reporting limit (MRL) for each analyte can be found in Appendix F. Generally, MRLs were 0.5 ppm for all air samples except for curing and cooling period air samples. These were Site 1 (10, 0.5 ppm), Site 2 (20, 2.5 ppm), and Site 3 (5, 0.5 ppm), respectively.

The analytical method was also unable to detect semi-volatile organic compounds (SVOCs), while SVOCs are known to be emitted by CIPP steam curing (Tabor et al. 2014). The highest styrene levels were detected during the curing process at all sites (Table 4.1), and styrene was also detected during the cooling process.

The chain of custody forms for all samples can be found in Appendix G.

The Occupational Safety and Health Administration (OSHA), the National Institute for Occupational Safety and Health (NIOSH), and the American Conference of Governmental Industrial Hygienists (ACGIH) have developed regulatory styrene exposure levels for healthy adults primarily because of its wide use in the plastics and composites industry (Table 4.2).

Table 4.1: Site Characteristics and Measured Styrene Air Concentration

Site Characteristics	***CIPP Installation Site***		
Characteristics of Pipe Being Rehabilitated	**1**	**2**	**3**
Pipe length (meters)	92.6	71.6	94.1
Pipe size (cm)	20.3	20.3	20.3
Number of laterals along pipe section	13	8	9
Location and Distance from Fabric Insertion Point (U/S MH)(meters)			
Ambient control sampling before construction began (The middle point between U/S and D/S)	46	36	47
Downstream manhole sampling during curing	92.6	71.6	94.1
Downstream manhole sampling during cooling	92.6	71.6	94.1
Nearest private property to the downstream manhole	89	-	-
Upstream manhole during liner inversion into the manhole	1	-	-
Styrene Concentration in Downstream Manhole (ppm)			
During curing	289	1,070	250
During cooling	5.26	76.7	3.62
During liner inversion and private property	nd	-	-

Results shown represent one replicate per sample and are presented exactly as reported by the laboratory; Dash (-) represents sampling not conducted at that location; nd = contaminant not detected above the MRL which was 0.5 ppm for samples were taken during liner inversion and near private property.

Table 4.2: Regulatory Styrene Exposure Limits for Healthy Adults

Agency	Standard	Conditions	Value, ppm
OSHA	PEL	TWA (8 hr workday); Workers should not experience adverse effect	100
	Ceiling	Not to be exceeded	200
NIOSH	REL	TWA (8-10 hr); Not to be exceeded	50
	STEL	TWA (15 min); Not to be exceeded	100
	IDLH	Immediately dangerous to life or health; likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from the environment	700
ACGIH	TLV	TWA which most workers can be exposed without adverse effects	20
	STEL	TWA (15 min); Not to be exceeded	40

OSHA: Occupational Safety and Health Administration; NIOSH: National Institute for Occupational Safety and Health; ACGIH: American Conference of Governmental Industrial Hygienists; PEL: Permissible Exposure Limit; REL: Recommended Exposure Limit; STEL: Short-Term Exposure Limit; IDLH: Immediately Dangerous to Life or Health; TLV: Threshold Limit Value; TWA: Time Weighted Averages acronyms]

The magnitude of styrene detected inside manholes indicates that an environmental as well as health and safety concern may exist at the worksite. A styrene concentration immediately dangerous to life and health (for healthy adults) was detected near the source in a manhole. The highest previously reported worksite styrene level found in the literature was 3.2 ppm (NASSCO, 2008). However, the previous data are not directly comparable because the measurements were conducted at different site locations, and the roles of the contractors, worksite, installation processes, and environmental conditions on measured styrene levels have not been investigated. Because additional air monitoring was not conducted during the present study, it is unknown if workers were exposed to styrene concentrations during the construction activity or if styrene migrated through sewer pipes away from the CIPP activity. Odor control units, styrene air monitoring devices, air treatment equipment, and personal respirators were not present at any of the sites. Results indicate that CIPP sewer pipe installation can generate chemical steam that contains styrene at levels in the hundreds of ppm. Table 4.3 presents the laboratory results of three sites for all 67 target analytes.

Table 4.3: Laboratory Reported Concentrations for Target Analytes at Three Sites

No.	Analytes	Site 1					Site 2			Site 3		
		Control	Inversion	Cure (MH)	Cure (near private residence)	Cool (MH)	Control	Cure (MH)	Cool (MH)	Control	Cure (MH)	Cool (MH)
1	Acetone	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2	Benzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
3	Bromobenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
4	Bromochloromethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
5	Bromodichloromethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
6	Bromoform	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
7	Bromomethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
8	2-Butanone	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
9	n-Butylbenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
10	sec-Butylbenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
11	tert-Butylbenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
12	Carbon disulfide	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
13	Carbon tetrachloride	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
14	Chlorobenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
15	Chloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
16	2-Chloroethyl vinyl ether	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
17	Chloroform	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
18	Chloromethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

(Table Continued)												
19	4-Chlorotoluene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
20	2-Chlorotoluene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
21	1,2-Dibromo-3-chloropropane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
22	Dibromochloromethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
23	1,2-Dibromoethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
24	Dibromomethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
25	1,2-Dichlorobenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
26	1,3-Dichlorobenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
27	1,4-Dichlorobenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
28	Dichlorodifluoromethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
29	1,1-Dichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
30	1,2-Dichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
31	1,1-Dichloroethene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
32	cis-1,2-Dichloroethene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
33	trans-1,2-Dichloroethene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
34	1,2-Dichloropropane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
35	1,3-Dichloropropane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
36	2,2-Dichloropropane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
37	1,1-Dichloropropene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
38	cis-1,3-Dichloropropene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
39	trans-1,3-Dichloropropene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
40	Ethylbenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

(Table Continued)												
41	Hexachlorobutadiene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
42	2-Hexanone	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
43	Isopropylbenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
44	p-Isopropyltoluene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
45	MTBE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
46	4-Methyl-2-pentanone	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
47	Methylene chloride	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
48	Naphthalene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
49	n-Propylbenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
50	**Styrene**	**ND**	**ND**	**289**	**ND**	**5.26**	**ND**	**1,070**	**76.7**	**ND**	**250**	**3.62**
51	1,1,1,2-Tetrachloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
52	1,1,2,2-Tetrachloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
53	Tetrachloroethene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
54	Toluene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
55	1,2,3-Trichlorobenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
56	1,2,4-Trichlorobenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
57	1,1,1-Trichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
58	1,1,2-Trichloroethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
59	Trichloroethene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
60	Trichlorofluoromethane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
61	1,2,3-Trichloropropane	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
62	1,2,4-Trimethylbenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

(Table Continued)												
63	1,3,5-Trimethylbenzene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
64	Vinyl acetate	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
65	Vinyl chloride	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
66	o-Xylene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
67	m- & p-Xylenes	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

The CIPP installations in the present study were outfitted with special liners reported to be “impermeable.” These liners are intended to reduce chemical permeation and release into the environment (Lubrizol Corp., OH). No studies, however, were found regarding the efficacy of their performance in reducing chemical permeation. It is unknown if these liners were installed correctly or the liners had been mechanically compromised before or during installation. Results nonetheless indicated that styrene can be emitted at levels immediately dangerous to life and health from CIPP installation sites even when a liner is used and additional work is needed to better understand conditions that resulted in these data.

Myriad literature reports indicate that CIPP sanitary sewer activities using styrene resin can contribute to styrene present inside nearby buildings. No indoor air monitoring was conducted during the present study for nearby sewer laterals and a limited number of samples on-site were collected. Evidence from the present study indicates that the greatest styrene concentration occurred during the curing process. No studies were found that have examined the physics of what takes place inside the CIPP tube during curing to define which conditions can result in chemical steam entering nearby sewer pipes and chemical transport to and into nearby buildings.

It is important to recognize that air styrene regulatory exposure limits established by OSHA and NIOSH are not protective of infants, children, or immunocompromised individuals who would be more susceptible to chemical toxicity. In accordance with risk assessments by the U.S. and the Netherlands, the International Toxicity Estimates for Risk (ITER) values for these susceptible populations range from 20 - 25 ppm (Table 4.4). In the absence of any thorough styrene exposure limit established for CIPP-caused conditions, health officials and utilities should consider requiring contractors not to allow styrene to escape the sewer pipe rehabilitation site at or above this limit. Also, sewer laterals require frequent air testing during CIPP installations.

Table 4.4: Non-Cancer Inhalation Styrene Exposure Limits to be Considered for Sensitive Populations

Agency	*Parameter*	*Conditions*	*Value (ppm)*
ATSDR	LOAEL	Lowest observed adverse effect level	20
RIVM	LOAEL	Lowest observed adverse effect level	25
EPA	NOAEL	No observed adverse effect level	22

Results obtained from ITER TOXNET (2015); ATSDR = Agency for Toxic Substances and Disease Registry, Department of Health and Human Services, USA; RIVM = National Institutes for Public Health and the Environment, Ministry of Health, Welfare, and Sport, The Netherlands; EPA = Environmental Protection Agency, USA

To prevent styrene intrusion into nearby buildings through sewer drains of a sewer pipe network, chemical transport phenomena in sewer pipes and premise plumbing configuration must be understood. There is some evidence of gas transport in normal operating sewer systems, primarily for H_2S (EPA, 1991), but no data were found regarding transport of contaminants released by sewer pipe CIPP rehabilitation activities. CIPP activities are very different from normal gravity operated collection systems because CIPP installations involve high temperature, pressure, and air flow. Sewer pipes undergoing rehabilitation are many times bypassed, but not completely isolated from nearby sewer laterals.

The presence of water seals in p-traps has been reported helpful in minimizing CIPP-caused styrene intrusion in the City of Toronto (2001). Water seals are required to be maintained in floor drains with trap primers in accordance with model plumbing codes (IPC, 2015; IAPMO, 2015). Discussions with homeowners in this study (outside the city where the testing was conducted) revealed that it is likely most homeowners are unaware that water seals are required for plumbing code compliance. Also important to note is that for most sinks and other fixtures that have water plumbed to the fixture and are used often enough to maintain trap seals, there are no requirements for a trap primer. In areas where emergency floor drains or similar fixtures do not have water piped to them, there should be a trap primer or other approved means of introducing a small amount of water

periodically to prevent p-trap evaporation and the escape of sewer gasses. In buildings where traps can dry out from long periods of non-use, a flexible seal without a liquid seal trap can be installed. Until additional VOC monitoring studies have been conducted, it is recommended that both CIPP contractors and sewer system owners warn and teach customers how to prevent CIPP generated chemicals from intruding into their buildings. Because of the serious public health risk, air monitoring in nearby sewer laterals is also recommended.

Odor control units and air treatment equipment could also be employed to capture and remove chemicals from contaminated steam before emission to the ambient environment and work area. While styrene is defined as a hazardous air pollutant (HAP) by the Clean Air Act, there is no legal requirement to restrict HAP emission from rehabilitation sites. Because no air regulatory permit is needed for chemical emissions from CIPP installations, the environmental and public health risk to workers remains poorly understood.

4.2 Solid Waste Generation

As discussed earlier, another goal of this study was to evaluate solid waste generation in both methods: remove and replace and CIPP. The remove and replace method produces construction and demolition (C&D) waste and CIPP activity generates plastic type solid waste. The results of both techniques will be explained in detail in this section.

4.2.1 Solid Waste from R&R Method

Of the 43 pipes targeted for R&R, 36 pipes in the basin had the open-cut procedure and 7 pipes had a small section of R&R followed by CIPP. Because of land disturbances during open-cut activities, a large amount of construction and demolition (C&D) waste including dirt, crushed asphalt, and road base were generated (Figure 4.1).

Approximately 5,657 yd^3 (4,325 m^3) of dirt, road base, and asphalt were excavated for these removal and replacement sites. Of this volume, 4,901 yd^3 (3,747 m^3) were backfilled into trenches and 756 yd^3 (578 m^3) of road base and asphalt were sent to recycling centers or for landfill disposal.

Information regarding trench dimensions and excavation waste volume can be found in Table 4.5.

Figure 4.2: Excavation Waste Generated by R&R Method
(Pictures were taken in public area)

Table 4.5: Solid Waste Generated by Sanitary Sewer Line Removal and Replacement Method

Pipe Number	Trench Characteristics		Excavation volume (yd^3)	Asphalt & road base (yd^3)	Dirt (yd^3)
	Trench Dimensions (ft^3)	Pipe depth (ft)			
1	641	7	20.6	3.7	17
2	4123	7	132.4	24.1	108
3	6081	8	195.3	31.2	164
4	6081	8	195.3	31.2	164
5	1021	16	35.3	2.9	32
6	11344	12	392.2	42.4	350
7	14187	14	490.5	45.6	445
8	7301	9	234.4	33.5	201
9	541	8	17.4	2.8	15
10	10111	12	349.6	37.8	312
11	432	12	13.9	1.5	12
12	9347	11	346.3	40.7	306
13	413	10	13.3	1.7	12
14	517	10	16.6	2.1	14
15	493	12	15.8	1.7	14
16	6248	8	200.6	32.1	169
17	1182	14	43.8	4.1	40
18	5621	9	180.5	25.8	155
19	840	9	27.0	3.9	23
20	479	8	15.4	2.5	13
21	7137	9	229.2	32.7	196
22	7231	9	232.2	33.2	199
23	8006	10	257.1	33.2	224
24	5808	9	186.5	26.6	160
25	750	8	24.1	3.9	20
26	7618	10	244.6	31.6	213
27	467	9	15.0	2.1	13
28	625	8	20.1	3.2	17
29	963	11	38.1	4.5	34
30	207	10	6.6	0.9	6
31	330	7	10.6	1.9	9
32	583	8	18.7	3.0	16
33	208	8	6.7	1.1	6
34	666	8	21.4	3.4	18

(Table Continued)					
35	680	11	23.5	2.8	21
36	125	8	4.0	0.6	3
37	1104	8	35.4	5.7	30
38	6123	8	196.6	31.5	165
39	9376	11	301.0	35.4	266
40	8419	10	270.3	34.9	235
41	4811	8	154.5	24.7	130
42	6164	8	197.9	31.7	166
43	7081	8	227.4	36.4	191
TOTAL (yd^3)			5657.5	756.2	4901

4.2.2 Solid Waste from CIPP Method

In this study, 22 pipes in the basin had the CIPP procedure, which also produces some solid waste. Some of these materials are considered in the plastic group and can be recycled.

Waste generated during 22 CIPP activities was substantially less than that generated by removal and replacement activities. Specifically, CIPP activities did not require asphalt removal. For CIPP activities, approximately 3 yd^3 (2.3 m^3) of waste were generated per each installation for a total of 66 yd^3 (50.4 m^3). In this research, the waste generated during CIPP works included the excess cured resin liner, latex gloves, napkins, plastic wraps, and insulating fabrics (Figure 4.2). Although the amount of waste was slight, the ultimate disposal of this waste was not reported. Furthermore, the application of waste management policies, such as recycling and reusing approaches for the plastic type generated waste, was also not announced.

Figure 4.3: Solid Waste Generated by CIPP Method
(Picture was taken in public area)

4.3 Criteria Air Pollutants and Greenhouse Gas Emissions for Both Methods

To review material from Chapter 3, GHGs and criteria pollutants from heavy equipment usage at job sites during both methods were measured. Air pollutants that are likely emitted by heavy equipment used for R&R constriction activities contain VOCs, CO, SO_x, NO_x, particulate matter of 2.5 and 10-micron size ($PM_{2.5}$, PM_{10}), CO_2, and CH_4. In an effort to calculate these pollutant emissions in this study, the following factors were considered for both techniques:

- On site work days,
- On site heavy equipment type, horsepower, and quantity,
- Daily hours of heavy equipment operation,
- Emission factors for each piece of equipment.

In both methods, the California Air Resources Board's emission factors were used to calculate the quantity of emitted pollutants (South Coast Air Management District 2015). A list of emission factors is provided in Appendix D.

4.3.1 Air Pollutants from R&R Method

In this research, 110 on-site work days were considered for 43 open-cut sites, and emissions calculations were conducted using equation 4-1:

Equation 4-1: Emission (lb) = Total hours of operation × Emission factor (lb/hour)

Table 4.6 shows information concerning equipment type and quantity, operation hours, related emission factors, and the amount of pollutants emitted during R&R activities.

Table 4.6: Calculation of Pollutants Emitted from Equipment Used at R&R Sites

	Equip. list	Air Compressor	Dump truck	Utility truck	Signal board	Mini excavator	Bypass pump	Concrete saw	Crushing machine	Backhoe	Roller	Paver
	Max horsepower	250	500	250	50	120	175	120	250	250	120	120
	Operating hours per day	2	2.5	1	8	1	4	2	1	4	2	2
	Construction days	110	110	110	110	110	110	110	110	110	110	110
	Total onsite operating hours	220	275	110	880	110	440	220	110	440	220	220
	Quantity	1	1	1	1	1	1	1	1	1	1	1
Emission factors (lb/hour)	VOC (ROG)	0.0892	0.1960	0.1252	0.0931	0.0912	0.1158	0.0892	0.1646	0.1082	0.0857	0.1235
	CO	0.2803	0.5949	0.3702	0.3227	0.5102	0.7365	0.4759	0.5171	0.3566	0.4000	0.4969
	NOx	0.9294	1.4165	0.9818	0.3148	0.5787	1.0489	0.6249	1.6355	0.9047	0.5498	0.7477
	SOx	0.0015	0.0027	0.0019	0.0005	0.0009	0.0016	0.0009	0.0028	0.0019	0.0007	0.0008
	PM	0.0286	0.0505	0.0328	0.0243	0.0455	0.0502	0.0486	0.0506	0.0294	0.0454	0.0636
	CO2	131	272	167	36.2	73.6	140	74.1	245	172	59.0	69.2

	(Table Continued)											
	CH4	0.0080	0.0177	0.0113	0.0084	0.0082	0.0104	0.0080	0.0149	0.0098	0.0077	0.0111
Pollutants emitted (lb)	**VOC (ROG)**	19.626	53.889	13.767	81.895	10.033	50.952	19.623	18.107	47.627	18.851	27.180
	CO	61.666	163.598	40.720	284.020	56.120	324.052	104.695	56.882	156.904	87.990	109.310
	NOx	204.463	389.525	107.995	277.011	63.657	461.497	137.467	179.908	398.078	120.947	164.501
	SOx	0.325	0.735	0.206	0.412	0.095	0.694	0.191	0.303	0.850	0.152	0.179
	PM	6.289	13.886	3.605	21.425	5.002	22.083	10.702	5.570	12.920	9.997	13.999
	PM10	6.038	13.331	3.460	20.568	4.802	21.199	10.274	5.347	12.403	9.597	13.439
	PM2.5	5.660	12.498	3.244	19.282	4.502	19.875	9.632	5.013	11.628	8.997	12.599
	CO2	28868.365	74891.813	18319.993	31847.896	8098.540	61654.291	16312.951	26898.573	75564.285	12977.525	15223.207
	CH4	1.771	4.862	1.242	7.389	0.905	4.597	1.771	1.634	4.297	1.701	2.452

ROG = Reactive Organic Gas which is approximately similar to VOC. California Air Resources Board (ARB) defines ROGs as follow (ARB 2009):
Total Organic Gas (TOG) – Exempt compounds (ARB list of methane, CFCs, etc.) = Reactive Organic Gas (ROG)

4.3.2 Air Pollutants from CIPP Method

For CIPP activities, 22 work days were considered and emissions calculated in the same way as the R&R method. Results can be found in Table 4.7.

Table 4.7: Calculation of Pollutants Emitted from Equipment Used at CIPP Sites

	Equip. list	Air Compressor	TV Truck	Utility truck	Jetter truck	Signal board	Generator sets	Refrigerated Truck
	Max horsepower	250	500	250	500	50	500	500
	Operating hours per day	2	8	1	0.5	8	2	4
	Construction days	22	22	22	22	22	22	22
	Total onsite operating hours	44	176	22	11	176	44	88
	Quantity	1	1	1	1	1	1	1
Emission factors (lb/hour)	VOC (ROG)	0.0892	0.1960	0.1252	0.1960	0.0931	0.1556	0.1960
	CO	0.2803	0.5949	0.3702	0.5949	0.3227	0.6639	0.5949
	NOx	0.9294	1.4165	0.9818	1.4165	0.3148	1.9429	1.4165
	SOx	0.0015	0.0027	0.0019	0.0027	0.0005	0.0033	0.0027
	PM	0.0286	0.0505	0.0328	0.0505	0.0243	0.0567	0.0505
	CO2	131	272	167	272	36.2	337	272
	CH4	0.0080	0.0177	0.0113	0.0177	0.0084	0.0140	0.0177
Pollutants emitted (lb)	VOC (ROG)	3.925	34.489	2.753	2.156	16.379	6.845	17.245
	CO	12.333	104.702	8.144	6.544	56.804	29.212	52.351
	NOx	40.893	249.296	21.599	15.581	55.402	85.488	124.648

(Table Continued)							
SOx	0.065	0.470	0.041	0.029	0.082	0.145	0.235
PM	1.258	8.887	0.721	0.555	4.285	2.494	4.444
PM10	1.208	8.532	0.692	0.533	4.114	2.395	4.266
PM2.5	1.132	7.999	0.649	0.500	3.856	2.245	3.999
CO2	5773.673	47930.760	3663.999	2995.673	6369.579	14821.527	23965.380
CH4	0.354	3.112	0.248	0.194	1.478	0.618	1.556

From criteria air pollutant and GHG emission bases, it was concluded that the R&R technique emitted a greater amount of each pollutant than the CIPP operations did. The equipment used in both methods from the point of emission was relatively similar, but pollutant reductions were observed for CIPP activities due to the shorter period of construction duration. As mentioned earlier, CIPP activities were conducted for 22 days and R&R activities were conducted for 110 days. Table 4.8 compares total emissions of each pollutant during both methods.

Table 4.8: Pollutants Total Emission for R&R and CIPP Rehabilitation Activities

Method	**Total Mass of Pollutant Emitted, tons**									
	VOC	**CO**	**NO_x**	**SO_x**	**PM**	**PM_{10}**	**$PM_{2.5}$**	**CO_2**	**CH_4**	**CO_2e**
Replacement	0.181	0.723	1.253	0.002	0.063	0.060	0.056	185.329	0.016	185.736
CIPP	0.042	0.135	0.296	0.001	0.011	0.011	0.010	52.760	0.004	52.855

(CO_2e) is used to compare the emissions from various greenhouse gases on the basis of their global warming potential (GWP) and report the whole amount of GHGs in terms of carbon dioxide. GWP for CH_4 is greater than 25 over 100 years and it means that emissions of 1 part CH_4 is equivalent to emissions of 25 parts carbon dioxide. In this study, emissions from two greenhouse gases (CO_2 and CH_4) were calculated and reported as a CO_2e.

An estimated 187 tons of CO_2 equivalent were generated as a GHG emission from R&R activities, and only 53 tons was estimated for CIPP activities. The main reason for this difference was the longer duration of equipment operation for open-cut activities in contrast to CIPP.

Chapter 5

5. Limitations and Recommendations

This study has limitations, but overall, the results indicate that the chemicals emitted from steam-cured CIPP sewer pipe rehabilitation warrant further study. A follow-up study should be conducted to fully describe chemical emissions during curing and cooling processes and determine if hazards to the CIPP workers and nearby population exist. Real-time air monitoring for styrene and other chemicals should be considered. Monitoring of air in nearby sewer pipes (i.e., laterals) would also provide insight into chemical emissions and migration from CIPP activity. Indoor air monitoring in nearby buildings would also provide insights, but these results would be subject to the condition of the infrastructure where gases would be transported and thus highly variable. Theoretically, styrene gas traveling through a highly degraded lateral with many cracks may enter the surrounding soil pores instead of moving in its entirety towards nearby buildings. In contrast, gas traveling through a sewer pipe lateral without cracks may proceed further towards and possibly into the building. There are many unknowns that must be investigated in order to describe the exact conditions that allow gases to travel from CIPP sites into nearby buildings through the sewer infrastructure. The first step in achieving a comprehensive understanding of chemical emissions would be to better understand chemical emissions at the source.

Two major limitations of this work were that only three CIPP installation sites were monitored, and that simultaneous replicate samples were not collected. The results presented provide an initial step towards understanding the chemical concentration in the air caused by CIPP activity, so additional sampling data should be obtained. These data can provide a better context for interpreting the presented results. Styrene levels detected in the present study indicate a high variability in the concentration of styrene present at each site even when the CIPP formulation, liner type, contractor, pipe size, ambient air temperature, curing and cooling temperatures, manhole depths, installation process, and materials were almost the same. A more thorough and more frequent sampling regime should be applied in a follow-up study. Additional testing is needed to understand the

range of VOC levels present in manholes, in sanitary sewer pipes, and emitted into the work area. Also needed is a better understanding if VOC concentrations in the air differ during the installation processes, which would require a greater air sampling frequency than the present study. Breathing zone (BZ) concentration monitoring is also important, but factors that affect VOC generation by CIPP processes must be understood for BZ results to be interpretable and representative.

Also important is that to date, no organization has fully characterized the chemical steam generated by CIPP activity. In the present study, air was only characterized for 67 VOCs, yet SVOCs can also be released into condensate during CIPP (Tabor et al., 2014). It is unknown if SVOCs would be released in emitted chemical steam. Steam likely contains droplets and gases. Testing should be conducted to explore which factor(s) control chemical emissions and to more fully understand their composition as well as environmental and public health risks. In parallel, characterization of the CIPP generated condensate and hot wastewater could help describe the suite of chemicals emitted by the installation activity.

The increasing need to rehabilitate sanitary sewer infrastructure, the increasing frequency of communities choosing CIPP, and the growing number of indoor air contamination incidents caused by CIPP activities underscores a need to better understand environmental emissions from *in-situ* rehabilitation activities. The results of this study indicate that CIPP chemical emissions may be a health risk to workers and nearby building inhabitants. Additional investigations regarding chemical emissions from CIPP should be commissioned to fill the environmental and public health knowledge gaps. The acute and chronic chemical exposure risks of CIPP chemical steam constituents and styrene to sensitive populations, if found to be significant, should be further examined.

Regarding the issue of waste generation, the results in this study showed that in total, 756 yd^3 (578 m^3) of solid waste were generated during R&R activities, while roughly 66 yd^3 (50.4 m^3) of solid waste were generated during CIPP activities. Waste generation was only considered during onsite construction activity and focused solely on *solid* waste. Liquid and semi-solid wastes were not evaluated in this study. Additional work is needed to more directly compare waste generation from CIPP and R&R procedures and consider waste generation for the entire process. In addition to the amount of the waste, the type and inherent characteristics of the waste are important as well and can greatly affect the selection of handling and management approaches. Styrene spill from excess sections of cured and uncured liners on the job site should be noted because it can complicate the transportation and handling of the waste.

From criteria air pollutants and GHG emission bases, the R&R technique emitted a greater amount of each pollutant than CIPP operations. The reasons for this include the fact that more time is required for construction with the open-cut method compared to in-situ pipeline rehabilitation, which results in a greater amount of emissions related to traffic congestion. The type of equipment utilized in both methods from the point of emission is relatively the same, but pollutant reductions were observed for CIPP activities owing to the shorter period of construction duration. The longer the duration of equipment operation, the greater amount of pollutants emitted.

The second section of this study has the following limitations:

a) Criteria pollutant and GHG emissions during CIPP installation were only estimated to include equipment and vehicle use during the installation period at the work site. Not included in this assessment were emissions generated by the manufacturer to produce the product, the transport of material and resin to and from the worksite, 24-hour refrigeration of the resin, emissions associated with condensate conveyance, or treatment in a wastewater treatment facility, and landfill and recycling center related emissions. Inclusion of this additional

activity would change the results, increasing the amount of pollutants emitted due to CIPP technology. A more life-cycle approach to examining pollutant emissions would result in a more representative comparison of CIPP and excavation pollutant emissions.

b) Some of the data related to work days and operation hours were estimated based on information provided by contractors.

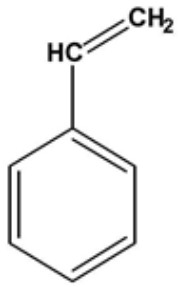
While CIPP is estimated to emit a smaller amount of criteria pollutants and GHGs, the results do not show that CIPP overall produces less GHG and criteria pollutants than the open-cut method. Additional work is needed to monitor pollutant emissions in the field in order to validate the assumptions. Also needed is a greater understanding of emissions within the broader cradle-to-grave life cycle of both methods and of the economic aspect of GHG reduction incentives.

Chapter 6

6. Health Effects

"Air pollution" is used to refer to an array of anthropogenic chemical emissions such as gaseous combustion products, volatile chemicals, aerosols (particle), and their atmospheric reaction products (PSR, 2016). The primary purpose of this chapter is to provide the toxicology and health impacts of styrene, criteria air pollutants, and greenhouse gasses.

6.1 Styrene



Styrene is a colorless liquid that vaporizes quickly. Pure styrene has a sweet smell, although manufactured styrene may consist of aldehydes, which results in a sharp and unpleasant odor. Styrene can be generated naturally by plants, bacteria, and fungi, but the major source of styrene production is anthropogenic. Styrene is extensively used in the plastics and rubber industries. Consumer products, including packaging materials, insulation for electrical uses (i.e., wiring and appliances), insulation for homes, fiberglass, plastic pipes, automobile parts, and drinking cups, contain styrene. Furthermore, some amounts of styrene exist naturally in various consumables such as vegetables, fruits, nuts, meats, and beverages. Figure 6-1 compares the amount of styrene in various foods and the amount of migration from a foam cup to the inside food (ATSDR, 2012).

Styrene can be present in air, soil, and water as a result of manufacturing and industrial activities and the consumption and disposal of styrene-based products. Usually it takes one or two days for styrene to break down in the air. Styrene can enter the air from shallow soils and surface water through the evaporation process. Bacteria and other microorganisms may be responsible for breaking down the remaining styrene in soil or water (ATSDR, 2012).

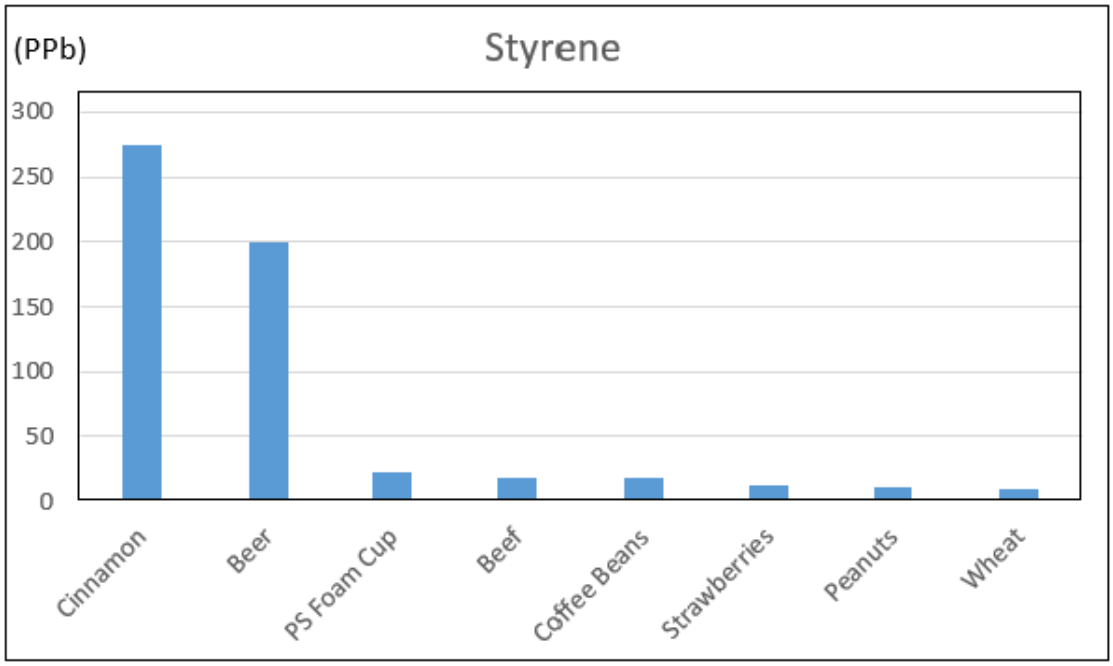


Figure 6.1: Amount of Styrene in Different Foods and Migration from a Foam Cup
(Source: www.foamfacts.com)

The main way that humans are exposed to styrene is inhalation. Commonly, rural and suburban areas contain styrene in lower concentrations than urban areas. Higher levels of styrene can be found in indoor air (0.07 - 11.5 ppb) than in outdoor ambient air (0.06 - 4.6 ppb) (ATSDR, 2012).

Also, drinking or bathing in water containing styrene may expose individuals to this chemical. Ingestion of styrene is also toxic but occurrence of this route of exposure is extremely unlikely in the workplace (ATSDR, 2012).

Many workers who are potentially exposed to styrene work in the reinforced-plastics industry, rubber manufacturing, at styrene-polyester resin facilities, and in photocopy centers. These workers are at risk for inhalation exposure to considerable air concentrations of styrene or dermal exposure to liquid styrene or resins (ATSDR, 2012). Figure 6.2 illustrates the states in the U.S. that have the most styrene-related jobs.

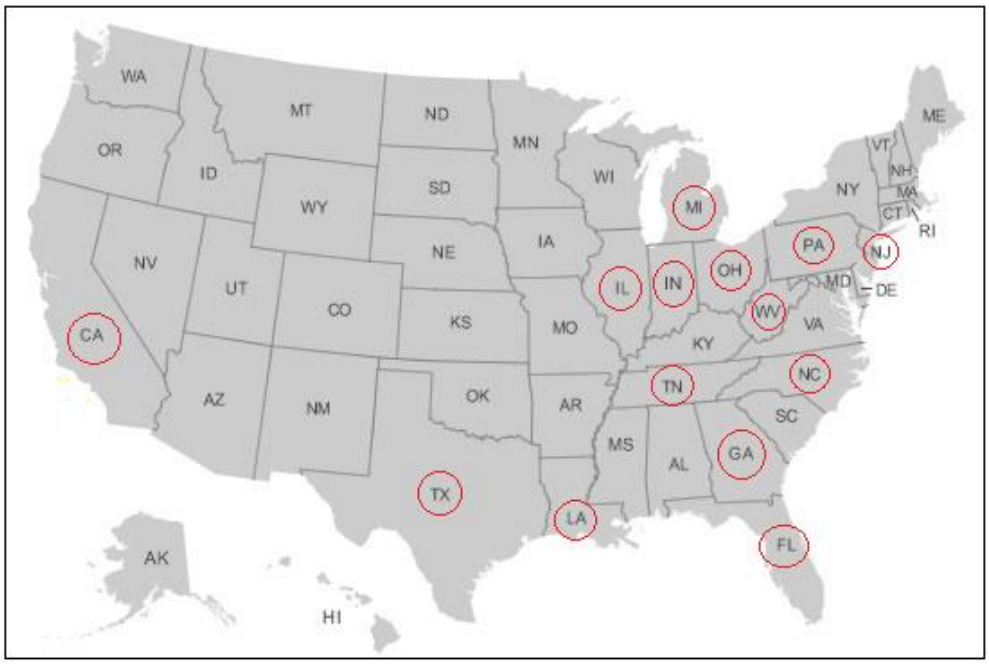


Figure 6.2: U.S. States with the Most Styrene-Related Jobs
(Source: Styrene Information & Research Center)

When styrene enters the human body, it is mostly metabolized into styrene oxide by cytochrome P450 through the hepatic oxidation procedure. Then, styrene oxide is further metabolized into phenylglyoxylic acid, mandelic acid, and hippuric acid, which are excreted in the urine. Styrene oxide is the active metabolite, and is considered toxic, mutagenic, and possibly carcinogenic (Liebman, 1975). The presence of styrene metabolites in urine might be an indication of styrene exposure, but these metabolites can also be created from exposure to other substances. Moderate-to-high concentrations of styrene can be detected and measured in blood, urine, and body tissues only for a short period of time after exposure since these metabolites leave the body rapidly. Ideally, in order to recognize the exposure, medical tests should be performed within a few hours. Actual exposure levels can be estimated by measuring styrene metabolites in urine within one day of exposure (ATSDR, 2012).

Factors that determine the effects of styrene on health include the dose (how much), the duration (how long), and the route of exposure. Laboratory animal studies

reported hearing loss, impaired learning, and sperm damage in animals exposed to high doses of styrene. Also, animal studies showed that changes in the lining of the nose and damage to the liver occurred in cases of styrene inhalation. However, the greater sensitivity of animals in the nose lining and liver may indicate that effects on them may be more significant than in humans (ATSDR, 2012).

The most common health impacts on workers exposed to styrene are related to nervous system dysfunction. These health problems include changes in color vision, fatigue, feeling drunk, slowed reaction time, decreased concentration, and balance problems (ATSDR, 2012).

Respiratory effects include mucous membrane irritation, increased nasal secretion, wheezing and coughing, and eye irritation. Gastrointestinal effects have also been reported from acute exposure to styrene in humans. Chronic exposure to styrene in humans mostly affects the central nervous system with symptoms such as headache, depression, weakness, peripheral neuropathy, intellectual dysfunction, minor effects on some kidney enzyme functions, and short term memory impairment (DHHS 1993; EPA 2000; ATSDR 2012).

In addition, long term exposure can alter liver function, electrocardiogram (ECG) results, psychological performance, and contribute to occupational asthma. Repeated or prolonged dermal exposure to styrene in liquid or vapor form can produce persisting itching and erythematous papular dermatitis. (ATSDR 2012; CCOHS 1994).

The Reference Concentration (RfC) is an estimate of the result of continuous inhalation exposure to the human population including sensitive subgroups, which is presumably without noticeable risk of non-cancer health effects during a lifetime. The RfC for styrene is 1 milligram per cubic meter (mg/m^3) according to studies of central nervous system (CNS) effects in workers with occupational exposure. Exposures greater than RfC increase the potential adverse health effects (EPA, 2000).

Reproductive and developmental effects of styrene on humans are unknown, and studies are inconclusive. Some studies reported no developmental effects in women who worked in the plastics industry, while an increased frequency of spontaneous abortions and decreased frequency of births were observed in another study. There have been no research studies to date evaluating the effects of styrene exposure on children or immature animals. There is a possibility that children would show the same health effects as adults. It is unknown whether children would be more susceptible than adults to the effects of styrene (ATSDR, 2012).

An association between styrene exposure and an increased risk of leukemia and lymphoma have been suggested in several epidemiologic studies, but the evidence is not sufficient, and the result is inconclusive. The EPA has not officially included styrene in its list of carcinogens (EPA, 2000).

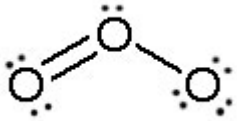
Based on limited evidence of carcinogenicity from studies in humans, adequate evidence of carcinogenicity in experimental animals, and data on mechanisms of carcinogenesis, the United States Department of Health and Human Services' National Toxicology Program listed styrene as "reasonably anticipated to be a human carcinogen" (NTP, 2014).

The International Agency for Research on Cancer (IARC) has announced that there is limited evidence in humans for the carcinogenicity of styrene, and has determined that styrene is a possible carcinogenic to humans (group 2B) (IARC, 1994).

6.2 Criteria Air Pollutants

The Environmental Protection Agency (EPA) has established National Ambient Air Quality Standards (NAAQS) under authority of the Clean Air Act (CAA). The NAAQS has singled out six principal pollutants (criteria pollutants) which are considered harmful to public health and the environment. These pollutants come from a variety of sources and are commonly found in outdoor air. Criteria air pollutants include ozone (O3) ground-level carbon monoxide (CO), nitrogen dioxide (NO2), particulate matter (PM), sulfur dioxide (SO2), and lead (EPA, 2016).

6.2.1 Ozone (O_3)



Ozone is a colorless gas that forms as a result of a complex series of chemical reactions between volatile organic compounds (VOCs), nitrogen oxides, and oxygen in the presence of solar ultraviolet (UV) irradiation (heat and sunlight). Ozone can be found in motor vehicles, electric utilities, landfills, industrial solvents, gas stations, lawn equipment, etc. Exposure to ozone can cause upper and lower respiratory irritative symptoms including coughing, wheezing, shortness of breath and chest tightness, restrictive and obstructive spirometric changes, and increased responsiveness to methacholine and allergen bronchoprovocation. Some epidemiological studies reported the association between ozone and hospitalization for people with asthma and respiratory disease. Asthmatic children playing outdoors in high ozone concentration areas are approximately 20% to 40% more likely to suffer an asthmatic exacerbation. Animal studies observed an increase in susceptibility to bacterial infection, which can impair the macrophage function. Some other evidence supports increased daily mortality rates related to ozone exposure. Ozone is a very strong oxidant which reacts with biomolecules to produce ozonides, then free radicals. This initiates the inflammatory response by releasing cytokines such as prostaglandins (PGE2, PGF2, TXB2), neutrophils, fibronectin, interleukin-6, lactate dehydrogenase, elastase, plasminogen activator, coagulation factors, and other proteins, which lead to increased airway

permeability. Certain studies reported lung scarring, especially at the bronchoalveolar junction (DES 2012; PSR 2016).

6.2.2 Carbon Monoxide (CO)

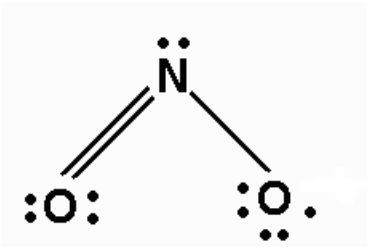
Carbon monoxide is an odorless and colorless gas which comes from incomplete fossil fuel combustion. It can be found near motor vehicles, boilers and incinerators, in parking garages, poorly ventilated tunnels, and traffic intersections, particularly during peak hours (DES, 2012).

Carbon monoxide causes a decrease in the oxygen carrying capacity of blood by attaching to the hemoglobin, creating a stable complex called carboxyhemoglobin. This decreases the hemoglobin available to transport oxygen to the tissues, causing hypoxemia and tissue hypoxia which can affect different organs in the body. Low level exposure may cause headache, fatigue, and flu-like symptoms, particularly in smokers and those with coronary artery disease (CAD), peripheral vascular disease, and chronic obstructive pulmonary disease (COPD) (PSR, 2016).

Carbon monoxide can cause adverse cardiac effects such as reductions in exercise capacity, and arrhythmias can occur in individuals with CAD. COPD sufferers experience a decrease in ventilatory elimination of CO, and they experience earlier symptoms and reductions in exercise tolerance. In addition, clinical manifestations of CO in the nervous system include changes in visual and auditory perception, psychomotor function, dexterity, vigilance, and time interval discrimination (PSR, 2016).

Epidemiologic studies have reported an association between ambient CO exposure and hospitalization for cardiovascular disease and congestive heart failure. Limitations of these studies include poor individual exposure evaluation and confounding co-pollutants. Nevertheless, these associations have been observed in several cities, even in instances of very low concentrations of CO exposure (PSR, 2016).

6.2.3 Nitrogen Dioxide (NO_2)



Nitrogen dioxide is a brownish gas which forms from burning fuel at high temperatures. It participates in the formation of ground-level ozone and fine particle pollution. The sources of this gas include motor vehicles, electric utilities, off-road equipment, and industrial boilers. Transportation and deposition of nitrogen dioxide can negatively affect terrestrial and aquatic ecosystems. This gas causes lung damage and predisposes to respiratory infections such as influenza. Lower concentrations of NO_2 impair mucociliary clearance, facilitate particle transport, and macrophage and local immunity dysfunction. Exposure to around 30 ppb has been associated with hyper reactivity of airways, and even lower concentrations (15 ppb) may cause stuffy nose and cough. Very high concentrations (more than 200 ppm) have significant adverse effects and result in lung injury, fatal pulmonary edema, and bronchopneumonia. Moderate exposure to 260 ppb (0.260 ppm or 0.490 mg/m3) for a duration of 30 minutes, results in the enhancement of nonspecific hyper-reactivity. Great increases in acute respiratory infections, sore throats, and colds have been reported in levels of about 80 ppb (DES 2012; PSR 2016).

Animal studies detected increased mortality due to microbial pathogen exposure. In humans, exposure between 2 to 5 ppm for a period of 3 hours led to airway inflammation and higher levels of antigen-specific serum IgE, local IgA, IgG, and IgE antibody (PSR 2016).

6.2.4 Particulate Matter (PM)

Particulate matter is a heterogeneous classification of solid particles and liquid droplets in the air. It is formed from windblown dust, transportation, crushing, grinding, unpaved roads and construction, high temperature industrial processes, fuel combustion, wood stoves, and plowing (DES, 2012). Figure 6.3 compares diameter size of PM, human hair, and beach sand.

Exposure to PM may cause irritation of the eye, nose or throat, asthma exacerbation, arrhythmia, and premature death in people with underlying heart or lung disease. Particles in smaller sizes (usually less than 3 micron) encompass viruses and some bacteria and are produced from anthropogenic activities containing sulfate and nitrate aerosols and other combustion-derived atmospheric reaction products. Particles in larger sizes (3 to 30 micron) include pollen, spores, crustal dusts, and other mechanically generated dusts. The size of particles plays a major role in their deposition in target organs. Larger particles mostly deposit in the nasal and tracheobronchial regions, while smaller ones penetrate deeper into the lungs (PSR, 2016).

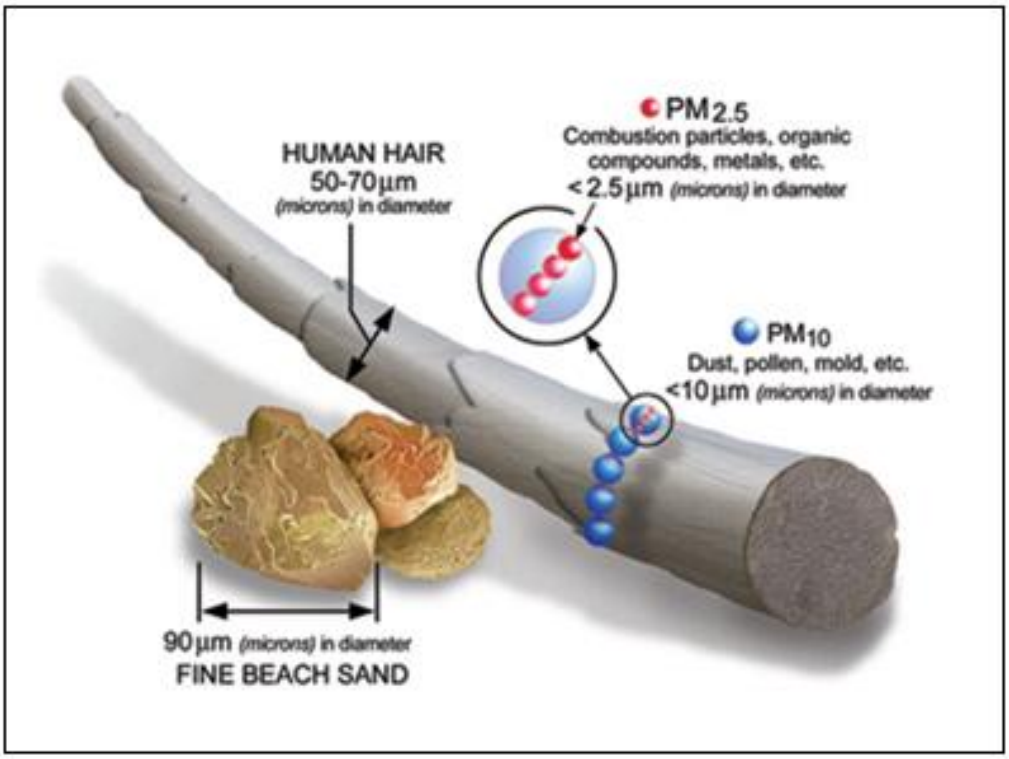


Figure 6.3: Particulate Matters Size in Comparison with Human Hair and Beach Sand
(Source: U.S. EPA, http://www3.epa.gov/pm/basic.html)

The size of the particles and the structural and functional characteristics of the airways affect the particles' airway distribution, and apparently their health impacts. Most smaller particles travel and can access the pulmonary system, and almost all particles greater than 10 microns are trapped in the upper airways by mucociliary mechanisms (Figure 6.4). A greater distal airway deposition of particles can occur in individuals with obstructive pulmonary disease, including smokers, asthmatics, and patients with small airway disease or COPD (PSR, 2016).

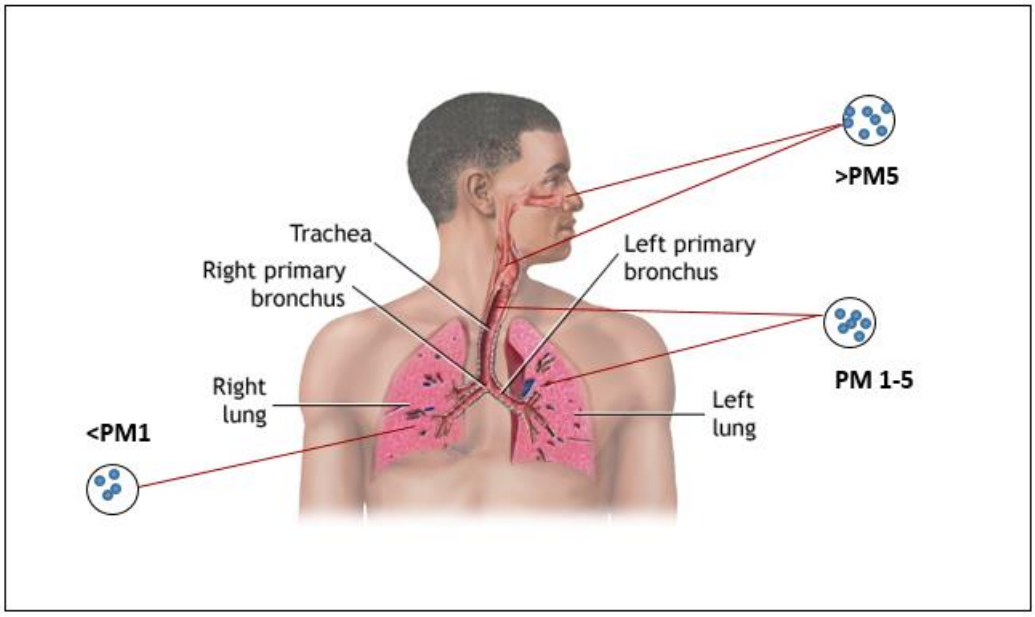
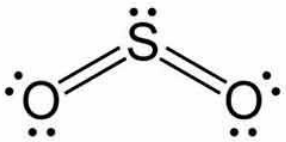


Figure 6.4: Deposition of Particulate Matter in Respiratory System
(Source: Alen Pure Air Corporation http://www.alencorp.com/ and www.nlm.nih.gov)

Respiratory illnesses, pulmonary dysfunction, increased asthma medication use, increased hospitalization, increased cardiac and respiratory mortality, asthma exacerbations, and COPD have been reported for particulate exposure. Elderly individuals (65 years and over), and persons with chronic heart and lung diseases are at particular risk of acute illnesses. Chronic particulate pollution can cause respiratory disorders such as bronchitis, COPD, asthma exacerbations, decreased longevity, and lung cancer. Recent epidemiologic studies have focused on determining the size specificity of health effects, and have implicated the gasses and smaller particles as the more relevant

components of hazardous particulate exposure. The National Research Council has requested more research on the toxicology profile of the particulate chemical components and the association between monitored community exposures and personal exposure (PSR, 2016).

6.2.5 Sulfur Dioxide (SO2)



Sulfur dioxide is a colorless and odorless gas (at low concentrations) forming from burning of fuel containing sulfur in industrial activities. Sulfur dioxide is converted to H2SO4, an acid aerosol, in the atmosphere. The health effects of SO2 come from this substance. High concentrations of SO2 can affect the cardiovascular and respiratory systems resulting in respiratory distress, chronic obstructive lung disease, asthma exacerbation, and worsening of existing cardiovascular disease in susceptible people such as children, the elderly, and people with asthma, COPD, or cardiovascular disease. The odor threshold is about 0.5 ppm, and 6 - 10 ppm causes irritation of the eyes, nose, and throat. At concentrations as low as 0.25 ppm asthma exacerbations in some exercising asthmatics have been observed. Furthermore, acidification of lakes and streams, accelerated corrosion of buildings, and reduced visibility have been reported in studies (PSR 2016; DES 2012).

6.2.6 Lead

Lead exposure can occur in different work settings, such as the manufacturing or use of batteries, ammunition, paint, car radiators, cable and wires, certain cosmetics, ceramic ware with lead glazes, and tin cans. Moreover, coal combustion, smelters, car battery plants, transportation sources using lead in their fuel, and waste containing lead products are recognized as sources associated with lead pollution (ATSDR, 2007).

Inorganic lead is absorbed by the lungs or gastrointestinal tract. In adults, the respiratory tract is the most significant route of entry for lead absorption. Activities such as scraping/sanding/burning leaded paint from surfaces can expose the individuals to

lead. Organic (tetraethyl) lead that is found in gasoline can be absorbed via the skin (Fischbein and Hu, 2007).

Once absorbed, lead is then distributed to the blood, soft tissues, and skeleton (Rabinowitz, 1991). Lead can affect the hematologic system by disrupting the hemoglobin synthesis causing the production of free erythrocyte protoporphyrins. As a result, anemia can develop at very high blood lead levels (usually greater than 80 ug/dL) (Valentine et al., 1976).

Acute exposure to lead can affect the gastrointestinal tract causing abdominal pain and constipation. Neurologic manifestations include headache, deficit in short term memory, difficulty concentrating, confusion, seizures, encephalopathy, and peripheral neuropathy which results in wrist/ankle drop. It can also cause nephrotoxicity (Cullen et al., 1983; Friedman et al., 2014). There is also an association between bone lead level and blood pressure, and bone lead level is considered an independent risk factor for the development of hypertension (Hu et. al, 1996; Korrick, 1999).

Chronic lead exposure can result in neuropsychiatric symptoms such as anxiety, depression, and hostility (Rajan et al., 2007; Eum et al., 2012) and lead exposure at low levels may be associated with an increased risk of cataracts, hearing loss, and tooth loss (Park et al., 2010; Schaumberg et al., 2004; Arora et al., 2009).

Some studies have shown that men with chronic lead exposure, have increased sperm abnormality manifested as abnormal morphology, decreased sperm concentration, and decreased total sperm count (Lancranjan et al., 1975; Alexander et al., 1996; Robins et al., 1997). High lead exposure in pregnant women can result in miscarriages, stillbirths, and preterm delivery. It can also cause neurodevelopmental disorders in offspring from the mother's exposure during the first trimester of pregnancy (Fischbein and Hu 2007; Taylor et al., 2015; Hu et al., 2006).

The National Toxicology Program of the U.S. Department of Health and Human Services classifies lead as a probable human carcinogen (NTP, 2011). The following picture demonstrates the health effects and target organs of all discussed pollutants.

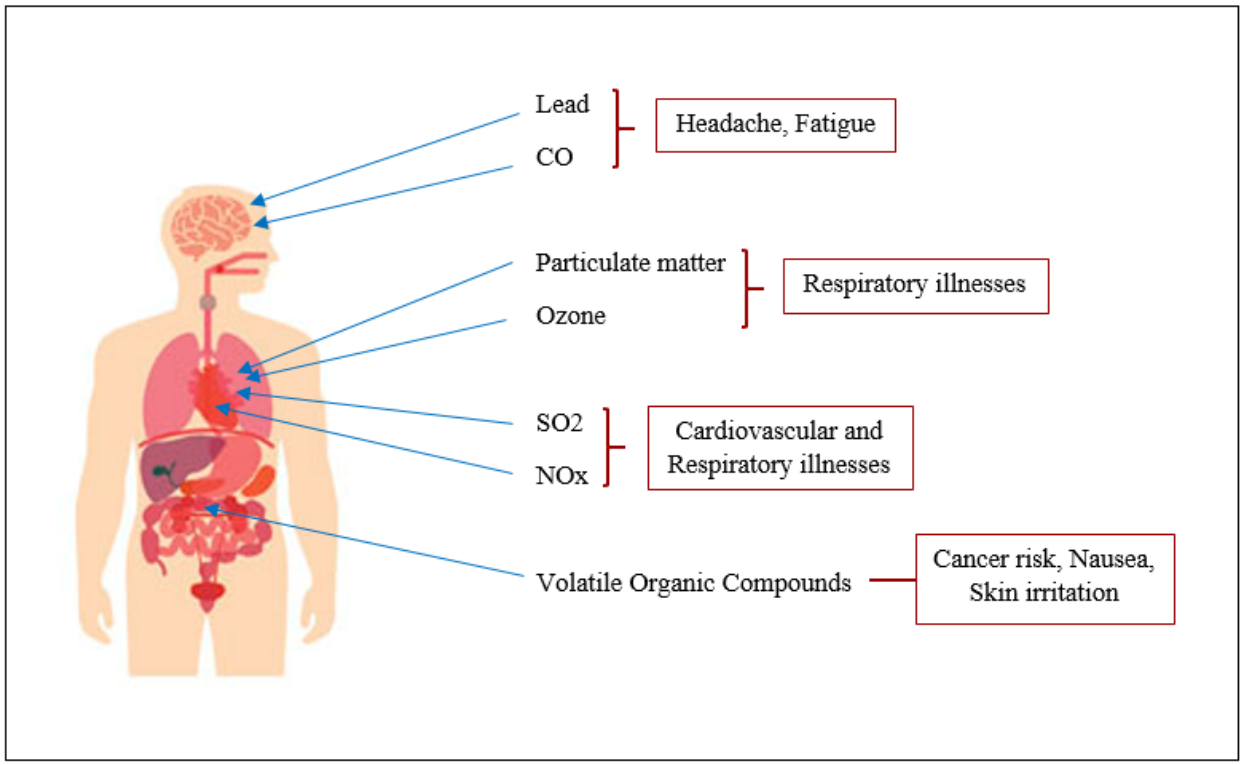


Figure 6.5: Health Effects and Target Organs of Common Pollutants
(Source: Mikael Haggstrom, Medical Gallery of Mikael Haggstrom, Wikiversity Journal of Medicine)

6.3 Greenhouse Gases (GHGs)

Climate change can affect human health through the following mechanisms:

1- An increase in average temperatures can directly deteriorate human health. Heat waves and hot extremes can occur due to increased temperature.

2- Changes in the frequency and severity of weather events such as hurricanes and severe floods can cause harm to human health.

3- Higher temperatures may enhance the risk of certain infectious diseases that appear in warm regions and are spread by mosquitoes and insects, such as malaria, dengue fever, encephalitis, and yellow fever (EPA, 2016).

4- Higher temperatures may also increase the frequency of warm-induced smog (ground-level ozone) events and particulate air pollution. Ozone is formed in higher temperatures with sunlight and a stable air mass. It is the primary ingredient of smog. This reactive gas can damage the lung tissue through chemical reactions. According to the EPA studies, global warming will probably cause an increase in peak ozone levels (American Lung Association of California, 2004). The following picture displays the impact of climate change on human health.

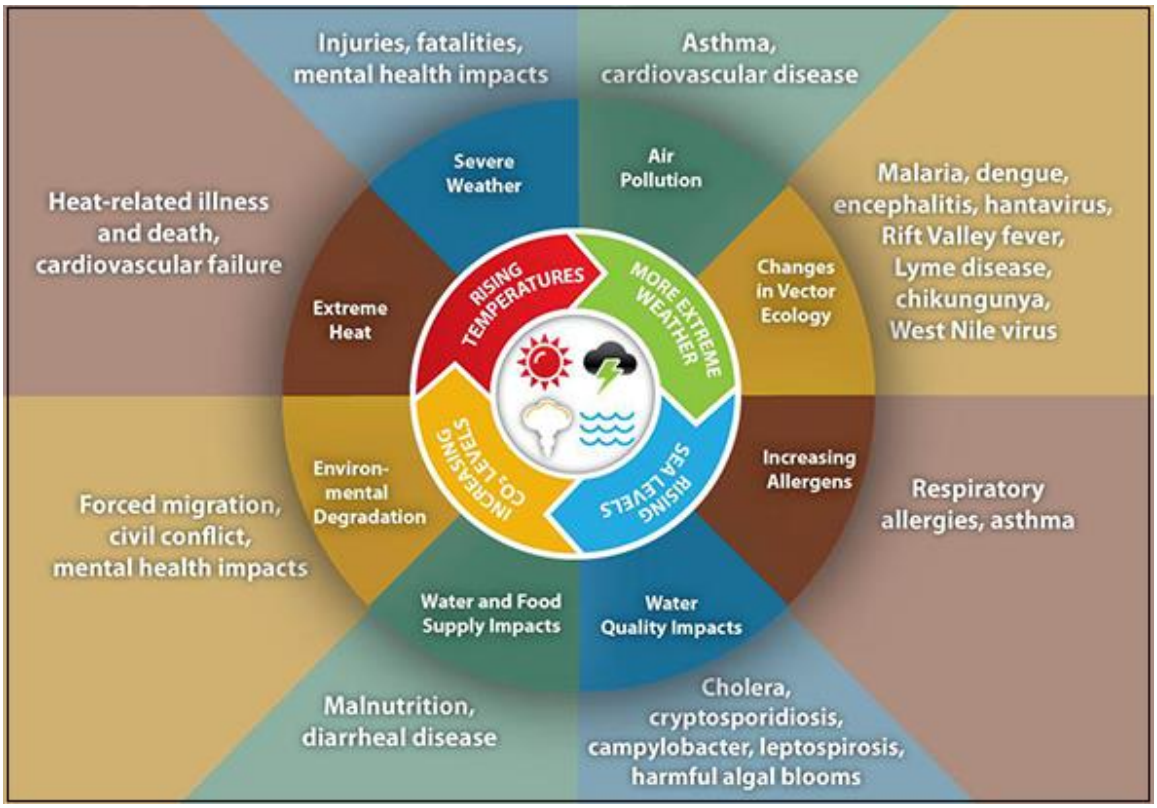


Figure 6.6: Incidents and Illnesses Associated with Global Warming
(Source: Centers for Disease Control and Prevention, http://www.cdc.gov/climateandhealth/effects/)

References

Alen Pure Air Corporation, http://www.alencorp.com/

Alexander BH, Checkoway H, van Netten C, et al. Semen quality of men employed at a lead smelter. Occup Environ Med, 1996

Allouche, E.; Alam, S.; Simicevic, J.; Sterling, R. A Retrospective Evaluation of Cured-in-Place Pipe (CIPP) Used in Municipal Gravity Sewers, *Environmental Protection Agency, Trenchless Technology Center at Louisiana Tech University, Battelle Memorial Institute, Jason Consultants, Inc*., New Jersey and Ohio, 2012

Alltech Associates, Inc., Quantitation Methods in Gas Chromatography, *GC Education*, 1998

ALS Environmental Lab, Formerly Columbia Analytical Services, Inc. Houston, TX, Accessed December 2015
http://www.caslab.com/Method_Reporting_Limit_MRL_Meaning/

American Lung Association of California, Air Quality and Health Impacts of Greenhouse Gas Emissions and Global Warming, Fact Sheet, 2004
http://www.dnrec.delaware.gov/dwhs/Info/Regs/Documents/alac_impacts_fs.pdf

AOC, LLC. *Material Safety Data Sheet: Vinyl Ester Resin.* Collierville, TN, USA, 2000

AOC, LLC. *Vipel Vinyl Ester Based Resin for Underground Sewer Pipe Liners*. Collierville, TN, USA, 2009

Arora M, Weuve J, Weisskopf MG, et al. Cumulative lead exposure and tooth loss in men: the normative aging study. Environ Health Perspect 2009

ATSDR (Agency for Toxic Substances & Disease Registry), Public Health Statement for Styrene, 2012 http://www.atsdr.cdc.gov/PHS/PHS.asp?id=419&tid=74

ATSDR (Agency for Toxic Substances & Disease Registry), *Styrene, Toxic Substances*, 2011 http://www.atsdr.cdc.gov/substances/toxsubstance.asp?toxid=74

ATSDR, Toxicological Profile for Lead. US Department of Health & Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry, Atlanta, GA 2007 http://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=96&tid=22

California Environmental Protection Agency, Air Resources Board, The Federal Clean Air Act, Accessed November 2015 http://www.arb.ca.gov/fcaa/fcaa.htm

Caltrans Division of Research and Innovation, Preliminary Investigation, Environmental Effects of Cured-in-Place Pipe Repairs, *Produced by CTC & Associates LLC*, August 2012

CCOHS (Canadian Centre for Occupational Health and Safety Styrene), Cheminfo, 1994

Centre for Radiation, Chemical and Environmental Hazards (CREC), *Log of CIPP Incident, Birmingham*, UK, March 2012

Chasteen, T. Coupling Gas Chromatography to Mass Spectrometry, *Department of Chemistry, Sam Houston State University*, Huntsville, Texas, Accessed January 2016 http://www.shsu.edu/chm_tgc/primers/gcms.html

Cullen MR, Robins JM, Eskenazi B. Adult inorganic lead intoxication: presentation of 31 new cases and a review of recent advances in the literature. *Medicine*, Baltimore, 1983

Department of Health and Human Services, Agency for Toxic Substances and Disease Registry, Division of Health Assessment and Consultation. *Health Consultation, Schlitz Park Office Building, Milwaukee, Milwaukee County, Wisconsin.* Atlanta, GA, September 13, 2005

DES (New Hampshire Department of Environmental Services), Environmental Fact Sheet, 2012 http://des.nh.gov/organization/commissioner/pip/factsheets/ard/documents/ard-41.pdf

DHHS (U.S. Department of Health and Human Services), Registry of Toxic Effects of Chemical Substances, National Toxicology Information Program, National Library of Medicine, Bethesda, MD, 1993

Donaldson B., Water Quality Implications of Culvert Repair Options: Vinyl Ester Based and Ultraviolet Cured-in-Place Pipe Liners, *Virginia Center for Transportation Innovation & Research*, Virginia, 2012

Donaldson, B. Environmental Implications of Cured-in-Place Pipe Rehabilitation Technology, *Virginia Transportation Research Council: Journal of the Transportation Research Board*, 2009

Donaldson, B.; Wallingford, ED. Creating Environmentally Sound Specifications for Culvert Rehabilitation. *Virginia applies Findings for Cured-in-Place Pipe Repair*. Virginia, 2010

Douglas, F. GC/MS Analysis, *Scientific Testimony, An Online Journal*, Accessed January 2016 http://www.scientific.org/tutorials/articles/gcms.html

Electronic Code of Federal Regulations (e-CFR), *Title 40: Protection of Environment, Chapter 1, Subchapter C, Part 51, Subpart F, §51.100 Definitions. (S) Volatile Organic* Compounds
http://www.ecfr.gov/cgi-bin/text-idx?SID=8d8a879c9aff7b2279245d89b062646b&mc=true&node=se40.2.51_1100&rgn=div8

Environmental Sampling Supply Inc. (ESS), San Leandro, CA

Eum KD, Korrick SA, Weuve J, et al. Relation of cumulative low-level lead exposure to depressive and phobic anxiety symptom scores in middle-age and elderly women. Environ Health Perspect, 2012

Fischbein A, Hu H. Occupational and environmental exposure to lead. In: Environmental and Occupational Medicine, Rom WN, Markowitz SB (Eds), Lippincott Williams & Wilkins, Philadelphia, 2007

Florida Department of Environmental Protection, *Laboratory Data MDLs/PQLs, Pretreatment Program*, March 2009

Friedman LS, Simmons LH, Goldman RH, Sohani AR. Case records of the Massachusetts General Hospital. Case 12-2014. A 59-year-old man with fatigue, abdominal pain, anemia, and abnormal liver function. N Engl J Med, 2014

Gabriel, L. Service Life of Drainage Pipes, Chapter 6: Installation and Construction, *California State University, Sacramento*, 1998

Heinselman, W. The History of Cured-in-Place-Pipe Lining in the United States, *Express Sewer & Drain*, 2012 http://www.expresssewer.com/blog/bid/242423/The-History-Of-Cured-in-Place-Pipe-Lining-in-the-United-States

Herwijnen, R.; Vos, J. Environmental Risk Limits for Styrene, *National Institute for Public Health and the Environment, Ministry of Health, welfare and sport (**RIVM**)*, The Netherland, 2009
http://www.rivm.nl/dsresource?objectid=rivmp:16026&type=org&disposition=inline&ns_nc=1

History of Sanitary Sewers website, Sponsored by Arizona Water Association, NASSCO, and Collection Systems Committee of the Water Environment Federation. Accessed January 2016 http://www.sewerhistory.org

Hu H, Aro A, Payton M, et al. The relationship of bone and blood lead to hypertension. The Normative Aging Study. JAMA, 1996

Hu H, Téllez-Rojo MM, Bellinger D, et al. Fetal lead exposure at each stage of pregnancy as a predictor of infant mental development. Environ Health Perspect, 2006

IAPMO (International Association of Plumbing and Mechanical Officials), Uniform Plumbing Code, 2015

IARC (International Agency for Research on Cancer), Styrene, *IARC MONOGRAPHS VOLUME 82, 1994* http://monographs.iarc.fr/ENG/Monographs/vol82/mono82-9.pdf

IPC (International Plumbing Code), 1st Edition. International Code Council, 2015
Jung, YJ.; Sinha SK. Evaluation of Trenchless Technology Methods for Municipal Infrastructure System, *Journal of Infrastructure Systems*, USA, 2007

Klee, M. GC Solutions #20: Calibration Curves – Part 2, Internal Standard Approach, *Separation Science*, Accessed December 2015
http://www.sepscience.com/Techniques/GC/Articles/189-/GC-Solutions-20-Calibration-Curves--Part-2-Internal-Standard-Approach?pageNo=1

Korrick SA, Hunter DJ, Rotnitzky A, et al. Lead and hypertension in a sample of middle-aged women. Am J Public Health, 1999

Kozman, DP. Evaluation of Cured-in-Place Pipe Allows Structural Renewal of Drinking Water Pipe, *R S Technik LLC*, USA, 2013.

Laboratory Connection Services (LCS) Inc. Ontario, Canada, Accessed December 2015 http://www.labconserv.com/about_lcs/

Lancranjan I, Popescu HI, GAvănescu O, et al. Reproductive ability of workmen occupationally exposed to lead. Arch Environ Health, 1975

Liebman, K. Metabolism and toxicity of styrene, *Environmental Health Perspectives*, 1975
Lubrizol Corporation, Ohio, USA https://www.lubrizol.com/

Matthews, J.; Condit, W.; Wensink, R.; Lewis, G. Performance Evaluation of Innovative Water Main Rehabilitation Cured-in-Place Pipe Lining Product in Cleveland, Ohio, *Battelle Memorial Institute, EPA (Environmental Protection Agency).* NJ and OH, 2012. http://nepis.epa.gov/Adobe/PDF/P100DZL3.PDF

McCarthy, J.; Copeland, C.; Parker, L.; Schierow, L. Clean Air Act: A Summary of the Act and Its Major Requirements, *Congressional Research Service*, January 2011

Minnesota Department of Health, *Volatile Organic Compounds in Your Home*, Accessed January 2016 http://www.health.state.mn.us/divs/eh/indoorair/voc/

Najafi, M. Pipeline Rehabilitation Systems for Service Life Extension-Chapter 10, *University of Texas at Arlington*, USA, 2011

National Association of Sewer Service Companies (NASSCO), Guideline for the Use and Handling of Styrenated Resins in Cured-in-place-Pipe, September, 2008

National Centers for Environmental Information (NOAA), Greenhouse Gases, Introduction: What Are Greenhouse Gases, Accessed January 2016 https://www.ncdc.noaa.gov/monitoring-references/faq/greenhouse-gases.php

National Toxicology Program, US Dept of Health and Human Services. 12th Report on Carcinogens, Lead and Lead Compounds (CAS No. 7439-92-1 (Lead)), 2011

NIH, US National Library of Medicine, Toxicology data network http://toxnet.nlm.nih.gov/cgi-bin/sis/search2/f?./temp/~cW94vz:1

NTP (National Toxicology Program), *Report on Carcinogens, Thirteenth Edition*. Research Triangle Park, NC: U.S. Department of Health and Human Services, Public Health, 2014 http://ntp.niehs.nih.gov/pubhealth/roc/roc13/

Occupational Safety and Health Administration (OSHA), SIC Division Structure, Accessed January 2016 https://www.osha.gov/pls/imis/sic_manual.html

OSHA, United States Department of Labor, *Styrene*, Accessed September 2015 https://www.osha.gov/dts/chemicalsampling/data/CH_268200.html

Park SK, Elmarsafawy S, Mukherjee B, et al. Cumulative lead exposure and age-related hearing loss: the VA Normative Aging Study. Hear Res, 2010

Poe, D. Quantitative Analysis Laboratory, Chemistry 2223 Home Page, *Department of Chemistry, University of Minnesota Duluth*, Accessed December 2015 http://www.d.umn.edu/~dpoe/index.htm

PSR (Physicians for Social Responsibility), Dickey, J. Air Pollution and Primary Care Medicine, Massachusetts, Accessed January 2016 http://www.psr.org/chapters/boston/health-and-environment/air-pollution-and-primary.html

Rabinowitz MB. Toxicokinetics of bone lead. *Environ Health Perspect*, 1991

Rajan P, Kelsey KT, Schwartz JD, et al. Lead burden and psychiatric symptoms and the modifying influence of the delta-aminolevulinic acid dehydratase (ALAD) polymorphism: the VA Normative Aging Study. Am J Epidemiol, 2007

Ren, D.; Smith, J. Evaluation of Environmental Impacts of Two Common Restoration Methodologies for Pipes that Convey Stormwater Runoff, *Bulletin of Environmental Contamination and Toxicology*, 2012

Restek Corporation, Optimizing the Analysis of Volatile Organic Compounds, *Technical Guide*, 2003

Robins TG, Bornman MS, Ehrlich RI, et al. Semen quality and fertility of men employed in a South African lead acid battery plant. Am J Ind Med, 1997

Salem, O.; Najafi, M.: Use of Trenchless Technologies for a Comprehensive Asset Management of Culverts and Drainage Structures, *Midwest Regional University Transportation Center, University of Wisconsin*, Madison, Ohio and Texas, USA, 2008

Schaumberg DA, Mendes F, Balaram M, et al. Accumulated lead exposure and risk of age-related cataract in men. JAMA, 2004

Shrivastava, A.; Gupta, V. Methods for the determination of limit of detection and limit of quantitation of the analytical methods, *Department of Pharmaceutical Analysis, B. R. Nahata College of Pharmacy*, India, 2011

South Coast Air Management District (AQMD), Off-Road-Model Mobile Source Emission Factors, Accessed December 2015
http://www.aqmd.gov/home/regulations/ceqa/air-quality-analysis-handbook/off-road-mobile-source-emission-factors

Tabor, M.; Newman, D.; Whelton, A. Stormwater Chemical Contamination Caused by Cured-in-Place Pipe (CIPP) Infrastructure Rehabilitation Activities, *Environmental Science & Technology*, 2014

Tafuri, A.; Selvakumar, A.Wastewater Collection System Infrastructure Research Needs in the USA, *Urban Water*, USA, 2001

Tafuri, AN.; Selvakumar, A. Wastewater Collection System Infrastructure Research Needs in the USA, *Urban Water*, USA, 2001

Taylor CM, Golding J, Emond AM. Adverse effects of maternal lead levels on birth outcomes in the ALSPAC study: a prospective birth cohort study. BJOG, 2015

TBL Performance Plastics Company, New Jersey, USA http://www.tblplastics.com/
TOXNET. International Toxicity Estimates for Risk (ITER). Accessed December 2015

U.S. Energy Information Administration (EIA), EIA Brochures, What Are Greenhouse Gases, Last Modified 2004, Accessed October 2015
http://www.eia.gov/oiaf/1605/ggccebro/chapter1.html

U.S. Geological Survey (USGS), Oblinger Childress, C.; Foreman, W.; Connor, B.; Maloney, T. New Reporting Procedures Based on Long-Term Method Detection Levels and Some Considerations for Interpretations of Water-Quality Data Provided by the U.S. Geological Survey National Water Quality Laboratory, Virginia, 1999

USEPA, Air Trends, Air Quality Trends, Accessed November 2015
http://www3.epa.gov/airtrends/aqtrends.html#comparison

USEPA, *Clean Watersheds Needs Survey, 2012 Report to Congress, EPA-830-R-15005*, January 2016

USEPA, Hydrogen Sulfide Corrosion in Wastewater Collection and Treatment Systems, *Report to Congress, Technical Report*, 1991

USEPA, Indoor Air Quality, *Technical Overview of Volatile Organic Compounds, General Definition and Classification*, Accessed October 2015 http://www.epa.gov/indoor-air-quality-iaq/technical-overview-volatile-organic-compounds#2

USEPA, Method 8260B, *Volatile Organic Compounds by Gas Chromatography/Mass Spectrometry (GC/MS)*, Revision 2, December 1996

USEPA, National Center for Environmental Assessment, Integrated Risk Information System (IRIS), Chemical Assessment Summary, Styrene, CASRN 100-42-5, 1987 http://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/0104_summary.pdf

USEPA, Particulate Matter (PM), Basic Information, Accessed January 2016
http://www3.epa.gov/pm/basic.html

USEPA, Six Common Air Pollutants, What Are the Six Common Air Pollutants, Accessed November 2015 http://www3.epa.gov/airquality/urbanair/

USEPA, State and Local Climate and Energy Program, Health Impacts Associated with Climate Change, Accessed January 2016
http://www3.epa.gov/statelocalclimate/state/topics/health.html

USEPA, Swift J., Method Detection Limit (MDL) Development and Standardization, *Eastern Research Group*, National Ambient Air Monitoring Conference, Nashville, TN, 2009 https://www3.epa.gov/ttnamti1/files/2009conference/swift.pdf

USEPA, Technology Transfer Network - Air Toxics Web Site, Styrene, 100-42-5, Revised in January 2000 https://www3.epa.gov/airtoxics/hlthef/styrene.html

USEPA, Technology Transfer Network, National Ambient Air Quality Standards (NAAQS), Accessed January 2016 http://www3.epa.gov/ttn/naaqs/

USEPA, Tentatively Identified Compounds, What are they and why are they important, Region III Quality Assurance Team, TIC Frequently Asked Questions, Revision No.:2.5, February 2006

USEPA, Wastes-Non-Hazardous Waste – Industrial Waste, Accessed January 2016 http://www3.epa.gov/epawaste/nonhaz/industrial/index.htm

USEPA, Wastes-Non-Hazardous Waste – Industrial Waste, Guide for Industrial Waste Management, Accessed January 2016
http://www3.epa.gov/epawaste/nonhaz/industrial/guide/index.htm

USEPA, Wastes-Non-Hazardous Waste, Accessed January 2016
http://www3.epa.gov/epawaste/nonhaz/

USEPA, Wastes-Resource Conservation-Common Wastes & Materials, Plastics, Accessed December 2015
http://www3.epa.gov/epawaste/wastes_archive/plastics.htm#recycle

USEPA, Wastes-Resource Conservation-Reduce, Reuse, Recycle-Construction & Demolition Materials, Reducing C&D Materials, Accessed January 2016 http://www3.epa.gov/epawaste/conserve/imr/cdm/reducing.htm

USEPA, What are Detection Limits (DL) and Reporting Limits (RL), *Placer Data Library*, 2011 https://www3.epa.gov/region1/npdes/merrimackstation/pdfs/ar/AR-17.pdf

USP United States Plastic Corp., Ohio, USA
http://www.usplastic.com/catalog/default.aspx?catid=707

Valentine WN, Paglia DE, Fink K, Madokoro G. Lead poisoning: association with hemolytic anemia, basophilic stippling, erythrocyte pyrimidine 5'-nucleotidase deficiency, and intraerythrocytic accumulation of pyrimidines. J Clin Invest, 1976

Wells, G.; Prest, H.; Russ IV, C. Signal, Noise, and Detection Limits in Mass Spectrometry, *Agilent Technologies Inc*., Technical Note, Chemical Analysis Group, 2011

Whelton, A.; Salehi, M.; Tabor, M.; Donaldson, B.; Estaba, J. Impact of Infrastructure Coating Materials on Storm-Water Quality: Review and Experimental Study, *Journal of Environmental Engineering*, USA, 2013

Appendices

Appendix A. Calibration Certificates of Devices Used at Three Sites

(Xitech, Calibration for Site 1)

INSTRUMENT CALIBRATION REPORT

Pine Environmental Services, LLC.

Pine Environmental Services, Inc.

Instrument ID 26973
Description Xitech
Calibrated 9/24/2015 12:04:51PM

Manufacturer Pine Environmental Services, Inc.
Model Number Xitech 1060H
Serial Number/ Lot Number 003497
Location California
Department

State Certified
Status Pass
Temp °C 24
Humidity % 45

Calibration Specifications

Group # 1
Group Name
Test Performed: Yes **As Found Result: Pass** **As Left Result: Pass**

Test Instruments Used During the Calibration **(As Of Cal Entry Date)**

Test Standard ID	Description	Manufacturer	Model Number	Serial Number / Lot Number	Next Cal Date / Last Cal Date/ Expiration Date Opened Date

Notes about this calibration

Calibration Result Calibration Successful
Who Calibrated Mike Kondziella

All instruments are calibrated by Pine Environmental Services, LLC. according to the manufacturer's specifications, but it is the customer's responsibility to calibrate and maintain this unit in accordance with the manufacturer's specifications and/or the customer's own specific needs.

Notify Pine Environmental Services, LLC. of any defect within 24 hours of receipt of equipment
Please call 866-960-7463 for Technical Assistance

Pine Environmental Services, LLC., Windsor Industrial Park, 92 North Main Street, Bldg 20, Windsor, NJ 08561, 800-301-9663
www.pine-environmental.com

(Xitech, Calibration for Sites 2 & 3)

INSTRUMENT CALIBRATION REPORT

Pine Environmental Services, LLC.

Pine Environmental Services, Inc.

Instrument ID 26973
Description Xitech
Calibrated 11/6/2015 12:06:16PM

Manufacturer Pine Environmental Services, Inc.
Model Number Xitech 1060H
Serial Number/ Lot Number 003497
Location California
Department

State Certified
Status Pass
Temp °C 24
Humidity % 45

Calibration Specifications

Group # 1
Group Name
Test Performed: Yes **As Found Result: Pass** **As Left Result: Pass**

Test Instruments Used During the Calibration **(As Of Cal Entry Date)**

Test Standard ID	Description	Manufacturer	Model Number	Serial Number / Lot Number	Last Cal Date/ Opened Date	Next Cal Date / Expiration Date

Notes about this calibration

Calibration Result Calibration Successful
Who Calibrated Mike Kondziella

All instruments are calibrated by Pine Environmental Services, LLC. according to the manufacturer's specifications, but it is the customer's responsibility to calibrate and maintain this unit in accordance with the manufacturer's specifications and/or the customer's own specific needs.

Notify Pine Environmental Services, LLC. of any defect within 24 hours of receipt of equipment
Please call 866-960-7463 for Technical Assistance

Pine Environmental Services, LLC., Windsor Industrial Park, 92 North Main Street, Bldg 20, Windsor, NJ 08561, 800-301-9663
www.pine-environmental.com

(Flowrate & Thermo Meter, Calibration for Sites 2 & 3)

INSTRUMENT CALIBRATION REPORT

Pine Environmental Services, LLC.

Pine Environmental Services, Inc.

Instrument ID 10978
Description Tsi VelociCalc Plus 8384
Calibrated 11/6/2015 2:53:56PM

Manufacturer Tsi
Model Number 8384
Serial Number/ Lot Number 56050214
Location California
Department

State Certified
Status Pass
Temp °C 24
Humidity % 45

Calibration Specifications

Group # 1
Group Name Functional Test and Download

Test Performed: Yes **As Found Result: Pass** **As Left Result: Pass**

Test Instruments Used During the Calibration **(As Of Cal Entry Date)**

Test Standard ID	Description	Manufacturer	Model Number	Serial Number / Lot Number	Next Cal Date / Last Cal Date/ Expiration Date Opened Date

Notes about this calibration

Calibration Result Calibration Successful
Who Calibrated Mike Kondziella

All instruments are calibrated by Pine Environmental Services, LLC. according to the manufacturer's specifications, but it is the customer's responsibility to calibrate and maintain this unit in accordance with the manufacturer's specifications and/or the customer's own specific needs.

Notify Pine Environmental Services, LLC. of any defect within 24 hours of receipt of equipment
Please call 866-960-7463 for Technical Assistance

Pine Environmental Services, LLC., Windsor Industrial Park, 92 North Main Street, Bldg 20, Windsor, NJ 08561, 800-301-9663
www.pine-environmental.com

(Flowrate and Thermo Meter, Annual Calibration)

INSTRUMENT CALIBRATION REPORT

Advanced Labs, Inc.

Pine Environmental Services, Inc

Instrument ID 10978
Description TSI 8384A VelociCalc Plus
Calibrated 4/16/2015

Manufacturer TSI
Model Number 8384A
Serial Number 56050214
Location New Jersey
Temp 76

Classification
Status pass
Frequency Yearly EOM
Department
Humidity 22

Calibration Specifications

Group # 1
Group Name Velocity
Stated Accy Pct of Reading

Range Acc % 0.0000
Reading Acc % 3.0000
Plus/Minus 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
0.00 / 0.00	ft/min	0.00	ft/min	0.00	0.00	0.00%	Pass
40.00 / 40.00	ft/min	40.00	ft/min	40.00	40.00	0.00%	Pass
70.00 / 70.00	ft/min	70.00	ft/min	67.00	70.00	0.00%	Pass
100.00 / 100.00	ft/min	100.00	ft/min	94.00	99.00	-1.00%	Pass
150.00 / 150.00	ft/min	150.00	ft/min	141.00	149.00	-0.67%	Pass
325.00 / 325.00	ft/min	325.00	ft/min	319.00	325.00	0.00%	Pass
700.00 / 700.00	ft/min	700.00	ft/min	655.00	690.00	-1.43%	Pass
1000.00 / 1000.00	ft/min	1000.00	ft/min	950.00	1,005.00	0.50%	Pass
1500.00 / 1500.00	ft/min	1500.00	ft/min	1,430.00	1,515.00	1.00%	Pass
2000.00 / 2000.00	ft/min	2000.00	ft/min	1,910.00	2,035.00	1.75%	Pass
5000.00 / 5000.00	ft/min	5000.00	ft/min	4,560.00	4,900.00	-2.00%	Pass
8000.00 / 8000.00	ft/min	8000.00	ft/min	7,435.00	8,100.00	1.25%	Pass

Group # 2
Group Name Temperature
Stated Accy Plus / Minus

Range Acc % 0.0000
Reading Acc % 0.0000
Plus/Minus 0.500

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
70.000 / 76.000	°F	76.000	°F	64.600	76.000	0.00%	Pass

Test Instruments Used During the Calibration

Test Instrument ID	Description	Manufacturer	Serial Number	Last Cal Date (As Of Cal Entry Date)	Next Cal Date (As Of Cal Entry Date)
MICHELL DM-509-TX-01	Relative Humidity Meter	Michell	273296	6/13/2014	6/13/2015
OMEGA HX93AC/DP25-E	Omega HX93AC/DP25-E	Omega Engineering	1010368 035025 035026	8/14/2014	8/14/2015
OMEGA PX02K1-16A5T /DP25-E-A	Omega PX02K1-16A5T/DP25-E-A	Omega Engineering	168377/8375030	8/14/2014	8/14/2015
OMEGA WT4401-D	Omega WT4401-D	Omega Engineering	101105	8/14/2014	8/14/2015

Advanced Labs, Inc., Windsor Industrial Park, 92 North Main Street, Bldg 20, Windsor, NJ 08561, 800-301-9663

Appendix B. Compounds Can be Determined by Method EPA8260B

No.	Compound	CAS No.	No.	Compound	CAS No.
1	Acetone	67-64-1	55	1,4-Dioxane	123-91-1
2	Acetonitrile	75-05-8	56	Epichlorohydrin	106-89-8
3	Acrolein (Propenal)	107-02-8	57	Ethanol	64-17-5
4	Acrylonitrile	107-13-1	58	Ethyl acetate	141-78-6
5	Allyl alcohol	107-18-6	59	Ethylbenzene	100-41-4
6	Allyl chloride	107-05-1	60	Ethylene oxide	75-21-8
7	Benzene	71-43-2	61	Ethyl methacrylate	97-63-2
8	Benzyl chloride	100-44-7	62	Fluorobenzene (IS)	462-06-6
9	Bis(2-chloroethyl)sulfide	505-60-2	63	Hexachlorobutadiene	87-68-3
10	Bromoacetone	598-31-2	64	Hexachloroethane	67-72-1
11	Bromochloromethane	74-97-5	65	2-Hexanone	591-78-6
12	Bromodichloromethane	75-27-4	66	2-Hydroxypropionitrile	78-97-7
13	4-Bromofluorobenzene (surr)	460-00-4	67	Iodomethane	74-88-4
14	Bromoform	75-25-2	68	Isobutyl alcohol	78-83-1
15	Bromomethane	74-83-9	69	Isopropylbenzene	98-82-8
16	n-Butanol	71-36-3	70	Malononitrile	109-77-3
17	2-Butanone (MEK)	78-93-3	71	Methacrylonitrile	126-98-7
18	t-Butyl alcohol	75-65-0	72	Methanol	67-56-1
19	Carbon disulfide	75-15-0	73	Methylene chloride	75-09-2
20	Carbon tetrachloride	56-23-5	74	Methyl methacrylate	80-62-6
21	Chloral hydrate	302-17-0	75	4-Methyl-2-pentanone (MIBK)	108-10-1
22	Chlorobenzene	108-90-7	76	Naphthalene	91-20-3
23	Chlorobenzene-d (IS)		77	Nitrobenzene	98-95-3
24	Chlorodibromomethane	124-48-1	78	2-Nitropropane	79-46-9
25	Chloroethane	75-00-3	79	N-Nitroso-di-n-butylamine	924-16-3
26	2-Chloroethanol	107-07-3	80	Paraldehyde	123-63-7
27	2-Chloroethyl vinyl ether	110-75-8	81	Pentachloroethane	76-01-7
28	Chloroform	67-66-3	82	2-Pentanone	107-87-9
29	Chloromethane	74-87-3	83	2-Picoline	109-06-8
30	Chloroprene	126-99-8	84	1-Propanol	71-23-8
31	3-Chloropropionitrile	542-76-7	85	2-Propanol	67-63-0
32	Crotonaldehyde	4170-30-3	86	Propargyl alcohol	107-19-7
33	1,2-Dibromo-3-chloropropane	96-12-8	87	β-Propiolactone	57-57-8

(Table Continued)					
34	1,2-Dibromoethane	106-93-4	88	Propionitrile (ethyl cyanide)	107-12-0
35	Dibromomethane	74-95-3	89	n-Propylamine	107-10-8
36	1,2-Dichlorobenzene	95-50-1	90	Pyridine	110-86-1
37	1,3-Dichlorobenzene	541-73-1	91	Styrene	100-42-5
38	1,4-Dichlorobenzene	106-46-7	92	1,1,1,2-Tetrachloroethane	630-20-6
39	1,4-Dichlorobenzene-d (IS)		93	1,1,2,2-Tetrachloroethane	79-34-5
40	cis-1,4-Dichloro-2-butene	1476-11-5	94	Tetrachloroethene	127-18-4
41	trans-1,4-Dichloro-2-butene	110-57-6	95	Toluene	108-88-3
42	Dichlorodifluoromethane	75-71-8	96	Toluene-d (surr)	2037-26-5
43	1,1-Dichloroethane	75-34-3	97	o-Toluidine	95-53-4
44	1,2-Dichloroethane	107-06-2	98	1,2,4-Trichlorobenzene	120-82-1
45	1,2-Dichloroethane-d (surr)		99	1,1,1-Trichloroethane	71-55-6
46	1,1-Dichloroethene	75-35-4	100	1,1,2-Trichloroethane	79-00-5
47	trans-1,2-Dichloroethene	156-60-5	101	Trichloroethene	79-01-6
48	1,2-Dichloropropane	78-87-5	102	Trichlorofluoromethane	75-69-4
49	1,3-Dichloro-2-propanol	96-23-1	103	1,2,3-Trichloropropane	96-18-4
50	cis-1,3-Dichloropropene	10061-01-5	104	Vinyl acetate	108-05-4
51	trans-1,3-Dichloropropene	10061-02-6	105	Vinyl chloride	75-01-4
52	1,2,3,4-Diepoxybutane	1464-53-5	106	o-Xylene	95-47-6
53	Diethyl ether	60-29-7	107	m-Xylene	108-38-3
54	1,4-Difluorobenzene (IS)	540-36-3	108	p-Xylene	106-42-3

Appendix C. Spectral Plots Produced by the Gas Chromatography for Three Sites

(Site 1. Samples for Control, Liner Inversion, Near Private Property, Curing, and Cooling)

Quantitation Report (Not Reviewed)

```
Data Path : C:\MSDCHEM\1\DATA\092515\
Data File : B0011.D
Acq On    : 25 Sep 2015   3:14 pm
Operator  :
Sample    : G-338567 DL=1 ELENA
Misc      :
ALS Vial  : 13   Sample Multiplier: 1

Quant Time: Sep 25 15:25:31 2015
Quant Method : C:\MSDCHEM\1\METHODS\8260BGAS.M
Quant Title  : 8260B+GAS+ETOH
QLast Update : Wed Sep 02 13:19:48 2015
Response via : Continuing Cal File: C:\MSDCHEM\1\DATA\081715\B0001.D
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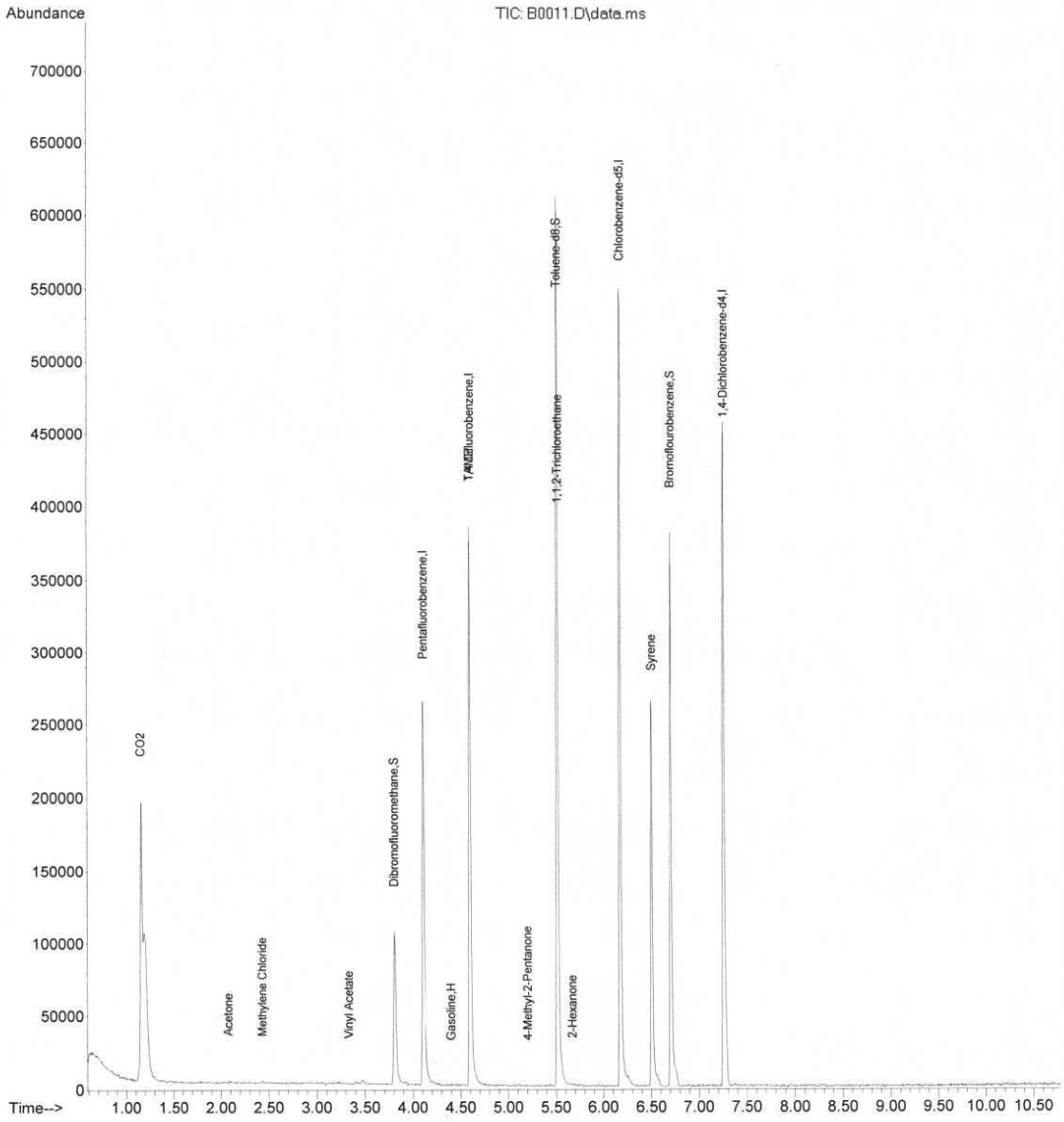
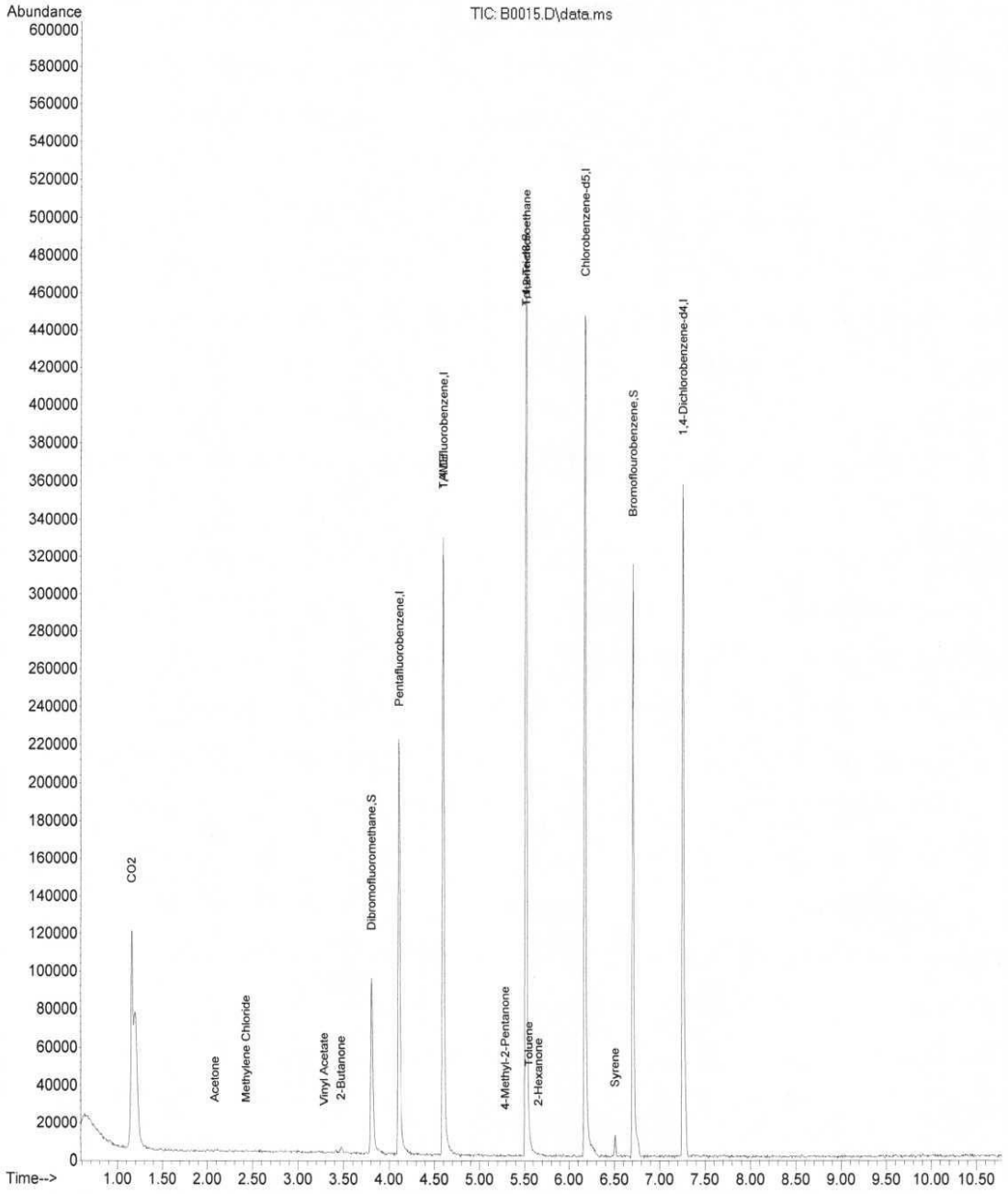


8260BGAS.M Tue Oct 06 13:15:40 2015 Page: 3

Quantitation Report (QT Reviewed)

Data Path : C:\MSDCHEM\1\DATA\092515\
Data File : B0015.D
Acq On : 25 Sep 2015 4:54 pm
Operator :
Sample : G-338563 DL=0.5 ELENA
Misc :
ALS Vial : 17 Sample Multiplier: 1

Quant Time: Sep 25 17:05:44 2015
Quant Method : C:\MSDCHEM\1\METHODS\8260BGAS.M
Quant Title : 8260B+GAS+ETOH
QLast Update : Wed Sep 02 13:19:48 2015
Response via : Continuing Cal File: C:\MSDCHEM\1\DATA\081715\B0001.D

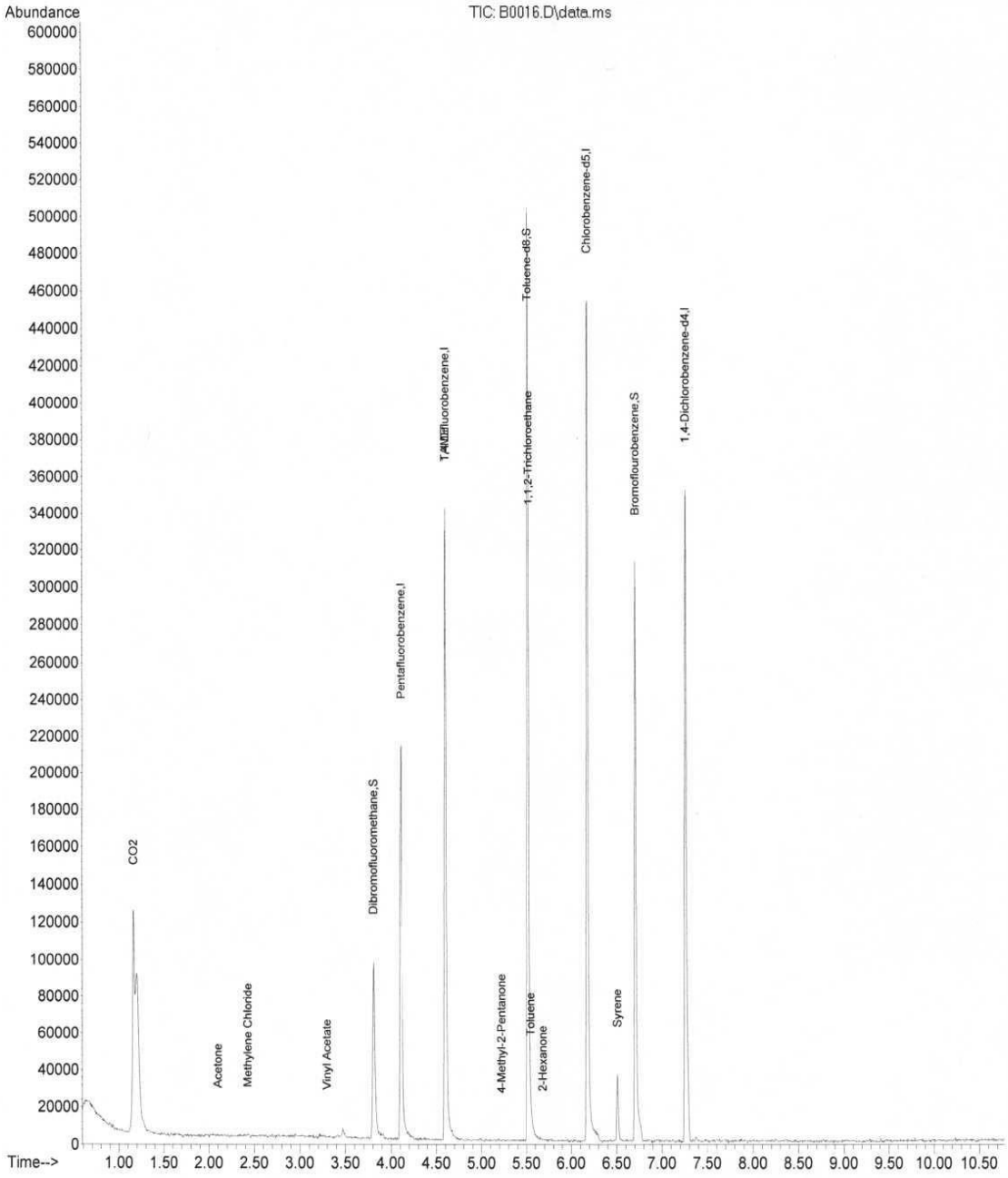


8260BGAS.M Tue Oct 06 13:15:48 2015 Page: 3

Quantitation Report (QT Reviewed)

Data Path : C:\MSDCHEM\1\DATA\092515\
Data File : B0016.D
Acq On : 25 Sep 2015 5:19 pm
Operator :
Sample : G-338564 DL=0.5 ELENA
Misc :
ALS Vial : 18 Sample Multiplier: 1

Quant Time: Sep 25 17:30:47 2015
Quant Method : C:\MSDCHEM\1\METHODS\8260BGAS.M
Quant Title : 8260B+GAS+ETOH
QLast Update : Wed Sep 02 13:19:48 2015
Response via : Continuing Cal File: C:\MSDCHEM\1\DATA\081715\B0001.D



8260BGAS.M Tue Oct 06 13:15:52 2015 Page: 3

Quantitation Report (QT Reviewed)

Data Path : C:\MSDCHEM\1\DATA\092515\
Data File : B0017.D
Acq On : 25 Sep 2015 5:45 pm
Operator :
Sample : G-338566 DL=0.5 ELENA
Misc :
ALS Vial : 19 Sample Multiplier: 1

Quant Time: Sep 25 17:55:57 2015
Quant Method : C:\MSDCHEM\1\METHODS\8260BGAS.M
Quant Title : 8260B+GAS+ETOH
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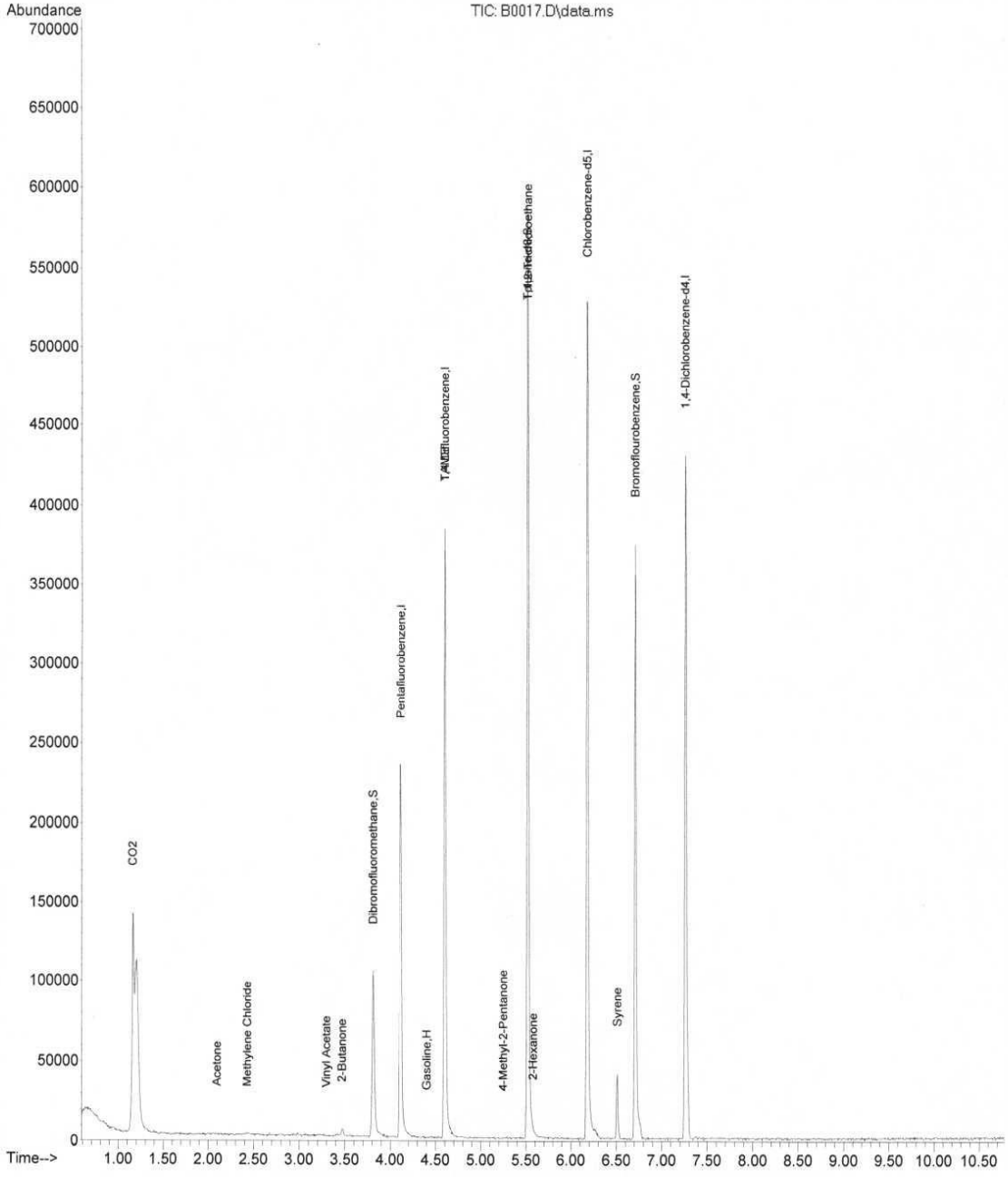
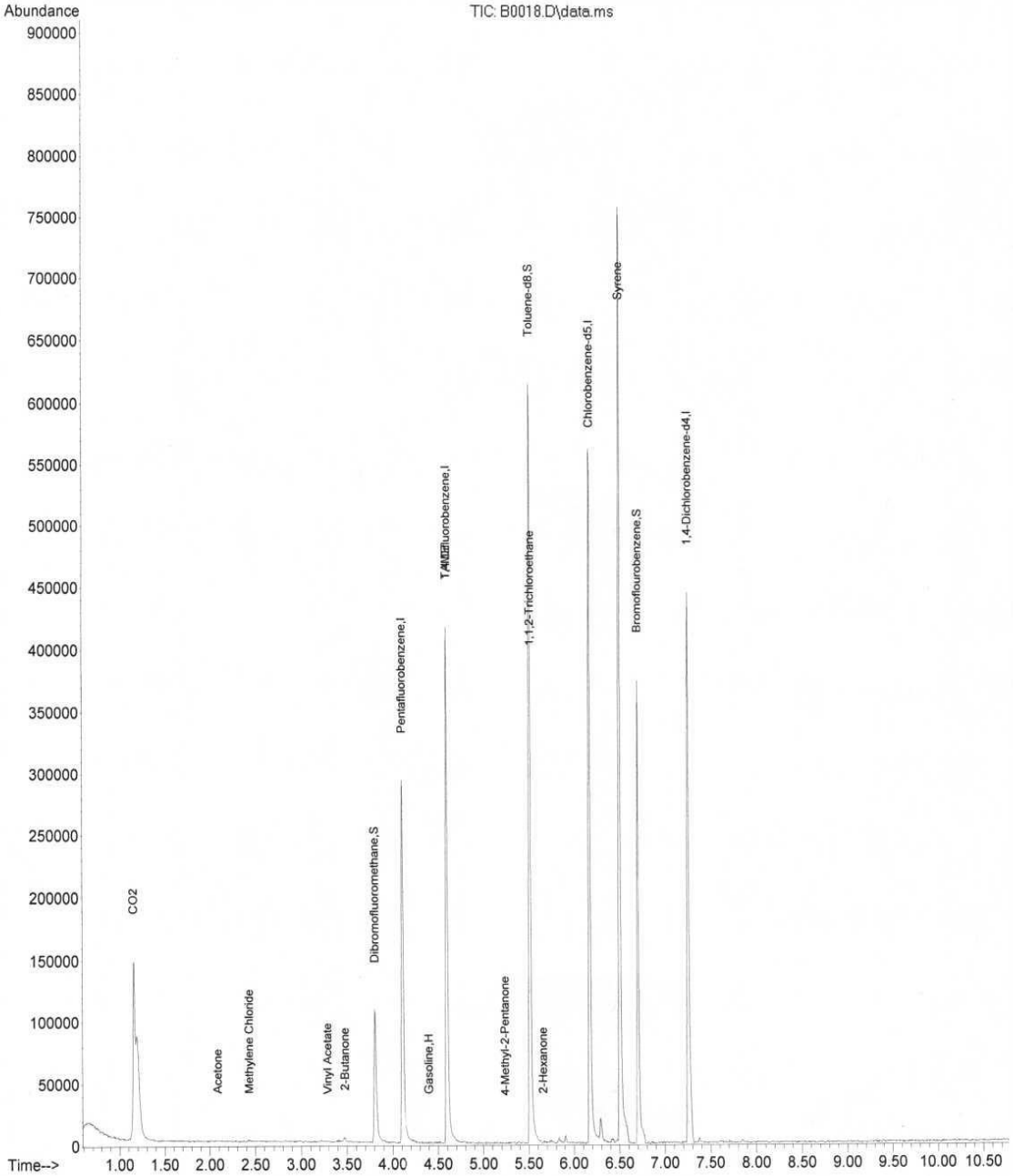


8260BGAS.M Tue Oct 06 13:15:57 2015 Page: 3

Quantitation Report (QT Reviewed)

Data Path : C:\MSDCHEM\1\DATA\092515\
Data File : B0018.D
Acq On : 25 Sep 2015 6:10 pm
Operator :
Sample : G-338565 DL=20 ELENA R
Misc :
ALS Vial : 20 Sample Multiplier: 1

Quant Time: Sep 25 18:21:02 2015
Quant Method : C:\MSDCHEM\1\METHODS\8260BGAS.M
Quant Title : 8260B+GAS+ETOH
QLast Update : Wed Sep 02 13:19:48 2015
Response via : Continuing Cal File: C:\MSDCHEM\1\DATA\081715\B0001.D



8260BGAS.M Tue Oct 06 13:16:06 2015

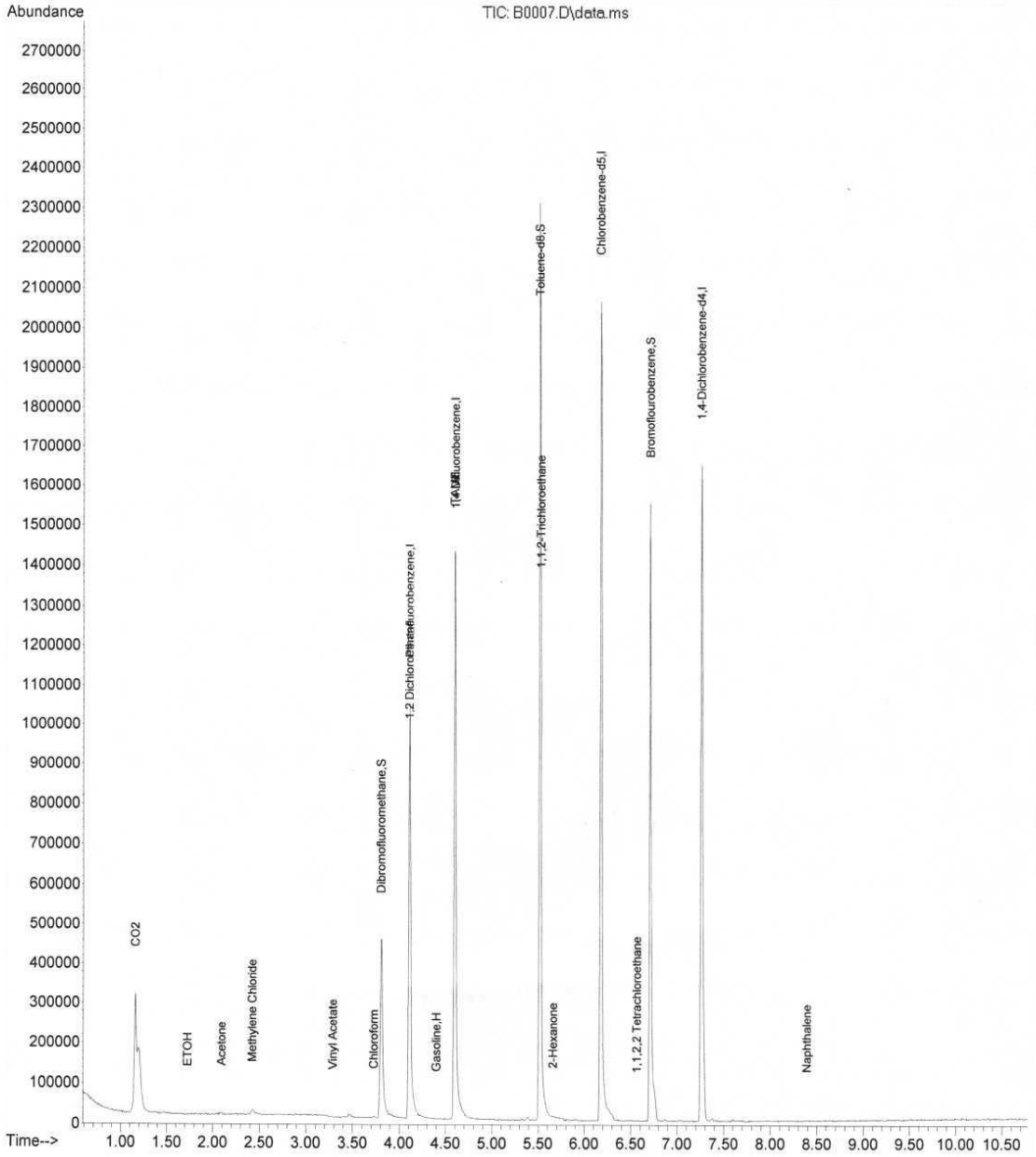
Page: 3

(Site 2. Samples for Control, Curing, and Cooling)

Quantitation Report (QT Reviewed)

Data Path : C:\MSDCHEM\1\DATA\111215\
Data File : B0007.D
Acq On : 12 Nov 2015 1:21 pm
Operator :
Sample : G-340066 DL=0.5 ELENA R
Misc :
ALS Vial : 9 Sample Multiplier: 1

Quant Time: Nov 16 09:56:09 2015
Quant Method : C:\MSDCHEM\1\METHODS\8260BGAS.M
Quant Title : 8260B+GAS+ETOH
QLast Update : Tue Nov 10 14:41:42 2015
Response via : Continuing Cal File: C:\MSDCHEM\1\DATA\111015\B0001.D

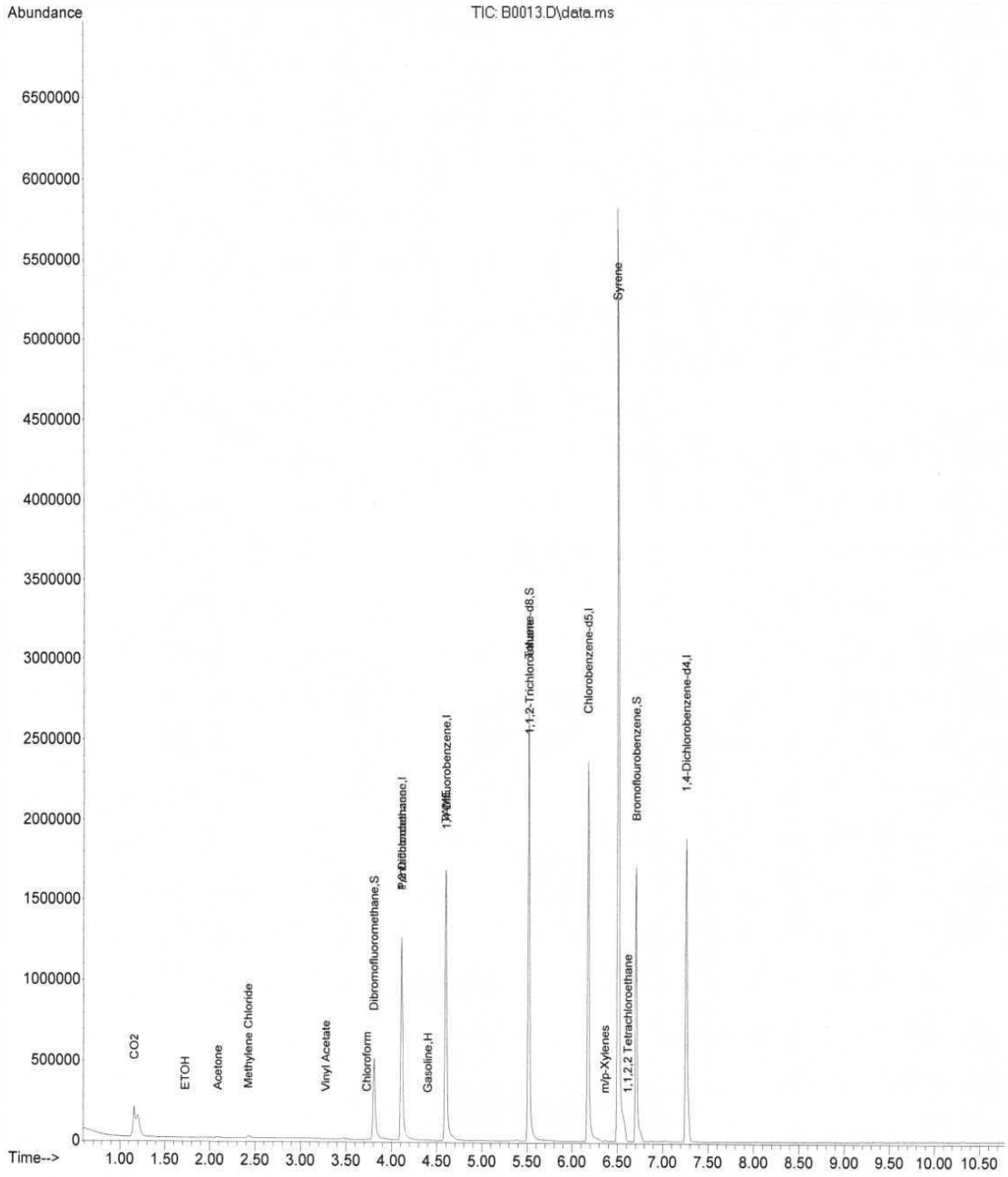


8260BGAS.M Mon Nov 16 09:56:24 2015 Page: 3

Quantitation Report (QT Reviewed)

Data Path : C:\MSDCHEM\1\DATA\111215\
Data File : B0013.D
Acq On : 12 Nov 2015 3:51 pm
Operator :
Sample : G-340067 DL=40 ELENA R
Misc :
ALS Vial : 15 Sample Multiplier: 1

Quant Time: Nov 16 10:06:03 2015
Quant Method : C:\MSDCHEM\1\METHODS\8260BGAS.M
Quant Title : 8260B+GAS+ETOH
QLast Update : Tue Nov 10 14:41:42 2015
Response via : Continuing Cal File: C:\MSDCHEM\1\DATA\111015\B0001.D



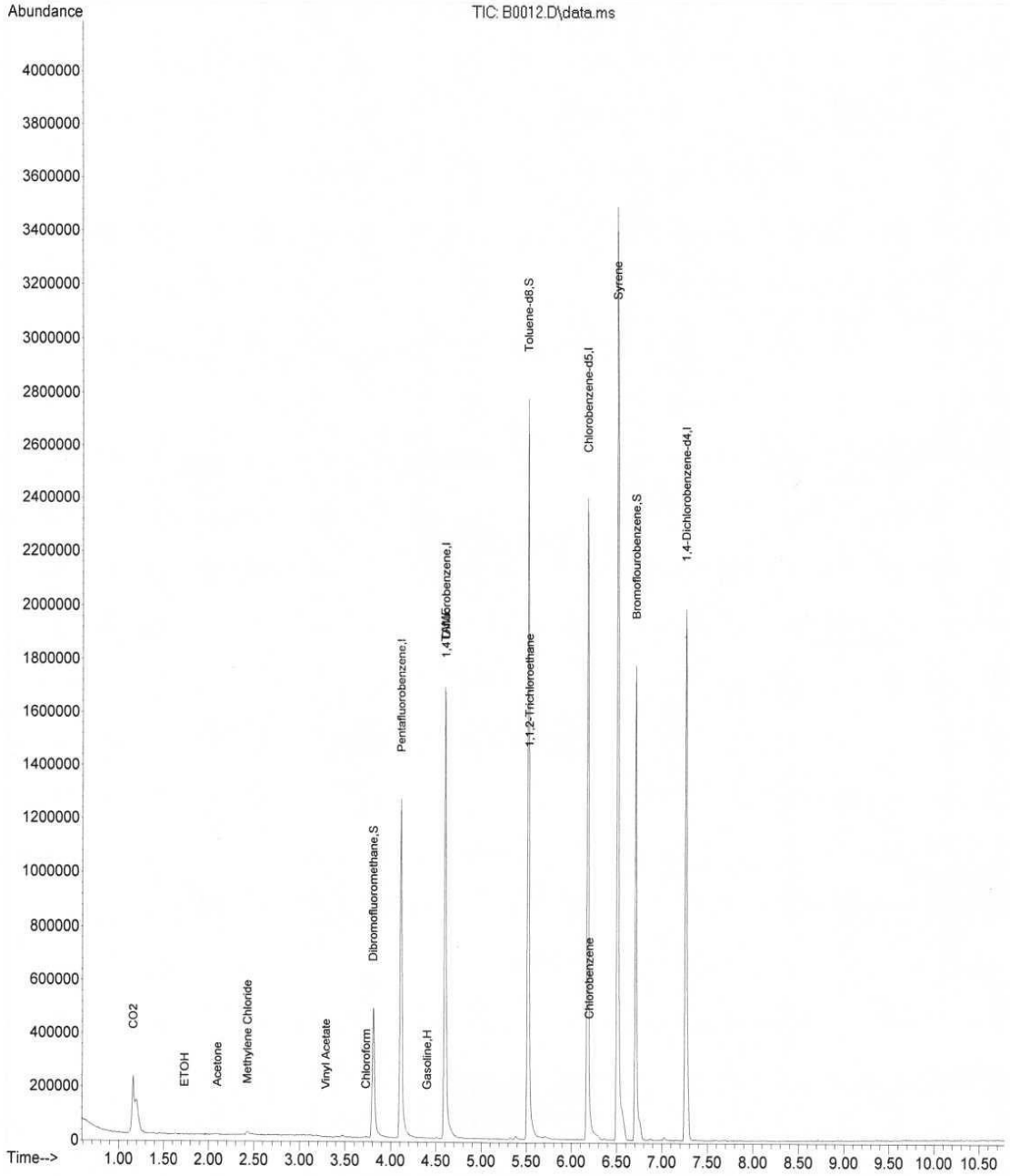
8260BGAS.M Mon Nov 16 10:06:16 2015

Page: 3

Quantitation Report (QT Reviewed)

Data Path : C:\MSDCHEM\1\DATA\111215\
Data File : B0012.D
Acq On : 12 Nov 2015 3:26 pm
Operator :
Sample : G-340068 DL=5 ELENA R
Misc :
ALS Vial : 14 Sample Multiplier: 1

Quant Time: Nov 16 10:13:05 2015
Quant Method : C:\MSDCHEM\1\METHODS\8260BGAS.M
Quant Title : 8260B+GAS+ETOH
QLast Update : Tue Nov 10 14:41:42 2015
Response via : Continuing Cal File: C:\MSDCHEM\1\DATA\111015\B0001.D



8260BGAS.M Mon Nov 16 10:13:12 2015

Page: 3

(Site 3. Samples for Control, Curing, and Cooling)

Quantitation Report (QT Reviewed)

Data Path : C:\MSDCHEM\1\DATA\111215\
Data File : B0008.D
Acq On : 12 Nov 2015 1:46 pm
Operator :
Sample : G-340117 DL=0.5 ELENA R
Misc :
ALS Vial : 10 Sample Multiplier: 1

Quant Time: Nov 16 09:58:24 2015
Quant Method : C:\MSDCHEM\1\METHODS\8260BGAS.M
Quant Title : 8260B+GAS+ETOH
QLast Update : Tue Nov 10 14:41:42 2015
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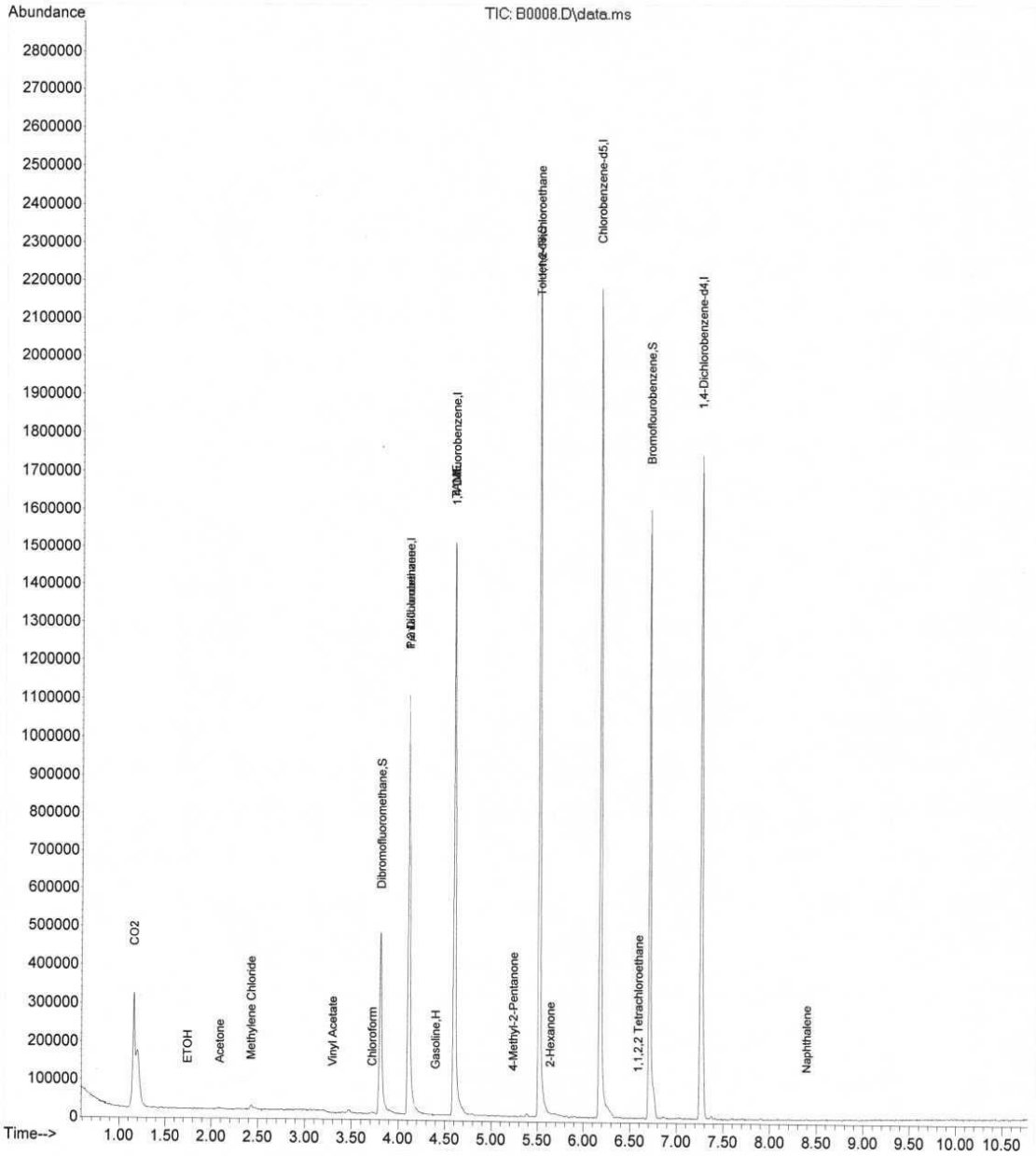

8260BCALIB.M Tue Nov 17 09:33:58 2015

Page: 3

Quantitation Report (QT Reviewed)

Data Path : C:\MSDCHEM\1\DATA\111215\
Data File : B0016.D
Acq On : 12 Nov 2015 5:07 pm
Operator :
Sample : G-340118 DL=10 ELENA R
Misc :
ALS Vial : 18 Sample Multiplier: 1

Quant Time: Nov 17 09:42:15 2015
Quant Method : C:\MSDCHEM\1\METHODS\8260BGAS.M
Quant Title : 8260B+GAS+ETOH
QLast Update : Tue Nov 10 14:41:42 2015
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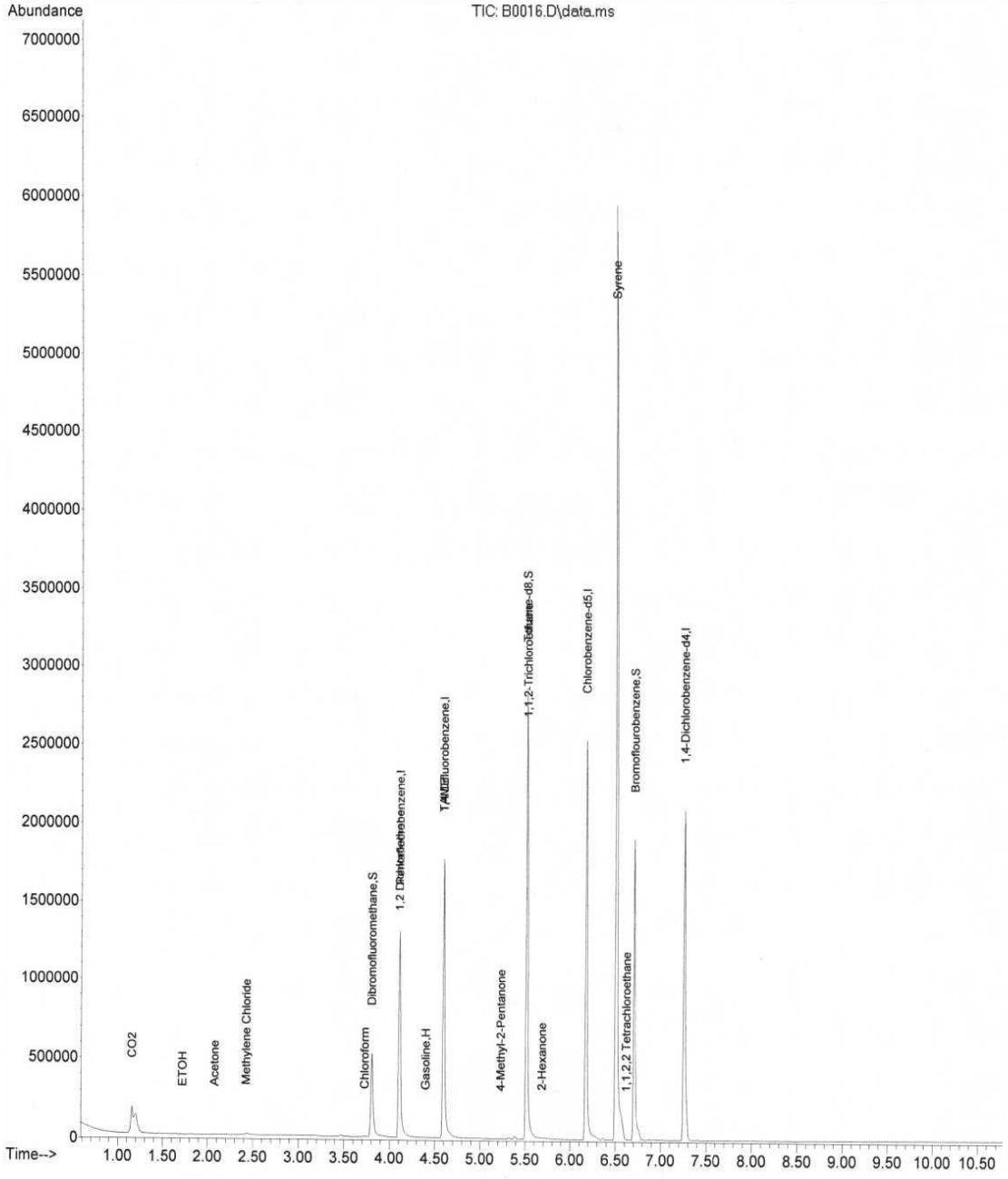

8260BCALIB.M Tue Nov 17 09:42:22 2015

Page: 3

Quantitation Report (QT Reviewed)

Data Path : C:\MSDCHEM\1\DATA\111215\
Data File : B0015.D
Acq On : 12 Nov 2015 4:41 pm
Operator :
Sample : G-340119 DL=1 ELENA R
Misc :
ALS Vial : 17 Sample Multiplier: 1

Quant Time: Nov 17 09:42:44 2015
Quant Method : C:\MSDCHEM\1\METHODS\8260BGAS.M
Quant Title : 8260B+GAS+ETOH
QLast Update : Tue Nov 10 14:41:42 2015
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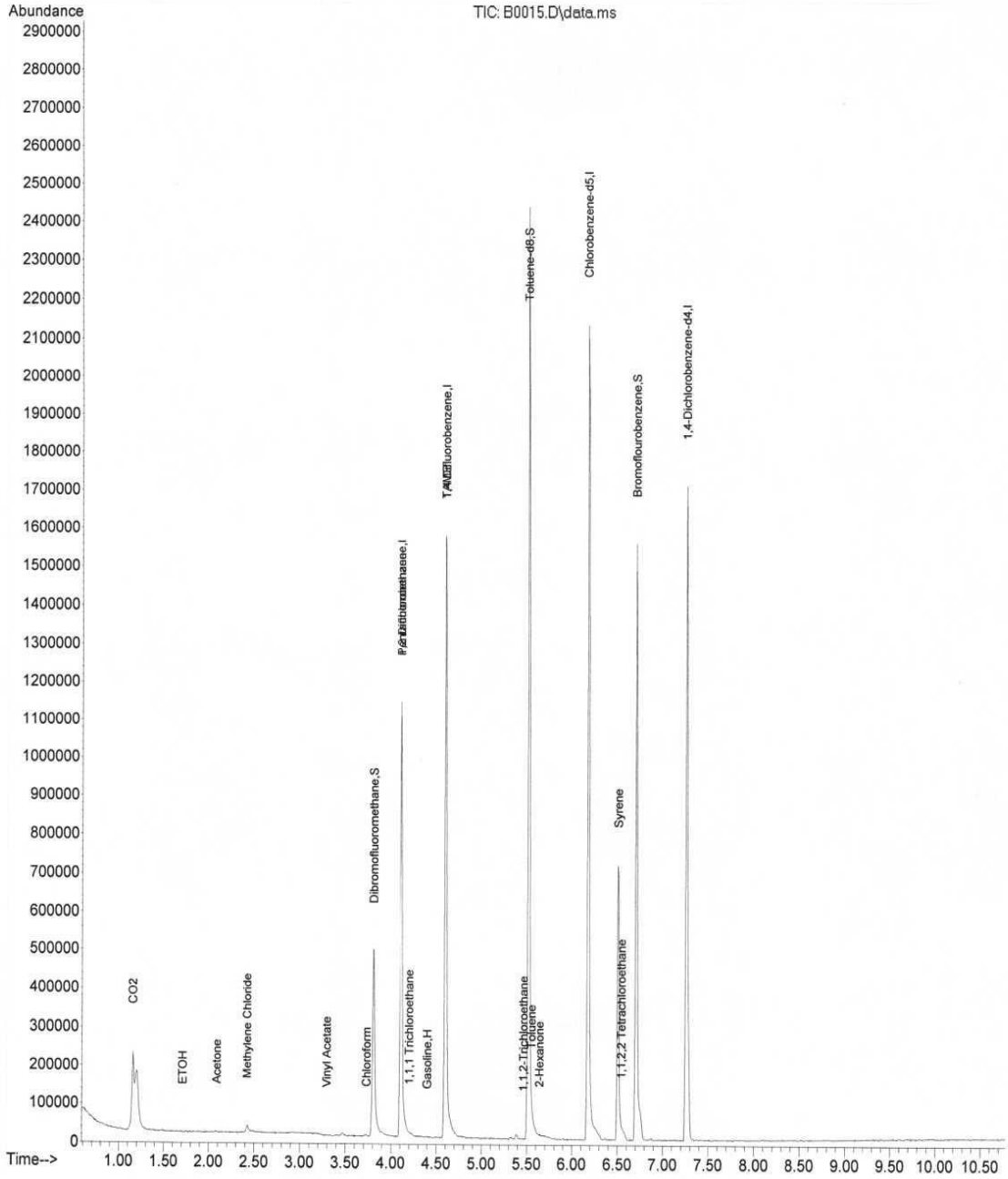

8260BCALIB.M Tue Nov 17 09:42:50 2015

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Appendix D. Emission Factors from California Air Resource Board's Off-Road Model 2015

Equipment	MaxHP	ROG	CO	NOX	SOX	PM	CO2	CH4
Aerial Lifts	15	0.0101	0.0528	0.0631	0.0001	0.0025	8.7	0.0009
	25	0.0155	0.0486	0.0902	0.0001	0.0046	11.0	0.0014
	50	0.0480	0.1641	0.1699	0.0003	0.0129	19.6	0.0043
	120	0.0460	0.2377	0.3272	0.0004	0.0246	38.1	0.0042
	500	0.1026	0.4261	1.2422	0.0021	0.0368	213	0.0093
	750	0.1912	0.7702	2.3263	0.0039	0.0680	385	0.0173
Aerial Lifts Composite		0.0439	0.1837	0.2670	0.0004	0.0167	34.7	0.0040
Air Compressors	15	0.0108	0.0466	0.0664	0.0001	0.0040	7.2	0.0010
	25	0.0229	0.0681	0.1247	0.0002	0.0069	14.4	0.0021
	50	0.0747	0.2360	0.2056	0.0003	0.0183	22.3	0.0067
	120	0.0691	0.3182	0.4334	0.0006	0.0375	47.0	0.0062
	175	0.0903	0.5019	0.7101	0.0010	0.0388	88.5	0.0082
	250	0.0892	0.2803	0.9294	0.0015	0.0286	131	0.0080
	500	0.1463	0.4915	1.4297	0.0023	0.0470	232	0.0132
	750	0.2285	0.7595	2.2932	0.0036	0.0743	358	0.0206
	1000	0.3551	1.1843	4.4558	0.0049	0.1239	486	0.0320
Air Compressors Composite		0.0773	0.3257	0.5175	0.0007	0.0357	63.6	0.0070
Bore/Drill Rigs	15	0.0120	0.0632	0.0754	0.0002	0.0029	10.3	0.0011
	25	0.0193	0.0658	0.1220	0.0002	0.0047	16.0	0.0017
	50	0.0234	0.2235	0.2240	0.0004	0.0075	31.0	0.0021
	120	0.0376	0.4676	0.3736	0.0009	0.0160	77.1	0.0034
	175	0.0618	0.7540	0.5364	0.0016	0.0198	141	0.0056
	250	0.0681	0.3425	0.4900	0.0021	0.0144	188	0.0061
	500	0.1118	0.5511	0.7692	0.0031	0.0236	311	0.0101
	750	0.2212	1.0888	1.5301	0.0062	0.0466	615	0.0200
	1000	0.3562	1.6528	4.9704	0.0093	0.1194	928	0.0321
Bore/Drill Rigs Composite		0.0673	0.5022	0.6138	0.0017	0.0200	165	0.0061
Cement and Mortar Mixers	15	0.0074	0.0386	0.0464	0.0001	0.0019	6.3	0.0007
	25	0.0251	0.0782	0.1456	0.0002	0.0074	17.6	0.0023
Cement and Mortar Mixers Composite		0.0088	0.0419	0.0545	0.0001	0.0024	7.2	0.0008
Concrete/Industrial Saws	25	0.0199	0.0678	0.1256	0.0002	0.0047	16.5	0.0018
	50	0.0782	0.2745	0.2652	0.0004	0.0206	30.2	0.0071
	120	0.0892	0.4759	0.6249	0.0009	0.0486	74.1	0.0080
	175	0.1340	0.8674	1.1593	0.0018	0.0585	160	0.0121
Concrete/Industrial Saws Composite		0.0835	0.3982	0.4921	0.0007	0.0374	58.5	0.0075
Cranes	50	0.0853	0.2729	0.2235	0.0003	0.0202	23.2	0.0077
	120	0.0800	0.3559	0.4822	0.0006	0.0415	50.1	0.0072
	175	0.0919	0.4794	0.6684	0.0009	0.0378	80.3	0.0083
	250	0.0925	0.2713	0.8284	0.0013	0.0286	112	0.0083
	500	0.1393	0.4663	1.1812	0.0018	0.0426	180	0.0126
	750	0.2358	0.7835	2.0490	0.0030	0.0729	303	0.0213
	9999	0.8682	2.8913	9.2743	0.0098	0.2775	971	0.0783
Cranes Composite		0.1204	0.4395	1.0200	0.0014	0.0426	129	0.0109
Crawler Tractors	50	0.1017	0.3087	0.2464	0.0003	0.0232	24.9	0.0092
	120	0.1143	0.4774	0.6815	0.0008	0.0579	65.8	0.0103
	175	0.1509	0.7384	1.0951	0.0014	0.0614	121	0.0136
	250	0.1582	0.4614	1.3531	0.0019	0.0514	166	0.0143
	500	0.2300	0.8352	1.8987	0.0025	0.0732	259	0.0207
	750	0.4140	1.4936	3.4863	0.0047	0.1327	465	0.0374
	1000	0.6278	2.3640	6.6574	0.0066	0.2075	658	0.0566
Crawler Tractors Composite		0.1415	0.5650	1.0059	0.0013	0.0594	114	0.0128
Crushing/Proc. Equipment	50	0.1392	0.4644	0.4024	0.0006	0.0346	44.0	0.0126
	120	0.1167	0.5646	0.7374	0.0010	0.0629	83.1	0.0105
	175	0.1654	0.9559	1.2783	0.0019	0.0700	167	0.0149

(Table Continued)								
	250	0.1646	0.5171	1.6355	0.0028	0.0506	245	0.0149
	500	0.2358	0.7790	2.1722	0.0037	0.0722	374	0.0213
	750	0.3723	1.2184	3.5561	0.0059	0.1154	589	0.0336
	9999	0.9726	3.0901	11.5626	0.0131	0.3225	1,308	0.0878
Crushing/Proc. Equipment Composite		0.1465	0.6549	0.9893	0.0015	0.0607	132	0.0132
Dumpers/Tenders	25	0.0093	0.0315	0.0591	0.0001	0.0025	7.6	0.0008
Dumpers/Tenders Composite		0.0093	0.0315	0.0591	0.0001	0.0025	7.6	0.0008
Excavators	25	0.0198	0.0677	0.1253	0.0002	0.0047	16.4	0.0018
	50	0.0650	0.2683	0.2256	0.0003	0.0167	25.0	0.0059
	120	0.0912	0.5102	0.5787	0.0009	0.0455	73.6	0.0082
	175	0.1052	0.6653	0.7408	0.0013	0.0405	112	0.0095
	250	0.1117	0.3431	0.8935	0.0018	0.0297	159	0.0101
	500	0.1577	0.4964	1.1619	0.0023	0.0413	234	0.0142
	750	0.2630	0.8225	1.9926	0.0039	0.0698	387	0.0237
Excavators Composite		0.1064	0.5248	0.7416	0.0013	0.0379	120	0.0096
Forklifts	50	0.0324	0.1522	0.1324	0.0002	0.0092	14.7	0.0029
	120	0.0345	0.2143	0.2326	0.0004	0.0174	31.2	0.0031
	175	0.0486	0.3316	0.3442	0.0006	0.0189	56.1	0.0044
	250	0.0518	0.1582	0.4040	0.0009	0.0133	77.1	0.0047
	500	0.0724	0.2164	0.5170	0.0011	0.0185	111	0.0065
Forklifts Composite		0.0459	0.2200	0.3163	0.0006	0.0156	54.4	0.0041
Generator Sets	15	0.0135	0.0658	0.0929	0.0002	0.0051	10.2	0.0012
	25	0.0247	0.0831	0.1522	0.0002	0.0080	17.6	0.0022
	50	0.0706	0.2465	0.2628	0.0004	0.0193	30.6	0.0064
	120	0.0910	0.4811	0.6607	0.0009	0.0484	77.9	0.0082
	175	0.1120	0.7350	1.0463	0.0016	0.0485	142	0.0101
	250	0.1090	0.4148	1.3776	0.0024	0.0381	213	0.0098
	500	0.1556	0.6639	1.9429	0.0033	0.0567	337	0.0140
	750	0.2599	1.0718	3.2483	0.0055	0.0934	544	0.0234
	9999	0.6582	2.3655	8.9789	0.0105	0.2325	1,049	0.0594
Generator Sets Composite		0.0640	0.2913	0.4717	0.0007	0.0268	61.0	0.0058
Graders	50	0.0897	0.3082	0.2569	0.0004	0.0217	27.5	0.0081
	120	0.1081	0.5230	0.6726	0.0009	0.0555	75.0	0.0098
	175	0.1299	0.7319	0.9534	0.0014	0.0526	124	0.0117
	250	0.1326	0.4046	1.1596	0.0019	0.0400	172	0.0120
	500	0.1666	0.5739	1.3760	0.0023	0.0496	229	0.0150
	750	0.3549	1.2133	3.0011	0.0049	0.1066	486	0.0320
Graders Composite		0.1277	0.5931	0.9795	0.0015	0.0489	133	0.0115
Off-Highway Tractors	120	0.1905	0.7051	1.1159	0.0011	0.0952	93.7	0.0172
	175	0.1870	0.8216	1.3703	0.0015	0.0771	130	0.0169
	250	0.1489	0.4320	1.2644	0.0015	0.0520	130	0.0134
	750	0.5975	2.5165	5.0885	0.0057	0.2047	568	0.0539
	1000	0.9006	3.9378	9.2072	0.0082	0.3063	814	0.0813
Off-Highway Tractors Composite		0.1893	0.7244	1.5085	0.0017	0.0717	151	0.0171
Off-Highway Trucks	175	0.1259	0.7559	0.8596	0.0014	0.0477	125	0.0114
	250	0.1252	0.3702	0.9818	0.0019	0.0328	167	0.0113
	500	0.1960	0.5949	1.4165	0.0027	0.0505	272	0.0177
	750	0.3198	0.9645	2.3779	0.0044	0.0835	442	0.0289
	1000	0.4873	1.4801	5.2216	0.0063	0.1505	625	0.0440
Off-Highway Trucks Composite		0.1924	0.5974	1.4932	0.0027	0.0516	260	0.0174
Other Construction Equipment	15	0.0118	0.0617	0.0737	0.0002	0.0029	10.1	0.0011
	25	0.0159	0.0544	0.1008	0.0002	0.0039	13.2	0.0014
	50	0.0597	0.2506	0.2369	0.0004	0.0162	28.0	0.0054
	120	0.0827	0.5202	0.6012	0.0009	0.0441	80.9	0.0075
	175	0.0796	0.5864	0.6636	0.0012	0.0331	107	0.0072
	500	0.1310	0.4963	1.1867	0.0025	0.0394	254	0.0118
Other Construction Equipment Composite		0.0768	0.3645	0.6392	0.0013	0.0264	123	0.0069

(Table Continued)								
Other General Industrial Equipment	15	0.0066	0.0391	0.0466	0.0001	0.0018	6.4	0.0006
	25	0.0185	0.0632	0.1170	0.0002	0.0044	15.3	0.0017
	50	0.0786	0.2532	0.2077	0.0003	0.0191	21.7	0.0071
	120	0.0987	0.4387	0.5864	0.0007	0.0521	62.0	0.0089
	175	0.1083	0.5684	0.7866	0.0011	0.0448	95.9	0.0098
	250	0.1050	0.3015	0.9812	0.0015	0.0312	136	0.0095
	500	0.1931	0.5811	1.6702	0.0026	0.0569	265	0.0174
	750	0.3208	0.9578	2.8569	0.0044	0.0959	437	0.0289
	1000	0.4546	1.4023	5.2482	0.0056	0.1513	560	0.0410
Other General Industrial Equipment Composite		0.1355	0.4843	1.1215	0.0016	0.0475	152	0.0122
Other Material Handling Equipment	50	0.1090	0.3501	0.2887	0.0004	0.0265	30.3	0.0098
	120	0.0959	0.4271	0.5727	0.0007	0.0509	60.7	0.0087
	175	0.1365	0.7201	0.9997	0.0014	0.0567	122	0.0123
	250	0.1109	0.3211	1.0483	0.0016	0.0332	145	0.0100
	500	0.1376	0.4182	1.2042	0.0019	0.0409	192	0.0124
	9999	0.6190	1.8527	6.9410	0.0073	0.1995	741	0.0558
Other Material Handling Equipment Composite		0.1289	0.4698	1.0967	0.0015	0.0460	141	0.0116
Pavers	25	0.0234	0.0780	0.1458	0.0002	0.0066	18.7	0.0021
	50	0.1198	0.3421	0.2775	0.0004	0.0271	28.0	0.0108
	120	0.1235	0.4969	0.7477	0.0008	0.0636	69.2	0.0111
	175	0.1608	0.7707	1.2155	0.0014	0.0673	128	0.0145
	250	0.1858	0.5585	1.6747	0.0022	0.0640	194	0.0168
	500	0.2059	0.8113	1.8097	0.0023	0.0697	233	0.0186
Pavers Composite		0.1347	0.5203	0.7607	0.0009	0.0526	77.9	0.0122
Paving Equipment	25	0.0152	0.0520	0.0963	0.0002	0.0037	12.6	0.0014
	50	0.1023	0.2901	0.2367	0.0003	0.0231	23.9	0.0092
	120	0.0969	0.3891	0.5874	0.0006	0.0503	54.5	0.0087
	175	0.1254	0.6025	0.9549	0.0011	0.0528	101	0.0113
	250	0.1140	0.3441	1.0498	0.0014	0.0394	122	0.0103
Paving Equipment Composite		0.1023	0.4234	0.6842	0.0008	0.0469	68.9	0.0092
Plate Compactors	15	0.0050	0.0263	0.0314	0.0001	0.0012	4.3	0.0005
Plate Compactors Composite		0.0050	0.0263	0.0314	0.0001	0.0012	4.3	0.0005
Pressure Washers	15	0.0065	0.0315	0.0445	0.0001	0.0024	4.9	0.0006
	25	0.0100	0.0337	0.0617	0.0001	0.0033	7.1	0.0009
	50	0.0251	0.0970	0.1183	0.0002	0.0077	14.3	0.0023
	120	0.0245	0.1416	0.1947	0.0003	0.0128	24.1	0.0022
Pressure Washers Composite		0.0133	0.0590	0.0799	0.0001	0.0049	9.4	0.0012
Pumps	15	0.0111	0.0479	0.0683	0.0001	0.0041	7.4	0.0010
	25	0.0309	0.0919	0.1682	0.0002	0.0094	19.5	0.0028
	50	0.0855	0.2910	0.2982	0.0004	0.0228	34.3	0.0077
	120	0.0949	0.4887	0.6710	0.0009	0.0508	77.9	0.0086
	175	0.1158	0.7365	1.0489	0.0016	0.0502	140	0.0104
	250	0.1088	0.3998	1.3270	0.0023	0.0376	201	0.0098
	500	0.1686	0.6929	2.0163	0.0034	0.0603	345	0.0152
	750	0.2872	1.1454	3.4529	0.0057	0.1018	571	0.0259
	9999	0.8773	3.1134	11.7387	0.0136	0.3072	1,355	0.0792
Pumps Composite		0.0621	0.2825	0.4121	0.0006	0.0267	49.6	0.0056
Rollers	15	0.0074	0.0386	0.0461	0.0001	0.0018	6.3	0.0007
	25	0.0161	0.0549	0.1018	0.0002	0.0039	13.3	0.0015
	50	0.0871	0.2754	0.2405	0.0003	0.0209	26.0	0.0079
	120	0.0857	0.4000	0.5498	0.0007	0.0454	59.0	0.0077
	175	0.1104	0.6166	0.8731	0.0012	0.0470	108	0.0100
	250	0.1107	0.3575	1.0948	0.0017	0.0368	153	0.0100
	500	0.1468	0.5595	1.3956	0.0022	0.0487	219	0.0132
Rollers Composite		0.0851	0.3979	0.5706	0.0008	0.0386	67.1	0.0077
Rough Terrain Forklifts	50	0.0942	0.3551	0.3066	0.0004	0.0243	33.9	0.0085
	120	0.0801	0.4260	0.5164	0.0007	0.0420	62.4	0.0072

(Table Continued)								
	175	0.1171	0.7240	0.8746	0.0014	0.0477	125	0.0106
	250	0.1168	0.3650	1.0385	0.0019	0.0338	171	0.0105
	500	0.1668	0.5337	1.3642	0.0025	0.0477	257	0.0150
Rough Terrain Forklifts Composite		0.0850	0.4577	0.5588	0.0008	0.0423	70.3	0.0077
Rubber Tired Dozers	175	0.1942	0.8333	1.3944	0.0015	0.0790	129	0.0175
	250	0.2209	0.6304	1.8273	0.0021	0.0762	183	0.0199
	500	0.2932	1.2456	2.3951	0.0026	0.0985	265	0.0265
	750	0.4423	1.8685	3.6712	0.0040	0.1494	399	0.0399
	1000	0.6883	3.0139	6.8297	0.0060	0.2311	592	0.0621
Rubber Tired Dozers Composite		0.2721	1.0420	2.2344	0.0025	0.0924	239	0.0246
Rubber Tired Loaders	25	0.0204	0.0697	0.1291	0.0002	0.0049	16.9	0.0018
	50	0.0993	0.3438	0.2888	0.0004	0.0242	31.1	0.0090
	120	0.0835	0.4090	0.5226	0.0007	0.0431	58.9	0.0075
	175	0.1094	0.6251	0.8077	0.0012	0.0445	106	0.0099
	250	0.1118	0.3444	0.9890	0.0017	0.0337	149	0.0101
	500	0.1678	0.5818	1.3980	0.0023	0.0499	237	0.0151
	750	0.3459	1.1905	2.9534	0.0049	0.1040	486	0.0312
	1000	0.4657	1.6412	5.2967	0.0060	0.1552	594	0.0420
Rubber Tired Loaders Composite		0.1050	0.4615	0.7838	0.0012	0.0416	109	0.0095
Scrapers	120	0.1665	0.6826	0.9915	0.0011	0.0846	93.9	0.0150
	175	0.1871	0.9030	1.3657	0.0017	0.0766	148	0.0169
	250	0.2021	0.5906	1.7470	0.0024	0.0665	209	0.0182
	500	0.2883	1.0688	2.4104	0.0032	0.0930	321	0.0260
	750	0.5001	1.8419	4.2634	0.0056	0.1624	555	0.0451
Scrapers Composite		0.2513	0.9443	2.0647	0.0027	0.0854	262	0.0227
Signal Boards	15	0.0072	0.0377	0.0450	0.0001	0.0018	6.2	0.0006
	50	0.0931	0.3227	0.3148	0.0005	0.0243	36.2	0.0084
	120	0.0970	0.5116	0.6762	0.0009	0.0525	80.2	0.0088
	175	0.1290	0.8300	1.1249	0.0017	0.0559	155	0.0116
	250	0.1416	0.5098	1.6229	0.0029	0.0474	255	0.0128
Signal Boards Composite		0.0171	0.0925	0.1250	0.0002	0.0066	16.7	0.0015
Skid Steer Loaders	25	0.0189	0.0601	0.1125	0.0002	0.0056	13.8	0.0017
	50	0.0378	0.2138	0.2052	0.0003	0.0113	25.5	0.0034
	120	0.0334	0.2710	0.2699	0.0005	0.0170	42.8	0.0030
Skid Steer Loaders Composite		0.0352	0.2220	0.2198	0.0004	0.0128	30.3	0.0032
Surfacing Equipment	50	0.0408	0.1333	0.1263	0.0002	0.0101	14.1	0.0037
	120	0.0840	0.4151	0.5756	0.0007	0.0439	63.8	0.0076
	175	0.0787	0.4705	0.6706	0.0010	0.0335	85.8	0.0071
	250	0.0891	0.3116	0.9338	0.0015	0.0309	135	0.0080
	500	0.1342	0.5759	1.3809	0.0022	0.0468	221	0.0121
	750	0.2139	0.9020	2.2264	0.0035	0.0745	347	0.0193
Surfacing Equipment Composite		0.1116	0.4705	1.0675	0.0017	0.0389	166	0.0101
Sweepers/Scrubbers	15	0.0124	0.0729	0.0870	0.0002	0.0034	11.9	0.0011
	25	0.0237	0.0808	0.1495	0.0002	0.0056	19.6	0.0021
	50	0.0782	0.3186	0.2828	0.0004	0.0211	31.6	0.0071
	120	0.0880	0.5056	0.5893	0.0009	0.0466	75.0	0.0079
	175	0.1193	0.7999	0.9051	0.0016	0.0488	139	0.0108
	250	0.1029	0.3286	0.9094	0.0018	0.0289	162	0.0093
Sweepers/Scrubbers Composite		0.0913	0.5034	0.5746	0.0009	0.0387	78.5	0.0082
Tractors/Loaders/Backhoes	25	0.0192	0.0653	0.1221	0.0002	0.0049	15.9	0.0017
	50	0.0702	0.3020	0.2646	0.0004	0.0186	30.3	0.0063
	120	0.0577	0.3480	0.3870	0.0006	0.0293	51.7	0.0052
	175	0.0854	0.5853	0.6331	0.0011	0.0335	101	0.0077
	250	0.1082	0.3566	0.9047	0.0019	0.0294	172	0.0098
	500	0.2085	0.7089	1.6070	0.0039	0.0559	345	0.0188
	750	0.3148	1.0631	2.4922	0.0058	0.0854	517	0.0284
Tractors/Loaders/Backhoes Composite		0.0666	0.3716	0.4501	0.0008	0.0298	66.8	0.0060
Trenchers	15	0.0099	0.0517	0.0617	0.0001	0.0024	8.5	0.0009

(Table Continued)								
	25	0.0397	0.1355	0.2509	0.0004	0.0094	32.9	0.0036
	50	0.1390	0.3900	0.3235	0.0004	0.0313	32.9	0.0125
	120	0.1144	0.4600	0.7060	0.0008	0.0590	64.9	0.0103
	175	0.1770	0.8534	1.3767	0.0016	0.0748	144	0.0160
	250	0.2105	0.6510	1.9456	0.0025	0.0750	223	0.0190
	500	0.2694	1.1349	2.4560	0.0031	0.0947	311	0.0243
	750	0.5107	2.1334	4.7300	0.0059	0.1802	587	0.0461
Trenchers Composite		0.1274	0.4541	0.6043	0.0007	0.0485	58.7	0.0115
Welders	15	0.0093	0.0400	0.0571	0.0001	0.0034	6.2	0.0008
	25	0.0179	0.0532	0.0974	0.0001	0.0054	11.3	0.0016
	50	0.0801	0.2564	0.2346	0.0003	0.0200	26.0	0.0072
	120	0.0547	0.2606	0.3567	0.0005	0.0296	39.5	0.0049
	175	0.0936	0.5424	0.7713	0.0011	0.0405	98.2	0.0084
	250	0.0749	0.2483	0.8249	0.0013	0.0248	119	0.0068
	500	0.0968	0.3491	1.0171	0.0016	0.0325	168	0.0087
Welders Composite		0.0534	0.1994	0.2301	0.0003	0.0187	25.6	0.0048

Appendix E. Temperatures and Flowrates of Steam Exiting the Hose and Downstream Manhole

Steam Hose	**Curing Period**		**Cooling Period**	
Site No.	**Temp, ^{0}F**	**Q, ft^3/min**	**Temp, ^{0}F**	**Q, ft^3/min**
2	134	142	73	115
3	129	119	70	121.5

Downstream Manhole	**Curing Period**		**Cooling Period**	
Site No.	**Temp, ^{0}F**	**Q, ft^3/min**	**Temp, ^{0}F**	**Q, ft^3/min**
2	100	46.9	87.5	21.1
3	162.5	55	97	23.3

Appendix F. Method Reporting Limits (MRL) for Each Sample and Site

No.	Analytes	Site 1 (MRL)					Site 2 (MRL)			Site 3 (MRL)		
		Control	Inversion	Cure (MH)	Cure (near private residence)	Cool (MH)	Control	Cure (MH)	Cool (MH)	Control	Cure (MH)	Cool (MH)
1	Acetone	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
2	Benzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
3	Bromobenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
4	Bromochloromethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
5	Bromodichloromethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
6	Bromoform	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
7	Bromomethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
8	2-Butanone	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
9	n-Butylbenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
10	sec-Butylbenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
11	tert-Butylbenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
12	Carbon disulfide	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
13	Carbon tetrachloride	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
14	Chlorobenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
15	Chloroethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
16	2-Chloroethyl vinyl ether	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
17	Chloroform	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
18	Chloromethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
19	4-Chlorotoluene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
20	2-Chlorotoluene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
21	1,2-Dibromo-3-chloropropane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
22	Dibromochloromethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500

(Table Continued)												
23	1,2-Dibromoethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
24	Dibromomethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
25	1,2-Dichlorobenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
26	1,3-Dichlorobenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
27	1,4-Dichlorobenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
28	Dichlorodifluoromethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
29	1,1-Dichloroethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
30	1,2-Dichloroethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
31	1,1-Dichloroethene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
32	cis-1,2-Dichloroethene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
33	trans-1,2-Dichloroethene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
34	1,2-Dichloropropane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
35	1,3-Dichloropropane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
36	2,2-Dichloropropane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
37	1,1-Dichloropropene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
38	cis-1,3-Dichloropropene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
39	trans-1,3-Dichloropropene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
40	Ethylbenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
41	Hexachlorobutadiene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
42	2-Hexanone	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
43	Isopropylbenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
44	p-Isopropyltoluene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
45	MTBE	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
46	4-Methyl-2-pentanone	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
47	Methylene chloride	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
48	Naphthalene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
49	n-Propylbenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
50	Styrene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500

(Table Continued)												
51	1,1,1,2-Tetrachloroethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
52	1,1,2,2-Tetrachloroethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
53	Tetrachloroethene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
54	Toluene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
55	1,2,3-Trichlorobenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
56	1,2,4-Trichlorobenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
57	1,1,1-Trichloroethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
58	1,1,2-Trichloroethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
59	Trichloroethene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
60	Trichlorofluoromethane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
61	1,2,3-Trichloropropane	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
62	1,2,4-Trimethylbenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
63	1,3,5-Trimethylbenzene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
64	Vinyl acetate	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
65	Vinyl chloride	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
66	o-Xylene	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500
67	m- & p-Xylenes	0.500	0.500	10.0	0.500	0.500	0.500	20.0	2.50	0.500	5.00	0.500

Appendix G. Chain of Custody Forms for Air Samples

(Samples Collected from Site 1)

AMERICAN SCIENTIFIC LABORATORIES, LLC
Environmental Testing Services

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COC# № 73274 GLOBAL ID _____ E REPORT: ☐ PDF ☐ EDF ☐ EDD ASL JOB# _____

CHAIN OF CUSTODY RECORD

Company: Elena Ajdari		Report To:	ANALYSIS REQUESTED
Address:	Project Name: VOC Analysis	Address:	
	Site Address:	Invoice To:	
Telephone: Fax:		Address:	
Special Instruction:	Project ID:		
E-mail: ajdari.e@gmail.com	Project Manager:	P.O.#:	

ITEM	LAB USE ONLY: Lab ID	SAMPLE DESCRIPTION: Sample ID	Date	Time	Container(s) #:	Container(s) Type	Matrix	Preservation	8260B VOC's	Remarks
		Ambient air Control	25th sep		1		TB		X	
		installation	25th sep		1				X	
		steam 1	25th sep		1				X	
		near the house	25th sep		1				X	
		steam 2	25th sep		1				X	

Collected By: Elena	Date 25th	Time	Relinquished By:	Date	Time
Relinquished By:	Date 25th	Time 12:20	Received For Laboratory	Date 9/25/1	Time 12:20
Received By:	Date	Time	Condition of Sample:		

TAT: ☒ Normal ☐ Rush

White - Report, Yellow - Laboratory, Pink - Client

(Samples Collected from Site 2)

AMERICAN SCIENTIFIC LABORATORIES, LLC
Environmental Testing Services

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COC# № 73506 GLOBAL ID _____ E REPORT: ☐ PDF ☐ EDF ☐ EDD ASL JOB# _____

CHAIN OF CUSTODY RECORD

Company: student		Report To:	ANALYSIS REQUESTED
Address:	Project Name: VoC analysis air samples	Address:	VOCs by 8260B
	Site Address:	Invoice To:	
Telephone: Fax:		Address:	
Special Instruction:	Project ID:		
E-mail: ajdari.e@gmail.com	Project Manager:	P.O.#:	

ITEM	LAB USE ONLY Lab ID	SAMPLE DESCRIPTION Sample ID	Date	Time	Container(s) #	Type	Matrix	Preservation	VOCs by 8260B	Remarks
1		Control 1	Nov 9th	10:50	1	tedlar bag	Air		X	
2		Curing 1	Nov 9th	10:50	1	tedlar bag	↓		X	
3		Cooling down 1	Nov 9th	10:50	1	tedlar bag			X	

Collected By: Elon Bourbour Ajdari	Date 11/9/15 Time 10:50	Relinquished By:	Date Time
Relinquished By:	Date 11/9/15 Time 11:50	Received For Laboratory Janet Chen	Date 11.9.15 Time 11:50
Received By:	Date Time	Condition of Sample:	

TAT ☐ Normal ☐ Rush

White - Report, Yellow - Laboratory, Pink - Client

(Samples Collected from Site 3)

AMERICAN SCIENTIFIC LABORATORIES, LLC
Environmental Testing Services

Page _____ Of _____

COC# № 73523 GLOBAL ID _____ E REPORT: ☐ PDF ☐ EDF ☐ EDD ASL JOB# _____

CHAIN OF CUSTODY RECORD

Company: student - Elena Bourbour Ajdari		Report To:	ANALYSIS REQUESTED
Address:	Project Name: VOC analysis for air samples	Address:	VOCs by 8260B
	Site Address:	Invoice To:	
Telephone: Fax:		Address:	
Special Instruction: Chrome of TIC	Project ID: —		
E-mail: ajdari.e@gmail.com	Project Manager: —	P.O.#:	

ITEM	LAB USE ONLY Lab ID	SAMPLE DESCRIPTION Sample ID	Date	Time	Container(s) #	Type	Matrix	Preservation	VOCs by 8260B	Remarks
1		Control 2	Nov 10th	11:30	1	tedlar bag	Air		x	
2		Curing 2	Nov 10th	11:30	1	tedlar bag	↓		x	
3		Cooling time 2	Nov 10th	11:30	1	tedlar bag			x	

Collected By: Elena Bourbour Ajdari	Date 11/10/15	Time 12:45	Relinquished By: Date Time
Relinquished By: Date	Time		Received For Laboratory Janet Chin Date 11/10/15 Time 12:45
Received By: Date	Time		Condition of Sample:

TAT ☑ Normal ☐ Rush

White - Report, Yellow - Laboratory, Pink - Client

Vita

Elena Bourbour Ajdari was born in Tehran, Iran. She obtained her Master degree in Civil & Environmental Engineering from Khajeh Nasir Toosi University of Technology in 2012 and her bachelor's degree in Civil Engineering from Shahrood University of Technology in her home country in 2009.

Ms. Bourbour Ajdari joined the University of New Orleans (UNO) College of Engineering graduate program to pursue a Ph.D. in Engineering and Applied Science specializing in Environmental Engineering in August 2012. She completed several courses and projects beyond the minimum requirement for the Ph.D. and was awarded a Master of Science in Engineering from UNO in 2014 while working in the Ph.D. program.

The author was the recipient of the 4-year Doctoral Scholarship Award during her tenure as a graduate student at the University of New Orleans from 2012-2016.

Elena Bourbour Ajdari can be reached at Ajdari.e@gmail.com or ebourbou@uno.edu.