COMPARISON OF ENVIRONMENTAL AND SOCIAL COSTS OF TRENCHLESS CURED-IN-PLACE PIPE RENEWAL METHOD WITH OPEN-CUT PIPELINE REPLACEMENT FOR SANITARY SEWERS

by

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Dedicated

to

My Parents, Mrs. Raj Rani Kaushal and Dr. C. P. Kaushal,

and

Brother, Vishwas

Acknowledgements

I feel highly indebted to express my deep sense of gratitude to my learned teacher and supervisor Dr. Mohammad Najafi, P.E., F.ASCE, Professor and Director, the Center for Underground Infrastructure Research & Education (CUIRE), Department of Civil Engineering, The University of Texas at Arlington, for his vigilant guidance, constant encouragement, keen interest, healthy and constructive critique and patient supervision in bringing out the work in the present shape. Working with him has been a matter of delight that I will cherish throughout my life.

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Abstract

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The development of underground infrastructure, environmental concerns, and economic trends is influencing society, resulting in the advancement of technology for more efficient, environment-friendly, and cost-effective pipeline installation and renewal. Comparison of environmental and social costs of a pipeline renewal and replacement is an essential element when considering sustainable development of underground infrastructure. Project owners, decision makers, design and consulting and contractors commonly take into consideration the construction costs only, and overlook the environmental and social cost aspects while making a choice between trenchless and open-cut pipeline installation.

Trenchless Cured-in-Place Pipe (CIPP) involves a liquid thermoset resin saturated material that is inserted into the existing pipeline by hydrostatic or air inversion, or by mechanically pulling-in and inflating. The liner material is cured-in-place using hot water, steam or light cured using UV light resulting in the CIPP product. The primary objective of this dissertation is to compare environmental and social costs of trenchless CIPP renewal method with open-cut pipeline replacement for small diameter sanitary sewers and to identify influencing factors Impacting costs

An actual case study based on the City of Pasadena, California, river basin was used for this research to evaluate the environmental and social costs implication of small diameter CIPP renewal and open-cut replacement. The results of this dissertation, for the case study used, show that the total environmental and social costs of trenchless CIPP method is 90% less as compared to open-cut pipeline replacement for small diameter sanitary sewers, such as 8 in. to 12 in. diameters. For this case study, it was determined that the environmental impacts of CIPP will be more than its social impacts. For open-cut, the social impacts are found to be more than environmental impacts. The methodology used in this dissertations can be applied for larger pipe diameters and other locations to develop a decision tool.

CIPP renewal caused less ozone depletion, global warming, smog, acidification, eutrophication, non carcinogenics, respiratory effects, ecotoxicity effects, and fossil fuel depletion. The liner, felt, and resin influenced environmental cost the most for CIPP compared to open-cut where power consumption of construction equipment, and pipe material drove the environmental cost. Cost of fuel for detour roads, detour delay, and pavement restoration were negligible for CIPP renewal method as compared with open-cut replacement that contributed a major social cost factor (approximately 75%).

List of Acronyms

ABS	Acrylonitrile Butadiene Styrene
ACGIH	American Conference of Governmental Industrial Hygienist
ACH	Air Change per Hour
AEGL	Acute Exposure Guideline Level
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing and Materials
AWWA	American Water Works Association
CF	Carbon Footprint
CIPP	Cured-in-Place Pipe
COD	Chemical Oxygen Demand
CTU	Comparative Toxic Units
CUIRE	Center for Underground Infrastructure Research and Education
DO	Dissolved Oxygen
DOT	Department of Transportation
EC	Effective Concentration
EPA	Environmental Protection Agency
ESL	Effect Screening Level
GHG	Greenhouse Gases
HDPE	High Density Polyethylene Pipe
HDD	Horizontal Directional Drilling
ISO	International Organization for Standardization
LCEA	Life Cycle Environmental Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Analysis
MCL	Maximum Contaminant Level
MJ	Megajoule
MPDM	Method Productivity Delay Model
MSW	Municipal Solid Waste
NASSCO	National Association of Sewer Service Companies
NASTT	North American Society for Trenchless Technology
NIOSH	National Institute for Occupational Safety and Health
NRMCA	National Ready-Mixed Concrete Association

OD	Outside Diameter
OSHA	Occupational Safety and Health Administration
PVC	Polyvinyl Chloride
SETAC	Society of Environmental Toxicology and Chemistry
SCC	Social Cost Calculator
STEL	Short-Term Exposure Limit
TAMIS	Texas Air Monitoring Information System
TCEQ	Texas Commission on Environmental Quality
TCM	Trenchless Construction Method
TCOC	Total Cost of Open-cut
TCTT	Total Cost of Trenchless Technology
TO-15	Toxic Organics - 15
TOC	Total Organic Carbon
TRACI	The Tool for the Reduction and Assessment of Chemical and other Impact Categories
TRM	Trenchless Renewal Method
TT	Trenchless Technology
TWA	Time Weighted Average
UNEP	United Nations Environment Programme
USIR	Underground Sustainability Index Rating
UV	Ultraviolet
VCP	Vitrified Clay Pipe
VER	Vinyl Ester Resin
WWTP	Wastewater Treatment Plant

Glossary

Acute Exposure Guideline Levels	Exposure guidelines designed to help responders deal with emergencies involving chemical spills or other catastrophic events where members of the public exposed to a hazardous airborne chemical.
Air Change Per Hour	A measure of the air volume added to or removed from a space (normally a room or house) divided by the volume of the space.
Air Quality Monitoring	The systematic, long-term assessment of pollutant levels by measuring the quantity and types of certain pollutants in the surrounding, outdoor air.
Analysis of Variance	A statistical method in which the variation in a set of observations divided into distinct components.
Chemical Oxygen Demand	Measure of the capacity of water to consume oxygen during the decomposition of organic matter and the oxidation of inorganic chemicals such as ammonia and nitrite.
Dissolved Oxygen	Dissolved oxygen refers to microscopic bubbles of gaseous oxygen mixed in water and available to aquatic organisms for respiration.
Effect Screening Level	Screening levels used in the environment quality air permitting process to evaluate air dispersion modeling predicted impacts used to evaluate the potential for effects to occur because of exposure to concentrations of constituents in the air.
Effective Concentration	*Concentration* of a substance that causes a defined magnitude of *response* in a given system.

Granular Activated Carbon	A highly porous adsorbent material, produced by heating organic matter, such as coal, wood and coconut shell, in the absence of air, which is then crushed into granules.
Leaching	*Leaching* is the loss or extraction of certain materials from a carrier into a liquid.
Lethal Concentration	The *lethal concentration* is the concentration of a chemical that will kill certain percent of the sample population under scrutiny.
Mass Spectrometer	An apparatus for separating isotopes, molecules, and molecular fragments according to mass.
Maximum Contaminant Level	Standards set by the United States Environmental Protection Agency (EPA) for drinking water quality.
Maximum Workplace Concentration	Maximum concentration of a chemical substance (as gas, vapor or particulate matter) in the workplace air which generally does not have known adverse effects on the health of the employee nor cause unreasonable annoyance even when the person is repeatedly exposed during long periods, usually for 8 hours daily but assuming on average a 40-hour working week.
Occupational Exposure Limits	An occupational exposure limit is an upper limit on the acceptable concentration of a hazardous substance in workplace air for a material or class of materials.
Permissible Exposure Limit	The limit for exposure of an employee to a chemical substance or physical agent.
Photoionization Detector	A type of gas detector to measure volatile organic compounds and other gases in concentrations from sub parts per billion to parts per million.

Precision Electro-Chemical Machining	Precision electrochemical machining is a nonconventional machining process that can help deliver complex and precise components quickly and accurately.
Quality Assurance	The maintenance of a desired level of quality in a service or product, especially by means of attention to every stage of the process of delivery or production.
Quality Control	A system of maintaining standards in manufactured products by testing a sample of the output against the specification.
Recommended Exposure Limit	An occupational exposure limit recommended by the United States National Institute for OSHA for adoption as a permissible exposure limit.
Short-Term Exposure Limit	The acceptable average exposure over a short period, usually 15 minutes as long as the time-weighted average not exceeded.
Threshold Limit Value	A level to which a worker exposed day after day for a working lifetime without adverse effects.
Time Weighted Average	The average exposure over a specified period, usually a nominal eight hours.
Total Organic Carbon	The amount of carbon found in an organic compound and used as a non-specific indicator of water quality.
Vinyl Ester Resin	A resin produced by the esterification of an epoxy resin with an unsaturated monocarboxylic acid.
Volatile Organic Compound	The organic chemicals that have a high vapor pressure at ordinary room temperature referred as the Volatile Organic Compounds.

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Chapter 1

Introduction and Background

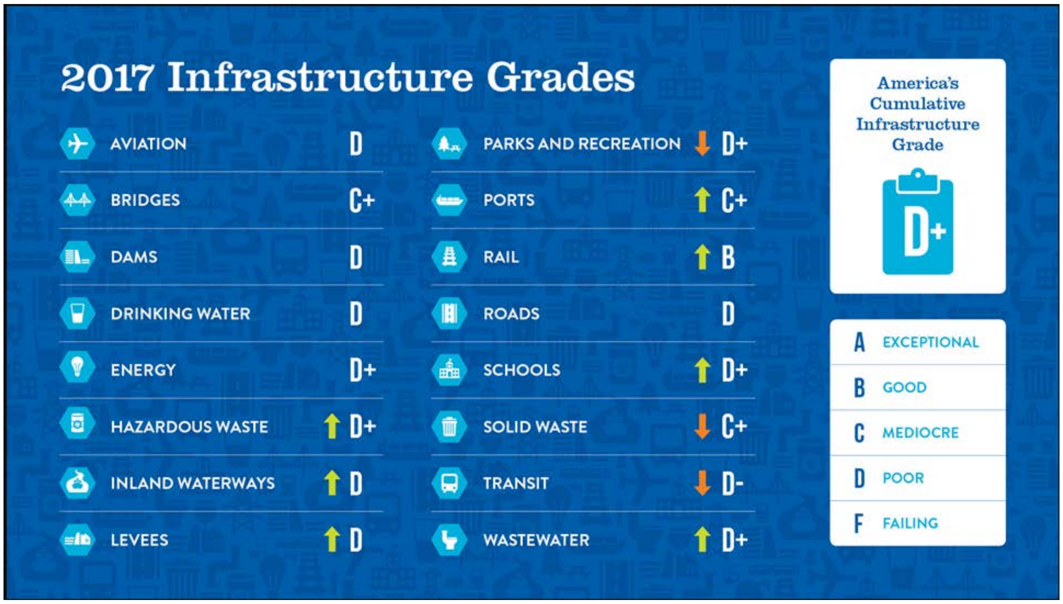
1.1 Introduction

A large proportion of underground infrastructure was installed in the 1950s and 1960s during a period of rapid economic growth in the United States and Canada. Today, these aging systems have exceeded their design lives and have deteriorated to the point of failure (Figure 1-1). Renewal and replacement of this aging and deteriorating underground infrastructure is a major obstacle faced by municipalities (Hashemi et al., 2011).

Figure 1-1 A Sample of Aging Underground Pipeline
Source: Melissa Thompson Available at: https://newsblaze.com

The sewer pipeline system is the basic urban infrastructure for public sanitation. In the U.S., there are 1.2 million miles of water supply mains, and there are nearly an equal number of sewer pipes, 26 miles of sewer pipes for every mile of interstate highway (Bartlett, 2017, Malek Mohammadi, 2019, and Alsadi, 2019). Each of these conveyance systems is susceptible to structural failure, blockages, and overflows (Najafi and Gokhale, 2005). EPA (2012) estimates that $271 billion is needed for wastewater infrastructure over the next 25 years. Of that amount, $51 billion is needed for conveyance system repair.

According to American Society of Civil Engineers (ASCE) 2017 Infrastructure Report Card, a D+ grade has been assigned to the condition of U.S. wastewater infrastructure (Figure 1-2). Clearly, this expenditure, no matter how financed, will ultimately be passed on to rate payers/utility customers. Maximizing the benefit of every dollar spent on collection system repair and rehabilitation should be the goal of every utility decision maker. Too often, only initial investment (least cost) is the main priority in the process of capital planning for collection system rehabilitation.



2017 Infrastructure Grades

AVIATION	D	PARKS AND RECREATION	↓ D+
BRIDGES	C+	PORTS	↑ C+
DAMS	D	RAIL	↑ B
DRINKING WATER	D	ROADS	D
ENERGY	D+	SCHOOLS	↑ D+
HAZARDOUS WASTE	↑ D+	SOLID WASTE	↓ C+
INLAND WATERWAYS	↑ D	TRANSIT	↓ D-
LEVEES	↑ D	WASTEWATER	↑ D+

America's Cumulative Infrastructure Grade

D+

A	EXCEPTIONAL
B	GOOD
C	MEDIOCRE
D	POOR
F	FAILING

Figure 1-2 ASCE 2017 Infrastructure Report Card
Source: ASCE Available at www.asce.org

Because of deterioration of municipal underground infrastructure systems and a growing population that demands better quality of life, the efficient and cost-effective installation, renewal, and replacement of underground utilities is becoming an increasing important issue. The traditional open-cut construction method requires reinstatement of the ground surface, such as sidewalks, pavement, landscaping; and therefore, considered to be a wasteful operation (Hashemi, 2008).

Additionally, considering social and environmental cost factors, open-cut pipeline replacement methods have negative impacts on the community, businesses, and commuters due to surface and traffic disruptions. Trenchless technologies include all methods of underground utility installation, replacement and renewal without or with minimum surface excavation. These methods can be used to repair, upgrade, replace, or renovate underground infrastructure systems with minimum surface disruptions, and therefore offer a viable alternative to the traditional open-cut methods (Najafi and Gokhale, 2005).

The total cost of every pipeline project varies with many factors such as pipe size, pipe material, depth and length of installation, project site, subsurface conditions, and type of pipeline or utility application. With open-cut replacement, it is estimated that approximately 70 percent of a project's direct costs will be spent for reinstatement of ground only, not installation of the pipe itself (Najafi, 2011). Among the different trenchless pipe rehabilitation techniques, cured-in-place pipe (CIPP) is considered a safe, cost-effective, efficient, and productive alternative (Das et al., 2016).

Trenchless cured-in-place pipe (CIPP) renewal method is an alternative to digging up and replacing sewers, and since 1970s hundreds of millions of feet of renewed pipe have been installed around the world. Currently, CIPP is one of the most widely used methods of trenchless pipeline renewal for both structural and nonstructural purposes. The CIPP process involves a liquid thermoset resin-saturated material that is inserted into the existing pipeline by hydrostatic or air inversion, or by mechanically pulling-in and inflating by air or water. The liner material is cured-in-place using hot water, steam- or light-cured using UV light resulting in the CIPP product (Kozman, 2013, Kaushal et al., 2019).

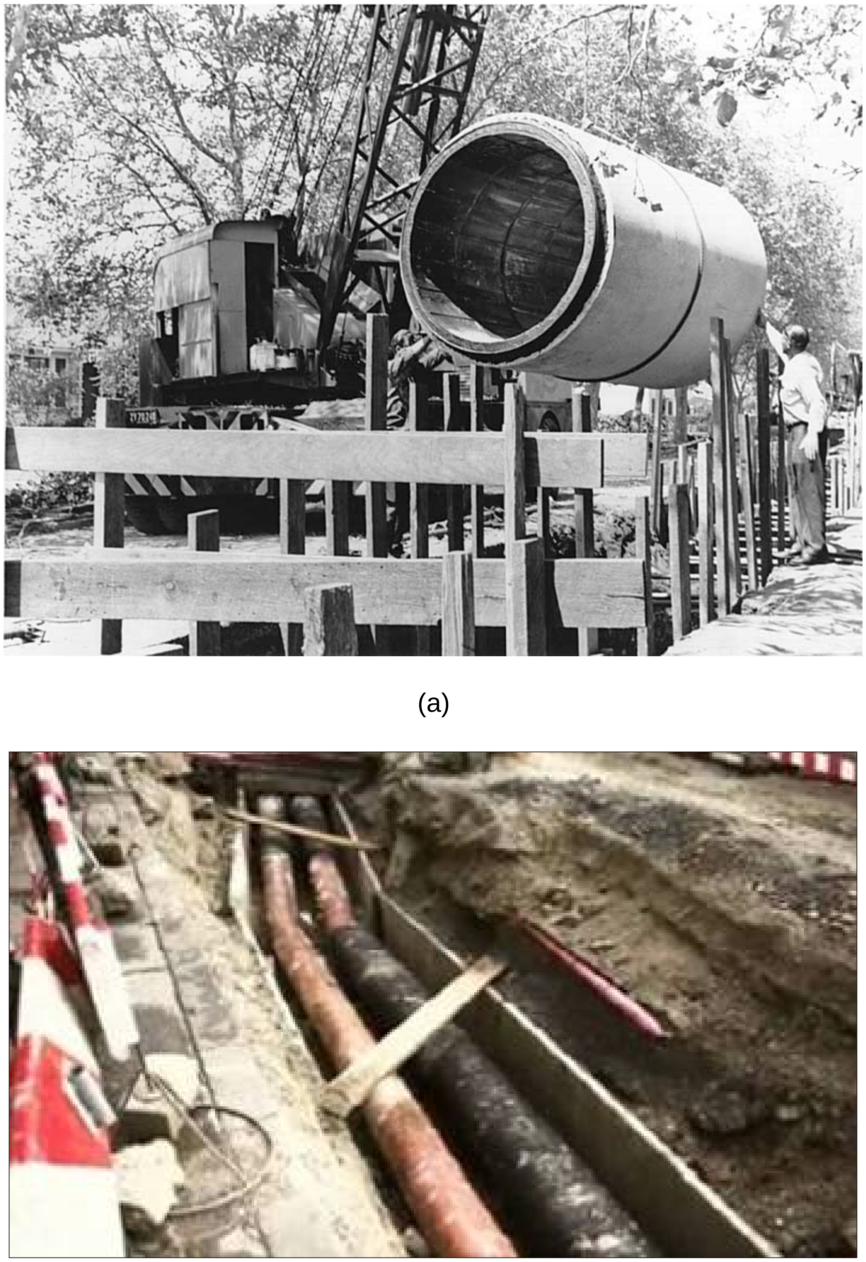
Total environmental and social costs can be used as an important and effective decision-making tool to determine the cost of pipeline renewal and/or replacement alternatives based on the service life of each alternative. Although there have been several preliminary studies regarding the cost comparison of trenchless CIPP renewal with open-cut pipeline replacement methods, a more comprehensive comparison between the environmental and social costs of these two methods will be an effective decision-making tool to determine the cost of possible pipe rehabilitation alternatives based on their service lives. The objective of this research is to provide a comparison of environmental and social costs of trenchless CIPP renewal with open-cut pipe replacement by analytical method.

1.2 Underground Pipeline Construction Methods

As stated earlier, there are two methods of underground pipeline construction: conventional open-cut pipeline replacement and trenchless technology methods. Both methods are explained in the below sections.

1.2.1 Open-cut Pipeline Replacement Method

Open-cut pipeline replacement (Figure 1-3 (a and b)) is a more common and traditional method of installation or replacement of the underground infrastructure. Based on the type of work, this method is also called dig-and-install, dig-and-repair, or dig-and-replace. This method includes trenching the ground for either placing new pipe or replacing existing old pipe with a new pipe and then reinstatement of the surface. This process includes selection for a new route, surface and sub-surface survey, engineering, planning and analysis, trench excavation, foundation and bedding, placing a new pipe, embedment and backfill with compaction with select soil, and reinstatement of the ground surface (Najafi, 2005).



(a)

(b)

Figure 1-3 (a and b) Open-cut Pipeline Replacement
Source: Najafi, 2011

The main elements related to open-cut pipeline replacement are described as follows:

1.2.1.1 Pipe Material

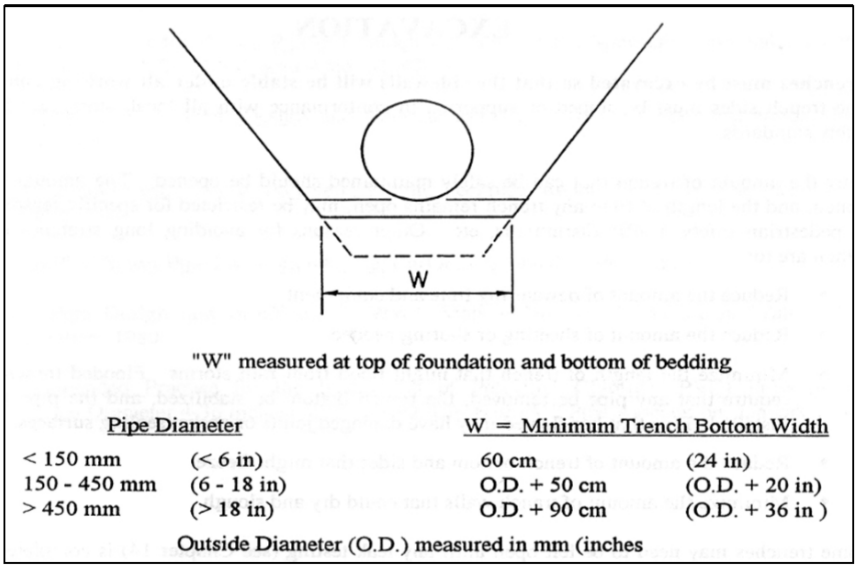
According to Howard (1996), a particular pipe type is usually considered as either a rigid or flexible pipe. Pipes have sometimes been referred to as semirigid or very flexible, but for open-cut replacement pipe is treated as either rigid or flexible pipe. Strength is the ability of a rigid pipe to resist stress that is created in the pipe wall due to internal pressure, backfill, live load, and longitudinal bending while stiffness is the ability of a flexible pipe to resist deflection.

Rigid pipes are proper for open-cut such as clay pipe, reinforced concrete pipe, unreinforced Concrete pipe, Reinforced Concrete Cylinder pipe, Prestressed Concrete Cylinder pipe. Rigid pipes are designed to transmit the load on the pipe through the pipe walls to the foundation soil beneath. Load on the buried pipe is created by backfill soil placed on top of the pipe and by any surcharge and/or live load on the backfill surface over the pipe.

Flexible pipes are designed to transmit part of the load on the pipe to the soil at the sides of the pipe. This load is created by the backfill soil. There are some type of flexible pipe such as Steel pipe, Ductile Iron pipe, Corrugated Metal pipe, Fiberglass pipe, Polyvinyl Chloride pipe (PVC), High Density Polyethylene pipe (HDPE), Acrylonitrile Butadiene Styrene pipe (ABS). Normally unless the type of the soil limits the design, the flexible pipe can be used in open-cut method (Hashemi, 2008).

1.2.1.2 Trench Excavation

First physical step in open-cut method is to trench the ground to start the operation of either installing a new underground pipe or replacing the exiting utility. Based on Howard (1996), the trench width normally depends on the pipe outside diameter (OD), construction methods, and inspection requirements. Figure 1-4 shows a typical specification required width for trench. There are some design assumptions as certain trench width at the top or bottom regarding to the specification of the project. There are some successors based on the design condition of the trench such as amount of dewatering time and equipment, sheeting or shoring, and volume of the excavation which are logically effective on the cost of one open-cut project (Serajiantehrani et al., 2019).



"W" measured at top of foundation and bottom of bedding

Pipe Diameter		**W = Minimum Trench Bottom Width**	
< 150 mm	(< 6 in)	60 cm	(24 in)
150 - 450 mm	(6 - 18 in)	O.D. + 50 cm	(O.D. + 20 in)
> 450 mm	(> 18 in)	O.D. + 90 cm	(O.D. + 36 in)

Outside Diameter (O.D.) measured in mm (inches

Figure 1-4 Open-cut Trench Width Requirements (Hashemi, 2008)

1.2.1.3 Trench Wall

According to Howard (1996), trench wall supports such as sheeting, bracing, shoring, or trench shields should be used in conditions including:

- Where required by national, state, or local safety regulations
- Where sloped trench walls are not adequate to protect personnel in the trench from slides, caving, sloughing, or other unstable soil conditions
- Where necessary to prevent structural damage to adjoining buildings, roads, utilities, vegetation, or anything else that cannot be removed

- Where necessary to prevent disruptions to businesses, provide traffic access, etc.
- Where necessary to remain within the construction easement of right-of-way

Basically, there are two main types of trench walls, vertical and sloping so that each one includes specific cost parameter characteristics and is related to the type of pipe material, soil, and project conditions. Figure 1-5 shows a schematic view of trench wall.

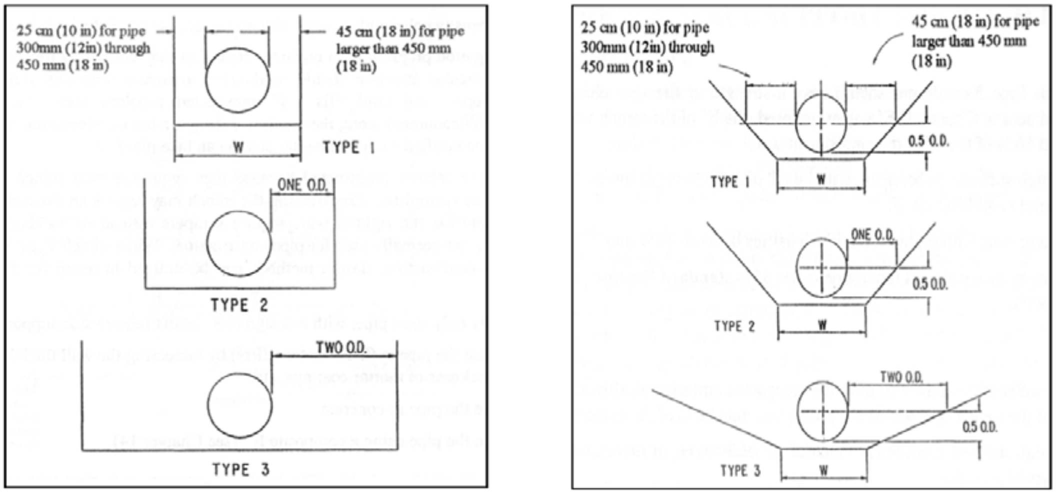


Figure 1-5 Site Clearances for Trench Walls: a) Vertical Trench Wall and b) Sloping Trench Wall. (O.D. is outside pipe diameter) (Hashemi, 2008)

1.2.1.4 Bedding and Laying

The bedding is the material placed on the bottom of the trench to provide uniform support for the pipe. Consistent support is essential to support the pipe longitudinally, as well as to spread out the load on the underside of the pipe. The bedding is placed in a way that the pipe will be at the appropriate elevation and slope when the pipe is laid on the bedding. The thickness of the bedding also varies depending on the type and size of pipe. Typically, the minimum bedding thickness is 4 to 6 inches (Howard, 1996).

1.2.1.5 Embedment

The embedment is the material placed around the pipe to act with the pipe together as a pipe-soil structure to support the external loads on the pipe. Each pipe-soil system has been selected or designed for the specific conditions of pipeline. The embedment is designed to serve different functions for either rigid or flexible pipe. The embedment for rigid pipe takes the load on the top of the pipe such as dead, live, or weight of the pipe and distribute the load to the soil on the bottom of the pipe. In the flexible pipe, the embedment gives the resistance to the pipe deflecting (Howard, 1996, Serajiantehrani et al., 2019).

1.2.1.6 Backfill and Compaction

Backfill is the material placed above the embedment soil and pipe which depending on the height of the embedment, backfill may or may not be in contact with the pipe. Usually the excavated material from the trench is used as backfill with a few exceptions such as scalping off large rock particles. When using a backfill material that will settle excessively, such as organic materials, frozen soil, and loosely-placed large mass of soil, the ground surface should be mounted over the trench, or other provisions should be made to prevent a depression over the pipe (Howard, 1996).

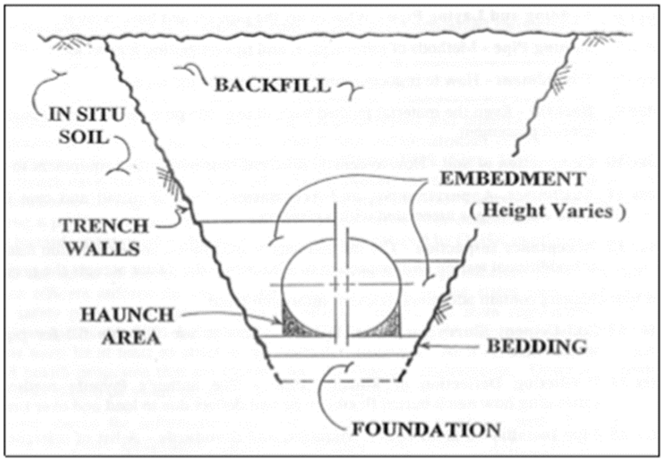


Figure 1-6 Cross Sectional View of an Open-cut Trench (Hashemi, 2008)

As Figure 1-6 shows, there are various steps in open-cut technique from excavation of the trench all the way to the compaction of the trench either in installing new underground pipeline or replacing the deteriorated or under–capacity size existing utility which each one of these operations consume the project budget.

1.2.2 Trenchless Technology Methods (TTMs)

Trenchless technology (TT) consists of a variety of methods, materials, and equipment for inspection, stabilization, rehabilitation, renewal, and replacement of existing pipelines and installation of new pipelines with minimum surface and subsurface excavation (Najafi, 2016).

Environmental and social costs, new and more stringent safety regulations, difficult underground conditions (containing natural or artificial obstructions, high water table, etc.) and new developments in equipment have increased demand for trenchless technology. These methods include installing or renewing underground utility systems with minimum surface or subsurface disruptions (Najafi and Gokhale, 2005).

As shown in Figure 1-7, TT methods are divided into two main areas as Trenchless Construction Methods (TCMs) and Trenchless Renewal Methods (TRMs). TCM include all the methods for new utility and pipeline installation, where a new pipeline or utility is installed. TRM include all the methods of renewing, rehabilitating and renovating, an existing, old or host pipeline or utility system (Mamaqani, 2014).

In summary, there are several advantages for trenchless renewal methods (TRMs) over conventional open-cut pipeline installation methods (Najafi and Gokhale, 2005):

- They take less effort in earthwork as TTs do not require select and native soil hauling, backfilling and compaction,
- They can be implemented in congested areas with minimum disturbance to traffic,

- They rarely require relocating existing underground utilities,
- They minimize the need for spoil removal and minimize damage to pavement and other utilities.

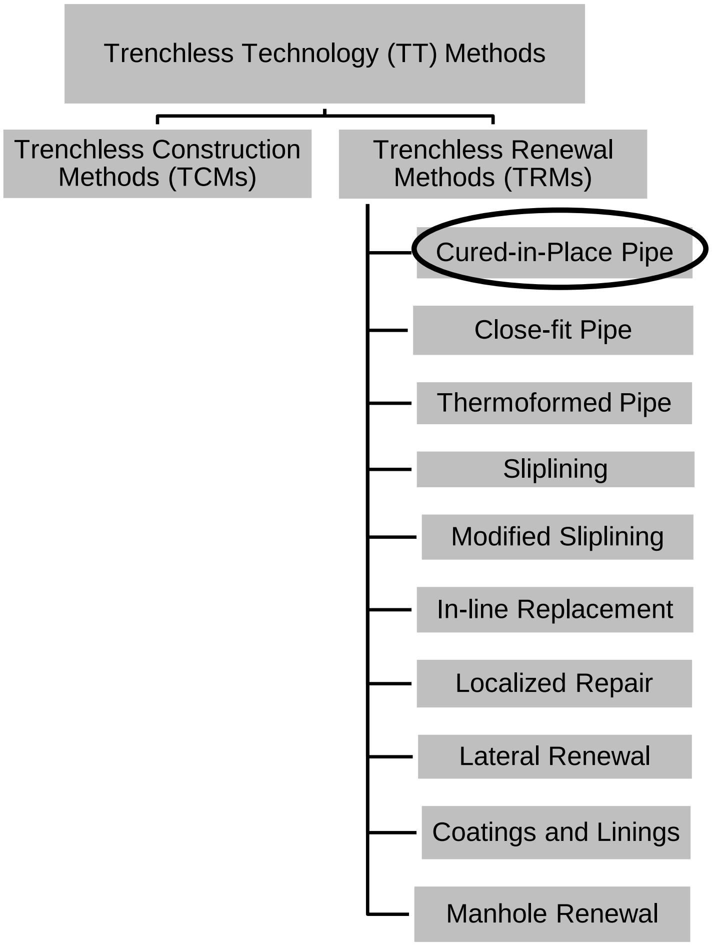


Figure 1-7 Trenchless Technology Methods
Adapted from Najafi & Gokhale, 2005

1.3 Cured-in-Place Pipe (CIPP) Method

1.3.1 CIPP Evolution

In 1971, Eric Wood, an engineer in U.K., 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, Ajdari, 2016).

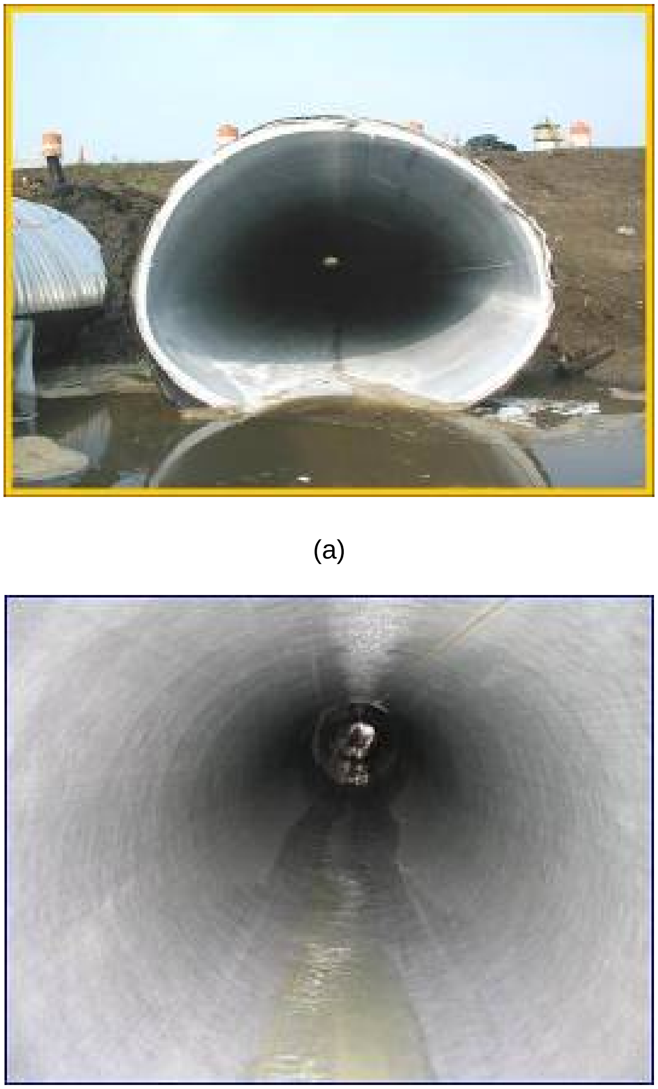
London was the first municipality that used Wood’s idea when they lined Marsh Lane sewer in Hackney, East London in 1971. The pipe was 100 years old, 230 feet in length, egg-shaped, and made from brick. In this procedure, the liner was pulled in and inflated inside the pipe. The work was performed by 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).

1.3.2 Cured-in-Place Pipe (CIPP) Renewal Method

CIPP trenchless renewal method can be used effectively for a wide range of applications that include storm and sanitary sewers, gas pipelines, potable water pipelines, chemical and industrial pipelines, and similar applications (Figure 1-8 (a and b)). The flexibility of uncured material makes CIPP especially suitable for different types of pipe geometries including straight pipes, pipes with bends, pipes with different cross-sectional geometries, pipes with varying cross sections, pipes with lateral connections, and deformed and misaligned pipelines. the old pipe and the like must be assessed before making a choice on the renewal system. CIPP is also used for localized repairs in a wide range of applications (Najafi, 2011).



(a)

(b)

Figure 1-8 (a and b) Cured-in-Place Pipe (CIPP)
Source: Insituform Technologies, Inc.

Several factors must be evaluated before choosing CIPP as the method of renewal for an individual project. Space availability, chemical composition of the fluid carried by the pipeline, number of service laterals, number of manholes, installation distance, renewal objectives, structural capabilities of vinyl ester and epoxy resin systems are typically used in industrial and pressure pipeline applications, where their tensile properties, special corrosion resistance, solvent resistance, and higher temperature performance are needed. These systems can also be used for sanitary sewers and house service laterals, however, will increase the costs (Zhao and Rajani, 2002, Najafi and Gokhale, 2005, Ajdari, 2016, Kaushal et al., 2019a, Alsadi, 2019).

The primary function of the fabric tube is to carry and support the resins until it is installed and cured. This requires that the fabric tube withstand installation stresses with a controlled amount of stretch but with enough flexibility to dimple at side connections and expand to fit the existing pipeline irregularities (Figure 1-9).

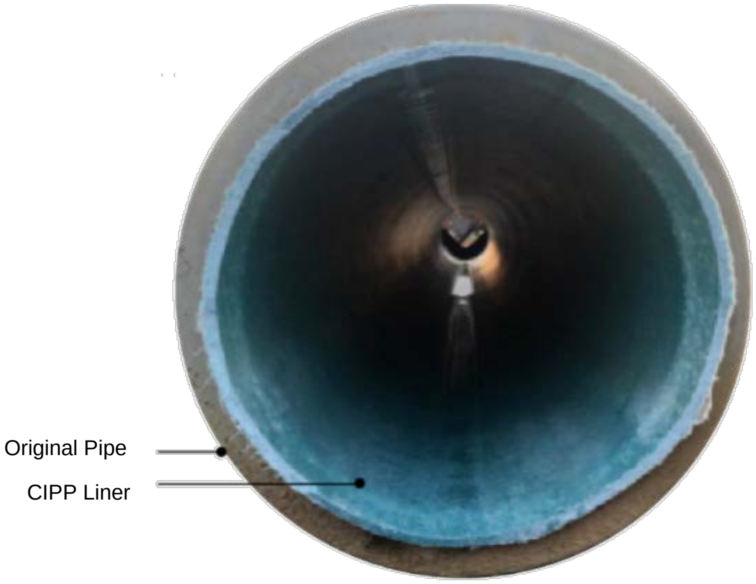


Figure 1-9 Original Pipe and CIPP Liner
Source: Robin Lloyd Available at: https://undark.org

The fabric tube material can be woven or nonwoven, with the most common material being a nonwoven, needled felt. Polyethylene, polypropylene and polyurethane coatings are commonly used on the exterior, or interior, or both surfaces of the fabric tube to protect the resin during installation. The layers of the fabric tube can be seamless, as with some woven material, or longitudinally joined with stitching or heat bonding (Zhao and Rajani, 2002, Najafi, 2005, Ajdari, 2016, Alsadi, 2019).

1.3.3 CIPP Procedure

The CIPP procedure begins with a resin-impregnated fabric tube, which is inserted into the defective pipe from an upstream manhole (Figure 1-10).

Figure 1-10 CIPP Installation Procedure
Source: Insituform Technologies, Inc.

Water or pressurized air inversion or winching is used for tube installation (Figure 1-11) 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.

Figure 1-11 Inlet Manhole (Kaushal et al., 2019)

After curing, the fabric becomes hard in the host pipe. CIPP has been utilized for both structural and nonstructural purposes (Najafi, 2011). Table 1-1 presents major specifications of different CIPP installation methods.

Table 1-1 Major Specifications of Different CIPP Installation Methods

Installation method	Diameter (in.)	Maximum insertion (ft)	Liner material	Applications
Inverted in place	4-108	3000	Thermoset resin/ Fabric composite	Gravity and pressure pipelines
Winched in place	4-54	1000	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 (Figure 1-12). Liner dimpling can assist in identifying the laterals location. However, dimpling of higher strength liners is less distinguishable (EPA, 2012).

Figure 1-12 Outlet Manhole (Kaushal et al., 2019)

1.4 Importance of Sustainability in Design of Pipelines

For sustainable design and construction, renewal and replacement of pipelines, economic, environmental and societal factors need to be combined and can be expressed using three overlapping ellipses, as shown in Figure 1-13. There is also an understanding that social and economic impacts will eventually be constrained or controlled by environmental considerations when limiting values of available materials required to sustain economic growth are reached (ASCE, 2019).

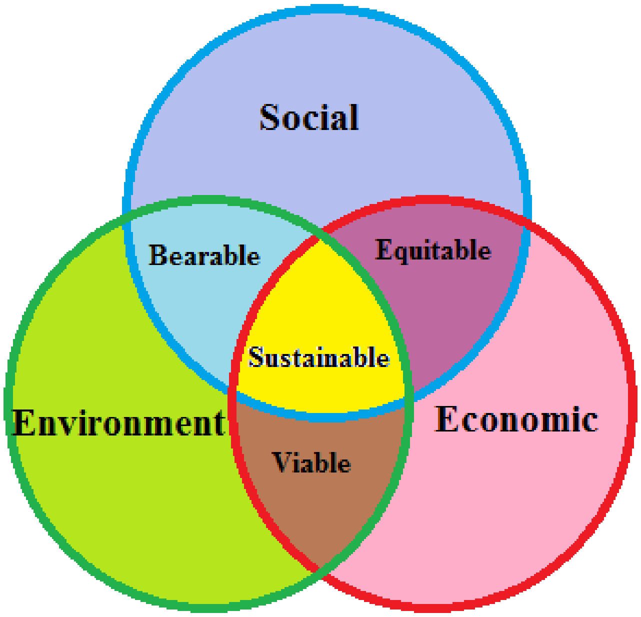


Figure 1-13 Three Pillars of Sustainability
Source: Available at https://www.thwink.org

Common to both the public policy and business perspectives is recognition of the continued need to support a growing, often global, economy while reducing the social, environmental and economic costs of growing underground infrastructure. Sustainable design and construction of pipelines can be facilitated or guided by public policies that integrate environmental, economic, and social values in the decision making process (ASCE, 2019).

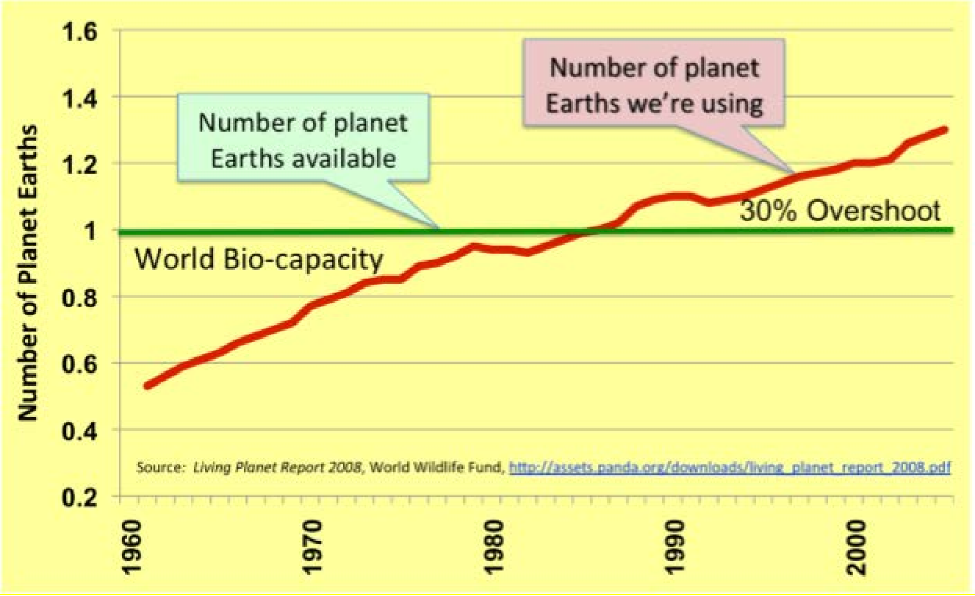
As said above, successful, long-term implementation of sustainable growth and development for underground pipelines reflect on the synergies between the business and the environmental issues and not on trade-offs, credits or mitigation banking so often touted as “green” solutions. It is recognized that there is a need to get to truly sustainable project development but also that there is the practicality (i.e., obtaining public acceptance) that this evolution and thus the level of improvement will occur in steps (ASCE, 2019):

- Conventional – state of the practice, specific sustainability considerations not addressed; i.e., “business as usual”
- Improved – incremental improvements above conventional practice reducing impacts previously expected
- Sustainable – achieves equilibrium with environmental and resource limitations without adverse impacts on society or excessive costs; i.e., “not making things worse”
- Restorative – restores resources and ecological capacity, improves economic and social systems; i.e., “investing in the future” (Fig. 1-14).

The USEPA has further defined four parameters specific to pipeline infrastructure sustainability as follows (ASCE, 2019):

- Better Management of water and wastewater utilities can encompass practices like asset management and environmental management systems. Consolidation and public/private partnerships could also offer utilities significant savings.
- Full Cost Pricing so that utility rates reflect the true cost of service and maintaining its assets.
- Efficient Water Use is critical, particularly in those parts of the country that are undergoing water shortages. Utilities provide incentives through its water rates to encourage more efficient use of water by customers to protect limited water resources. Water waste includes not just leakage but excessive flushing to overcome poor water quality. Utilities need to promote water conservation not water use.
- Watershed Approaches that look more broadly at water resources in a coordinated way. Regional approaches can often be more efficient and reduce duplication of facilities.

Within a global economy, the basic tenants of sustainable development need to be applied on a global scale. One consequence of over-development are the inarguable consequences of climate change. While climate change may not be totally attributable to human activities, there can be little doubt that they are a contributing factor over which we have some control. It has been recognized for some time that human beings use world's resources faster than they can be replaced, as illustrated in Figure 1-14.



Source: *Living Planet Report 2008*, World Wildlife Fund, http://assets.panda.org/downloads/living_planet_report_2008.pdf

Figure 1-14 Utilization Rate of Resources (ASCE, 2019)

1.5 Cost Comparison: Open-cut Replacement and Trenchless Renewal

Figure 1-15 shows a breakdown of different cost categories for open-cut replacement and trenchless renewal projects. The main costs include material, labor, social, and indirect/overhead.

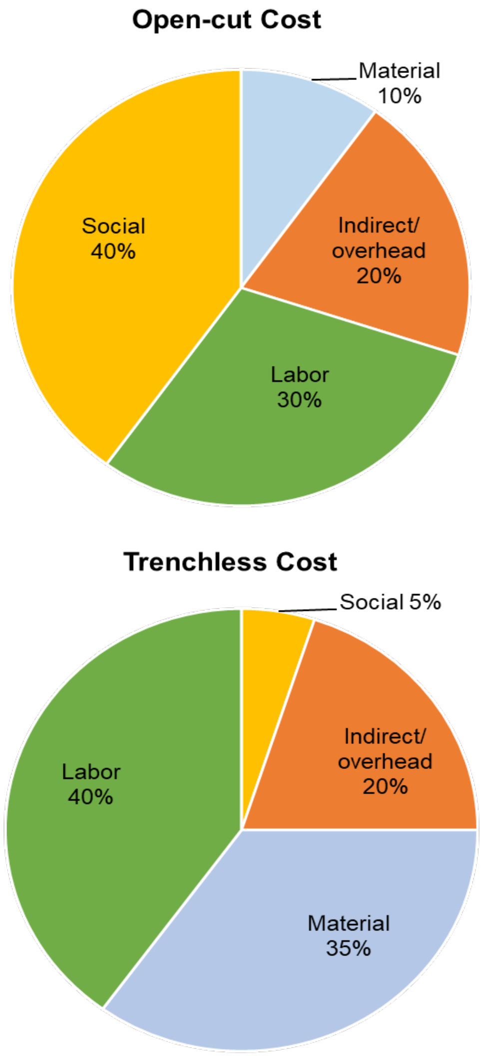


Figure 1-14 Breakdown of Main Cost Categories for Open-cut
Replacement and Trenchless Renewal
Source: Najafi and Gokhale, 2005

It can be observed that there is a significant difference between social costs of both the methods. It is 40% for open-cut pipeline replacement whereas it is only 5% for trenchless renewal of pipelines. Both social and environmental costs have been compared and analyzed in Chapter 3 of this Dissertation.

1.6 Environmental Cost Assessment of Pipeline Renewal and Replacement

1.6.1 Environmental Cost Assessment

Environmental cost assessment is a scientific method for analysis of the environmental costs associated with the life cycle of a product (UNEP/SETAC, 2009). In this process (Figure 1-16), the information about the raw materials, processes, and product manufacturing (pipe) are fed into the system (SimaPro software in this Dissertation: discussed in detail in Section 3.3.2 of Chapter 3) to get the associated emissions and waste output.

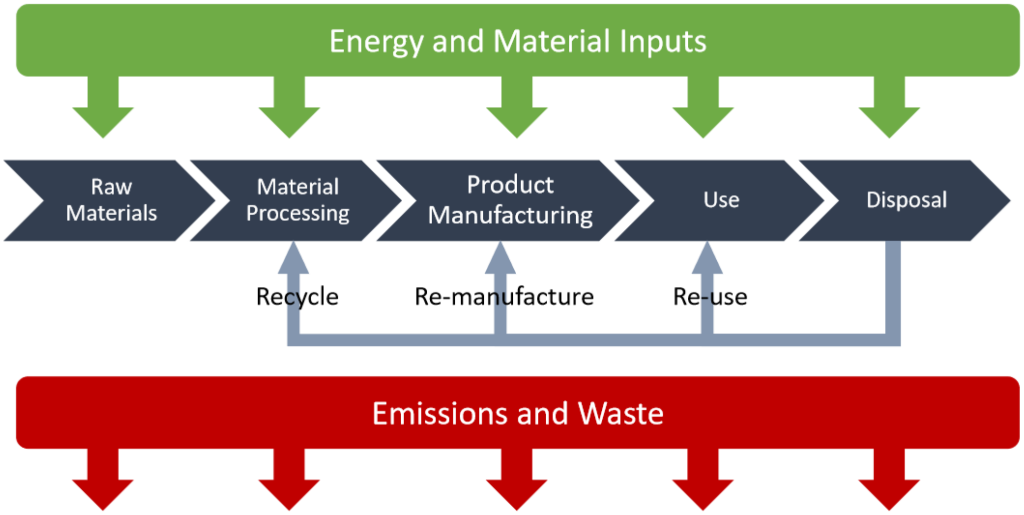


Figure 1-15 Environmental Impact Assessment Process
Source: Earthshift, 2009

It is an established methodology to evaluate environmental cost impacts over the entire life cycle as per ISO standards 14040 and 14044 on principles and framework, and requirements and guidelines, respectively. Figure 1-17 presents an overview of sustainability principles involved in the environmental impact analysis.

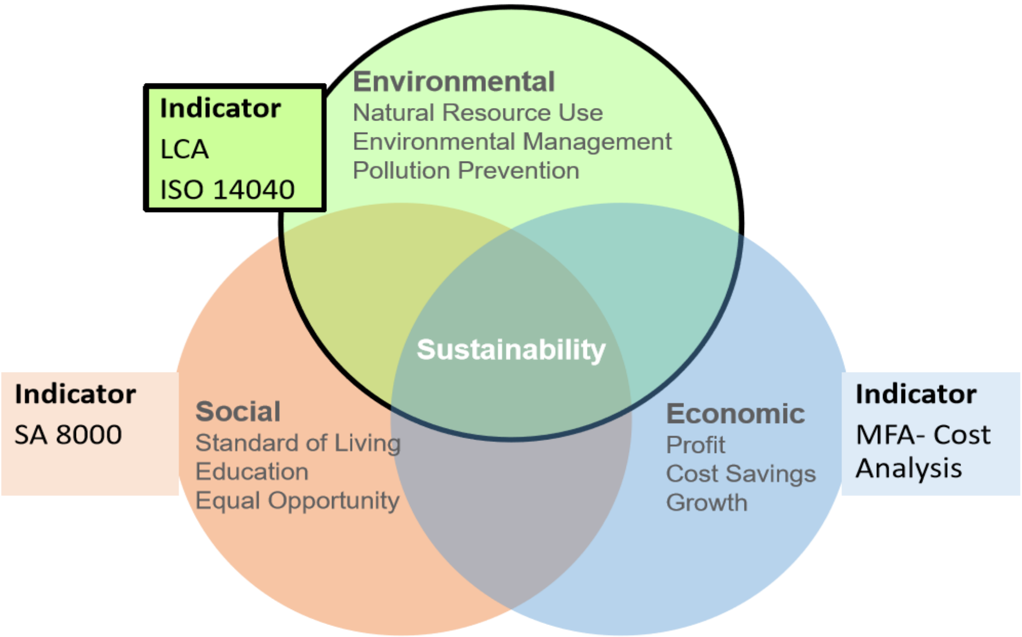


Figure 1-16 Overview of Sustainability Principles involved in the Environmental Impact Analysis
Source: Earthshift, 2009

1.6.2 Purpose of *Environmental Impact Assessment*

The purpose of environmental impact assessment has been discussed as follows:

- Identifying opportunities to improve the environmental performance of products at various points in their life cycle;
- Informing decision-makers in industry, governmental or non-governmental organizations (e.g., strategic planning, priority setting, product or process design or redesign); and
- Selection of relevant indicators of environmental performance (UNEP/SETAC, 2009).

1.7 Social Costs of Pipeline Renewal and Replacement

The social costs of pipeline renewal and replacement include inconvenience to the general public and damage to surrounding and existing structures (Figure 1-18). Social costs are becoming more important as the public awareness grows and the needs to conserve and protect our environment and quality of life are more understood. These needs have resulted in identification and evaluation of social costs of utility and pipeline installations. Using trenchless methods can significantly reduce social costs. Social costs for open-cut replacement can be as high as several times the value of construction, whereas for trenchless projects as low as 3 to 10 percent of the total cost of the project (Najafi and Gokhale, 2005).

Figure 1-17 Social Costs of Open-cut Pipeline Replacement
Source: www.gundacorp.com

If social costs are evaluated and included in the overall cost of a project, trenchless technology methods can prove to be more cost-effective than open-cut method. For the purpose of this research, following social costs of CIPP renewal and open-cut replacement are included:

- Vehicular traffic disruption

- Road and pavement damage
- Damage to adjacent structures
- Business and trade loss
- Damage to detour roads
- Site and public safety
- Environmental impacts

Each of the above social costs are described and calculated in section 3.3.3 of Chapter 3.

1.8 Need Statement

According to Hashemi (2008), the traditional open-cut pipeline replacement method includes direct costs that greatly increased by the need to restore ground surfaces such as sidewalks, pavement, and landscaping. Moreover, considering social and environmental factors, open-cut methods have negative impacts on the communities, businesses, and commuters due to surface and traffic disruptions. In comparison, CIPP renewal method is considered a safe, cost-effective, efficient, and productive alternative and there is no need to excavate the old pipe and replace it by digging a trench (Das et al., 2016).

Additionally, almost all past CIPP studies have focused on the direct costs, and its social and environmental cost impacts are poorly investigated and documented (Allouche et al., 2012). With an increase in the renewal and replacement of sanitary sewer infrastructure by CIPP and open-cut pipeline methods, there is a need to better understand the associated environmental and social costs (Ajdari, 2016).

Although there have been several preliminary studies to compare trenchless CIPP with open-cut pipe installation, no in-depth study has been conducted so far to compare the environmental and social costs between these two methods. To determine the cost of possible pipe rehabilitation alternatives, a comprehensive environmental and social cost comparison will be an effective decision-making tool in the planning and design phase of any pipeline project.

1.9 Objectives

The primary objective of this research is:

- To carry out a comparison of environmental and social costs of trenchless cured-in-place pipe (CIPP) renewal with open-cut pipeline replacement for small diameter sanitary sewers[1].

The secondary objectives of this research are:

- To present a methodology for an in-depth analysis of social and environmental costs of CIPP and open-cut for different types of pipelines, locations and diameters, and to provide a decision tool for designers and project owners.
- To identify the factors that influence the environmental and social costs of CIPP and open-cut pipeline methods.

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[1] Small diameter = 8 in. – 12 in.

1.10 Scope of Work

The scope of this research is illustrated in the following Table 1-3.

Table 1-2 Scope of Research

Method	Included	Not Included
CIPP	• Environmental and social costs • Sanitary sewers • Pipe diameter: 8-12 in. • Vinyl ester resin • Curing type: steam	• Storm sewers • Effect of different resins • Effect of different curing methods • Different liner thicknesses
Open-cut	• Environmental and social costs • Sanitary sewers • Pipe diameter: 8-12 in. • Pipe material: PVC	• Effect of different soils • Effect of water table

1.11 Hypotheses[2]

1.10.1 Hypothesis 1

Null Hypothesis (H_0): The environmental cost of CIPP renewal method is more than open-cut pipeline replacement method.

Alternative Hypothesis (H_A): The environmental cost of CIPP renewal method is equal to open-cut pipeline replacement method.

1.10.2 Hypothesis 2

Null Hypothesis (H_0): The social cost of CIPP renewal method is more than open-cut pipeline replacement method.

Alternative Hypothesis (H_A): The social cost of CIPP renewal method is less than open-cut pipeline replacement method.

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[2] This dissertation was not able to test this hypothesis due to lack of availability of variability of data.

1.12 Overall Methodology

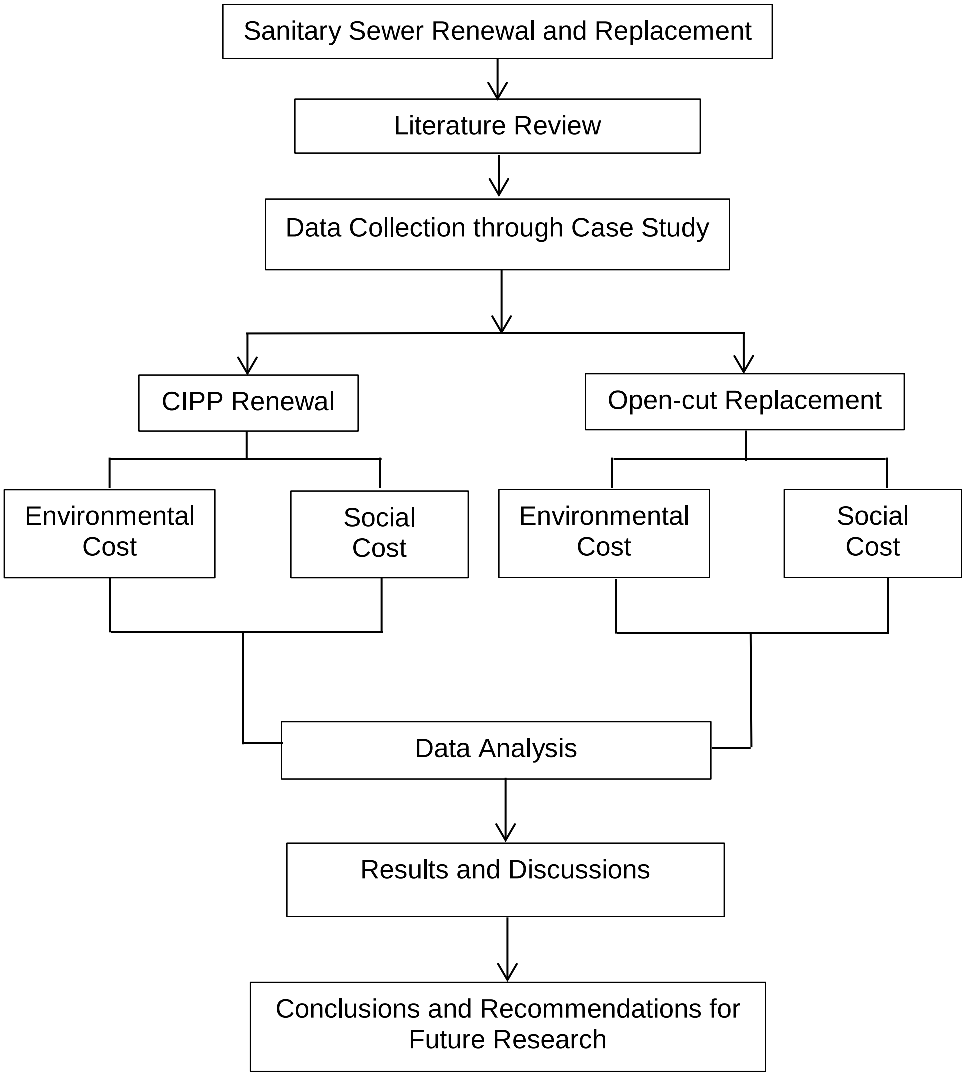

Figure 1-18 Research Methodology

1.13 Contribution to the Body of Knowledge

The key contributions of this study are:

- Presentation or a framework and methodology for environmental and social costs analysis of pipeline installation and replacement.

- An evaluation and comparison of environmental and social costs per unit length and as a function of diameter for trenchless cured-in-place pipe (CIPP) renewal with open-cut pipeline replacement.
- An Identification of the factors that influence the environmental and social costs of CIPP and open-cut pipeline methods.

1.14 Dissertation Organization

This dissertation is organized into the following five chapters:

- Chapter 1 presents a general introduction and background to the underground pipeline construction methods, i.e., open-cut pipeline replacement and CIPP renewal method. It also illustrates the concept of environmental and social costs, and presents problem statement, objectives, scope of work, hypothesis, methodology, and contribution to the body of knowledge.
- Chapter 2 presents a comprehensive literature review of costs of trenchless CIPP renewal method and open-cut pipeline replacement. It also reviews various sustainability aspects like life cycle assessment, owner costs, social costs and its reduction, and its application in the underground utility system.
- Chapter 3 presents the methodology adopted to obtain the environmental and social costs of CIPP renewal method and open-cut pipeline replacement for small diameter sanitary sewers.
- Chapter 4 presents the results, analysis, and discussion of environmental and social costs of CIPP renewal with open-cut pipeline replacement. In addition, discussion of results and limitations of this dissertation are presented in this chapter.

- Finally, Chapter 5 presents conclusions and recommendations for future research.

1.15 Chapter Summary

This chapter introduced the state of underground infrastructure in the North America. A general background of open-cut pipeline replacement and trenchless cured-in-place pipe (CIPP) renewal was presented. Problems and costs associated with replacement and renewal of underground utilities, along with concept of environmental and social costs were highlighted. In addition, the need statement, objectives, scope, hypotheses, methodology, contribution to the body of knowledge, and organization of this dissertation were also presented.

Chapter 2

Literature Review

2.1 Introduction

Chapter 1 presented a general background of open-cut pipeline replacement and trenchless cured-in-place pipe (CIPP) renewal and environmental and social costs associated with them. In this chapter, a literature review of costs of trenchless CIPP renewal and open-cut pipeline replacement is presented. In addition, this chapter reviews various sustainability aspects like life cycle assessment, owner costs, social costs and its reduction, and its application in the underground utility system.

2.2 Cost of Open-cut Pipeline Replacement and Trenchless Technology Renewal Methods

Tighe et al. (1999) studied traffic delay cost savings associated with trenchless technologies. This study focused on cost savings in trenchless methods due to the elimination of traffic disruptions associated with excavation and trenching in conventional open-cut methods. Tighe et al. suggested a methodology to consider the cost of traffic delays associated with open-cut trenching methods. The results showed that eliminating traffic disruption in trenchless technologies makes them an economical alternative to open-cut replacement.

Tighe et al. (2002) also performed a study to compare the overall project costs of traditional open-cut methods with trenchless technologies. They considered different factors, such as performance, future maintenance costs, and user-delay costs in the study. It was concluded that surface restoration costs were comparable and trenchless construction methods a feasible alternative to open trenching options, especially in developed urban areas. The results indicated that traditional open cut methods reduce the life of pavement about 30 percent and increase the maintenance and rehabilitation costs of pavement from \$64/m^2 (690/ft^2) to \$110/m^2 (1,185/ft^2). However, trenchless technologies have fewer costs associated with pavement disruptions.

According to Zhao and Rajani (2002), increase in the cost of pipe renewal with size is due to the increased level of complexity and difficulty of carrying out the renewal work. To demonstrate the range of costs in one location, the cost diameter relationship for the CIPP projects in Phoenix is shown in Figure 2-1. In the same study, Zhao and Rajani (2002) reported a cost curve for open-cut pipeline replacement (Figure 2-2).

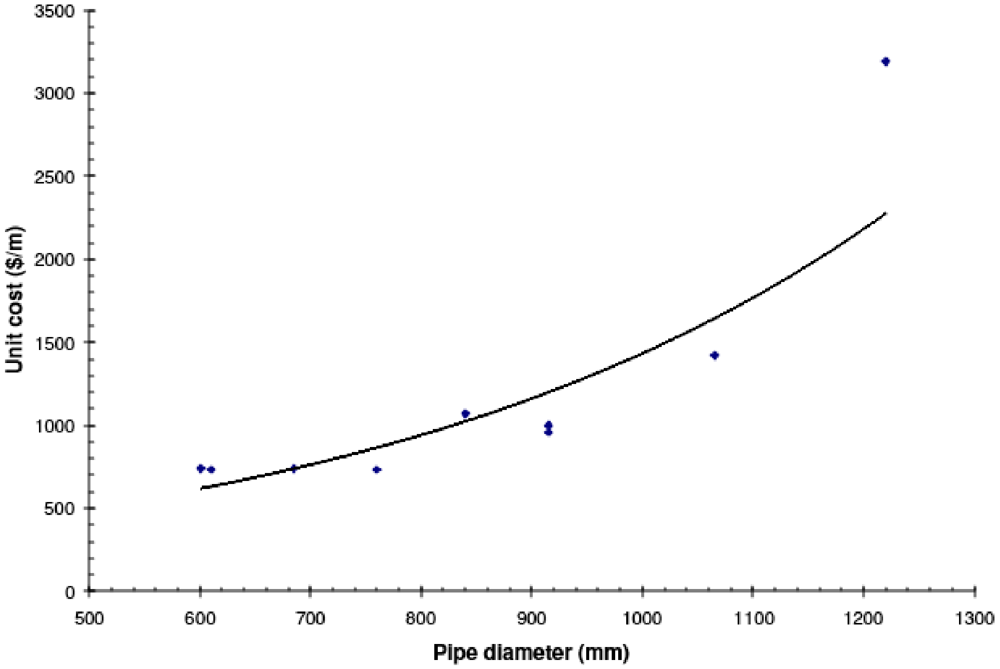

Figure 2-1 Increase of CIPP Renewal Cost with Pipe Diameter
(Zhao and Rajani, 2002)

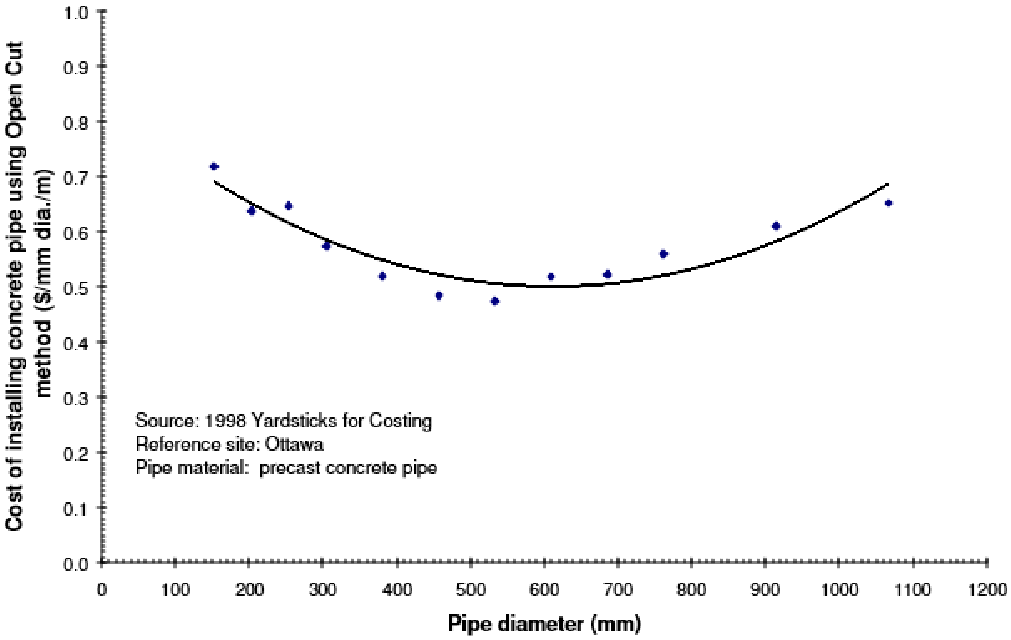

Figure 2-2 Cost Curve for Open-cut Pipeline Replacement
(Zhao and Rajani, 2002)

Gangavarapu (2003) presented a case study to compare traffic and road disruption costs during utility construction when open-cut and trenchless construction methods are used. The author presented a breakdown of social costs involved in utility construction. He investigated traffic flow rates and patterns during two sample utility construction projects to analyze the impact of construction on the traffic flow. Using traffic delay estimates obtained from the traffic flow and length of detoured roads, he developed a flow chart for estimating costs of traffic disruption. He did not consider costs due to damage to pavement, environmental impacts, safety issues, and noise and dust in his study. Although he considered important social costs of a utility project, he did not compare direct cost of open-cut with trenchless techniques which is the main subject of this thesis.

Najafi and Kim (2004) presented an investigation of parameters involved in constructing underground pipelines with trenchless methods in urban centers in comparison with conventional open-cut method. Their study included a breakdown of the engineering and capital costs of the construction and the social costs for both methods. They considered life-cycle cost of a project with the point of view of pre-construction, construction, and post-construction parameters. They asserted that considering the life-cycle costs of a project, innovative methods and trenchless technology are more cost-effective than traditional open-cut method. Although the authors considered cost parameters for both trenchless and open cut methods, they did not consider an actual cost data analysis for comparison of these two methods. Such actual cost analysis is the main consideration of this thesis.

According to Allouche and Gilchrist (2004), communities that surround an operating construction site often found themselves subjected to negative impacts. Construction activities can have a significant effect on their surrounding environment, and the negative impacts are often called social cost as shown in Figure 2-3. Social cost, while widely acknowledged, is rarely considered in the design, planning, or bid evaluation phases of the construction project in North America.

Social cost can range from costs associated with traffic conditions (e.g., delays and increased on vehicle operation expenses), environmental costs (e.g., pollution), costs resulting from decreased safety (e.g., higher rate of traffic accidents and risk to pedestrians), accelerated deterioration of road surfaces (e.g., due to pavement cuts), lower business turnovers, decreased property values, and damage to existing utilities.

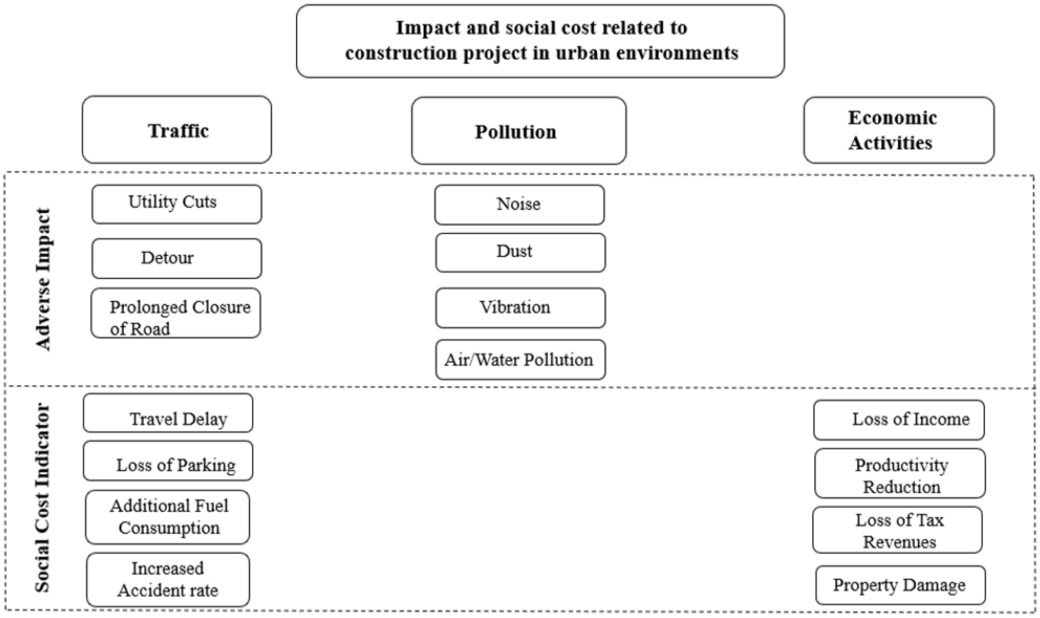

Figure 2-3 Potential Impacts and Social Cost Related to Pipeline Construction Projects (Allouche and Gilchrist, 2004)

Atalah (2004) studied interaction between pipe bursting and surrounding soil especially in sand and gravel with the goal of comparing the cost effectiveness of pipe bursting versus open-cut. He studied a comparison of these two methods based on soil characteristics. He did not concentrate on the relationship between cost as a function of pipe diameter and length for open-cut and pipe bursting methods.

According to Piehl (2005), the cost for CIPP method ranges from $100 per linear foot for 18-inch diameter pipe ($5.50 per inch-per-foot) to $800 or more per linear foot for large-diameter pipe. Shahata (2006) predicted the life cycle cost for water mains, taking into consideration the uncertainty involved in determining its service life, discounted rate, and the cost of new installation or rehabilitation alternatives. Monte Carlo simulation was used to address the probability factor. Sensitivity analysis was performed to examine the effect of variability of cost information and deterioration on the LCCA. It was found that the open-cut pipeline method proved to be cost-effective for large diameter pipeline ranges (i.e. >30”) than CIPP method.

Lee (2006) presented the advantages in costs of trenchless technology, particularly pipe bursting, compared to the costs of traditional open-cut. A practical example of cost comparison of pipe bursting and open-cut methods was presented with the actual cases and a price range of the actual pipe bursting projects was worked-out to show the analysis of the different project costs in the price range. It was found that pipe bursting method showed advantages in terms of cost, time, and minimum disruption to the environment compared to open-cut method.

Lee et al. (2007) described the cost of an actual pipe bursting project on the campus of Michigan State University (MSU) and compared with estimated costs of traditional open-cut pipeline method. A cost estimate based on the quantity of pipe bursting project was prepared. A cost comparison with two other pipe bursting projects was also made to show the price range of pipe bursting projects. It was found that average estimated cost of traditional open-cut pipeline method was $380/LF for 18-inch diameter pipe.

According to Jung and Sinha (2007), there are various costs related to a renewal pipeline project either with open-cut or pipe bursting. The authors considered some parameters related to these kinds of projects; namely, direct, social, and environmental. They asserted that the interrelation among these costs is becoming more important with growing public awareness of societal and environmental issues. They provided two general formulas for open-cut and trenchless methods as:

$$TCOC = C_{\text{Direct}} + C_{\text{Social}} + C_{\text{Environmental}} + C_{\text{Other Factors}}$$

$$TCTT = C_{\text{Direct}} + C_{\text{Social}} + C_{\text{Environmental}} + C_{\text{Other Factors}}$$

Where,

TCOC = total cost of open-cut method

TCTT = total cost of trenchless technology

C_{Direct} = earthwork cost, restoration cost, overhead cost, and so on (including material, labor, and equipment cost).

C_{Social} = traffic delay cost, income loss of business, and so on.

$C_{Environmental}$ = noise pollution cost, air pollution cost, and so on.

$C_{Other\ Factors}$ = productivity loss cost, safety hazard cost, structural behavior cost, and so on.

The authors concluded that with above parameters, pipe bursting as a trenchless method would be less expensive than open-cut technique. However, they did not consider any actual project data for prediction of the pipe bursting or open-cut costs.

Adedapo (2007) has verified and compared the impact of traditional open cut method and horizontal directional drilling (HDD) as a trenchless technology method on the life of pavement structure. He considered deteriorating aspects of open-cut construction to asphalt pavement and concluded that HDD would cause less damage to the pavement than open-cut. His focus in this research was more on physical aspects of two methods and did not cover cost aspects. In this thesis, the focus is on cost comparison of open-cut and pipe bursting methods.

Woodroffe and Ariaratnam (2008) presented a comparison of risk factors of another trenchless technology technique called horizontal directional drilling (HDD) and compared those factors with traditional open cut applications. They found that HDD can minimize risks and reduce the overall costs of construction in an urban environment. The main concentration of their research was based on risk factors shown in Figure 2-4, however; they failed to present a cost analysis of the two methods.

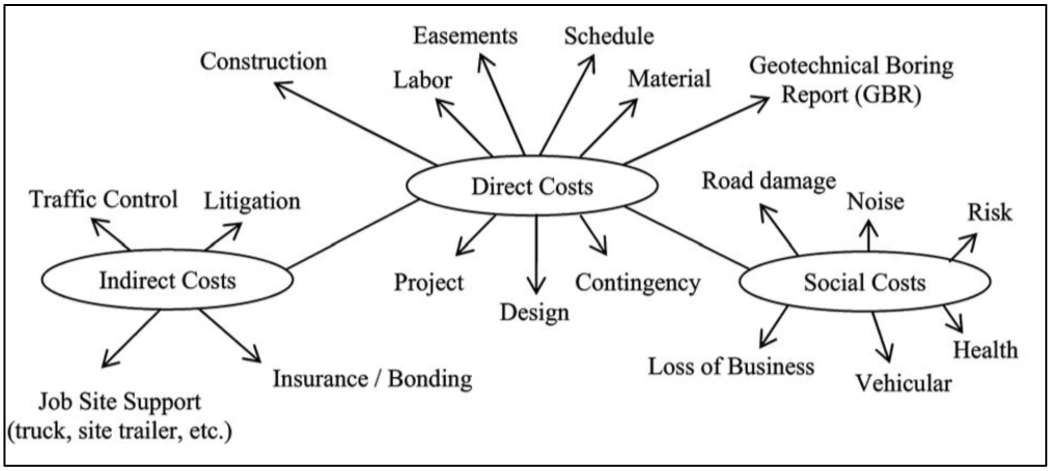

Figure 2-4 Cost Identification for Underground Utility Project (Woodroffe & Ariaratnam, 2008)

Hashemi (2008) conducted a cost comparison for pipe bursting and open-cut pipeline installations. This study included a case study as an example of a cost comparison for replacing sewer pipeline in the city of Troy, Michigan. The results of the study found that the pipe bursting method is much less expensive than the open-cut method for replacing the underground sewer pipelines. Also, the results from the case study found that the cost of installation per-inch-per-foot of pipe bursting is $11per-inch-per-foot while for open-cut is $18 per-inch-per-foot. Consequently, there is $7 per-inch-per-foot or about 40% saving by using trenchless pipe bursting method.

Maldikar (2010) investigated the loss in construction productivity due to surrounding outdoor noise conditions and found the relationship between the surrounding varying noise conditions and rate of accidents. A case study was conducted under varying noise conditions at a construction job site. A total of 8 subcontractor crews were surveyed and studied, working simultaneously on 2 building sites, performing similar work, but under varying sound conditions using Method Productivity Delay Model (MPDM). Results were gathered, and data was analyzed to identify the problems. It was found that rate of accidents were highest for sound levels above 90 dB with an average of 1.35 accidents per person per year, moderate for sound levels ranging between 80 dB to 90 dB with an average of 0.33 accident per person per year, and least for sound levels below 80 dB with an average of 0.26 accident per person per year.

Hashemi et al. (2011) evaluated the CIPP AWWA Class IV, pipe bursting, and open-cut methods based on cost, diameter size ability, and service re-connection to find out the best renewal option for water main distribution. They used statistical techniques to analyze the data for 6, 8, and 12 in. diameter pipes and found the average costs of open-cut and CIPP pipeline renewal as $750/ft and $325/ft, respectively.

Kamat (2011) compared the generation of respirable suspended particulate matter (RSPM) between an open-cut and trenchless technology method to justify the need for replacing traditional open-cut methodologies with trenchless methods. He used the sampled filter paper to determine the amount of RSPM in each of the sampled sites to analyze the results. The detailed results were then compared with the EPA to check the allowed RSPM in the air from open-cut and trenchless methods. The average RSPM generated for an open-cut and trenchless technology sites were 59.45~60 and 34.28~35 micrograms/m^3, respectively.

Kulkarni et al. (2011) studied a cost comparison of horizontal directional drilling (HDD) with traditional open cut installation in three different projects. These projects included installation of a 100 mm (4 in.) and a 150 mm (6 in.) PVC pipe in Texas, and a 150 mm (6 in.) PVC pipe in Florida. The results of cost analysis indicated that HDD is more cost effective than open cut for the installation of the small diameter PVC pipelines, with an average of 39 percent in these case studies.

Ariaratnam et al. (2013) examined environmental impact, costs, and social impacts of four construction techniques: open cut, pilot tube microtunneling, horizontal directional drilling, and vacuum micro-tunneling technology, which are common methods in the installation of underground utility infrastructure. The paper contributed to developing an overall underground sustainability index rating (USIR) through case studies based on the aforementioned factors. An installation project in Portland, Oregon, was used as a case study to demonstrate the application of USIR. The project consisted of 313 m (1,027 ft) of 400 mm (16 in.) PVC sewer line. The project costs were estimated, all cost factors related to this project were considered, and a subjective evaluation quantified social impacts. The results emphasized the inherent advantages of trenchless methods in these areas.

In another study, Ariaratnam et al. (2014) provided a discussion on trenchless technologies, especially pipe bursting trends, for replacement and renewal of underground systems. The study included results from a survey questionnaire examining 886 projects from 2007 to 2010 in Canada and the United States, and the results supported the advantages of trenchless technologies.

Islam et al. (2014) assessed social costs in trenchless projects, comparing them to traditional trenching methods through five case histories in different countries, including the United States, Austria, Italy, and Belgium. They used the Social Cost Calculator (SCC) developed in the Trenchless Technology Center (TTC) at Louisiana Tech University, and the results showed that the social cost of trenchless alternatives are significantly lower than the open cut method, and trenchless methods reduce a project’s associated social costs by a factor of 5 to 17.

Whitehead et al. (2015) studied various challenges in constructing the underground pipeline in a heavily-populated area through the Southern Delivery System (SDS) in Colorado. The study identified some challenges with potential disruption to neighbouring businesses, traffic control, safety, construction noise, vibration, and dust.

Whitehead et al. found that trenchless technologies saved time and money in this project, and also facilitated a safer project with fewer social inconveniences.

As per Khan and Tee (2015), the carbon price is based on the social cost of carbon (SC-CO_2) which generally refers to the cost to mitigate climate change or the marginal social damage from one ton of emitted carbon. However, the actual carbon price is often determined by the market value.

EPA (2016) and other federal agencies are using the estimates of the social cost of carbon to evaluate the climate impacts. The social cost of carbon is measured in dollars. The SC-CO_2 is meant to be a general estimate of climate change damages and includes, among other things, changes in net agricultural productivity, human health, property damages from increased flood risk and change in energy system costs, such as reduced cost for heating and increased costs for air conditioning. Estimates of the SC-CO_2 are a helpful measure to assess the climate impacts of CO_2 emissions change.

Table 2-1 summarizes the Social Cost-CO_2 estimates for the years between 2010 to 2050. The central value is the average of SC-CO_2 estimates based on the 3 percent discount rate. For purposes of capturing uncertainty around the SC-CO_2 estimates in regulatory impact analysis, the interagency working group emphasizes the importance of considering all four SC-CO_2 values (EPA, 2016).

Table 2-1 Social Cost (SC) of CO_2 Estimates from 2010 to 2050
(in 2007 dollars per metric ton of CO_2)
Source: EPA, 2016

Year	5% discount rate average	3% discount rate average	2.5% discount rate average	High impact at 3% discount rate
2010	10	31	50	86
2015	11	36	56	105
2020	12	42	62	123
2025	14	46	68	138
2030	16	50	73	152
2035	18	55	78	168
2040	21	60	84	183
2045	23	64	89	197
2050	26	69	95	212

According to Monfared (2018), trenchless technologies provide cost effective alternatives to traditional open-cut pipeline installations as these methods offer less trench and less footprint, and they are environmentally friendly.

2.3 Factors Affecting Failure Rate of Pipelines

Presently, an extensive research effort has been made to develop models for predicting the failure rate of pipelines. The factors utilized in these models can be classified into two clusters based on; (1) whether these factors are static or dynamic through the lifecycle of pipelines and (2) whether these factors are physical or environmental or operational (Karimian, 2015).

After reviewing previous studies, it was observed that the second type of classification is more widely used in the recent research efforts.

2.2.1 Static and Dynamic Factors

Stone et al. (2002) categorized factors contributing to the failure of water pipelines into two groups: static factors and dynamic factors. The characteristics of static parameters do not depend on the time, but dynamic factors’ specifications change over time. Static parameters include the diameter, length, soil type, pipe material, etc.

On the other hand, the age, cumulative number of breaks, soil corrosivity and water pressure are examples of dynamic factors influencing pipe failure rate. Osman and Bainbridge (2011) studied the effect of time-dependent variables like pipe age, temperature and soil moisture on the deterioration of water pipes. Static factors such as soil type, length, wall thickness and diameter of the pipe were not considered in their study because of the unavailability of reliable data (Karimian, 2015).

2.2.2 Physical, Environmental, and Operational Factors

InfraGuide (2003) classified the factors contributing to the failure of pipes to three main categories; physical, environmental and operational as shown in Table 2-2. According to InfraGuide (2003), physical factors include pipe material, pipe wall thickness, pipe age, pipe vintage, pipe diameter, type of joints, thrust restraint, pipe lining and coating, dissimilar metals, pipe installation and pipe manufacture. In other researches, pipe length and buried depth are also known as physical factors.

InfaGuide (2003) considered pipe bedding, trench backfill, soil type, groundwater, climate, pipe location, disturbances, stray electrical currents, and seismic activity as the environmental factors. While, other researchers included rainfall, traffic and loading, and trench backfill as the environmental factors as well.

Table 2-2 Factors Affecting Pipe Failure (Karimian, 2015)

Factor		Explanation
Physical	Pipe material	Pipes made from different materials fail in different ways.
	Pipe wall thickness	Corrosion will penetrate thinner walled pipe more quickly.
	Pipe age	Effects of pipe degradation become more apparent over time.
	Pipe vintage	Pipes made at a particular time and place may be more vulnerable to failure.
	Pipe diameter	Small diameter pipes are more susceptible to beam failure.
	Type of joints	Some types of joints have experienced premature failure (e.g., leadite joints).
	Thrust restraint	Inadequate restraint can increase longitudinal stresses.
	Pipe lining and coating	Lined and coated pipes are less susceptible to corrosion.
	Dissimilar metals	Dissimilar metals are susceptible to galvanic corrosion.
	Pipe installation	Poor installation practices can damage pipes, making them vulnerable to failure.
	Pipe manufacture	Defects in pipe walls produced by manufacturing errors can make pipes vulnerable to failure. This problem is most common in older pit cast pipes.
Environmental	Pipe bedding	Improper bedding may result in premature pipe failure.
	Trench backfill	Some backfill materials are corrosive or frost susceptible.
	Soil type	Some soils are corrosive; some soils experience significant volume changes in response to moisture changes, resulting in changes to pipe loading. Presence of hydrocarbons and solvents in soil may result in some pipe deterioration.
	Groundwater	Some groundwater is aggressive toward certain pipe materials.
	Climate	Climate influences frost penetration and soil moisture. Permafrost must be considered in the north.
	Pipe location	Migration of road salt into soil can increase the rate of corrosion.
	Disturbances	Underground disturbances in the immediate vicinity of an existing pipe can lead to actual damage or changes in the support and loading structure on the pipe.
	Stray electrical currents	Stray currents cause electrolytic corrosion.
	Seismic activity	Seismic activity can increase stresses on pipe and cause pressure surges.
Operational	Internal water pressure, transient pressure	Changes to internal water pressure will change stresses acting on the pipe.
	Leakage	Leakage erodes pipe bedding and increases soil moisture in the pipe zone.
	Water quality	Some water is aggressive, promoting corrosion
	Flow velocity	Rate of internal corrosion is greater in unlined dead-ended mains.
	Backflow potential	Cross connections with systems that do not contain potable water can contaminate water distribution system.
	O&M practices	Poor practices can compromise structural integrity and water quality.

Kabir et al. (2015) studied the effect of soil type on the failure rate of water pipelines and highlighted that soil type can be classified further to major and minor factors. The five major soil's factors include soil electrical resistivity, soil pH, redox potential, soil sulfide contents and soil moisture. The five minor soil factors are; temperature of soil, oxygen contents, presence of acids, sulfates, and sulfates reducing bacteria.

Karimian (2015) summarized the factors to predict the failure rate of pipelines. These factors included physical and operational, physical and environmental and physical, operational and environmental (Table 2-3).

2.4 Cost Analysis of Pipeline Renewal and Replacement

2.4.1 Cost Analysis

Cost Analysis is an evaluation technique used to compare possible alternatives based on costs including initial construction, operation, maintenance, rehabilitation and other cost anticipated throughout the entire service life of asset and determine the most cost-effective way to complete the project (Sompura, 2017).

Theoretically, cost analysis can be done by two methods depending on the techniques and methods applied: deterministic method and stochastic method. The traditional deterministic approach typically consists of five steps, beginning with the development of alternatives to accomplish the objectives for the project. The author then defines the schedule of initial and future activities involved in implementing each project design alternative. In the next step, the costs associated with these activities are estimated (Sompura, 2017 and Milousi, 2018).

Table 2-3 Factors Affecting Pipe Failure Rate by Different Researchers (Karimian, 2015)

	Physical Factors													Environmental Factors										Operational Factors						
	Pipe Material	Pipe Wall Thickness	Pipe Age	Pipe Length	Pipe Vintage	Pipe Diameter	Type of Joint	Thrust Restraint	Pipe Lining and Coating	Dissimilar Metals	Depth Laid	Pipe Installation	Pipe Manufacture	Pipe Bedding	Trench Backfill	Soil Type	Ground water	Climate	Pipe Location	Disturbances	Stray Electrical Currents	Traffic and Loading	Seismic Activity	Internal Water Pressure, Transient Pressure	Leakage	Water Quality	Flow Velocity	Backflow Potential	O&M Practices	Other Factors
Moglia et al. (2007)		✓	✓	✓		✓																		✓						corrosion rate
Berardi et al. (2008)			✓	✓		✓																								Number of Properties Supplies
Wang et al. (2009)	✓		✓	✓		✓					✓																			
Jafar et al. (2010)	✓	✓	✓	✓		✓										✓			✓					✓						
Wang et al. (2010)	✓		✓			✓			✓					✓	✓	✓					✓	✓		✓						
Xu et al. (2011)			✓	✓		✓																								
Asnaashari et al. (2013)	✓		✓	✓		✓			✓							✓														
Arsénio et al. (2014)			✓																											Ground Movement
Shirzad et al. (2014)			✓	✓		✓					✓													✓						
Aydogdu and Firat (2014)			✓	✓		✓																								
Nishiyama and Filion (2014)			✓	✓		✓										✓														
Kabir et al. (2014)		✓	✓	✓		✓										✓						✓		✓		✓				
Jenkins et al. (2014)			✓			✓																								
Francis et al. (2014)			✓													✓		✓	✓											
Kutyłowska (2015)	✓		✓	✓		✓																								
Kabir et al. (2015a)			✓	✓	✓	✓										✓			✓											Number of Connection for Each Pipe
Kimutai et al. (2015)	✓			✓		✓										✓		✓												Soil Resistivity, Freezing Index, and Rain Deficit
Kabir et al. (2015b)			✓	✓	✓	✓										✓														Soil Resistivity and Soil Corrosivity Index

Best practice cost analysis calls for including not only direct agency expenditures but also costs to facility users that result from these agencies' activities. And then, using a discounting technique, these costs are converted into constant dollars and summed for each alternative. Finally, the analyst determines which alternative is the most cost-effective (ISO, 2006 and Sompura, 2017).

2.4.2 Life Cycle Environmental Assessment (LCEA)

ISO 14040:2006 presents life cycle environmental assessment as one of the techniques developed for understanding and addressing the possible environmental impacts associated with both manufactured and consumed products and services. It addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (ISO, 2006).

LCEA consists of four different phases including

- Scope definition,
- Life Cycle Inventory (LCI),
- Life Cycle Impact Analysis (LCIA), and
- Interpretation.

The methodologies for each of these phases can be found in ISO 14040 – 14044.

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2.4.3 *Integrated LCA-LCCA Model*

There is a need to include the social costs in evaluation of alternatives. Kendall et al. (2008) used such model for cost analysis of concrete bridge deck.

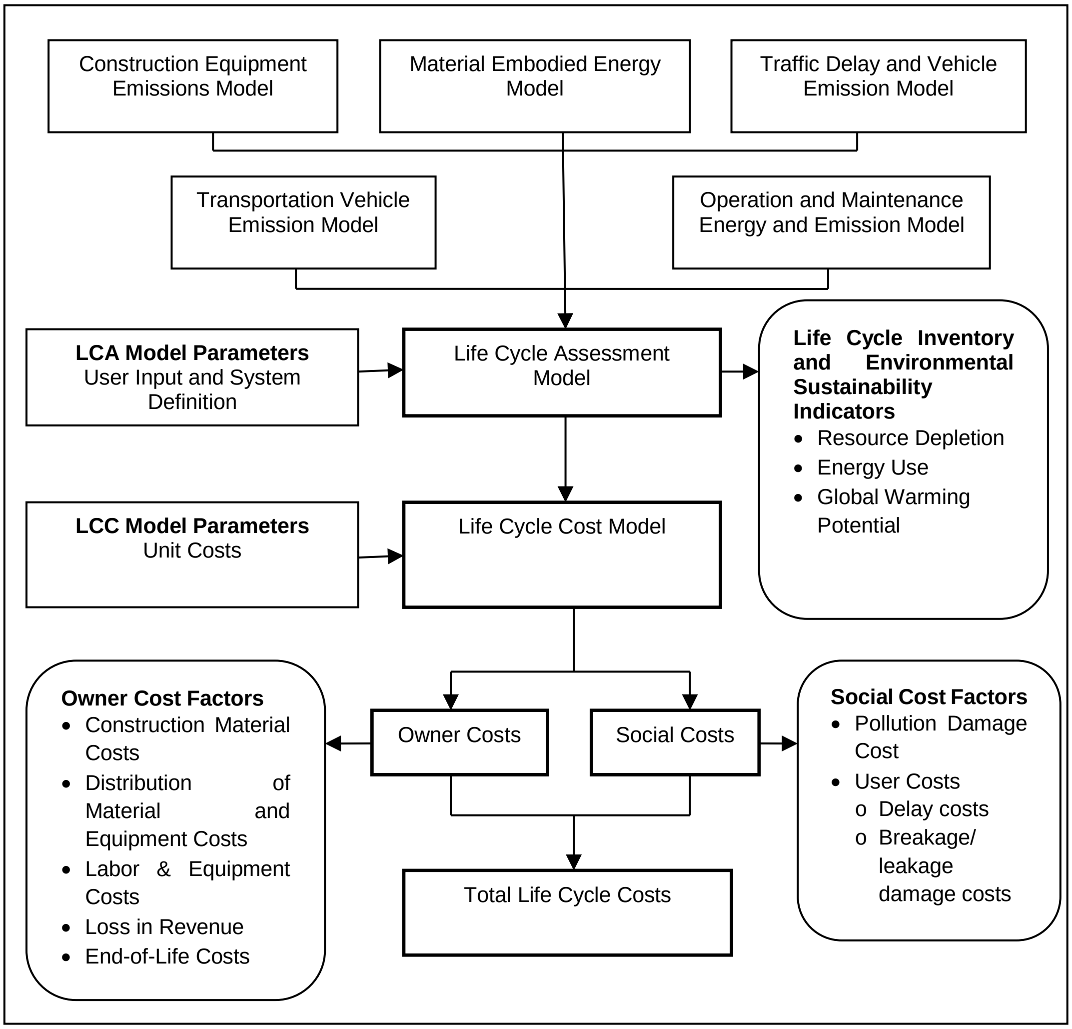

Figure 2-5 Integrated LCA-LCCA Model Flow Diagram
Adapted from Kendall et al., 2008

Similar approach can be adopted for sustainable design of pipelines. In the integrated LCA-LCCA model, the environmental and user costs obtained as an output from

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LCA is used in LCCA model. Figure 2-5 illustrates a flow chart for the integrated LCA-LCCA Model for pipeline.

2.4.4 Owner Costs

When integrated LCA-LCAA model is adopted, owner costs are relatively easier to determine. Owner costs include planning and design costs, construction costs including material, labor and equipment costs, operation and maintenance costs, and inspection and repair costs. Owner costs can be categorized into following three categories (Najafi and Gokhale, 2005, Kendall et al., 2008, ASCE, 2019, and Beaudet et al., 2019): Pre-construction cost, construction cost, and post-construction cost.

2.4.5 Social Costs

Social costs which include pollution damage costs (costs due to emissions) and user costs are very difficult to determine. For calculation of pollution damages, Environmental Protection Agency (EPA) has developed some models to calculate emissions. For example, MOBILE6 is a model developed for calculation of emission from vehicles and NONROAD is a model developed for calculation of emission from construction equipment. Likewise, embodied energy models for different pipe materials can be used to calculate emissions during manufacture of pipes.

Calculation of total emissions or pollution damages is output of LCA. To be able to use it in LCCA, the dollar value for the damage must be determined. Many research works have been carried out to ascertain the pollution damage costs and have been summarized by Tol (2005). Tol (2005) analyzed 28 articles on pollution damage costs and found that the mean pollution cost from those 28 articles was $97 per metric ton of carbon (tC) emitted with standard deviation of $203/tC. The mean for peer reviewed articles was $50/tC. Therefore, it is found that there is high level of uncertainty in determining the pollution damage costs.

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Matthews et al. (2015) identified eight most important social cost categories for 48-60 in. open-cut pipeline construction projects, presented mathematical methods for calculating them, and summarized their social cost impacts. Two case histories of utility construction projects were used to provide information as follows: a) project background; b) social cost categories; and c) estimated monetary values for each category. The case histories were analyzed and compared to identify trends and derive typical cost values and cost ranges. Methods used to compute the various social cost values are also compared, and their effectiveness and viability are discussed. It was found that social costs for two cases were \$400/LF and \$460/LF, respectively. It was suggested to include social costs in the LCCA to make trenchless technology more advantageous in comparison with open-cut construction for high density urban areas.

2.4.6 Reducing Social Costs

As discussed above, owner costs are easier to quantify than the social costs. There is a need to develop proper methodology to determine the social costs (including both pollution damage costs and user costs). In order to determine the social costs, it is necessary to answer questions like how much should be spent to reduce greenhouse gas emission by 1 ton of carbon, or how much should be spent to reduce traffic delay of users by one hour (Kendall et al., 2008, ASCE, 2019, and Beaudet et al., 2019) .

When the social costs are reduced through optimization of the pipe manufacturing, construction and operation processes by minimizing wastes, using recycled materials, using optimum pumping facilities, etc., reduction in the costs to owners and overall life cycle costs are realized as illustrated in Figure 2-6.

However, when the social costs are reduced through premium like by using more environment friendly pipe materials, construction equipment and methodologies, etc., the

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cost to owners may increase even when overall life cycle cost may remain constant. This is illustrated in Figure 2-7.

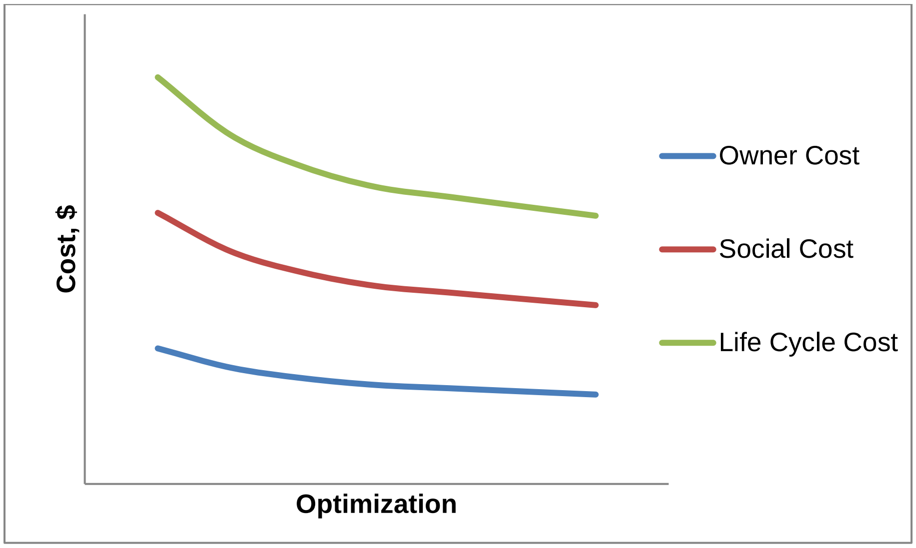

Figure 2-6 Cost Curve for Reduction of Social Cost through Optimization (ASCE, 2019)

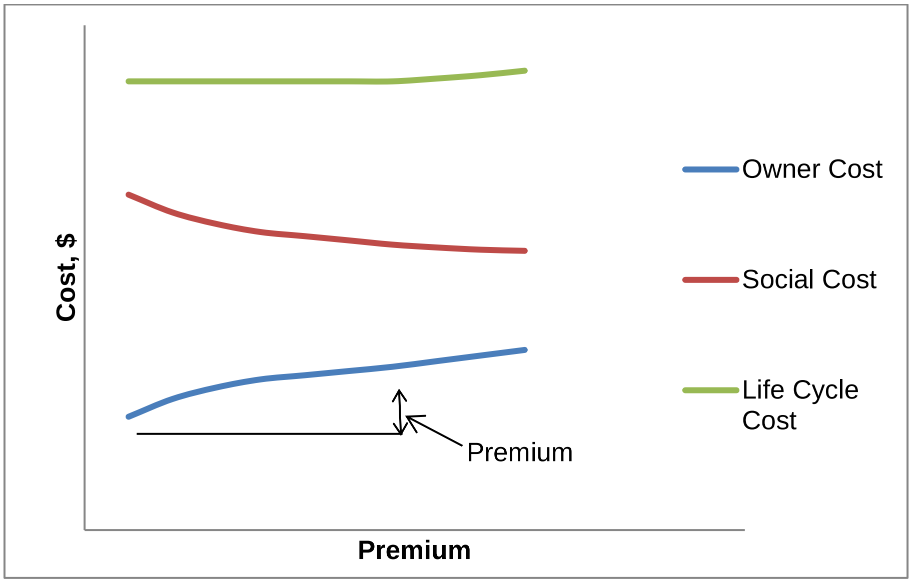

Figure 2-7 Cost Curve for Reduction of Social Cost through Premium (ASCE, 2019)

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2.5 Carbon Footprint

"Carbon footprint" refers to the amount of greenhouse gases (GHG) emitted into the atmosphere each year by an individual, household, building, organization or country. It is usually measured in pounds of carbon dioxide equivalents, and it typically includes both direct and indirect emissions (EPA). Direct emissions, according to the EPA, are the ones that a person can directly control, such as driving a car or heating a home with natural gas. Indirect emissions are consequences of activities for which individuals cannot control the amount of emissions. For example, homeowners can control the amount of electricity they use, but they cannot control the emissions associated with the generation of that electricity, because the electric company controls that (Chilana, 2011).

Carbon footprint (CF), also named Carbon profile, is the overall amount of carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions (e.g. methane, laughing gas, etc.) associated with a product, along its supply-chain, and sometimes including from use and end-of-life recovery and disposal (EPLCA, 2007).

The carbon footprint of a product or service is the total amount of carbon dioxide (CO_2) and other greenhouse gases (GHG) emitted over the life cycle of that product or service, expressed as kilograms of CO_2 equivalents (www.cleanmetrics.com).

A carbon footprint is a measure of the impact our activities have on the environment, and in particular climate change. It relates to the amount of greenhouse gases (GHG) produced in our day-to-day lives through burning fossil fuels for electricity, heating and transportation etc. The carbon footprint is a measurement of all greenhouse gases (GHG) we individually produce and has units of tones (or kg) of carbon dioxide equivalent (www.carbonfootprint.com). Table 2-4 illustrates distinctive definitions of carbon footprint used by various industries.

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Table 2-4 Definitions of Carbon Footprint (Chilana, 2011)

Reference	Definition
BP, 2007	"The carbon footprint is the amount of carbon dioxide emitted due to your daily activities – from washing a load of laundry to driving a carload of kids to school."
British Sky Broadcasting (Sky)	The carbon footprint was calculated by "measuring the CO_2 equivalent emissions from its premises, company-owned vehicles, business travel and waste to landfill." (Patel, 2006)
Carbon Trust, 2007	"… a methodology to estimate the total emission of greenhouse gases (GHG) in carbon equivalents from a product across its life cycle from the production of raw material used in its manufacture, to disposal of the finished product (excluding in-use emissions). "… a technique for identifying and measuring the individual greenhouse gas emissions from each activity within a supply chain process step and the framework for attributing these to each output product (we [The Carbon Trust] will refer to this as the product's 'carbon footprint')."
Energetics, 2007	"… the full extent of direct and indirect CO_2 emissions caused by your business activities."
Environmental Technology Action Plan (ETAP), 2007	"…the 'Carbon Footprint' is a measure of the impact human activities have on the environment in terms of the amount of greenhouse gases (GHG) produced, measured in tons of carbon dioxide."
Global Footprint Network (2007)	"The demand on biocapacity required to sequester (through photosynthesis) the carbon dioxide (CO_2) emissions from fossil fuel combustion."
Grub & Ellis, 2007	"A carbon footprint is a measure of the amount of carbon dioxide emitted through the combustion of fossil fuels. In the case of a business organization, it is the amount of CO_2 emitted either directly or indirectly as a result of its everyday operations. It also might reflect the fossil energy represented in a product or commodity reaching market."
Parliamentary Office of Science and Technology (POST), 2006	"A 'carbon footprint' is the total amount of CO_2 and other greenhouse gases (GHG), emitted over the full life cycle of a process or product. It is expressed as grams of CO_2 equivalent per kilowatt hour of generation (gCO_2eq/kWh), which accounts for the different global warming effects of other greenhouse gases (GHG)."

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Leuke et al. (2015) compared the estimated carbon footprint and greenhouse gas emissions during the rehabilitation of two asbestos cement water main projects by CIPP and Pipe bursting methods. Number of equipment utilized, cycle times, activity durations, and productivities of the crews were recorded. NASTT BC, Vermeer's E-Calc, and NASTT's carbon calculators were used to compare the emissions. It was found that emissions per 100 m (328 ft) length of pipe for CIPP method through NASTT, E-Calc, and NASTT BC were 3.11, 2.90, and 2.66 tonnes, respectively.

Tavakoli et al. (2017) compared carbon footprint for conventional open-cut and trenchless technology methods, particularly tunneling in rural area, and quantify carbon emissions produced by construction equipment for hauling excavated soils during pipeline construction. They estimated CO_2 emissions for open-cut and tunneling methods for UFT construction. Statistical data was used to calculate the quantity of CO_2 emissions to determine the magnitude of environmental impacts of both methods. A potential UFT route is considered for 25-mile distance from Huntsville to Madisonville, Texas, in rural area. Total CO_2 produced using trenchless technology method was 887 tons and for open-cut method was 5,379 tons.

Chilana et al. (2016) analyzed and compared the CO_2 footprint of two pipeline materials used for large diameter water transmission pipelines, steel pipe (SP) and PCCP, for 150-miles of a pipeline of different large diameters (66, 72, 84 and 108-inch), and the installation method was open-cut construction method. Three life-cycle phases were considered: fabrication, installation, and operation. The result found that pipe manufacturing consumed a large amount of energy and thus contributed more than 90% of life-cycle carbon emissions for both pipes. SP had 64% larger CO_2 emissions from manufacturing compared to PCCP. Figure 2-8 shows production energy (GJ/ton) for various construction materials.

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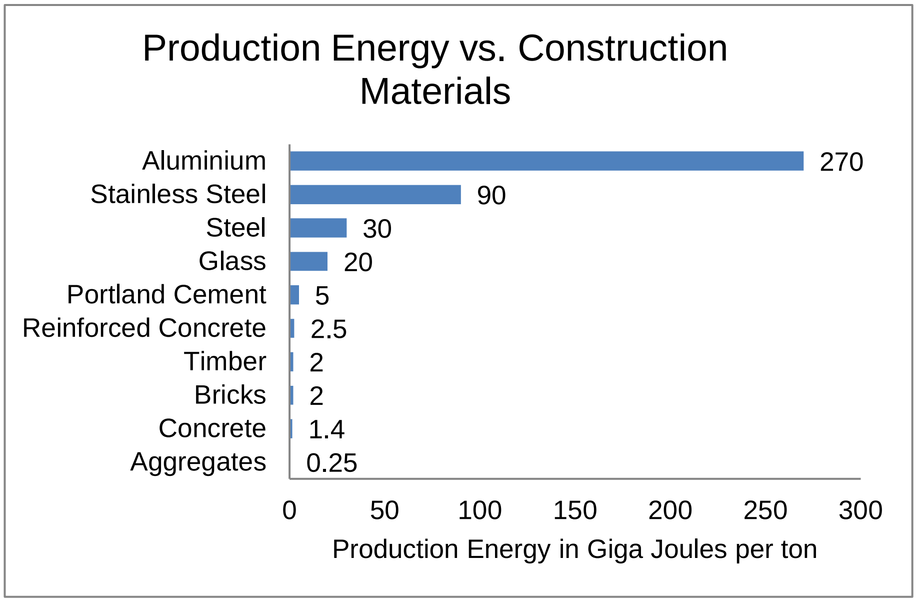

Figure 2-8 Production Energy in Giga Joules per ton for Various Construction Materials
Source: National Ready-Mixed Concrete Association (NRMCA)

For the transportation stage, PCCP had larger CO_2 emissions due to the heavy weight of the PCCP pipe. In this study, fuel consumption by construction equipment for installation of pipe in the trench was found to be similar for both PCCP and SP. Overall, PCCP was found to have smaller carbon footprint emissions due to the greater energy used during manufacturing of SP.

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2.6 Greenhouse Gas Emissions in Pipeline Installations

Greenhouse gases are those that absorb infrared radiation in the atmosphere, trapping heat and warming the surface of the Earth. The three greenhouse gases (GHGs) associated with pipeline construction are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Other important GHGs include water vapor and many volatile organic compounds, however, their emissions are not easy to be quantified and analyzed (Pandey et al., 2011). Figure 2-9 shows carbon impact from pipeline installation.

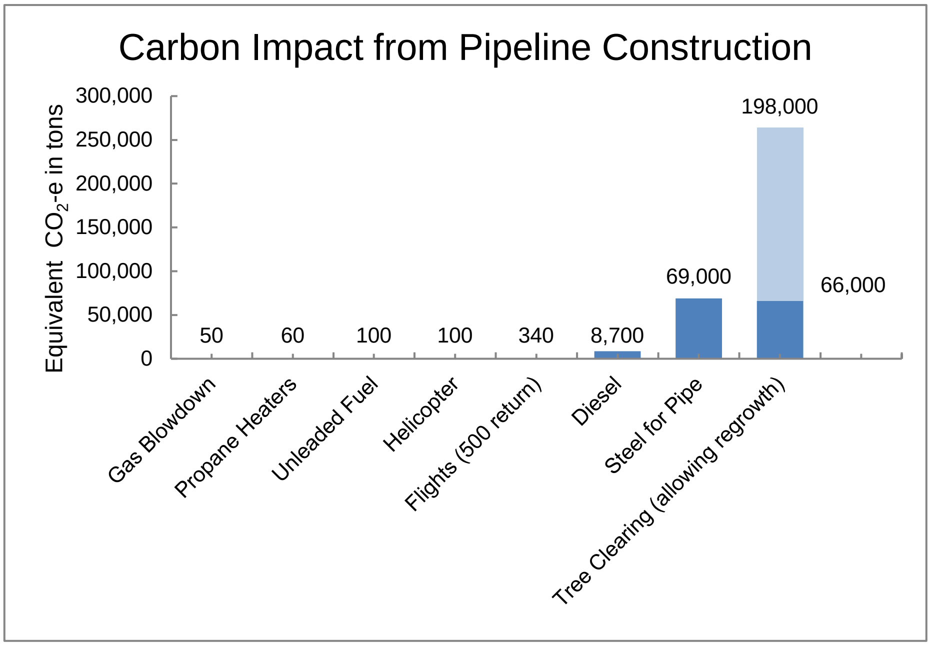

Figure 2-9 Carbon Impact from Pipeline Installation
Source: Chilana, 2011

Greenhouse Gas (GHG) emission analysis is becoming more popular in the construction industry, and it is also critical to estimate emissions for all pipeline projects. The investigation and quantification of the amount of GHG emissions were conducted during previous years in several studies, and various efforts to estimate emissions from pipeline construction operations can be found in the literature. Key models are the

Environmental Protection Agency (EPA)'s Nonroad model (EPA, 2010), and the California off-road model.

Sihabuddin and Ariaratnam (2009a) applied the EPA Nonroad model to estimate the emissions generated by equipment and transportation in a utility installation project employing HDD. Project emissions were calculated by an emissions calculator based on the EPA model, and the site details and equipment usage hours that were collected onsite were used as inputs in the calculator to estimate the total number of emissions. The developed model could be used by policy makers to select the proper construction methods based on estimated emissions. This initial estimation would be helpful to narrow and reduce airborne pollution in future PI projects (Mohit et al., 2017).

The EPA has developed an equation (Eq. 2-1) to calculate the amount of GHG emissions produced by construction equipment (Mohit et al., 2017).

$$Emissions_i = EF_i * HRS * HP * LF \qquad \text{Equation 2-1}$$

where, Emissions i is the emission amount generated by the equipment i (g), EFi is the emission factor for the impact i (g/hp-hr), i is the type of pollutant (CO_2, SO_2, NO_X, CO, PM, HC), HRS is the hours of use, HP is the average rated horsepower of the equipment, and LF is the load factor (operating hp/maximum rated HP). Table 2-5 shows the EF equations used for construction equipment for HC, CO, NO_X, PM, CO_2, and SO_2 (Mohit et al., 2017).

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Table 2-5 Emission Factor (EF) Equations for Construction Equipment (EPA, 2010 and Mohit et al., 2017)

Notation	Description	Equations
EF (HC, CO, NOx)	HC, CO, and NO_X EF	EF_{SS} × TAF × DF
EF (PM)	PM EF	EFSS × TAF × DF – S_{PMadj}
EF (CO_2)	CO_2 EF	$44gCO_2/12gC$ × 0.87 × (BSFC × TAF × 453.6 − HC)
EF (SO_2)	SO_2 EF	$64gSO_2/32gS$ × 0.01 × SO_x dsl × (BSFC × TAF × 453.6 × (1 − SO_xconv) − HC)

Note: EFSS: Steady-state emission factor; TAF: Transient adjustment factor; DF: Deterioration factor; BSFC: Brake-specific fuel consumption; SPmadj: Sulfur content adjustment to PM EF; SO_xdsl: Episodic fuel sulfur percentage; and SOxconv: Fraction of fuel sulfur converted to PM.

The transportation footprint is calculated using equation (Eq. 2-2) (Sihabuddin and Ariaratnam, 2009a; Mohit et al., 2017):

$$Emissions_{ti} = EF_{i*n} * (DO + DR) \qquad \text{Equation 2-2}$$

where Emissionsti is the transportation emission, EFi is the transportation EF from pollutant i (g/mi), n is the number of trips required to transport materials and equipment, DO is the one-way distance hauling to the site, and DR is the return distance from the site.

The EF equations of transportation are presented in Table 2-6 for different pollutants (EPA, 2010a and 2010b).

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Table 2-6 EF Equations for Transportation (EPA, 2010 and Mohit et al., 2017)

Notation	Description	Equations
EF_t (HC, CO, NO_x)	HC, CO, and NO_X transportation EF	$\{EF_{ZM}(HC, CO, NOx) + (D \times M/10{,}000)\} \times AF \times CF$
EF (PM)	PM transportation EF	$EF_{ZM(PM)} + (D \times M/10{,}000)$
EF (CO_2)	CO_2 transportation EF	$44gCO_2/12gC \times 0.87 \times (F_D/F_E \text{ x } 453.6 - HC)$
EF (SO_2)	SO_2 EF	$64gSO_2/32gS \times 0.01 \times SO_x\,dsl \times (F_D/F_E \times 453.6 \times (1 - SO_xconv) - HC)$

Note: EF_{ZM}: Zero-mile emission factor; D: Deterioration; M: Mileage; AF: Altitude adjustment factor; CF: Conversion factor; FD: Field density; FE: Fuel economy.

Pipeline installation activities are increasing atmospheric concentration of CO_2 and other GHG released by human activities are warming the earth (Latake, 2015). The mechanism is generally known as the “greenhouse effect” is what makes the Earth habitable. These activities have changed the chemical composition of the atmosphere through the buildup of GHGs primarily. These gases in the atmosphere act like the glass of a greenhouse, allowing the sunlight in and blocking heat from escaping (Latake, 2015). CO_2 accounted for 82% of all human GHG emissions in the U.S in 2013 (Rudolph 2016).

The majority of CO_2 is released from fossil fuels, coal, oil, the gas used for electricity production, transportation, and industrial processes. Other important GHG include CH4, N_2O, black carbon (BC), and various fluorinated gases. Although these gases are emitted in a smaller amount to the atmosphere compared to CO_2, they trap more heat in the atmosphere than CO_2 does (Rudolph, 2016). The most common and popular criteria used to describe sustainability efforts from the environmental viewpoint is the concept of CF. While GHGs exist naturally in the atmosphere, increases in their concentrations have been attributed to global warming or more accurately, climate change. For simplicity and

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understanding, the level of GHG emissions, or CF, is often expressed in terms of the equivalent amount of emitted carbon dioxide (CO2EQ) (ASCE, 2019).

2.7 Previous Studies on Environmental Impacts of Cured-in-Place Pipe (CIPP) Renewal Method

Previous sections presented a literature review of costs of trenchless renewal methods and open-cut pipeline replacement. To understand the environmental implications of CIPP renewal, this section has been divided into CIPP air emission studies and CIPP water quality studies. These are discussed one by one as follows.

2.7.1 CIPP Air Emission Studies

In the U.S., the National Institute of Occupational Safety and Health (NIOSH) and U.S. Environmental Protection Agency (EPA) recommend styrene short-term exposure limits and exposure limit guidelines are enforced by the Occupational Health and Safety Administration (OSHA). As shown in Table 2-7, national short-term exposure limit values for styrene vary from 20-1900 ppm, depending on averaging time and severity of effects. For countries in the European Union, 8-hour styrene exposure limits vary from 10 to 100 ppm (most common are 20 ppm and 50 ppm), and 10-30 min. exposure limits range from 37.5-250 ppm.

Table 2-8 summarizes field measurements of styrene concentrations at CIPP installation sites. The first section of the Table 2-9 (Rows 1 through 4) shows cases of styrene being measured in response to citizen’s complaints. Indoor levels ranging from 0.32 to 200 ppm are reported. Two of the three indoor styrene measurements are above the 10-min. 20-ppm discomfort guideline recommended by U.S. EPA; two of the four studies report concentrations above the 100-ppm short-term (15-min.) exposure limit recommended by U.S. NIOSH. This indicates that additional study is warranted to investigate potential exposures.

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Table 2-7 Gas-Phase Regulatory Standards/Guidelines for Styrene (CUIRE, 2018)

Agency	Guidelines or Standards		Short-Term Guideline/Standard				Long-Term Guideline/Standard			
			Value (mg/m^3)***	Value (ppm)	Averaging Time	Basis	Value (mg/m^3)	Value (ppm)	Averaging Time	Basis
Occupational Safety and Health Administration (OSHA) (from ACGIH)	Construction Permissible Exposure Limit (PEL) Standard		420	100	8-hr	Health	N/A	N/A	N/A	N/A
			840	200	8-hr ceiling (must not be exceeded for any 15-min. period)	Health	N/A	N/A	N/A	N/A
			2,520	600	5-min.	Health	N/A	N/A	N/A	N/A
National Institute for Occupational Safety and Health (NIOSH)	Recommended Exposure Limit (REL)		215	50	10-hr	Health	N/A	N/A	N/A	N/A
			425	100	15-min	Health	N/A	N/A	N/A	N/A
US Environmental Protection Agency (EPA)	Acute Exposure Guideline Level (AEGL)	Level 1 (discomfort/ transient effects)	85	20	10-min	Health	N/A	N/A	N/A	N/A
			85	20	30-min	Health	N/A	N/A	N/A	N/A
			85	20	1-hr	Health	N/A	N/A	N/A	N/A
			85	20	4-hr	Health	N/A	N/A	N/A	N/A
			85	20	8-hr	Health	N/A	N/A	N/A	N/A
		Level 2 (serious, irreversible impacts)	980	230	10-min	Health	N/A	N/A	N/A	N/A
			680	160	30-min	Health	N/A	N/A	N/A	N/A
			550	130	1-hr	Health	N/A	N/A	N/A	N/A
			550	130	4-hr	Health	N/A	N/A	N/A	N/A
			550	130	8-hr	Health	N/A	N/A	N/A	N/A
		Level 3 (life-threatening)	8080	1,900	10-min	Health	N/A	N/A	N/A	N/A
			8080	1,900	30-min	Health	N/A	N/A	N/A	N/A

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Table 2-7 Gas-Phase Regulatory Standards/Guidelines for Styrene (CUIRE, 2018)

Agency	Guidelines or Standards	Short-Term Guideline/Standard				Long-Term Guideline/Standard			
		Value (mg/m^3)***	Value (ppm)	Averaging Time	Basis	Value (mg/m^3)	Value (ppm)	Averaging Time	Basis
		4680	1,100	1-hr	Health	N/A	N/A	N/A	N/A
		1450	340	4-hr	Health	N/A	N/A	N/A	N/A
		1450	340	8-hr	Health	N/A	N/A	N/A	N/A
Texas Commission on Environmental Quality (TCEQ)	Effect Screening Level (ESL) Guideline*	0.110	0.026	1-hr	Odor	0.140	0.033	Annual	Health
	Air Quality Monitoring Value (AQMV)**	0.110	0.026	1-hr	Odor	N/A	N/A	N/A	N/A
	Air Quality Monitoring Value (AQMV)	22	5.2	1-hr	Health	0.470	0.110	Annual	N/A

*ESLs are screening levels used in TCEQ’s air permitting process to evaluate air dispersion modeling’s predicted impacts. ESLs are set to protect human health and welfare

**AQMVs are screening levels for ambient air data that are set to protect human health and welfare.

*** The conversion between mg/m^3 and ppm is calculated as follows:

$C_{mg/m^3} = \frac{MW*P}{R*T} C_{ppm}$, where:

C_{mg/m^3} = concentration in mg/m^3

C_{ppm} = concentration in ppm

MW = molecular weight (104.15 for styrene), R = ideal gas law constant = 0.08206 l-atm/(mol-K), T = temperature in K = 298 (equivalent to 25 ^{0}C), and P = 1 atmospheric pressure

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Table 2-8 Previous Field Measurements of Styrene Concentrations at CIPP Installation Sites (CUIRE, 2018)

No.	Reference	Type of Reference	Location	Cure Type	No. of Sites	Process Phases Measured	Liner Length, Dia., Thickness	Curing Time & Temp.	Measurement/Analysis Method	Styrene Concentrations				
										Termination MH (ppm)	Surrounding Property		Worker Exposure (ppm)	Other (ppm)
											Outdoors (ppm)	Indoors (ppm)		
MEASUREMENTS IN RESPONSE TO CITIZEN COMPLAINTS														
1	*Washington Post* (Gowen, 2004)	News article	Alexandria, VA	Not known	1	Unknown	N/A	N/A	N/A	N/A	N/A	N/A	N/A	500: hose at site
2	U.S. Agency for Toxic Substances & Disease Registry (ATSDR, 2005)	Govt. document	Milwaukee, WI	Not known	1	Unknown	N/A	N/A	N/A	N/A	N/A	0.32	N/A	N/A
3	Public Health, England (CRCE, 2011)	Govt. log	Birmingham, UK	Not known	1	After cooling	N/A	N/A	N/A	N/A	N/A	15-200	N/A	N/A
4	*Worcester Telegram and Gazette* (Dayal, 2011)	New article	Worcester, MA	Not known	1	Unknown	N/A	N/A	N/A	N/A	N/A	60-70	N/A	N/A
STUDIES WITH WATER OR UV CURE														
5	AirZOne (2001)	Consultant report	Toronto, Canada	Hot water	N/A	Before, during, after CIPP installation	N/A	4-6 h at 80°C	Sorbent tubes with sampling pumps, GC/MS	0.16-3.2	Outside homes, upwind of manholes	0.1-0.2 (8 houses)	0.08-0.5	N/A

Table 2-8 Previous Field Measurements of Styrene Concentrations at CIPP Installation Sites (CUIRE, 2018)

No.	Reference	Type of Reference	Location	Cure Type	No. of Sites	Process Phases Measured	Liner Length, Dia., Thickness	Curing Time & Temp.	Measurement/Analysis Method	Styrene Concentrations				
										Termination MH (ppm)	Surrounding Property		Worker Exposure (ppm)	Other (ppm)
											Outdoors (ppm)	Indoors (ppm)		
6	IKT (2007, 2008, 2013)	Report	A special test stand, Germany	UV	6	Before, during, after curing	8.7’ x 23.6” x 0.28”; 8.7’ x 11.8” x 0.15”	N/A	Air layer of test rig, closed & sealed against ambient air, measurements via adsorption (activated charcoal tubes) with auto sampler	N/A	N/A	N/A	N/A	0.001 – 0.013 ppm, air layer of test stand, closed & sealed against ambient air
STUDIES WITH STEAM CURE														
7	Bauer & McCartney (2004)	Conference proceeding	Ottawa, Canada	Steam	4	Before, during, after curing (cont.)	253’ x 30” x 1.16”; 53’ x 30” x 1.34”	N/A	PID: PE Photovac Model 2020	20, 115		2.5	N/A	N/A
8	Ajdari (2016) (University of New Orleans)	Ph.D. dissertation	New Orleans, LA, US	Steam	3	Before, during, after curing	235’, 304’, 309’; x 8”	45-60 min., 60°C	Tedlar bag with pump, GC	250-1,070	N.D. (One location only)	N/A	N/A	Steam hose
9	Wessex Water (2016)	Consultant Report	Bath, UK	Steam (1) & water (3)	4	Before, during, after curing (cont.)	568’ x 11.8” x 0.24”	4 h, 40°C - 100°C	Field PID – 4 sites; Sorbent tubes (thermal desorption/ GC) – 2 sites	PID: Steam cure max.: 165	Steam cure: PID: max 6 (1 m from term MH), 24(in gully); Sorbent tubes: all 8 < UK 8-h TWA & 15-min STEL	N/A	N/A	N/A

Table 2-8 Previous Field Measurements of Styrene Concentrations at CIPP Installation Sites (CUIRE, 2018)

No.	Reference	Type of Reference	Location	Cure Type	No. of Sites	Process Phases Measured	Liner Length, Dia., Thickness	Curing Time & Temp.	Measurement/Analysis Method	Styrene Concentrations				
										Termination MH (ppm)	Surrounding Property		Worker Exposure (ppm)	Other (ppm)
											Outdoors (ppm)	Indoors (ppm)		
10	Sendesi et al. (2017)	Journal article	CA (5 sites), US; IN (2 sites), US	Steam	7	Before, during, after curing (cont.)	19.7' x 18" x 0.3"	N/A	PID	Styrene not independently measured		Styrene not indepen-dently measured	Styrene not indepen-dently measured	
11	Prince William County Service Authority (2017)	Report	VA, US	Steam	4	Before, during, after curing (cont.)	353'; 248, 272, and 124'	N/A	Personal PID & passive monitoring badge on 2 employees	N/A	N/A	N/A	104 ppm peak; 0.077 avg	N/A
12	Unpublished data (2017)	N/A	N/A	Steam	N/A	N/A	N/A	N/A	Personal data logger, GC/MS	N/A	N/A	N/A	1.4 ppm 8-h TWA	N/A
13	IKT (2011)	Report	Ruhr, Germany	Steam	1	During curing	15.7" dia.	N/A	DRÄGER Accuro tubes/pump	N/A	20 at 5 m away from term. MH, 1.5 m height	N/A	N/A	N/A
14	RIVM (2006)	Report	Cuijk-Vianen, Barendrecht, Sevenum, The Netherlands	Not known (likely steam)	3	During & after curing & cooling, during cutting of holes for laterals	249' x 11.8", 167' x 13.8", 469' x 17.7"	N/A	Not known	300 in MH; 85 (vent)	N/A	9	N/A	N/A

Studies conducted with the goal of measuring styrene emissions from CIPP installation are reported in References 5-14 in Table 2-8. Studies 5 and 6 were for hot water cured and UV-cured, respectively, and found a maximum styrene level of 3.2 ppm. Studies 7-14 included steam-cure, and found noticeably higher concentrations than the hot water and UV cure studies. The steam-cure studies will thus be discussed in more detail.

Most of the steam-cure studies captured temporal variation in emissions, by measuring concentrations before, during, and after curing. The studies were less complete, however, in capturing spatial variation in concentrations. Most studies measured styrene at the termination manhole, or inside the sewer pipe itself. Maximum values at the terminal manhole ranged from 20 to 300 ppm, which are levels that exceed short-term exposure limits, as well as some long-term limits. However, since even workers would typically not stand directly at the termination manhole in the exhaust plume, this information is not very helpful (Kaushal et al., 2019b).

At steam-cure sites, additional field measurements of styrene concentrations surrounding the terminal manhole are needed. Only four of the steam-cure studies in Table 3.2 (Rows 9, 10, 11 and 14) measured concentrations at locations surrounding the terminal manhole (at least 1 m away, not in the manhole itself or in the exhaust plume). Ajdari (2016) measured styrene at only one location besides the terminal manhole. Sendesi et al. (2017) measured concentrations at only one location away from the terminal manhole per site. IKT (2011) measured in 5-m increments from 5-20 m downwind from the manhole at one site. Wessex Water (2016) measured 1 m away from the manhole, and in surrounding gullies at one site.

Atmospheric concentrations of compounds are functions of the source emission rate, meteorological conditions, and the receptor location. Since concentrations are expected to vary as a function of distance from the manhole, measuring at few locations gives an incomplete picture. In addition, concentrations are expected to vary with wind speed and wind direction, so measuring on one day does not capture what levels may be under differing meteorological conditions. Finally, measuring concentrations at one site does not capture variability in emission rate, for projects with larger diameter pipes, longer pipe segments, higher curing temperatures, etc.

At steam-cure sites, additional field measurements of worker exposure to styrene are also needed. Only two of the steam-cure studies in Table 2-8 (Rows 12 and 13) measured worker exposure using a personal sampling device. For study 12, employees walked the construction area periodically but spent a good deal of time in their work trucks due to the cold weather. Hence, these measurements were likely not typical of worker exposure. For study 12 in Table 2-8, the worker exposures are much lower than the 8-hour exposure guidelines; however, the study is not publicly available. Additional worker exposure data should be collected to capture variability in source emission rate, meteorological conditions, and the worker's location with respect to the terminal manhole.

In summary, existing studies did not adequately capture worker exposure, or levels in the surrounding area to which workers or citizens may be exposed. Spatial variation of concentrations, and variations in concentrations with different meteorological conditions, were not well determined. Studies also did not adequately capture variations in concentrations from different kinds of pipe (different diameters, lengths, curing temperatures, etc.).

2.7.2 CIPP Water Quality Studies

Water quality concerns have been documented for styrene-based resins used in the CIPP process, particularly for steam cure. Under the Safe Drinking Water Act, the Maximum Contaminant Level (MCL) permitted for styrene is 0.1 mg/L, and the following studies measured concentrations above these levels:

- Lee et al. (2008) measured styrene concentrations in CIPP-repaired pipe of 51 mg/L after hot water cure, and 5.5 mg/L for steam-cure after two flushings.
- Tabor et al. (2014) measured styrene levels ranging from 0.01 to 7.4 ppm (equivalent to mg/L in water) at the outlet of a culvert that had been repaired via steam-cure CIPP, as well as a 50-m downstream, for a period of 35 days.
- In a study conducted for the Virginia Transportation Research Council, Donaldson and Baker (2008) studied seven steam-cure CIPP installations in surface water and stormwater conveyances in Virginia. Styrene levels at five of the seven sites were higher than the styrene MCL. Styrene was detected at five sites for a minimum of 5 days to at least 71 days after installation and was detected at these sites up to 40 m downstream.

However, subsequent Virginia DOT studies showed that the release of styrene was caused by poor CIPP installation practices, and implementing new specifications could eliminate these problems.

Other studies have also documented approaches for successfully mitigating water quality concerns from steam cure:

- Leondorf (2009) reported that styrene levels in water from CIPP installation (water and steam cure) were successfully reduced to less than 2 mg/L using a granular activated carbon system.
- Currier (2017) found that adherence to the Caltrans specification for CIPP installation (based on the Virginia DOT specifications) is sufficient to avoid fish kills.
- Another study (Donaldson, 2012) assessed the impacts of UV cure as an alternative to steam cure, and vinyl ester-based resin as alternatives to styrene-based resins. Following UV CIPP installations, no water quality impacts were

documented from culvert outlets with water flow; however, styrene concentrations following one of the installations exceeded toxicity thresholds for aquatic species in standing water. For the vinyl ester CIPP, concentrations of the primary resin constituent exceeded toxicity thresholds for aquatic species in six subsequent water-sampling events; however, adherence to Virginia Department of Transportation CIPP specifications for styrene-based liners is expected to minimize contaminant leaching from the installation and use of this product.

2.8 Chapter Summary

This chapter presents a comprehensive literature review of costs of trenchless CIPP renewal and open-cut pipeline replacement. Various environmental aspects of trenchless CIPP renewal, including worksite chemical air emissions and workers' safety, associated volatile organic compounds and risks, and water quality issues were also discussed. Various researches show that analyzing the environmental and social costs for trenchless CIPP renewal method and open-cut pipeline replacement is important in the decision-making process to choose an alternative pipeline method

Chapter 3

Methodology for Environmental and Social Costs Analysis

3.1 Introduction

Previous chapters indicated that there is lack of study on evaluation and comparison of environmental and social costs of CIPP renewal with open-cut pipeline replacement. Almost all the previous studies recommended a comprehensive environmental and social costs implication for both these pipeline methods. This chapter presents the methodology adopted to calculate and analyze the environmental and social costs of CIPP renewal and open-cut pipeline replacement for this research. The overall methodology, however was shown in Chapter 1. A case study by Ajdari (2016) was used to evaluate the environmental and social costs for small diameter sanitary sewers. This project contained 58 sanitary sewer pipes designed for CIPP renewal and open-cut pipeline replacement. More details about the case study are discussed in the following section.

3.2 Case Study

The cities that have various wastewater basins and contain several sewer pipes, all the sewage from each basin heads to one destination, one wastewater treatment plant. In other words, for large 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 the City of South Pasadena was used as a case study for this dissertation. The City of South Pasadena is in Los Angeles County, California, United States (Figure 3-1). It is located in the West San Gabriel Valley. It is 3.42 square miles in area and lies between the much larger city of Pasadena, of which it was once a part, and the metropolis of Los Angeles. A renewal and replacement project (Figure 3-2), funded by clean water state revolving fund, was conducted by the City of South Pasadena to address City's aging sewer collection system.

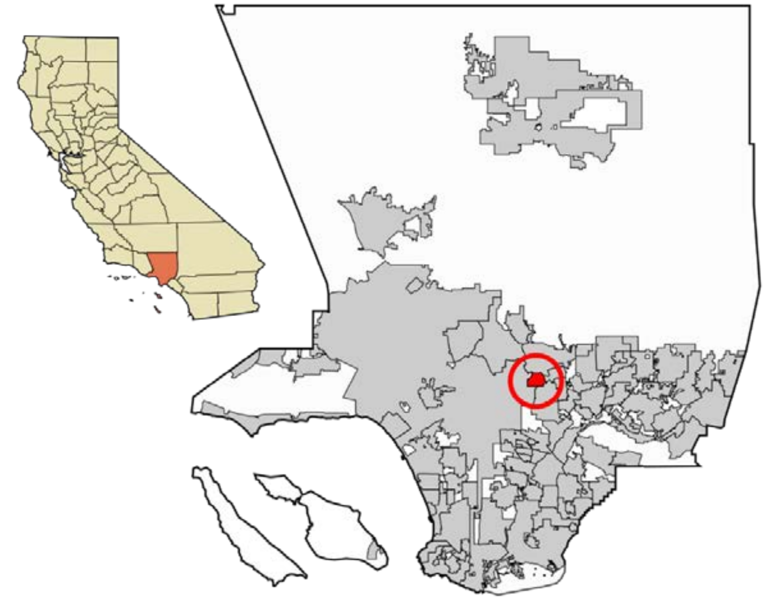

Figure 3-1 Location of City of South Pasadena in the State of California
Source: Google Maps

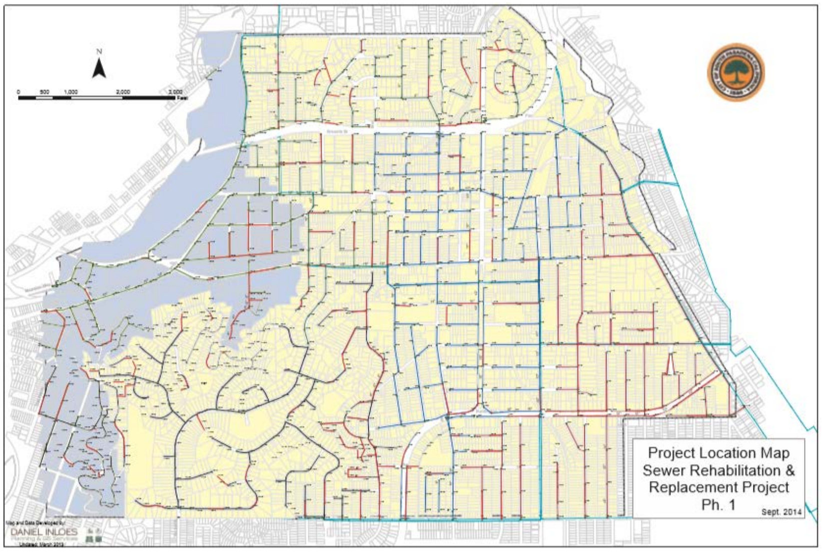

Figure 3-2 Project Location Map
Source: Public Works Department, City of South Pasadena, CA

A total of 390 sewer mains of 8-12 in. diameter and 116,000 ft in length were renewed by CIPP method, whereas 4,000 ft was replaced by open-cut method. While majority of sewer lines were renewed with the CIPP lining, when poor condition to line open-cut replacement was used. Figure 3-3 shows manhole to manhole view of river basin, where this renewal and replacement project was carried out.

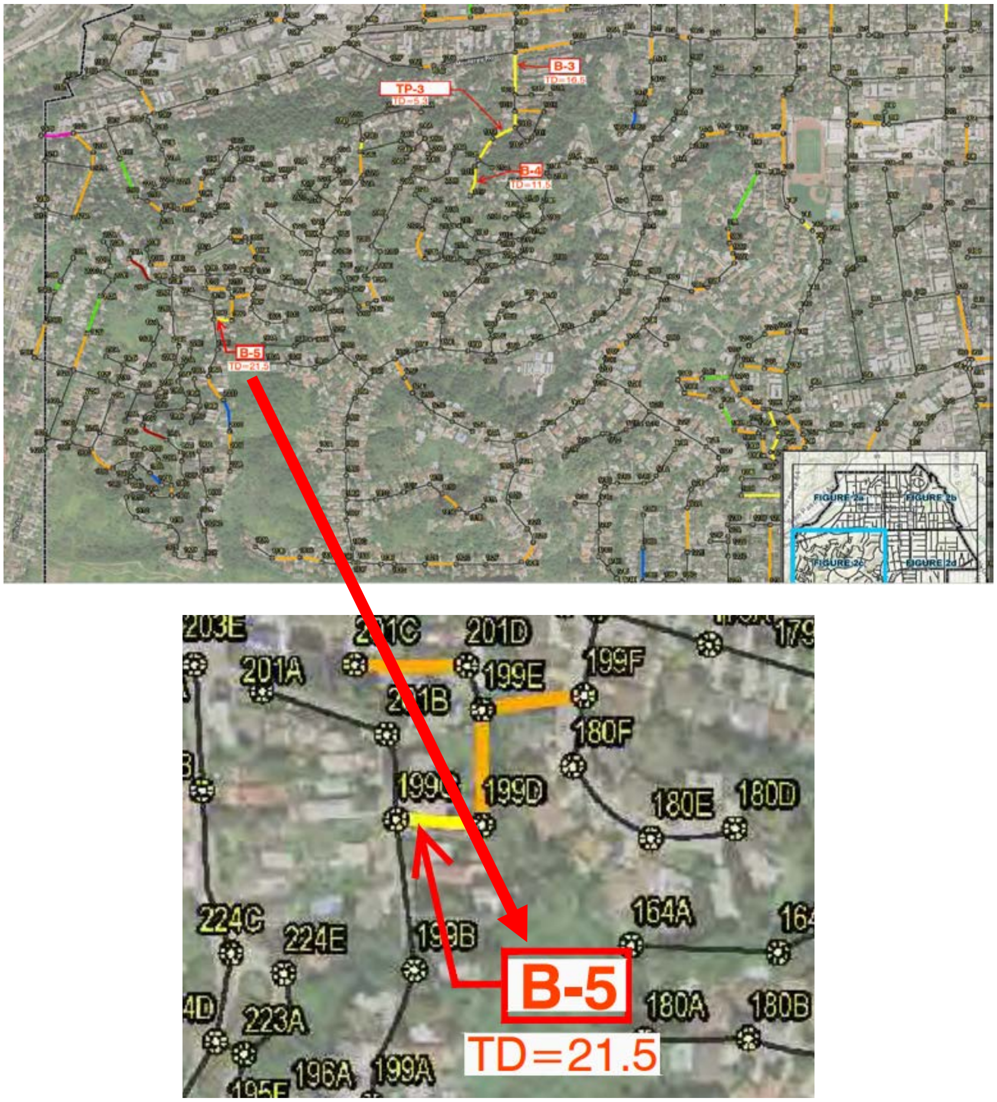

Figure 3-3 Manhole to Manhole View of River Basin in City of South Pasadena
Source: Public Works Department, City of South Pasadena, CA

Information about 58 sanitary sewer pipes related to this project was available from Ajdari (2016). Out of these 58 sanitary sewer pipes in the project, 22 were targeted for CIPP lining, 36 were targeted for open-cut pipeline installation, and 7 were to undergo both spot repair and CIPP lining. In total, the 58 pipes were 13,516 ft in length; 6,561 ft were targeted for CIPP renewal, and 6,955 ft were targeted for open-cut pipeline replacement. The pipes were 8, 10, and 12 inches in diameter. The oldest and newest pipes were installed in 1908 and 1957, respectively. Sanitary sewer pipes were buried 7 to 16 ft below ground surface. Figure 3-4 presents pipe length distribution for CIPP renewal and open-cut replacement. Table 3-1 presents the specifications of all 58 sanitary sewer pipes.

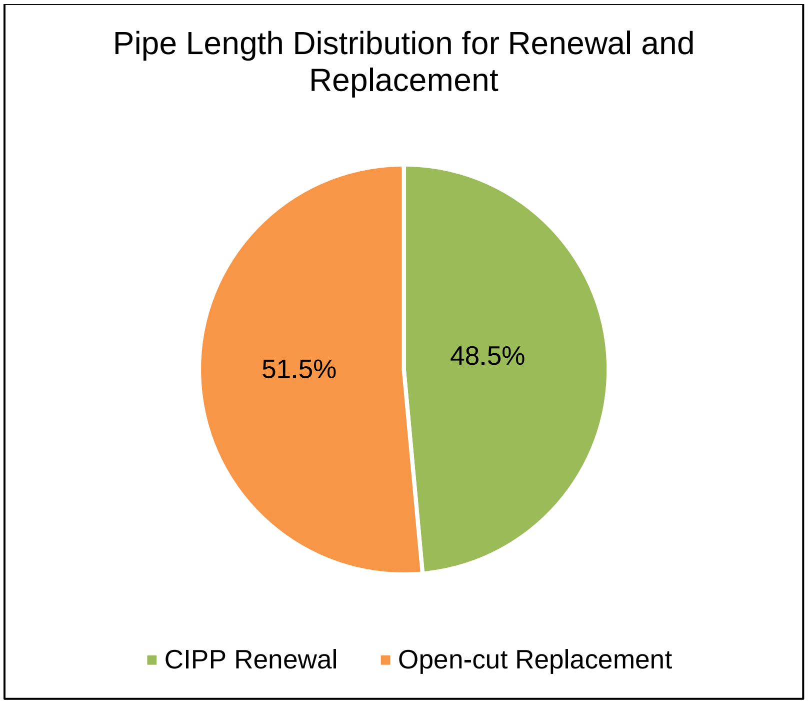

Figure 3-4 Pipe Length Distribution for CIPP Renewal and Open-cut Pipeline Replacement

Figures 3-5 and 3-6 show pipe diameter distributions for CIPP renewal and open-cut pipe replacement, respectively.

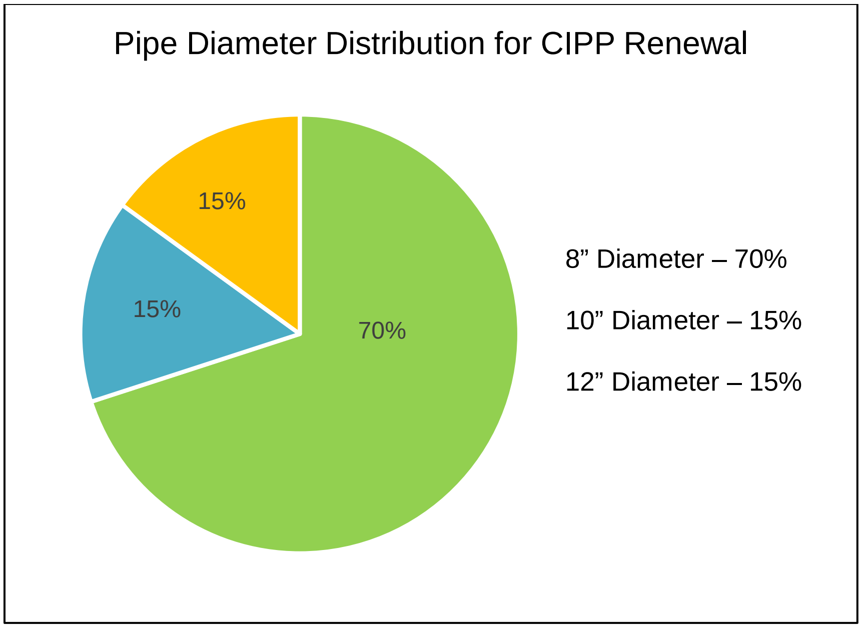

Figure 3-5 Pipe Diameter Distribution for CIPP Renewal

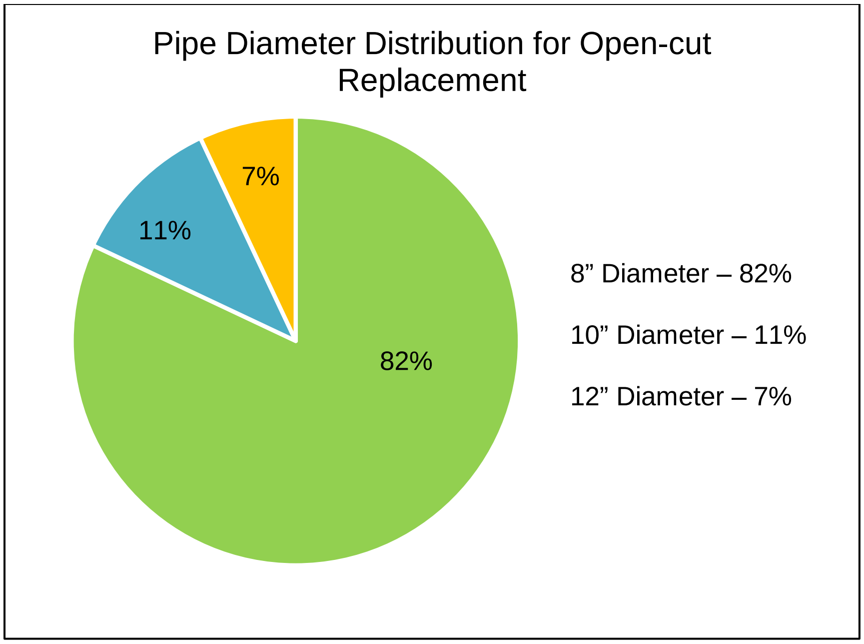

Figure 3-6 Pipe Diameter Distribution for Open-cut Pipeline Replacement

Table 3-1 Specifications of Sanitary Sewer Pipes

No.	Pipe Diameter (in.)	Pipe Material	Year Built	Open-Cut Length (LF)	CIPP Length (LF)
1	8	VCP	1912	35	235
2	8	VCP	1912	225	
3	8	VCP	1915	292	
4	8	VCP	1915	292	
5	10	VCP	1911	25	333
6	10	VCP	1911		323
7	8	VCP	1913		226
8	8	VCP	1911		312
9	10	VCP	1913	367	
10	10	VCP	1911	396	
11	12	VCP	1911		336
12	8	VCP	1912	313	
13	8	VCP	1912	18	
14	10	VCP	1913	328	
15	8	VCP	1912	14	
16	12	VCP	1913	330	
17	8	VCP	1910		254
18	12	VCP	1910		304
19	8	VCP	1910	16	309
20	8	VCP	1911		422
21	8	VCP	1910	20	
22	8	VCP	1910	16	232
23	8	VCP	1915		305
24	8	VCP	1913	300	
25	12	VCP	1910	33	329
26	8	VCP	1910	241	
27	8	VCP	1913	34	305
28	8	VCP	1910	21	
29	8	VCP	1910		328
30	8	VCP	1910		192
31	8	VCP	1908	306	
32	8	VCP	1912	310	
33	8	VCP	1912	310	
34	8	VCP	1912		308
35	8	VCP	1908	249	
36	8	VCP	1908	24	
37	8	VCP	1913		293
38	8	VCP	1913	295	
39	8	VCP	1913	20	
40	8	VCP	1913	30	
41	12	VCP	1908	34	
42	8	VCP	1908	6	
43	8	VCP	1913	18	

No.	Pipe Diameter (in.)	Pipe Material	Year Built	Open-Cut Length (LF)	CIPP Length (LF)
44	8	VCP	1913	28	
45	8	VCP	1957	93	
46	8	VCP	1908	32	
47	10	VCP	1957	18	342
48	8	VCP	1913	6	
49	8	VCP	1908		304
50	8	VCP	1957	42	
51	8	VCP	1913	294	
52	8	VCP	1957		245
53	8	VCP	1919	331	
54	8	VCP	1919	326	
55	8	VCP	1915	231	
56	8	VCP	1919	296	
57	8	VCP	1919	340	
58	8	VCP	1911		324

For carrying out the environmental and social cost analysis, these sewer pipes were divided into CIPP and open-cut pipeline projects. Table 3-2 presents the project details of CIPP renewal and open-cut pipeline replacement. Table 3-3 shows distribution of CIPP renewal and open-cut pipeline replacement as per diameters.

Table 3-2 Project Details of CIPP Renewal and Open-cut Pipeline Replacement

Project Characteristics	Unit	Open-cut	CIPP
Project duration	Days	110	22
Total pipeline length	ft	6,955	6,561
Pipe diameter	in.	8-12	8-12

Table 3-3 Distribution of CIPP Renewal and Open-cut Pipeline Replacement

Methods	Distribution of Lengths as per Diameters		
	8 in.	10 in.	12 in.
CIPP Renewal	4,594	998	969
Open-cut Replacement	5,424	371	397

3.3 Methodology for Environmental and Social Costs Analysis

This section presents a methodology for calculating the environmental and social costs of CIPP renewal and open-cut pipeline replacement. Each of these costs have been described in detail along with factors on the individual costs depend.

3.3.1 Environmental Cost

For calculating the environmental costs of CIPP renewal method and open-cut replacement, the environmental impact assessment was carried out with the help of SimaPro 2017 software using TRACI 2.1 method and then, the emissions were converted into costs as per EPA (2019) and other relevant sources' cost conversion scale. The following section explains the environmental impact analysis and lists the factors that were considered to calculate the environmental costs of CIPP and open-cut pipeline methods for 8 in., 10 in., and 12 in. diameter pipes.

3.3.1.1 Environmental Impact Assessment

Environmental impact assessment, also known as life-cycle assessment (LCA), is a systematic tool or framework used to identify and evaluate the environmental impacts associated with the energy and resources to create materials or services throughout the product's entire lifespan (ISO, 2006; Theis and Tomkin, 2013). Figure 3-7 shows the four steps as per ISO published framework that were followed for LCA.

The first most important step is to define the scope of the LCA. This involves setting clear boundaries of the investigated system, allowing the quantity and quality of inputs and outputs across this boundary to be measured. Thereafter, the goal and scope is defined. The inventory analysis is next step, which involves collecting data on the use of energy and materials for the product or service. The impact assessment uses the inventory data to sum the resources and energy consumed and wastes emitted by all processes in the system to estimate potential impacts to the environment. Interpretation of these results allows decisions to be made to reduce potential impacts by changing energy/material sources or updating processes, or to decide between products/services (ISO, 2006; Theis and Tomkin, 2013).

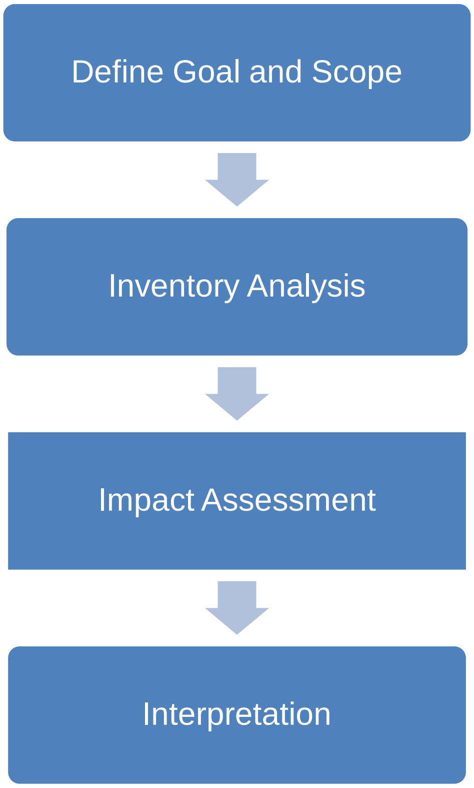

Figure 3-7 Framework for Life Cycle Environmental Analysis using SimaPro 2017 Software

3.3.1.2 SimaPro

SimaPro is a software containing inventory databases and impact assessment methodologies to perform LCA studies (PRé, 2019). These installed databases contain the energy and material requirements and waste emissions for over 10,000 industrial and commercial processes (PRé, 2016) (Figure A-1, Appendix A).

SimaPro models the end-of-life phase through waste scenarios and waste treatment processes. Waste treatments document the emissions and impacts that arise from landfilling, burning, recycling, or composting of waste (PRé, 2016). The waste scenarios in SimaPro are based on material flow and do not observe product characteristics (PRé, 2016). For example, the waste treatment “Landfilling of municipal solid waste” gives the emissions and fuel requirements to landfill a unit mass of generic MSW and does not delineate the chemical composition of the MSW.

SimaPro has several pre-installed waste treatment scenarios that are useful in LCA, but does allow for the creation of custom waste treatment scenarios. Using data, the material, fuel, and energy inputs and corresponding emissions to air, the ground, and water can be defined for a specified waste. These inputs to construct custom waste treatment scenarios are in units of mass, meaning energy and fuel requirements and emissions are calculated as masses given the mass of treated waste.

SimaPro uses the previously defined boundaries and pulls inventory data from its database to perform the impact assessment. An indicator substance is used in each impact category, and all emissions across material and fuel inputs and waste are converted to equivalents of these indicator substances (PRé, 2016). For example, to measure impacts to Global Warming, emissions from all steps or system processes are converted to equivalent masses of CO_2 and totaled. This conversion and summation is performed for all categories to allow meaningful comparison between products or processes.

The outputs provided by SimaPro can then be displayed in an easy-to-read bar chart. For each impact category, the scenario with the largest impact will be scaled to 100, and the remaining processes will have their impact scaled off of the 100. For example, comparing two generic waste treatments 1 and 2 for impacts to global warming: If treatment 1 has 50kg CO_2 equivalent emissions and treatment 2 has 25kg CO_2 equivalents, treatment 1 will be represented by a bar with height 100, and treatment 2 with a bar height of 50. This is done for each impact category and all impact categories are shown on the same graph.

3.3.1.3 Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.1

The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) is an environmental impact assessment tool created by the US Environmental Protection Agency (EPA) (EPA, 2016; PRé, 2016) (Figure A-2, Appendix A). TRACI calculates impact assessments based on ten impact categories:

1. Ozone depletion (measured in kg CFC-11 (Freon-11) equivalents)
2. Global warming (measured in kg CO_2 equivalents)
3. Smog (measured in kg O_3 equivalents)
4. Acidification (measured in kg SO_2 equivalents)
5. Eutrophication (measured in kg N equivalents)
6. Carcinogenics (measured in comparative toxic units (CTU) for morbidity (h))
7. Non-carcinogenics (measured in CTUh)
8. Respiratory effects (measured in kg particulate matter (PM) 2.5 equivalents)
9. Ecotoxicity (measured in CTU for aquatic ecotoxicity (CTUe))
10. Fossil Fuel Depletion (measured in MJ)

TRACI has factors for normalization to allow for comparison between impact categories. The normalization divides the calculated outputs for the individual impact categories by the averaged impact values of a US or Canadian citizen for each impact category for a year (PRé, 2016). This division will mean relative bar height is scaled off of how much more or less impact the scenario produces compared to the average citizen. A higher bar would mean more detrimental impacts than an average citizen, while lower bars mean relatively less detrimental impacts. This allows for qualitative comparison between impact categories. Tables 3-4 and 3-5 show various inputs related to material and specifications for 8 in., 10 in., and 12 in. CIPP renewal, respectively (Figures A-3, A-5, A-7, Appendix A).

Table 3-4 CIPP Material[3] Input in SimaPro Software

Materials/Assemblies	Unit	Amount (8 in.)	Amount (10 in.)	Amount (12 in.)	Remark/Reference
Glassfiber reinforced plastic (polyester resin, hand layup, at plant/US- US-EI U)*	lb	45,289	12,298	9,024	Weight = Volume x Density Density = 158.6 lb/CF, Volume = 453 CF (Alsadi, 2019)
Dummy Plastic* (unspecified)	lb	195	53	39	Weight = Volume x Density Density of vinyl ester = 6 lb/CF, Volume = 51.5 CF (Alsadi, 2019)
Polyester resin (unsaturated, at plant/US- US-EI U)*	lb	5,205	1,414	1,037	Weight = Volume x Density Density of polyester resin = 106 lb/CF, Volume = 77.9 CF (Alsadi, 2019)
Styrene E*	lb	8,972	2,436	1,788	(Ajdari, 2016)
PET (amorphous) E*	lb	1,043	283	208	(Ajdari, 2016)
Polyethylene (linear low density, resin, at plant, CTR/kg/RNA)*	lb	10,433	2,833	2,079	(Ajdari, 2016)

*SimaPro codes

Table 3-5 CIPP Specifications

Material Factor	Input	Remark/Reference
Resin used	Alpha Owens Corning L010-PPA-38 Vinyl Ester	(Ajdari, 2016)
Thickness of felt	0.16 in.	Calculated as per ASTM F1216
Internal pressure	80 psi	(Ajdari, 2016)

Tables 3-6 and 3-7 show various equipment and material related factors used for assessing the environmental impacts of CIPP renewal method, respectively.

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[3] The distribution of material for each diameter has been done after experts' interview and as per industry practice. According to this practice, as we go from 8 in. to 10 in., material increase by 25% and same way for going from 10 in. to 12 in.

Table 3-6 Equipment Related Factors used for Environmental Impact Assessment of CIPP

Factors	Equipment Used*						
	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

*Number of equipment used for each type is 1.

Figure 3-8 illustrates a typical layout of CIPP renewal method. It shows manhole to manhole section of pipe to be renewed by CIPP method along with location of equipment to be used, such as jetter truck, air compressor, refrigerated truck, utility truck, generator set, and TV truck.

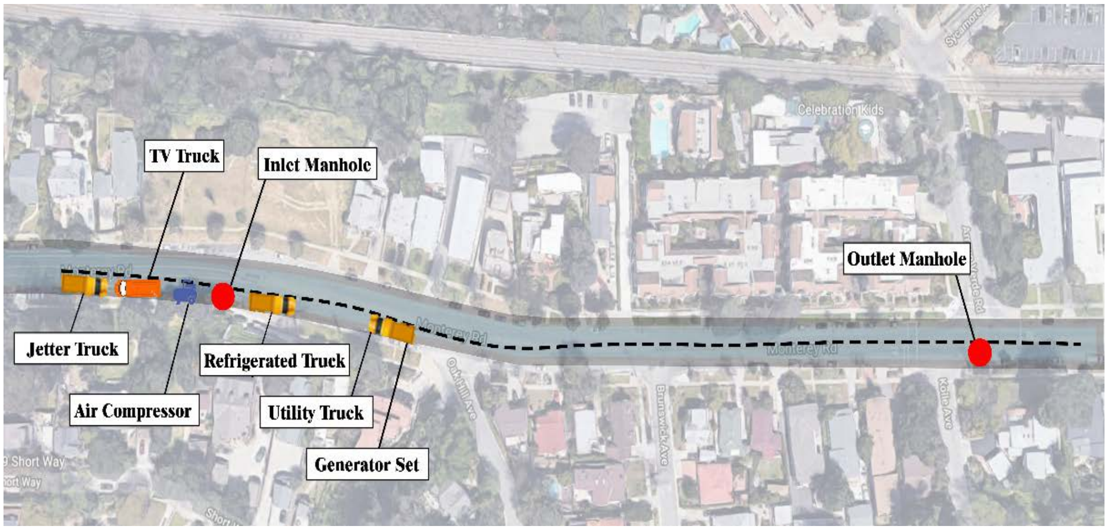


Figure 3-8 Typical Layout of CIPP Renewal Method
Source: Ramtin Serajiantehrani

Table 3-7 CIPP Processes Input in SimaPro Software

Processes	Unit	Amount (8 in.)	Amount (10 in.)	Amount (12 in.)	Remark/Reference
Air compressor (screw-type compressor, 300 kW, at plant/US-/I US-EI U)*	Piece	0.007	0.002	0.001	Considering 1% of total emissions from production of an air compressor
Transport (single unit truck, diesel powered/US)*	Ton-mile	711	155	150	Total material weight*Transportation distance
Van (<3.5t/US-/I US-EI U)*	Piece	0.025	0.005	0.005	Ajdari, 2016
On-site steam average E*	lb	79,110	17,186	16,687	Ajdari, 2016
Generator (200kWe/US-/I US-EI U)*	Piece	0.021	0.005	0.004	3 generators, considering 1% of total emissions from production of generator
Electricity (mix, California/US US-EI U)*	HP.hr	187,163	40,659	39,479	HP of each equipment x Number of hours equipment used (Ajdari, 2016)

*SimaPro code

Tables 3-8 and 3-9 show various equipment and material related factors used for assessing the environmental impacts of open-cut pipeline replacement, respectively.

Table 3-10 shows various inputs related to processes for 8 in., 10in., and 12 in. open-cut pipeline replacement (Figures A-4, A-6, and A-10, Appendix A).

Figure 3-9 illustrates a typical layout of open-cut pipeline replacement. It shows a section of pipe to be replaced by a new PVC pipe with the help of open-cut method along with location of equipment to be used, such as air compressor, dump truck, utility truck, signal board, excavator, concrete saw, jack hammer, backhoe, and compactor.

Table 3-8 Equipment* Related Factors used for Environmental Impact Assessment of Open-cut Pipeline Replacement

Equipment	Air Compressor	Dump truck	Utility truck	Signal board	Mini excavator	Bypass pump	Concrete saw	Jack Hammer	Backhoe	Roller	Paver
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

*Number of equipment used for each type is 1.

Table 3-9 Open-cut Replacement Materials Input in SimaPro Software

Pipe used	PVC		Remark/Reference
Weight of PVC pipe	8 in.	29,235 lb	www.midcoonline.com
	10 in.	2,801 lb	
	12 in.	3,974 lb	

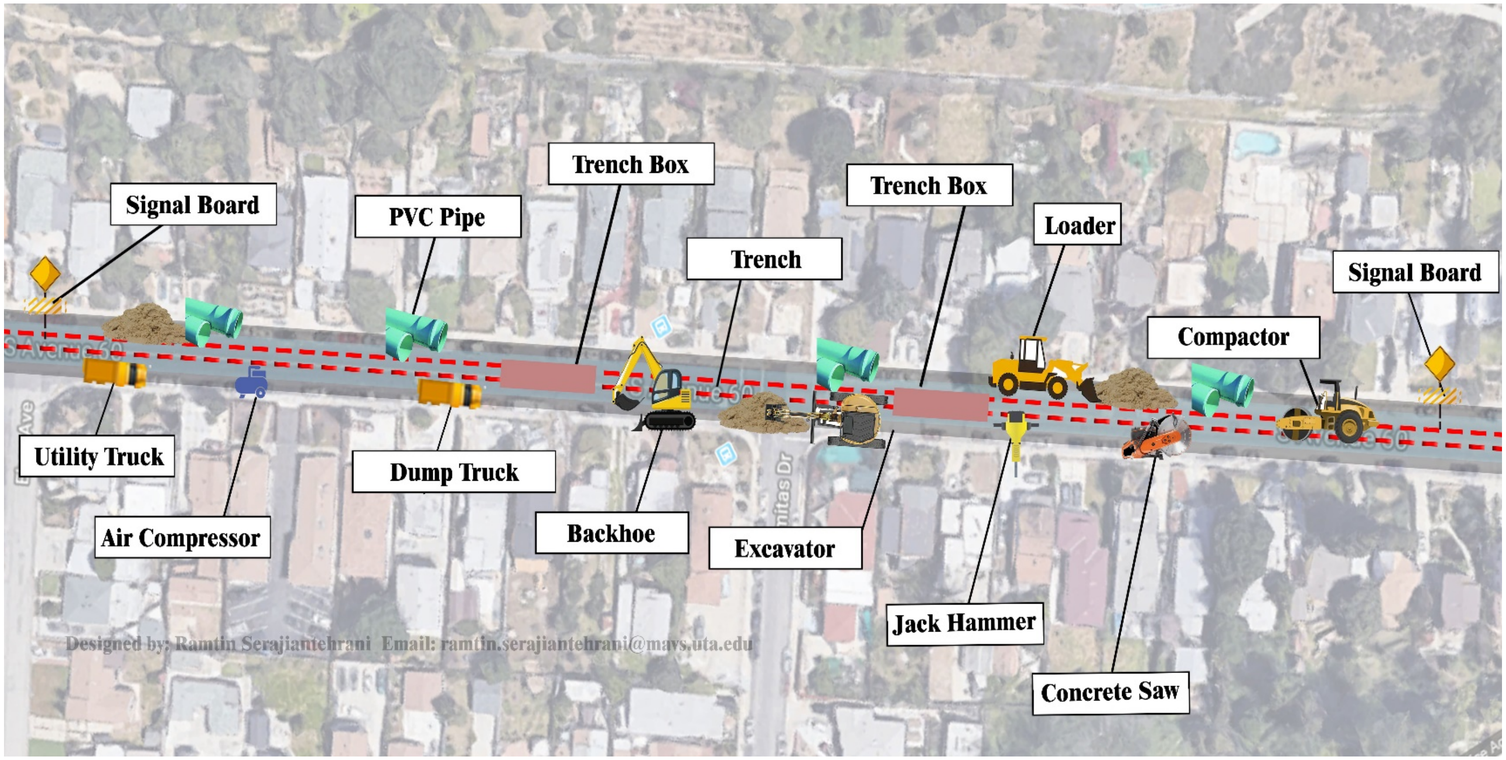


Figure 3-9 Typical Layout of Open-cut Replacement Method
Source: Ramtin Serajiantehrani

Table 3-10 Open-cut Processes Input in SimaPro

Processes	Unit	Amount (8 in.)	Amount (10 in.)	Amount (12 in.)	Remark/Reference
Excavator (technology mix, 100 kW, Construction GLO)*	lb	1,086,983	73,915	73,915	(Ajdari, 2016)
Transport (combination truck, short-haul, diesel powered, Southeast/tkm/RNA)*	Ton-mile	2,718	185	185	Total material weight x Transportation distance (Ajdari, 2016)
Van (<3.St/US-/1 US-EI U)*	Piece	0.0176	0.001	0.001	2 Vans, considering 1% of total emissions from production of van (Ajdari, 2016)
Pump (40W, at pl ant/US*/I US-EI U)*	Piece	0.07	0.004	0.004	8 Pumps, considering 1% of total emissions from production of pump (Ajdari, 2016)
Power saw (with catalytic converter/US-/I US-EI U)*	Piece	0.008	0.001	0.001	1 Power saw, considering 1% of total emissions from production of power saw (Ajdari, 2016)
Jack hammer (rock/US- US-EI U)*	lb	362,328	24,638	24,638	(Ajdari, 2016)
Generator (200kWe/US-/I US-EI U)*	Piece	0.08	0.001	0.001	1 Generator, consuming 1% of energy per piece (Ajdari, 2016)
Electricity (mix, California/US US-EI U)*	HP.Hr	415184	28233	28233	HP of each equipment x Number of hours equipment used (Ajdari, 2016)
Air compressor, (screw-type compressor, 300 kW, at plant/US-/I US-EI U)*	Piece	0.08	0.001	0.001	1 Air compressor, consuming 1% of energy per piece (Ajdari, 2016)
Loader (operation, large, INW NREL/RNA U)*	hr	387	26	26	(Ajdari, 2016)

*denotes SimaPro code

Table 3-11 shows unit costs of emissions used for calculating the environmental costs for CIPP renewal and open-cut pipeline replacement.

Table 3-11 Unit Costs of Emissions for Calculation of Environmental Cost of CIPP Renewal and Open-cut Pipeline Replacement

Impact category	Unit	Unit Cost ($)	Remark/Reference
Ozone depletion	kg CFC-11 eq	387.8	Visentil et al., 2019
Global warming	kg CO2 eq	0.04	USEPA, 2019
Smog	kg O3 eq	12.3	Visentil et al., 2019
Acidification	kg SO2 eq	9.6	Visentil et al., 2019
Eutrophication	kg N eq	3.45	CE Delft, 2017
Carcinogenics	CTUh	180.2	Visentil et al., 2019
Non carcinogenics	CTUh	180.2	Visentil et al., 2019
Respiratory effects	kg PM2.5 eq	39.7	Visentil et al., 2019
Ecotoxicity	CTUe	N/A	-
Fossil fuel depletion	MJ surplus	N/A	-

N/A – Not available

The detailed environmental cost results are presented and discussed in Chapter 4.

Assumptions: Following are the assumptions and limitations for calculation of environmental cost of CIPP and open-cut pipeline replacement:

CIPP Renewal

1. The analysis is done as per Alpha Owens Corning L010-PPA-38 Vinyl Ester resin.
2. Ajdari (2016) was used as a source for information about CIPP renewal, material, equipment, operation hours, etc.
3. Steam-curing CIPP method was used.
4. Pickup trucks are needed, however, were not considered because it will be same for both the methods.

Open-cut Pipeline Replacement

1. The new pipe to be installed is assumed to be PVC because it is the most commonly used pipe in sanitary sewers.
2. Ajdari (2016) was used as a source for information about open-cut pipeline replacement, equipment, operation hours, etc.
3. The open-cut pipeline replacement did not include soil transportation. Same material was used for backfill.
4. Pickup trucks are needed, however, were not considered because it will be same for both the methods.

3.3.2 Social Cost

For calculating the social costs of CIPP renewal method and open-cut pipeline replacement for 8, 10, and 12 in. diameter, various equations from Najafi and Gokhale (2005) and reasonable assumptions from various relevant sources were used.

Various social cost concepts and equations (Najafi and Gokhale, 2005) for calculating them have been discussed as follows:

Duration of the Project

The duration of the project plays an important role in the value of social costs involved in utility construction. For example, sometimes contractors need to close one or two lanes of traffic during open-cut pipeline replacement. The lane-closure procedure often continues for the entire duration of the project, resulting in congestion and delays for daily commuters.

The cost of delay and congestion is significantly less for projects of short duration. But with an increase in time, the traffic disruption costs will increase. Also, the place and location of the lane closure affects the social costs of the project.

Cost of Fuel

Utility construction using open-cut replacement method often results in lane closures and traffic congestion. The amount of time spent in traffic delays is directly related to the cost of fuel wasted. The cost of fuel is estimated based on the number of gallons wasted per car in waiting during traffic delays or going through detour roads. The average fuel consumption of a car is used to calculate the amount of fuel wasted in traffic. Costs of fuel for detour roads or delay per vehicle are calculated according to Eq. 3-1

$$\frac{Cost\ of\ fuel\ for\ detour\ roads}{vehicles} = \left(\frac{Avg\ gal}{mile}\right) * (Avg\ additional\ mile) * \left(\frac{Avg\ cost\ of\ fuel}{gal}\right) \qquad \text{Equation 3-1}$$

Cost of Travel Time

Travel time costs vary widely depending on factors such as the type of trip, distance of travel, traveler, and travel condition. Per-minute travel time costs tend to be higher for passengers during uncomfortable and congested conditions. Cost of detour delay can be calculated according to Eq. 3-2

$$Cost\ of\ detour\ delay = \left(\frac{Avg\ time}{mile}\right) * (Additional\ miles\ to\ travel) * (Value\ of\ time\ in\ dollars) \qquad \text{Equation 3-2}$$

Road Damage

Road damage due to utility construction can be of two forms. One is the pavement damage due to utility cuts, trenching, and poor patching procedures. These damages show in the forms of potholes, surface roughness, and cracks. The second cost is the damage to detour roads, due to the additional heavy traffic during construction. The following Eq. 3-3 can be used in estimating the cost of pavement restoration:

$$Pavement\ restoration\ cost = \left(\frac{Restoration\ cost}{ft^2}\right) * (number\ of\ ft^2) \qquad \text{Equation 3-3}$$

Loss of Sales Tax

Loss of tax revenue is incurred by businesses and shops affected by the utility construction (Figure 3-10). People try to avoid roads with lane closures due to utility construction. Loss of customers transforms to a loss in income for the shops. The following Eq. 3-4 can be used in estimating the loss of sales tax:

$$Loss\ of\ sales\ tax = \left(\frac{Average\ dollar\ loss}{day}\right) * (Duration\ of\ project\ in\ days) \qquad \text{Equation 3-4}$$

Figure 3-10 Business Loss due to Open-cut Pipeline Replacement
Source: Najafi and Gokhale, 2005

Loss of Productivity

Loss of productivity can be associated with the noise pollution generated during construction activity. Most of the time, the effect of noise on people is impossible to quantify. People react differently to noise; some can continue functioning with less productivity, whereas others are unable to put up with the noise. In residential neighborhoods, noise and vibration can disrupt the normal life of the residents (Eq. 3-5).

$$Cost\ of\ productivity\ = \left(\frac{Time\ lost}{day}\right) * (Number\ of\ persons) *$$

$$(Value\ of\ time) * (Duration\ of\ project\ in\ days) \quad \text{Equation 3-5}$$

Dust

One way of estimating the cost of dust is to calculate the additional time spent in cleaning. The following Eq. 3-6 can be used to estimate the cost of dust and dirt control:

$$Cost\ of\ dust\ control = \left(\frac{Increased\ cleaning\ time\ in\ hours}{Day}\right) * (Hourly\ pay\ rate)(Number\ of\ units\ impacted) *$$

$$(Duration\ of\ project\ in\ days) + (Cost\ of\ cleaning\ materials) \quad \text{Equation 3-6}$$

Tables 3-12 and 3-13 illustrate the cost factors for social cost calculation of CIPP renewal method and open-cut pipeline replacement.

Table 3-12 Cost Factors for Social Cost Calculation of CIPP Renewal Method

Cost Factors	Unit	CIPP Renewal			Remark/Reference
		8 in.	10 in.	12 in.	
Project Duration (days)	days	16	3	3	Ajdari, 2016
Average gal/mile	gal/mile	0.0625	0.0625	0.0625	Considering average of vehicle as 16 miles/gal
Average additional mile	mile	0	0	0	There is no complete road closure
Average cost of fuel/gal	$/gal	2.5	2.5	2.5	Average price of fuel
Average time/mile	hr/mile	35	35	35	Assumption (Najafi, 2005)
Value of time in dollars	$	35	35	35	Calculated as per Matthews et al., 2015
Number of vehicles	No.	-	-	-	AADT, 2019
Restoration cost	$/SF	-	-	-	There is no restoration of pavement involved
Number of SF	SF	-	-	-	Area (SF) = Length of replacement (ft) x Width of trench (ft)
Average dollars loss per day	$/day	-	-	-	No dollar loss per day involved
Time loss/day	hr/day	0.028	0.028	0.028	Due to 35 mph decreased speed (Najafi, 2005)
Increased cleaning time in hr/day	Hr/day	2	2	2	As per Matthews et al., 2015
Hourly pay rate	$/hr	25	25	25	RS Means, 2019
Number of units impacted	No.	23	6	6	As per Google Map
Cost of cleaning materials	$	100	50	50	RS Means, 2019

Table 3-13 Cost Factors for Social Cost Calculation of Open-cut Pipeline Replacement

Cost Factors	Unit	Open-cut Replacement			Remark/Reference
		8 in.	10 in.	12 in.	
Project Duration (days)	days	96	7	7	Ajdari, 2016
Average gal/mile	gal/mile	0.0625	0.0625	0.0625	Considering average of vehicle as 16 miles/gal
Average additional mile	mile	1	0.1	0.1	Assumption (Matthews et al., 2015)
Average cost of fuel/gal	$/gal	2.5	2.5	2.5	Average price of fuel
Average time/mile	hr/mile	35	35	35	Assumption (Najafi, 2005)
Value of time in dollars	$	35	35	35	Calculated as per Matthews et al., 2015
Number of vehicles	No.	12,000	12,000	12,000	AADT, 2019
Restoration cost	$/SF	200	200	200	Converted to NPV from Hashemi, 2008
Number of SF	SF	10,848	742	794	Area (SF) = Length of replacement (ft) x Width of trench (ft)
Average dollars loss per day	$/day	11,000	11,000	11,000	As per Matthews et al., 2015
Time loss/day	hr/day	0.028	0.028	0.028	Due to 35 mph decreased speed (Najafi, 2005)
Increased cleaning time in hr/day	Hr/day	2	2	2	As per Matthews et al., 2015
Hourly pay rate	$/hr	25	25	25	RS Means, 2019
Number of units impacted	No.	23	2	2	As per Google Map
Cost of cleaning materials	$	200	50	50	RS Means, 2019

Therefore, social cost is the summation of all the factors listed in the Tables 3-10 and 3-11 for CIPP renewal and open-cut pipeline replacement, respectively. The detailed social cost results are presented and discussed in the next chapter.

Assumptions: Following are the assumptions as per relevant literature for calculation of social cost of CIPP renewal and open-cut pipeline replacement:

CIPP Renewal

1. Mileage of a vehicle is assumed to be 16 miles/gal.
2. Cost of fuel is taken as $2.5/gal.
3. Average time/mile is assumed to be 35.
4. Value of time in dollars is assumed to be $35.
5. Time lost per day is calculated as per 35 mph decreased speed .
6. Increased cleaning time is taken as 2 hour per day.
7. Hourly pay rate is considered as $25.
8. Number of units impacted are assumed to be 23, 6, and 6 for 8 in., 10 in., and 12 in., respectively.
9. Cost of cleaning materials is taken $100, $50, and $50 for 8 in., 10 in., and 12 in., respectively.
10. Pickup trucks are needed, however, were not considered because it will be same for both the methods.

Open-cut Pipeline Replacement

1. Mileage of a vehicle is assumed to be 16 miles/gal.
2. It is assumed that on an average a car will have to travel an additional 1.3 miles.
3. Cost of fuel is taken as $2.5/gal.
4. Average time/mile is assumed to be 35.
5. Value of time is assumed to be $35.
6. Restoration cost/SF is assumed to be $200.

7. Average dollars loss per day is taken as $11,000.
8. Time lost per day is assumed to be 35 minutes.
9. Increased cleaning time is taken as 2 hour per day.
10. Hourly pay rate is considered as $25.
11. Number of units impacted are assumed to be 23, 2, and 2 for 8 in., 10 in., and 12 in., respectively.
12. Cost of cleaning materials is taken $200, $50, and $50 for 8 in., 10 in., and 12 in., respectively.
13. Pickup trucks are needed, however, were not considered because it will be same for both the methods.

3.4 Chapter Summary

The methodology for calculation of environmental and social costs of CIPP renewal method and open-cut pipeline replacement for 8 in., 10 in., and 12 in. diameter sanitary sewers was presented along with factors affecting each cost. A case study was studied to determine the type of pipeline construction method, construction equipment used, project duration, operation hours, etc. Experts were contacted to obtain and verify the specifics for different construction activities during CIPP and open-cut construction. Reasonable assumptions were made in case of unavailability of the data and limitations were established related to each cost calculation.

Chapter 4

Results and Analysis

4.1 Introduction

This chapter presents the results and analysis of the research undertaken for this dissertation as explained in Chapter 3. The results are categorized into environmental and social costs for 8 in., 10 in., and 12 in. diameters CIPP renewal and open-cut pipeline replacement. At the end, a comparative analysis between the total environmental and social costs of CIPP and open-cut pipeline methods is also presented.

4.2 Environmental Cost Results

1. Figures 4-1, 4-2, and 4-3 show the comparison of environmental impact assessment as per TRACI 2.1 method of SimaPro for 8 in., 10 in., and 12 in. diameter, respectively, for CIPP renewal method with open-cut pipeline replacement.

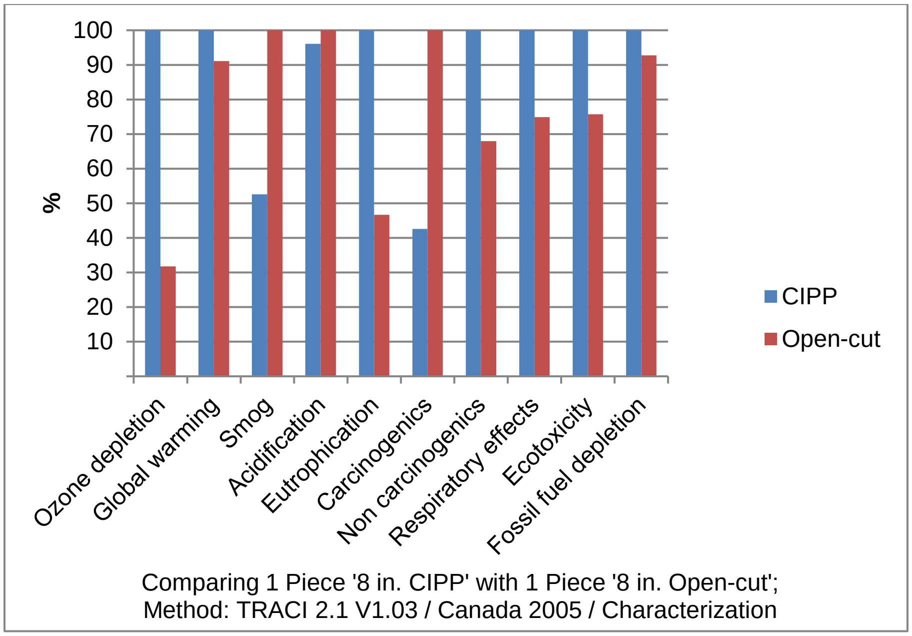


Figure 4-1 Environmental Impact Assessment of 8 in. diameter CIPP Renewal and Open-cut Pipeline Replacement

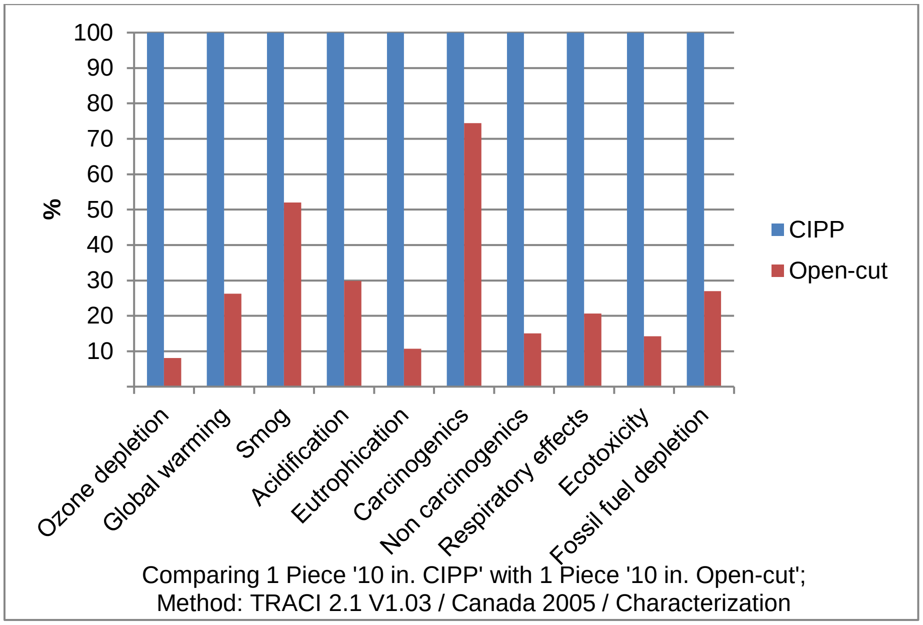


Figure 4-2 Environmental Impact Assessment of 10 in. diameter CIPP Renewal and Open-cut Pipeline Replacement

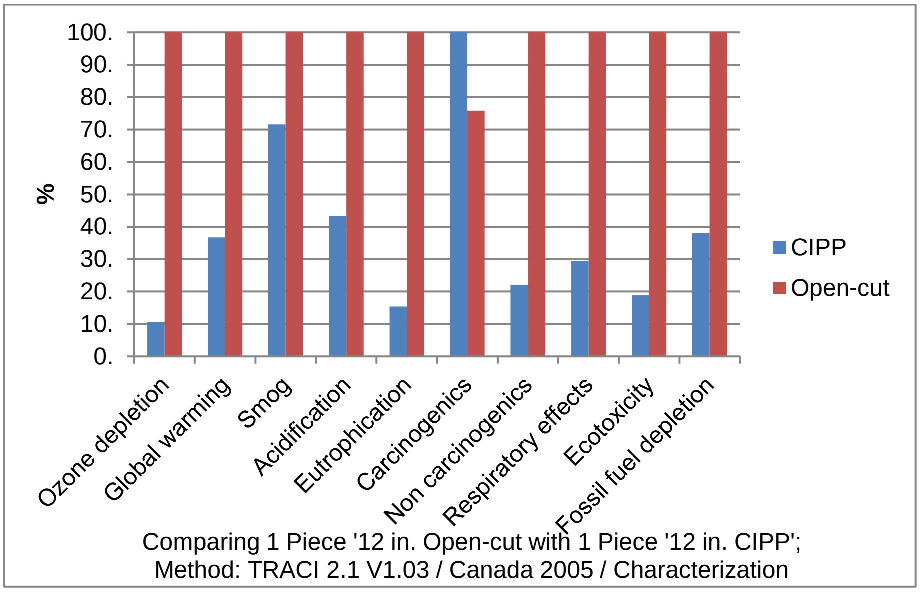


Figure 4-3 Environmental Impact Assessment of 12 in. diameter CIPP Renewal and Open-cut Pipeline Replacement

2. Tables 4-1, 4-2, and 4-3 show the detailed environmental impact assessment results for 8 in., 10 in., and 12 in. diameter, respectively, for CIPP renewal method.

Table 4-1 Environment Impact Assessment Results for 8 in. CIPP Renewal Method

Impact category	Unit	Glassfiber reinforced plastic	Dummy plastic	Polyester resin	Styrene E	PET (amorphous)	Polyethylene (linear low density, resin, at plant, CTR/ kg/ RNA)*	Total Emissions
Ozone depletion	kg CFC-11 eq	0.00766	N/A	0.00167	N/A	N/A	2.83E-5	0.0108
Global warming	kg CO_2 eq	1.11E5	N/A	1.89E4	1.26E4	1.55E3	8.93E3	2.24E5
Smog	kg O_3 eq	4.73E3	N/A	540	435	87	287	8.01E3
Acidification	kg SO_2 eq	408	N/A	48.4	38.6	7.27	27.3	706
Eutrophication	kg N eq	170	N/A	31.7	0.913	0.221	0.541	230
Carcinogenics	CTUh	0.00366	N/A	0.000496	2.83E-6	4.01E-6	2.35E-5	0.0052
Non carcinogenics	CTUh	0.0236	N/A	0.00273	2.38E-6	1.2E-6	0.000249	0.0315
Respiratory effects	kg PM2.5 eq	30.1	N/A	3.92	1.74	0.317	1.61	51.3
Ecotoxicity	CTUe	3.27E5	N/A	4.84E4	474	58.8	4.11E3	4.61E5
Fossil fuel depletion	MJ surplus	1.93E5	N/A	3.4E4	4.8E4	4.84E3	5.2E4	4.81E5

*SimaPro code

Table 4-2 Environment Impact Assessment Results for 10 in. CIPP Renewal Method

Impact category	Unit	Glassfiber reinforced plastic	Dummy plastic	Polyester resin	Styrene E	PET (amorphous)	Polyethylene (linear low density, resin, at plant, CTR/ kg/ RNA)*	Total Emissions
Ozone depletion	kg CFC-11 eq	0.00208	N/A	0.000453	N/A	N/A	7.7E-6	0.00286
Global warming	kg CO_2 eq	3.01E4	N/A	5.13E3	3.42E3	420	2.43E3	5.7E4
Smog	kg O_3 eq	1.28E3	N/A	147	118	23.6	77.9	2.07E3
Acidification	kg SO_2 eq	111	N/A	13.1	10.5	1.97	7.41	182
Eutrophication	kg N eq	46.2	N/A	8.62	0.248	0.0598	0.147	61.2
Carcinogenics	CTUh	0.000995	N/A	0.000135	7.7E-6	1.09E-6	6.37E-6	0.00136
Non carcinogenics	CTUh	0.00642	N/A	0.000743	6.47E-6	3.26E-7	6.75E-5	0.00832
Respiratory effects	kg PM2.5 eq	8.17	N/A	1.07	0.472	0.086	0.437	13.2
Ecotoxicity	CTUe	8.88E4	N/A	1.32E4	129	16	1.12E3	1.21E5
Fossil fuel depletion	MJ surplus	5.24E4	N/A	9.24E3	1.3E4	1.31E3	1.41E4	1.23E5

*SimaPro code

Table 4-3 Environment Impact Assessment Results for 12 in. CIPP Renewal Method

Impact category	Unit	Glassfiber reinforced plastic	Dummy plastic	Polyester resin	Styrene E	PET (amorphous)	Polyethylene (linear low density, resin, at plant, CTR/ kg/ RNA)*	Total Emissions
Ozone depletion	kg CFC-11 eq	0.00153	N/A	0.000332	N/A	N/A	5.65E-6	0.00218
Global warming	kg CO_2 eq	2.21E4	N/A	3.76E3	2.51E3	309	1.78E3	4.55E4
Smog	kg O_3 eq	943	N/A	108	86.6	17.4	57.2	1.62E3
Acidification	kg SO_2 eq	81.2	N/A	9.63	7.7	1.45	5.44	143
Eutrophication	kg N eq	33.9	N/A	6.32	0.182	0.044	0.108	46.1
Carcinogenics	CTUh	0.00073	N/A	9.89E-5	5.65E-6	8E-8	4.68E-6	0.00104
Non carcinogenics	CTUh	0.00471	N/A	0.000545	4.75E-6	2.4E-7	4.95E-5	0.0063
Respiratory effects	kg PM2.5 eq	5.99	N/A	0.781	0.346	0.0632	0.321	10.4
Ecotoxicity	CTUe	6.52E4	N/A	9.65E3	94.4	11.7	819	9.21E4
Fossil fuel depletion	MJ surplus	3.85E4	N/A	6.78E3	9.56E3	965	1.04E4	9.76E4

*SimaPro code

3. Tables 4-4, 4-5, and 4-6 show the detailed environmental impact assessment results for 8 in., 10 in., and 12 in. diameter, respectively, for open-cut pipeline replacement.

Table 4-4 Environment Impact Assessment Results for 8 in. Open-cut Pipeline Replacement

Impact category	Unit	PVC Pipe E	Excavator	Total Emissions
Ozone depletion	kg CFC-11 eq	N/A	2.16E-6	0.00345
Global warming	kg CO_2 eq	4.29E4	987	2.04E5
Smog	kg O_3 eq	2.01E3	98.5	1.52E4
Acidification	kg SO_2 eq	187	4.68	735
Eutrophication	kg N eq	14	0.266	108
Carcinogenics	CTUh	0.00889	5.14E-7	0.0122
Non carcinogenics	CTUh	0.00355	3.11E-6	0.0214
Respiratory effects	kg PM2.5 eq	8.47	0.256	38.4
Ecotoxicity	CTUe	2.07E3	31.8	3.5E5
Fossil fuel depletion	MJ surplus	1.01E5	1.98E3	4.47E5

Table 4-5 Environment Impact Assessment Results for 10 in. Open-cut Pipeline Replacement

Impact category	Unit	PVC Pipe E	Excavator	Total Emissions
Ozone depletion	kg CFC-11 eq	N/A	1.47E-7	0.000231
Global warming	kg CO_2 eq	4.11E3	67.1	1.5E4
Smog	kg O_3 eq	192	6.7	1.08E3
Acidification	kg SO_2 eq	17.9	0.318	54.3
Eutrophication	kg N eq	1.35	0.0181	6.53
Carcinogenics	CTUh	0.000852	3.49E-8	0.00102
Non carcinogenics	CTUh	0.000341	2.11E-7	0.00125
Respiratory effects	kg PM2.5 eq	0.811	0.0174	2.73
Ecotoxicity	CTUe	198	2.16	1.73E4
Fossil fuel depletion	MJ surplus	9.68E3	135	3.31E4

Table 4-6 Environment Impact Assessment Results for 12 in. Open-cut Pipeline Replacement

Impact category	Unit	PVC Pipe E	Excavator	Total Emissions
Ozone depletion	kg CFC-11 eq	N/A	1.47E-7	0.000231
Global warming	kg CO_2 eq	5.83E3	67.1	1.67E4
Smog	kg O_3 eq	273	6.7	1.16E3
Acidification	kg SO_2 eq	25.4	0.318	61.8
Eutrophication	kg N eq	1.91	0.0181	7.09
Carcinogenics	CTUh	0.00121	3.49E-8	0.00137
Non carcinogenics	CTUh	0.000483	2.11E-7	0.0014
Respiratory effects	kg PM2.5 eq	1.15	0.0174	3.07
Ecotoxicity	CTUe	281	2.16	1.74E4
Fossil fuel depletion	MJ surplus	1.37E4	135	3.71E4

4. Figures 4-4, 4-5, and 4-6 show the environmental impact assessment processes for 8 in., 10 in., and 12 in. diameter, respectively, for CIPP renewal method.

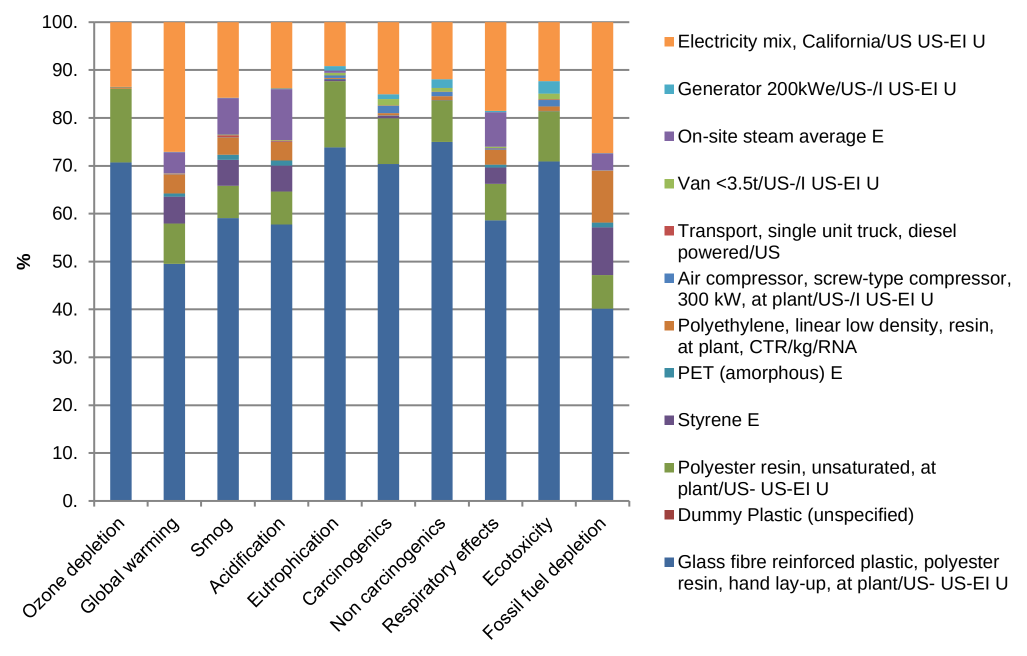


Figure 4-4 Environmental Impact Assessment Process of 8 in. diameter CIPP Renewal Method

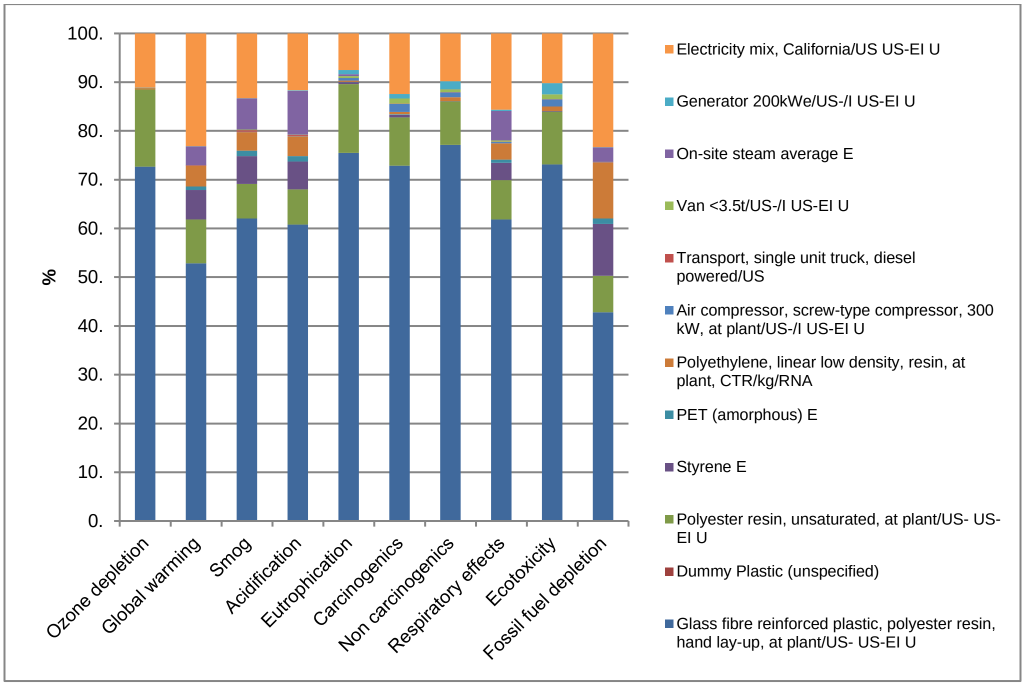


Figure 4-5 Environmental Impact Assessment Process of 10 in. diameter CIPP Renewal Method

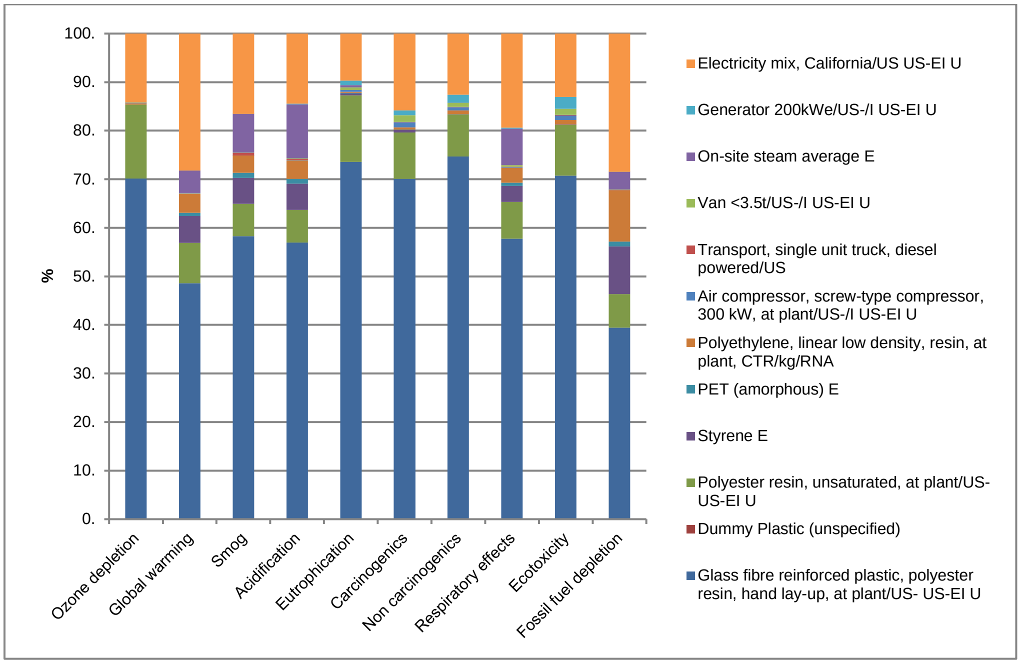


Figure 4-6 Environmental Impact Assessment Process of 12 in. diameter CIPP Renewal Method

5. Figures 4-7, 4-8, and 4-9 show the environmental impact assessment processes for 8 in., 10 in., and 12 in. diameter, respectively, for open-cut pipeline replacement.

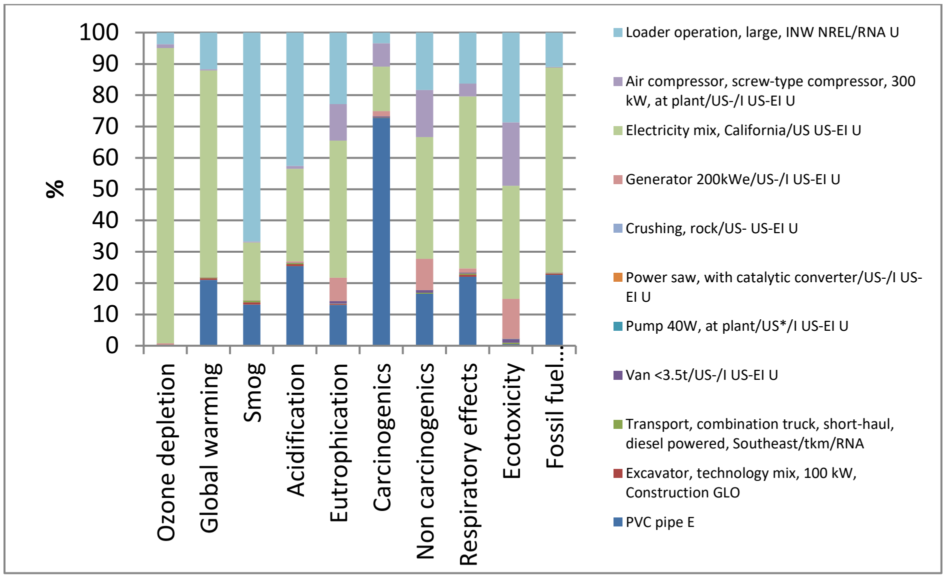


Figure 4-7 Environmental Impact Assessment Process of 8 in. Diameter Open-cut Pipeline Replacement

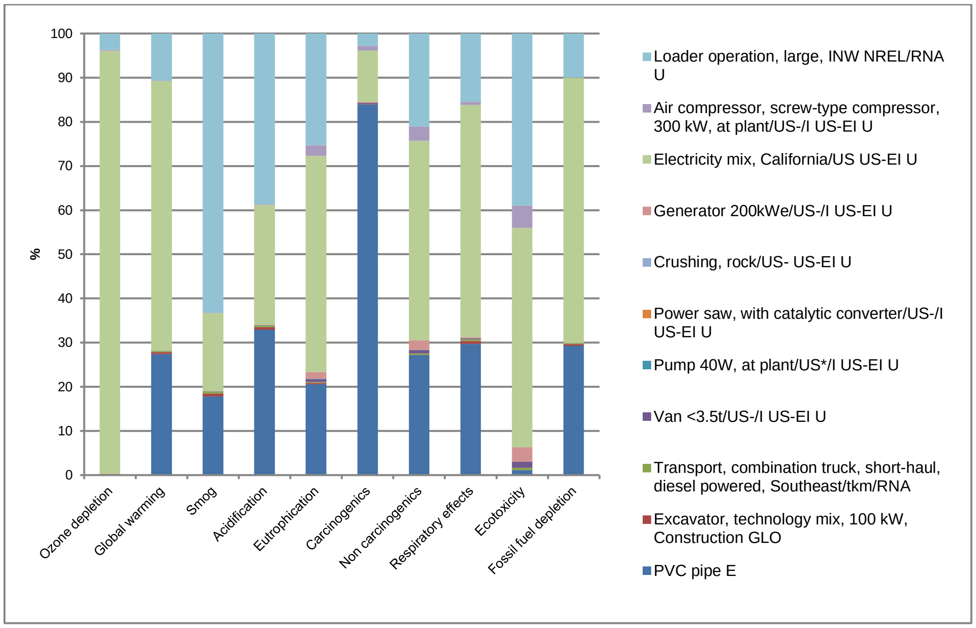


Figure 4-8 Environmental Impact Assessment Process of 10 in. Diameter Open-cut Pipeline Replacement

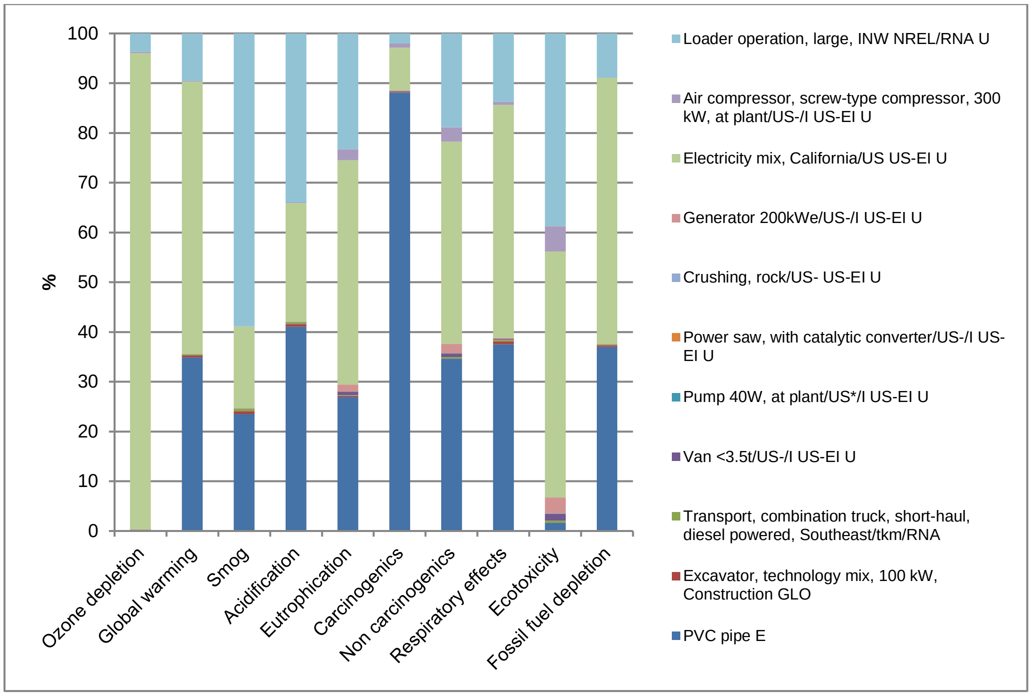


Figure 4-9 Environmental Impact Assessment Process of 12 in. Diameter Open-cut Pipeline Replacement

6. Tables 4-7, 4-8, and 4-9 show the environmental cost calculations for 8 in., 10 in., and 12 in. diameter, respectively, for CIPP renewal method.

Table 4-7 Environment Cost Calculation for 8 in.
CIPP Renewal Method
(2019 Dollars)

Impact category	Emission Amount	Unit	Unit Cost ($)	Total Cost ($)
Ozone depletion	0.0108	kg CFC-11 eq	387.8	4.1
Global warming	2.24E5	kg CO2 eq	.04	8,960
Smog	8.01E3	kg O3 eq	12.3	98,523
Acidification	706	kg SO2 eq	9.6	6,778
Eutrophication	230	kg N eq	3.45	794
Carcinogenics	0.0052	CTUh	180.2	0.93
Non carcinogenics	0.0315	CTUh	180.2	5.67
Respiratory effects	51.3	kg PM2.5 eq	39.7	2,036
Total Cost	**$117,102**			

Table 4-8 Environment Cost Calculation for 10 in.
CIPP Renewal Method
(2019 Dollars)

Impact category	Emission Amount	Unit	Unit Cost ($)	Total Cost ($)
Ozone depletion	0.00286	kg CFC-11 eq	387.8	1.10
Global warming	5.7E4	kg CO2 eq	.04	2,280
Smog	2.07E3	kg O3 eq	12.3	25,461
Acidification	182	kg SO2 eq	9.6	1,747
Eutrophication	61.2	kg N eq	3.45	211
Carcinogenics	0.00136	CTUh	180.2	0.25
Non carcinogenics	0.00832	CTUh	180.2	1.5
Respiratory effects	13.2	kg PM2.5 eq	39.7	524
Total Cost	**$30,226**			

Table 4-9 Environment Cost Calculation for 12 in.
CIPP Renewal Method
(2019 Dollars)

Impact category	Emission Amount	Unit	Unit Cost ($)	Total Cost ($)
Ozone depletion	0.00218	kg CFC-11 eq	387.8	0.85
Global warming	4.55E4	kg CO2 eq	.04	1,820
Smog	1.62E3	kg O3 eq	12.3	19,926
Acidification	143	kg SO2 eq	9.6	1,373
Eutrophication	46.1	kg N eq	3.45	159
Carcinogenics	0.00104	CTUh	180.2	0.2
Non carcinogenics	0.0063	CTUh	180.2	1.13
Respiratory effects	10.4	kg PM2.5 eq	39.7	413
Total Cost	**%31,008**			

7. Tables 4-10, 4-11, and 4-12 show the cost calculations for 8 in., 10 in., and 12 in. diameter, respectively, for open-cut pipeline renewal method.

Table 4-10 Environment Cost Calculation for 8 in.
Open-cut Pipeline Replacement
(2019 Dollars)

Impact category	Emission Amount	Unit	Unit Cost ($)	Total Cost ($)
Ozone depletion	0.00345	kg CFC-11 eq	387.8	1.33
Global warming	2.04E5	kg CO2 eq	.04	8,160
Smog	1.52E4	kg O3 eq	12.3	186,960
Acidification	735	kg SO2 eq	9.6	7,056
Eutrophication	108	kg N eq	3.45	372
Carcinogenics	0.0122	CTUh	180.2	2.2
Non carcinogenics	0.0214	CTUh	180.2	3.85
Respiratory effects	38.4	kg PM2.5 eq	39.7	1,524
Total Cost	**$204,079**			

Table 4-11 Environment Cost Calculation for 10 in.
Open-cut Pipeline Replacement
(2019 Dollars)

Impact category	Emission Amount	Unit	Unit Cost ($)	Total Cost ($)
Ozone depletion	0.000231	kg CFC-11 eq	387.8	0.09
Global warming	1.5E4	kg CO2 eq	.04	600
Smog	1.08E3	kg O3 eq	12.3	13,284
Acidification	54.3	kg SO2 eq	9.6	521
Eutrophication	6.53	kg N eq	3.45	22.5
Carcinogenics	0.00102	CTUh	180.2	0.184
Non carcinogenics	0.00125	CTUh	180.2	0.23
Respiratory effects	2.73	kg PM2.5 eq	39.7	108
Total Cost	**$14,536**			

Table 4-12 Environment Cost Calculation for 12 in.
Open-cut Pipeline Replacement
(2019 Dollars)

Impact category	Emission Amount	Unit	Unit Cost ($)	Total Cost ($)
Ozone depletion	0.000231	kg CFC-11 eq	387.8	0.09
Global warming	1.67E4	kg CO2 eq	.04	668
Smog	1.16E3	kg O3 eq	12.3	14,268
Acidification	61.8	kg SO2 eq	9.6	594
Eutrophication	7.09	kg N eq	3.45	25
Carcinogenics	0.00137	CTUh	180.2	0.25
Non carcinogenics	0.0014	CTUh	180.2	0.25
Respiratory effects	3.07	kg PM2.5 eq	39.7	122
Total Cost	**$15,678**			

8. Table 4-13 shows a summary of environmental results for 8 in., 10 in., and 12 in. diameter CIPP renewal method and open-cut replacement, respectively.

Table 4-13 Environmental Cost Results of CIPP Renewal and
Open-cut Pipeline Replacement
(2019 Dollars)

Diameter	CIPP ($/ft)	Open-cut ($/ft)
8 in.	26	38
10 in.	30	39
12 in.	32	40

9. Figure 4-10 shows the graphical representation of environmental costs of CIPP and open-cut pipeline methods for 8 in., 10 in., and 12 in. diameters.

Figure 4-10 Environmental Costs of CIPP Renewal and Open-cut Pipeline Replacement

4.3 Social Cost Results

1. Tables 4-14, 4-15, and 4-16 show the social cost calculation and results of CIPP renewal for 8, 10, and 12 in., respectively.

Table 4-14 Social Cost Calculation for 8 in. CIPP Renewal Method (2019 Dollars)

Cost Factors	Unit	Equation Used	Input	Result
Cost of fuel for detour delay	$	((Avg gal)/(mile))*(Avg additional mile)*(Avg cost of fuel)/gal)*(Number of vehicles)	0.0625*0*2.5 *12,000	-
Cost of detour delay	$	((Avg time)/(mile))*(Additional miles to travel)*(Value of time in dollars)	35*0*35	-
Pavement restoration cost	$	(Restoration cost)/SF)*(number of SF)	0*0	-
Loss of sales tax	$	((Avg dollar loss)/(day))*(Duration of project in days)	0*16	-
Cost of productivity loss	$	((Time loss)/(day))*(Number of persons)*(Value of time)*(Duration of project in days)	0.028*12,000 *35*16	188,160
Cost of dust control	$	((Increased cleaning time in hours)/(Day))*(Hourly pay rate)(Number of units impacted)*(Duration of project in days)+(Cost of cleaning materials)	(2*25*23*16) + (100)	18,500
Total Social Cost	**$206,660**			

Table 4-15 Social Cost Calculation for 10 in. CIPP Renewal Method (2019 Dollars)

Cost Factors	Unit	Equation Used	Input	Result
Cost of fuel for detour delay	$	((Avg gal)/(mile))*(Avg additional mile)*(Avg cost of fuel)/gal)*(Number of vehicles)	0.0625*0*2.5*12,000	-
Cost of detour delay	$	((Avg time)/(mile))*(Additional miles to travel)*(Value of time in dollars)	35*0*35	-
Pavement restoration cost	$	(Restoration cost)/SF)*(number of SF)	0*0	-
Loss of sales tax	$	((Avg dollar loss)/(day))*(Duration of project in days)	0*3	-
Cost of productivity loss	$	((Time loss)/(day))*(Number of persons)*(Value of time)*(Duration of project in days)	0.028*12,000*35*3	35,280
Cost of dust control	$	((Increased cleaning time in hours)/(Day))*(Hourly pay rate)(Number of units impacted)*(Duration of project in days)+(Cost of cleaning materials)	(2*25*6*3) + (50)	950
Total Social Cost	**$36,230**			

Table 4-16 Social Cost Calculation for 12 in. CIPP Renewal Method (2019 Dollars)

Cost Factors	Unit	Equation Used	Input	Result
Cost of fuel for detour delay	$	((Avg gal)/(mile))*(Avg additional mile)*(Avg cost of fuel)/gal)*(Number of vehicles)	0.0625*0*2.5* 12,000	-
Cost of detour delay	$	((Avg time)/(mile))*(Additional miles to travel)*(Value of time in dollars)	35*0*35	-
Pavement restoration cost	$	(Restoration cost)/SF)*(number of SF)	0*0	-
Loss of sales tax	$	((Avg dollar loss)/(day))*(Duration of project in days)	0*3	-
Cost of productivity loss	$	((Time loss)/(day))*(Number of persons)*(Value of time)*(Duration of project in days)	0.028*12,000* 35*3	2,520
Cost of dust control	$	((Increased cleaning time in hours)/(Day))*(Hourly pay rate)(Number of units impacted)*(Duration of project in days)+(Cost of cleaning materials)	(2*25*6*3) + (50)	950
Total Social Cost	**$36,230**			

2. Tables 4-9, 4-10, and 4-11 show the social cost calculation and results of open-cut pipeline replacement for 8, 10, and 12 in., respectively.

Table 4-17 Social Cost Calculation for 8 in. Open-cut Replacement Method (2019 Dollars)

Cost Factors	Unit	Equation Used	Input	Result
Cost of fuel for detour delay	$	((Avg gal)/(mile))*(Avg additional mile)*(Avg cost of fuel)/gal)*(Number of vehicles)	0.0625*1*2.5* 12,000	1,875
Cost of detour delay	$	((Avg time)/(mile))*(Additional miles to travel)*(Value of time in dollars)	35*1*35	1,225
Pavement restoration cost	$	(Restoration cost)/SF)*(number of SF)	200*10,848	2,169,600
Loss of sales tax	$	((Avg dollar loss)/(day))*(Duration of project in days)	11,000*96	1,056,000
Cost of productivity loss	$	((Time loss)/(day))*(Number of persons)*(Value of time)*(Duration of project in days)	0.028*12,000* 35*96	1,128,960
Cost of dust control	$	((Increased cleaning time in hours)/(Day))*(Hourly pay rate)*(Number of units impacted)*(Duration of project in days)+(Cost of cleaning materials)	(2*25*23*96) + (200)	110,600
Total Social Cost	**$4,468,260**			

Table 4-18 Social Cost Calculation for 10 in. Open-cut Replacement Method (2019 Dollars)

Cost Factors	Unit	Equation Used	Input	Result
Cost of fuel for detour delay	$	((Avg gal)/(mile))*(Avg additional mile)*(Avg cost of fuel)/gal)*(Number of vehicles)	0.0625*0.1*2.5*12,000	188
Cost of detour delay	$	((Avg time)/(mile))*(Additional miles to travel)*(Value of time in dollars)	35*0.1*35	123
Pavement restoration cost	$	(Restoration cost)/SF)*(number of SF)	200*742	148,400
Loss of sales tax	$	((Avg dollar loss)/(day))*(Duration of project in days)	11,000*7	77,000
Cost of productivity loss	$	((Time loss)/(day))*(Number of persons)*(Value of time)*(Duration of project in days)	0.028*12,000*35*7	82,320
Cost of dust control	$	((Increased cleaning time in hours)/(Day))*(Hourly pay rate)*(Number of units impacted)*(Duration of project in days)+(Cost of cleaning materials)	(2*25*2*7) + (50)	750
Total Social Cost	**$308,781**			

Table 4-19 Social Cost Calculation of Open-cut Replacement for 12 in. diameter (2019 Dollars)

Cost Factors	Unit	Equation Used	Input	Result
Cost of fuel for detour delay	$	((Avg gal)/(mile))*(Avg additional mile)*(Avg cost of fuel)/gal)*(Number of vehicles)	0.0625*0.1*2.5*12,000	188
Cost of detour delay	$	((Avg time)/(mile))*(Additional miles to travel)*(Value of time in dollars)	35*0.1*35	123
Pavement restoration cost	$	(Restoration cost)/SF)*(number of SF)	200*794	158,800
Loss of sales tax	$	((Avg dollar loss)/(day))*(Duration of project in days)	11,000*7	77,000
Cost of productivity loss	$	((Time loss)/(day))*(Number of persons)*(Value of time)*(Duration of project in days)	0.028*12,000*35*7	82,320
Cost of dust control	$	((Increased cleaning time in hours)/(Day))*(Hourly pay rate)*(Number of units impacted)*(Duration of project in days)+(Cost of cleaning materials)	(2*25*2*7) + (50)	750
Total Social Cost	**$332,289**			

3. Table 4-20 shows a summary of social results for 8 in., 10 in., and 12 in. diameter CIPP and open-cut pipeline replacement methods, respectively.

Table 4-20 Social Costs Results of CIPP Renewal and Open-cut Pipeline Replacement (2019 Dollars)

Diameter	CIPP ($/ft)	Open-cut ($/ft)
8 in.	45	824
10 in.	36	832
12 in.	38	837

4. Figure 4-11 shows the graphical representation of social costs of CIPP renewal and open-cut replacement for 8 in., 10 in., and 12 in. diameters.

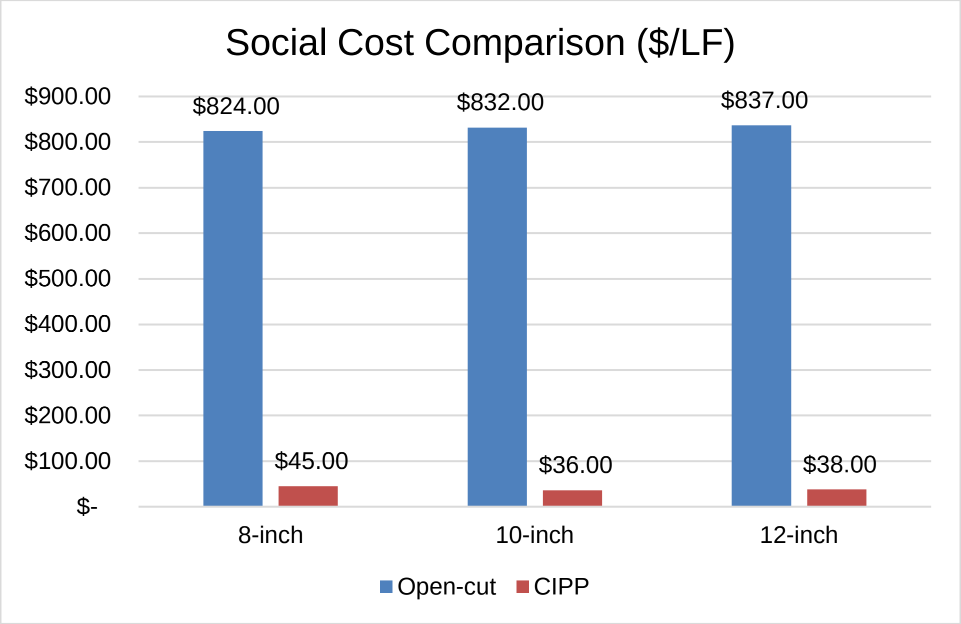


Figure 4-11 Social Costs of CIPP Renewal and Open-cut Pipeline Replacement

4.4 Environmental and Social Costs Results

1. Table 4-8 shows the environmental and social costs for CIPP renewal and open-cut pipeline replacement for 8 in., 10 in., and 12 in. diameter pipes.

Table 4-21 Environmental and Social Costs of CIPP Renewal and Open-cut Pipeline Replacement (2019 Dollars)

		Social cost ($/ft)	Environmental cost ($/ft)
Open-cut	8 in.	824	38
	10 in.	832	39
	12 in.	838	40
	Total cost	**2,494**	**117**
		Social cost ($/ft)	Environmental cost ($/ft)
CIPP	8 in.	45	26
	10 in.	36	30
	12 in.	38	32
	Total cost	**119**	**88**

2. Figure 4-6 shows the graphical representation of total environmental and social costs of CIPP and open-cut pipeline installations.

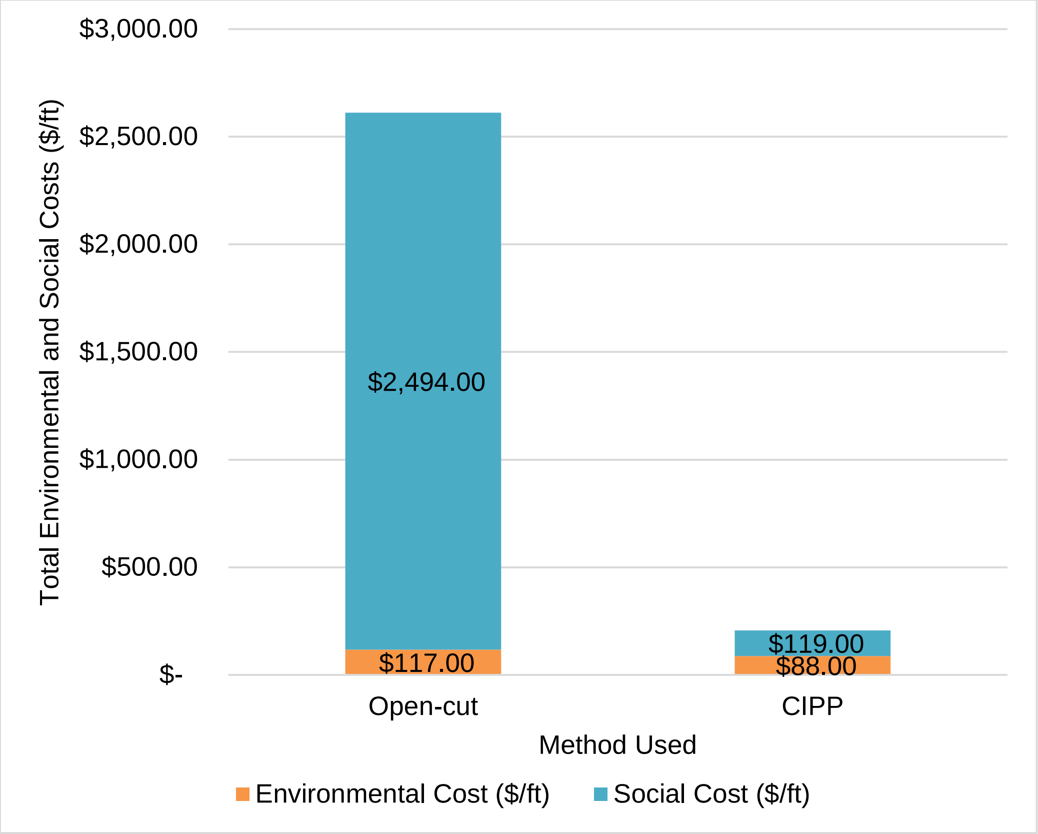


Figure 4-12 Total Environmental and Social Costs of CIPP Renewal and Open-cut Pipeline Replacement for Small Diameter Sanitary Sewers

4.5 Discussion of Results

This section discusses and compares the environmental and social cost results of CIPP renewal with open-cut pipeline replacement for 8 in., 10 in., and 12 in. diameters. Based on the results obtained, following statements can be made:

- The results of this dissertation for the case study used show that the total environmental and social costs of trenchless CIPP method is 90% less as compared to open-cut pipeline replacement for small diameter sanitary sewers, such as 8 in. to 12 in. diameters.

- The environmental cost of CIPP is about 25% less as compared to open-cut pipeline replacement for small diameter sanitary sewers.
- The social cost of CIPP is about 95% less as compared to open-cut pipeline replacement for small diameter sanitary sewers.
- From the environmental impact analysis, it was found that:
    - CIPP renewal caused less ozone depletion, global warming, smog, acidification, eutrophication, non carcinogenics, respiratory effects, ecotoxicity effects, and fossil fuel depletion.
    - For small diameter sanitary sewers, the liner, felt and resin influenced the environmental cost of the project for CIPP by 68% as compared to open-cut pipeline replacement where power consumption of all equipment and usage, and pipe material drove the cost.
- From the social cost impact analysis, it was found that:
    - Cost of fuel for detour roads, detour delay, and pavement restoration were almost negligible for CIPP renewal method as compared to open-cut replacement that contributes a major cost factor (approximately 75%) of its total social cost.
- Figure 4-13 shows that the environmental and social costs of CIPP renewal contribute to 57% and 43%, respectively, whereas, Figure 4-14 illustrates for open-cut pipeline replacement, the environmental and social costs are 4% and 96%, respectively.
- For this case study, it was determined that the environmental impacts of CIPP will be more than its social impacts. For open-cut, the social impacts will be more than environmental impacts. Same methodology can be used for different site and project conditions.

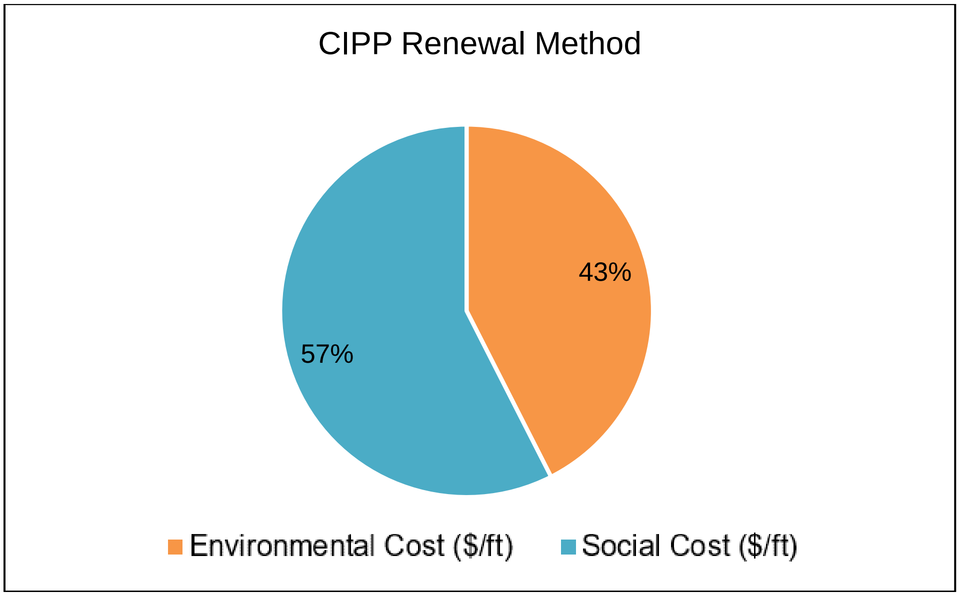


Figure 4-13 Environmental and Social Costs Distribution
for CIPP Renewal Method

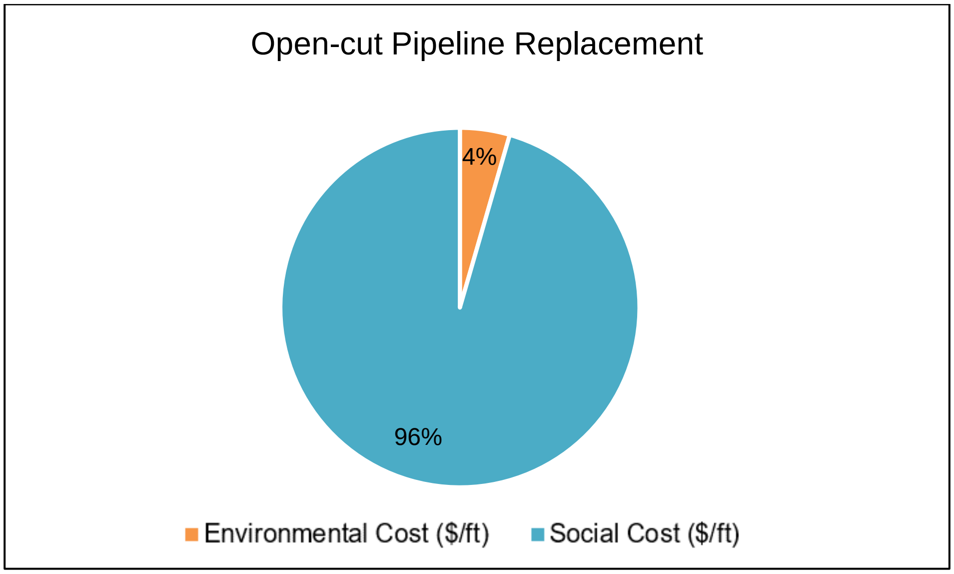


Figure 4-14 Environmental and Social Costs Distribution
for Open-cut Pipeline Replacement

4.6 Limitations of this Dissertation

The limitations of this dissertation are discussed below:

- There was a lack of data corresponding to similar project and site conditions, both for CIPP renewal and open-cut pipeline replacement.
- Test of hypothesis, particularly, and other statistical analysis, in general, could not be performed due to unavailability of different CIPP and open-cut pipeline data. This weakness can be overcome by adding more case studies.
- The results for CIPP renewal and open-cut pipeline replacement are based on a case study for small diameter sanitary sewer pipes.

4.7 Chapter Summary

This chapter presented and compared the environmental and social costs results of CIPP renewal with open-cut pipeline replacement. A comprehensive cost comparison between total environmental and social costs has been also done for both methods to obtain a comparative cost per linear feet of pipeline installation for 8 in., 10 in. and 12 in. diameters. Thereafter, discussion of results and limitations of this research were presented.

Chapter 5

Conclusions and Recommendations for Future Research

5.1 Conclusions

This dissertation compared the environmental and social costs of trenchless CIPP renewal with open-cut pipeline replacement and analyzed both the costs per unit pipe length for 8 in., 10 in., and 12 in. diameters. The study also identified the factors influencing environmental and social costs of CIPP and open-cut pipeline methods. Based on the results obtained in this dissertation, following conclusions can be made:

- Evaluation of environmental and social costs of pipeline installation method is an essential element when considering sustainable development of underground infrastructure.
- This dissertation provided a framework for the environmental and social costs analysis and its application for different project with different site conditions for small diameter sanitary sewers.
- Project owners, decision makers, and contractors commonly take into consideration the construction costs only, and sometimes overlook the environmental and social cost aspects while making a choice between trenchless and open-cut pipeline installation. Comparison of environmental and social costs per unit length of CIPP renewal with open-cut replacement will be helpful for project owners and contractors in the decision-making process to select a proper method for environmentally and socially friendly pipeline project implementations.
- The results of this dissertation for the case study used show that the total environmental and social costs of trenchless CIPP method is 90% less as compared to open-cut pipeline replacement for small diameter sanitary sewers, such as 8 in. to 12 in. diameters. While the conclusions are derived from a case study for particular conditions, the methodology can be applied to similar projects.

- The results are expected to be valid for similar type and diameter sanitary sewers, however, they might be location specific.
- CIPP renewal caused less ozone depletion, global warming, smog, acidification, eutrophication, non carcinogenics, respiratory effects, ecotoxicity effects, and fossil fuel depletion.
- The liner, felt, and resin influenced environmental cost the most for CIPP compared to open-cut where power consumption of all equipment and usage, and pipe material drove the cost.
- Cost of fuel for detour roads, detour delay, and pavement restoration were almost negligible for CIPP renewal method as compared to open-cut replacement that contributes a major cost factor (approximately 75%) of its total social cost.

5.2 Recommendations for Future Research

Based on the conclusions and findings of this study, following are the recommendations for future research on evaluation of environmental and social costs of trenchless CIPP renewal and open-cut pipeline replacement:

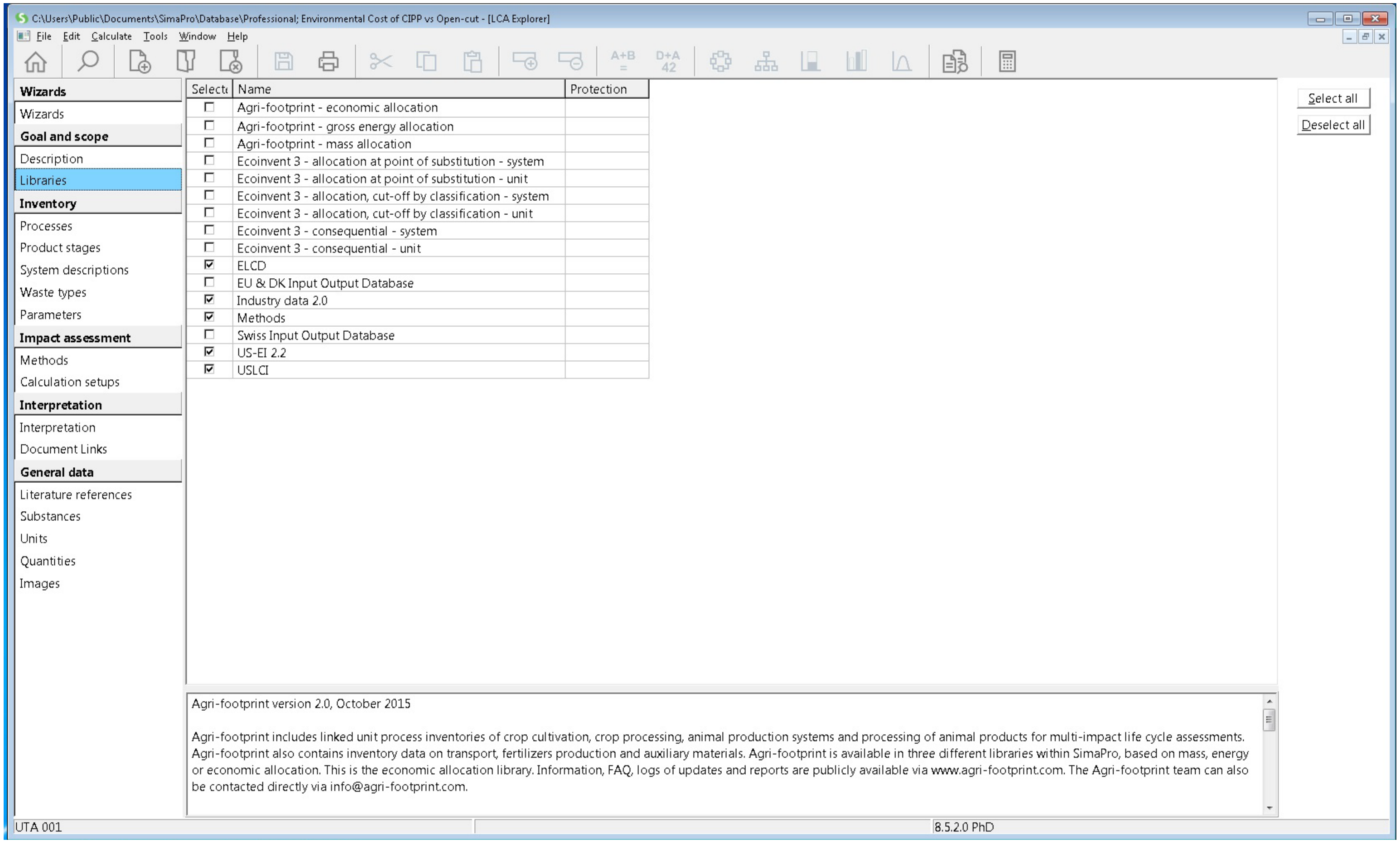
- There is a need to develop a prediction model that can determine the total environmental and social costs of CIPP renewal with open-cut pipeline replacement based on different project conditions, locations and diameters.
- A spreadsheet model can also be developed for CIPP renewal and open-cut pipeline replacement to determine environmental and social costs based on cost data pertaining to different soil, site, and project conditions, equipment used, problems encountered, etc. for each associated project.
- Phase 1 of NASSCO Report (available at www.CUIRE.org) entitled “Evaluation of Potential Release of Organic Chemicals in the Steam Exhaust and Other Release Points during Pipe Rehabilitation Using the Trenchless Cured-In-Place Pipe (CIPP) Method“ was referenced in this dissertation. A second phase of this project to

measure onsite emissions for different projects is currently ongoing and will contribute to further research for environmental impacts of CIPP.

- For the environmental cost analysis, effect of different pipe sizes, types (gravity and pressure), and materials (resin, felt, etc. for CIPP) should be considered (Appendix C).
- Effect of different CIPP curing methods like water, steam, UV should be studied and evaluated to see the change in the environmental costs.
- A study is needed to evaluate the effect of change in different chemical compounds (Appendix B) on the total environmental and social of CIPP installation and open-cut pipeline installations.

Appendix A

SimaPro Software Screenshots

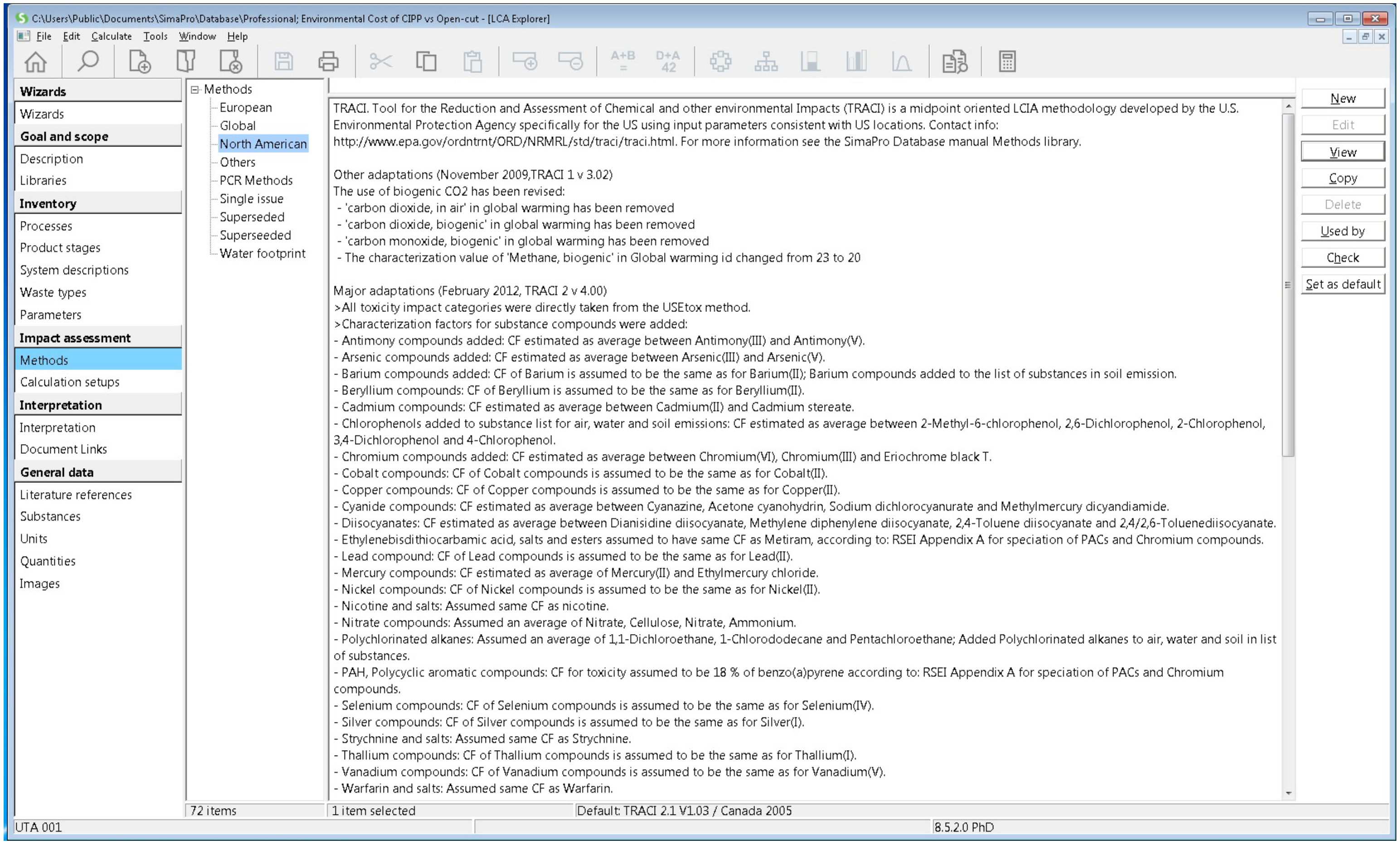


Select	Name	Protection
☐	Agri-footprint - economic allocation	
☐	Agri-footprint - gross energy allocation	
☐	Agri-footprint - mass allocation	
☐	Ecoinvent 3 - allocation at point of substitution - system	
☐	Ecoinvent 3 - allocation at point of substitution - unit	
☐	Ecoinvent 3 - allocation, cut-off by classification - system	
☐	Ecoinvent 3 - allocation, cut-off by classification - unit	
☐	Ecoinvent 3 - consequential - system	
☐	Ecoinvent 3 - consequential - unit	
☑	ELCD	
☐	EU & DK Input Output Database	
☑	Industry data 2.0	
☑	Methods	
☐	Swiss Input Output Database	
☑	US-EI 2.2	
☑	USLCI	

Agri-footprint version 2.0, October 2015

Agri-footprint includes linked unit process inventories of crop cultivation, crop processing, animal production systems and processing of animal products for multi-impact life cycle assessments. Agri-footprint also contains inventory data on transport, fertilizers production and auxiliary materials. Agri-footprint is available in three different libraries within SimaPro, based on mass, energy or economic allocation. This is the economic allocation library. Information, FAQ, logs of updates and reports are publicly available via www.agri-footprint.com. The Agri-footprint team can also be contacted directly via info@agri-footprint.com.

A-1 Library Used for SimaPro Analysis

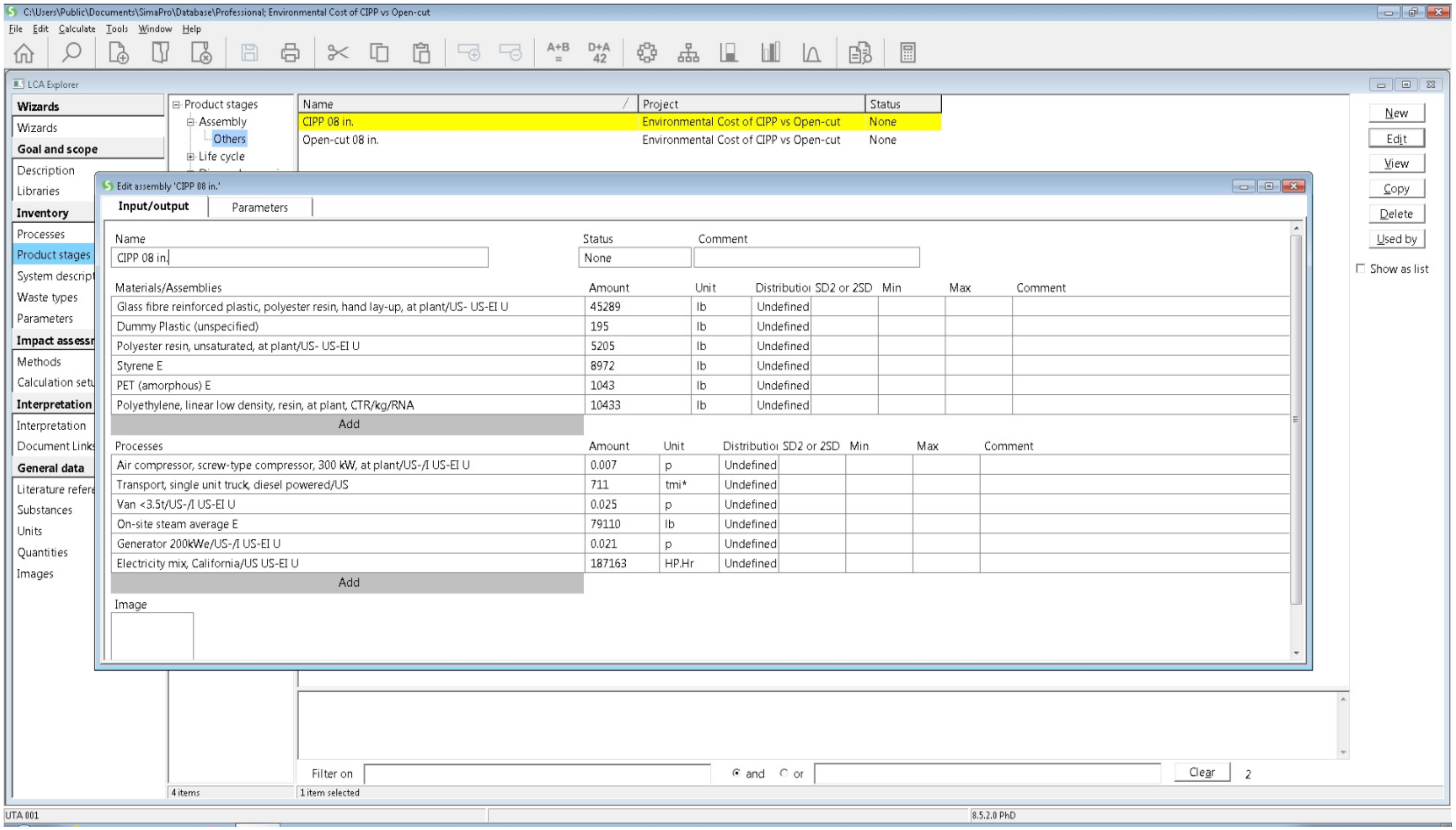


TRACI. Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) is a midpoint oriented LCIA methodology developed by the U.S. Environmental Protection Agency specifically for the US using input parameters consistent with US locations. Contact info: http://www.epa.gov/ordntrnt/ORD/NRMRL/std/traci/traci.html. For more information see the SimaPro Database manual Methods library.

Other adaptations (November 2009,TRACI 1 v 3.02)
The use of biogenic CO2 has been revised:
- 'carbon dioxide, in air' in global warming has been removed
- 'carbon dioxide, biogenic' in global warming has been removed
- 'carbon monoxide, biogenic' in global warming has been removed
- The characterization value of 'Methane, biogenic' in Global warming id changed from 23 to 20

Major adaptations (February 2012, TRACI 2 v 4.00)
>All toxicity impact categories were directly taken from the USEtox method.
>Characterization factors for substance compounds were added:
- Antimony compounds added: CF estimated as average between Antimony(III) and Antimony(V).
- Arsenic compounds added: CF estimated as average between Arsenic(III) and Arsenic(V).
- Barium compounds added: CF of Barium is assumed to be the same as for Barium(II); Barium compounds added to the list of substances in soil emission.
- Beryllium compounds: CF of Beryllium is assumed to be the same as for Beryllium(II).
- Cadmium compounds: CF estimated as average between Cadmium(II) and Cadmium stereate.
- Chlorophenols added to substance list for air, water and soil emissions: CF estimated as average between 2-Methyl-6-chlorophenol, 2,6-Dichlorophenol, 2-Chlorophenol, 3,4-Dichlorophenol and 4-Chlorophenol.
- Chromium compounds added: CF estimated as average between Chromium(VI), Chromium(III) and Eriochrome black T.
- Cobalt compounds: CF of Cobalt compounds is assumed to be the same as for Cobalt(II).
- Copper compounds: CF of Copper compounds is assumed to be the same as for Copper(II).
- Cyanide compounds: CF estimated as average between Cyanazine, Acetone cyanohydrin, Sodium dichlorocyanurate and Methylmercury dicyandiamide.
- Diisocyanates: CF estimated as average between Dianisidine diisocyanate, Methylene diphenylene diisocyanate, 2,4-Toluene diisocyanate and 2,4/2,6-Toluenediisocyanate.
- Ethylenebisdithiocarbamic acid, salts and esters assumed to have same CF as Metiram, according to: RSEI Appendix A for speciation of PACs and Chromium compounds.
- Lead compound: CF of Lead compounds is assumed to be the same as for Lead(II).
- Mercury compounds: CF estimated as average of Mercury(II) and Ethylmercury chloride.
- Nickel compounds: CF of Nickel compounds is assumed to be the same as for Nickel(II).
- Nicotine and salts: Assumed same CF as nicotine.
- Nitrate compounds: Assumed an average of Nitrate, Cellulose, Nitrate, Ammonium.
- Polychlorinated alkanes: Assumed an average of 1,1-Dichloroethane, 1-Chlorododecane and Pentachloroethane; Added Polychlorinated alkanes to air, water and soil in list of substances.
- PAH, Polycyclic aromatic compounds: CF for toxicity assumed to be 18 % of benzo(a)pyrene according to: RSEI Appendix A for speciation of PACs and Chromium compounds.
- Selenium compounds: CF of Selenium compounds is assumed to be the same as for Selenium(IV).
- Silver compounds: CF of Silver compounds is assumed to be the same as for Silver(I).
- Strychnine and salts: Assumed same CF as Strychnine.
- Thallium compounds: CF of Thallium compounds is assumed to be the same as for Thallium(I).
- Vanadium compounds: CF of Vanadium compounds is assumed to be the same as for Vanadium(V).
- Warfarin and salts: Assumed same CF as Warfarin.

A-2 Method of Analysis by SimaPro Software



Name	Project	Status
CIPP 08 in.	Environmental Cost of CIPP vs Open-cut	None
Open-cut 08 in.	Environmental Cost of CIPP vs Open-cut	None

Edit assembly 'CIPP 08 in.'

Input/output | Parameters

Name: CIPP 08 in.

Status: None

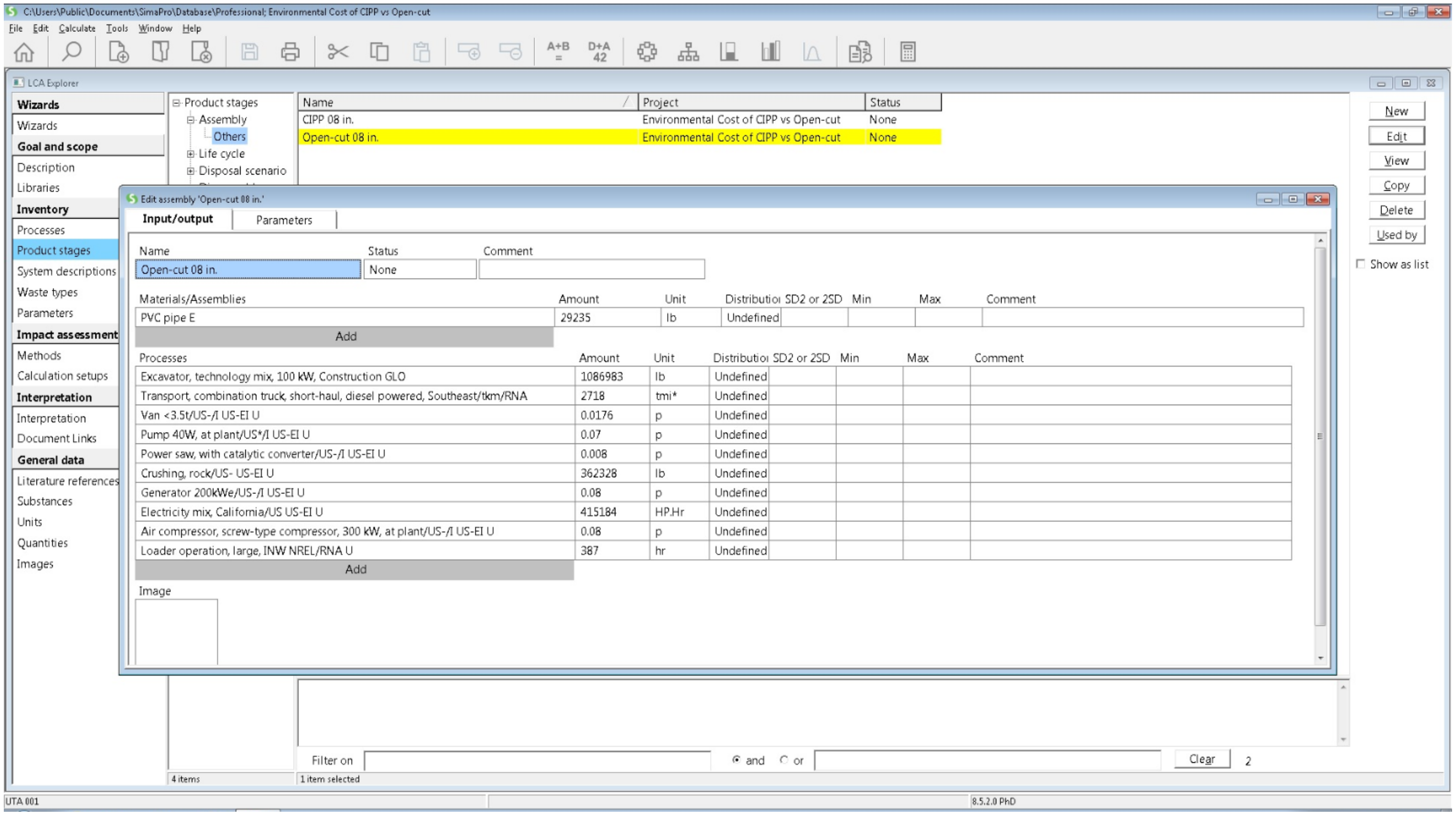
Comment:

Materials/Assemblies	Amount	Unit	Distributioı	SD2 or 2SD	Min	Max	Comment
Glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/US- US-EI U	45289	lb	Undefined				
Dummy Plastic (unspecified)	195	lb	Undefined				
Polyester resin, unsaturated, at plant/US- US-EI U	5205	lb	Undefined				
Styrene E	8972	lb	Undefined				
PET (amorphous) E	1043	lb	Undefined				
Polyethylene, linear low density, resin, at plant, CTR/kg/RNA	10433	lb	Undefined				
Add							

Processes	Amount	Unit	Distributioı	SD2 or 2SD	Min	Max	Comment
Air compressor, screw-type compressor, 300 kW, at plant/US-/I US-EI U	0.007	p	Undefined				
Transport, single unit truck, diesel powered/US	711	tmi*	Undefined				
Van <3.5t/US-/I US-EI U	0.025	p	Undefined				
On-site steam average E	79110	lb	Undefined				
Generator 200kWe/US-/I US-EI U	0.021	p	Undefined				
Electricity mix, California/US US-EI U	187163	HP.Hr	Undefined				
Add							

Image

A-3 Input for 8 in. CIPP Renewal Environmental Analysis



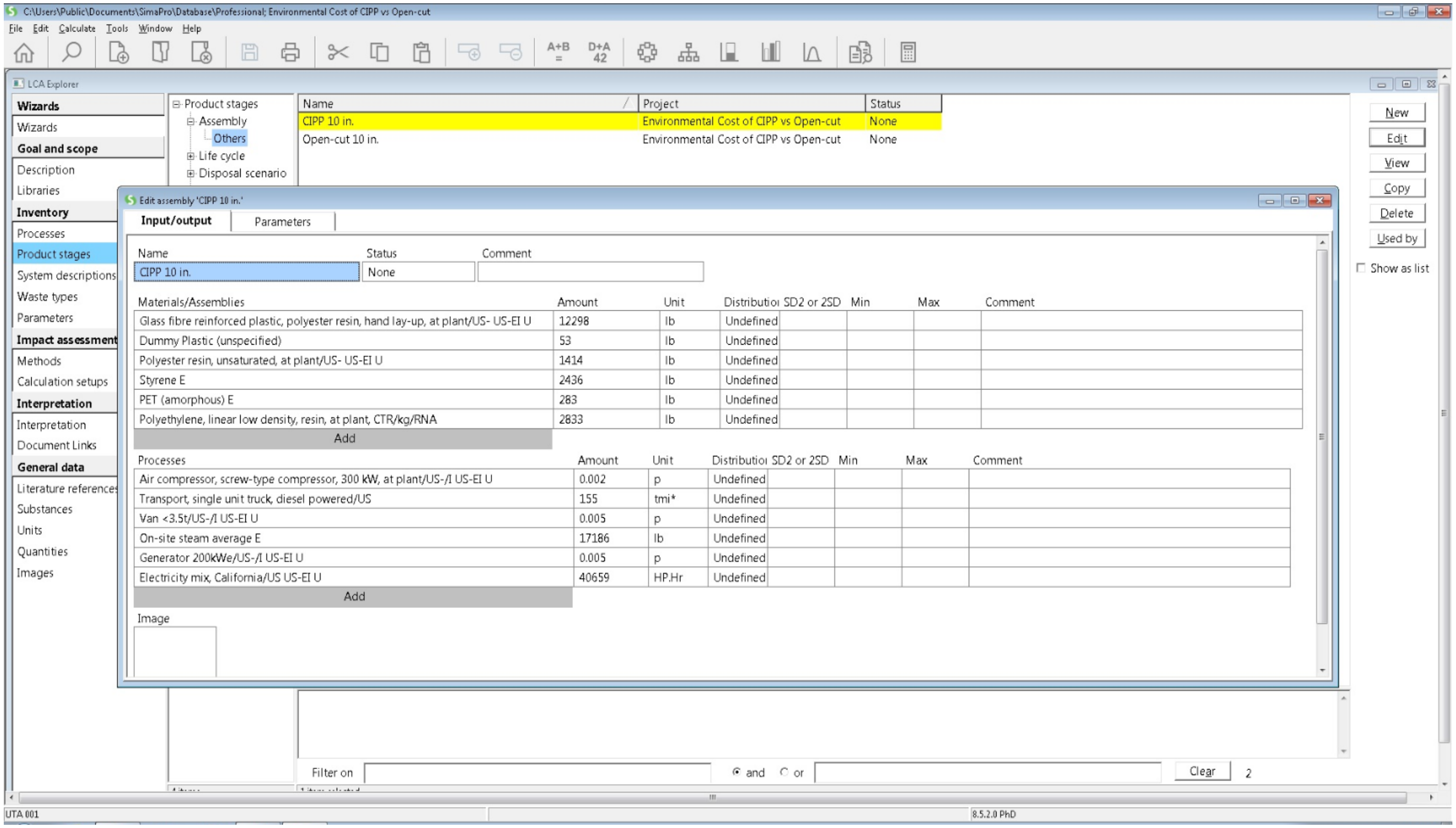
Name	Project	Status
CIPP 08 in.	Environmental Cost of CIPP vs Open-cut	None
Open-cut 08 in.	Environmental Cost of CIPP vs Open-cut	None

Name: Open-cut 08 in.
Status: None
Comment:

Materials/Assemblies	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
PVC pipe E	29235	lb	Undefined				

Processes	Amount	Unit	Distribution	SD2 or 2SD	Min	Max	Comment
Excavator, technology mix, 100 kW, Construction GLO	1086983	lb	Undefined				
Transport, combination truck, short-haul, diesel powered, Southeast/tkm/RNA	2718	tmi*	Undefined				
Van <3.5t/US-/I US-EI U	0.0176	p	Undefined				
Pump 40W, at plant/US*/I US-EI U	0.07	p	Undefined				
Power saw, with catalytic converter/US-/I US-EI U	0.008	p	Undefined				
Crushing, rock/US- US-EI U	362328	lb	Undefined				
Generator 200kWe/US-/I US-EI U	0.08	p	Undefined				
Electricity mix, California/US US-EI U	415184	HP.Hr	Undefined				
Air compressor, screw-type compressor, 300 kW, at plant/US-/I US-EI U	0.08	p	Undefined				
Loader operation, large, INW NREL/RNA U	387	hr	Undefined				

A-4 Input for 8 in. Open-cut Pipeline Replacement Environmental Analysis



Name	Project	Status
CIPP 10 in.	Environmental Cost of CIPP vs Open-cut	None
Open-cut 10 in.	Environmental Cost of CIPP vs Open-cut	None

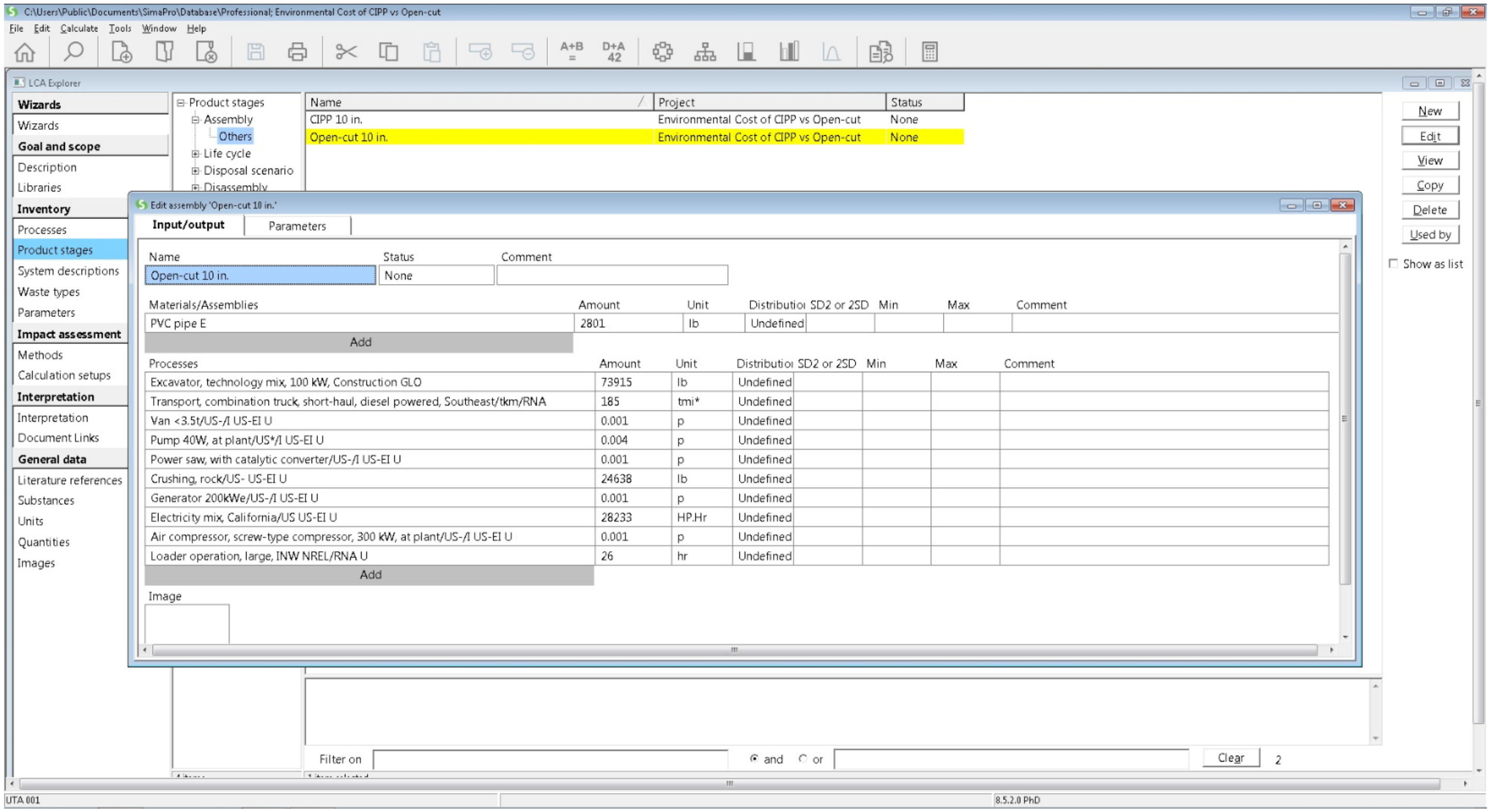
Edit assembly 'CIPP 10 in.'

Name	Status	Comment
CIPP 10 in.	None	

Materials/Assemblies	Amount	Unit	Distributioi	SD2 or 2SD	Min	Max	Comment
Glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/US- US-EI U	12298	lb	Undefined				
Dummy Plastic (unspecified)	53	lb	Undefined				
Polyester resin, unsaturated, at plant/US- US-EI U	1414	lb	Undefined				
Styrene E	2436	lb	Undefined				
PET (amorphous) E	283	lb	Undefined				
Polyethylene, linear low density, resin, at plant, CTR/kg/RNA	2833	lb	Undefined				

Processes	Amount	Unit	Distributioi	SD2 or 2SD	Min	Max	Comment
Air compressor, screw-type compressor, 300 kW, at plant/US-/I US-EI U	0.002	p	Undefined				
Transport, single unit truck, diesel powered/US	155	tmi*	Undefined				
Van <3.5t/US-/I US-EI U	0.005	p	Undefined				
On-site steam average E	17186	lb	Undefined				
Generator 200kWe/US-/I US-EI U	0.005	p	Undefined				
Electricity mix, California/US US-EI U	40659	HP.Hr	Undefined				

A-5 Input for 10 in. CIPP Renewal Environmental Analysis



C:\Users\Public\Documents\SimaPro\Database\Professional; Environmental Cost of CIPP vs Open-cut

Name	Project	Status
CIPP 10 in.	Environmental Cost of CIPP vs Open-cut	None
Open-cut 10 in.	Environmental Cost of CIPP vs Open-cut	None

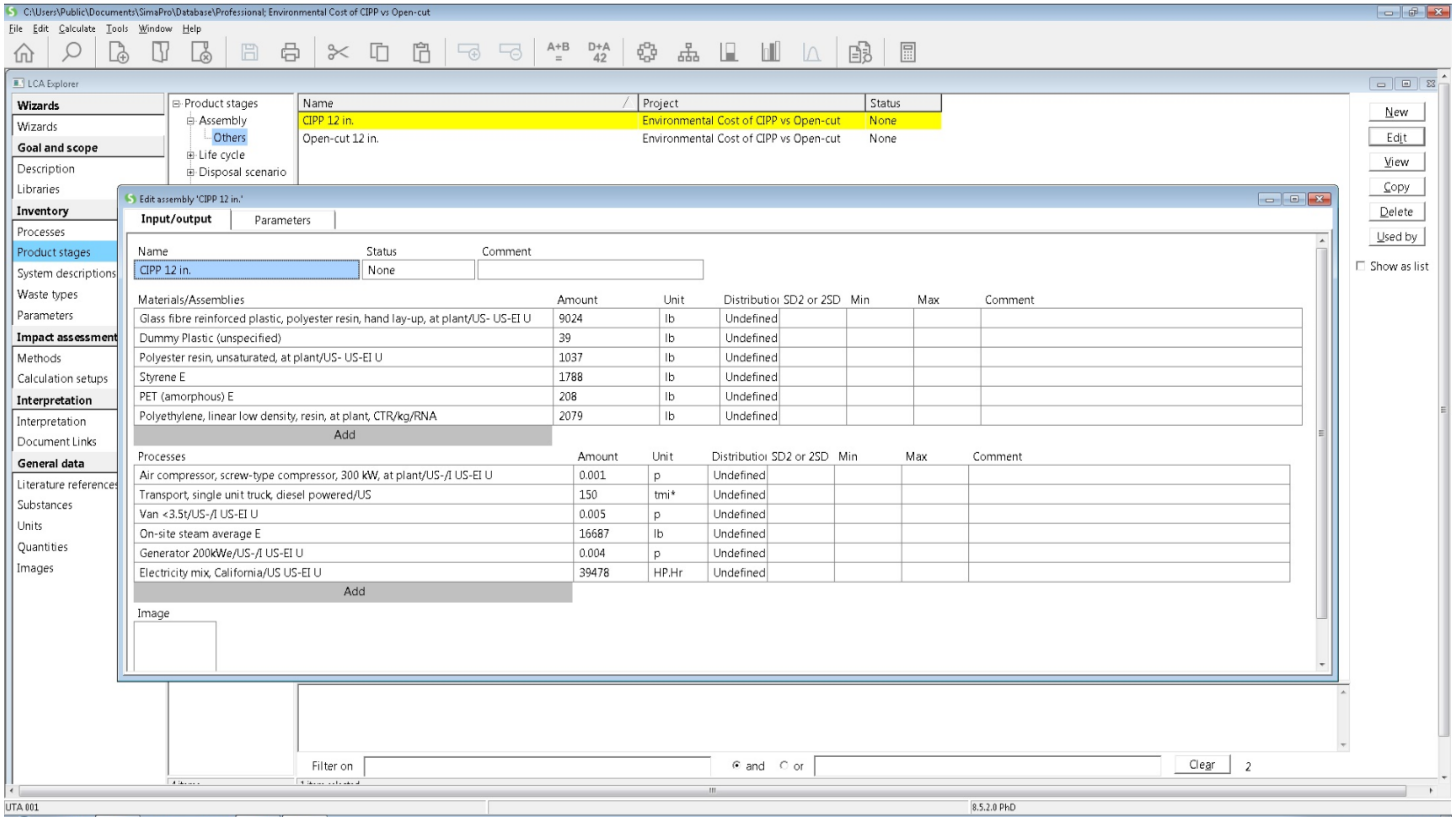
Edit assembly 'Open-cut 10 in.'

Name	Status	Comment
Open-cut 10 in.	None	

Materials/Assemblies	Amount	Unit	Distributioı	SD2 or 2SD	Min	Max	Comment
PVC pipe E	2801	lb	Undefined				

Processes	Amount	Unit	Distributioı	SD2 or 2SD	Min	Max	Comment
Excavator, technology mix, 100 kW, Construction GLO	73915	lb	Undefined				
Transport, combination truck, short-haul, diesel powered, Southeast/tkm/RNA	185	tmi*	Undefined				
Van <3.5t/US-/I US-EI U	0.001	p	Undefined				
Pump 40W, at plant/US*/I US-EI U	0.004	p	Undefined				
Power saw, with catalytic converter/US-/I US-EI U	0.001	p	Undefined				
Crushing, rock/US- US-EI U	24638	lb	Undefined				
Generator 200kWe/US-/I US-EI U	0.001	p	Undefined				
Electricity mix, California/US US-EI U	28233	HP.Hr	Undefined				
Air compressor, screw-type compressor, 300 kW, at plant/US-/I US-EI U	0.001	p	Undefined				
Loader operation, large, INW NREL/RNA U	26	hr	Undefined				

A-6 Input for 10 in. Open-cut Pipeline Replacement Environmental Analysis



Name	Project	Status
CIPP 12 in.	Environmental Cost of CIPP vs Open-cut	None
Open-cut 12 in.	Environmental Cost of CIPP vs Open-cut	None

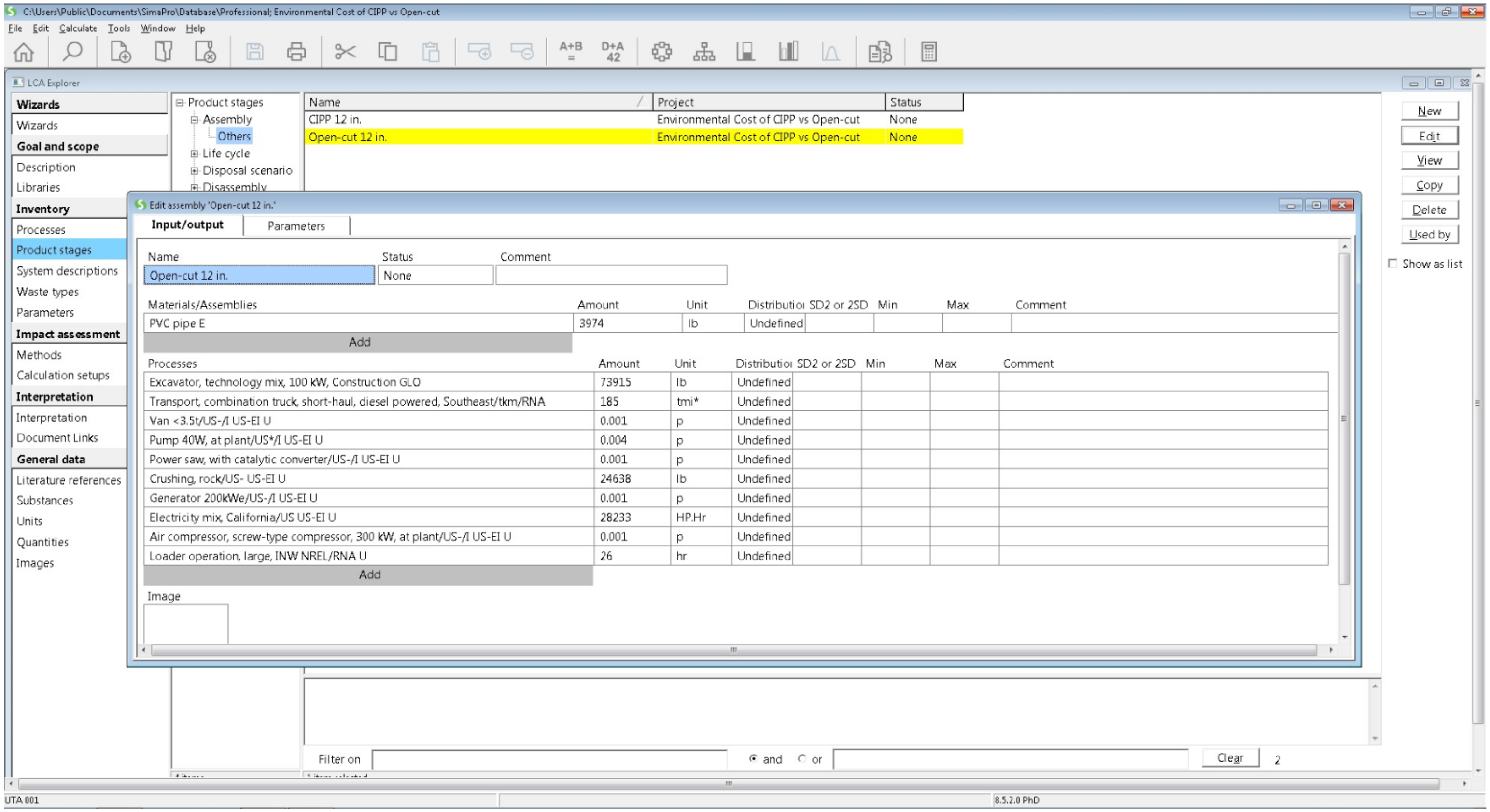
Edit assembly 'CIPP 12 in.'

Name: CIPP 12 in.
Status: None
Comment:

Materials/Assemblies	Amount	Unit	Distributioi	SD2 or 2SD	Min	Max	Comment
Glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/US- US-EI U	9024	lb	Undefined				
Dummy Plastic (unspecified)	39	lb	Undefined				
Polyester resin, unsaturated, at plant/US- US-EI U	1037	lb	Undefined				
Styrene E	1788	lb	Undefined				
PET (amorphous) E	208	lb	Undefined				
Polyethylene, linear low density, resin, at plant, CTR/kg/RNA	2079	lb	Undefined				

Processes	Amount	Unit	Distributioi	SD2 or 2SD	Min	Max	Comment
Air compressor, screw-type compressor, 300 kW, at plant/US-/I US-EI U	0.001	p	Undefined				
Transport, single unit truck, diesel powered/US	150	tmi*	Undefined				
Van <3.5t/US-/I US-EI U	0.005	p	Undefined				
On-site steam average E	16687	lb	Undefined				
Generator 200kWe/US-/I US-EI U	0.004	p	Undefined				
Electricity mix, California/US US-EI U	39478	HP.Hr	Undefined				

A-7 Input for 12 in. CIPP Renewal Environmental Analysis



Name	Project	Status
CIPP 12 in.	Environmental Cost of CIPP vs Open-cut	None
Open-cut 12 in.	Environmental Cost of CIPP vs Open-cut	None

Edit assembly 'Open-cut 12 in.'

Input/output | Parameters

Name: Open-cut 12 in.
Status: None
Comment:

Materials/Assemblies	Amount	Unit	Distributioi	SD2 or 2SD	Min	Max	Comment
PVC pipe E	3974	lb	Undefined				

Processes	Amount	Unit	Distributioi	SD2 or 2SD	Min	Max	Comment
Excavator, technology mix, 100 kW, Construction GLO	73915	lb	Undefined				
Transport, combination truck, short-haul, diesel powered, Southeast/tkm/RNA	185	tmi*	Undefined				
Van <3.5t/US-/I US-EI U	0.001	p	Undefined				
Pump 40W, at plant/US*/I US-EI U	0.004	p	Undefined				
Power saw, with catalytic converter/US-/I US-EI U	0.001	p	Undefined				
Crushing, rock/US- US-EI U	24638	lb	Undefined				
Generator 200kWe/US-/I US-EI U	0.001	p	Undefined				
Electricity mix, California/US US-EI U	28233	HP.Hr	Undefined				
Air compressor, screw-type compressor, 300 kW, at plant/US-/I US-EI U	0.001	p	Undefined				
Loader operation, large, INW NREL/RNA U	26	hr	Undefined				

A-8 Input for 12 in. Open-cut Pipeline Replacement Environmental Analysis

Appendix B

SimaPro Software Inventory

SimaPro 8.5.2.0 Educational Inventory

Inventory

No	Substance	Compartment	Unit	CIPP	Open-cut
1	1-Butanol	Air	µg	29.7	0.97
2	1-Butanol	Water	mg	315	0.525
3	1-Pentanol	Air	µg	15.1	0.51
4	1-Pentanol	Water	µg	36.3	1.22
5	1-Pentene	Air	µg	11.4	0.385
6	1-Pentene	Water	µg	27.4	0.925
7	1-Propanol	Air	mg	15.7	0.0669
8	1-Propanol	Water	µg	65.4	2.22
9	1,4-Butanediol	Air	mg	1.1	0.00471
10	1,4-Butanediol	Water	µg	439	1.88
11	2-Aminopropanol	Air	µg	16.4	0.596
12	2-Aminopropanol	Water	µg	39.7	1.45
13	2-Butene, 2-methyl-	Air	ng	2.53	0.0855
14	2-Butene, 2-methyl-	Water	ng	6.08	0.205
15	2-Chloroacetophenone	Air	µg	25.5	0.475
16	2-Hexanone	Water	mg	21.6	186
17	2-Methyl-1-propanol	Air	µg	47.7	1.64
18	2-Methyl-1-propanol	Water	µg	114	3.93
19	2-Nitrobenzoic acid	Air	µg	36.3	1.28
20	2-Propanol	Air	g	18.4	0.0298
21	2-Propanol	Water	µg	287	8.49
22	2,4-D	Soil	mg	11.7	0.768
23	4-Methyl-2-pentanone	Water	mg	343	126
24	5-methyl Chrysene	Air	µg	7.31	0.0992
25	Acenaphthene	Air	mg	3.89	0.0981
26	Acenaphthene	Water	mg	1.69	3.57
27	Acenaphthylene	Air	µg	83.1	1.13
28	Acenaphthylene	Water	mg	0.106	1.34
29	Acetaldehyde	Air	g	772	106
30	Acetaldehyde	Water	kg	3.85	1.62E-6
31	Acetamide	Soil	µg	402	7.81
32	Acetic acid	Air	kg	12.6	0.000979
33	Acetic acid	Water	kg	54.5	0.000207
34	Acetochlor	Soil	mg	23.7	0.459
35	Acetone	Air	g	29.5	0.107
36	Acetone	Water	mg	819	300
37	Acetonitrile	Air	mg	15	0.552
38	Acetonitrile	Water	µg	12	0.424
39	Acetophenone	Air	µg	54.6	1.02
40	Acetyl chloride	Water	µg	28.5	0.961
41	Acidity, unspecified	Air	µg	x	29.1
42	Acidity, unspecified	Water	g	48.6	0.353
43	Acids, unspecified	Water	kg	0.03	2.72
44	Aclonifen	Soil	mg	14.3	1.49
45	Acrolein	Air	g	2.49	12.9
46	Acrylate	Water	mg	113	0.183
47	Acrylic acid	Air	mg	47.6	0.0774
48	Acrylonitrile	Water	ng	x	369
49	Actinides, radioactive, unspecified	Air	kBq	13.8	0.374
50	Actinides, radioactive, unspecified	Water	Bq	20	0.685
51	Aerosols, radioactive, unspecified	Air	Bq	690	15
52	Air	Raw	tn.lg	4.81	79.3
53	Alachlor	Soil	mg	1.65	0.032

No	Substance	Compartment	Unit	CIPP	Open-cut
54	Aldehydes, unspecified	Air	g	34.4	325
55	Aldicarb	Soil	mg	6.38	0.204
56	Aldrin	Soil	mg	1.23	0.00206
57	Aluminium	Raw	kg	326	3.56
58	Aluminium	Air	kg	6.73	0.194
59	Aluminium	Water	kg	77.6	8.78
60	Aluminium	Soil	g	313	8.9
61	Americium-241	Water	mBq	x	167
62	Ammonia	Air	kg	6.24	2.51
63	Ammonia	Water	g	64.6	542
64	Ammonia	Soil	g	x	17.4
65	Ammonia, as N	Water	µg	1.56	3.2
66	Ammonium carbonate	Air	mg	134	2.5
67	Ammonium chloride	Air	mg	913	13
68	Ammonium, ion	Air	ng	x	125
69	Ammonium, ion	Water	kg	5.72	3.89
70	Anhydrite	Raw	g	151	0.0155
71	Aniline	Air	µg	646	21.1
72	Aniline	Water	mg	1.55	0.0508
73	Animal matter	Raw	mg	49.7	4.35
74	Anthracene	Air	µg	69.8	24
75	Anthracene	Water	µg	x	982
76	Anthranilic acid	Air	µg	28	0.98
77	Antimony	Air	g	724	0.195
78	Antimony	Water	g	209	6.1
79	Antimony	Soil	g	3.53	1.08E-6
80	Antimony-122	Water	mBq	21.5	0.43
81	Antimony-124	Air	µBq	53.3	59.5
82	Antimony-124	Water	Bq	4.12	0.142
83	Antimony-125	Air	µBq	557	11.1
84	Antimony-125	Water	Bq	4.31	0.166
85	AOX, Adsorbable Organic Halogen as Cl	Water	g	2.12	255
86	Argon-41	Air	Bq	41.7	369
87	Arsenic	Air	g	456	2.39
88	Arsenic	Water	g	326	22.3
89	Arsenic	Soil	g	1.67	0.00354
90	Arsenic trioxide	Air	ng	x	43.5
91	Arsine	Air	µg	0.555	3.61
92	Asbestos	Air	mg	0.000144	8.95
93	Atrazine	Soil	mg	39	0.751
94	Azinphos-methyl	Soil	µg	610	19.5
95	Azoxystrobin	Soil	mg	3.02	0.0966
96	Barite	Raw	kg	46.9	40.4
97	Barite	Water	g	933	44
98	Barium	Air	g	10.8	0.581
99	Barium	Water	kg	27.8	35.4
100	Barium	Soil	g	202	4.25
101	Barium-140	Air	mBq	36.2	0.724
102	Barium-140	Water	mBq	94.2	1.88
103	Basalt	Raw	kg	16.2	0.0801
104	Bauxite	Raw	kg	5.62	1.82
105	Benomyl	Soil	µg	32.1	1.18
106	Bentazone	Soil	mg	7.28	0.76
107	Benzal chloride	Air	µg	56.2	0.315
108	Benzaldehyde	Air	mg	4.18	0.0274
109	Benzene	Air	kg	12.5	0.143
110	Benzene	Water	kg	4.48	0.0521
111	Benzene, 1-methyl-2-nitro-	Air	µg	31.3	1.1
112	Benzene, 1-methyl-4-(1-methylethyl)-	Water	mg	0.221	2.84

No	Substance	Compartment	Unit	CIPP	Open-cut
113	Benzene, 1,2-dichloro-	Air	µg	113	3.96
114	Benzene, 1,2-dichloro-	Water	mg	138	0.259
115	Benzene, 1,3,5-trimethyl-	Air	ng	x	6.57
116	Benzene, chloro-	Air	µg	80.1	1.49
117	Benzene, chloro-	Water	g	2.84	0.00523
118	Benzene, ethyl-	Air	g	167	0.343
119	Benzene, ethyl-	Water	g	14.3	3.21
120	Benzene, hexachloro-	Air	mg	8.54	0.911
121	Benzene, pentachloro-	Air	µg	926	9.77
122	Benzene, pentachloronitro-	Soil	mg	6.29	0.201
123	Benzene, pentamethyl-	Water	mg	0.166	2.13
124	Benzenes, alkylated, unspecified	Water	g	0.535	1.4
125	Benzo(a)anthracene	Air	µg	26.6	12
126	Benzo(a)anthracene	Water	µg	x	778
127	Benzo(a)pyrene	Air	mg	279	13.3
128	Benzo(b,j,k)fluoranthene	Air	µg	36.6	0.496
129	Benzo(g,h,i)perylene	Air	µg	8.98	10.5
130	Benzo(k)fluoranthene	Air	µg	x	20.7
131	Benzo(k)fluoranthene	Water	µg	x	859
132	Benzoic acid	Water	g	3.3	28.8
133	Benzyl chloride	Air	mg	2.55	0.0475
134	Beryllium	Air	mg	302	7.04
135	Beryllium	Water	g	51.3	2.62
136	Bifenthrin	Soil	µg	86.2	1.67
137	Biomass	Raw	tn.lg	0.0529	3.18
138	Biphenyl	Air	µg	565	7.67
139	Biphenyl	Water	mg	34.7	90.4
140	BOD5, Biological Oxygen Demand	Water	tn.lg	1.01	0.0376
141	Borate	Water	mg	4.79	0.165
142	Borax	Raw	g	142	0.0128
143	Boron	Air	g	40.9	0.619
144	Boron	Water	kg	4.35	0.375
145	Boron	Soil	g	12.2	0.435
146	Boron trifluoride	Air	ng	7.6	0.0123
147	Bromate	Water	kg	1.48	0.0777
148	Bromide	Water	kg	0.443	6.09
149	Bromide	Soil	mg	x	5.17
150	Bromine	Raw	mg	426	14.5
151	Bromine	Air	g	1.32	0.0466
152	Bromine	Water	kg	17.5	0.355
153	Bromoform	Air	µg	142	2.65
154	Bromoxynil	Soil	µg	259	5.02
155	BTEX (Benzene, Toluene, Ethylbenzene, and X	Air	g	1.1	2.21
156	Butadiene	Air	g	0.0482	5.42
157	Butane	Air	g	949	37
158	Butene	Air	g	5.91	0.258
159	Butene	Water	mg	847	2.99
160	Butyl acetate	Water	mg	409	0.679
161	Butyrolactone	Air	µg	295	0.502
162	Butyrolactone	Water	µg	708	1.21
163	Cadmium	Raw	g	9.34	0.646
164	Cadmium	Air	g	152	0.767
165	Cadmium	Water	g	101	11.7
166	Cadmium	Soil	mg	616	0.412
167	Calcite	Raw	tn.lg	8.88	0.0384
168	Calcium	Air	g	229	4.03
169	Calcium	Water	kg	790	186
170	Calcium	Soil	kg	1.26	0.0388

No	Substance	Compartment	Unit	CIPP	Open-cut
171	Calcium carbonate	Raw	g	x	660
172	Calcium chloride	Raw	ng	x	93.5
173	Calcium sulfate	Raw	g	63	479
174	Carbaryl	Soil	µg	94.8	3.08
175	Carbetamide	Soil	mg	1.48	0.154
176	Carbofuran	Soil	mg	18.7	0.68
177	Carbon	Soil	kg	1.59	0.0259
178	Carbon-14	Air	kBq	18.2	0.711
179	Carbon-14	Water	Bq	x	8.43
180	Carbon dioxide	Air	tn.lg	29.9	463
181	Carbon dioxide, biogenic	Air	kg	583	60.3
182	Carbon dioxide, fossil	Air	tn.lg	144	25.9
183	Carbon dioxide, in air	Raw	kg	633	18.5
184	Carbon dioxide, land transformation	Air	kg	1.33	0.029
185	Carbon disulfide	Air	g	372	34.5
186	Carbon disulfide	Water	µg	461	15.5
187	Carbon monoxide	Air	kg	37.9	573
188	Carbon monoxide, biogenic	Air	g	469	7.79
189	Carbon monoxide, fossil	Air	kg	213	226
190	Carbon, organic, in soil or biomass stock	Raw	g	22.3	0.817
191	Carbonate	Water	kg	2.65	145
192	Carboxylic acids, unspecified	Water	kg	1.17	0.0531
193	Cerium-141	Air	mBq	8.78	0.175
194	Cerium-141	Water	mBq	37.7	0.753
195	Cerium-144	Water	mBq	11.5	0.229
196	Cesium	Water	mg	272	12.3
197	Cesium-134	Air	mBq	0.42	46.3
198	Cesium-134	Water	Bq	3.52	8.61
199	Cesium-136	Water	mBq	6.68	0.134
200	Cesium-137	Air	mBq	7.45	94.6
201	Cesium-137	Water	kBq	2.31	0.157
202	Chemical waste, inert	Waste	tn.lg	0.0463	1.74
203	Chemical waste, regulated	Waste	tn.lg	3.58	0.698
204	Chloramine	Air	µg	92.4	3.19
205	Chloramine	Water	µg	828	28.7
206	Chlorate	Water	kg	11.3	45
207	Chloride	Air	mg	0.000148	613
208	Chloride	Water	tn.lg	14.2	9.6
209	Chloride	Soil	kg	4.53	0.0813
210	Chlorimuron-ethyl	Soil	µg	503	52.5
211	Chlorinated fluorocarbons, soft	Air	kg	0.00013	2.77
212	Chlorinated solvents, unspecified	Water	g	4.47	117
213	Chlorine	Air	kg	11.2	23.3
214	Chlorine	Water	g	19.9	594
215	Chloroacetic acid	Air	mg	2.96	0.035
216	Chloroacetic acid	Water	mg	16.3	0.362
217	Chloroacetyl chloride	Water	µg	52.9	1.94
218	Chloroform	Air	mg	726	18.2
219	Chloroform	Water	mg	6.35	0.0118
220	Chlorosilane, trimethyl-	Air	mg	8.83	0.0378
221	Chlorosulfonic acid	Air	µg	17.5	0.618
222	Chlorosulfonic acid	Water	µg	43.6	1.54
223	Chlorothalonil	Soil	mg	90.8	2.91
224	Chlorpyrifos	Soil	mg	3.53	0.206
225	Chromium	Raw	kg	35.9	2.28
226	Chromium	Air	g	217	31.2
227	Chromium	Water	g	56.4	73.3
228	Chromium	Soil	g	7.47	0.0798

No	Substance	Compartment	Unit	CIPP	Open-cut
229	Chromium-51	Air	µBq	562	11.2
230	Chromium-51	Water	Bq	8.9	0.237
231	Chromium III	Air	µg	x	9.35
232	Chromium III	Water	mg	52.1	99.4
233	Chromium III	Soil	ng	x	86.7
234	Chromium VI	Air	g	4.08	0.166
235	Chromium VI	Water	g	541	24
236	Chromium VI	Soil	g	18.5	1.98
237	Chrysene	Air	µg	33.2	29
238	Chrysene	Water	mg	x	4.39
239	Chrysotile	Raw	g	280	0.0295
240	Cinnabar	Raw	g	25.9	0.00279
241	Clay	Raw	tn.lg	11.2	0.00727
242	Clay, bentonite	Raw	kg	28.4	6.46
243	Clay, unspecified	Raw	g	0.838	429
244	Clethodim	Soil	µg	726	75.3
245	Clopyralid	Soil	µg	2.07	0.15
246	Cloransulam-methyl	Soil	µg	216	22.6
247	Coal tailings	Waste	kg	56.3	721
248	Coal, 26.4 MJ per kg	Raw	kg	12.4	10.3
249	Coal, bituminous, 24.8 MJ per kg	Raw	kg	697	x
250	Coal, brown	Raw	kg	193	3.02
251	Coal, hard	Raw	tn.lg	22.7	0.547
252	Cobalt	Raw	g	73.8	0.00483
253	Cobalt	Air	g	4.6	0.281
254	Cobalt	Water	g	802	33.9
255	Cobalt	Soil	mg	24.5	0.907
256	Cobalt-57	Water	mBq	212	4.24
257	Cobalt-58	Air	µBq	783	305
258	Cobalt-58	Water	Bq	49.8	1.53
259	Cobalt-60	Air	mBq	6.92	7.49
260	Cobalt-60	Water	Bq	41.1	37.5
261	COD, Chemical Oxygen Demand	Water	tn.lg	1.1	2.5
262	Colemanite	Raw	tn.lg	9.39	4.51E-6
263	Compost	Waste	g	6.21	32.1
264	Construction waste	Waste	kg	0.354	16.9
265	Copper	Raw	kg	1.35	18.1
266	Copper	Air	g	100	11
267	Copper	Water	kg	1.22	0.758
268	Copper	Soil	g	22.7	1.24
269	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8	Raw	kg	4	0.377
270	Copper, 1.18% in sulfide, Cu 0.39% and Mo 8	Raw	kg	22	2.09
271	Copper, 1.42% in sulfide, Cu 0.81% and Mo 8	Raw	kg	5.83	0.555
272	Copper, 2.19% in sulfide, Cu 1.83% and Mo 8	Raw	kg	29.1	2.75
273	Cresol	Water	ng	x	882
274	Cumene	Air	kg	2.58	7.17E-5
275	Cumene	Water	kg	6.19	0.00017
276	Curium alpha	Water	mBq	x	221
277	Cyanide	Air	g	24	0.564
278	Cyanide	Water	g	28.3	1.59
279	Cyanoacetic acid	Air	µg	14.3	0.506
280	Cyclohexane	Air	µg	x	3.73
281	Cyclohexane	Water	mg	751	x
282	Cyfluthrin	Soil	µg	436	13.7
283	Cymoxanil	Soil	µg	282	9.02
284	Cypermethrin	Soil	mg	2.5	0.0916
285	Decane	Water	g	0.0945	7.72
286	Decane	Soil	mg	x	8.91

No	Substance	Compartment	Unit	CIPP	Open-cut
287	Demolition waste, unspecified	Waste	g	x	32.4
288	Detergent, oil	Water	kg	0.199	1.62
289	Diatomite	Raw	mg	2.86	0.0357
290	Diazinon	Soil	mg	2.31	0.0741
291	Dibenz(a,h)anthracene	Air	µg	x	6.46
292	Dibenzofuran	Water	mg	0.42	5.4
293	Dibenzothiophene	Water	mg	0.428	4.66
294	Dicamba	Soil	µg	690	13.4
295	Dichlorprop-P	Soil	mg	156	5
296	Dichromate	Water	mg	485	52.8
297	Diethylamine	Air	µg	291	9.56
298	Diethylamine	Water	µg	700	23
299	Diflufenzopyr-sodium	Soil	µg	76.6	1.49
300	Dimethenamid	Soil	mg	2	0.0388
301	Dimethoate	Soil	mg	1.6	0.0512
302	Dimethomorph	Soil	µg	60.3	1.93
303	Dimethyl malonate	Air	µg	18	0.635
304	Dimethylamine	Water	µg	741	25.4
305	Dinitrogen monoxide	Air	kg	170	0.0993
306	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Air	mg	0.169	54.7
307	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Water	g	2.69E-9	1.23
308	Dipropylamine	Air	µg	177	5.77
309	Dipropylamine	Water	µg	424	13.8
310	Dipropylthiocarbamic acid S-ethyl ester	Soil	mg	25	0.801
311	Diquat	Soil	mg	4.83	0.155
312	DOC, Dissolved Organic Carbon	Water	kg	308	27.6
313	Docosane	Water	mg	2.37	30.4
314	Dodecane	Water	g	0.179	1.57
315	Dolomite	Raw	kg	3.98	3.82
316	Eicosane	Water	mg	49.2	433
317	Electricity usage	Raw	TOE	7.55	0.154
318	Endosulfan	Soil	mg	2.09	0.067
319	Endothall	Soil	µg	21.5	0.779
320	Energy, from biomass	Raw	MWh	0.136	7.97
321	Energy, from coal	Raw	TJ	0.0616	1.47
322	Energy, from coal, brown	Raw	MMBTU	0.00322	1.58
323	Energy, from gas, natural	Raw	GWh	0.103	1.45
324	Energy, from hydro power	Raw	TOE	0.0425	3.81
325	Energy, from hydrogen	Raw	TOE	0.0581	2.39
326	Energy, from oil	Raw	GWh	0.099	1.21
327	Energy, from peat	Raw	MJ	6.22	463
328	Energy, from sulfur	Raw	MJ	11.8	-717
329	Energy, from uranium	Raw	TJ	0.0145	1.26
330	Energy, from wood	Raw	TOE	4.67E-5	1.94
331	Energy, geothermal	Raw	MWh	0.032	2.54
332	Energy, geothermal, converted	Raw	kJ	x	386
333	Energy, gross calorific value, in biomass	Raw	MWh	2.61	0.0558
334	Energy, gross calorific value, in biomass, prim	Raw	MJ	1.54	0.0566
335	Energy, kinetic (in wind), converted	Raw	MWh	4.42	2.74
336	Energy, potential (in hydropower reservoir), c	Raw	MWh	7.26	0.2
337	Energy, recovered	Raw	TOE	-0.289	-1.99
338	Energy, solar, converted	Raw	MMBTU	1.94	0.102
339	Energy, unspecified	Raw	MMBTU	0.0487	1.22
340	Esfenvalerate	Soil	µg	342	11
341	Ethalfluralin	Soil	µg	72.5	5.25
342	Ethane	Air	g	994	67.6

No	Substance	Compartment	Unit	CIPP	Open-cut
343	Ethane, 1,1-dichloro-	Water	g	0.000236	378
344	Ethane, 1,1-difluoro-, HFC-152a	Air	mg	442	1.73
345	Ethane, 1,1,1-trichloro-, HCFC-140	Air	mg	133	4.37
346	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	g	4.05	0.0181
347	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-11	Air	mg	2.26	0.00367
348	Ethane, 1,2-dibromo-	Air	mg	7.63	8.15E-5
349	Ethane, 1,2-dibromo-	Water	pg	x	877
350	Ethane, 1,2-dichloro-	Air	kg	0.00885	9.03
351	Ethane, 1,2-dichloro-	Water	mg	331	1.69
352	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-	Air	g	1.23	0.028
353	Ethane, chloro-	Air	kg	9.66E-6	14.6
354	Ethane, chloro-	Water	kg	2.07E-7	1.79
355	Ethane, hexafluoro-, HFC-116	Air	g	1.53	0.0831
356	Ethanol	Air	g	16.9	0.0717
357	Ethanol	Water	g	17.4	0.00143
358	Ethene	Air	kg	1	2.71
359	Ethene	Water	g	121	0.0607
360	Ethene, chloro-	Air	g	2.46	0.0794
361	Ethene, chloro-	Water	mg	21.5	1.01
362	Ethene, tetrachloro-	Air	mg	309	9.61
363	Ethoprop	Soil	mg	5.79	0.186
364	Ethyl acetate	Air	g	93.4	0.144
365	Ethyl acetate	Water	g	2.68	2.34E-5
366	Ethyl cellulose	Air	mg	173	0.281
367	Ethylamine	Air	µg	87	2.92
368	Ethylamine	Water	µg	209	7
369	Ethylene diamine	Air	µg	136	3.59
370	Ethylene diamine	Water	µg	328	8.63
371	Ethylene oxide	Air	g	51	0.0308
372	Ethylene oxide	Water	mg	87.5	0.741
373	Ethyne	Air	g	33.2	0.121
374	Feldspar	Raw	mg	30.3	1.47
375	Fenoxaprop	Soil	µg	431	45
376	Fenpiclonil	Soil	mg	1.12	0.0716
377	Fentin hydroxide	Soil	mg	1	0.0321
378	Ferromanganese	Raw	g	2.78	274
379	Fipronil	Soil	µg	115	2.23
380	Fluazifop-P-butyl	Soil	µg	144	15
381	Flumetsulam	Soil	µg	134	2.6
382	Flumioxazin	Soil	µg	252	26.3
383	Fluoranthene	Air	µg	236	78.4
384	Fluoranthene	Water	µg	x	907
385	Fluorene	Air	µg	302	243
386	Fluorene	Water	mg	13.8	x
387	Fluorene, 1-methyl-	Water	mg	0.252	3.23
388	Fluorenes, alkylated, unspecified	Water	mg	31	80.9
389	Fluoride	Air	mg	182	312
390	Fluoride	Water	kg	18	0.574
391	Fluoride	Soil	g	26	1.94
392	Fluorine	Raw	kg	1.71	0.00192
393	Fluorine	Air	g	27.4	1.5
394	Fluorine	Water	mg	0.719	40.3
395	Fluorine, 4.5% in apatite, 3% in crude ore	Raw	g	54.1	0.95
396	Fluorspar	Raw	kg	101	0.496
397	Fluosilicic acid	Air	g	1.6	0.0968
398	Fluosilicic acid	Water	g	2.87	0.174
399	Flutolanil	Soil	mg	1.14	0.0365
400	Fomesafen	Soil	mg	1.65	0.172

No	Substance	Compartment	Unit	CIPP	Open-cut
401	Foramsulfuron	Soil	µg	14.4	0.279
402	Formaldehyde	Air	g	174	166
403	Formaldehyde	Water	g	102	0.011
404	Formamide	Air	µg	27.6	0.933
405	Formamide	Water	µg	66.3	2.24
406	Formic acid	Air	mg	207	3.86
407	Formic acid	Water	µg	19.3	0.65
408	Formic acid, thallium(1+) salt	Water	mg	9.42	0.348
409	Furan	Air	g	7.54	0.00105
410	Gallium	Raw	mg	3.34	0.0131
411	Gas, mine, off-gas, process, coal mining/m3	Raw	m3	155	3.84
412	Gas, natural/kg	Raw	tn.lg	6.41	x
413	Gas, natural/m3	Raw	MMCF	1.5	0.0184
414	Glufosinate	Soil	µg	970	25.1
415	Glutaraldehyde	Water	mg	115	5.43
416	Glyphosate	Soil	g	2.55	0.0542
417	Gold	Raw	mg	372	0.622
418	Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore	Raw	mg	169	0.283
419	Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore	Raw	mg	311	0.52
420	Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore	Raw	mg	568	0.95
421	Gold, Au 4.3E-4%, in ore	Raw	mg	141	0.236
422	Gold, Au 4.9E-5%, in ore	Raw	mg	337	0.564
423	Gold, Au 6.7E-4%, in ore	Raw	mg	522	0.873
424	Gold, Au 7.1E-4%, in ore	Raw	mg	589	0.985
425	Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu	Raw	mg	35.3	0.059
426	Granite	Raw	µg	141	39.9
427	Gravel	Raw	tn.lg	20.7	0.164
428	Gypsum	Raw	kg	4	0.0876
429	Heat, waste	Air	TJ	2.01	0.0155
430	Heat, waste	Water	TOE	3.22	0.163
431	Heat, waste	Soil	MMBTU	1.86	0.606
432	Helium	Air	g	13.5	0.492
433	Heptane	Air	g	63	3.36
434	Hexadecane	Water	g	0.196	1.72
435	Hexamethylene diamine	Air	ng	x	6.28
436	Hexane	Air	g	380	10.3
437	Hexane	Water	ng	x	96.7
438	Hexanoic acid	Water	g	0.684	5.97
439	Hydrazine, methyl-	Air	µg	619	11.5
440	Hydrocarbons, aliphatic, alkanes, cyclic	Air	g	149	0.347
441	Hydrocarbons, aliphatic, alkanes, unspecified	Air	kg	4.32	0.0104
442	Hydrocarbons, aliphatic, alkanes, unspecified	Water	g	35.4	1.6
443	Hydrocarbons, aliphatic, unsaturated	Air	g	39.7	0.555
444	Hydrocarbons, aliphatic, unsaturated	Water	g	3.27	0.147
445	Hydrocarbons, aromatic	Air	kg	3.12	3.75
446	Hydrocarbons, aromatic	Water	g	146	6.55
447	Hydrocarbons, chlorinated	Air	kg	0.012	1.93
448	Hydrocarbons, unspecified	Air	kg	31.4	419
449	Hydrocarbons, unspecified	Water	g	684	609
450	Hydrogen	Air	kg	6.69	820
451	Hydrogen-3, Tritium	Air	kBq	6.27E3	138
452	Hydrogen-3, Tritium	Water	kBq	3.81E4	1.14E3
453	Hydrogen bromide	Air	µg	x	30.7
454	Hydrogen chloride	Air	kg	14.5	34.3
455	Hydrogen chloride	Water	µg	x	9.45
456	Hydrogen cyanide	Air	µg	1.47E-5	5.43
457	Hydrogen fluoride	Air	kg	2	0.916

No	Substance	Compartment	Unit	CIPP	Open-cut
458	Hydrogen fluoride	Water	µg	x	78.1
459	Hydrogen iodide	Air	ng	x	27.3
460	Hydrogen peroxide	Air	mg	130	1.08
461	Hydrogen peroxide	Water	g	1.21	0.0107
462	Hydrogen sulfide	Air	kg	1.81	0.0662
463	Hydrogen sulfide	Water	g	38.2	24.4
464	Hydroxide	Water	g	3.96	0.00765
465	Hypochlorite	Water	g	4.24	0.0384
466	Imazamox	Soil	µg	216	22.6
467	Imazapyr	Soil	µg	1.92	0.0372
468	Imazethapyr	Soil	µg	546	56.5
469	Imidacloprid	Soil	mg	1.65	0.0528
470	Indeno(1,2,3-cd)pyrene	Air	µg	20.3	7.99
471	Indium	Raw	mg	321	11.4
472	Inert rock	Raw	kg	x	40.8
473	Iodide	Water	g	30.1	1.29
474	Iodine	Raw	mg	187	6.21
475	Iodine	Air	mg	997	14.1
476	Iodine-129	Air	Bq	12.3	0.783
477	Iodine-129	Water	Bq	x	24.1
478	Iodine-131	Air	Bq	643	14.1
479	Iodine-131	Water	mBq	798	28.4
480	Iodine-133	Air	kBq	2.58	0.056
481	Iodine-133	Water	mBq	59.1	1.18
482	Iodine-135	Air	kBq	5.59	0.122
483	Iprodione	Soil	mg	2.04	0.0654
484	Iron	Raw	kg	820	374
485	Iron	Air	g	749	11.1
486	Iron	Water	kg	79.7	9.49
487	Iron	Soil	kg	4.89	0.0643
488	Iron-59	Water	mBq	16.3	0.325
489	Iron ore	Raw	g	874	16.5
490	Isocyanic acid	Air	mg	381	5.25
491	Isophorone	Air	mg	2.11	0.0394
492	Isoprene	Air	g	4.84	9.95
493	Isopropylamine	Air	µg	51.8	1.53
494	Isopropylamine	Water	µg	124	3.68
495	Isoxaflutole	Soil	µg	230	4.46
496	Kaolin ore	Raw	mg	x	8.02
497	Kaolinite	Raw	g	365	11
498	Kerosene	Air	mg	437	6.23
499	Kieserite	Raw	g	2.21	0.0471
500	Krypton-85	Air	kBq	0.156	6.22E3
501	Krypton-85m	Air	Bq	522	10.4
502	Krypton-87	Air	Bq	116	2.34
503	Krypton-88	Air	Bq	154	3.08
504	Krypton-89	Air	Bq	65.2	1.3
505	Lactic acid	Air	µg	139	4.52
506	Lactic acid	Water	µg	333	10.8
507	Lambda-cyhalothrin	Soil	µg	81.6	7.71
508	Lanthanum-140	Air	mBq	3.09	0.0619
509	Lanthanum-140	Water	mBq	100	2.01
510	Lead	Raw	g	780	641
511	Lead	Air	g	68	27.2
512	Lead	Water	g	271	186
513	Lead	Soil	g	11	0.00183
514	Lead-210	Air	kBq	8.14	0.142
515	Lead-210	Water	kBq	30.2	0.64

No	Substance	Compartment	Unit	CIPP	Open-cut
516	Lead-210/kg	Water	ng	0.338	2.95
517	Lead dioxide	Air	ng	x	7.75
518	Limestone	Raw	tn.lg	0.0902	4.73
519	Linuron	Soil	mg	1.63	0.0441
520	Lithium	Raw	µg	800	27
521	Lithium	Water	kg	87.1	1.77
522	m-Xylene	Air	mg	177	15.1
523	m-Xylene	Water	g	2.51	0.909
524	Magnesite	Raw	kg	12.3	1.33
525	Magnesium	Raw	g	6.93	8.02
526	Magnesium	Air	g	369	3.83
527	Magnesium	Water	kg	322	31.4
528	Magnesium	Soil	g	236	7.34
529	Magnesium chloride	Raw	g	x	20.3
530	Malathion	Soil	µg	91.6	2.94
531	Maleic hydrazide	Soil	mg	6.34	0.203
532	Mancozeb	Soil	mg	108	3.46
533	Maneb	Soil	µg	147	4.72
534	Manganese	Raw	kg	5.77	0.622
535	Manganese	Air	g	22.5	1.06
536	Manganese	Water	kg	23.8	1.22
537	Manganese	Soil	g	15.1	0.678
538	Manganese-54	Air	µBq	288	5.76
539	Manganese-54	Water	Bq	3.09	5.72
540	Mercaptans, unspecified	Air	g	0.919	4.31
541	Mercury	Raw	g	0.066	516
542	Mercury	Air	g	8.96	59.7
543	Mercury	Water	g	7.39	4.75
544	Mercury	Soil	mg	3.68	0.00316
545	Mesotrione	Soil	µg	623	12.1
546	Metal waste	Waste	kg	0.00255	22.5
547	Metalaxil	Soil	mg	3.26	0.104
548	Metaldehyde	Soil	ng	70.4	2.52
549	Metallic ions, unspecified	Water	kg	0.233	7.55
550	Metals, unspecified	Air	g	61.4	676
551	Metam-sodium dihydrate	Soil	g	1.03	0.033
552	Metamorphous rock, graphite containing	Raw	g	362	5.15
553	Methane	Air	tn.lg	0.251	5.34
554	Methane, biogenic	Air	kg	1.39	6.62
555	Methane, bromo-, Halon 1001	Air	µg	596	10.9
556	Methane, bromochlorodifluoro-, Halon 1211	Air	mg	131	0.239
557	Methane, bromotrifluoro-, Halon 1301	Air	mg	160	6.77
558	Methane, chlorodifluoro-, HCFC-22	Air	mg	642	2.53
559	Methane, chlorotrifluoro-, CFC-13	Air	mg	39	0.139
560	Methane, dichloro-, HCC-30	Air	g	2.13	58.5
561	Methane, dichloro-, HCC-30	Water	g	3.19	0.143
562	Methane, dichlorodifluoro-, CFC-12	Air	mg	58.9	1.32
563	Methane, dichlorofluoro-, HCFC-21	Air	µg	21	0.0478
564	Methane, fossil	Air	kg	941	25.4
565	Methane, monochloro-, R-40	Air	g	4.22	0.0958
566	Methane, monochloro-, R-40	Water	mg	0.089	1.17
567	Methane, tetrachloro-, CFC-10	Air	g	12.6	0.000965
568	Methane, tetrafluoro-, CFC-14	Air	g	12.3	0.745
569	Methane, trichlorofluoro-, CFC-11	Air	mg	0.034	1.03
570	Methane, trifluoro-, HFC-23	Air	mg	6.67	0.0152
571	Methanesulfonic acid	Air	µg	14.5	0.512
572	Methanol	Air	kg	5.1	0.000275
573	Methanol	Water	g	32.6	0.0253

No	Substance	Compartment	Unit	CIPP	Open-cut
574	Methyl acetate	Air	µg	8.4	0.296
575	Methyl acetate	Water	µg	20.1	0.71
576	Methyl acrylate	Air	mg	54	0.0878
577	Methyl acrylate	Water	g	1.06	0.00171
578	Methyl borate	Air	µg	7.08	0.24
579	Methyl ethyl ketone	Air	g	86.8	0.145
580	Methyl ethyl ketone	Water	mg	0.178	2.29
581	Methyl formate	Air	µg	217	0.586
582	Methyl formate	Water	µg	86.5	0.234
583	Methyl lactate	Air	µg	152	4.96
584	Methyl methacrylate	Air	µg	72.8	1.36
585	Methylamine	Air	µg	136	2.28
586	Methylamine	Water	µg	327	5.48
587	Metiram	Soil	mg	4.3	0.138
588	Metolachlor	Soil	mg	30.4	1.07
589	Metribuzin	Soil	mg	12.3	0.518
590	Metsulfuron-methyl	Soil	ng	3.79	0.274
591	Mineral waste	Waste	tn.lg	0.00774	1.68
592	Molybdenum	Raw	g	142	13.6
593	Molybdenum	Air	g	1.66	0.0242
594	Molybdenum	Water	g	219	10.5
595	Molybdenum	Soil	mg	13.2	0.0652
596	Molybdenum-99	Water	mBq	34.6	0.691
597	Molybdenum, 0.010% in sulfide, Mo 8.2E-3%	Raw	g	541	51.1
598	Molybdenum, 0.014% in sulfide, Mo 8.2E-3%	Raw	g	76.5	7.28
599	Molybdenum, 0.022% in sulfide, Mo 8.2E-3%	Raw	g	70.8	6.75
600	Molybdenum, 0.025% in sulfide, Mo 8.2E-3%	Raw	g	280	26.7
601	Monoethanolamine	Air	g	2.38	0.00592
602	n-Hexacosane	Water	mg	1.48	19
603	N-octane	Air	mg	x	411
604	Naphthalene	Air	mg	44.3	30.9
605	Naphthalene	Water	mg	59.2	634
606	Naphthalene, 2-methyl-	Water	mg	50.4	450
607	Naphthalenes, alkylated, unspecified	Water	mg	8.77	22.9
608	Napropamide	Soil	ng	125	4.45
609	Natural aggregate	Raw	g	x	236
610	Nickel	Raw	g	199	8.02
611	Nickel	Air	g	225	39.7
612	Nickel	Water	kg	2.44	0.324
613	Nickel	Soil	g	4.95	0.0107
614	Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.7	Raw	g	269	35.7
615	Nickel, 1.98% in silicates, 1.04% in crude ore	Raw	kg	86.9	4.2
616	Nicosulfuron	Soil	µg	105	2.04
617	Niobium-95	Air	µBq	34.2	0.683
618	Niobium-95	Water	mBq	473	22
619	Nitrate	Air	g	4.98	0.112
620	Nitrate	Water	kg	26	2.67
621	Nitrate compounds	Water	mg	381	7.19
622	Nitric acid	Water	µg	94.4	194
623	Nitric oxide	Air	µg	x	2.36
624	Nitrite	Water	g	26.3	16.2
625	Nitrobenzene	Air	µg	888	29.1
626	Nitrobenzene	Water	mg	3.56	0.117
627	Nitrogen	Raw	tn.lg	0.959	14
628	Nitrogen	Water	kg	1.34	0.0119
629	Nitrogen dioxide	Air	kg	0.00137	6.85
630	Nitrogen oxide	Air	kg	x	2.33
631	Nitrogen oxides	Air	tn.lg	0.403	1.56

No	Substance	Compartment	Unit	CIPP	Open-cut
632	Nitrogen, atmospheric	Air	kg	6.34	0.16
633	Nitrogen, organic bound	Water	g	147	338
634	Nitrogen, total	Water	kg	0.0211	2.72
635	NMVOC, non-methane volatile organic compound	Air	tn.lg	3.04	0.0832
636	Noble gases, radioactive, unspecified	Air	kBq	1.38E5	4.48E3
637	o-Cresol	Water	mg	93.7	818
638	o-Xylene	Water	g	1.79	0.0351
639	Occupation, arable	Raw	m2a	0.627	0.0171
640	Occupation, arable, non-irrigated	Raw	m2a	3.38	0.347
641	Occupation, construction site	Raw	m2a	14.5	0.154
642	Occupation, dump site	Raw	m2a	253	7.72
643	Occupation, dump site, benthos	Raw	m2a	1.5	0.0706
644	Occupation, forest, intensive	Raw	m2a	26.7	0.383
645	Occupation, forest, intensive, normal	Raw	m2y	1.67E3	22.4
646	Occupation, forest, intensive, short-cycle	Raw	m2a	0.387	0.0142
647	Occupation, industrial area	Raw	m2a	56.7	1.8
648	Occupation, industrial area, benthos	Raw	cm2a	310	5.76
649	Occupation, industrial area, built up	Raw	m2a	107	0.608
650	Occupation, industrial area, vegetation	Raw	m2a	49.6	0.253
651	Occupation, mineral extraction site	Raw	m2a	140	1.95
652	Occupation, permanent crop, fruit, intensive	Raw	m2a	0.366	0.0199
653	Occupation, shrub land, sclerophyllous	Raw	m2a	3.14	0.113
654	Occupation, traffic area, rail network	Raw	m2a	34.2	0.271
655	Occupation, traffic area, rail/road embankmen	Raw	m2a	31	0.245
656	Occupation, traffic area, road embankment	Raw	m2a	28.8	0.239
657	Occupation, traffic area, road network	Raw	m2a	41.5	1.33
658	Occupation, unknown	Raw	m2y	8.22E3	190
659	Occupation, urban, discontinuously built	Raw	cm2a	48.3	1.83
660	Occupation, water bodies, artificial	Raw	m2a	42	1.06
661	Occupation, water courses, artificial	Raw	m2a	34.6	1.01
662	Octadecane	Water	mg	48.5	424
663	Oil, crude	Raw	tn.lg	22.1	8.06
664	Oils, biogenic	Soil	g	41.2	0.356
665	Oils, unspecified	Water	kg	19.7	1.52
666	Oils, unspecified	Soil	kg	18.5	0.873
667	Olivine	Raw	kg	0.0866	2.83
668	Orbencarb	Soil	mg	3.28	0.105
669	Organic acids	Air	mg	3.35	0.0478
670	Organic substances, unspecified	Air	kg	1.87	12.8
671	Organic substances, unspecified	Water	kg	0.33	29.4
672	Other minerals, extracted for use	Raw	kg	1.71	0.0322
673	Oxamyl	Soil	mg	4.85	0.155
674	Oxygen	Raw	tn.lg	0.0163	14.4
675	Oxygen	Air	g	0.000495	382
676	Ozone	Air	g	395	7.96
677	p-Cresol	Water	mg	101	882
678	p-Xylene	Water	mg	29.5	x
679	Packaging waste, paper and board	Waste	kg	8.59E-6	174
680	Packaging waste, plastic	Waste	mg	0.0159	1.71
681	Packaging waste, wood	Waste	mg	2.17	9.23
682	PAH, polycyclic aromatic hydrocarbons	Air	g	59.2	24.1
683	PAH, polycyclic aromatic hydrocarbons	Water	g	1.85	0.103
684	Palladium	Raw	ng	x	11.7
685	Palladium	Air	pg	x	2.59
686	Palladium, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-	Raw	mg	39.3	0.39
687	Palladium, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-	Raw	mg	94.5	0.938
688	Paraquat	Soil	µg	566	15
689	Parathion	Soil	µg	1.27	0.0922

No	Substance	Compartment	Unit	CIPP	Open-cut
690	Particulates, < 10 um	Air	kg	12	253
691	Particulates, < 10 um	Water	ng	x	654
692	Particulates, < 2.5 um	Air	kg	17.7	0.651
693	Particulates, > 10 um	Air	kg	65.1	1.36
694	Particulates, > 10 um	Water	g	x	790
695	Particulates, > 2.5 um, and < 10um	Air	kg	26.2	14.6
696	Particulates, unspecified	Air	kg	1.53	1.87
697	Peat	Raw	kg	3.86	0.00467
698	Pendimethalin	Soil	mg	19.9	1.53
699	Pentane	Air	kg	1.38	0.0271
700	Permethrin	Soil	µg	244	7.28
701	Phenanthrene	Air	µg	898	774
702	Phenanthrene	Water	mg	2.34	8.1
703	Phenanthrenes, alkylated, unspecified	Water	mg	3.64	9.48
704	Phenol	Air	kg	1.83	2.15E-5
705	Phenol	Water	kg	1.75	0.115
706	Phenol, 2,4-dichloro-	Air	µg	42.8	1.62
707	Phenol, 2,4-dimethyl-	Water	mg	91.2	796
708	Phenol, pentachloro-	Air	mg	47.6	1.38
709	Phenols, unspecified	Air	mg	63.1	82.6
710	Phenols, unspecified	Water	g	0.717	1.79
711	Phorate	Soil	mg	10.5	0.335
712	Phosmet	Soil	mg	1.15	0.0369
713	Phosphate	Water	kg	80.7	2.99
714	Phosphate	Soil	g	x	9.97
715	Phosphine	Air	µg	41.2	0.0755
716	Phosphorus	Raw	g	337	3.83
717	Phosphorus	Air	g	5.57	0.0709
718	Phosphorus	Water	g	90.3	0.231
719	Phosphorus	Soil	g	15.3	0.587
720	Phosphorus pentoxide	Raw	g	17.1	417
721	Phosphorus, 18% in apatite, 4% in crude ore	Raw	kg	6.83	0.00769
722	Phosphorus, total	Water	kg	0.00541	5.94
723	Phthalate, dioctyl-	Air	µg	266	4.96
724	Piperonyl butoxide	Soil	µg	34.4	1.1
725	Pirimicarb	Soil	µg	689	71.9
726	Plastic waste	Waste	kg	1.77	909
727	Platinum	Raw	ng	x	141
728	Platinum	Air	ng	6.04	0.109
729	Platinum, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5	Raw	µg	163	375
730	Platinum, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5	Raw	mg	0.584	1.34
731	Plutonium-238	Air	µBq	1.68	0.0575
732	Plutonium-alpha	Air	µBq	3.85	11
733	Plutonium-alpha	Water	mBq	x	663
734	Polonium-210	Air	kBq	11.1	0.16
735	Polonium-210	Water	kBq	7.85	0.193
736	Polychlorinated biphenyls	Air	mg	13.7	1.44
737	Polycyclic organic matter, unspecified	Air	mg	99.4	x
738	Potassium	Air	g	188	4.77
739	Potassium	Water	kg	191	14
740	Potassium	Soil	g	104	8.24
741	Potassium-40	Air	kBq	6.64	0.159
742	Potassium-40	Water	kBq	7.36	0.199
743	Potassium chloride	Raw	kg	0.345	194
744	Primisulfuron	Soil	µg	47.9	0.929
745	Process solvents, unspecified	Water	mg	751	x
746	Propamocarb HCl	Soil	µg	50.3	1.61
747	Propanal	Air	mg	13.9	0.0952

No	Substance	Compartment	Unit	CIPP	Open-cut
748	Propanal	Water	µg	52.5	1.77
749	Propane	Air	g	728	118
750	Propane, 1,2-dichloro-	Water	pg	x	5.04
751	Propargite	Soil	mg	3.36	0.108
752	Propene	Air	kg	7.62	0.509
753	Propene	Water	kg	18.1	8.56E-5
754	Propionic acid	Air	g	15.5	0.0799
755	Propionic acid	Water	µg	191	7.13
756	Propylamine	Air	µg	8.74	0.295
757	Propylamine	Water	µg	21	0.708
758	Propylene oxide	Air	kg	8.5	2.15E-5
759	Propylene oxide	Water	kg	20.5	1.27E-5
760	Prosulfuron	Soil	µg	8.62	0.167
761	Protactinium-234	Air	Bq	956	25.3
762	Protactinium-234	Water	kBq	2.24	0.0491
763	Pumice	Raw	µg	x	779
764	Pymetrozine	Soil	µg	322	10.3
765	Pyrene	Air	µg	110	1.49
766	Quizalofop-P	Soil	µg	4.99	0.362
767	Radioactive species, alpha emitters	Water	Bq	48.5	0.067
768	Radioactive species, Nuclides, unspecified	Water	kBq	137	2.91
769	Radioactive species, other beta emitters	Air	kBq	4.59	0.0572
770	Radioactive species, unspecified	Air	kBq	1.86E4	271
771	Radionuclides (Including Radon)	Air	g	24.4	0.349
772	Radium-224	Water	kBq	13.6	0.614
773	Radium-226	Air	kBq	6.29	0.128
774	Radium-226	Water	kBq	1.53E3	36.5
775	Radium-226/kg	Water	µg	0.118	1.03
776	Radium-228	Air	kBq	5.01	0.0316
777	Radium-228	Water	kBq	176	4.19
778	Radium-228/kg	Water	ng	0.602	5.26
779	Radon-220	Air	kBq	120	3.28
780	Radon-222	Air	kBq	1.6E7	3.52E5
781	Rhenium	Raw	µg	214	7.69
782	Rhodium	Raw	pg	x	392
783	Rhodium	Air	pg	x	2.5
784	Rhodium, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4	Raw	µg	124	5.49
785	Rhodium, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4	Raw	µg	388	17.2
786	Rimsulfuron	Soil	µg	202	5.87
787	Rubidium	Water	g	2.72	0.123
788	Ruthenium-103	Air	µBq	7.51	0.15
789	Ruthenium-103	Water	mBq	7.3	0.146
790	Ruthenium-106	Water	mBq	x	167
791	Rutile	Raw	mg	5.5E-21	301
792	Sand	Raw	kg	7.57	104
793	Sand, quartz	Raw	pg	0.0133	0.184
794	Scandium	Air	g	1.55	0.0325
795	Scandium	Water	g	110	4.26
796	Selenium	Air	g	12.4	0.427
797	Selenium	Water	g	135	6.88
798	Selenium compounds	Air	mg	0.252	2.06
799	Sethoxydim	Soil	µg	157	5.93
800	Shale	Raw	kg	3.98	1.42
801	Silicon	Air	kg	1.17	0.00577
802	Silicon	Water	kg	660	16.9
803	Silicon	Soil	g	124	2.25
804	Silicon tetrafluoride	Air	mg	51.6	0.0579
805	Silver	Air	mg	140	100

No	Substance	Compartment	Unit	CIPP	Open-cut
806	Silver	Water	g	177	63.6
807	Silver-110	Air	µBq	74.4	1.49
808	Silver-110	Water	Bq	37.9	0.997
809	Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn,	Raw	g	4.11	0.00776
810	Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and T	Raw	g	2.94	0.00556
811	Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore	Raw	mg	271	0.512
812	Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore	Raw	mg	618	1.17
813	Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore	Raw	mg	606	1.15
814	Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, C	Raw	mg	400	0.756
815	Simazine	Soil	µg	967	18.8
816	Slags	Waste	g	x	1.38
817	Slags and ashes	Waste	tn.lg	0.138	5.93
818	Slate	Raw	g	73.3	1.38
819	Sodium	Air	g	97.3	1.15
820	Sodium	Water	tn.lg	4.48	5.22
821	Sodium	Soil	g	612	38.1
822	Sodium-24	Water	mBq	262	5.23
823	Sodium carbonate	Raw	g	172	4.82
824	Sodium chlorate	Air	mg	47.8	0.803
825	Sodium chloride	Raw	tn.lg	9.63	188
826	Sodium dichromate	Air	mg	133	14.2
827	Sodium formate	Air	mg	4.53	0.0642
828	Sodium formate	Water	mg	10.9	0.154
829	Sodium hydroxide	Air	mg	483	4.49
830	Sodium nitrate	Raw	mg	6.41	2.65
831	Sodium sulfate	Raw	g	925	14.1
832	Soil	Raw	g	x	87
833	Solids, inorganic	Water	kg	14.1	0.0706
834	Spinosad	Soil	µg	6.7	0.215
835	Spoil, unspecified	Waste	g	x	592
836	Stibnite	Raw	µg	298	3.71
837	Strontium	Air	g	14	0.071
838	Strontium	Water	kg	12.8	1.94
839	Strontium	Soil	g	2.7	11.1
840	Strontium-89	Water	mBq	860	27.1
841	Strontium-90	Water	Bq	481	24.2
842	Styrene	Air	g	28.8	0.0229
843	Styrene	Water	mg	7.51	x
844	Sulfate	Air	kg	27.7	0.0149
845	Sulfate	Water	tn.lg	2.09	0.692
846	Sulfate	Soil	mg	x	551
847	Sulfentrazone	Soil	mg	2.59	0.271
848	Sulfide	Water	g	1.23	43.4
849	Sulfide	Soil	g	x	3.31
850	Sulfite	Water	g	22.7	0.429
851	Sulfosate	Soil	mg	10.7	1.11
852	Sulfur	Raw	kg	199	-77.4
853	Sulfur	Water	g	270	100
854	Sulfur	Soil	g	204	5.27
855	Sulfur dioxide	Air	tn.lg	0.621	1.79
856	Sulfur hexafluoride	Air	g	11.2	0.273
857	Sulfur monoxide	Air	kg	0.415	25.8
858	Sulfur oxides	Air	kg	3.93	3.05E-6
859	Sulfur trioxide	Air	mg	6.79	0.222
860	Sulfur, bonded	Raw	g	6.24	14.5
861	Sulfuric acid	Air	mg	102	0.792
862	Sulfuric acid	Soil	g	1.18	0.0379
863	Sulfuric acid, dimethyl ester	Air	µg	175	3.26

No	Substance	Compartment	Unit	CIPP	Open-cut
864	Surfactants	Water	g	1.35	x
865	Suspended solids, unspecified	Water	tn.lg	3.63	6.35
866	t-Butyl methyl ether	Air	mg	34.3	0.279
867	t-Butyl methyl ether	Water	mg	687	26.4
868	t-Butylamine	Air	µg	30.6	1.13
869	t-Butylamine	Water	µg	73.3	2.71
870	Talc	Raw	g	43.6	1.21
871	Tantalum	Raw	g	3.19	0.00572
872	Tar	Air	ng	166	341
873	Tar	Water	ng	2.38	4.88
874	Tebupirimphos	Soil	µg	402	7.81
875	Tebutam	Soil	ng	295	10.5
876	Technetium-99m	Water	mBq	795	15.9
877	Teflubenzuron	Soil	µg	40.5	1.3
878	Tefluthrin	Soil	µg	316	6.13
879	Tellurium	Raw	mg	440	0.834
880	Tellurium	Air	µg	x	1.25
881	Tellurium-123m	Water	mBq	439	17.3
882	Tellurium-132	Water	mBq	2	0.04
883	Terbufos	Soil	mg	1.07	0.0208
884	Terpenes	Air	mg	12.5	0.46
885	Tetradecane	Water	mg	77.1	689
886	Thallium	Air	mg	112	0.363
887	Thallium	Water	g	10.9	1
888	Thiamethoxam	Soil	µg	295	9.45
889	Thiazole, 2-(thiocyanatemethylthio)benzo-	Soil	mg	97.6	3.13
890	Thiram	Soil	µg	57	2.09
891	Thorium	Air	mg	125	0.406
892	Thorium-228	Air	Bq	873	14.9
893	Thorium-228	Water	kBq	54.5	2.46
894	Thorium-230	Air	kBq	1.35	0.0326
895	Thorium-230	Water	kBq	306	6.7
896	Thorium-232	Air	Bq	745	14.7
897	Thorium-232	Water	kBq	1.34	0.0365
898	Thorium-234	Air	Bq	956	25.3
899	Thorium-234	Water	kBq	2.24	0.0491
900	Tin	Raw	kg	2.07	0.000461
901	Tin	Air	g	3.28	0.239
902	Tin	Water	g	125	37.9
903	Tin	Soil	g	7.01	1.94E-5
904	Tin oxide	Air	pg	x	675
905	TiO2, 54% in ilmenite, 2.6% in crude ore	Raw	kg	3.36	0.142
906	TiO2, 95% in rutile, 0.40% in crude ore	Raw	mg	25.9	3.49
907	Titanium	Raw	mg	x	252
908	Titanium	Air	g	51.7	0.665
909	Titanium	Water	kg	7.02	0.138
910	Titanium	Soil	mg	253	22.8
911	TOC, Total Organic Carbon	Water	kg	309	26.1
912	Toluene	Air	kg	4.26	0.074
913	Toluene	Water	g	165	49.6
914	Toluene, 2-chloro-	Air	µg	299	9.93
915	Toluene, 2-chloro-	Water	µg	581	19.2
916	Toluene, 2,4-dinitro-	Air	µg	1.02	0.019
917	Transformation, from arable	Raw	dm2	96.1	2.28
918	Transformation, from arable, non-irrigated	Raw	m2	3.54	0.359
919	Transformation, from arable, non-irrigated, fal	Raw	cm2	395	4.31
920	Transformation, from dump site, inert materia	Raw	sq.in	637	2.43
921	Transformation, from dump site, residual mate	Raw	sq.in	328	7.51

No	Substance	Compartment	Unit	CIPP	Open-cut
922	Transformation, from dump site, sanitary land	Raw	cm2	50	161
923	Transformation, from dump site, slag compart	Raw	mm2	987	34.6
924	Transformation, from forest	Raw	m2	7.37	0.248
925	Transformation, from forest, extensive	Raw	m2	13.2	0.165
926	Transformation, from forest, intensive, clear-c	Raw	cm2	138	5.07
927	Transformation, from industrial area	Raw	cm2	559	12
928	Transformation, from industrial area, benthos	Raw	mm2	190	0.286
929	Transformation, from industrial area, built up	Raw	cm2	24.4	0.0274
930	Transformation, from industrial area, vegetatio	Raw	cm2	41.6	0.0467
931	Transformation, from mineral extraction site	Raw	m2	1.51	0.00469
932	Transformation, from pasture and meadow	Raw	m2	1.29	0.0357
933	Transformation, from pasture and meadow, in	Raw	mm2	0.786	0.0281
934	Transformation, from sea and ocean	Raw	m2	1.6	0.0706
935	Transformation, from shrub land, sclerophyllo	Raw	dm2	77.6	2.69
936	Transformation, from tropical rain forest	Raw	cm2	138	5.07
937	Transformation, from unknown	Raw	m2	8.87	0.152
938	Transformation, to arable	Raw	m2	1.99	0.0237
939	Transformation, to arable, non-irrigated	Raw	m2	3.55	0.359
940	Transformation, to arable, non-irrigated, fallow	Raw	cm2	845	4.92
941	Transformation, to dump site	Raw	m2	1.94	0.0564
942	Transformation, to dump site, benthos	Raw	m2	1.5	0.0706
943	Transformation, to dump site, inert material la	Raw	sq.in	637	2.43
944	Transformation, to dump site, residual materia	Raw	sq.in	328	7.51
945	Transformation, to dump site, sanitary landfill	Raw	cm2	50	161
946	Transformation, to dump site, slag compartme	Raw	mm2	987	34.6
947	Transformation, to forest	Raw	dm2	90.6	2.43
948	Transformation, to forest, intensive	Raw	sq.in	276	3.95
949	Transformation, to forest, intensive, clear-cutt	Raw	cm2	138	5.07
950	Transformation, to forest, intensive, normal	Raw	m2	12.9	0.16
951	Transformation, to forest, intensive, short-cycl	Raw	cm2	138	5.07
952	Transformation, to heterogeneous, agricultura	Raw	sq.in	679	19
953	Transformation, to industrial area	Raw	m2	1.18	0.0317
954	Transformation, to industrial area, benthos	Raw	sq.in	164	0.0739
955	Transformation, to industrial area, built up	Raw	m2	2.19	0.013
956	Transformation, to industrial area, vegetation	Raw	m2	1.04	0.00608
957	Transformation, to mineral extraction site	Raw	m2	8	0.265
958	Transformation, to pasture and meadow	Raw	cm2	239	0.307
959	Transformation, to permanent crop, fruit, inte	Raw	cm2	51.5	2.8
960	Transformation, to sea and ocean	Raw	mm2	190	0.286
961	Transformation, to shrub land, sclerophyllous	Raw	sq.in	974	34.9
962	Transformation, to traffic area, rail network	Raw	cm2	792	6.26
963	Transformation, to traffic area, rail/road emba	Raw	cm2	720	5.7
964	Transformation, to traffic area, road embankm	Raw	sq.in	487	2.56
965	Transformation, to traffic area, road network	Raw	sq.in	955	20.9
966	Transformation, to unknown	Raw	m2	1.11	0.00189
967	Transformation, to urban, discontinuously buil	Raw	mm2	96.2	3.65
968	Transformation, to water bodies, artificial	Raw	sq.in	618	12.5
969	Transformation, to water courses, artificial	Raw	sq.in	598	17.5
970	Tributyltin compounds	Water	mg	478	18
971	Trichlorfon	Soil	µg	5.03	0.161
972	Triethylene glycol	Water	mg	57.4	0.108
973	Trifluralin	Soil	mg	15.9	1.6
974	Trimethylamine	Air	µg	17.4	0.599
975	Trimethylamine	Water	µg	107	2.7
976	Tungsten	Air	mg	166	3.64
977	Tungsten	Water	g	128	9.04
978	Ulexite	Raw	g	30.4	0.403
979	Unspecified input	Raw	mg	8.89E-38	244

No	Substance	Compartment	Unit	CIPP	Open-cut
980	Uranium	Raw	g	559	10.9
981	Uranium	Air	mg	165	0.456
982	Uranium-234	Air	kBq	3.11	0.0756
983	Uranium-234	Water	kBq	2.69	0.0589
984	Uranium-235	Air	Bq	68.5	3.02
985	Uranium-235	Water	kBq	4.43	0.0972
986	Uranium-238	Air	kBq	3.78	0.0799
987	Uranium-238	Water	kBq	10.3	0.285
988	Uranium alpha	Air	kBq	6.54	0.143
989	Uranium alpha	Water	kBq	129	2.83
990	Uranium oxide, 332 GJ per kg, in ore	Raw	g	17.2	0.245
991	Urea	Water	µg	82.1	2.79
992	Used air	Air	kg	x	57.2
993	Vanadium	Air	g	95	0.866
994	Vanadium	Water	g	536	17
995	Vanadium	Soil	mg	7.23	0.652
996	Vermiculite	Raw	g	38.2	0.0505
997	Vinyl acetate	Air	µg	27.7	0.516
998	VOC, volatile organic compounds	Air	kg	11.7	12.1
999	VOC, volatile organic compounds, unspecified	Water	g	101	4.44
1000	Volume occupied, final repository for low-activ	Raw	cm3	724	15.9
1001	Volume occupied, final repository for radioacti	Raw	cm3	151	3.32
1002	Volume occupied, reservoir	Raw	m3y	207	5.36
1003	Volume occupied, underground deposit	Raw	cu.in	192	20.4
1004	Waste in incineration	Waste	kg	128	779
1005	Waste returned to mine	Waste	tn.lg	0.525	11.3
1006	Waste to recycling	Waste	kg	1.17	123
1007	Waste, industrial	Waste	kg	23.7	-716
1008	Waste, solid	Waste	tn.lg	-0.0129	-4.15
1009	Waste, unspecified	Waste	kg	23.2	294
1010	Water	Air	kg	9.11	33.4
1011	Water	Water	tn.lg	58.6	x
1012	Water, cooling, drinking	Raw	kg	x	235
1013	Water, cooling, salt, ocean	Raw	kton	0.0439	1.06
1014	Water, cooling, surface	Raw	kton	0.00588	6.6
1015	Water, cooling, unspecified natural origin, US	Raw	ML	4.9	0.037
1016	Water, cooling, unspecified natural origin/kg	Raw	kton	0.894	5.51
1017	Water, cooling, unspecified natural origin/m3	Raw	m3	64.7	0.763
1018	Water, cooling, well	Raw	tn.lg	0.971	39.9
1019	Water, lake	Raw	dm3	0.2	266
1020	Water, lake, US	Raw	m3	40.2	0.0534
1021	Water, process, drinking	Raw	tn.lg	8.55	443
1022	Water, process, salt, ocean	Raw	tn.lg	3.77	35.2
1023	Water, process, surface	Raw	tn.lg	5.84	154
1024	Water, process, unspecified natural origin/kg	Raw	kton	0.0111	1
1025	Water, process, well	Raw	tn.lg	0.000286	116
1026	Water, river	Raw	m3	3.29	0.0716
1027	Water, river, US	Raw	m3	226	3.23
1028	Water, salt, ocean	Raw	m3	9.59	0.09
1029	Water, salt, sole	Raw	m3	3.53	0.158
1030	Water, turbine use, unspecified natural origin	Raw	m3	53.6	1.81
1031	Water, turbine use, unspecified natural origin,	Raw	MMCF	8.68	0.257
1032	Water, unspecified natural origin, US	Raw	m3	703	1.49
1033	Water, unspecified natural origin/m3	Raw	m3	8.38	0.357
1034	Water, well, in ground	Raw	m3	4.82	0.079
1035	Water, well, in ground, US	Raw	m3	97.1	0.418
1036	Wood waste	Waste	kg	0.00442	174
1037	Wood, hard, standing	Raw	dm3	152	6.38

No	Substance	Compartment	Unit	CIPP	Open-cut
1038	Wood, primary forest, standing	Raw	cm3	143	5.25
1039	Wood, soft, standing	Raw	dm3	553	12.6
1040	Wood, unspecified, standing/m3	Raw	cu.in	550	0.00353
1041	Xenon-131m	Air	Bq	611	17.3
1042	Xenon-133	Air	kBq	22.4	1.28
1043	Xenon-133m	Air	Bq	21.5	0.439
1044	Xenon-135	Air	kBq	8.95	0.454
1045	Xenon-135m	Air	kBq	5.65	0.113
1046	Xenon-137	Air	Bq	179	3.64
1047	Xenon-138	Air	kBq	1.33	0.0359
1048	Xylene	Air	kg	2.43	0.0531
1049	Xylene	Water	g	93.4	27.2
1050	Yttrium	Water	mg	21.9	192
1051	Zinc	Raw	kg	15.6	0.209
1052	Zinc	Air	g	122	6.66
1053	Zinc	Water	kg	6.87	0.817
1054	Zinc	Soil	g	24	0.195
1055	Zinc-65	Air	mBq	1.44	0.0287
1056	Zinc-65	Water	Bq	3.55	0.0709
1057	Zinc oxide	Air	ng	x	1.35
1058	Zirconium	Raw	g	4.09	0.00672
1059	Zirconium	Air	mg	14.6	1.27
1060	Zirconium-95	Air	mBq	1.41	0.0281
1061	Zirconium-95	Water	mBq	41.1	0.821

Appendix C

Related Excerpt from Greenbook 2012

TABLE 500-1.3.7 (A)

DIFFERENTIAL-PRESSURE (VACUUM OR EXTERNAL FLUID)
CAPABILITY FOR UNSUPPORTED PIPE AT 73.4 °F (23 °C)

SOR	kPa (psi)
32.5	4 (28)
26	8 (55)
21	16(110)
19	21 (145)
17	28 (193)
15.5	36 (248)

500-1.3.8 Service Connections and End Seals. The Contractor shall be responsible for locating all service laterals and cleanouts. Service connections shall not be made until the liner pipe has stabilized, which is normally accomplished after a 24-hour waiting period. Service laterals shall be connected to the liner pipe by use of a heat-fused saddle or mechanical saddle as approved by the Engineer.

500-1.3.9 Repair and Rejection. Liner pipe may be repaired for minor superficial pipe damage. Damaged liner pipe which has been penetrated over 10 percent of the wall thickness at either the inner or outer wall surface, shall be repaired by cutting out the damaged section and replacing it with new pipe. All repair methods shall be submitted to the Engineer for prior approval in accordance with 2-5.3. The remaining liner pipe sections shall be a minimum of 8 feet (2.4m) in length. Liner pipes shall be inspected for damage immediately prior to installation. If liner pipe is found to be superficially damaged, the Engineer may allow the pipe to be repaired or may reject it. Rejected liner pipe shall be replaced with a new section of liner pipe.

500-1.4 Cured-In-Place Pipe Liner

500-1.4.1 General. CIPP liner for the rehabilitation of pipelines shall be either the Type A - inversion process in compliance with ASTM F1216 or the Type B - pull-in-place process in compliance with ASTM Fl 743 for installation using heatedwater cure. The CIPP liner shall use an approved epoxy or epoxy-vinyl ester-resin-impregnated flexible fabric tube. The tube is installed by an inversion method using a hydrostatic head or by pulling it through an existing pipe and inflating by inverting a membrane using a hydrostatic head.

500-1.4.2 Material Composition and Testing. The fabric tube shall consist of one or more layers of flexible, needled felt or an equivalent nonwoven material and have plastic coating(s). The material shall be compatible with and capable of carrying epoxy or epoxy-vinyl-ester resin, be able to withstand installation pressures and curing temperatures, and be compatible with the approved resins used. The approved epoxy or epoxy-vinyl-ester resin shall be compatible with the application and pipeline environment and be able to cure in the presence of water. The initiation temperature for cure shall be as recommended by the resin manufacturer and approved by the Engineer. The CIPP liner shall comply with ASTM D5813 and shall have, as a minimum, the initial structural properties per Table 500-1.4.2 (A).

TABLE 500-1.4.2 (A)

Epoxy Resin Properties	ASTM Test Method*	Initial Values psi (MPa)
Flexural Strength	D 790	5,000 (34.5)
Flexural Modulus	D 790	300,000 (2068)
Tensile Strength	D 638	4,000 (27.6)
Tensile Modulus	D 638	250,000 (1724)
Epoxy-Vinyl-Ester Resin Properties	ASTM Test Method	Initial Values psi (MPa)
Flexural Strength	D 790	4,500 (31.0)
Flexural Modulus	D 790	250,000 (1724)
Tensile Strength	D 638	3,000 (21.0)
Tensile Modulus	D 638	250,000 (1724)

*The initial values are determined by ASTM D638 and D790.

The Contractor shall provide field-cured samples as directed by the Engineer and as specified in the Special Provisions. The physical properties of the finished CIPP shall be verified through a field- sampling procedure in accordance with ASTM Fl216 or ASTM Fl743 and in accordance with ASTM D5813.

500-1.4.3 Resin and Tube Acceptance. At the time of resin impregnation, the entire fabric tube shall be inspected for defects. The resin shall not contain fillers, except those required for viscosity control, fire retardance, or extension of pot life. Thixotropic agents that do not interfere with visual inspection may be added for viscosity control. Also, the opacity of the plastic coating shall not interfere with visual inspection. Resins may contain pigments, dyes, or colors that do not interfere with visual inspection of the CIPP liner or its required properties. Additives may be incorporated that enhance the physical and/or chemical resistance.

500-1.4.4 Chemical Resistance. The CIPP liner system shall conform to 211-2 and to the weight change requirement of Table 210-2.4.1 (A).

500-1.4.5 Installation. The host pipeline shall be cleaned and televised in accordance with 500-and 500-1.1.5. The OD of the tube being installed shall be properly sized to allow for expansion so that the CIPP can fit tightly against the existing pipe.

The CIPP shall be installed in accordance with ASTM Fl216 or ASTM Fl 743 and the Contractor's recommendations as approved by the Engineer. Immediately prior to installation, the CIPP liner tube shall be saturated with resin (on or off the Work site) and stored/transported at a cool temperature as recommended by the resin manufacturer.

500-1.4.6 Curing. After tube placement is completed, a suitable heat source and distribution equipment shall be provided by the Contractor to distribute or recirculate hot water throughout the installed CIPP liner tube. Temperature shall be maintained during the curing period as recommended by the resin manufacturer and approved by the Engineer. After the tube is cured, a cool-down period shall be used prior to opening the downstream end, reconnection of services, and returning normal flow back into the system. Heat curing of the resin shall occur within the manufacturer's approved recommended time frame (pot life). The water in the CIPP shall be cooled to below 100°F (38°C) before discharge.

500-1.4.7 Service Connections and End Seals. After the curing is complete, existing service connections shall be re-established. This may be done without excavation by means of a remote-control cutting device operating within small diameter pipe. A CCTV camera shall be attached to the cutting device for precise location of service connections and inspection of the CIPP liner.

500-1.4.8 Repair and Rejection. Internal and external repairs may be made to CIPP liner pipe in accordance with the manufacturer's recommendations and approval by the Engineer. Internal repairs may be made with approved fabric and epoxy or epoxy-vinyl-ester resins to restore strength and integrity. External repairs may be made by using standard plastic pipe repair techniques, including replacement of the damaged section using PVC pipe coupled to the CIPP liner, as approved by the Engineer.

500-1.5 PVC Pipe Lining System

500-1.5.1 General. PVC profile extrusions with annular space grouting shall be installed for use in sanitary sewers and storm drains. This applies to the rehabilitation of small-diameter pipe and person- entry pipe (36 inches (900mm) and larger) or conduits in terms of materials and installations.

500-1.5.2 Material Composition. The material shall be made from unplasticized PVC compounds conforming to 207-17, having a cell classification of 12334, 12454, or 13354 as defined in ASTM Dl 784.

500-1.5.3 Material and Equipment Acceptance. At the time of manufacture, each lot of plastic strips shall be inspected for defects and the physical properties certified in accordance with the ASTM Standards listed in this subsection, or as indicated in the Special Provisions. There are 2 strips of PVC used in this process. The former strip is a ribbed panel which varies in width and height as a function of pipe diameter. The joiner strip is a "U"-shaped strip of PVC which is used to lock together the former strip edges as the PVC strips or panels are being spirally wound upon themselves. The minimum thickness of the strips and panels shall be per Table 500-1.5.3 (A).

TABLE 500-1.5.3 (A)

Nominal ID of Original Pipe inches (mm)	Minimum Thickness		Minimum Profile Height mils (mm)
	Former Strip mils (mm)	Joiner Strip mils (mm)	
8 to 12 (200 to 300)	25 (0.64)	25 (0.64)	192 (4.88)
15 to 18 (375 to 400)	30 (0.75)	31 (0.79)	242 (6.15)
24 to 36 (600 to 900)	45 (1.15)	58 (1.48)	480 (12.20)
30 to 72 (750 to 1800)*	60 (1.53)	-	488 (12.40)

*In some lining applications for pipes and conduits 30 to 36 inches (750 to 900mm) in diameter, it may be determined to use person-entry techniques.

References

Ajdari, E. (2016). Volatile Organic Compound (VOC) Emission during Cured-in-Place-Pipe (CIPP) Sewer Pipe Rehabilitation. *Ph.D. Dissertation*, University of New Orleans, LA, in in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Allouche, E. N., & Gilchrist, A. (2004). Quantifying construction related social costs. *Proc.* NASTT No-Dig Conference, 2004.

Allouche, E., Alam, S., Simicevic, J. and Sterling, R. (2012). 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.

Alsadi, A. (2019). Evaluation of Carbon Footprint During the Life-Cycle of Four Different Pipe Materials. *Ph.D. Dissertation*, Louisiana Tech, 2019.

American Public Health Association (APHA), American Water Works Association (AWWA) and Water Environment Federation (WEF). (2000). Standard Methods for the Examination of Water and Wastewater. 22nd Ed., American Public Health Association (APHA), Baltimore, MD.

Ariaratnam, S.T., Piratla, K., Cohen, A. and Olson, M. (2013). Quantification of sustainability index for underground utility infrastructure projects. *Journal of Construction Engineering and Management*, 139(12), p.A4013002.

Ariaratnam, S.T., Lueke, J.S. and Michael, J.K. (2014). Current trends in pipe bursting for renewal of underground infrastructure systems in North America. *Tunnelling and Underground Space Technology*, 39, pp.41-49.

ASCE (2019). Guidelines for the Sustainable Design of Pipelines. Reston, VA (Under Print).

ASCE (2010). Trenchless Renewal of Culverts and Storm Sewers. *Manuals and Reports on Engineering Practice No. 120.*, Reston, VA.

Atalah, A. (2004). Ground movement in hard rock conditions related to Pipe bursting. *Proc.* ASCE Pipelines 2004.

Baik, H. S., Abraham, D. M., & Gipson, D. J. (2004). Impacts of Deteroriation Based Life Cycle Cost Analysis (LCCA) on the Assessment of Values of Wastewater Infrastructure Assets. *Proc.* Pipeline Engineering and Construction: What's on the Horizon? (pp. 1-10).

Bauer, G., and McCartney, D. (2004). Odor Control-More than Sewage When Installing Cured-In-Place Sewer Pipe Liners. *Proc.* of the North American Society for Trenchless Technology (NASTT) No-Dig Conference, New Orleans, LA.

Bartlett, S., Cisneros, H., Decker, P., Heartwell, G., Warnock, A., Nellenbach, M., and Campanelli, B. (2017). Executive Council on Infrastructure Water Task Force.

Beaudet, B. A., Tobey, B., and Harder, S. (2019). Life Cycle Cost Analysis for Decision Making in Collection System Rehabilitation. *Proc.* NASTT No-Dig Show, Chicago, IL, Mar 17-20, 2019.

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

Carbon Trust. (2007). Carbon footprinting: An introduction for organizations. London: Carbon Trust.

CE Delft. (2017). *Handbook Environmental Prices*. Netherlands, 2017.

Chilana, L. (2011). Carbon footprint analysis of a large diameter water transmission pipeline installation. *Master’s Thesis*, The University of Texas at Arlington, 2011.

Chilana, L., A. H. Bhatt, M. Najafi, and M. Sattler (2016). Comparison of carbon footprints of steel versus concrete pipelines for water transmission. *Journal of the Air & Waste Management Association*, vol. 66, no. 5, pp. 518–527, May 016.

Crawford, S., & Lungu, C. T. (2011). Influence of Temperature on Styrene Emission from a Vinyl Ester Resin Thermoset Composite Material. *Science of the Total Environment*, 409(18), 3403-3408.

CUIRE. (2018). Evaluation of Potential Release of Organic Chemicals in the Steam Exhaust and Other Release Points during Pipe Rehabilitation Using the Trenchless Cured-In-Place Pipe (CIPP) Method. *Final Report*, NASSCO's Phase 1 CIPP Steam Emissions Study, 2018.

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

Das, S., Bayat, A., Gay, L., Salimi, M., & Matthews, J. (2016). A Comprehensive Review on the Challenges of Cured-in-Place pipe (CIPP) Installations. *Journal of Water Supply: Research and Technology-Aqua*, 65(8), 583-596.

Dayal, P. (2011). Worcester day care center evacuated. *Worcester Telegram and Gazette*, Oct. 28.

Donaldson B. (2012). 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.M., and A. Baker. (2008). The Environmental Implications of Cured-in-Place Pipe Rehabilitation. VTRC 08-CR12, *Virginia Transportation Research Council*, Charlottesville, 2008.

Dusseldorp, A.; and Schols, E. (2006). Rioolrenovatie met kousmethoden-Achtergronden bij het informatieblad. RIVM rapport 609021038/2006, Bilthoven, RIVM-Rijksinstituut voor Volksgezondheid en Milieu.

Gangavarapu, B. S. (2003). Analysis and comparison of traffic disruption using open-cut and trenchless methods of pipe installation. ProQuest Information and Learning Company. Ann Arbor, MI.

Gowen, A. (2004). Fumes from Va. sewer work cited in illnesses: Alexandria Officials Reevaluating Effects of Styrene Vapor on Residents. *Washington Post*, May 12, B08.

Hashemi, B. (2008). Construction Cost of Underground Infrastructure Renewal: A Comparison of Traditional Open-Cut and Pipe Bursting Technology. *Master's Thesis*, University of Texas at Arlington, 2008.

Hashemi, B., Iseley, T., & Raulston, J. (2011). Water Pipeline Renewal Evaluation Using AWWA Class IV CIPP, Pipe Bursting, and Open-cut. *Proc.* International Conference on Pipelines and Trenchless Technology, October 26-29, 2011.

Heinselman, W. (2012). The History of Cured-in-Place-Pipe Lining in the United States, *Express Sewer & Drain*, 2012

Howard, A. (1996). Pipeline Installation. *Relativity Publishing*., Lake Wood, Colorado.

InfraGuide (2003). Coordinating Infrastructure Works. DMIP Best Practice, *National Research Council of Canada*, Ottawa, Canada.

International Organization for Standardization (ISO). (2006). Environmental management - Life cycle assessment - Principles and framework. *ISO 14040*, Geneva.

Islam, A., Allouche, E. and Matthews, J. (2014). Assessment of social cost savings in trenchless projects. *Proc.* North American Society for Trenchless Technology (NASST), Orlando, FL.

Joshi, A. (2012). A Carbon Dioxide Comparison of Open Cut and Pipe Bursting. Master of Technology Management Plan II Graduate Projects. Paper 7.

Jung, Y., Sinha, S. (2007). Evaluation of Trenchless Technology Methods for Municipal Infrastructure System. *Journal of Infrastructure Systems*, Vol. 13, No. 2, pp. 144-156.

Kabir, G., Tesfamariam, S., & Sadiq, R. (2015). Predicting water main failures using bayesian model averaging and survival modelling approach. *Reliability Engineering & System Safety*, 142, 498-514.

Kamat, S. M. (2011). Comparison of Dust Generation from Open Cut And Trenchless Technology Methods for Utility Construction. *Master's Thesis*, The University of Texas at Arlington.

Kampbell, E. (2009). Understanding Environmental Implications of CIPP Rehab Technology. *Rehabilitation Technology, Underground Technology Cutting Edge Technical Information for Utility Construction and Rehabilitation*, 2009.

Karimian, S. F. (2015). Failure Rate Prediction Models of Water Distribution Networks. *Master's Thesis*, Concordia University, 2015.

Kaushal, V., Iyer, G., Najafi, M., Sattler, M., and Schug, K. (2019). Review of Literature for Cured-in-Place Pipe (CIPP) Chemical Emissions and Worker Exposures. *Proc.* Transportation Research Board Annual Meeting, Washington, D.C., 2019.

Kaushal, V., Najafi, M., Sattler, M., and Schug, K. (2019a). Evaluation of Potential Release of Organic Chemicals in the Steam Exhaust and Other Release Points during Pipe Rehabilitation Using the Trenchless Cured-In-Place Pipe (CIPP) Method. *Proc.* North American Society for Trenchless Technology-No-Dig Conference, Chicago, IL.

Kaushal, V., Najafi, M., Sattler, M., & Schug, K. (2019b). Review of Literature on Chemical Emissions and Worker Exposures Associated with Cured-In-Place Pipe (CIPP) Installation. *Proc.* ASCE Pipelines 2019, Nashville, TN.

Kendall, A., Keoleian, G. A., and Helfand G. E. (2008). Integrated Life-Cycle Assessment and Life-Cycle Cost Analysis Model for Concrete Bridge Deck Applications. *Journal of Infrastructure Systems*, 14(3), 214-222.

Khan, L.R. and Tee, K.F. (2015). Quantification and comparison of carbon emissions for flexible underground pipelines. *Canadian Journal of Civil Engineering*, 42(10), pp.728-736.

Kleiner, Y., Adams, B. J., & Rogers, J. S. (2001). Water distribution network renewal planning. *Journal of Computing in Civil Engineering*, 15(1), 15-26.

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

Kulkarni, T., M. Kanchwala, M. Najafi, and C. Fisher. (2011). Cost comparison of PVC water pipe for horizontal directional drilling (HDD) and open-cut installations. *Proc.* North American Society for Trenchless Technology (NASTT), Washington, D.C.

Lee, H. (2006). Cost comparison of pipeline asset replacement: Open-cut and Pipe-bursting. *Master's Thesis*, Michigan State University, 2006.

Lee H., Najafi, M., & Matthys, J. (2007). Cost comparison of pipeline asset replacement: Open-cut and Pipe-bursting. *Proc.* ASCE Pipelines 2007, Boston, Massachusetts.

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

Loendorf, T., & Waters, D. (2009). Styrene Removal Adds to the Challenges of Rehabilitating Sewer Pipeline in Reno, Nevada. *Proc.* of the North American Society for Trenchless Technology (NASTT) No-Dig Conference. Liverpool, NY.

Lueke, J. S., Matthews, J. C., Stowe, R., and Lamont, C. (2015). Comparing Carbon Footprints of Trenchless Water Main Renewal Technologies. *Proc.* NASTT No-Dig Show, 2015, Denver, Co.

Maldikar, S. (2010). An Investigation of Productivity Loss Due to Outdoor Noise Conditions. *Master's Thesis*, The University of Texas at Arlington, 2010.

Malek Mohammadi, M. (2019). Development of Condition Prediction Models for Sanitary Sewer Pipes. *Doctoral Dissertation*, University of Texas, Arlington, TX.

Mamaqani, B. (2014). Numerical Modeling of Ground Movements Associated with Trenchless Box Jacking Technique. *Ph.D. Dissertation*. The University of Texas at Arlington, TX.

Matthews, J. C., Allouche, E. N., & Sterling, R. L. (2015). Social Cost Impact Assessment of Pipeline Infrastructure Projects. *Environmental Impact Assessment Review*, 50, 196-202.

Matthews, J., Condit, W., Wensink, R., and Lewis, G. (2012). 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.

Milousi, M. (2018). Stochastic Life Cycle Assessment and Cost analysis in Renewable Energy Systems. *Master's Thesis*, School of Production Engineering and Management, Technical University of Crete, Chania, Greece.

Mohit, S., Monfared, M. A. N., Kang, C., and Bayat, A. 2017. Comparative study of greenhouse gas emissions from hand tunneling and pilot tube method underground construction methods. *Journal of Green Building*, 12(4), 54-69.

Monfared, M. A. N. 2018. Comparison of Trenchless Technologies and Open Cut Methods in New Residential Land Development. *Master's Thesis*, University of Alberta, Canada.

Najafi, M. and Kim, K. O. (2004). Life-Cycle-Cost Comparison of Trenchless and Conventional Open-Cut Pipeline Construction Projects. *Proc.* ASCE Pipeline Division Specialty Congress, 2004.

Najafi, M. and Gokhale, S.B. (2005). *Trenchless Technology: Pipeline and Utility Design, Construction, and Renewal*, New York: McGraw-Hill; 2005.

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

Najafi, M. (2016). *Pipeline Infrastructure Renewal and Asset Management*, New York: McGraw-Hill Education; 2016.

National Ready-Mixed Concrete Association. (2008). Concrete CO_2 Fact Sheet, 2008.

Osman, H., & Bainbridge, K. (2010). Comparison of statistical deterioration models for water distribution networks. *Journal of Performance of Constructed Facilities*, 25(3), 259-266.

Pandey, D., Agrawal, M., and Pandey, J. S. 2011. Carbon footprint: current methods of estimation. *Environmental monitoring and assessment*, 178(1-4), 135-160.

Piehl, R. (2005). Summary of trenchless technology for use with USDA Forest Service culverts. US Department of Agriculture, *Forest Service*, San Dimas Technology and Development Center.

Sendesi, S., K. Ra, E. Conkling, B. Boor, M. Nuruddin, J. Howarter, J. Youngblood, L. Kobos, J. Shannahan, C. Jafvert, and A. Whelton. (2017). Worksite chemical air emissions and worker exposure during sanitary sewer and stormwater pipe rehabilitation using cured-in-place-pipe (CIPP). *Environmental Science & Technology Letters*, 4(8), 325-333, 2017.

Serajiantehrani, R., Janbaz, S., Najafi, M., Korky, S., & Mohammadi, M. M. (2019). Impact of Tunnel Boring Machine Advance Rate for Pipeline Construction Projects. *Proc.* Pipelines 2019, pp. 650-660, Reston, VA.

Shahata, K. (2006). Stochastic Life Cycle Cost Modelling Approach for Water Mains. *Master's Thesis*, Concordia University, Montreal, Canada.

Sihabuddin, S. and Ariaratnam, S.T., 2009a. Quantification of carbon footprint on underground utility projects. *Proc.* Construction Research Congress 2009: Building a Sustainable Future (pp. 618-627).

Sihabuddin, S.S. and Ariaratnam, S.T., 2009b. Methodology for estimating emissions in underground utility construction operations. *Journal of Engineering, Design and Technology*, 7(1), pp. 37-64.

Sompura, S. J. (2017). Life Cycle Cost Analysis of Precast Concrete Pavement. *Master's Thesis*, California State University, Fullerton, CA.

Stone, S. L., Dzuray, E. J., Meisegeier, D., Dahlborg, A., Erickson, M., & Tafuri, A. N. (2002). Decision-support tools for predicting the performance of water distribution and wastewater collection systems US Environmental Protection Agency, Office of Research and Development. EPA/600/R-02/029.

Tabor, M. L. (2014). The Influence of Rehabilitated Stormwater Infrastructure on Water Quality and Daphnia magna Toxicity: A Field and Laboratory Investigation. *Master's Thesis*, University of South Alabama, 2014.

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

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

Tavakoli, R., Najafi, M., Tabesh, A., and Ashoori, T. (2017). Comparison of Carbon Footprint of Trenchless and Open-Cut Methods for Underground Freight Transportation. *Proc.* ASCE Pipelines 2017.

Tighe, S., Lee, T., McKim, R., and Haas, R. (1999). Traffic delay cost savings associated with trenchless technology. *Journal of infrastructure systems*, 5(2), 45-51.

Tighe, S., Knight, M., Papoutsis, D., Rodriguez, V., & Walker, C. (2002). User cost savings in eliminating pavement excavations through employing trenchless technologies. *Canadian Journal of Civil Engineering*, 29(5), 751-761.

Tol, R. S. J. (2005). The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties. *Journal of Energy Policy*, 33 2064-2074.

UNEP/SETAC (2009). Life Cycle Management: How business uses it to decrease footprint, create opportunities and make value chains more sustainable. UNEP/SETAC, 2009.

USEPA, NR-009d 2010. Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling Compression Ignition. Document No. EPA-420-R-10-018, Office of Transportation and Air Quality, *U.S. Environmental Protection Agency*, Washington D.C.

USEPA. NR-005d. 2010. Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling. Document No. EPA-420-R-10-016, Office of Transportation and Air Quality, *U.S. Environmental Protection Agency*, Washington D.C.

USEPA (2012). Clean Watersheds Needs Survey. 2012 Report to Congress, EPA-830-R-15005, January 2012.

US Environmental Protection Agency EPA (2016). Social Cost of Carbon. EPA, 2016.

Visentin, C., da Silva Trentin, A. W., Braun, A. B., & Thomé, A. (2019). Lifecycle assessment of environmental and economic impacts of nano-iron synthesis process for application in contaminated site remediation. *Journal of Cleaner Production.*

Whelton, A. J., M. Salehi, M. Tabor, B. Donaldson, and J. Estaba, J. (2013). Impact of Infrastructure Coating Materials on Storm-Water Quality: Review and Experimental Study. *Journal of Environmental Engineering*, 139(5), 746-756, 2013.

Whitehead, B., B. Williams, B. Robless, and D. Bryden. (2015). Minimizing Community Impacts and Reducing Costs through Trenchless Pipe Installation. *Proc.* North American Society for Trenchless Technology (NASTT), Denver, CO.

Willett, M. (2017). Industrial Hygiene Evaluation: CIPP-Styrene Exposure. Prince William County Service Authority, Woodbridge, VA, 2017.

Woodroffe, N. J. A., & Ariaratnam, S. T. (2008). Cost and Risk Evaluation for Horizontal Directional Drilling versus Open Cut in an Urban Environment. Practice Periodical on Structural Design and Construction, pp. 85-92.

Zhao, J. Q. and Rajani, B. (2002). Construction and Rehabilitation Costs for Buried Pipe With a Focus on Trenchless Technologies. *Final Report*, Institute for Research in Construction National Research Council Canada, Ottawa, Canada.

Biographical Information

Vinayak Kaushal was born on February 27, 1993, in Mandi, a district in the state of Himachal Pradesh (HP), India. He obtained his Bachelor's degree in Civil Engineering from Jawaharlal Nehru Government Engineering College in Sundernagar, HP, India in 2015. He then worked in a highway construction project and taught undergraduate civil engineering students for one year but was always keen for pursuing higher studies and research.

Vinayak joined the University of Texas at Arlington (UT Arlington) in August 2016 to pursue his Master's degree in Civil Engineering. After a few months of attending UT Arlington, he was fortunate enough to have got accepted for his Doctoral studies by Dr. Mohammad Najafi and joined the Center for Underground Infrastructure Research and Education (CUIRE) research group at UT Arlington.

While working at CUIRE/UTA, Vinayak was a teaching assistant for various graduate courses such as Pipeline Construction and Trenchless Technology, Construction Planning and Scheduling, and Construction Sustainability. Vinayak also had an opportunity to work on several high-profile research assignments and projects for companies and organizations (both governments and industry associations) under the supervision of Dr. Mohammad Najafi at CUIRE. He attended and presented at a number of conferences in different states of the USA and Canada, and published several journal and conference papers during this time. He was a recipient of Outstanding Graduate Student Award for Academic Excellence in Civil Engineering at UT Arlington, and also received the NASSCO's Jeffrey D. Ralston Memorial Award and the North Texas Chapter of Construction Management Association of America (CMAA) Student Scholarships in 2018. Vinayak earned his certification in NASSCO's Pipeline Assessment Certification Program (PACP) in 2018 through receiving a scholarship. Vinayak's great enthusiasm in the field of pipelines and trenchless technology led him to complete his dissertation on comparison of environmental and social costs of trenchless cured-in-place pipe renewal method with open-cut pipeline replacement.