SustainableSolutions
CORPORATION

IERE
Institute for Environmental Research & Education

Chair, Independent Expert Review Panel
PVC Pipe LCA/Standards ISO 14040 Series
& EPD/ISO 14025 Standard

NSF Sustainability
Sustainability Assured

Verified LCA Conformity to Product
Category Rule and ISO 14025

APRIL 2017

LIFE CYCLE ASSESSMENT OF PVC WATER AND SEWER PIPE AND COMPARATIVE SUSTAINABILITY ANALYSIS OF PIPE MATERIALS

This study evaluates underground pipe infrastructure in the context of providing sustainable water and sewer service over a 100-year period: (1) with minimal risk of degrading water quality; (2) while reducing the costs of operations, maintenance and repair; and (3) by taking into consideration the variables which can influence pipe performance and service-level expectations. The report also provides relevant data which can assist utility officials with their asset management plans and life cycle cost assessments for different pipe materials.

FOREWORD

This 2017 *Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials* is the first comprehensive environmental review of underground piping systems in North America based on a 100-year life cycle assessment methodology. The overall review includes a study of polyvinyl chloride (PVC) pipe conducted according to life cycle assessment (LCA) standards ISO 14040 series, and subsequent publication of a PVC pipe Environmental Product Declaration (EPD), which complies with ISO 14025 standards and was independently certified by NSF International.

The purpose of this study is to provide a thorough review of the LCA data and to transparently report the findings of the PVC pipe LCA to the water, sanitary sewer and storm drain industries.

The PVC pipe LCA and EPD support the goals and vision of the 2010 U.S. EPA Clean Water and Safe Drinking Water Infrastructure Sustainability Policy and the 2015 U.S. EPA National Water Program on Climate Change for ensuring the long-term sustainability of water infrastructure. This study also contains a comparative review of the corresponding competing pipe products based on publicly available information for the alternative pipe options.

The PVC pipe LCA was subject to critical review from an international panel of experts on life cycle assessment. Based on the results from the LCA on PVC pipe, PVC pipe provides both environmental and economic advantages to solving the water and sewer infrastructure needs for utilities and municipal projects. The LCA and research conducted for this study show that PVC has lower environmental impacts from a life cycle and carbon footprint perspective – lower embodied energy, lower use-phase energy and longer life attributes compared to other pipe materials. It is important for engineers and municipal officials to understand all life cycle aspects of piping materials and utilize current and complete data to assess life cycle environmental impacts for piping infrastructure. This report is presented at a time when aging piping infrastructure, underground corroded pipe materials and water quality issues are at the forefront, highlighting significant challenges with the nation's water and wastewater infrastructure.

Sustainable Solutions Corporation (SSC) is a firm recognized as an expert in life cycle assessment and sustainable product design and analysis. To ensure industry transparency, Uni-Bell PVC Pipe Association commissioned SSC to perform an independent LCA for commonly used PVC pipes for drinking water, sanitary sewer, and storm sewer piping covering the 4" to 60" rigid PVC pipe market sector. The pipe represented in this study is manufactured in the U.S. and Canada using a tin-based stabilizer. Rigid PVC pipe manufactured in North America does not contain phthalates, lead or cadmium. The completion of the North American PVC pipe industry LCA and publication of the PVC pipe EPD provide complete transparency on the life cycle impacts and benefits of PVC pipe.

SUSTAINABLE SOLUTIONS CORPORATION

EXECUTIVE SUMMARY

OVERVIEW

This report on *Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials* includes:

- Thorough examination of a PVC pipe Life Cycle Assessment (LCA) for seven pipe products
- Comparisons to other piping materials regarding performance and durability attributes
- Additional sustainability topics

BACKGROUND – PVC PIPE LIFE CYCLE ASSESSMENT (LCA)

The Uni-Bell PVC Pipe Association (PVCPA) commissioned an LCA on seven PVC pipe products in three market segments (potable water pressure pipe, sanitary sewer gravity pipe and storm drainage gravity pipe). Gravity piping included both solid-wall and profile-wall products. The goals of the LCA were to:

- Determine "cradle-to-grave" energy-related impacts for the seven PVC pipes
- Compare these results to publicly available information on competitive products

The LCA was conducted by Sustainable Solutions Corporation (SSC), a firm specializing in life cycle assessment and sustainable product design and analysis.

LCA TRANSPARENCY

To ensure that the LCA would be transparent:

- Methodology – the LCA was conducted in accordance with the life cycle assessment standards of the International Organization for Standardization (ISO): the ISO 14040 series.
- Peer review – the LCA was critically reviewed by a panel of independent experts in the field of sustainability. The reviewers were: Rita Schenck (Institute for Environmental Research and Education), Nigel Howard (Clarity Environment) and Charlie He (Carollo Engineers).

LCA KEY FINDINGS

The LCA found that PVC has lower life cycle impacts in most categories than alternative materials analyzed. Areas studied included:

- Raw material production and transportation
- Pipe production, transportation and installation
- Pipe use phase (including maintenance, repair and replacement) analyzed and reported separately
- Pipe end-of-life phase

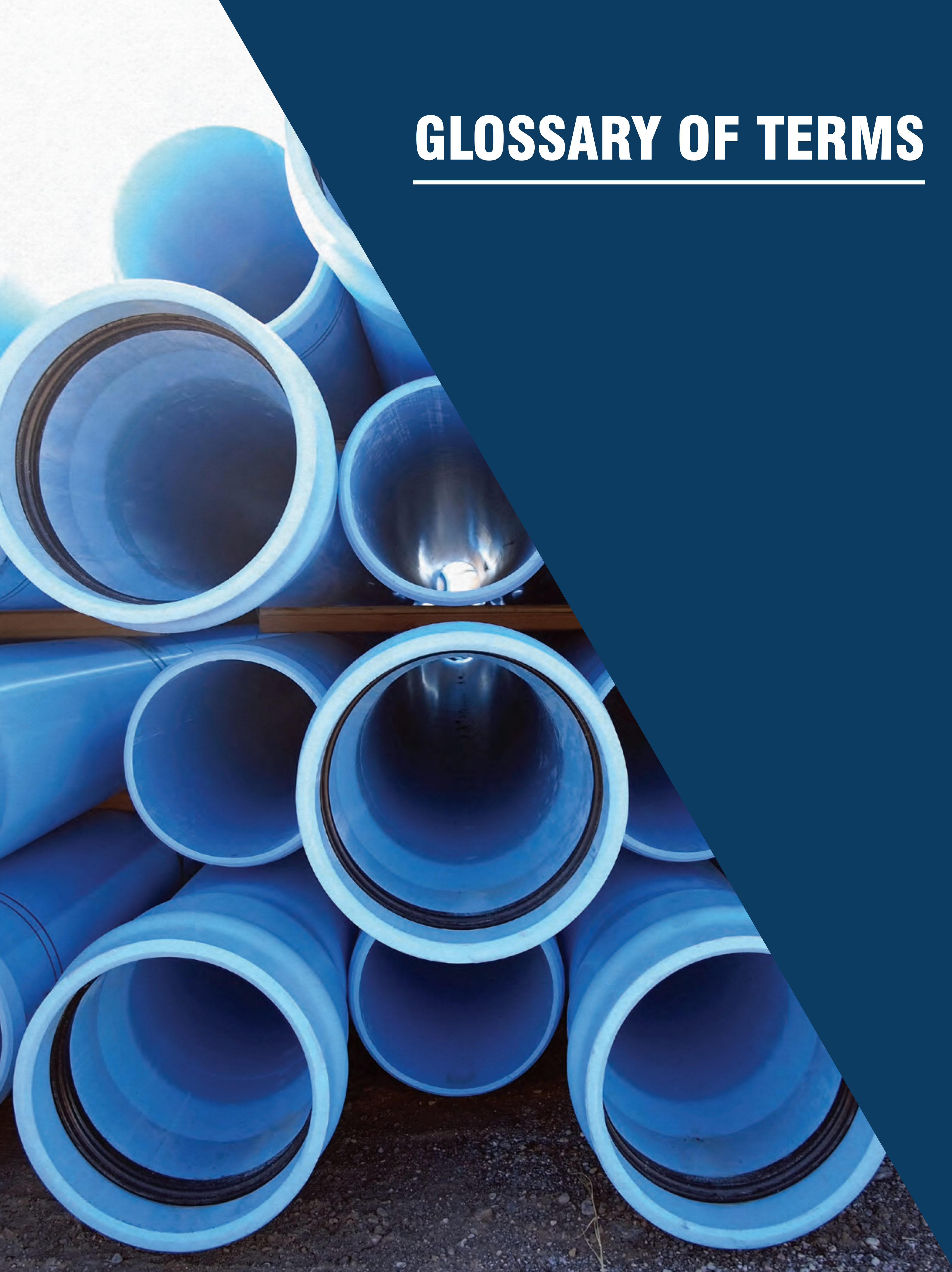
Based on the results of the LCA and literature-based comparisons to competing piping materials, PVC pipe provides a competitive advantage for most piping applications.

ADDITIONAL INFORMATION

This report is intended to explain the LCA, the PVC pipe data generated and the comparisons made to other pipe materials. In addition, this study examines important topics that will help utilities to better assess the performance and suitability of different piping materials, such as:

- Health and safety
- Air and water quality
- Monetary impacts of pipe leakage, internal corrosion and external corrosion

GLOSSARY OF TERMS



ACIDIFICATION POTENTIAL propensity of a chemical to form acidifying H+ ions which degrade the natural environment.

BRITTLENESS having hardness and rigidity but little tensile strength.

CRADLE-TO-GATE partial Life Cycle Assessment of a product from resource extraction ("cradle") to the manufactured product at the factory ("gate"); transportation, installation, use, and disposal phases of the product are omitted.

CRADLE-TO-GRAVE full Life Cycle Assessment of a product from resource extraction ("cradle") through use and disposal phases ("grave").

CRADLE-TO-INSTALLATION partial Life Cycle Assessment of a product from resource extraction ("cradle"), production, transportation to site, and installation; use and disposal phases of the product are omitted.

CUMULATIVE ENERGY DEMAND (CED) the sum of all energy sources drawn directly from the earth, such as natural gas, oil, coal, biomass, or hydropower energy used to produce a product; another term for embodied energy.

DESIGN LIFE period of time during which the piping system is expected by its designers to operate within its specified parameters.

ENVIRONMENTAL PRODUCT DECLARATION (EPD) an independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of products; also known as "Type III Environmental Declarations."

EMBODIED ENERGY the sum of all energy sources drawn directly from the earth, such as natural gas, oil, coal, biomass, or hydropower energy used to produce a product; another term for cumulative energy demand.

EUTROPHICATION POTENTIAL relative measure of the levels of phosphorus and nitrogen compounds released to inland waters.

FAILURE when a pipe does not perform its design function, either structurally or hydraulically (by excessive leakage or reduced flow capacity).

FEEDSTOCK ENERGY potential energy of the raw material contained within the product.

GLOBAL WARMING POTENTIAL relative measure of how much heat a greenhouse gas traps in the atmosphere.

LIFE CYCLE a series of stages through which a product, process, or service passes during its lifetime.

LIFE CYCLE ASSESSMENT (LCA) technique to identify the environmental impacts associated with a product, process, or service over its lifetime; in contrast, the LCC focuses on monetary costs.

LIFE CYCLE COSTING (LCC) method to evaluate the monetary costs involved with a product, process, or service over its lifetime; in contrast, LCA focuses on environmental impacts.

OZONE DEPLETION POTENTIAL relative amount of degradation to the Earth's ozone layer that a chemical compound can cause.

PHYSICAL LIFE time during which the pipe system can be used (not necessarily economically).

PRODUCT CATEGORY RULE (PCR) set of specific requirements and guidelines for developing an Environmental Product Declaration (EPD).

RECURRING EMBODIED ENERGY energy consumed to maintain, repair, restore, refurbish, or replace materials, components, or systems during the pipe's use.

SERVICE LIFE time during which a product, process, or service performs within its specified parameters, i.e., performance based.

PHOTOCHEMICAL OZONE ("SMOG") CREATION POTENTIAL relative contribution of a chemical compound to formation of ground-level ozone ("smog") in an air space.

STRAIN CREEP property of some pipe materials where pipe under a load will continue to slowly deflect over time.

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1.0

KEY FINDINGS OF THE PVC PIPE LCA AND SUSTAINABILITY REVIEW OF PIPE ATTRIBUTES

The *Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials* study combines two major components of sustainability analysis. First, this study documents the cumulative embodied energy of PVC pipe for each of its life cycle stages from cradle-to-grave. This creates a common platform to both discuss and compare aspects of the product's carbon footprint and its environmental impacts in scientific terms.

The second component takes into consideration the elements which can influence pipe performance and service level expectations. While manufacturers suggest a pipe life expectancy based on testing and manufacturing processes, utilities typically select a different service life in the installed environment. Service life is determined by design features, operational conditions, environmental conditions both inside and outside the pipe, and intended use. This study recognizes this fact and develops a performance-based service life for each pipe material. This performance-based service life in the installed environment focuses on the pipe's ability to deliver a sustained level of high water quality in a cost-effective manner. In order to accomplish this, the major pipe materials and environmental and sustainability variables were considered. This includes an in-depth review of the two most common water pipe materials – PVC and ductile iron – as well as the specific attributes of other pipe materials. Sustainability, in terms of consistent water quality and delivery through underground pipe infrastructure, includes the variables of corrosion risk, climate impacts and energy costs. When determining a pipe material's service life, a 100-year system design life is used. When all of these elements are combined, monetized costs can be applied to better compare the results. The following provides highlights of key findings of the overall study.

1.1 PVC Pipe's LCA Meets ISO Standards and the PVC Pipe EPD Provides Transparent Disclosure of the Environmental Impacts

- The PVC pipe LCA provides a comprehensive and transparent life cycle assessment and sustainability review to the North American water and sewer industry.
- The PVC pipe LCA contains the required cradle-to-grave life cycle stages which include:
  - Extraction and processing of raw materials
  - Manufacturing
  - Transportation and distribution
  - Installation, use and maintenance
  - Recycling and final disposal
- By including the impacts throughout the product life cycle, the LCA provides a comprehensive view of the environmental aspects of the product and an accurate picture of the environmental tradeoffs in product selection.
- Pipe life cycle assessments are based on a minimum 100-year design life benchmark due to the very long asset life of pipe infrastructure.
- LCA is a more comprehensive and transparent analysis of the environmental impacts of a product throughout its life and is a much better indicator of environmental performance than single attribute claims like recycled content. Some materials, like metal, require large amounts of energy to recycle; and in the process emit additional toxic emissions compared to non-recycled primary metal production.

- The Institute for Market Transformation to Sustainability's SMaRT Certification for ductile iron and vitrified clay pipes (VCP) does not provide complete transparency for environmental certification.
  - No life cycle environmental information about the products is disclosed, preventing comparability with other pipe materials.
  - Without transparent disclosure of environmental impact data, it is not clear if ductile iron pipe corrosion mitigation treatments such as cement lining and other additives to reduce corrosion are included in the analysis or certification of the pipe.
  - SMaRT Certification requires that dioxins are not produced during manufacturing; however, the manufacturing of ductile iron pipe produces dioxins.

1.2 Pipe Service Life Assumptions Are Critical in Life Cycle Analysis

- When evaluating the sustainability of piping products for life cycle design, it is important to understand and evaluate the life cycle impacts of all materials used in the piping system.
- This PVC pipe LCA study supports the efforts of asset management best practices and concepts that strive to reduce the life cycle costs of underground water, sewer and storm sewer assets while maintaining performance and reliable service levels, protecting water quality and minimizing water main breaks, water loss, infiltration and pavement repairs.
- Pipe manufacturers market various pipe materials with an estimated life. This "estimated" life does not represent the point at which pipe performance may begin to fail to meet intended service levels.
- This study considers the various literature and manufacturers' estimated pipe life, but it also incorporates the practical evidence of industry pipe failure trends and dig-up studies to attribute a real-life pipe performance age to be used in the 100-year evaluation period.
  - As an example, iron pipe has been used in water distribution systems for over 100 years. With up to an 80% water loss, the pipe's practical service life expired decades before. When a pipe is operated beyond its service life, the results are: higher costs for water treatment and pumping, increased customer water bills, more property damage claims, and risk to both water quality for customer and trust for public officials.
- This study provides some examples of 50-, 75- and 100-year service lives to assist utility operators in understanding the modeling assumptions used in this study.
- PVC pipe is assigned a 100-year service life based on 60 years of experience, extensive industry studies, dig-up field samples and historical data demonstrating low failure and water main break rates.
- A study of exhumed PVC sewer pipe estimated its service life between 100 and 300 years.
- PVC water pipe break rates reduce with time, whereas failures in corrosion-prone iron and concrete pipes increase over time, resulting in higher operating and maintenance costs.
- Based on data from existing literature and industry pipe failure trends, ductile iron (DI) and high density polyethylene (HDPE) pipes with thinner walls are not expected to last for 100 years due to internal/external corrosion and oxidation/strain creep, respectively.
  - For instance, thicker-walled cast iron pipe is often cited as having a 75- to 100-year physical life, yet during a good portion of the time it is in use, the pipe's performance may have significantly degraded because of internal and external corrosion and tuberculation, thereby impacting water quality and driving up pumping costs. Therefore, these pipes were operated inefficiently well past their service life.
- DI, like PVC, has been used for water and wastewater infrastructure for about 60 years. For this study, DI pipe is assigned a 50-year service life based on failure data of DI pipes and the fact that new ductile iron pipes have much thinner walls than older iron pipes and lack independent dig-up and pipe material testing studies.
- Metallic pipe systems require extensive condition assessment, corrosion surveys, corrosion protection systems and water quality testing.
- Since there is very little data on the actual longevity and performance of newer HDPE pipe with thinner walls, a 50-year service life was assumed due to the potential for oxidation, strain creep and reduced Safety Factor.

1.3 Consistent Long-Term Water Quality Is a Critical Sustainability Requirement During the Life of the Pipe

- PVC pipe does not corrode from bacteria and biofilm and PVC pipe does not serve as a nutrient source for bacterial growth.
- PVC pipe will not degrade, corrode or leach when exposed to corrosive water, wastewater, sewer gases or disinfectants.
- PVC pipe does not require chemical additives to prevent internal corrosion.
- PVC pipe does not have oxidation-induced premature failures.
- PVC pipe does not contain plasticizers such as DEHP or other phthalates.
- PVC pipe does not contain lead.
- PVC pipe does not contain BPA.
- PVC pipe does not leach vinyl chloride monomer.
- Cast iron pipes have used molten lead as a pipe joint since the late 1800s. Any iron pipe water distribution systems older than 60 years most likely used lead to seal pipe joints. These iron pipes face severe corrosion issues, high water loss and can be a source of lead contamination to drinking water supplies.
- Metallic and concrete pipes are always at risk and subject to internal and external corrosion. They require chemical additives (phosphates) in the drinking water to help reduce pipe wall corrosion. Phosphates increase the chances of bio-growth (such as algae blooms in extreme cases) in drinking water sources, lakes and rivers.
- Corroded iron pipes cause rusty water events with an increase of iron ions. This can cause a water disinfectant to become ineffective, creating an increased risk of contamination.
- The inside area of a ductile iron pipe from the beginning of the bell to the gasket is not coated with lining material so that portion of each joint of installed DI pipe has potable water exposed to a surface not certified to NSF/ANSI 61.
- Studies demonstrate that cement-mortar linings used in ductile iron pipes may fail or degrade between 10 and 30 years due to structural issues and chemical leaching. This leaves potable water exposed to a pipe wall not certified to NSF/ANSI 61.

1.4 Manufacturing Is an Important Life Cycle Stage – Consider Pipe Materials that Utilize an Efficient Manufacturing Process with Minimal Emissions to the Environment

- PVC pipe manufacturing is a very efficient process. It requires low inputs of energy and water, and scrap and rework materials (regrind) can be returned directly into the manufacturing process. This results in virtually no manufacturing waste.
- Only a small amount of energy is required for the extrusion of PVC pipe, so manufacturing is a small contributor to cradle-to-grave impacts.
- The use of closed-loop water conservation technology has significantly reduced water consumption for the manufacturing of PVC pipe, demonstrating the industry's commitment to continuous improvement and efficiency.
- Many pipe material production processes emit dioxins, such as manufacturing of ductile iron pipe, cast iron pipe for plumbing, concrete pipe and PVC resin. U.S. EPA data on dioxin emissions from PVC resin manufacturing show that dioxin levels are extremely low for PVC resin production and are continually being reduced.
- U.S. EPA data show that dioxin emissions released from a ductile iron foundry were almost six times as high as a facility producing PVC resin.
- PVC pipe manufacturing facilities do not emit dioxins.
- Ductile iron pipe manufacturing, which uses recycled metals, can release a host of additional chemicals such as lead, mercury, manganese, zinc, chromium compounds, trimethylamine, xylene, methanol and phenol in the process.
- Greenhouse gas (GHG) emissions are far higher for concrete than for PVC pipe. This clearly illustrates the need to evaluate all life cycle aspects when selecting piping materials. The cement industry is ranked as the third-largest GHG emitter in the world, releasing over 5% of the world's carbon dioxide emissions.
- The production of PVC pipe using virgin material is less energy-intensive than ductile iron pipe production using recycled materials, resulting in fewer environmental impacts for water infrastructure projects.

1.5 Pipe Material Transportation and Installation Have Significant Impact on Life Cycle Cost and Carbon Footprint

- PVC pipe has a lower transportation carbon footprint per installed foot than ductile, concrete and clay pipes.
- PVC pipe is 25% of ductile iron's weight per foot, which means PVC pipe can be transported with a lower carbon footprint compared to equivalent lengths of ductile iron pipe.
- PVC pipe manufacturing facilities are found throughout the United States and Canada which reduces transportation costs and environmental impacts.
- The light weight and durability of PVC pipe can reduce installation costs and environmental impacts as well as greenhouse gas emissions. Lighter-duty equipment and smaller crew sizes can be used with PVC pipe installation compared to other pipe materials.
- PVC pipe eliminates traffic costs, related construction and environmental impacts as well as other lost revenue associated with pipe replacements over a 100-year design life.
- PVC pipes can be installed with a 30% installation time savings over concrete pipes.
- 8-inch ductile iron pipe produces nine times more carbon emissions during manufacturing, transportation and installation than equivalent PVC pipe.
- Pipe materials such as ductile iron, polypropylene, polyethylene, clay and concrete require additional costs and have increased environmental impacts due to the need to replace them at least once over a 100-year design life.

1.6 Energy Consumption for Pumping Causes a Significant Cost and Impact During the Life of the Piping System

- A significant cost during the design life of a pressure pipe system is the energy required to pump the water. Using pipe materials that do not corrode reduces pumping energy and lowers the carbon footprint of the piping system over its design life. This study provides utility engineers with pumping energy costs for different pipe materials over a 100-year period.
- Municipal water treatment and delivery systems require a significant amount of energy to move water. Water and wastewater utilities often represent as much as 40% of a municipality's total energy consumption.
- The energy required to pump water through a pressurized pipe system over the life of the pipe is a significant source of potential environmental impacts.
- More utilities and local governments are implementing strategies to reduce greenhouse gas emissions as part of their long-term goals.
- Iron and concrete pipes are shown to not perform optimally for much of the time they are "in use," since they are often plagued with water main breaks, water loss, water quality issues as well as high operating and maintenance costs due to corrosion.
- Corrosive soils affect 75% of water utilities. The durability and corrosion resistance of a pipe greatly affect life cycle environmental impacts. Ductile iron pipe may last as little as 11-14 years in moderately corrosive soils, requiring numerous replacements over a 100-year period. This increases the embodied environmental energy impacts of iron pipe by up to nine times compared to PVC.
- Reducing interior and exterior ductile iron pipe corrosion requires the addition of other materials such as a cement lining on the interior and a polyethylene encasement on the exterior. Cathodic protection systems are also used in water systems to help prevent corrosion in cast iron and ductile iron pipes. Incorrect or overuse of cathodic protection can corrode ductile iron pipes. The addition of other materials to prevent corrosion increases resource consumption, embodied energy and the carbon footprint of the product. PVC pipes do not require additional materials to address corrosion.

- Corrosion reduces the Hazen-Williams flow coefficient and increases Manning's n due to the roughening of the internal surface of the pipe.
- Corrosion affects pumping efficiency significantly. Keeping pipes in use past their useful service lives results in higher operating and maintenance costs. Internal pipe wall degradation may begin almost immediately after ductile iron and concrete pipes are installed.
- The energy required to pump water through PVC pipe over a 100-year design life remains constant because PVC pipe walls are smooth and do not roughen over time. This generates overall life cycle cost savings and a lower carbon footprint compared to ductile iron and concrete pipes that require more pumping energy over time due to corrosion, leaks and internal degradation.
- For equivalent 8-inch pipes, the primary pumping energy demand is up to 100% greater for HDPE than for PVC, and for DI is up to 54% greater than PVC.
- The capital cost of a new PVC pipe can be nearly 23% less expensive than cleaning and re-lining existing ductile iron pipe.
- PVC pipe has low embodied energy impacts as well as consistently smooth, non-corroding walls which helps utilities and local governments minimize the energy (and thus GHGs) required to operate water systems.

1.7 Water Pumping Efficiency and Sewer Capacity Are Significant Cost Drivers for Municipalities Over Time

- Polyethylene (HDPE) pipe has a much smaller internal diameter than either ductile iron or PVC pipe, significantly impacting its pumping efficiency over time.
- Materials such as ductile iron (DI) and prestressed concrete cylinder pipe (PCCP) may have a larger initial internal diameter and a respectable friction factor when new, but pumping facilities are not designed based on the capacity of new pipes. The deterioration of the mortar-lining and corrosion of DI pipe requires greater pumping energy over the 100-year design life than for PVC.
- Ductile iron and prestressed concrete cylinder pressure pipe may experience a 30% or greater decrease in friction factor over their pipe lives. This means that older DI and PCCP pipelines can require 100% more pumping energy than new pipe.
- 66% of water supply pipes in the U.S. are 8-inches or smaller. Nationally, using PVC instead of ductile iron pipe could save $21 billion in pumping costs over a 100-year system design life. If PVC were used instead of HDPE pipe, $37 billion could be saved (2016 dollars).
- Pump stations for non-PVC pipes must be designed to have larger capacities with larger electrical supply power lines due to increased internal pipe friction over time. These larger capacity pumping facilities require greater embodied energy to construct, operate and maintain over their design life.
- For equivalent 24-inch solid-wall sewer pipes on the same slope, PVC has 24% more capacity than DI pipe, 50% more capacity than clay pipe and 35% more capacity than non-reinforced concrete pipe (NRCP).

1.8 End of Life Management Is an Important Life Cycle Consideration

- PVC pipe can be recycled back into itself up to eight times without a reduction in mechanical properties.
- PVC pipe can be recycled into many products. PVC is an inert material and does not readily degrade, so when PVC pipe does reach the end of its service life it will have minimal environmental impacts if left in the ground.
- Recycled content is only a single attribute and is far from a complete view of life cycle environmental impacts. Iron drain pipe was removed as a green alternative in GreenSpec® because of the "high embodied energy and pollution emissions from coking plants" used to produce the product.
- The largest single source of recycled metal for ductile iron pipe is discarded automobiles. This type of scrap is the most difficult to use because the chemical composition is variable and can include mercury (a volatile air pollutant) and other toxins.
- PVC pipe is recyclable. However, since it is so durable, most of it has yet to enter the recycling stream.

1.9 Worldwide PVC Pipe LCAs Provide Similar Findings

- This study examined multiple publicly available LCA studies conducted around the world, and the results of those studies were consistent with the LCA results for PVC pipe.
- PVC pipe has numerous sustainability attributes. International studies have identified benefits regarding PVC pipe's environmental performance and sustainability over other materials.
- An independent LCA on wastewater piping systems states that ductile iron has the maximum environmental impact and PVC has the minimum environmental impact.
- Studies confirm that PVC pipe is a low initial cost option and provides long-term savings because of its superior pumping efficiency, corrosion resistance and longevity.

2.0

SUSTAINABLE WATER INFRASTRUCTURE

2.1 Background

In 2010, the U.S. Environmental Protection Agency (U.S. EPA) released the Clean Water and Safe Drinking Water Infrastructure Sustainability Policy which describes an overall vision and priority for ensuring the long-term sustainability of water infrastructure.[1] The policy encourages utilities to enhance their existing planning processes to ensure that water infrastructure investments are cost-effective over the design life, are resource efficient, and support community goals. This policy includes analyzing a range of alternatives and other innovative approaches, based on full life cycle analysis, while facing the challenge of repairing and replacing the aging water infrastructure.

In 2015, the EPA released the work plan for the National Water Program on Climate Change. The plan states, "In the face of a changing climate, resilient and adaptable drinking water, wastewater and storm water utilities need to ensure clean and safe water to protect the nation's public health and environment by making smart investment decisions to improve the sustainability of their infrastructure and operations and the communities they serve, while reducing greenhouse gas emissions through greater energy efficiency."[2]

This *Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials* focuses on the comprehensive review of the environmental impacts, benefits and sustainability of PVC pipe for both water and sewer infrastructure. Life cycle assessment (LCA) was chosen as the tool to transparently analyze, quantify and report the potential environmental impacts associated with PVC pipe along each stage in the life cycle. The LCA was peer reviewed and is the basis from which the PVC pipe industry Environmental Product Declaration (EPD) was developed and published through NSF International. The EPD, as validated by NSF International, states, *"PVC pipe and fittings are resistant to chemicals generally found in water and sewer systems, preventing any leaching or releases to ground and surface water... No known chemicals are released internally into the water system. No known toxicity effects occur in the use of the product."*[3]

In addition to the LCA findings, this study comprehensively analyzes the environmental impacts of PVC pipe based on current environmental practices across the piping industry and through comparative analyses. The results demonstrate that PVC pipe has significant environmental and economic attributes for long-lasting water and sewer systems.

2.2 PVC Pipe in North America

PVC was discovered in the 1830s but not introduced as pipe in North America until 1951. Dr. P. Heilmayr, Ph.D., considered by many as one of the founding fathers of modern PVC extrusion, along with PVC historians Dr. J. Summers and A. Whitney, confirm that PVC pipe produced in 1952 for the U.S. Navy used tin stabilizers, which became the industry standard thereafter for both pipe and fittings. Lead as a stabilizer was rejected at the outset by the North American PVC pipe and fittings industry. In 1955 the American Society for Testing and Materials (ASTM) started developing plastic pipe standards. The National Sanitation Foundation (now known as NSF International) began certifying tin-stabilized PVC pipe for drinking water in 1956.

The LCA, as well as this comprehensive review, was commissioned by the Uni-Bell PVC Pipe Association. This industry association represents the 4-inch through 60-inch rigid PVC pipe market in North America. Rigid PVC water and wastewater pipe, manufactured in the U.S. and Canada, does not use or contain phthalates, lead or cadmium. As a result, PVC pipe is recognized as a safe pipe product and beneficial to public health.

While this *Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials* is focused on PVC piping systems, this overall study includes publicly available life cycle information and a comparative review of the corresponding alternative pipe products. Comparability can be a challenge due to a lack of understanding of the materials and processes and the complexities involved in measuring the environmental and energy consumption impacts of pipes with different service lives.

Comparing LCA data is also difficult due to the inherent uncertainty and differences in parameters and data.

2.2.1 NSF/ANSI Standard 61 Certification Verifies No Vinyl Chloride Leaching from PVC Pipe

The EPA has found no instances of vinyl chloride leaching from gasketed PVC pipes manufactured in North America for water transmission and distribution in sizes 4 to 60 inches. According to a 2002 EPA study on permeation and leaching, some ungasketed (solvent cemented) PVC pipes less than 2 inches in diameter manufactured in the U.S. prior to 1977 experienced vinyl chloride leaching. However, no instances of vinyl chloride leaching from any North American PVC pipe manufactured post-1977 have ever been cited.[4]

It is important to understand what vinyl chloride leaching means and how it is regulated. U.S. states require public water supply products in contact with drinking water to be certified to NSF/ANSI 61 Drinking Water System Components - Health Effects. The standard was developed to measure and limit levels of chemical contaminants and impurities that are indirectly imparted to drinking water from products, components and materials used in drinking water systems. This standard sets a limit for the amount of residual vinyl chloride contained in PVC pipe and fittings and ensures all drinking water health and safety requirements are met. However, monitoring for vinyl chloride in water systems can be challenging since studies have shown that vinyl chloride can be a disinfection byproduct from chlorinated treatment systems.[5]

NSF/ANSI 61 requires residual vinyl chloride monomer (RVCM) measured in PVC pipe that is sold and installed in the U.S. to consistently be below 0.2 parts per billion, which is one-tenth of the EPA's allowable level for drinking water. Modern PVC pipe consistently tests "Non-Detect" for vinyl chloride monomer.[6] NSF International led the development of the American national standards for all materials and products that treat or come in contact with drinking water. In 1990, the EPA replaced its own drinking water product advisory program with the NSF International standards.

2.2.2 PVC Pipe Longevity

The application of incorrect pipe characteristics, combined with a lack of PVC pipe system design knowledge, has understated the longevity of PVC pipe service lives. The American Water Works Association's *Buried No Longer* report inaccurately published a PVC pipe service life based on 1960-1970s perceptions.[7] Those perceptions have been disproven through extensive research, studies, and testing of PVC pipe life and performance.[8 9 10 11 12] The actual life expectancy of PVC water and sewer pipe has been found to be in excess of 100 years. Inaccurate pipe performance and life expectancy can overstate water asset management pipe replacement costs.[13] For water utilities with asset management programs, an inaccurate pipe life assumption will distort maintenance strategies, asset management plans and cost projections, resulting in overstated infrastructure replacement funding projections. This drives rate increases and a misalignment of long-term bond financing.

2.3 Redefining Sustainability and Water Quality

This comprehensive sustainability review sets a new benchmark standard with both clarity and transparency for U.S. and Canadian water, wastewater and stormwater pipe manufacturers, utility engineers and elected officials. It also redefines sustainability planning for underground pipe infrastructure.

Sustainability is the ability to maintain a certain level of performance, a resource or an operation for the long term. Sustainability includes an evaluation and focus on economic, environmental and social performance for an organization or a product. By considering the social and environmental features of a product, in addition to its financial and economic aspects, a balance can be met. Sustainability concerns are increasing as more than 50% of U.S. municipal water and wastewater infrastructure is nearing the end of its service life. According to a 2002 congressional study, corrosion costs U.S. water and wastewater systems over $50.7 billion annually. Since January 2000, the financial impact of corrosion on U.S. water and sewer infrastructure is more than $700 billion and climbing.[14] With over 300,000 water main breaks per year over the next ten years, municipal utilities have set the stage for over $532 billion in capital improvements to address deteriorating piping networks, sewer overflows and rising population demands for new water supplies.[15]

2.3.1 Sustainable Pipe Characteristics

A sustainable piping product should have the following characteristics:

- Low initial and operating costs
- Longevity, with a service life of at least 100 years
- Low pumping energy over the lifetime
- Corrosion resistance (no additional materials or costs required)
- Low maintenance
- Low embodied energy
- Minimum waste during manufacturing
- Sustainable manufacturing practices
- Minimal installation costs
- Minimal transportation impacts
- Recyclability at end of life
- Consistent high water quality without chemical additives
- No infiltration or exfiltration

PVC pipe meets the sustainable pipe characteristics listed above, and performance and durability is additionally ensured by the characteristics listed below. The PVC pipe industry has also transparently disclosed its environmental impacts in this report and through NSF International's Certified Environmental Product Declaration.

PVC's sustainability is also attributed to:

- Corrosion and chemical resistance without the need for additional protective coatings, liners or attachments
- Lighter-weight (compared to other materials) and ease of transport
- High strength-to-weight ratio
- Low modulus of elasticity which reduces the magnitude of pressure surges
- Long-term tensile strength over other thermoplastic pipes
- Watertight joints eliminating leaks or infiltration
- Outstanding resistance to external and internal abrasion
- High impact strength even in low temperatures
- Flame resistance
- Superior flow coefficients, which contribute to low costs for operations and maintenance over its design life[16]

Sustainability concerns are increasing as more than 50% of U.S. municipal water and wastewater infrastructure is nearing the end of its service life.

3.0

INTRODUCTION TO LIFE CYCLE ASSESSMENT (LCA)

Life cycle assessment is a tool used to identify the environmental impacts of a product, process or activity over its entire lifespan. LCA studies also quantify and interpret the environmental flows to and from the environment (including emissions to air, water and land, as well as the consumption of energy and other material resources) over the entire life cycle of a product (or process or service).[17]

Typical cradle-to-grave life cycle stages, as shown in Figure 3.1, include:

01 : Extraction and processing of raw materials
02 : Manufacturing
03 : Transportation and distribution
04 : Installation, use and maintenance
05 : Recycling and final disposal

By including the impacts throughout the product life cycle, the LCA provides a comprehensive view of the environmental aspects of the product and an accurate picture of the true environmental tradeoffs in product selection.

The LCA study examined seven PVC piping products from raw materials extraction through final disposal. The use phase was analyzed separately. The piping products are described in Table 3.1.

FIGURE 3.1 : LIFE CYCLE OF PVC PIPE

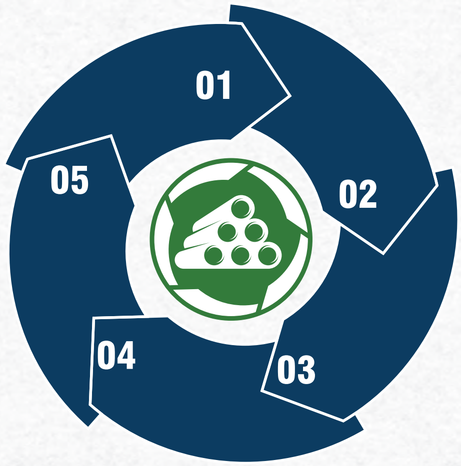


TABLE 3.1 : PVC PIPE PRODUCTS UNDER THE SCOPE OF THE LCA

Application	Standard	Nominal Diameter	Dimension Ratio/ Pipe Stiffness	Average Weight* (lb./ft.)
Potable Water	AWWA C900	8"	DR18	9.1
	AWWA C900	8"	DR25	6.7
	AWWA C905**	24"	DR25	55.9
Storm Water	ASTM F794 AASHTO M304	24" Profile Wall	PS46	19.2
Sanitary Sewer	ASTM F794	8" Profile Wall	PS46	2.5
	ASTM D3034	8" Solid Wall	PS46	4.3
	ASTM F679	24" Solid Wall	PS46	38.7

**Weights based on manufacturers' literature and pipe standards.*
***Effective August 2016 the provisions of the AWWA C905 standard have been replaced and included in the AWWA C900 standard.*

There are various methods globally for categorizing and characterizing the life cycle impact of the flows to and from the environment which can somewhat complicate the comparability of different LCA studies. Other variables in LCA include the system boundary (how far upstream, downstream and side-stream does the analysis go), the functional unit (what is the volume/mass/purpose of the object being assessed), and specific LCA methods such as allocation (how are impacts assigned to the product, by-products, and on what basis). When comparing two LCA studies, these factors are critical in order to interpret the analysis.

The PVC pipe EPD and LCA for the North American PVC pipe industry provides complete transparency on the life cycle impacts and benefits of PVC pipe. The manufacturing and installation of PVC pipe is completed per ASTM International (formerly American Society for Testing and Materials), AWWA (American Water Works Association), AASHTO (American Association of State Highway and Transportation Officials), CSA (Canadian Standards Association) and NSF International standards and certifications. This ensures that PVC pipe products meet the highest standards for quality and safety.

The results of the LCA are presented in this study. Additionally, these results can be found in the PVC pipe industry EPD published through NSF International. An EPD is considered a Type III environmental declaration, which provides LCA data in a standardized way, allowing the reader to compare the environmental performance of products on a life cycle basis. An EPD is based on a Product Category Rule (PCR), which is a set of specific rules, requirements and guidelines for Type III declarations. Before an EPD is published, the PCR and LCA undergo a review by a third party. The EPD is also independently verified and published through a program operator.

3.1 Life Cycle Assessment Objectives

The objectives of the PVC pipe life cycle assessment were to:

- Quantify environmental impact results using the life cycle assessment methodology following standards established by the International Organization for Standardization (ISO) 14040 series
- Investigate each life cycle stage of a PVC pipe for the associated impacts
- Review use of modern technology on PVC pipe production
- Investigate use-phase characteristics and pipe performance
- Investigate installation methodologies

3.2 Key Aspects of the PVC Pipe LCA ISO Standards Methodology

The North American PVC pipe LCA study was conducted according to the life cycle inventory (LCI) and life cycle impact assessment (LCIA) standards as referenced in Section 3.1 established by the International Organization for Standardization (ISO) life cycle assessment standards ISO 14040 series. Key aspects of the study include:

- The results of the LCA study have been published in an environmental product declaration which complies with ISO 14025 standards and was independently verified by NSF International according to the requirements set forth by the Product Category Rule for Piping Systems for Use for Sewage and Storm Water (Under Gravity) addendum for North America, which includes potable water piping systems per version 2 of the addendum.[18]
- The study was peer reviewed by a panel of independent industry and LCA experts to confirm conformance with international LCA standards.
- The PVC pipe LCA offers comprehensive environmental transparency from cradle-to-grave, resulting in the first industry-wide study in the North American pipe industry to provide an ISO 14025 compliant EPD.
- The published EPD complements existing testing and certifications of PVC pipe from NSF International, substantiating no toxic or adverse health effects to drinking water from PVC pipe.[19]

3.3 Independent Expert Review Panel

The LCA analysis for PVC pipe was subject to critical review from an international panel of experts on life cycle assessment. The EPD published used the results from this critically reviewed LCA. The review panel consisted of:

Rita Schenck, Ph.D., LCACP (Chair) : Executive Director
Institute for Environmental Research and Education (IERE)

Global expert and Institute Executive Director, Dr. Rita Schenck brings her knowledge of LCA and the critical review process to this project. As a member of the committee that formed the original ISO 14000 series in the 1990s, she is fully versed in how these standards govern LCA and EPD. Rita Schenck founded the Institute of Environmental Research and Education (IERE) after working for many years as an environmental manager. Rita represented the U.S. in negotiating the ISO standards on LCA. She continues to work as an international expert in LCA, serving on the scientific committee for the LCA of foods conference, CILCA (the Latin American LCA conference), and as a speaker, reviewer and expert witness.

Nigel Howard, C.Chem. : Managing Director
Clarity Environment

Mr. Nigel Howard has an international reputation for his work, especially on LCA and the environmental rating of buildings. In his early career in the U.K. he worked for the Greater London Council's Scientific Branch undertaking product assessments (including plastics) and investigating product failures (including pipework). He also completed the U.K. Environmental Profiles Project (consensus agreed methodology for 24 U.K. building product sectors) and pioneered the LCA-based *Green Guide to Specification*. He chaired the U.K. Government's Department of Environment, Transport and Region's Public Consultation Panel on PVC. He spent 5 years in the U.S. as VP and CTO for the U.S. Green Buildings Council (USGBC) where he contributed to the U.S. Life Cycle Inventory database project and managed the USGBC Technical and Scientific Advisory Committee investigating LCA and health risk implications of PVC products and alternatives.

Charlie He, P.E. : Associate Vice President
Carollo Engineers

Mr. Charlie (Qun) He, an Associate Vice President and Principal Engineer with Carollo, has more than 12 years of experience in water and wastewater treatment, water quality data analysis, computer modeling, advanced analytical work, environmental chemistry, water resources, hydrology, water distribution, and wastewater collection and treatment. Mr. He is a LEED AP and has gained extensive exposure in the field of sustainability. He is an expert on green building design and its impacts on water quality. He has conducted life cycle environmental impact assessment, carbon emission accounting, participated in water and wastewater system optimization studies and energy efficiency analyses.

3.4 Understanding Life Cycle Costing

LCA should not be confused with life cycle costing (LCC) analyses. LCC evaluates the monetary costs involved with a product or service, whereas LCA focuses on the potential environmental impacts of a product, system or service.[20] The total life cycle cost of a project is not limited to the initial capital investment of the project. Additional costs are considered during the life of the project, including costs for operations, maintenance, replacement and end of life. Each aspect is considered for each design proposed for a project. The U.S. EPA, the U.S. Conference of Mayors and the American Water Works Association all recommend life cycle costing for project verification and selection and as part of a repair and replacement planning strategy. A tool has been developed by the Water Environment Research Foundation (WERF) for water utilities to help with a life cycle costing analysis.[21] European studies have found that PVC pipe has the best total cost of ownership for drinking water networks. HDPE pipe is on average 9-12% more expensive, while ductile iron is 19-26% more expensive over a 50-year period compared to PVC pipe.[22] Combining life cycle cost and environmental life cycle assessment analysis provides a strong and compelling enviro-economic decision making process.

3.5 Industry Recommended Functional Units of 100 Feet

The function of the studied PVC pipes is to carry potable water, storm water, or wastewater across a specified distance. This study uses a pipe system length of 100 feet, at specified and common diameters, to disclose the resulting environmental impacts. Gaskets and lubricant are required for the joints of installed integral-belled pipe, and thus are included in this analysis. The distance of 100 feet was determined based on the Product Category Rule addendum published by UL Environment for Environmental Product Declarations.[23] The functional unit is particularly important, as different materials have different densities and wall thicknesses to perform an equivalent function of transporting fluids. Therefore, the 100-foot length of the pipe system is considered the most appropriate unit for the function.

3.6 Industry Coverage

This study used data from 23 facilities of members of the Uni-Bell PVC Pipe Association (see Table 3.2 for participating companies), representing roughly 22% of all PVC pipe manufacturing plants in the United States and Canada (see Figure 3.2). Table 3.3 lists the number of manufacturing facilities that submitted primary data for each of the seven pipe types analyzed.

FIGURE 3.2 : MAP OF PARTICIPATING PVC PIPE FACILITIES FOR LCA

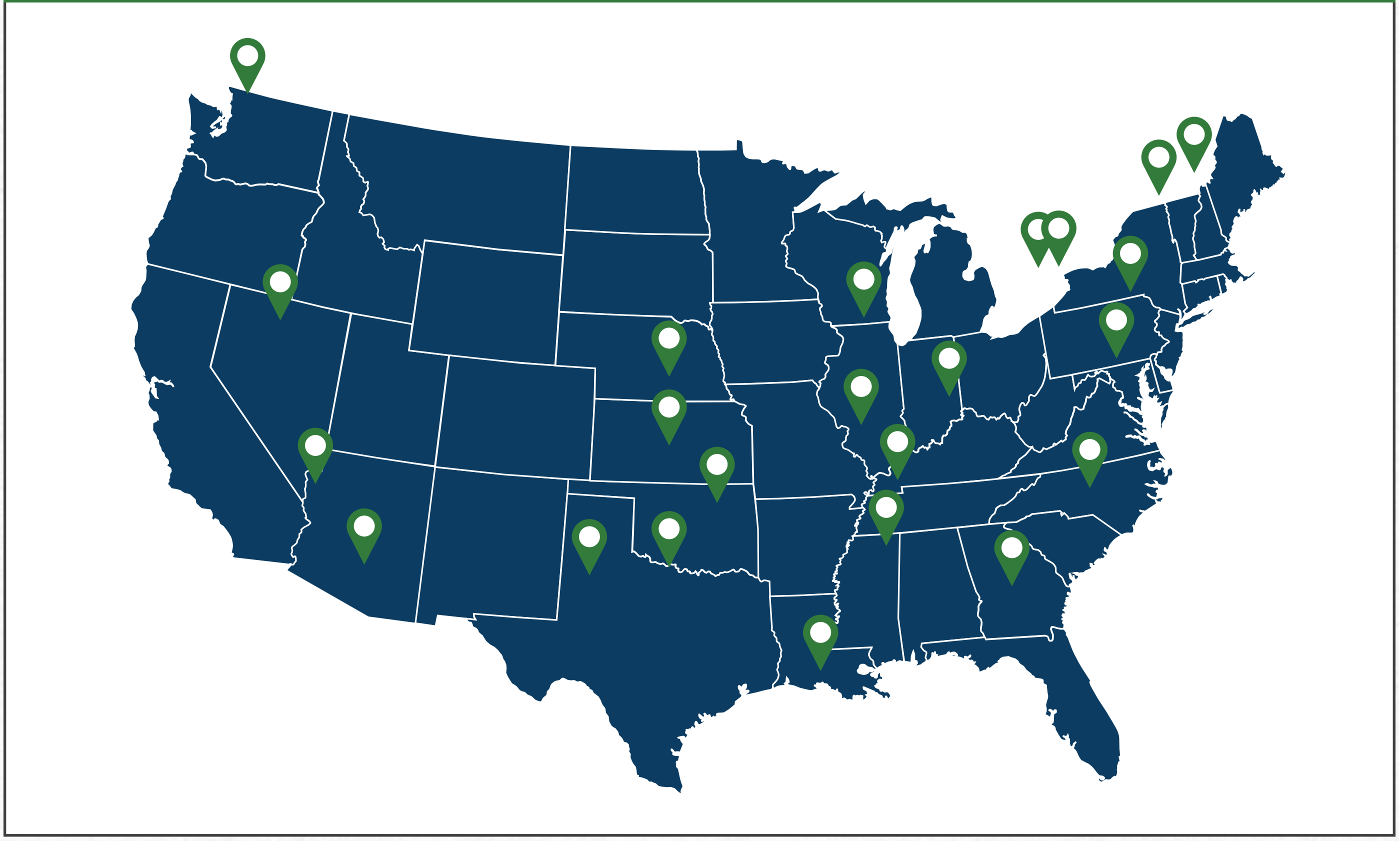


TABLE 3.2 : PARTICIPATING PVC PIPE MANUFACTURERS

Participating PVC Pipe Manufacturers	Number of Facilities Participating
Diamond Plastics Corp.	7
IPEX, Inc.	3
National Pipe & Plastics Corp.	1
North American Pipe Corp.	8
North American Specialty Products	1
PipeLife Jet Stream, Inc.	1
Royal Building Products	2

TABLE 3.3 : PVC PIPE MANUFACTURING FACILITES WHICH SUBMITTED PRIMARY DATA

Standard / Size / Product	Number of Facilities
AWWA C900 / 8" / DR18	21
AWWA C900 / 8" / DR25	3
AWWA C905 / 24" / DR25	11
ASTM F794 / AASHTO M304 / 24" / PS46	3
ASTM F794 / 8" / PS46	2
ASTM D3034 / 8" / PS46	17
ASTM F679 / 24" / PS46	11

4.0

LIFE CYCLE IMPACT ASSESSMENT

The following information describes and illustrates the potential life cycle environmental impacts for PVC pipe and should be used in evaluating all pipe products and systems. The LCA results presented in this section focus on two products: 8-inch PVC DR25 PC165 AWWA C900 pressure pipe and 8-inch PVC PS46 SDR35 ASTM D3034 solid-wall sewer pipe, presented in 100-foot units for a 100-year design life.

Due to cost, the common practice for most utilities is to leave the pipes in the ground at the end of their service life instead of digging them up to recover materials. PVC pipes, due to the long-term life of the material, have not entered into the recycled waste stream. As a result the end of life impacts are considered negligible. Additionally, PVC pipe will remain as an inert material.

The use-phase impacts for pressure water pipe, that is the energy consumed from the friction of the pipe walls as water is being pumped through, is considered separately. Therefore, the results presented in this section include: raw materials extraction and processing, raw material transportation to the pipe manufacturer, pipe manufacturing, packaging, distribution and installation.

4.1 TRACI Environmental Impact Definitions and Results

Cumulative energy demand and greenhouse gas (GHG) emissions and additional environmental impact results were included in the study. The U.S. EPA environmental impact methodology and Tools for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) were used. TRACI impact categories included are ozone depletion, smog, acidification, eutrophication, and GHG emissions or global warming potential (GWP).

The impact category definitions include: [24]

- **Ozone Depletion Potential:** The decline in ozone in the Earth's stratosphere. The depletion of the ozone layer increases the amount of short wave ultraviolet B radiation (UVB) that reaches the Earth's surface. UVB is generally accepted to be a contributing factor to skin cancer, cataracts and decreased crop yields.
- **"Smog" Photochemical Ozone Creation Potential:** Ozone in the troposphere is a constituent of smog that is caused by a reaction between sunlight, nitrogen oxide and volatile organic compounds (VOCs). This is a known cause for respiratory health problems and damage to vegetation.
- **Acidification Potential:** A process whereby pollutants are converted into acidic substances which degrade the natural environment. Common outcomes of this are acidified lakes and rivers, toxic metal leaching, forest damage and destruction of buildings.
- **Eutrophication Potential:** An increase in the levels of nutrients released to the environment. A common outcome of this is high biological productivity that can lead to oxygen depletion, as well as significant impacts on water quality, affecting all forms of aquatic and plant life.
- **Global Warming Potential:** Increase in the Earth's average temperature, mostly through the release of greenhouse gases. Common outcomes are an increase in natural disasters and sea level rise.

The extraction and processing of raw materials is the main driver of ozone depletion and greenhouse gas emissions, for both water and sewer pipe. However, installation is the driver of the remaining categories of smog, acidification and eutrophication. This report investigates these stages in more detail and discusses the initiatives the industry has and is taking to reduce these environmental impacts of PVC pipe.

4.2 Cumulative Energy Demand (Embodied Energy)

Cumulative energy demand (CED) is another term for embodied energy and is an important benchmark used for many products, including pipe. Cumulative energy demand is the sum of all energy sources drawn directly from the earth, such as natural gas, oil, coal, biomass or hydropower energy used to produce a product. Feedstock energy is the potential energy of the material contained within the product. This energy is often referred to as the (high or low) heating value or (net of gross) calorific value. For PVC pipe, the feedstock source is the natural gas used to make ethylene. Fuel energy is the energy released when fuel is burned to manufacture the product. Thus, unlike fuel energy, feedstock energy is not consumed in the process of fabricating the product and does not contribute to the creation of CO_2 or other pollutants. The CED for piping systems is tabulated and summarized in Table 4.1.

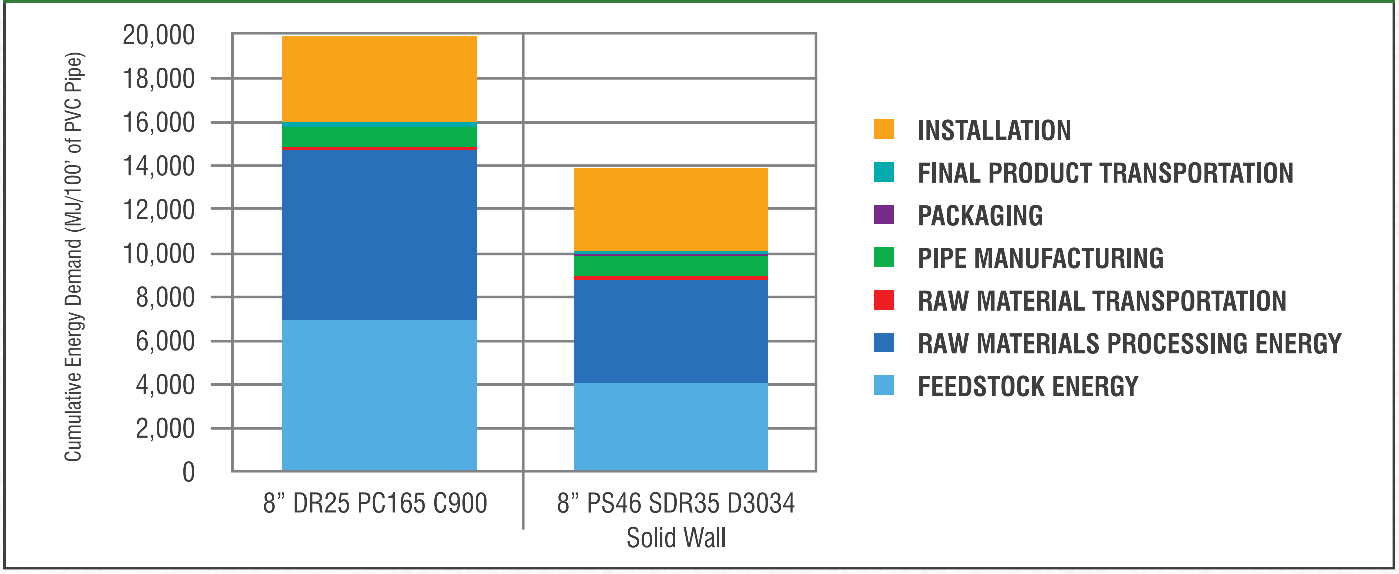
The raw materials processing energy and feedstock energy are the main drivers of cumulative energy demand; however, the installation stage is also a large driver of CED.

Initial embodied energy is influenced by the raw material source, pipe product and the nature of the installation as shown in Figure 4.1. The use phase also consumes energy, but is shown separately in a later section. During the use phase, any recurring embodied energy (energy consumed to maintain, repair, restore, refurbish or replace materials, components or systems during the pipe's use) should be taken into account. LCA studies not extending to the same design life of 100 years for pipe materials will miss the embodied energy and environmental impacts cost of rehabilitation and if necessary, during the specified time, the impacts required for pipe replacement.

TABLE 4.1 : OVERALL LIFE CYCLE CUMULATIVE ENERGY DEMAND FOR PVC PIPE (MJ/100')

Life Cycle Stage	8" DR25 PC165 C900	8" PS46 SDR35 D3034 Solid Wall
Raw Materials	1.5E+04	8.7E+03
Feedstock Energy	7.0E+03	4.1E+03
Raw Material Processing Energy	7.7E+03	4.6E+03
Raw Material Transportation	1.3E+02	1.1E+02
Pipe Manufacturing	9.7E+02	1.2E+03
Packaging	4.4E+01	4.2E+01
Cradle-to-Gate Total	**1.6E+04**	**1.0E+04**
Cradle-to-Gate Minus Feedstock Energy	**8.9E+03**	**5.9E+03**
Final Product Transportation	2.0E+02	1.0E+02
Installation	3.8E+03	3.7E+03
Total	**2.0E+04**	**1.4E+04**
Total, Minus Feedstock Energy	**1.3E+04**	**9.8E+03**

FIGURE 4.1 : OVERALL CRADLE-THRU-INSTALLATION LIFE CYCLE CUMULATIVE ENERGY DEMAND FOR THE VARIOUS LIFE CYCLE STAGES OF PVC PIPE (MJ/100')



4.3 Greenhouse Gas Emissions (Global Warming Potential) and TRACI Environmental Impacts

Carbon dioxide and other GHGs are emitted whenever fossil fuels are burned. GHG emissions can also result from a number of other human activities including the methane released from landfills. These gases can trap heat close to the earth and contribute to global warming. In September 2013, the Intergovernmental Panel on Climate Change (IPCC) concluded that "it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century" with a 95% confidence interval.[25] The GWP of an activity's emission is calculated on the basis of the kilograms of carbon dioxide equivalents (CO_2 eq).

Only a modest amount of energy is required for the extrusion of PVC pipe, so manufacturing is a small contributor towards GHG emissions in the cradle-through-installation analysis. Table 4.2 and Figure 4.2 show the GHG emissions for the various life cycle stages of PVC potable water and sewer pipes. Table 4.3 and Figure 4.3 show the TRACI environmental impacts for 8-inch PVC DR25 PC165 AWWA C900 PVC pressure pipe. See Table 4.4 and Figure 4.4 for the TRACI environmental impacts for 8-inch PVC PS46 SDR35 ASTM D3034 solid-wall sanitary sewer pipe.

TABLE 4.2 : OVERALL CRADLE-THRU-INSTALLATION LIFE CYCLE GHG EMISSIONS IMPACT OF PVC PIPE (KG CO_2 EQ PER 100')

Life Cycle Stage	8" DR25 PC165 C900	8" PS46 SDR35 D3034 Solid Wall
Raw Materials	680	400
Raw Material Transportation	9	8
Pipe Manufacturing	77	73
Packaging	2	2
Final Product Transportation	15	8
Installation	178	250
Total	**960**	**740**

FIGURE 4.2 : OVERALL CRADLE-THRU-INSTALLATION LIFE CYCLE GHG EMISSIONS IMPACT OF PVC PIPE (KG CO_2 EQ PER 100')

For these two piping products, the raw materials stage is the main driver of impacts; however, the installation stage is also a large driver of GHG emissions.

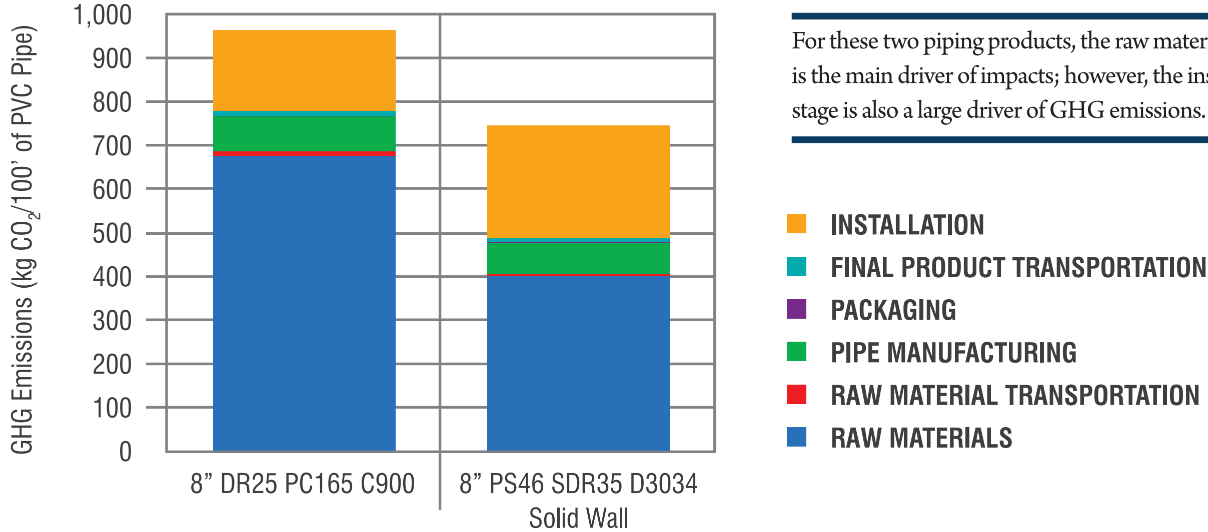


FIGURE 4.3 : ENVIRONMENTAL IMPACTS OF 8" PVC DR25 PC165 C900 PRESSURE PIPE (TRACI IMPACT ASSESSMENT METHODOLOGY)

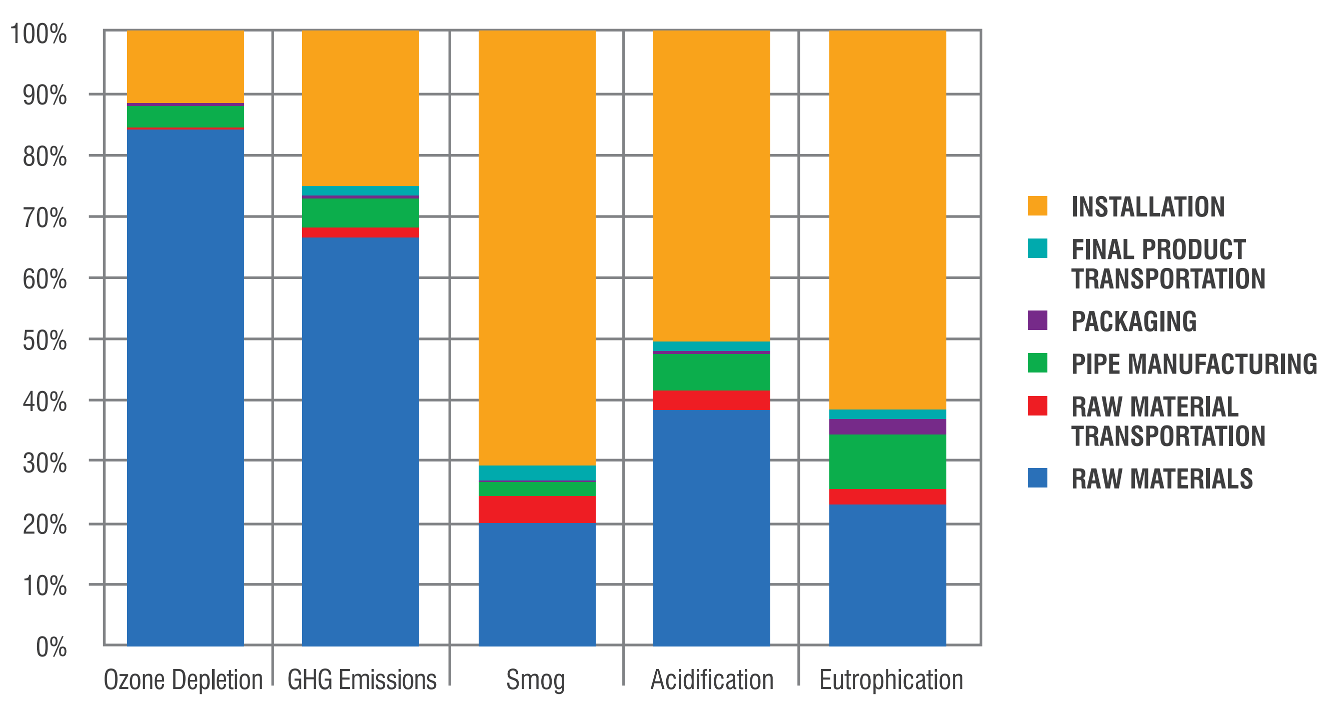


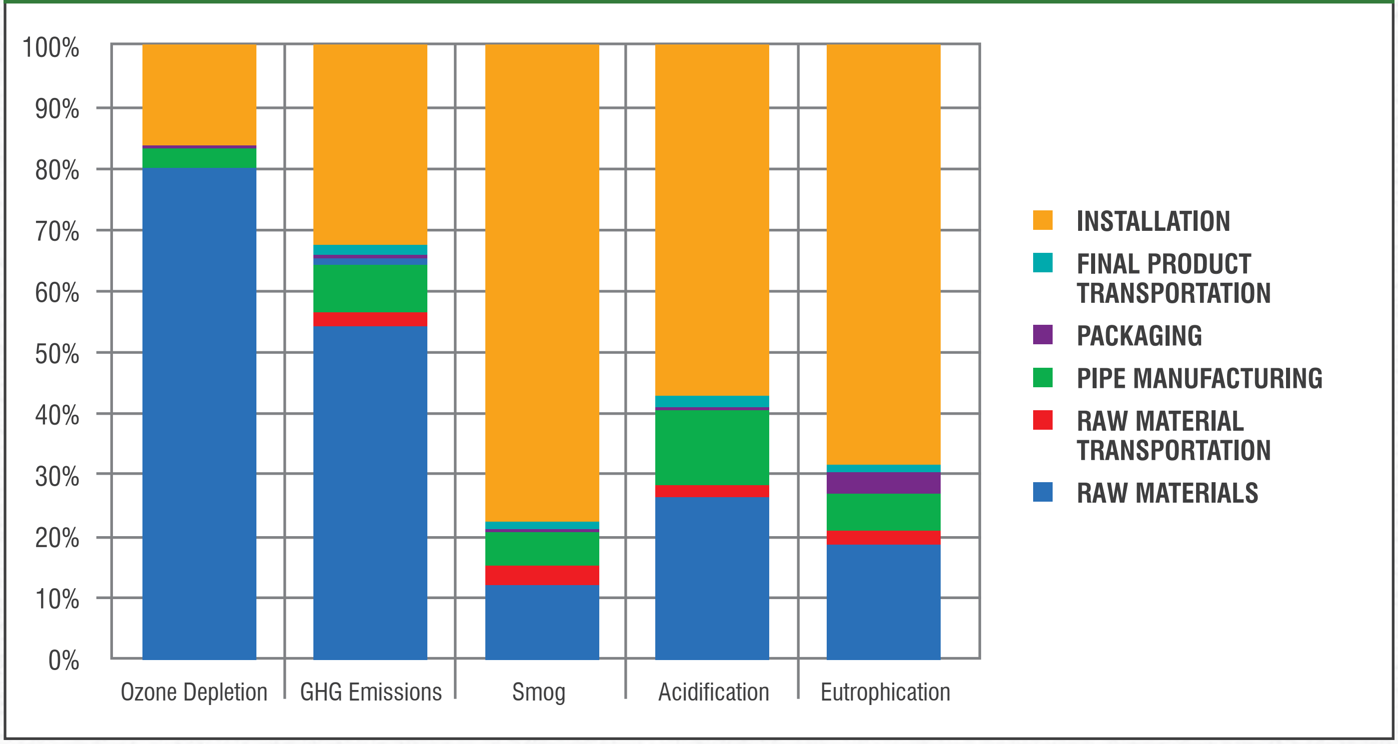
TABLE 4.3 : 8" PVC DR25 PC165 C900 PRESSURE PIPE ENVIRONMENTAL IMPACTS USING THE TRACI IMPACT METHODOLOGY

Impact Category	Unit per 100 ft.	Raw Materials		Manufacturing		Construction		Total
		Raw Material Extraction & Processing	Raw Material Transportation	Manufacturing Process	Packaging	Final Product Transportation	Installation	
Ozone Depletion	kg CFC-11 eq	3.9E-05	3.5E-10	9.6E-07	1.1E-07	5.7E-10	5.2E-06	4.6E-05
GHG Emissions	kg CO_2 eq	6.8E+02	9.3E+00	4.9E+01	1.9E+00	1.5E+01	2.5E+02	1.0E+03
Smog	kg O_3 eq	2.4E+01	5.1E+00	2.9E+00	1.3E-01	2.4E+00	8.5E+01	1.2E+02
Acidification	mol H^+ eq	1.3E+02	9.0E+00	2.0E+01	5.7E-01	5.0E+00	1.7E+02	3.3E+02
Eutrophication	kg N eq	1.4E-01	9.6E-03	5.2E-02	1.5E-02	5.0E-03	3.8E-01	6.0E-01

TABLE 4.4 : 8" PVC PS46 SDR35 D3034 SOLID-WALL SANITARY SEWER PIPE ENVIRONMENTAL IMPACTS USING THE TRACI IMPACT METHODOLOGY

Impact Category	Unit per 100 ft.	Raw Materials		Manufacturing		Construction		Total
		Raw Material Extraction & Processing	Raw Material Transportation	Manufacturing Process	Packaging	Final Product Transportation	Installation	
Ozone Depletion	kg CFC-11 eq	2.4E-05	3.0E-10	5.4E-07	1.0E-07	2.9E-10	5.2E-06	2.9E-05
GHG Emissions	kg CO_2 eq	4.0E+02	7.8E+00	7.3E+01	1.7E+00	7.5E+00	2.5E+02	7.4E+02
Smog	kg O_3 eq	1.5E+01	3.2E+00	4.5E+00	1.3E-01	1.2E+00	8.5E+01	1.1E+02
Acidification	mol H^+ eq	7.7E+01	5.7E+00	3.2E+01	5.4E-01	2.5E+00	1.7E+02	2.8E+02
Eutrophication	kg N eq	1.1E-01	6.0E-03	3.6E-02	1.6E-02	2.5E-03	3.8E-01	5.4E-01

FIGURE 4.4 : 8" PVC PS46 SDR35 D3034 SOLID-WALL SANITARY SEWER PIPE ENVIRONMENTAL IMPACTS (TRACI IMPACT ASSESSMENT METHODOLOGY)



5.0

PIPE CRADLE-TO-GATE

With the adoption of sustainable products and design improvements, the PVC resin industry has taken great strides in reducing emissions and environmental impacts during raw material extraction and processing of materials to produce PVC resin. As evidenced in this report, the raw materials and installation stages are the main drivers of potential environmental impacts for the cradle-through-installation life cycle stages of PVC pipe. This section goes deeper into the progress that has occurred in the upstream production of PVC resin for pipe production, as well as investigates the pipe production process.

5.1 Raw Materials Extraction and Production

The production of PVC resin utilizes vinyl chloride monomer (VCM) which is produced from chlorine and ethylene. Chlorine is manufactured from salt, predominately through diaphragm/membrane cell electrolysis. The use of this technology, compared to the previous mercury cell process, significantly reduces energy consumption, emissions and hazardous waste. In the United States and Canada, over 99% of PVC resin is produced from vinyl chloride monomer that is manufactured using diaphragm/membrane cell electrolysis.[26]

PVC pipe made in the U.S. and Canada does not contain lead.

Concerns regarding vinyl chloride come from airborne emissions during resin production, not from the manufacturing and use of PVC pipe. Airborne emissions during resin production have steadily decreased since 1987. According to the Vinyl Institute, PVC resin production has increased by 76% since 1987, but vinyl chloride emissions published using the U.S. Environmental Protection Agency Toxic Release Inventory (TRI) have declined by 75% in the same time period.[27] Over the years, the reduction of vinyl chloride emissions has caused a reduction of the overall environmental impact of the raw materials stage of the life cycle.

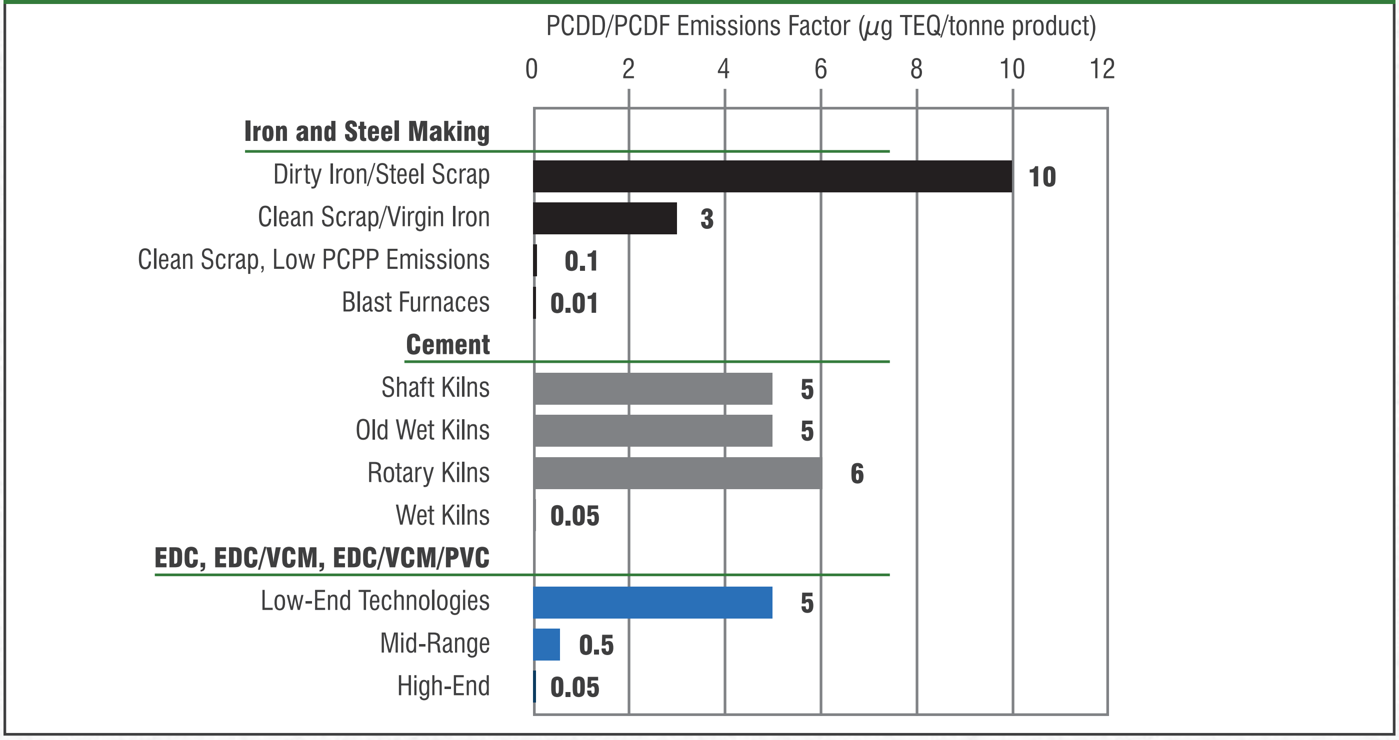
Rigid PVC pipe manufactured in the United States and Canada does not contain plasticizers, such as diethylhexyl phthalate (DEHP), BPA, or other phthalates. PVC pipe made in the U.S. and Canada also does not contain lead. The North American PVC pipe industry uses a tin-based heat stabilizer. Very small quantities of heat stabilizers are used in PVC products to facilitate processing at the high extrusion temperatures required during manufacturing.

5.1.1 Emissions Reporting

A similar downward trend to vinyl chloride emissions has also occurred in dioxin emissions over the years. Dioxin emissions from PVC resin are currently emitted at a rate of less than one part per trillion of PVC resin produced. The EPA Toxic Release Inventory and the Vinyl Institute report showed dioxin emissions have decreased 79% from 2000 to 2011.[28]

There have been concerns by some groups about dioxin emissions from PVC, however, PVC resin production is not the only industry that produces dioxins. The manufacturing processes of ductile iron, cast iron for plumbing, and concrete pipes also produce dioxins. Total PVC resin production for pipes is responsible for less than 0.09% of the total dioxin released into the environment in the United States as compared with diesel trucks (approx. 5%), heavy equipment (approx. 2%) and industrial wood burning (approx. 3%) which are each responsible for the production of more dioxin on an annual basis.[29]

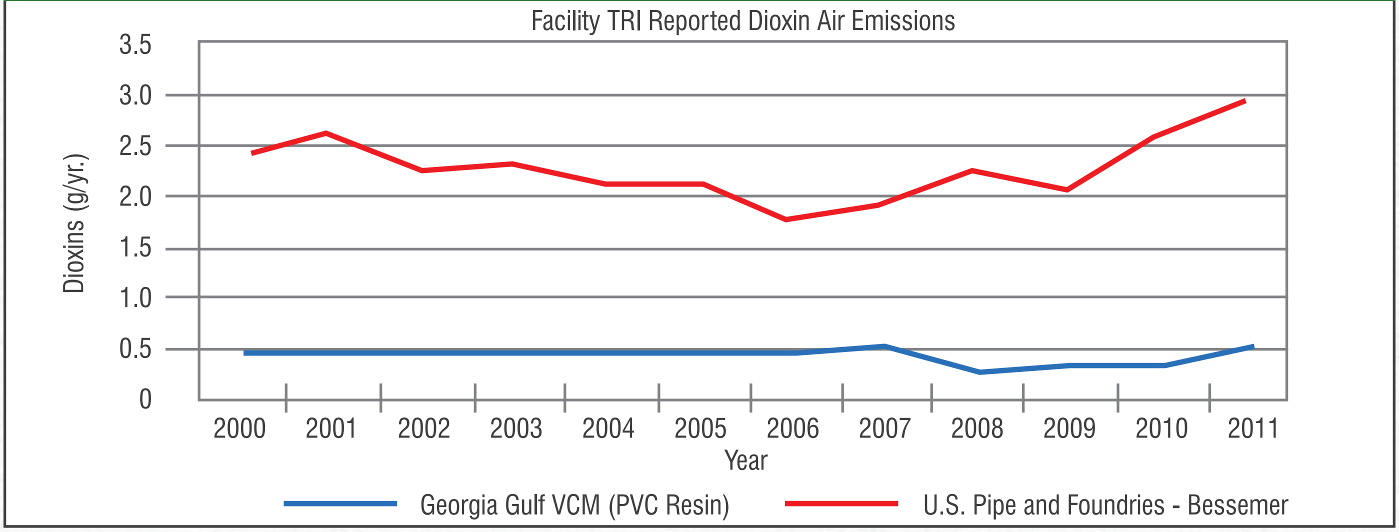
FIGURE 5.1 : UNEP ESTIMATED DIOXIN EMISSIONS FACTORS FROM GIVEN PRODUCTION SOURCES



According to the EPA and the United Nations Environment Programme (UNEP), metal sintering and magnesium production (both used in steel and iron production) and coal-fired electricity production are also major sources of dioxin emissions.[30 31 32] UNEP has standard emissions factors for facilities that are major sources of dioxin emissions.[33] A sample of these factors is shown in Figure 5.1. GreenSpec® has removed cast-iron drain pipe from their listings because of the high embodied energy and pollution emissions from coking plants.[34]

When selecting pipe materials it is important to use life cycle thinking and understand all the impacts of the materials, especially emissions during the manufacturing phase.

FIGURE 5.2 : ANNUAL DIOXIN AIR EMISSIONS FROM A VCM PVC RESIN PLANT AND A DUCTILE IRON PIPE PLANT TO THE U.S. EPA TOXIC RELEASE INVENTORY



Dioxin emissions are tracked by the U.S. EPA through the Toxic Release Inventory (TRI). TRI data are made publicly available. Figure 5.2 is a sampling of the dioxin air emissions reported by a VCM (PVC resin) manufacturer and a ductile iron manufacturer. [35]

As shown in Figure 5.2, the PVC resin facility reports less dioxin emission than the ductile iron plant. This illustration confirms that dioxin emission are also a concern for other piping materials.

The U.S. EPA has developed regulations to control and reduce emissions of toxic air pollutants from iron foundries. The EPA's regulations for iron and steel foundries were issued in April 2004 and the EPA claims the regulations have reduced particulate matter, total metal hazardous air pollutants (HAPs) comprised of cadmium, chromium, lead, manganese and nickel as well as organic HAPs including benzene, dioxin, formaldehyde, methanol, naphthalene and triethylamine. Health effects associated with exposure to these pollutants can include cancer and chronic or acute disorders of the respiratory, reproductive and central nervous systems.[36]

Many ductile iron facilities also report heavy metal emissions such as lead and mercury as well as a host of other toxic chemical emissions. The top five air emissions during ductile iron pipe production are triethylamine, xylene, methanol, phenol and ammonia which are created during the molding process of ductile iron. The slag and dust generated in the production process can also be contaminated with manganese, zinc, lead and chromium compounds.[37 38 39]

Emissions reporting from the iron industry are based on emission factors from the AP-42 Compilation of Air Pollutant Emission Factors: Stationary Point and Area Sources.[40] In the Dioxin Policy Project by the EPA, dioxins were noted in the processing of ores to obtain metals, including the secondary production of the recovery of metals from scrap. The American Foundry Society has noted that due to the poor quality of some stack testing protocols, emissions factors reporting for iron production can be understated. Moreover, it has been shown that secondary iron production using scrap iron emits even more pollutants than primary iron production.

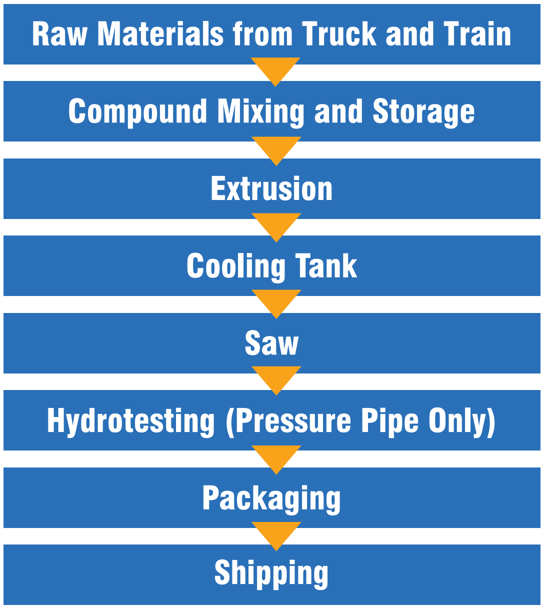
"Metal recycling has the potential for higher levels of dioxin formation because the scrap metal usually contains paints, oils, coatings, plastics and other impurities that may provide both chlorine and carbon. In this case, dioxins can be generated during scrap pretreatment to remove these impurities or during metal refining in the furnaces (smelting). Dioxins may also originate from fuels combusted in the furnaces. In addition, casting operations involve melting and pouring the hot metal into molds. These high-temperature processes can also result in dioxin emissions, depending on the mold material. Dioxin emissions from metal production are poorly characterized, in part because a large fraction of the emissions is fugitive; and thus, they do not come out at a specific smoke stack where they can be measured."[41]

5.2 Pipe Production

PVC pipe manufacturing is a very efficient process. It requires low inputs of energy and water and has the ability to immediately return scrap materials directly into the manufacturing process as regrind. This results in virtually no manufacturing waste.

PVC resin and a few additives are mixed together and then extruded to make pipe of a specified diameter and wall thickness. The extruded pipe is next cooled with water. Cooling water is typically a closed-loop process, which saves millions of gallons of water each year per facility. The increased use of closed-loop water conservation technology demonstrates the PVC pipe industry's commitment to continuous improvement and efficiency. After the cooling process, pipes are cut into standard lengths with an electric saw, and one end of each pipe is put into a belling machine to achieve the bell shape. Every standard length of pipe used in municipal potable water systems is pressure-tested on the production line. The finished pipes are then arranged onto wood frames and strapped into place, loaded onto a truck or train car, and shipped to a distributor or job site. Almost all scrap material is ground and fed back into the extruder, resulting in very little waste. The manufacturing process uses small amounts of electricity and results in almost zero emissions. Figure 5.3 outlines the steps involved in the PVC pipe manufacturing process.

FIGURE 5.3 : PROCESS FLOW DIAGRAM FOR PVC PIPE



Since original widespread introduction of PVC pipe in the 1960s, the PVC pipe industry has continued to innovate while improving manufacturing performance. The PVC pipe LCA used data from 2012 provided by PVC resin manufacturers to account for the most recent technology in use. By using this data, the LCA accurately reflects current PVC pipe production.

Typical manufacturing of ductile iron includes the use of scrap metals, alloying ingredients, sand, and bonding metals. The largest single source of recycled metal for ductile iron pipe is discarded automobiles. This type of scrap is the most difficult to use because the chemical composition is variable and can include mercury (a volatile air pollutant) and other toxins.[42 43] If a cupola furnace is used in the ductile iron production process, coke and limestone are also needed for slagging.[44] Scrap and recycled metal are melted and often injected with alloys such as magnesium.[45] The molten iron is cast using the centrifugal casting method. The ductile iron pipe is cooled, annealed, and then undergoes finishing for its end-use application.[46] Slag and dust are generated as waste. Energy consumption in an iron foundry is high: a ductile iron cupola uses an estimated 13.7 MJ per kilogram of ductile iron and a ductile iron induction process uses 29.2 MJ per kilogram of ductile iron.[47]

Old cast iron or ductile iron pipes are rarely recycled. Should any iron pipe installed prior to the 1950s be recycled, special care should be taken since they likely have lead joints. Lead-joint iron pipe should be removed from the ground and disposed of as a hazardous waste.

5.3 Recycled Materials

Recyclability is one attribute to consider in an environmental analysis of a product. PVC pipe can be recycled back into PVC pipe. The ability to recycle material back into the same or equal value item is called a closed-loop product. Closed-loop recycling is often a way to reduce life cycle impacts and to conserve resources. During production, PVC pipe manufacturers can regrind manufacturing scrap and integrate it back into the product, which significantly reduces waste from the manufacturing operation. All pressure and non-pressure PVC pipes manufactured in North America are permitted to use internal regrind. Using internal regrind prevents significant volumes of waste going to landfills.

Due to PVC pipes being installed in the ground, it is generally economically unfeasible to excavate at the pipe's end of life for the purpose of recycling. Additionally, for all pipe materials, the energy required for excavation would counteract the benefits of recycling. However, PVC pipe excavated for other reasons (e.g. new construction) has a high recyclability potential and can be mechanically recycled back into a pipe product performing the same structural function as one made only from virgin material.

There is ongoing research investigating the closed-loop life cycle of PVC pipe. In fact, a recent study shows that the mechanical properties of PVC pipe using 100% recycled content do not change even after eight cycles of grinding and extruding the same material.[48]

Recycled content, as a single attribute, is not always a relevant indicator of low environmental impacts. As an example, a relatively large amount of energy is required to process the recycled metals to manufacture ductile iron pipe. The production of PVC pipe using virgin material is less energy-intensive than ductile iron pipe production using recycled materials, resulting in fewer environmental impacts for water infrastructure projects.

6.0

PIPE INSTALLATION

As shown in the overall life cycle results, pipe installation is an important phase of potential environmental impacts for PVC pipe. Since installation is highly variable, the following will discuss many aspects and considerations of the installation phase of PVC pipe systems, notwithstanding the ease of installation.

6.1 Pipe Transportation

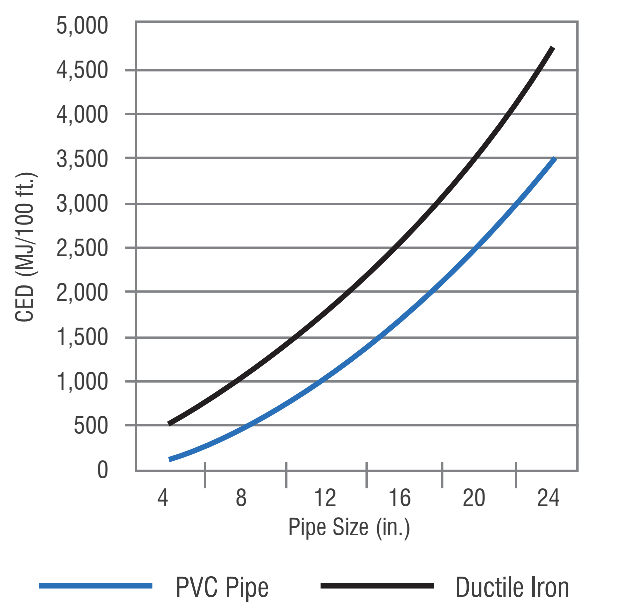
The light weight of PVC pipe contributes to lower transportation environmental impacts (and costs) and enables easier pipe handling once it arrives at the job site (see Figure 6.1).

6.2 Potential Environmental Impacts of Installing Pipe

Installation of PVC pipe is assumed to be similar to installation of pipe made from other materials. Installation requires the excavation and refilling of a trench. The depth and time required to dig and refill a trench vary widely per region, soil type, climate, existing infrastructure, equipment operator, local convention and other factors – therefore, the actual installation time and effort are widely variable. For 8-inch pipe, the trench width should be at least 24 inches. For 24-inch pipe, the trench should be between 36 and 48 inches in width. Typically, an excavator is used to dig the trench and a small loader re-fills the trench.

There are environmental impacts of installing pipe caused by the use of fossil fuels in the excavation equipment that emit greenhouse gases and other emissions. Additionally, mining for bedding materials and the resources required for roadway repairs contribute to environmental impacts at the installation phase. PVC pipe's light weight (25% of ductile iron's weight per foot) and durability can reduce installation impacts and costs since lighter-duty equipment can be used to handle the pipe and a smaller crew size is needed.

FIGURE 6.1 : CUMULATIVE ENERGY DEMAND FOR TRANSPORTATION



By using smaller equipment, greenhouse gas emissions and other environmental impact categories can be reduced.

Since pipe installation time varies widely, a brief sensitivity analysis was performed on the cumulative energy demand of installing an 8-inch water pipe.

Table 6.1 and Figure 6.2 list the values and show graphically the results of a sensitivity analysis of installation time for 100 feet of 8-inch pressure pipe. Reducing time for pipe installation is a key aspect that can be pursued in the overall life cycle design of the product.

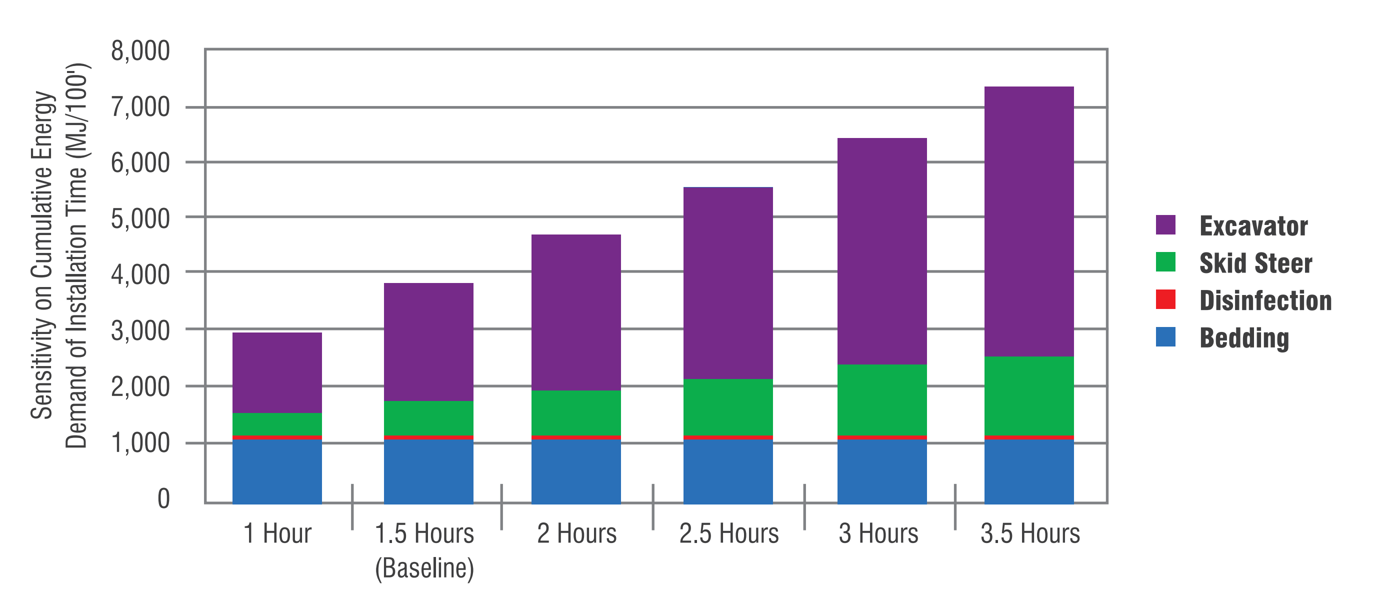
Traffic costs and lost revenue are the two leading costs for installation.[49] Ultimately, to reduce these costs, the frequency of replacing and the need to install new piping infrastructure should be reduced. Therefore, by installing PVC pipe that is highly durable, maintains a low failure rate and is not subject to corrosion, the costs for installation and operation will be reduced when amortized over the course of a 100-year design life. Since PVC pipe does not require replacement during the 100-year design life, it eliminates traffic costs, related construction and environmental impacts as well as other lost revenue associated with pipe replacements. In an open-cut sewer pipe installation, PVC was installed 30% quicker than concrete pipe.[50]

When selecting pipe materials, designers need to consider installation and operational costs and related environmental impacts.

TABLE 6.1 : SENSITIVITY ANALYSIS OF INSTALLATION TIME FOR 100' OF 8" PRESSURE PIPE (CUMULATIVE ENERGY DEMAND METHODOLOGY - MJ PER 100')

	1.5 Hours (Baseline)	2 Hours	2.5 Hours	3 Hours	3.5 Hours
Excavator	2,100	2,800	3,500	4,200	4,900
Skid Steer	530	700	880	1,100	1,200
Disinfection	70	70	70	70	70
Bedding	1,100	1,100	1,100	1,100	1,100
Total	**3,800**	**4,700**	**5,600**	**6,500**	**7,300**

FIGURE 6.2 : SENSITIVITY ANALYSIS OF INSTALLATION TIME FOR 100' OF 8" PRESSURE PIPE (CUMULATIVE ENERGY DEMAND METHODOLOGY - MJ PER 100')



7.0

PVC PIPE USE-PHASE AND PERFORMANCE

Underground water and sewer pipe infrastructure has a very long design life. The costs are significant to build these critical assets and are even greater if the pipe must be replaced during the system's design life. The system design process should focus on a long-term sustainable service life of products.

7.1 Pipe Life with a 100-Year Benchmark

The service life of PVC is expected to exceed 100 years.[51 52 53] Based on over 60 years of field experience and laboratory testing, a 100-year service life is used for PVC in this study. The service life of a product is the time over which the product can be used economically. The new standard or goal of a sustainable service life for underground pipe infrastructure is considered to be 100 years. When determining a pipe's service life, external and internal pipe performance measures and service levels must be taken into account. It is recommended that all future LCAs related to underground pipe materials use this 100-year benchmark.

In order to distribute potable water during its expected service life, water is pressurized and pumped through the pipe to be delivered to a destination at a specified volumetric flow rate. By traveling through the pipe, the water creates friction against the pipe walls causing pressure loss over the pipe distance. This friction requires pumping power to overcome this pressure head loss, adding significant costs to a system. This study analyzed the environmental impacts of this pumping energy. The average U.S. electrical grid was used to model these environmental impacts over a 100-year design life.

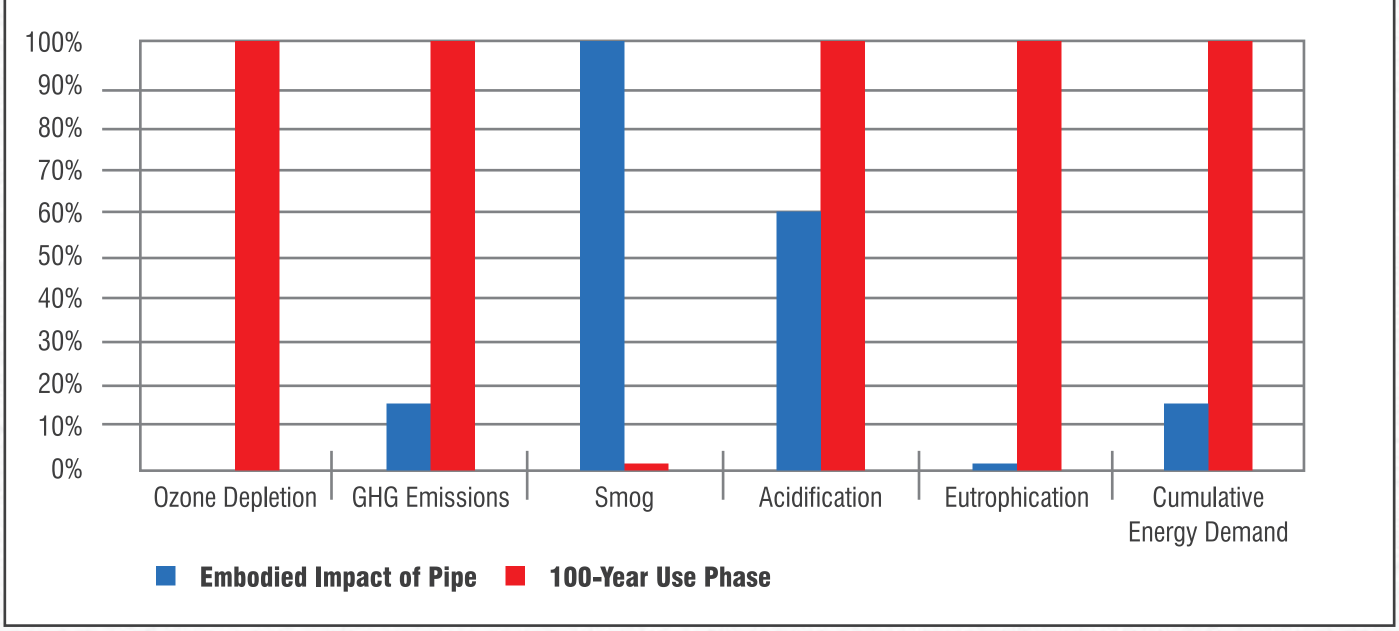
Table 7.1 and Figure 7.1 show the environmental impacts of the cradle-through-installation of 8-inch PVC DR25 pipe compared to the use-phase impacts for 100 years of pumping energy at a constant water flow of 336 gallons per minute (gpm), with a pump energy efficiency of 75%. The flow rate of 336 gpm is equal to a flow velocity of 2 feet per second (fps) in an 8-inch PVC DR25 pipe. Because water demand is based on volumetric flow rate, the same flow rate of 336 gpm was used for comparison of all the 8-inch PVC DR25 pipe alternatives. The same methodology was used for comparison of the 8-inch PVC DR18 and the 24-inch PVC DR25 pipe alternatives.

The use phase of the pipe life cycle dominates as the primary cause of environmental impacts of PVC pipe with the exception of smog which is primarily caused by production of electricity and burning of fuel in the pipe installation equipment and from raw materials extraction and production.

TABLE 7.1 : ENVIRONMENTAL IMPACTS OF THE USE PHASE OF 8" PVC DR25 PC165 C900 PIPE

Impact Category	Unit per 100 ft. of Pipe	Embodied Impact of Pipe	100-Year Use Phase
Ozone Depletion	kg CFC-11 eq	4.6E-05	9.0E+03
GHG Emissions	kg CO_2 eq	1.0E+03	6.1E+03
Smog	kg O_3 eq	1.2E+02	1.1E+00
Acidification	mol H^+ eq	3.3E+02	5.5E+02
Eutrophication	kg N eq	6.0E-01	7.8E+01
Cumulative Energy Demand	MJ	2.0E+04	1.3E+05

FIGURE 7.1 : ENVIRONMENTAL IMPACTS OF THE USE PHASE OF 8" PVC DR25 PC165 C900 PIPE VS. EMBODIED IMPACTS OF THE PIPE



8.0

REVIEW OF ALTERNATIVE PIPE MATERIALS

8.1 Research Methodology and Assumptions

The purpose of this section is to state the assumptions and calculations supporting this study's comparisons of pipe service life, pipe selections, energy calculations, cost calculations and conclusions which were developed to provide real-world insight based on the design, construction and operational experiences of pipe design engineers.

8.2 Factors Impacting Pipe Service Life Analysis

The expected service life of each pipe material type is important in life cycle assessment as well as life cycle costing calculations. A limited study may only use a 50-year design life and have all pipes with the same duration assuming that the pipe would be replaced due to capacity issues. It may not take into consideration sustainable infrastructure decision-making issues encompassing reliability, durability and the need to maintain a constant service or performance level.

Another component of determining a performance-based service life is to assign a value to the various pipe materials for comparison purposes, which includes going beyond manufacturers' marketing claims and reviewing additional data and sources to better understand the expected service level of a pipe.

Actual pipe service lives that are less than 100 years increase embodied energy in the cradle-to-gate phase which includes manufacturing replacement pipe as well as additional energy for transportation and installation.

Due to the comprehensive nature of this study and the requirements of the pipe Product Category Rule, the design life used is 100 years. This was done in order to achieve a new benchmark standard for sustainability analysis and to take into consideration the many risks facing the delivery of potable water and collection of sanitary sewage and stormwater. Pipes can have service lives that range from 15 to over 100 years.[54] Actual pipe service lives that are less than 100 years increase embodied energy in the cradle-to-gate phase which includes manufacturing replacement pipe as well as additional energy for transportation and installation. Pipe replacements during the 100-year design life also greatly increase the overall life cycle costs because of the debt service payments for the design, additional right-of-way, bond sale and construction costs associated with an additional project.

8.3 Pipe Material Selections Used for Comparisons

The following products are considered to be comparable pipe material selections used by utilities when planning for new or replacement piping infrastructure. See Table 8.1 for comparable pressure pipe products and Table 8.2 for comparable gravity pipe products.

TABLE 8.1 : COMPARABLE PRESSURE PIPE PRODUCTS

PVC Size and Product	Comparable Products	Standard
8” PVC DR18 PC235 C900	8” PVC DR18	AWWA C900
	8” DI CL51	AWWA C151
	8” HDPE 4710 DR9	AWWA C906
8” PVC DR25 PC165 C900	8” PVC DR25	AWWA C900
	8” DI CL51	AWWA C151
	8” HDPE 4710 DR13.5	AWWA C906
24” PVC DR25 PC165 C905	24” PVC DR25	AWWA C905
	24” DI CL51	AWWA C151
	24” HDPE 4710 DR13.5	AWWA C906
	24” PCCP PC200	AWWA C301

Note: All ductile iron pressure pipes in this study are cement-lined per AWWA C104.

As sustainability management is integrated with managing assets to the lowest financial and environmental costs, then a new performance-based service life can be determined.

TABLE 8.2 : COMPARABLE GRAVITY PIPE PRODUCTS

PVC Size and Product	Comparable Products	Standard
8” PVC PS46 F794 Profile Wall	8” PVC PS46	ASTM F794
	8” DI	ASTM A746
24” PVC PS46 F794 Profile Wall	24” PVC PS46	ASTM F794
	24” PP PS46	ASTM F2736
	24” HDPE PS34	ASTM F2306
	21” PVC PS46	ASTM F794
8” PVC PS46 SDR35 D3034 Solid Wall	8” PVC PS46	ASTM D3034
	8” DI	ASTM A746
	8” VCP	ASTM C700
24” PVC PS46 F679 Solid Wall	24” PVC PS46	ASTM F679
	24” DI	ASTM A746
	24” VCP	ASTM C700
	24” NRCP	ASTM C14
	21” PVC PS46	ASTM F679

Note: All ductile iron sewer pipes in this study are double cement-lined per AWWA C104.

8.4 Service Life of Underground Pipes

Determining infrastructure service life is an important process in developing the maintenance management strategies applied to various assets. Service life determination is based on many factors including condition assessment, decay curves, computerized maintenance management systems (CMMS), GIS-centric work histories or hot spots, validated service levels and industry standards, as well as regional and local experience. Service life is an important consideration in calculating life cycle costs in order to demonstrate the ability to manage assets at the lowest life cycle cost. These costs are included in projected repair and replacement strategies and in funding projections as published in an asset management plan.

Historically, piping system design focused on the capacity of the pipe. A pipe would fail based on the "end of capacity life" or at a point of failure of use "end of physical life." An "end of service life" could be related to water leakage or pressure loss or some other evaluated compliance requirement or defined community service level. Early infrastructure asset management efforts were only focused on extending the service.[55] Financial reporting requirements focused only on an "end of financial life" when the asset is fully depreciated. Asset management practices and technology have increased the utilities' ability to better analyze the relationships between service levels, performance measures and the financial costs of managing assets.[56] Thus, "end of economic life" is when an asset ceases to be the lowest cost alternative to satisfy a specified performance or service level.

As sustainability management is integrated with managing assets to the lowest financial and environmental costs, then a new service life can be determined.

Water, wastewater and drainage engineers typically think of the term "performance-based" only applying to contracting, defined as "a results-oriented contracting method that focuses on the outputs, quality or outcomes…to the achievement of specific, measurable performance standards and requirements."[57] The traditional design approach has been very prescriptive in nature, which has resulted in a lack of insight into the consequences; this means that, at the design stage, there is a lack of understanding of in-service durability performance. A performance-based specification approach would require a careful and realistic assessment of the interrelation between design and durability along with future maintenance, repair and operational costs. The conceptual basis of a performance-based approach is to ensure that the required performance is maintained throughout the intended life along with the optimization of the incurred lifetime costs.[58] In the case of underground water pipe infrastructure and for the purpose of determining a service life for this study, the user defined performance requirements of water pipe assets include:

- Provide water service delivery over a 100-year period with minimal risk of degrading the water quality.
- Provide a consistent high level of water quality service delivery in a cost-effective manner without significantly raising the cost of operations, maintenance and repair over a 100-year period.

A key element of this service life focuses on the energy requirement and pumping energy costs associated with the operations of a pipe system.

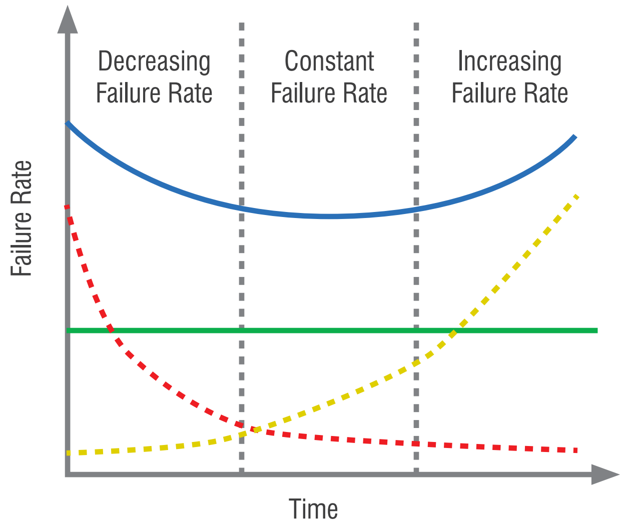
The overall total cost of ownership includes the initial capital outlay, maintenance costs and the operational costs of a pipe system. Life cycle cost analysis is applied to compare various pipe selection alternatives. In this type of comparable analysis, the embodied energy and other social and environmental impacts can be evaluated while considering public health and financial risks. As this process matures, performance-based pipe selection can be added to the procurement process to ensure that the water ratepayers can benefit from the user defined requirements.

One consideration in determining pipe service life includes the application of the bathtub theory. The bathtub theory is a function of the probability of failure with time and can take into consideration pipe failure data and field samples.[59] This theory, illustrated in Figure 8.1, recognizes that the water pipe may not be in perfect condition when placed and installed in the ground. Some defects and damage may have taken place during manufacturing, transportation and installation which ultimately lowers the overall quality of the product. Some causes of failure are improper design, poor quality control and manufacturing defects. The construction process may also have an effect on pipe failure; examples include failure due to transit, human error and poor workmanship. Careless or improper construction or installation processes may also lower the performance of the pipe. Throughout years of service, operation and maintenance will affect pipe performance through various failure causes such as mechanical, thermal, chemical, biological, external interferences, natural catastrophes, and inappropriate services and maintenance.[60]

Best practices to extend the service life of underground assets include: correcting distribution system design flaws; reducing human error; and using pressure reducing valves, automated systems, and improved training. These system improvements are important considerations for all piping materials.

Service life is an important consideration in calculating life cycle costs in order to demonstrate the ability to manage assets at the lowest life cycle cost.

FIGURE 8.1 : APPLYING THE "BATHTUB" THEORY TO DETERMINING PIPE SERVICE LIFE



Early "Infant Mortality" Failure
Observed Failure Rate
Constant (Random) Failures
Wear Out Failures

One consideration in determining pipe service life includes the application of the bathtub theory. The bathtub theory is a function of the probability of failure with time and can take into consideration pipe failure data and field samples.

Another component of determining a service life is to assign a value to the various pipe materials for comparison purposes, which includes going beyond manufacturers' marketing claims and reviewing additional sources to better understand the expected service level of a pipe. The combination of performance and service delivery are critical in order to assign a value.[61] This takes into consideration when water main breaks begin to occur, water quality issues arise, or pipe degradation (internal and/or external) is a concern and needing attention. In these circumstances the pipe has effectively met its service life as a low cost managed asset and now its total life cycle cost or total cost of ownership will begin to drastically increase.

8.4.1 Service Life for Each Pipe Material

For the purposes of this 100-year modeling and evaluation of sustainable underground water infrastructure, the following pipe service lives have been assigned as shown in Table 8.3.

General Consideration for Assigning Pipe Lives:

- Historical failure/replacement data
- Average soil conditions in the U.S.
- Pipe thickness
- Corrosion rates
- Brittleness
- Water loss and infiltration

TABLE 8.3 : SERVICE LIFE ASSUMPTIONS OF SELECTED PIPES FOR COMPARISON

Pipe Lives Before Replacement for LCA		
Pipe Material	Standard	Service Life (Years)
PVC	AWWA C900	100
PVC	AWWA C905	100
PVC	ASTM D3034	100
PVC	ASTM F679	100
PVC	ASTM F794	100
DI	AWWA C151	50
DI	AWWA A746	50
HDPE	AWWA C906	50
HDPE	ASTM F2306	50
PCCP	AWWA C301	75
PP	ASTM F2736	50
VCP	ASTM C700	50
NRCP	ASTM C14	50

Refer to Section 9 for detailed discussion on assigned service lives.

8.4.2 PVC Pipe 100-Year Service Life

PVC has a service life of over 100 years for water, wastewater, and storm water applications, because it is not subject to corrosion. PVC has over 60 years of successful in-service pipe performance. The May 2014 *PVC Pipe Longevity Report: Affordability and the 100+ Year Benchmark Standard* by Dr. S. Folkman examined the lives of PVC water and wastewater piping.[62] The conclusions of this study were that the combination of research, field dig-ups, testing and analysis confirmed a 100+ year benchmark standard for PVC pipes. In Europe, dig ups and testing after 70 years of use confirm that PVC pipe will last in excess of 170 years.[63] According to the article, *Predicting the Residual Life of PVC Sewer Pipes* by A.J. Whittle and J. Tennakoon, a study based on the testing of exhumed PVC sewer pipe, the additional life expectancy for the PVC sewer pipe studied is a minimum of about 100 years and a "best value" of almost 300 years.[64] PVC sewer pipes that were also dug up and tested in Europe had similar results.[65] *An Examination of Innovative Methods Used in the Inspection of Wastewater Systems*, published by the Water Environment and Reuse Foundation (WERF) stated, "If a utility has primarily PVC pipes, it would be pointless to invest in an inspection system designed to measure the amount of wall loss due to corrosion."[66] Likewise, when a metallic pipe's complete unit cost is used, the total price tag would increase for both the capital cost and the operations and maintenance expenditures when corrosion control program costs are added. Pipe selection will drive the cost either up or down for a local community.[67]

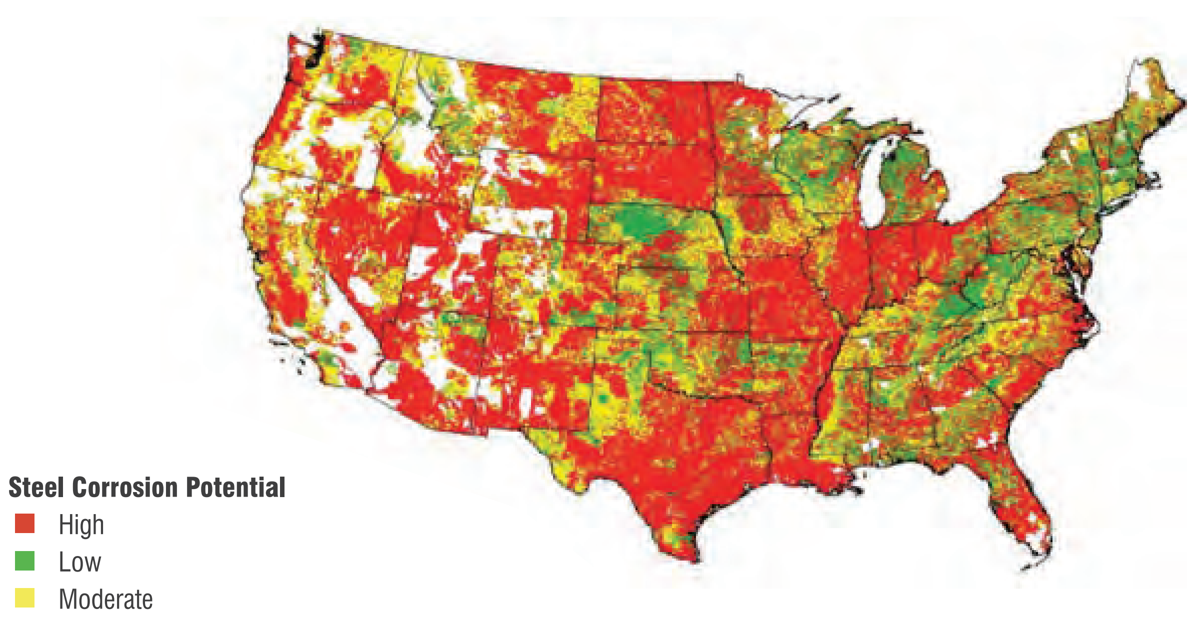
8.5 Factors Influencing Service Lives of Water Pipes

There are many factors which influence the actual life of underground water infrastructure. Corrosion, in its various forms, is the leading cause of pipe failure in North America, creating a host of corrosion-related issues which impact service delivery and water quality. Other factors include oxidation induced failures caused by disinfection products used in water systems, excessive infiltration or exfiltration due to corrosion or leaking joints, and loss of flow capacity or greater pumping costs due to increased friction in the pipe or buildup of biosolids/tuberculation inside the pipe.

8.5.1 External Corrosion

Corrosion is the major risk and cause of water main breaks and pipe failures in the U.S. and needs to be considered when designing piping systems. The risk of various types of corrosion will always exist (climate change will only exacerbate this problem) and will always need to be monitored. Iron pipe corrosion will adversely impact water quality.[68] According to *Water Main Break Rates in the USA and Canada: A Comprehensive Study* by Dr. S. Folkman, 75% of all utilities have corrosive soil conditions.[69] The map in Figure 8.2 shows the potential for corrosion in the United States.

FIGURE 8.2 : U.S. CORROSIVE SOILS MAP (CONUS POTENTIAL FOR STEEL CORROSION)



Leakage from water infrastructure results in approximately 2.2 trillion gallons of water loss each year.[70] Most of this leakage is due to corroded and broken pipes. Corrosion and leakage increase pumping energy, can cause bacteria and other organisms to grow, and may result in the leaching of metals into the water supply. Studies estimate that PVC pipe has a life expectancy of over 100 years.[71] One reason for this longevity is that PVC pipe is resistant to both internal and external corrosion. In high pH soils, metal pipes are likely to corrode and fail well before the manufacturers' published life expectancy.

Ductile iron is most likely to fail between a 21 and 40-year period. Pits or holes from corrosion were identified as the largest cause of ductile iron pipe material failures. The service life of ductile iron pipe corresponds to impacts of low to moderate soil corrosion on unprotected pipe. Likewise, concrete pressure pipe also fails most commonly between 21 to 40 years, indicating that corrosive soils influence the service life of concrete as well. According to B. Cohen in *Fixing America's Crumbling Underground Water Infrastructure*, the early thicker-walled ductile iron pipes were expected to last 50-75 years.[72] However, a study of a utility in Wisconsin shows that 79% of DI pipes installed between 1953 and 1982 lasted only 25-50 years.[73] The National Research Council (NRC) was requested by the U.S. Bureau of Reclamation to evaluate the reliability of ductile iron pipe with polyethylene encasement and cathodic protection for a 50-year service life. The NRC concluded: "the committee does not find that the studies of DIPRA confirm that DI pipe with PE can meet the expected reliability of over 50 years of service life." [74]

In soils where there is a potential for corrosion, metal pipes such as ductile iron will need frequent replacement. According to a 2011 study by the AWWA Water Research Foundation, ductile iron pipes with the thinnest walls (representing the majority of metallic pipes sold) in moderately corrosive soils have a life expectancy of only 11 to 14 years.[75] If the same corrosion-prone pipe materials are used in high-risk soil and locations, and the pipe is replaced every 15 years over the course of 100 years, then the pipe would need to be replaced up to 7 times. This increases the embodied environmental impacts and the costs of the system commensurably by up to 7 times.

Corrosion, in its various forms, is the leading cause of pipe failure in North America, creating a host of corrosion-related issues which impact service delivery and water quality.

8.5.2 Internal Corrosion

Corrosion from Wastewater Sources

Corrosion not only occurs from the external surroundings of a pipe, but may also occur internally from sewage, wastewater or other fluids or gases inside the pipe. For example, wastewater and sewage "…contain significant levels of biological and organic materials, including many bacteria that remain active in the waste streams. From a corrosion point of view, the most important types of bacteria are those that metabolize sulfur compounds because this microbiological activity can produce acidic chemicals that are corrosive to concrete and steel or iron. Some bacteria also oxidize ferrous ions to ferric ions, which makes the local environment more corrosive to carbon steel." [76]

The most common way these microorganisms affect wastewater streams is by growing colonies, creating a local environment that is acidic enough to dissolve concrete and to corrode steel and ductile iron. Another important commercial problem, due to the action of *Thiobacillus ferrooxidans* in particular, is the formation of highly insoluble, ferric oxyhydroxide mounds that can clog steel or iron pipes. Gaseous hydrogen sulfide (H_2S), the familiar "rotten egg" odor, is also formed, which acidifies surface moisture in headspaces of enclosed or covered structures, causing acidic corrosion of concrete or metal surfaces. H_2S and oxygen combine to form polythionic acids – a weak form of sulfuric acid.

The wastewater industry takes corrosion and public health issues very seriously. An independent industry survey on wastewater collection pipe materials that provide the highest public benefits once in service was conducted in 2010 and 2012 and published in the *Trenchless Technologies Pipe Materials Guide* (the *Guide*).[77] The wastewater industry responded that longevity and service life were the most important factors in choosing pipe. Wastewater engineers consider pipe to not only be a transport medium but also an important public health barrier to possible contamination. Due to internal corrosive and caustic conditions, the *Guide* ranked PVC as the most commonly used pipe which achieves the longest service life over all other pipe materials including brick, clay, concrete, fiberglass, polymer concrete, polyethylene, cast iron, ductile iron and steel. PVC has been around for decades, and its non-corrosive material characteristics have made it widely accepted in the wastewater industry.[78]

Corrosion from Source Water

Excessively high and low pH can be detrimental to water systems. High pH causes water pipes and water-using appliances to become encrusted with deposits, which reduce the effectiveness of the chlorine disinfection, thereby causing the need for additional chlorine. Low-pH water will corrode or dissolve metals and other substances.[79] In general, water with a pH < 7 is considered acidic and a pH > 7 is considered basic. The EPA recommends that public water systems maintain pH levels between 6.5 and 8.5. "The negative chloride ions are corrosive, so when the high-chloride water is pumped through lead pipes (or iron and copper pipes joined together with lead solder), lead leaches into the water."[80] Pipe networks require constant water quality testing due to changes in temperature, degradation of cementitious and metal components in piping materials, pipe breaks, corrosion-control chemicals and disinfectant additives.

Leakage from water infrastructure results in approximately 2.2 trillion gallons of water loss each year. Most of this leakage is due to corroded and broken pipes.

8.6 Corrosion Risk and Water Quality Issues

As underground water pipe infrastructure is extended beyond practical service life expectations, utilities must assess known hazards including lead in iron pipe joints, water main breaks, boil water notices, drinking water contamination, corrosion treatment errors, rusty water that create risks to public health, private property damage, increased maintenance costs, water loss, increased water bills and politically difficult, public mistrust issues. These are known factors and holding on to traditional business practices will continue to trouble the water industry by offering the same results where corrosion is a risk to the pipe material and quality of the drinking water. Climate change and other trends will continue to affect corrosion-prone pipe materials. The following findings and evidence presented in this study can help utility managers engage in more informative discussions to improve expectations with customers and public officials as it relates to their sustainable infrastructure and water quality planning and policy development.

8.6.1 Corrosion of Cast Iron Pipes with Lead Joints: A Water Quality and Public Health Issue

Historically, various kinds of pipe materials and joints have been used in the U.S. water industry. "Materials used to make and join distribution system piping have improved."[81] As seen in Figure 8.3, lead was the predominant pipe joint material for most types of cast iron piping and presents a significant water quality risk today. Lead was used as a joint material for cast iron pipe until the 1980s. Corrosion in metallic drinking water pipe systems will continually be a risk factor to public health. According to a report by the U.S. Conference of Mayors, lead-jointed iron water main pipes are one of the possible sources of lead contamination in the potable water supply of Flint, Michigan.[82]

Additional discussions on iron pipe corrosion and water quality issues can be found in the Appendix.

8.7 Internal Corrosion and Energy Loss

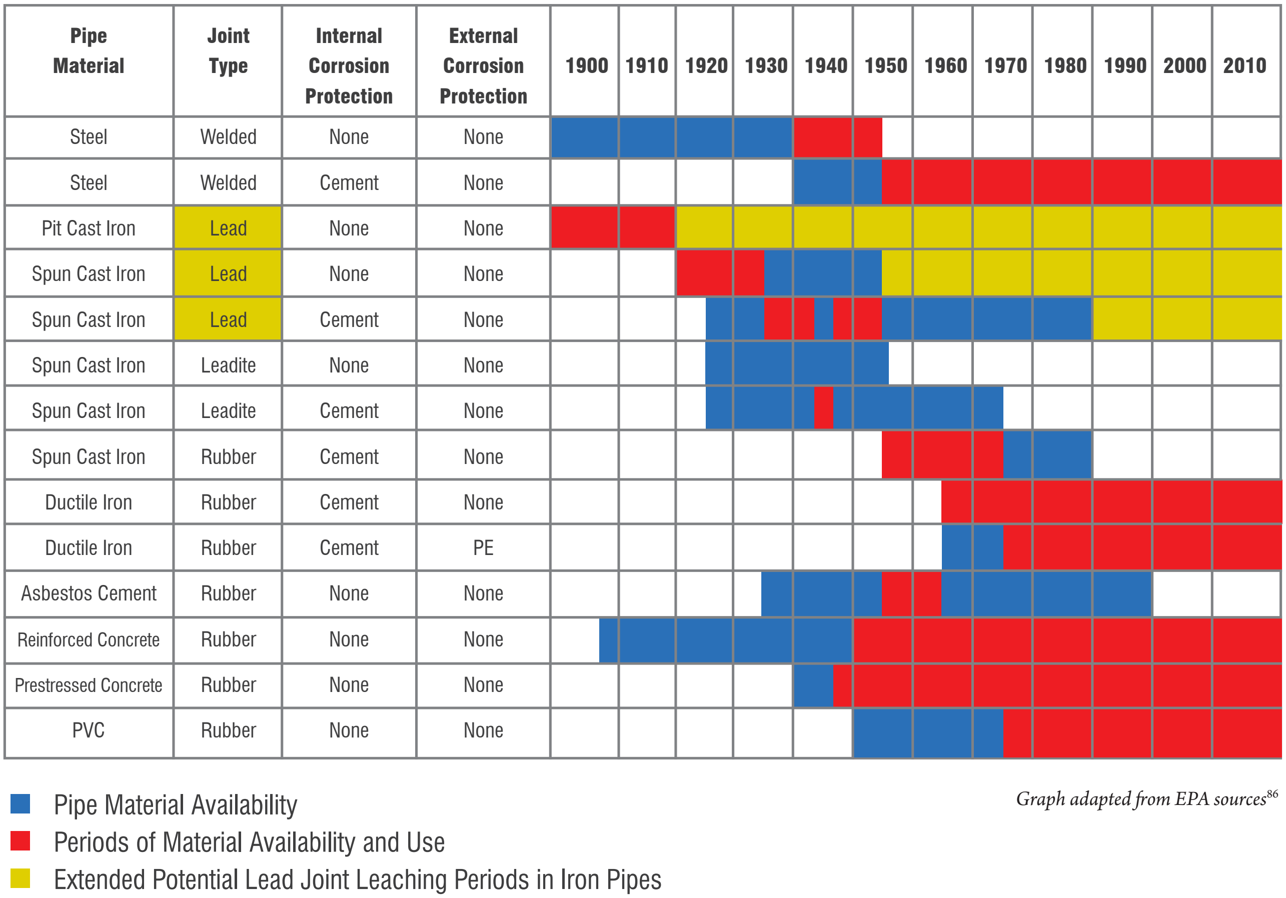
8.7.1 Pipe Inside Diameters

The pipe inside diameter dimension is critical in determining the hydraulic characteristics of pressure and gravity pipes. For the selected pipes used in the analyses in this study, the internal diameters were determined using pipe standards, dimensional tolerances allowed in standards, standard lining thickness and manufacturers' literature.

8.7.2 Pipe Friction Factors

Pipe friction factors were based on a literature search and compilation of data from 55 sources. For instance, a recent City of Detroit analysis shows that the pumping efficiency for ductile iron pipe continually declines with age and does not remain at factory specifications.[83] The Western Virginia Water Authority (WVWA) arrived at similar conclusions in its analysis of ductile iron water pipe.[84] Based on the compilation and review, the values for Hazen-Williams C factors used for pressure pipes and for the Manning's n friction factors used for gravity pipes are summarized in Table 8.4. Research revealed documentation for deterioration rates for the friction factors, particularly for the Hazen-Williams C factor used for pressure pipes. These deterioration rates over time were incorporated into the hydraulic energy calculations for the various pipe material types.[85]

FIGURE 8.3 : TIMELINE OF PIPE TECHNOLOGY IN THE U.S. IN THE 20TH CENTURY



Graph adapted from EPA sources[86]

TABLE 8.4 : PIPE FRICTION FACTORS USED

Pipe Material	Standards	Hazen-Williams C	Manning's n
PVC	C900, C905, F794, D3034, F679	155 - 150	0.009
DI	C151, C104, A746	≤ 140	0.013
HDPE	C906, F2306	155 - 150	0.012
PP	F2736	N/A	0.012
PCCP/NRCP	C301, C14	≤ 140	0.013
VCP	C700	N/A	0.013

Designers of pump stations, water transmission pipelines and water distribution systems use a friction factor, normally Hazen-Williams C, which is representative of the weighted age for the system that they are designing. To demonstrate the environmental impacts caused by the roughening of the pipe surface, sample analyses were performed using accepted degradation rates of the Hazen-Williams coefficient for different piping materials. The coefficients were varied for the degradation over time from their new values to the lowest degraded value. Table 8.5 lists comparisons among the Hazen-Williams coefficients for newly installed pipe, 50-year life and 100-year life data points. Table 8.5 also lists the resulting energy loss for each of those milestones which add to the overall cost and environmental impacts of the system. Figure 8.4 shows graphically the effects of the increased friction loss over time on pumping energy. Figure 8.4 assumes a 100-year plus life for PVC, a 75-year life for PCCP, a 50-year life for HDPE pressure pipe and a 50-year life for ductile iron.

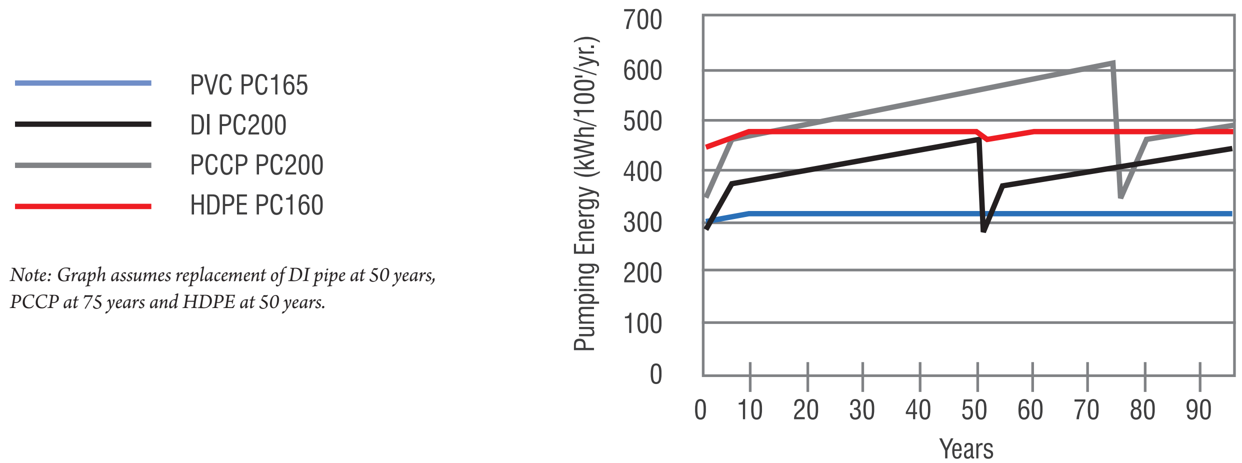
Throughout the service life, the surface of the pipe may roughen, causing more frictional energy loss the pumps must overcome to transport potable water. Not all piping materials roughen to the same degree over time. PVC pipe does not corrode or roughen, thus maintaining the water system's hydraulic properties close to the original installation design specifications.

Corrosion impacts pumping efficiency and operating costs. Studies have documented that pumping efficiency continually declines with age as a pipe corrodes.

TABLE 8.5 : EFFECTS OF FRICTION FACTOR DETERIORATION ON HEAD LOSS FOR AN 8" POTABLE WATER PIPE ASSUMING CONSTANT FLOW

	Hazen-Williams Coefficients			Frictional Energy Loss (kWh/100'/yr.)		
Life-Cycle Milestone	PVC (DR25)	HDPE (DR13.5)	Cement-Lined DI (350 psi)	PVC (DR25)	HDPE (DR13.5)	Cement-Lined DI (350 psi)
Install	155	155	140	125	185	140
50 Years	150	150	110	130	195	225
100 Years	150	150	95	130	195	280

FIGURE 8.4 : ANNUAL PUMPING ENERGY COMPARISONS FOR 24" PIPES

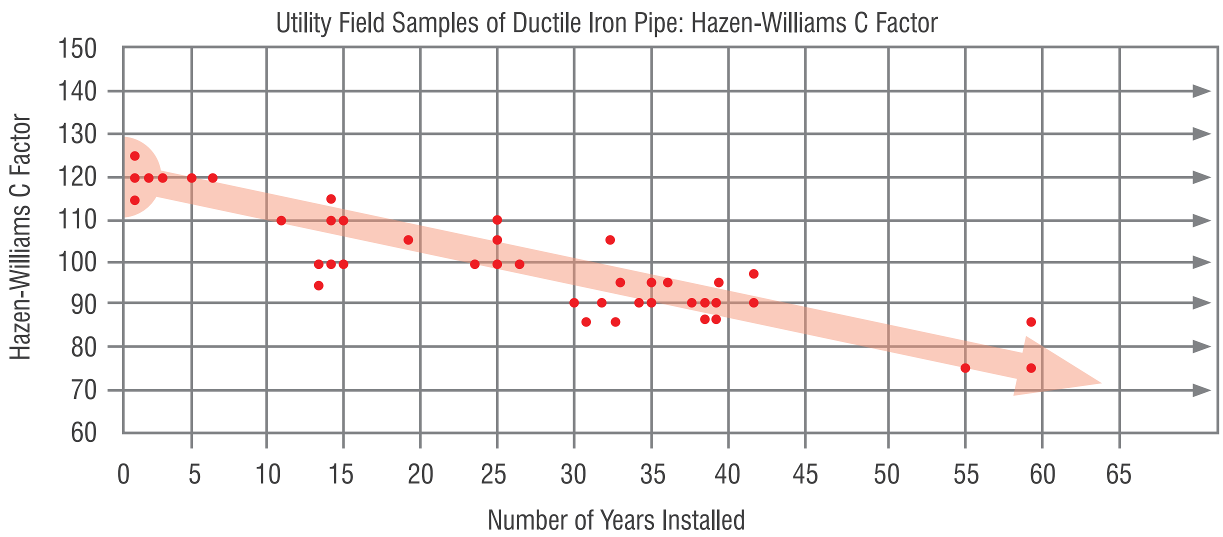


Note: Graph assumes replacement of DI pipe at 50 years, PCCP at 75 years and HDPE at 50 years.

Since PVC pipe does not corrode as it ages, the smoothness of the internal pipe wall surface does not decrease. PVC pipe has a smooth surface which reduces frictional energy loss over the pipe's life compared to metallic or concrete pipes. The Hazen-Williams coefficient (C factor) for new PVC pipe is 155-165 (the higher the value, the smoother the pipe).[87] A flow coefficient of C = 150 is generally used as a conservative value for the design of PVC piping sytems.[88 89 90] In contrast, new mortar-lined ductile iron pipes can have a C factor of 140 as claimed by the Ductile Iron Pipe Research Association (DIPRA). However, due to corrosion and deterioration of the lining material, the internal walls of iron pipes become significantly rougher over time, decreasing the C factor.[91] To prevent corrosion and provide a pipe wall that is listed for contact with potable water, cement lining is added to ductile iron water pipes. Concrete pipes and cement-mortar lined metallic pipes' C factors typically range from 120-140 for new pipe and 75-100 for older pipe as it degrades over time.[92] Field samples of over 60 mortar-lined ductile iron pipes from the WVWA demonstrates how the C factor decreases from 125 to 75 over a 55-year timeframe. The Washington Suburban Sanitary Commission (WSSC), which is the eighth largest water and wastewater utility in the U.S. and provides drinking water to 1.8 million people, provided 27 iron pipe field data samples which show a similar trend. See Figure 8.5.[93] HDPE is also not subject to internal corrosion and has a smooth internal wall. A C factor of 150 is generally used for HDPE pressure pipe.

PVC pipe does not corrode or roughen, thus maintaining the water system's hydraulic properties close to the original installation design specifications.

FIGURE 8.5 : FIELD SAMPLES SHOWING DECLINING C FACTOR FOR DI PIPE



9.0

ENVIRONMENTAL AND PERFORMANCE ATTRIBUTES OF ALTERNATIVE PIPING MATERIALS

While the ability to understand the environmental impacts of PVC pipe products is valuable in itself, some perspective can also be gained by seeing how the results of the LCA study compare to other published pipe LCA and performance studies.[94 95] All of these studies were conducted by different practitioners with potentially different methodological considerations. The LCA and performance studies were reviewed for consistency in their conclusions. This section presents the results from these published and widely available studies. These studies may vary between system boundaries and assumptions.

9.1 Ductile Iron (DI) Pipe

Ductile iron pipe has been a widely used material in water pipe systems throughout the U.S. and Canada. However, according to a report by the National Taxpayers Union, ductile iron pipe longevity has plummeted because of its thinner walls and greater susceptibility to corrosion compared to older iron piping.[96] Ductile iron pipe is now rarely used in Canada and the downward trend in its use in the U.S. is well known.

9.1.1 Ductile Iron (DI) Pipe Service Life

Over time, ductile iron pipes have been made with progressively thinner walls, making corrosion a major risk that will always exist.[97] Studies have demonstrated the failure of cement-mortar linings (structural and chemical-leaching) between 10 and 30 years. These failures have an impact on the expected service life.[98 99] The increased use of recycled materials can lead to accelerated corrosion because of inferior quality material that can be contained in recycled scrap iron. All of the factors that lead to the deterioration of ductile iron pipe can reduce its service life to less than 50 years.[100]

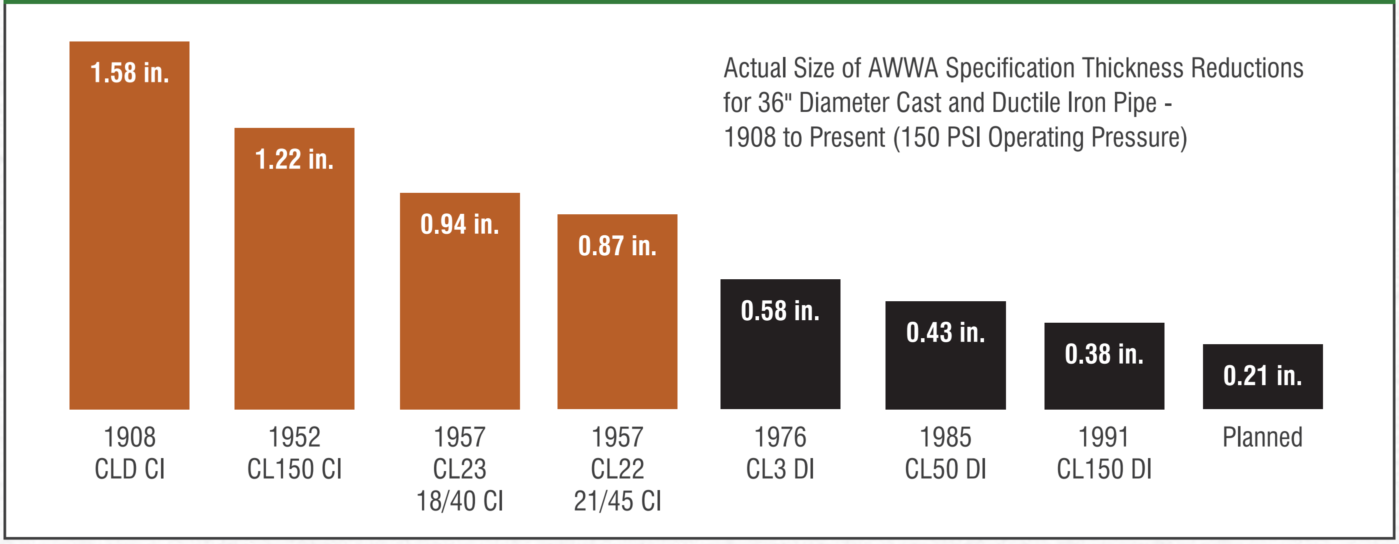
Initially, ductile iron was advertised as exceeding the corrosion resistance of gray cast iron. This idea gained acceptance in the marketplace and allowed thinner-walled ductile iron pipe to replace thicker-walled cast iron pipe. However, research provides evidence of corrosion being consistent among iron pipe types:

- Research by the National Bureau of Standards (now the National Institute of Standards and Technology) indicated decades ago that ductile iron, cast iron and steel corrode at similar rates in low-resistivity soils.[101]
- National Bureau of Standards testing concluded in a 1976 article that ductile iron and steel “buried in the same soils… corrode at nearly the same rates.”[102]
- The Ductile Iron Pipe Research Association (DIPRA) acknowledges that, for practical purposes, ductile iron and cast iron can be considered to corrode at the same rate.[103] However, DIPRA has not adjusted the marketplace expectation based on a 76% reduction in pipe wall thickness.

The thinner wall of ductile iron pipe is the main factor that contributes to its shorter service life compared to cast iron and the increase in corrosion-related water main failures.[104] Historically, the extra thickness of the cast iron pipe provided more metal for corrosion to attack (i.e., a corrosion allowance). As shown in Figure 9.1, the historical wall thickness difference can be as much as 76% thinner for a similar pressure class and diameter pipe.[105] If the wall thickness of ductile iron pipe is only one-fifth of the cast iron wall thickness and the corrosion rate is the same, then its expected life will be substantially less than for cast iron in similar environments. The walls of iron pipe were reduced from 1.58 inches in 1908 to 0.38 inches by 1991. New proposed reductions would thin the pipe wall to 0.21 inches. The difference in wall thickness is one consideration that must be taken into account during corrosion evaluations and selection of control methods. Some utilities are specifying increased ductile iron thickness classes for additional wall thickness (resulting in higher embodied energy and capital costs) in an attempt to provide a greater corrosion allowance. The simple fact is that thinner metallic pipes, under similar soil and moisture conditions, corrode and fail more quickly than their thicker cast iron predecessors.[106] Thick cast iron pipes took a longer time to corrode through the pipe wall than today's thinner-walled ductile iron (DI) pipes.[107] However, for much of the time these older pipes were underperforming hydraulically. They were also causing water quality issues and required expensive maintenance.

"Corrosion is the main cause in ductile iron pipe failure, followed by transverse break failure and then joint failure."[108] As previously stated, 75% of the utilities in the United States have corrosive soil conditions. The rate of corrosion through the thickness of the pipe wall results in a less than 50-year life for ductile iron pipe.[109 110] Clay soils tend to have much higher corrosion rates than other soil types.[111] With the standard wall dimension as low as 0.25-inch, a moderate corrosion rate can generate pit depths that penetrate the ductile pipe walls in less than a decade. Incorrect or overuse of cathodic protection can corrode ductile iron pipes. Acceptance of polyethylene encasement as a viable corrosion control method is still a controversial subject in the corrosion control community. Claims by pipe manufacturers, coating suppliers and cathodic protection firms are often slanted by their vested interests in selling their products.[112] Many corrosion engineers consider polywrap to be an ineffective means of corrosion protection on DI pipe.[113] Even with polyethylene encasement (which is not approved by the National Association of Corrosion Engineers as a corrosion control method)[114] and with the use of thicker class pipe to achieve additional sacrificial pipe wall depth, ductile iron pipe can have a service life of less than 50 years due to corrosive soils. Other factors affecting ductile iron pipe's service life include deterioration of the cement lining and internal corrosion. These factors reduce the pipe's ability to meet customer demands. Moreover, only the lining of cement-mortar lined ductile iron pipe is certified to NSF/ANSI Standard 61 Drinking Water System Components – Health Effects. The inside of the ductile iron pipe wall is not certified to NSF/ANSI 61. When the cement-mortar lining degrades during use or breaks off during tapping, installation, transport or mishandling, potable water can come into contact with iron material, thus posing a potential risk to the public health. As well, the bell area of DI pipe poses a risk to public health since potable water is exposed to a non-certified surface as it passes through this portion of the pipe. The capital cost of installing a new PVC pipe can be nearly 23% less expensive than cleaning and re-lining existing ductile iron pipe.[115]

FIGURE 9.1 : IRON PIPE WALL THICKNESS REDUCTIONS OVER TIME



9.1.2 Ductile Iron (DI) LCA and Embodied Energy

According to the Ductile Iron Pipe Research Association (DIPRA), the ductile iron pipe industry has conducted an LCA.[116] Unfortunately, the LCA results have not been released to the public and could not be used in this report. However, published studies were found that analyzed the embodied energy of ductile iron pipe. When comparing the material energy of pipes such as ductile iron, it is very important to consider the weight per foot of an actual pipe product. Because PVC weighs less than an equivalent length of DI pipe, the actual embodied energy is lower. Similarly, the amount of carbon dioxide emitted during the production of PVC pipe is far below that of ductile iron.

Sources used for this study assumed that the weight of mortar lining increases in proportion to the diameter of ductile iron pipe, so the embodied energy of mortar-lined ductile iron per kilogram can be assumed to be a constant value.

For DI pipe, the corrosion potential of interior and exterior pipe walls may require the addition of other materials such as a cement lining on the interior and a polyethylene encasement with or without an anti-microbial biocide and a corrosion inhibitor, asphalt coating or another material on the exterior. These additional materials increase resource consumption, embodied energy and the carbon footprint of the product. When evaluating the sustainability of piping products for life cycle design, it is important to understand and evaluate the life cycle impacts of all materials used in the piping system. The European Plastics Pipes and Fittings Association (TEPPFA) commissioned an LCA comparing DI and PVC pipes.[117] A similar LCA study was conducted by the Environmental Modelling Laboratory at the Polytechnic University of Catalonia in 2005.[118] Though these studies did not include an evaluation of all the components of ductile iron piping systems, they showed, as with this study, that PVC pipe has far lower embodied energy and other impacts than ductile iron pipe.

Understanding pumping energy over the pipe's life cycle is very important since this impacts operating costs and the municipality's carbon footprint for many decades.

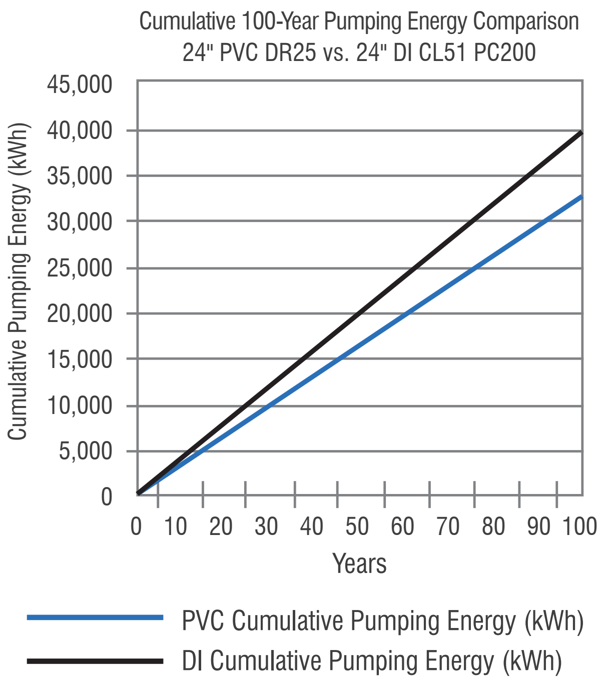
The AWWA Standard for DI pipe, AWWA C151, does not require NSF International listing for potable water use. Therefore, in order to be used for the transportation and distribution of potable water, DI pipe must be lined with an NSF listed lining material such as cement-mortar or epoxy. This lining reduces the internal diameter and changes the friction factor. Studies have documented that the friction factor of mortar linings decreases over time. This additional frictional resistance increases the pumping effort to deliver a constant flow rate of water and it decreases the amount of water that can be delivered in a distribution system over time.

When evaluating the sustainability of piping products for life cycle design, it is important to understand and evaluate the life cycle impacts of all materials used in the piping system.

9.1.3 Ductile Iron (DI) Pipe Use-Phase Performance

Ductile iron pressure pipes begin service with a slightly larger internal diameter than PVC's. However, usually by DI pipe's third year of life, a greater amount of pumping energy is required than PVC pipe of the same nominal size and the same flow rate. DI pressure pipe's pumping energy costs increase throughout its service life due to internal corrosion continually increasing frictional resistance, whereas PVC's remain constant. Figure 9.2 delineates the difference between the 100-year cumulative pumping energy for 24-inch PVC and DI pressure pipes at the same flow rate. The DI pumping energy in Figure 9.2 includes DI being replaced after 50 years of service with a reset of its friction factor (C). If ductile iron pipe is used past it service life of 50 years, increasing frictional resistance causes higher pumping costs as well as operation and maintenance expenses. As discussed in the Appendix, the cumulative pumping energy for DI pipe would be much greater than shown in Figure 9.2 over a 100-year period without replacement, since the internal wall of the pipe degrades more and more with time.

FIGURE 9.2 : COMPARISON OF CUMULATIVE 100-YEAR PUMPING ENERGY FOR 24" PVC AND DI PIPE



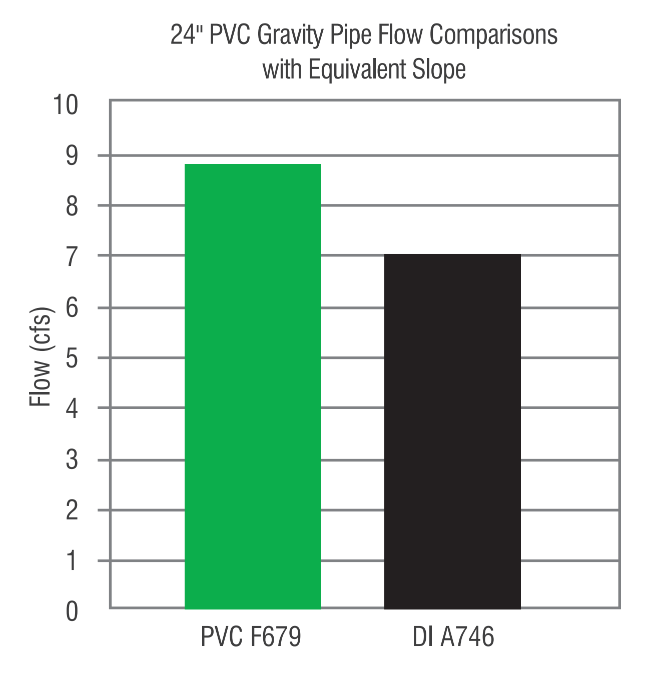
Note: Graph assumes replacement of DI pipe at 50 years.

Ductile iron gravity pipe is subject to external and internal corrosion that deteriorates the pipe to the point of leakage (infiltration/exfiltration) through corrosion holes in the walls. The cement lining and the ductile iron substrate are susceptible to corrosion when exposed to a sanitary sewer environment. Additionally, the DI gravity pipe standard, ASTM A746, does not require that the joints be tested for external pipe pressure/internal vacuum (infiltration pressure). Infiltration can lead to higher treatment plant costs.

Similarly, the DI pressure pipe standard, AWWA C151, does not require joints to be tested for external pressure/internal vacuum. This is an important water quality issue considering that leaky pipes can allow potential contaminants into the water system during a dynamic pressure drop (pump or valve failure, firefighting, or other sudden demand changes on the system), which could allow contaminated ground water to enter the pipe.[119] For gravity pipes the deterioration of the interior walls of DI pipe causes a greater resistance to flow and a higher Manning's n factor. The greater hydraulic friction inside DI pipe means that a DI gravity pipe laid on the same slope as a PVC pipe will have less hydraulic capacity. Figure 9.3 compares the flow of 24-inch PVC and DI pipes on the same slope.

As shown in Figure 9.3, the flow is about 20% more for a 24-inch PVC pipe than a 24-inch ductile iron equivalent pipe when installed with the same slope.

FIGURE 9.3 : FLOW COMPARISON WITH EQUIVALENT SLOPE OF 24" SOLID-WALL PVC AND DI PIPE



9.2 Concrete Pipes

While concrete is often considered as having low embodied energy per pound produced, the cement industry is one of the largest greenhouse gas emitters in the world, ranked as the third largest emitter. The cement industry releases over 5% of the world's overall carbon dioxide emissions due to the coal consumption in the kilns and limestone decomposition.[120]

The Concrete Pipe Association in the U.K., supported by the British Cement Association, published an LCA study on concrete pipe. The primary data in this study are from 1999 and 2000, which does not meet the temporal data quality recommendations by ISO 14044. The differences in LCA methodologies and assumptions prevents accurate comparability.

Non-reinforced concrete pipe (NRCP) has an estimated 1.34 MJ/kg embodied energy,[121] while prestressed concrete pipe has 3.74 MJ/kg.[122] This report details an estimate of the embodied energy of a comparable concrete piping system based on the embodied energy determined and the weights of the pipe obtained from the manufacturers' literature and product standards.

An extensive review of LCA literature of PVC in various applications (including pipe) was commissioned by the European Commission in 2004, for which dozens of LCA studies were reviewed and summarized. Several of these studies confirmed that plastic sewer pipes, including PVC, cause fewer life cycle impacts in all reported categories of global warming, municipal waste, acidification, summer smog and nutrient enrichment when compared to a similar concrete pipe.[123]

9.2.1 Non-Reinforced Concrete Pipe (NRCP) Service Life

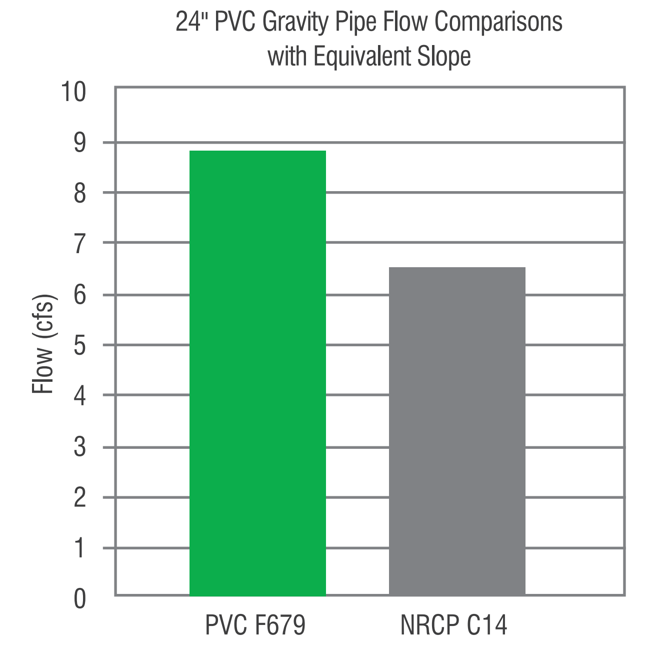
Non-reinforced concrete gravity pipe is assumed to have a 50-year service life because of the corrosion of the pipe material in sanitary sewer applications. NRCP is more prone to collapse because it has no structural reinforcing steel to partially support the pipe as the upper half of the pipe dissolves due to hydrogen sulfide gas condensation. Concrete pipe is difficult to repair/rehabilitate with a non-structural lining material, since the loss of the pipe wall from corrosion lessens the structural strength of the remaining wall.

9.2.2 Prestressed Concrete Cylinder Pipe (PCCP) Service Life

A 75-year service life was used for PCCP due to the documented failures of the prestressed wires and the degradation of the mortar lining over time.[124] Chlorides and sulfates can react with cementitious materials and eventually erode the concrete pipe.

The AWWA standard for prestressed concrete pressure pipe, AWWA C301, does not require certification to NSF/ANSI 61 for potable water use. With the AWWA standard allowing for the use of fly ash, silica fume and other concrete admixtures, and the tendency of concrete pipes to crack, the linings and the inner core of concrete pipe can leach hazardous materials such as arsenic, beryllium, chromium, lead, manganese, mercury and selenium into drinking water. Studies have documented that the friction factor of concrete decreases over time. This increased frictional resistance increases the pumping effort to deliver a constant flow of water, and it decreases the amount of water that can be delivered in a distribution system over time.

FIGURE 9.4 : FLOW COMPARISON WITH EQUIVALENT SLOPE OF 24" SOLID-WALL PVC AND NRCP



9.2.3 Non-Reinforced Concrete Pipe (NRCP) Use-Phase Performance

Concrete pipe's use-phase energy is significantly impacted by the corrosion and deterioration of the pipe itself for gravity sewer applications.

Concrete gravity pipe is subjected to internal corrosion that deteriorates the pipe to the point of leakage (infiltration) through corrosion holes in the walls and eventually to pipe structural failures. The interior walls of concrete pipe are susceptible to corrosion when exposed to a sanitary sewer atmosphere. Design manuals state that this corrosion can be as much as one inch of wall thickness per year in high-sulfide environments. This is why many city specifications that allow for the use of concrete pipe for sewers require the design of extra sacrificial concrete or liner materials such as PVC.

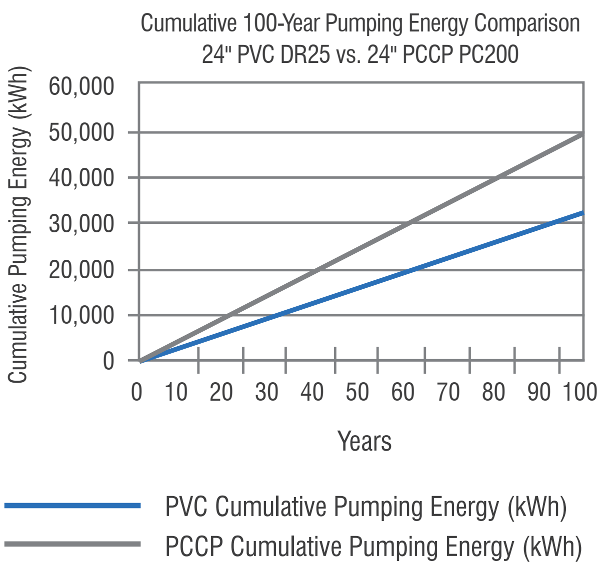
Concrete gravity pipe standards, ASTM C14 and ASTM C76, do not require that the joints be tested against infiltration pressure. PVC sewer pipe standards require joints to be vacuum tested to ensure they won't leak due to external hydrostatic pressure (infiltration). The deterioration of the interior walls of concrete pipe causes a greater resistance to flow and a higher Manning's n factor. The greater pipe wall friction of concrete pipe means that a concrete gravity pipe laid on the same slope as a PVC pipe will have less hydraulic capacity. Figure 9.4 compares the flow of 24-inch PVC and concrete pipes on the same slope. As shown in Figure 9.4, the flow is less for a 24-inch concrete pipe than an equivalent 24-inch PVC sewer pipe at equivalent slopes.

9.2.4 Prestressed Concrete Cylinder Pipe (PCCP) Use-Phase Performance

Concrete pipe's use-phase energy is significantly impacted by the deterioration of the interior pipe wall's friction factor for pressure pipe.

Modeled as part of this study, concrete pressure pipes begin service with a slightly larger internal diameter and an internal friction greater than PVC's. Because internal friction continues to increase over the life of the pipe, concrete pressure pipe will require greater pumping energy than PVC over the design life for the same nominal size and the same flow rate. Figure 9.5 delineates the difference between the 100-year cumulative pumping energy for 24-inch PVC DR25 and 24-inch PCCP PC200 at the same flow rate. The pumping energy in Figure 9.5 includes the PCCP being replaced after 75 years of service with a reset of its friction factor. As discussed in the Appendix, the cumulative pumping energy for PCCP would be much greater than shown in Figure 9.5 over a 100-year period without replacement since the internal wall of the pipe degrades more and more with time, increasing pumping costs.

FIGURE 9.5 : COMPARISON OF CUMULATIVE 100-YEAR PUMPING ENERGY FOR 24" PVC AND PCCP



Note: Graph assumes replacement of PCCP at 75 years.

9.3 Polyethylene and Polypropylene Pipes

9.3.1 Polyethylene (HDPE) Pipe Service Life

HDPE is used for water, sanitary sewer and storm water applications. HDPE pressure pipe is considered to have a 50-year service life pipe because of strain creep and oxidation by chlorine and other chemicals that limit its longevity.[125] Thinner-walled HDPE 4710 pipe's life expectancy is only about half that of thicker-walled HDPE 3608 pipe according to independent test results.[126] HDPE 3408 was listed in the C906-07 Standard with a factor of safety of 2.0. HDPE 3408 is not listed in the C906-15 Standard. It has been replaced or renamed with other compounds in the new standard. HDPE 4710 has a Safety Factor of only 1.6 (equal to a Design Factor of 0.63).

AWWA's *Manual of Water Supply Practices M55, PE Pipe – Design and Installation* has one reference to a 50-year life and no reference to any recommendation for a greater life.[127] The difficulty in determining HDPE longevity is due to the effects of disinfectants, pressure and temperature on the pipe. Other factors such as pipe defects and damage during installation can accelerate failures. Claims of improvements to resistance to disinfectant degradation with the new resin compound, PE4710, may well be more than offset by the reduction in the pipe wall thickness, the increased wall stress associated with the design, and the reduced Safety Factor. The service life of HDPE 4710 is currently unproven and lacks field samples and dig-up studies. Based on research, for comparison purposes in this study, a service life of 50 years is used.[128 129 130] This may be overstated given the undocumented performance and longevity of newer HDPE 4710 pipe and its lower Safety Factor.

The service life of a pipe may be affected by corrosion, installation, strain, stress and other factors. While corrosion degradation is common for metal pipes, plastic pipes are not susceptible to electrochemical corrosion. There has been some concern about oxidation from consistent exposure to a chlorinated disinfectant; however, studies and tests have concluded that PVC pipe is not prone to oxidation after exposure to chlorine or ClO_2 (chlorine dioxide).[131] Other plastic materials, such as HDPE, are susceptible to this oxidation which affects the durability of these products.[132 133 134] HDPE, polypropylene and fiberglass pipes are susceptible to strain creep. Strain creep can be a factor in the service life for these products when used in gravity applications. These and other factors influence design decisions on estimating the service life of a pipe material in its operating environment while meeting all of its sustainable service levels.

Research indicates that chlorine dioxide is the most aggressive disinfectant, followed by chlorine and then chloramines. HDPE pipelines in the presence of chlorine, chlorine dioxide and chloramine disinfectants may experience oxidation on the inner wall surface. Penetration due to oxidant diffusion and free radical attacks result in additional cracking into the pipe wall structure while under pressure.[135 136]

A study analyzing the structural performance of 22 HDPE non-pressure pipelines throughout Texas showed that 100% of the pipelines tested suffered from at least one failure mode, including cracking/fracture, excessive deformation, joint displacement, inverse curvature and buckling. This study is significant because the pipe was installed under the state transportation department's inspection and according to standard procedures for HDPE pipe. Another consideration for profile-wall HDPE gravity pipe is that corrugation growth may be significant, which would require the use of higher Manning's n value to account for the increased roughness of the pipe over time.[137]

9.3.2 Polyethylene (HDPE) Pipe Embodied Energy

The University of Bath's Sustainable Energy Research Team developed an inventory of carbon and energy of various materials, including HDPE pipe, which was published in 2011.[138] The embodied energy of HDPE pipe is reported to be 84.4 MJ/kg, with an embodied carbon footprint of 2.54 kg CO_2/kg. HDPE has a much greater embodied energy than equivalent PVC when the wall thickness and weight per foot are taken into consideration.

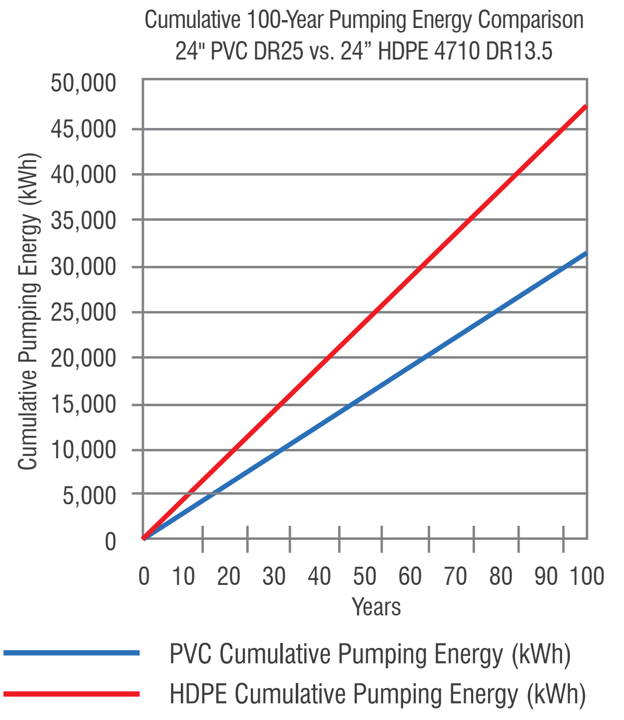
9.3.3 Polyethylene (HDPE) Pipe Use-Phase Performance

The hoop strength of polyethylene pipe to establish the hydrostatic design basis is only 40% of PVC pipe. Because of its low tensile strength, HDPE pressure pipe must have thicker walls to produce pipe with a comparable pressure class to PVC. The thicker walls of HDPE pipe translate into a smaller internal diameter and a smaller flow conveyance area. HDPE and PVC pressure pipes have similar internal friction factors. The embodied energy for the use-phase for the life cycle for HDPE is much greater than that of PVC because of the smaller conveyance area of polyethylene. As a comparison, 8-inch PVC DR18 pipe has a 33.2% greater conveyance area than the comparable HDPE pipe, and a 24-inch PVC DR25 pipe has a 17.9% greater conveyance area than an equivalent HDPE pipe. Figure 9.6 clearly depicts the greater 100-year pumping energy required for 24-inch HDPE 4710 DR13.5 pipe versus 24-inch PVC DR25 pipe.

9.3.4 Polypropylene (PP) Pipe Service Life

Polypropylene pipe for gravity applications has a 50-year service life due to strain creep and the reduction in its long-term modulus of elasticity. PP pipe is used for storm water and sanitary sewer applications. Polypropylene has an embodied energy estimated at 81 MJ/kg by a Franklin Associates' study.[139] Franklin's data confirm the assumptions for PP applied in this study.

FIGURE 9.6 : COMPARISON OF CUMULATIVE 100-YEAR PUMPING ENERGY FOR 24" PVC AND HDPE PIPE

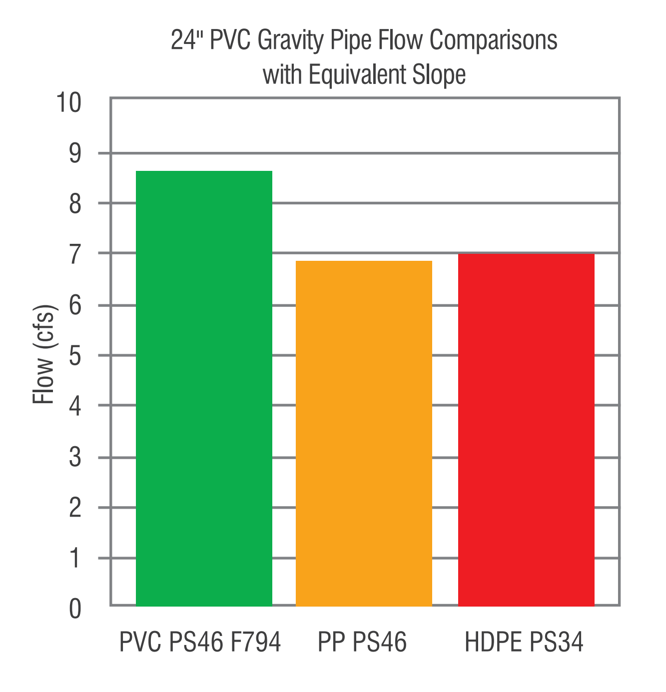


Note: Graph assumes replacement of HDPE at 50 years.

9.3.5 Profile-Wall Polyethylene (HDPE) and Polypropylene (PP) Gravity Pipes Use-Phase Performance

Polyethylene and polypropylene gravity pipes have smooth interior walls with annular corrugations with or without smooth exterior walls. The smooth inner walls of HDPE and PP pipe are very thin, causing reflection of the annular corrugations on the inner pipe walls. The wavy surface of the inner wall of corrugated HDPE and PP pipe may cause greater hydraulic friction than solid-wall or corrugated-wall PVC pipes. The increased pipe friction causes HDPE and PP gravity pipes laid on the same slope as PVC pipe to have less hydraulic capacity. Figure 9.7 compares the flow of 24-inch PVC to 24-inch HDPE and PP pipes on the same slope.

FIGURE 9.7 : FLOW COMPARISON WITH EQUIVALENT SLOPE OF 24" PVC, PP AND HDPE PROFILE-WALL PIPES



HDPE and PP pipes are subject to strain creep. Strain creep is a property of some materials whereby, when subjected to a load, the pipe will continue to slowly flex under the load over time. For buried HDPE and PP gravity pipes, strain creep means that the pipes will continue to deflect over time. The standards for HDPE and PP gravity pipes make allowances for strain creep over the expected lifetime of the pipes.

- For HDPE pipe, the 50-year tensile strength can decrease to less than one-third of the initial tensile strength and the 50-year modulus of elasticity can decrease to one-fifth of the initial modulus of elasticity.
- For PP pipe, the 50-year tensile strength can decrease to less than one-third of the initial tensile strength and the 50-year modulus of elasticity can decrease to one-sixth of the initial modulus of elasticity.

Since most pipe designers use the short-term modulus for strain limits, long-term deflections can lead to failure at joints and in the pipe wall. Designers must take the decrease in structural strength of HDPE and PP pipe into account for design lives up to 50 years. Longer design lives would require special, more costly backfills and special designs.

Additional comparisons including profile-wall PVC pipe can be found in the Appendix.

9.4 Clay Pipes

Vitrified clay has been used for sewer pipe in the U.S. since the late 1800s.

9.4.1 Vitrified Clay Pipe (VCP) Service Life

Vitrified clay gravity pipe has had a history of structural failures in expansive clay soils (which affect 75% of North America). VCP has also been subject to failure at the pipe joints because of root intrusion resulting in cracked pipe though these issues may allow the pipeline to continue to partially function. From an operational and maintenance standpoint, the pipeline may be functionally obsolete long before the end of its anticipated service life.[140] Before installation, clay pipes should be checked for out-of-roundness to confirm they are within the specification tolerance. VCPs are susceptible to bell/joint breakage during shipping, installation and use. As a result of its brittleness, VCP is assigned a 50-year service life. It should be noted that throughout the period of its use, VCP requires significant maintenance relating to cleaning root intrusions and addressing stoppages and overflows. As well, operational costs are high for VCP because of its susceptibility to infiltration, increasing the volume of wastewater to be treated. Infiltration also may result in regulatory fines and budget impacts for required capital improvement replacements.

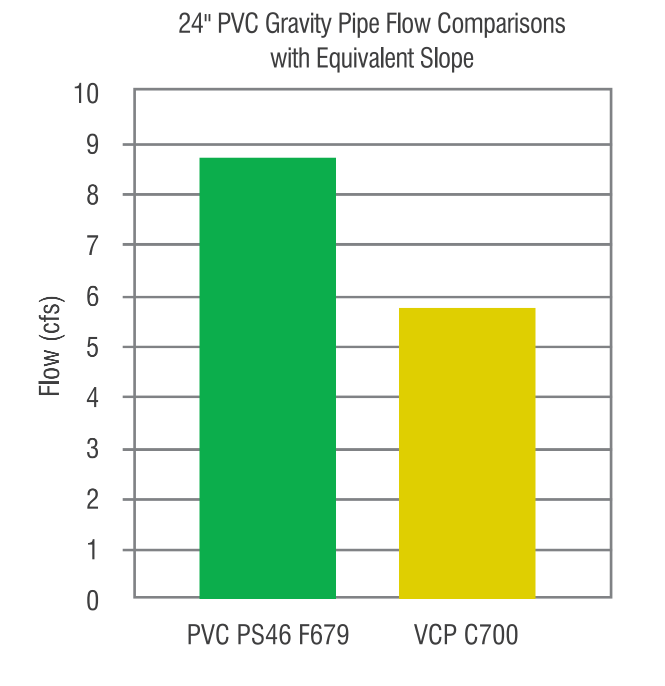
9.4.2 Vitrified Clay Pipe (VCP) Embodied Energy

The embodied energy of VCP is 7.9 MJ/kg, while carbon emissions are 0.55 kg CO_2/kg of pipe.[141] NCPI, the National Clay Pipe Institute, has obtained the SMaRT certification. To obtain this certification, a life cycle assessment must be conducted. Unfortunately, these results have not been published by the certification body or by the industry association. This *Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials* details an estimate of the embodied energy of a comparable piping system based on the embodied energy determined and the weights of the pipe obtained from manufacturers' literature and standards.

9.4.3 Vitrified Clay Pipe (VCP) Use-Phase Performance

The undulations on the interior walls of new vitrified clay gravity pipes increase the hydraulic friction. VCP has a tendency for the constituents of sewage (especially grease) to adhere to the pipe walls. The matter collected on the pipe walls increases the hydraulic friction. VCP is a rigid pipe with a low tensile strength. Rigid pipe, by its nature, carries more load from the overburden than flexible pipe. If the pipe is not loaded uniformly, tensile stresses can cause cracking. When the pipe experiences stresses due to less-than-perfect installation, from service connections to the pipe, from over-deflected joints, from uneven loading or from the movement of the surrounding soils, the pipe walls can crack. The cracks in VCP can cause unevenness of the pipe walls which can further increase the hydraulic friction. Cracks in the pipe walls may allow root intrusion which reduces the flow area and the hydraulic capacity. The friction factor for VCP is widely recognized as not being as good as solid-wall and corrugated-wall PVC pipes. The increased pipe friction causes the vitrified clay gravity pipe laid on the same slope as PVC pipe to have less hydraulic capacity. Figure 9.8 compares the flow of 24-inch PVC pipe to 24-inch VCP on the same slope. It should be noted that VCP's poor flow performance compared to PVC pipe would be even worse than shown if cracks, offset joints and root intrusions were included in the hydraulic calculations. Cracked VCP allows for infiltration and inflows into the pipe. Historically, VCP collection systems have contributed to infiltration and inflow problems that led to regulatory issues and massive remediation plans.[142 143]

FIGURE 9.8 : FLOW COMPARISON WITH EQUIVALENT SLOPE OF 24" SOLID-WALL PVC AND VCP



9.5 Summary of Environmental and Performance Attributes of Alternative Piping Materials

Table 9.1 lists the cradle-to-gate embodied energy for 100 feet of pipe for PVC and for each material that is similar in specification to the PVC products analyzed in the study. Understanding that each material result is derived from a different source with a varying degree of data quality, this data can still accurately illustrate potential cradle-to-gate embodied energy values for the various pipe products.

When comparing the material energy of pipes, it is very important to consider the weight per foot of an actual pipe product because weight directly influences embodied energy and carbon footprint.

TABLE 9.1 : SUMMARY OF CRADLE-TO-GATE EMBODIED ENERGY FOR PVC AND ALTERNATIVE PIPE MATERIALS

PVC Size and Product	Comparable Products	Standard	Embodied Energy (MJ/100 ft.)
8” PVC DR18 PC235 C900	8” PVC DR18	AWWA C900	23,300
	8” HDPE 4710 DR9	AWWA C906	42,600
	8” DI CL51	AWWA C151	50,900
8” PVC DR25 PC165 C900	8” PVC DR25	AWWA C900	15,900
	8” HDPE 4710 DR13.5	AWWA C906	29,600
	8” DI CL51	AWWA C151	50,900
24” PVC DR25 PC165 C905	24” PVC DR25	AWWA C905	137,900
	24” HDPE 4710 DR13.5	AWWA C906	240,800
	24” DI CL51	AWWA C151 AWWA C104	206,600
	24” PCCP PC200	AWWA C301	53,500
24” PVC PS46 F794 Profile Wall	24” PVC PS46	ASTM F794 AASHTO M304	49,700
	24” PP PS46	ASTM F2736	43,700
	24” HDPE PS34	ASTM F2306	42,900
8” PVC PS46 F794 Profile Wall	8” PVC PS46	ASTM F794 AASHTO M304	5,900
	8” DI	ASTM A746	46,500
8” PVC PS46 SDR35 D3034 Solid Wall	8” PVC PS46	ASTM D3034	10,000
	8” DI	ASTM A746	46,500
	8" VCP	ASTM C700	10,800
24” PVC PS46 F679 Solid Wall	24” PVC PS46	ASTM F679	98,600
	24” DI	ASTM A746	176,600
	24” VCP	ASTM C700	82,400
	24” NRCP	ASTM C14	21,300

Note: All ductile iron pressure pipes in this study are cement-lined per AWWA C104.
All ductile iron sewer pipes in this study are double cement-lined per AWWA C104.

10.0

PVC PIPE PUMPING ENERGY SAVINGS

Three pressure pipe scenarios are presented in Figure 10.1. This sample analysis assumes that the hydraulic friction of each pipe increased over time at its normal rate. Each pipe was analyzed using the same flow rate (in gpm = gallons per minute) for each pressure class; the flow rate was based on a PVC pipe fluid velocity of 2 feet per second (fps). The reason for this is that utilities process and sell water on a volumetric basis. The pipe fluid velocity chosen is within the range of use for the pipe sizes selected for this study. Use of a common flow rate allowed for accurate comparisons among the pipe materials with differing internal diameters and Hazen-Williams C factors.

For the first design example, 8-inch PVC DR18 PC235 was compared to equivalent HDPE and DI pipes of similar pressure classes. The second design example compared 8-inch PVC DR25 PC165 against comparable HDPE and DI pipes of similar pressure classes. The third scenario examines 24-inch PVC DR25 PC165 pipe against equivalent HDPE, DI and PCCP pipes of similar pressure classes as well.

The analysis for each pipe size and pressure class involved the computation and summation of the annual pumping energy needed for the common flow rate over a 100-year life cycle period for 100 feet of pipe based on each pipe's internal diameter, the C factor deterioration over time, a common pump efficiency and a common motor efficiency. The results for the three analyses are shown in Figure 10.1. The pumping energy use for 8-inch PVC DR18 is 23% less than the equivalent DI pipe while 8-inch PVC DR25 uses 35% less pumping energy than the equivalent DI pipe. Pumping energy is significant. Assuming 1.2 million miles of water supply pipes in the United States and 66% of those are 8 inches and smaller,[144] the energy savings over a 100-year period by using PVC instead of DI pipe and using the energy usage from these examples is up to 298 billion kWh. At an electrical power cost of $0.07 per kWh this would represent a savings of up to $21 billion by using PVC instead of DI pipe.

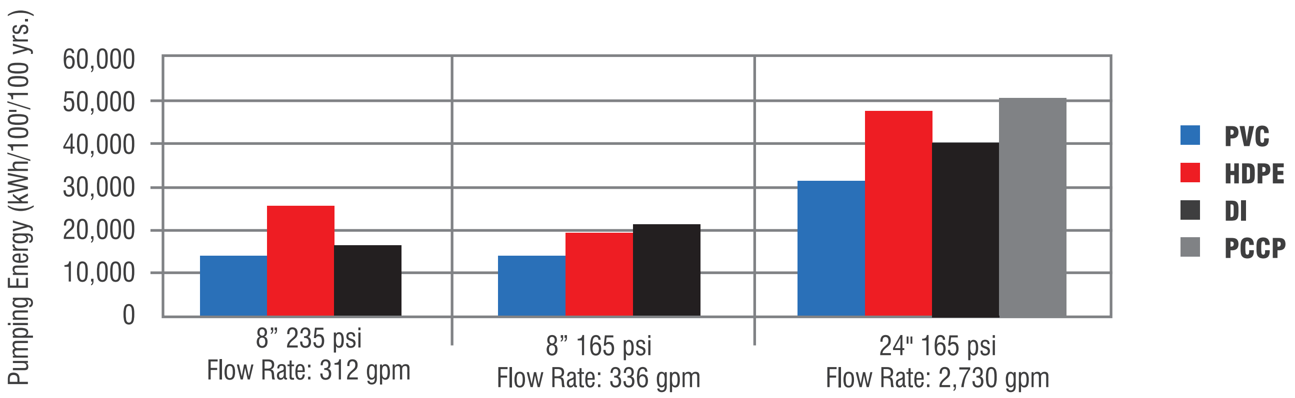
The pumping energy required for 8-inch PVC DR18 is 50% less than the equivalent HDPE pipe, while 8-inch PVC DR25 uses 33% less pumping energy. Stated another way, for equivalent 8-inch pipes the primary pumping energy demand is as much as 100% greater for HDPE than for PVC. In these comparisons, 8-inch HDPE pipe uses twice the pumping energy compared to PVC DR18 pipe and 1.5 times the pumping energy of PVC DR25. The energy savings over a 100-year period by using PVC rather than HDPE and using the energy usage from these examples is up to 532 billion kWh. At an electrical power cost of $0.07 per kWh this would represent a savings of up to $37 billion by using PVC instead of HDPE pipe.

10.1 PVC Pipe Pumping Energy Cost Savings

Energy usage translates into cost when electrical power for pumping is considered. The three pipe scenarios consider the cost of pumping energy using current average electrical rates and escalating them by one cent per decade over the 100-year life cycle. The total 100-year pumping energy cost differences for PVC and the alternate materials are shown in Figure 10.2.

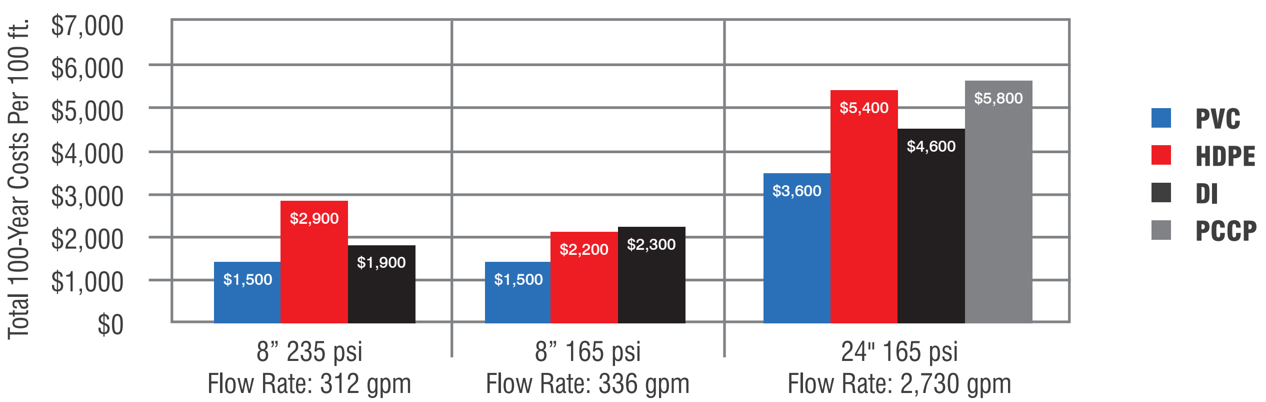
Medium to large utilities typically have 1,000 miles of pipe so the potential savings of using PVC pipe can be significant. This study used a common flow generated by an equivalent 2 feet per second velocity in a PVC pipe for analysis of various pipe material options. Based on this, the 100-year average annual pumping cost savings were calculated. The savings for a utility using 8-inch PVC compared to equivalent DI pipe are up to $440,000 annually. Savings for 8-inch PVC pipe versus HDPE are up to $770,000 annually. Power costs for these 8-inch, 1,000-mile pipe networks are shown in Figure 10.3. Refer to the Appendix for the calculation methodology.

FIGURE 10.1 : COMPARISON OF TOTAL 100-YEAR PUMPING ENERGY USE PER 100 FEET OF PIPE



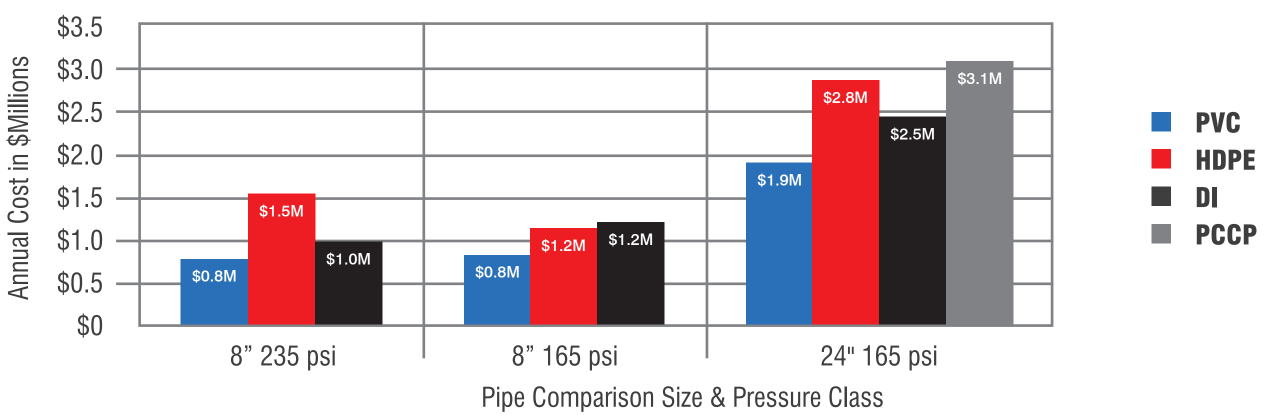
Note: Graph assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

FIGURE 10.2 : COMPARISON OF TOTAL 100-YEAR PUMPING ENERGY COSTS PER 100 FEET OF PIPE



Note: Graph assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

FIGURE 10.3 : COMPARISON OF AVERAGE ANNUAL PUMPING ENERGY COSTS PER 1,000 MILES OF PIPE BASED ON 2 FPS VELOCITY



The average annual pumping cost savings for 8-inch pipe using PVC instead of DI can be up to $440,000, and the savings using PVC instead of HDPE can be up to $770,000.

Note: Graph assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

Comparisons are also provided for 24-inch water transmission mains to demonstrate the potential savings for large diameter piping. Alternative pipe materials are shown to have higher operating costs than PVC pipe: PCCP has a 60% higher operating cost; HDPE is 49% higher; and DI is 28% more expensive to operate than PVC pipe.

Based on average per capita water distribution system demand in the U.S., the average velocity for 8-inch pipes is between 0.3 and 0.5 fps. A velocity of 0.4 fps was used to provide a realistic comparison flow rate for all 8-inch pipe materials. The pumping costs for each alternative pipe material were computed using that flow rate. Power costs for these 8-inch, 1,000-mile pipe networks with an average velocity of 0.4 fps are shown in Figure 10.4.

The difference in electrical power consumption between PVC and DI pipe in a 1,000-mile network could power 4 homes annually. Savings in electricity achieved by PVC compared to HDPE pipe would power 6 homes every year based on an average U.S. household using 10,812 kWh/year.[145]

For comparison purposes this study used a flow rate of 2 fps, rather than the average per capita flow rate of 0.4 fps. Discussions with numerous design engineers, municipalities, and utilities determined that a 2 fps flow rate is commonly used when designing municipal water systems. Although this number is greater than the 0.4 fps noted above, the trends for the various materials are the same.

10.2 PVC Pipe Low Monetized Carbon Footprint

When energy use (MJ/100') is taken into consideration for the different pipe materials, their carbon footprints can be established. As shown in Figure 10.5, 8-inch PVC pipe has the lowest total life cycle energy usage compared to equivalent HDPE and DI products. HDPE has the greatest total energy consumption over a 100-year design life at nearly 2.5 times that of PVC pipe while DI pipe's is 2.4 times that of PVC. Total life cycle energy usage is composed of cradle-through-installation for the pipe as well as the total pumping energy used over a 100-year period and any required pipe replacements.

FIGURE 10.5 : 8" PVC DR18 EQUIVALENT PIPES 100-YEAR TOTAL EMBODIED ENERGY

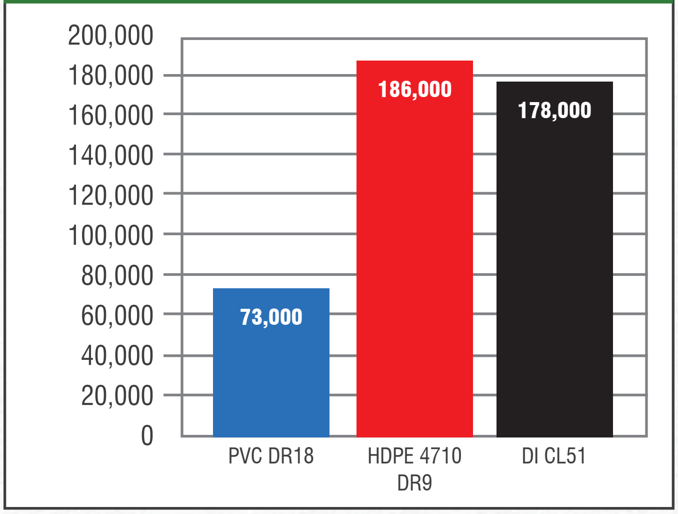
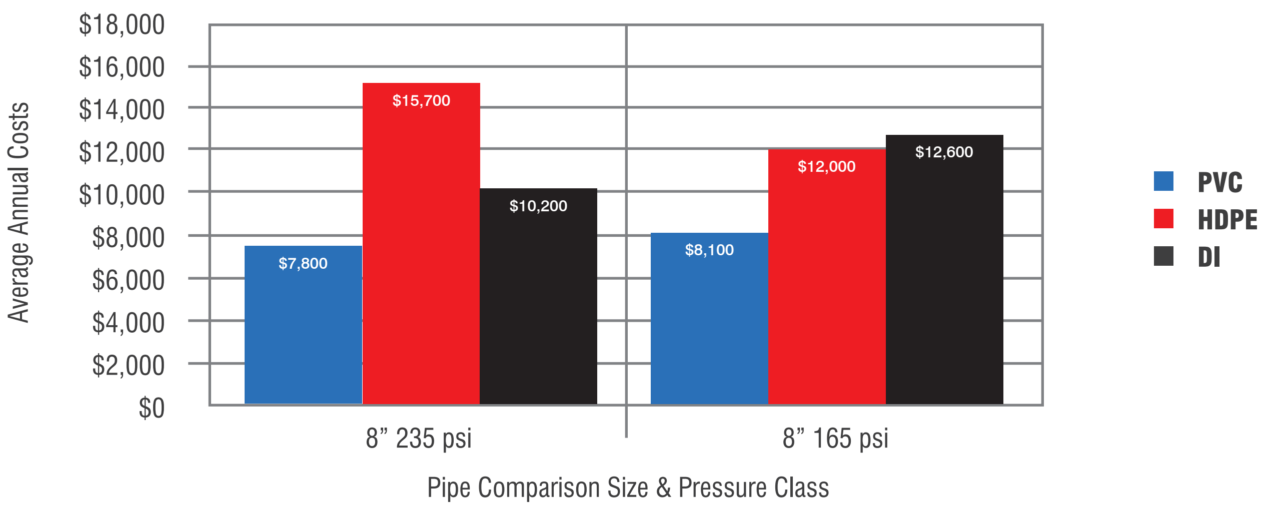


FIGURE 10.4 : COMPARISON OF AVERAGE ANNUAL 100-YEAR PUMPING ENERGY COSTS PER 1,000 MILES OF PIPE BASED ON 0.4 FPS VELOCITY



Note: Graph assumes replacement of HDPE and DI pipe at 50 years.

Table 10.1 takes the cradle-through-installation output and converts it to carbon output for PVC and equivalent DI pipes. As shown in Figure 10.6, if carbon output for cradle-through-installation were penalized for 8-inch PVC and DI equivalent pipes at a functional length of 100 feet, PVC would be ranked lowest at $25 or $35 (depending on pressure class) compared to DI pipe at $225. Each replacement for DI pipe over a 100-year period would require the payment of a new penalty. As discussed previously, DI pipe may only last 11-14 years in moderately corrosive soils and may need to be replaced 7 to 9 times over a 100-year period. This would mean a carbon penalty for DI pipe of $1,575 to $2,025 per 100 feet over 100 years compared to PVC at $25 or $35. The penalties over 100 years for a one mile pipeline could be $83,160 to $106,920 for DI pipe versus $1,320 or $1,848 for PVC.

FIGURE 10.6 : MONETIZED CARBON OUTPUT COMPARISON OF 100 FEET OF 8" PIPE

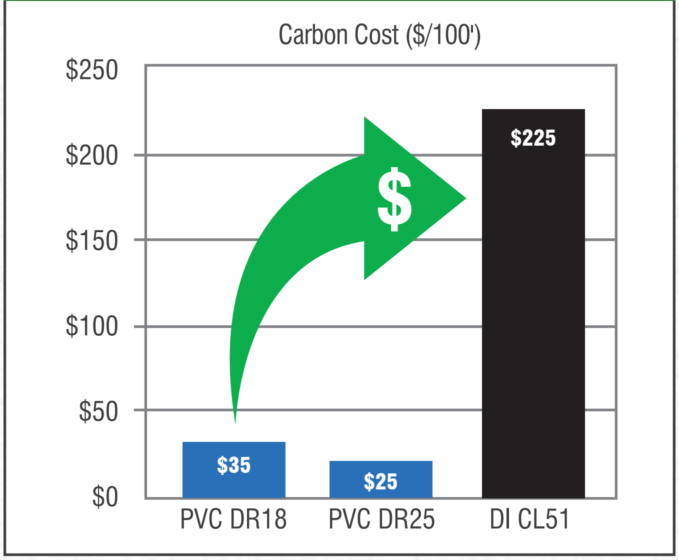


TABLE 10.1 : COMPARISON OF MONETIZED CARBON OUTPUT OF PIPE MATERIALS PER 100 FEET OF 8" PIPE

Pipe Materials	Total GWP (kg CO_2/100')	Cradle-to-Gate (kg CO_2/100')	Distribution (kg CO_2/100')	Installation (kg CO_2/100')	Total Cost
8" PVC DR18	1,400	1,100	20	250	$35
8" PVC DR25	1,000	700	15	250	$25
8" DI CL51	9,000	8,600	61	300	$225

11.0

SUSTAINABILITY STANDARDS

The United States is the largest consumer of the Earth's natural resources, using about 20% of the world's energy, 93% of which is supplied by non-renewable resources. On a per capita basis, the U.S. leads the world in water usage, with a substantial portion of water lost or leaked by infrastructure systems. Because of water availability, competing water demands and changing hydrologic conditions, the U.S. Department of Interior predicts that multiple water conflicts will occur in the western U.S. by 2025. Sustainable water infrastructure is vital to providing the American public with clean and safe water and helping to ensure the environmental, economic and social health of the nation's communities.

As municipalities across the United States and Canada focus on sustainably delivering, clean water, providing efficient wastewater treatment and controlling storm water run-off, appropriate pipe characteristics and costs are essential considerations. Government officials, engineers and the companies that install, operate and maintain water pipe infrastructure need to understand that a life cycle systems approach means more than just looking at the piping material. It means using life cycle thinking to design, install and operate water systems sustainably for at least 100 years.

11.1 Sustainable Infrastructure and Ratings

LCAs help manufacturers understand all of the potential environmental impacts associated with a product. Along with economic analysis, this can be used to make a more sustainable product, and is a valuable tool for engineering firms, municipalities, and utilities in helping them to achieve sustainability goals.

Many building codes and standards are now referencing the use of an LCA as a means of selecting products and materials with lower environmental impacts compared to alternatives. Codes and standards also use LCAs as a means of integrating life cycle thinking into building and infrastructure projects.

11.1.1 Institute for Sustainable Infrastructure (ISI): Envision™

The Institute for Sustainable Infrastructure developed the Envision™ Standard, a rating system to evaluate, rate and improve the sustainability for infrastructure projects such as potable water distribution systems, wastewater collection systems and storm water systems.

There are several credits in the Envision™ Standard related to life cycle impacts, including reducing net embodied energy and greenhouse gas emissions throughout the life cycle of a product. An LCA can be used to determine these impacts of a product or systems, as well as determine any reductions in environmental impacts.

The ISI Envision™ Standard also considers reducing energy consumption during the use phase of a product, so the overall project will have a reduced contribution to potential global warming and climate change and will have lower operating costs.

Table 11.1 outlines the ISI Envision™ Standard credits pertaining to life cycle assessment.

Government officials, engineers and the companies that install, operate and maintain water pipe infrastructure need to understand that a life cycle systems approach means more than just looking at the piping material. It means using life cycle thinking to design, install and operate water systems sustainably for at least 100 years.

Projects seeking these credits to reduce the net embodied energy of materials must first understand the embodied energy of materials. Then seeking to reduce this impact, projects must select not only the materials that have lower embodied energy, but materials that will continue to perform over a duration of time while consuming, or passively causing, minimal energy. Maintaining low pumping energy requirements help keep the energy and carbon footprints of projects low, allowing projects to more easily achieve Envision™ credits CR1.1 as well as RA2.1.

NSF International has developed a standard for the sustainability of water contact products.[146] This standard provides a science-based, consistent framework for communicating information on the sustainable attributes of water contact products. The development of products that have a reduced impact on the environment and society is encouraged through this standard. Within this framework, manufacturers and industry associations with published life cycle assessment data contribute to earning points in this standard, and additional points are awarded if systems are shown to reduce overall environmental impacts.

The Leadership for Energy and Environmental Design (LEED) standards have integrated specific credits for life cycle assessment and EPDs. There are pilot credits in LEED Version 3 and specific credits in LEED Version 4. This standard is strictly focused on buildings and does not provide specific credits for utility piping infrastructure. However, depending on the size of the project and the project boundary, storm water systems and onsite wastewater and potable water systems may be included.

As municipalities across the United States and Canada focus on delivering sustainable, clean water, efficient wastewater treatment and the controlled runoff of storm water, appropriate pipe characteristics and costs are essential considerations.

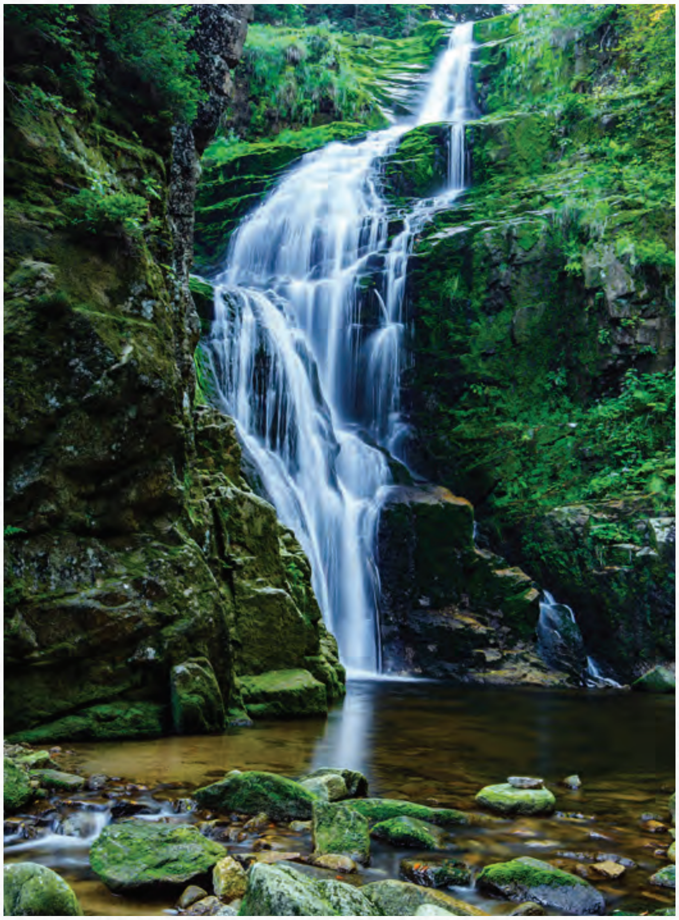
TABLE 11.1 : ISI ENVISION™ CREDITS PERTAINING TO LCA

ISI Envision™	Intent	Metric
Resource Allocation		
RA1.1: Reduce Net Embodied Energy	Conserve energy by reducing the net embodied energy of project materials over the project life.	Percentage reduction in net embodied energy from a life cycle energy assessment.
RA1.2: Support Sustainable Procurement Practices	Obtain materials and equipment from manufacturers and suppliers who implement sustainable practices.	Percentage of materials sourced from manufacturers who meet sustainable practices requirements.
RA2.1: Reduce Energy Consumption	Conserve energy by reducing overall operation and maintenance energy consumption throughout the project life cycle.	Percentage reductions achieved.
Climate and Risk		
CR1.1: Reduce Greenhouse Gas Emissions	Conduct a comprehensive life cycle carbon analysis and use this assessment to reduce the anticipated amount of net greenhouse gas emissions during the life cycle of the project reducing project contribution to climate change.	Life cycle net carbon dioxide equivalent (CO_2 eq) emissions.

11.1.2 SMaRT Certification

The Institute for Market Transformation to Sustainability (MTS) has developed a rating system called the SMaRT Certification. Several industry groups, including the Ductile Iron Pipe Research Association (DIPRA) and the National Clay Pipe Institute (NCPI) have received this environmental certification. DIPRA has not released the results of the ductile iron pipe LCA, although LCA is a requirement of the SMaRT Certification. This is clearly not transparent and does not appear to fulfill the requirements of relevant ISO standards. The following items critique the SMaRT Certification for ductile iron pipe:

- *No environmental information about the product is disclosed.* ISO 14025, §7.2.1 requires a life cycle impact assessment, a life cycle inventory and information module data to be presented; however, none of this information is presented in the DIPRA SMaRT Certification.
- *The SMaRT program does not enable comparability.* ISO 14025, §5.6 intends environmental declarations to allow a user to compare the environmental performance of products on a life cycle basis; however, as no impacts are reported on a life cycle basis, products can only be compared on the level of certification and total points achieved, which is not transparent.
- *The SMaRT Product Category Rule (PCR) does not represent a specific product, category or product function* as required by ISO 14025, §6.2 and ISO 14025, §6.7.2b. In fact, the SMaRT PCR states, "Product Category and Definition is all products other than airplanes and vehicles. The Product Category includes all building products. SMaRT's scope is identical with this category and definition. (SMaRT §2) (ISO 21930 §§6.21(a) & 6.22)." Without proper definitions for categories and specific product functions or by not making use of existing PCRs that have undergone public comment, the true environmental impacts of a product system cannot be determined and compared.
- *SMaRT excludes certain material types*, which goes directly against ISO 14025, §6.2: "The scope of the programme shall be clear and shall define whether the programme is limited, for example, to a certain geographical area or to certain industrial sectors, products or groups of products. A programme should be accessible to all organizations interested in developing a PCR or Type III environmental declarations within the defined scope." As this program does not certify PVC products, it is not accessible to all materials or industries.
- *No life cycle impact data are released.* ISO 14025, §6.8.2 requires that quantified environmental information based on an LCA be included. A guiding principle of greener products is transparency and customers should not accept anything less than a full disclosure of life cycle environmental impacts from a product claiming to be "green."



- *The SMaRT Certification prerequisites require that no Stockholm Treaty toxic chemicals are released* in the manufacture, sale, reuse, and end of life of the product. Due to this prerequisite, SMaRT explicitly bans PVC[147] as dioxin emissions are released in the production of PVC resin. However, as shown in this study, a review of the EPA Toxic Release Inventory shows reported releases of dioxin and other toxic chemicals such as lead and mercury from ductile iron manufacturing facilities, whereas PVC pipe manufacturers are reporting no toxic chemical releases from their manufacturing facilities.

Additionally, MTS is now calling the SMaRT Certification an "Environmental Product Declaration/Health Product Declaration." A Health Product Declaration (HPD), per the HPD Collaborative, "objectively defines the critical information needed to support accurate chain disclosure by manufacturers and suppliers, and informed decisions by building designers, specifiers, owners, and users." The HPD standard requires each ingredient's disclosure of health hazards in a product to be complete. No health hazards are reported throughout the SMaRT Certification, thus, not conforming to the HPD standard set forth by the HPD Collaborative.

12.0

SUMMARY FINDINGS - EMBODIED ENERGY AND SUSTAINABILITY

12.1 Summary Findings for Total 100-Year Embodied Energy Comparisons for Pressure and Gravity Pipes

This *Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials* has shown that PVC pressure and gravity pipes have the lowest embodied energy of most alternative pipe materials. Total embodied energy for pipes includes cradle-to-gate, transportation, installation, use-phase and end-of-life energy. For this study, a 100-year system design life was used to compare most alternative pipe materials. Cradle-to-gate embodied energy is composed of the following: energy used for raw materials, manufacturing and packaging. Embodied energy for transportation and installation includes the energy for transporting the pipe from the manufacturing plant to the job site and installing it with any corrosion protection. Use phase includes 100-year hydraulic energy and 100-year water loss. When pipes are replaced during the 100-year system design life, the energy consumed during cradle-to-gate, transportation and installation of the replacement pipe is included in total embodied energy calculations. End-of-life embodied energy was not considered since pipelines are rarely removed at the end of their lives.

12.1.1 Pressure Pipe Total Embodied Energy Comparisons

Figure 12.1 compares 8-inch PVC, HDPE and DI pipes with a pressure class at or equivalent to PVC DR18 PC235. As shown, the total 100-year embodied energy for PVC pipe is 61percent less than HDPE and 59 percent less than DI pipes.

FIGURE 12.1 : TOTAL 100-YEAR EMBODIED ENERGY FOR 8” PVC DR18 EQUIVALENT PRESSURE PIPES

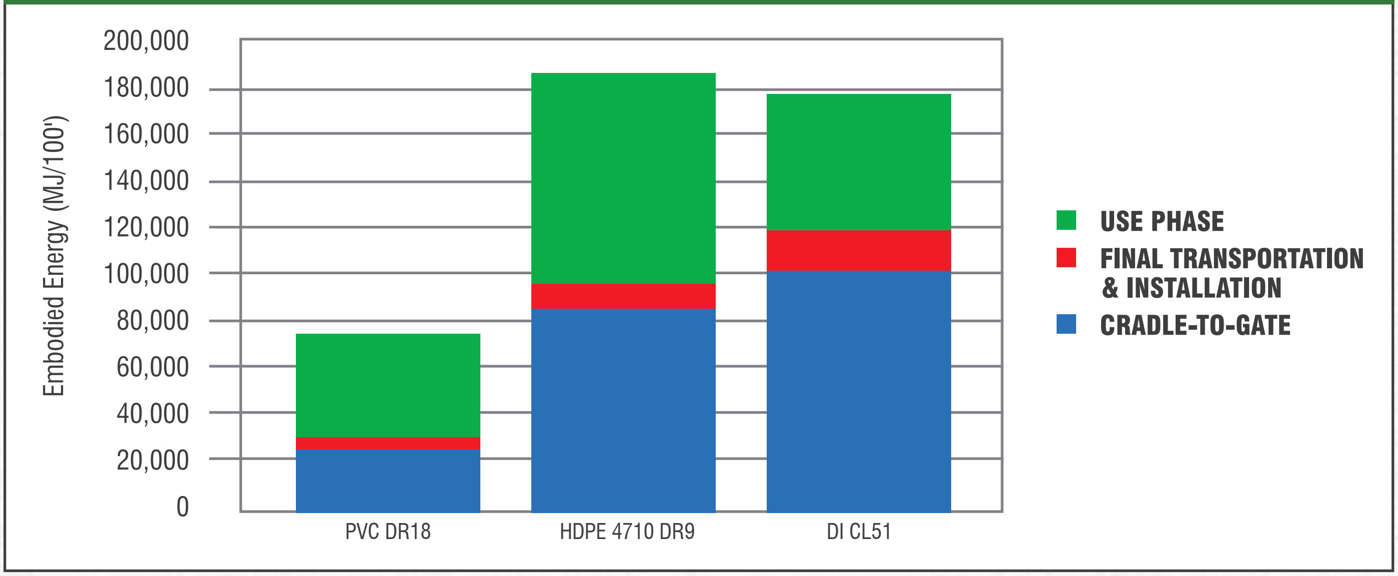


FIGURE 12.2 : TOTAL 100-YEAR EMBODIED ENERGY FOR 8" PVC DR25 EQUIVALENT PRESSURE PIPES

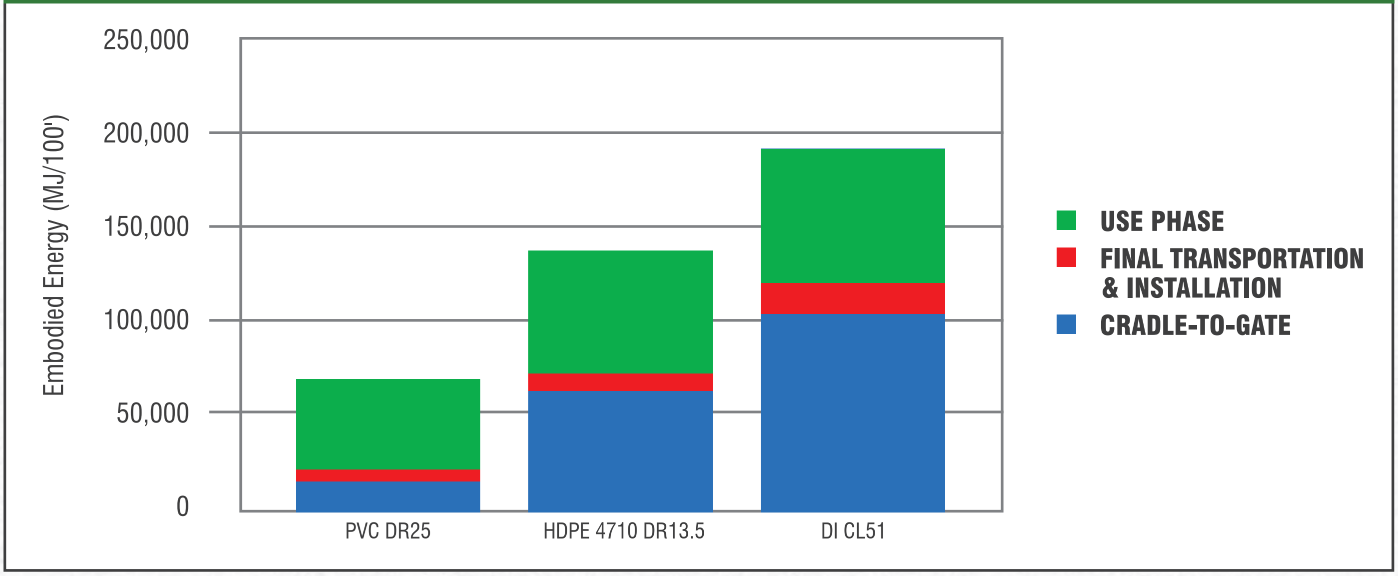


Figure 12.2 compares 8-inch PVC, HDPE and DI pipes with a pressure class at or equivalent to PVC DR25 PC165. As demonstrated, the total 100-year embodied energy for PVC pipe is 52 percent less than HDPE and 56 percent less than DI pipes.

Figure 12.3 compares 24-inch PVC, HDPE and DI pipes with a pressure class at or equivalent to PVC DR25 PC165. As demonstrated, the total 100-year embodied energy for PVC pipes is 61 percent less than HDPE, 56 percent less than DI and 17 percent less than PCCP pipes.

FIGURE 12.3 : TOTAL 100-YEAR EMBODIED ENERGY FOR 24" PVC DR25 EQUIVALENT PRESSURE PIPES

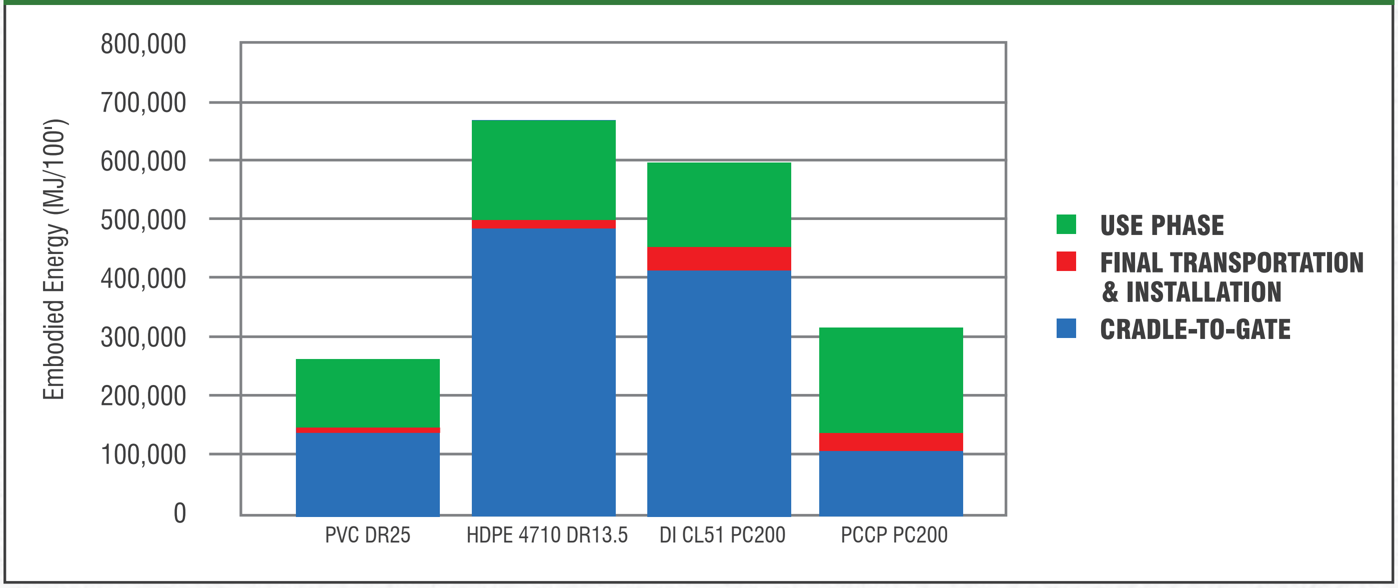
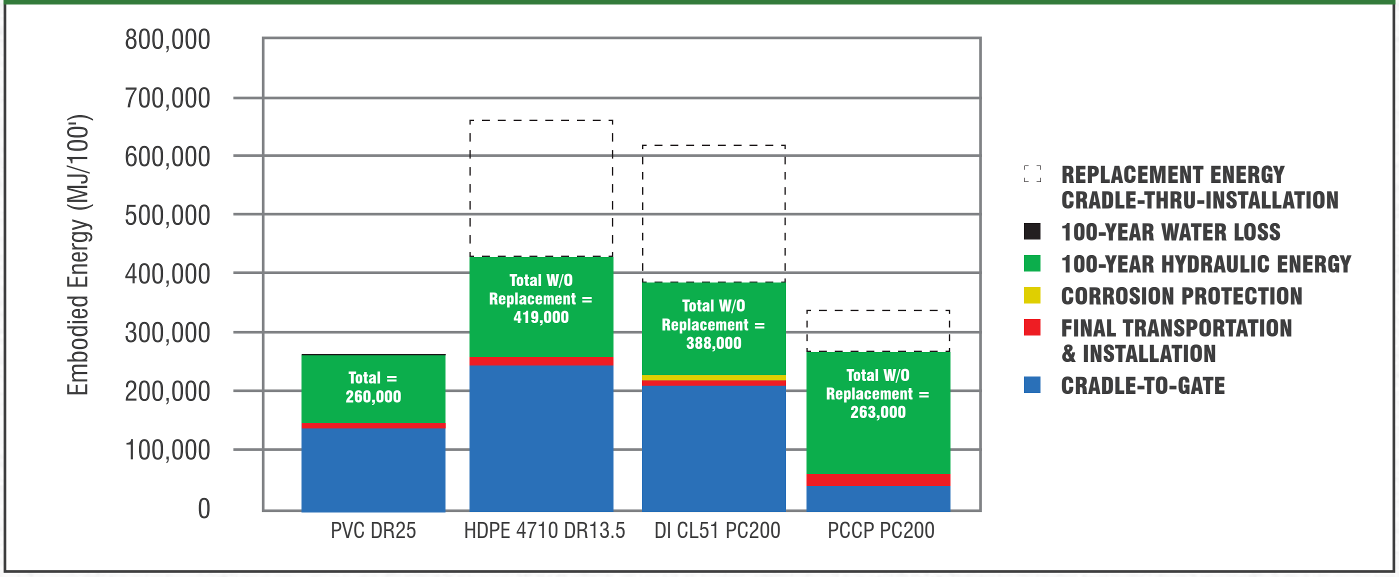
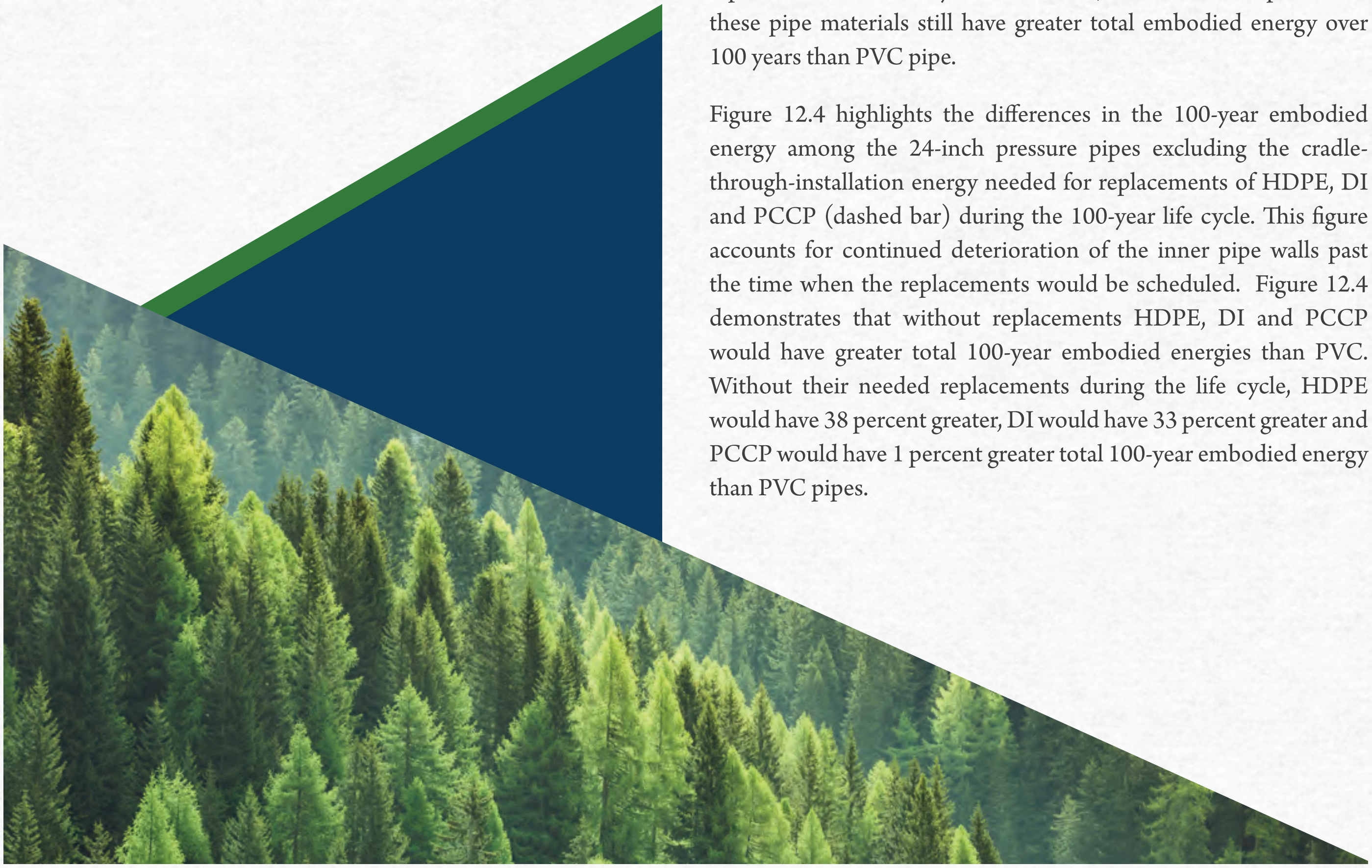


FIGURE 12.4 : TOTAL 100-YEAR EMBODIED ENERGY FOR 24" PVC DR25 EQUIVALENT PRESSURE PIPES (HYDRAULIC ENERGY WITHOUT REPLACEMENT)



Manufacturers of HDPE, DI and PCCP pressure pipes may claim that their pipes should not be replaced during the 100-year system design life and that this study unfairly represents their products. However, this study has demonstrated that these pipe products need replacement within 50 years. Moreover, even without replacement these pipe materials still have greater total embodied energy over 100 years than PVC pipe.

Figure 12.4 highlights the differences in the 100-year embodied energy among the 24-inch pressure pipes excluding the cradle-through-installation energy needed for replacements of HDPE, DI and PCCP (dashed bar) during the 100-year life cycle. This figure accounts for continued deterioration of the inner pipe walls past the time when the replacements would be scheduled. Figure 12.4 demonstrates that without replacements HDPE, DI and PCCP would have greater total 100-year embodied energies than PVC. Without their needed replacements during the life cycle, HDPE would have 38 percent greater, DI would have 33 percent greater and PCCP would have 1 percent greater total 100-year embodied energy than PVC pipes.



12.1.2 Gravity Pipe Total Embodied Energy Comparisons

The total 100-year embodied energy for gravity pipe comparisons includes energy for cradle-to-gate, transportation, installation and additional energy for any replacements of pipes with a less than a 100-year service life. Use-phase energy is not calculated for gravity pipes because no electricity is required to move fluids through them, and the energy associated with maintenance activities and treating infiltration flows is difficult to quantify. Infiltration from leaking pipes is a significant cost and energy multiplier at the wastewater treatment plant. Ductile iron and concrete pipes are susceptible to corrosion from sewer gases, while clay pipes are prone to cracking. Corrosion and cracking of pipes allows for wastewater to leak into the environment which may be environmentally harmful. Corrosion and cracking of pipes also allows ground water to enter sewer lines thus needlessly increasing pump energy and chemical usage at wastewater treatment plants. HDPE and PP pipes are also prone to leaking because of deflection and strain creep issues.[148 149]

PVC pipes are not prone to corrosion from sewer gases and PVC pipe joints are leak free, thus eliminating any issues caused by infiltration or exfiltration. If the energy and operations costs associated with infiltration were added to the charts below, PVC sewer pipe would be shown to be even more sustainable than alternative pipe materials.

Figure 12.5 compares 8-inch PVC PS46 F794 profile-wall pipe and equivalent DI gravity pipe. The total 100-year embodied energy of PVC pipe is 91 percent less than equivalent DI sewer pipe.

FIGURE 12.5 : TOTAL 100-YEAR EMBODIED ENERGY FOR 8" PVC PS46 F794 PROFILE-WALL EQUIVALENT GRAVITY PIPES

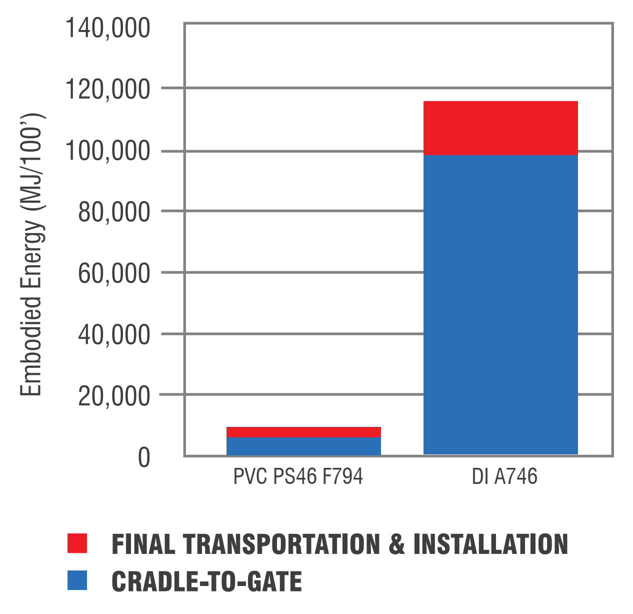


Figure 12.6 compares 8-inch PVC solid-wall, DI and VCP gravity pipe materials equivalent to PVC PS46 D3034 solid-wall pipe. The total 100-year embodied energy of PVC sewer pipe is 88 percent less than equivalent DI sewer pipe and 64 percent less than VCP pipe.

FIGURE 12.6 : TOTAL 100-YEAR EMBODIED ENERGY FOR 8" PVC PS46 D3034 SOLID-WALL EQUIVALENT GRAVITY PIPES

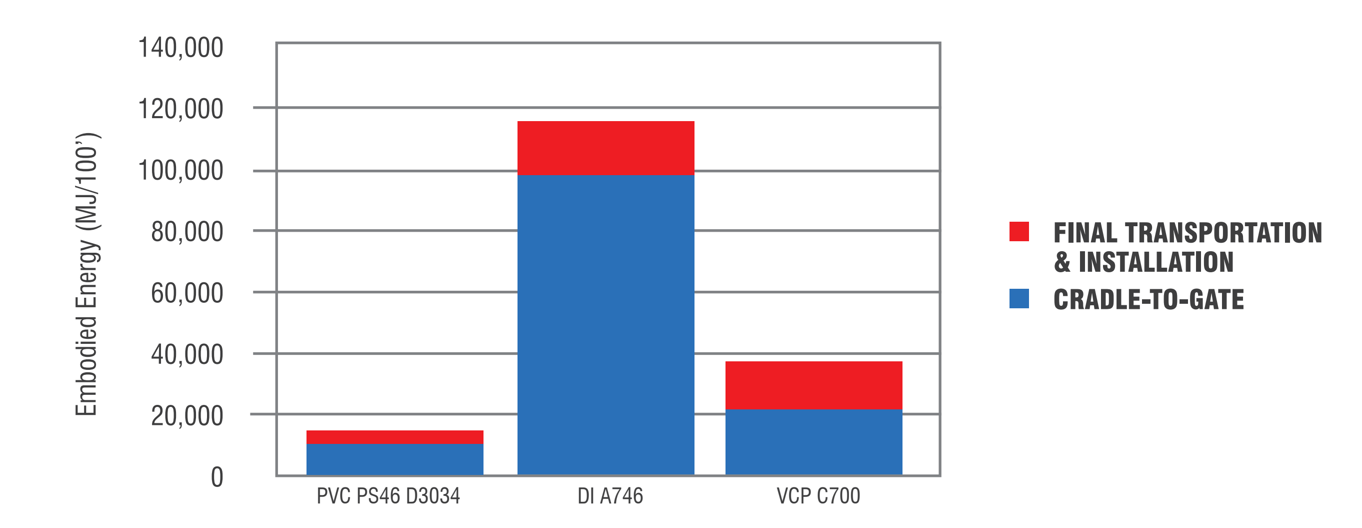


FIGURE 12.7 : TOTAL 100-YEAR EMBODIED ENERGY FOR 24" PVC PS46 F794 PROFILE-WALL EQUIVALENT GRAVITY PIPES

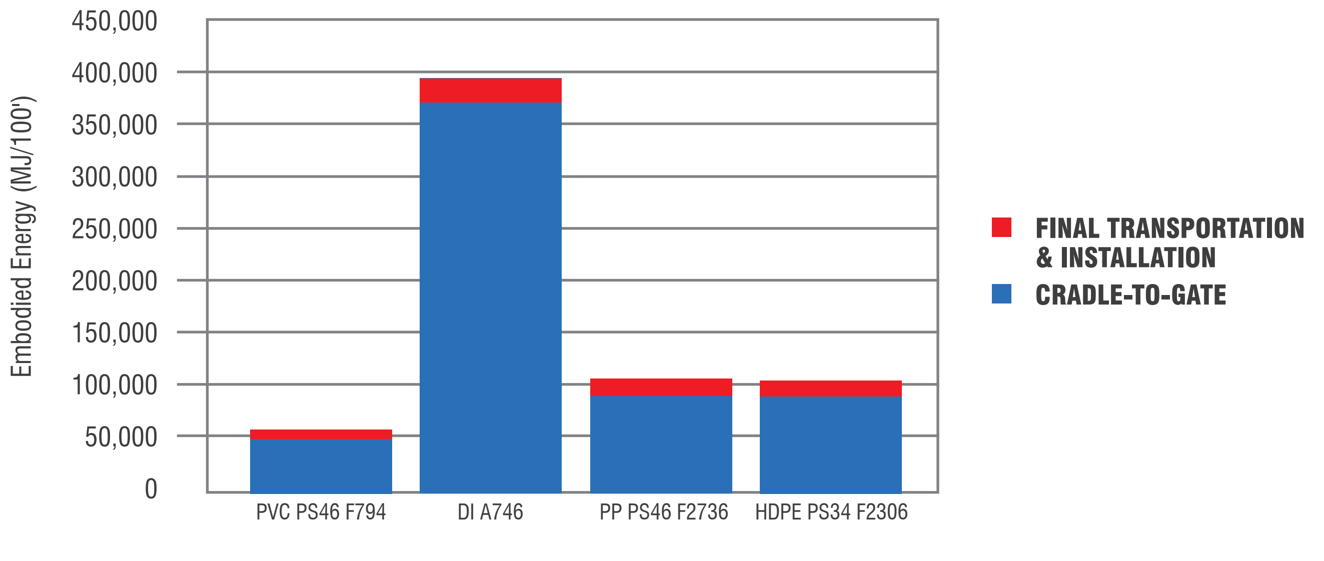


Figure 12.7 compares 24-inch PVC profile-wall, DI, PP and HDPE pipes equivalent to PVC PS46 F794 profile-wall pipe. The total 100-year embodied energy of PVC sewer pipe is 85 percent less than equivalent DI sewer pipe; 44 percent less than PP and 43 percent less than HDPE sewer pipes. It should be noted that the equivalent HDPE sewer pipe has a pipe stiffness that is 26 percent less than the pipe stiffness of PVC pipe.

Figure 12.8 compares 24-inch PVC solid wall, DI, VCP and NRCP pipe materials equivalent to PVC PS46 F679 solid-wall pipe. The total 100-year embodied energy of PVC sewer pipe is more than 73 percent less than equivalent DI sewer pipe and 44 percent less than VCP.

FIGURE 12.8 : TOTAL 100-YEAR EMBODIED ENERGY FOR 24" PVC PS46 F679 SOLID-WALL EQUIVALENT GRAVITY PIPES

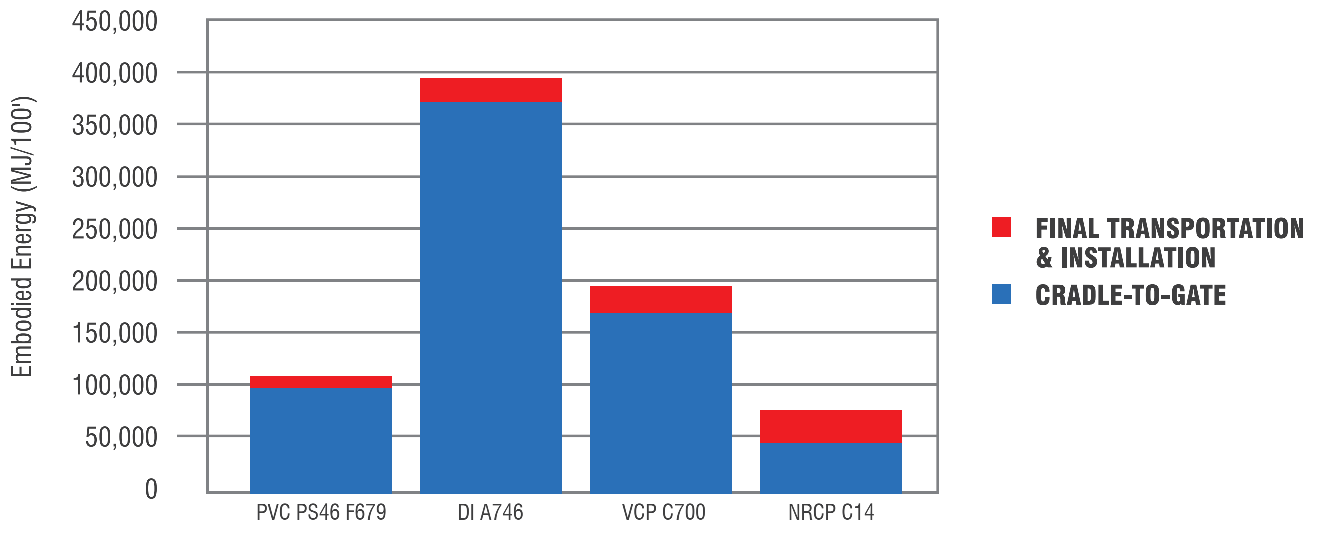
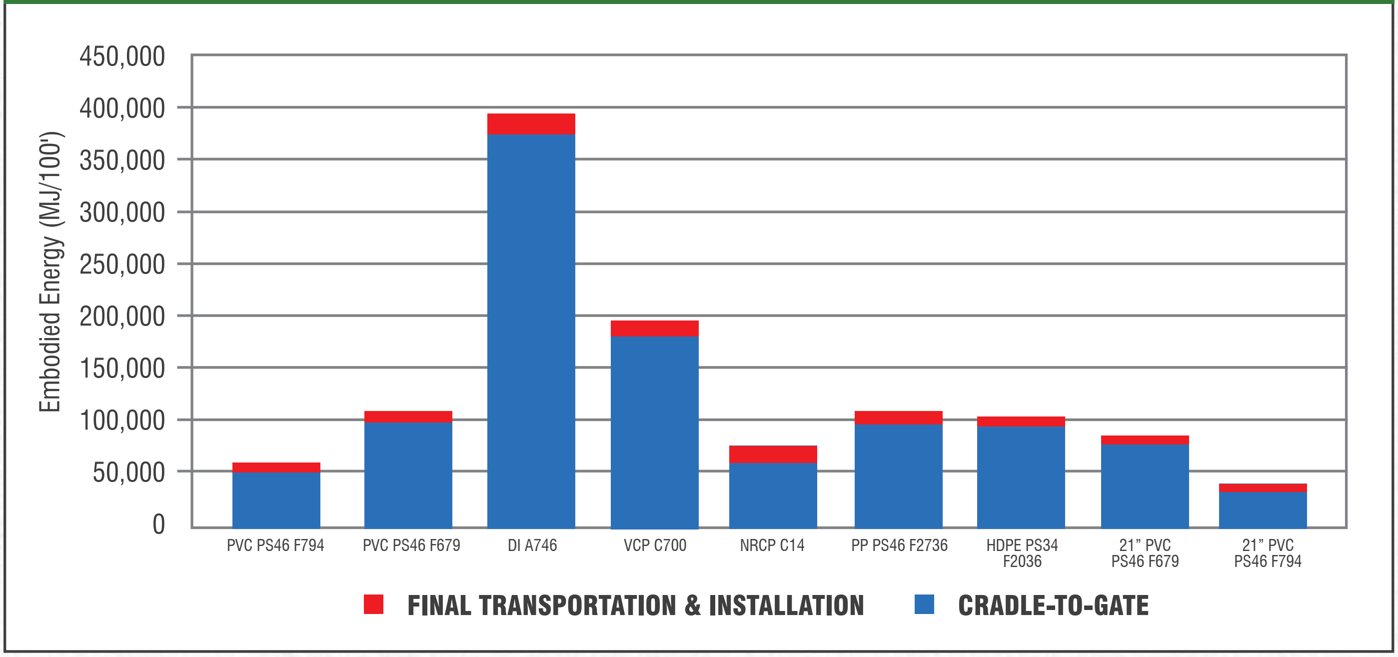


FIGURE 12.9 : TOTAL 100-YEAR EMBODIED ENERGY FOR 24” PVC PS46 SOLID-WALL & PROFILE-WALL EQUIVALENT GRAVITY PIPES



PVC has greater embodied energy compared to NRCP pipe, but NRCP is highly susceptible to deterioration from gases produced by wastewater. Due to this deterioration, NRCP would likely be required to be replaced two or more times during a 100-year design life for the pipe system. The corrosion of the pipe wall would also lead to increased infiltration and possibly pipe collapse. Increased infiltration significantly increases energy requirements and costs of a wastewater system. A pipe collapse not only requires large costs to repair, but could cause significant environmental contamination and endanger the safety of the public by undermining the support structure for buildings and roads built near sewer lines.

Figure 12.9 summarizes the total 100-year embodied energy values for the 24-inch solid-wall and profile-wall pipe alternatives. This figure includes the addition of 21-inch PVC solid-wall and profile-wall pipes that have been shown to have a flow capacity equivalent to the 24-inch DI, VCP, NRCP, PP and HDPE pipes in Table A.8 of the Appendix. PVC pipes with the same or greater carrying capacity have equal or better total 100-year embodied energy values than competitive pipe products.

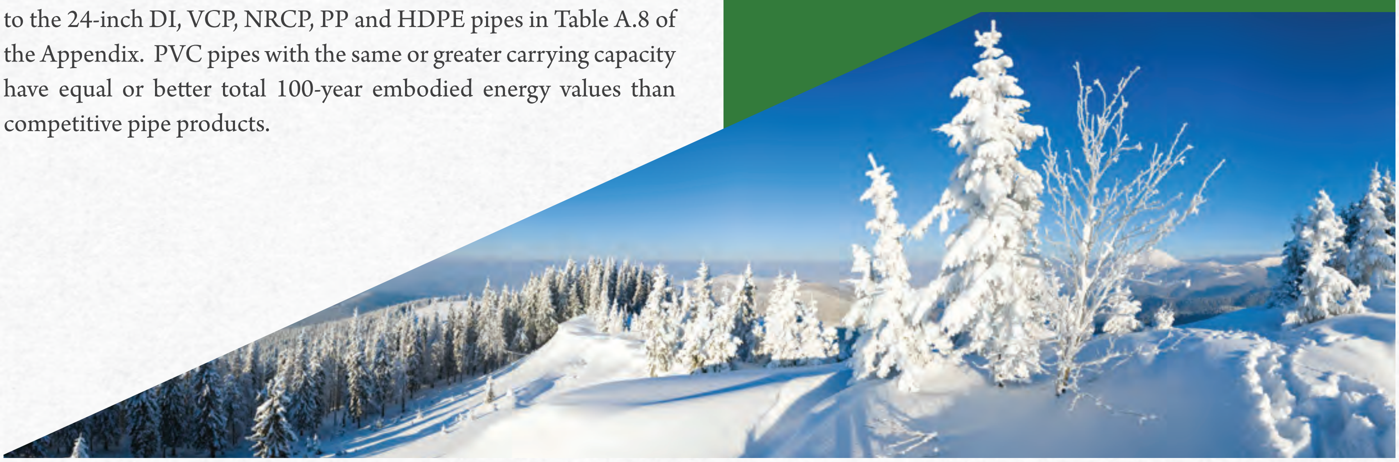
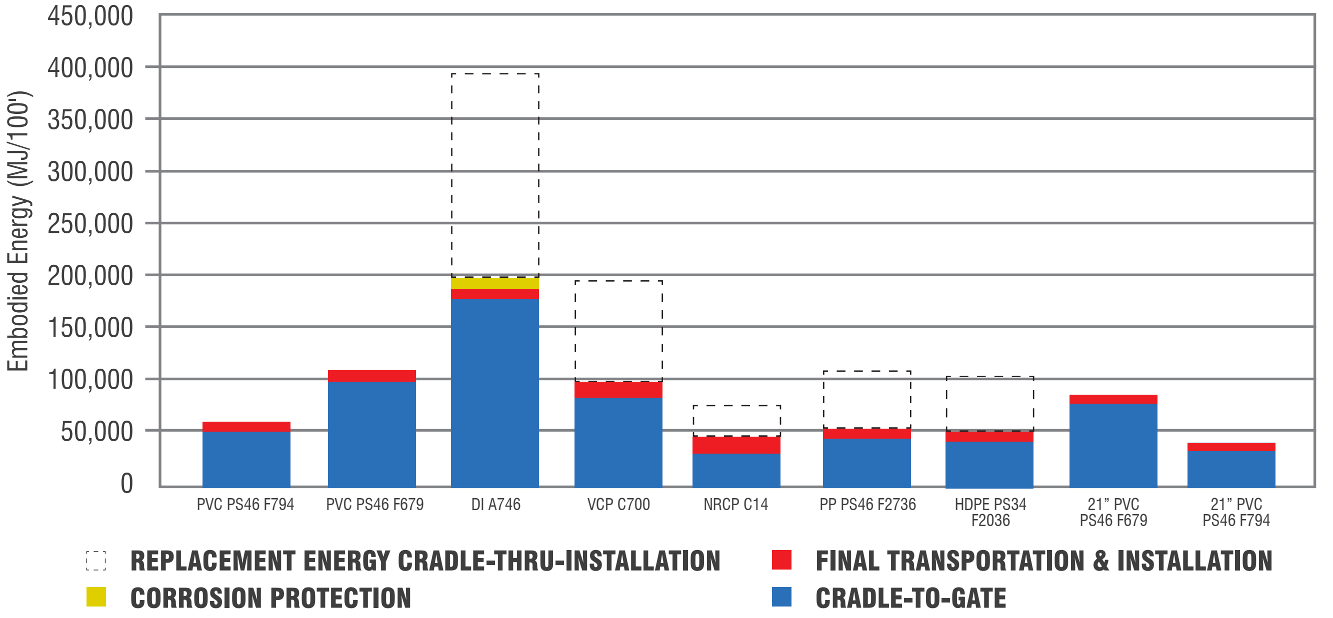


FIGURE 12.10 : TOTAL 100-YEAR EMBODIED ENERGY FOR 24" PVC PS46 SOLID-WALL & PROFILE-WALL EQUIVALENT GRAVITY PIPES



In order to be transparent, Figure 12.10 highlights the differences in embodied energy among the 24-inch gravity pipes without the needed replacements during the 100-year design life. Examination of Figure 12.10 reveals that 24-inch DI, VCP, PP and HDPE pipes have higher or equivalent 100-year embodied energies than PVC pipes even when replacement embodied energies are not considered.

Gravity pipeline design should be based on the flow-carrying capacity, which is a function of inside diameter and pipe roughness. Calculations show that on a common slope, 21-inch PVC pipes have equal or greater capacity than 24-inch pipes of alternative materials. The total 100-year embodied energy for the 21-inch PVC alternatives offer an even greater advantage over competitive pipes.

It is unrealistic to consider the use of the alternate pipe materials without anticipating at least one replacement during the 100-year life cycle. Issues with leaking, corrosion, brittleness, or strain creep may limit the economic feasibility of operating these pipelines beyond a certain point. DI and NRCP pipes' susceptibility to internal and external corrosion in a sanitary sewer environment will require that more than one replacement during a 100-year design life should be considered. The brittleness and joint issues with VCP and the strain creep and deflection issues with PP and HDPE limit the service life of those products, requiring at least one replacement during the 100-year design life. An important factor that was not included in the replacement embodied energy values shown in Figure 12.10 is the embodied energies associated with surface rehabilitation, road reconstruction, paving materials and traffic delays caused by reconstruction. Those factors could easily double the replacement embodied energy values. PVC with a service life in excess of 100 years would have an even greater advantage if the additional replacement embodied energy values were considered.

This report demonstrates the embodied energy and sustainability advantages in PVC pressure and gravity piping systems. Utilities that consider the sustainability, total embodied energy impacts and the effects of greenhouse gases on the environment should be selecting PVC pipes for their new and replacement projects. PVC should also be the clear choice for projects where utilities consider the total life cycle environmental and economic impacts for pipe materials.

13.0

CONCLUSIONS

Water system designers, purchasers, and operators who are responsible for reducing operational costs and environmental impacts should look at independently verified LCA results and EPDs as objective benchmarks of environmental performance.

13.1 Summary of LCA Findings and Conclusions

Below are some of the key findings and conclusions of the *LCA of PVC Pipe and Comparative Sustainability Analysis of Pipe Materials:*

- PVC pipe has the lowest carbon footprint when compared to most other pipe products for pressure and gravity pipe applications.
- PVC pipe does not emit or leach toxic substances in its manufacture or in its conveyance of water.
- PVC pipe does not corrode internally or externally or require chemical additives to inhibit corrosion.
- PVC pressure pipes provide long-term pumping energy savings due to corrosion resistance, smooth walls and large conveyance area.
- PVC gravity pipes have greater capacity than other materials due to their smooth walls, resistance to abrasion, resistance to infiltration and lack of corrosion.
- PVC pipe has a 100-year plus service life as verified by numerous studies and dig-ups.
- PVC gravity pipe has the lowest 100-year life cycle embodied energy – no replacements, no infiltration and no corrosion protection compared to other materials.
- PVC pressure pipe has the lowest 100-year life cycle embodied energy – no replacements, less pumping energy, lower main breaks and no corrosion protection compared to other materials.
- PVC pipe allows for reduced carbon footprints of water distribution systems due to the low embodied energy and pumping energy required.
- PVC pressure pipe has the lowest annual and life cycle pumping costs of any piping material.
- PVC pressure and gravity pipes have the lowest life cycle costs because of their low installation and operating costs and require no capital funding for replacements.
- PVC pipe is completely recyclable, but its durability has kept most of it from entering the recycling stream.
- A smaller diameter PVC gravity pipe can often be used to transport an equal amount of flow as larger-sized competitive pipe products. This decrease in material results in reduced life cycle impacts.

The majority of environmental impacts lie within the raw material extraction and processing required for PVC resin manufacturing and the installation of pipes in the ground. Comparatively little impact is caused by PVC pipe manufacturing facilities. From the feed-mix ingredients, PVC resin is responsible for the majority of all environmental impacts and use of resources, although additives were still found to have a significant impact. During pipe installation, it is the fuel consumed during the operation of the excavator which is responsible for significant impact.[150] Excavator use is common to all pipe installation operations regardless of the pipe material.

During the use stage of pressure pipe, pumps overcome friction and elevation head to move water through the pipe; this generally contributes the highest of the overall life cycle impacts of potable PVC water pipe. This study demonstrates that compared to other pipe materials during use stage, PVC's attributes reduce the friction head component of energy use and resulting environmental impacts. Second to the use stage, and for non-pressure storm water and sewer pipe, the cradle-to-gate stage is generally the primary source of environmental impacts.

Based on the results of this study, PVC pipe provides a competitive environmental and economic advantage for its use in a variety of water and sewer infrastructure projects, including life cycle cost advantages and the opportunity to substantially reduce GHGs compared to other materials. PVC pipe addresses affordability concerns and enables communities to work towards meeting their sustainable infrastructure goals because of its durability, low break rate, corrosion resistance and long-lasting performance.

APPENDIX

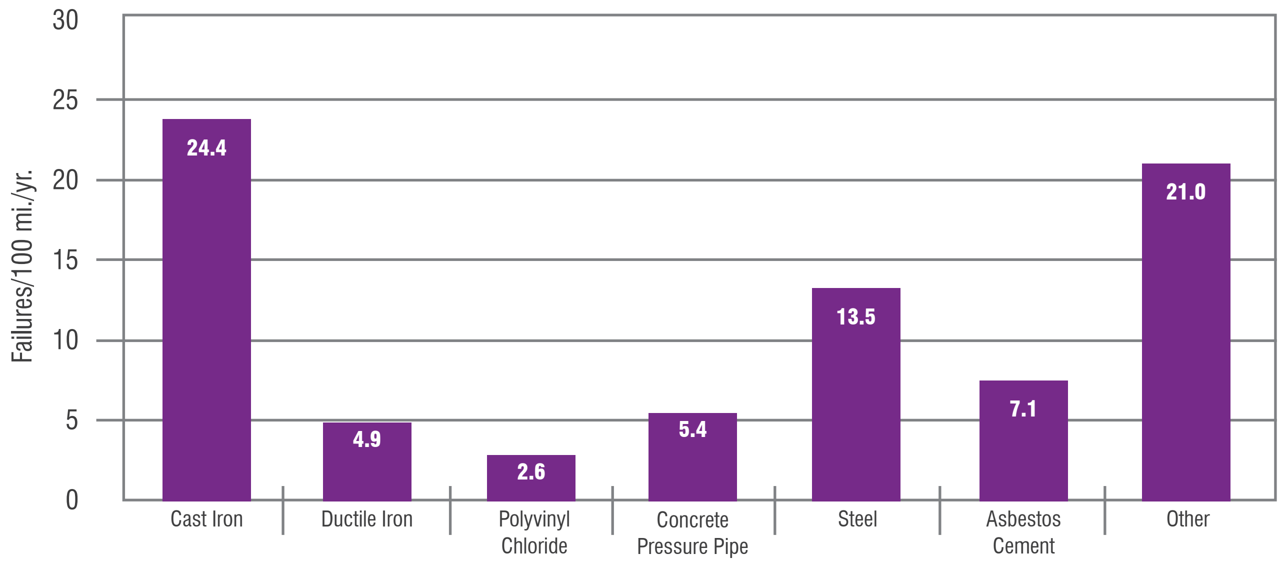
This Appendix documents the calculation methodology used throughout the report. Additional data and information are also provided on corrosion and water quality. For the pipe selections used in this study, the dimensions, weights, hydraulics and embodied energy parameters are described.

PRESSURE PIPE

▶ Main Breaks

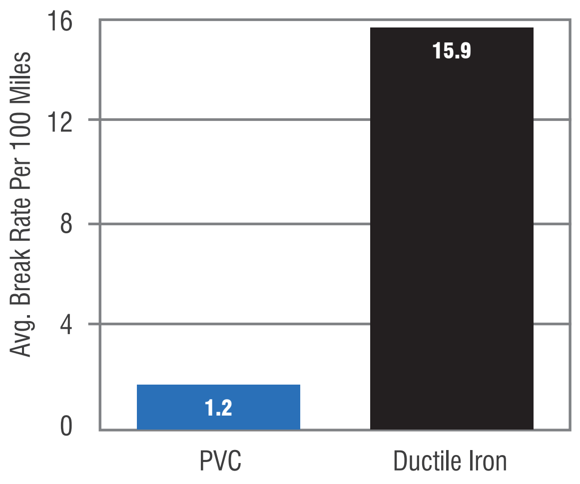
Water main breaks can be wasteful, dangerous and costly to repair. PVC pipes used in water distribution have substantially lower break rates than other materials. One study shows PVC pipe has an average rate of 2.6 breaks per 100 miles per year, versus 24.4 breaks for cast iron and 4.9 breaks for ductile iron as shown in Figure A.1.[151] The same study shows that for Canada the comparable figures were 0.7 breaks per 100 miles per year for PVC versus 35 for cast iron and 15.2 for DI. A study by the National Research Council (NRC) of Canada reported that historical break rates per 100 miles of pipe for ductile iron were 15.87. PVC exhibited only 1.17 breaks per 100 miles of pipe. The NRC report showed that ductile iron pipe had 13.57 times more breaks than PVC pipe. This difference in break rates results in significant repair cost differences for PVC and ductile iron, as shown in Figure A.2. Subsequent research in 1992 confirmed 14.9 breaks per 100 miles for DI and only 1.45 for PVC pipe. In 1993, additional data reported that DI pipe had 15.7 breaks per 100 miles, while PVC had 0.8 breaks per 100 miles.[152]

FIGURE A.1 : FAILURE RATES OF EACH PIPE MATERIAL PER 100 MILES OVER A ONE-YEAR PERIOD



Source: Folkman, S. "Water Main Break Rates in the USA and Canada: A Comprehensive Study." Utah State University Buried Structures Laboratory. April 2012.

FIGURE A.2 : NRC CANADA PVC AND DI PIPE BREAK RATES



A survey by Utah State University's Buried Structures Laboratory found that: [153]

- The average age of a failed pipe in the U.S. and Canada is 47 years.
- The cause for pipe failure depends on the pipe material.
- Corrosion does not cause PVC pipe failures.
- PVC pipe failures reduce with time.
- Ductile iron pipe failures increase with time due to corrosion.

"The failure rates are influenced by various factors like soil conditions, depth of installation, internal loads (operating and surge pressure), external loads (traffic and frost), temperature changes and bedding conditions."[154] PVC pipe has the lowest industry failure rates in the U.S. and Canada.[155]

Iron pipe fails primarily due to corrosion. According to a 2011 study by the AWWA Water Research Foundation, ductile iron pipes with the thinnest walls (representing the majority of metallic pipes sold) in moderately corrosive soils have a life expectancy of only 11 to 14 years.[156] "With corrosive soils affecting 75% of all U.S. water utilities, coupled with significant iron pipe wall thickness reductions over the last century, iron pipe longevity has plummeted."[157] The AWWA Water Research Foundation confirms the life expectancy of PVC water pipes in excess of 110 years and a European study determined PVC pipe's longevity at 170 years.[158 159] Also, a new study by Utah State University's Buried Structures Laboratory supports PVC as a sustainable pipe material with a service life in excess of 100 years.[160]

Pressure Pipe Water Loss

Water loss in pressure pipes has long been recognized and accounted for in water systems. Pipes subject to corrosion have had leakage from pitted pipe and leaking joints that have generated unmetered water loss and have created saturated trench lines. In the past repairs were undertaken only when the leaks reached the severity to create a pressurized stream above ground or caused a pavement failure. Unfortunately, there is little documentation of historic leak rates for the different pipe materials used in distribution systems. There is, however, documentation on failure rates of different pipe materials. The study *Water Main Break Rates in the USA and Canada: A Comprehensive Study* was used to identify the water main break loss volume per 100 feet.[161] Based on the water main break rates per 100 miles per year identified in the study, the water loss per 100 feet of pipe per year was calculated assuming a 240-minute time to shut off a break and a flow rate roughly equivalent to the flow produced at 2 feet per second (fps). The annual volume loss due to water main breaks for each pipe material was then converted to the 100-year embodied energy for the lost water using 1,410 kWh/million gallons determined by the study, *Embodied Energy of Lost Water: Evaluating the Energy Efficiency of Infrastructure Investments.*[162]

Water loss related to main breaks was considered in this study for the embodied energy calculations for pressure pipes. Water main breaks can have great variations in volume of water loss due to the size of the break and the time before the break is discovered and shut off. While there are many variables to take into consideration for leaks and breaks, for the purposes of this study the flow rate was assumed to be common to all pipe alternatives within each pressure class based on the volumetric flow rate for PVC pipe at 2 fps of velocity. As stated previously, all pipe break rate data to calculate water loss are listed in Figure A.1. The break rates used for DI pipe for this study are conservative per Table A.1 which shows that other studies assign a much higher break rate for ductile iron pipes.[163 164 165] Table A.2 provides the data, calculations and results for the 100-year water loss embodied energy for each pipe material.

TABLE A.1 : WATER MAIN BREAKS AND FAILURE RATE SURVEYS/STUDIES

Study	Year	Methodology	Failure Rate			Limitations
			CI Pipe	DI Pipe	PVC Pipe	
Rajani and McDonald	1992	21 survey responses from Canada	56.2	14.9	1.44	Diameter, size, age of pipe, failure rate for each utility, regression analysis of failure not given
	1993		58.7	15.7	0.8	
Folkman	2012	188 survey responses from U.S. and Canada	24.4	4.9	2.6	Less than 24" diameter size, failure rate for each utility not given
CUIRE	2012	21 survey responses from U.S.	49.3	9.5	N/A*	Larger than 24" diameter size, failure rate for each year not given

**PVC was not included in this study.*

TABLE A.2 : WATER LOSS VOLUME PER YEAR AND 100-YEAR WATER LOSS EMBODIED ENERGY

Pipe Material	PVC Size/DR/PC	Flow Rate (gpm)	Break Time (min)	Failure Rate (#/100'/yr.)	Annual Loss Volume (gal/100'/yr.)	Treated Water Embodied Energy (kWh/Mgal)	100-Year Water Loss Embodied Energy (kWh/100')
PVC	8"/18/235	312	240	0.000492	36.9	1410	5.2
	24"/25/165	2730	240	0.000492	322.6	1410	45.5
DI	8"/-/350	312	240	0.000928	69.5	1410	9.8
	24"/-/200	2730	240	0.000928	608.0	1410	85.7
HDPE	8"/9.0/250	312	240	0.000492	36.9	1410	5.2
	24"/13.5/160	2730	240	0.000492	322.6	1410	45.5
PCCP	24"/-/200	2730	240	0.001023	670.0	1410	94.5

Pressure Pipe: Hydraulic Energy Calculations

In order to make calculations over a 100-year period for underground pipe infrastructure, various assumptions and methodologies were required. The ensuing tables and figures apply the following assumptions in the computations for the comparison of pressure pipe products:

- Use the computed average internal diameter for each pipe to be compared and compute the conveyance area of the pipe.
- Compute the flow for the PVC pipe to be compared based on 2 fps velocity in the PVC pipe.
- Using the computed pipe flow rate, calculate the pipe friction head loss in feet per 100 feet using the Hazen-Williams equation with the C factor based on the annual deterioration rate for the pipe being compared and any replacements that reset the C factor.
- Compute hydraulic power based on flow rate and head loss.
- Determine pump power required based on an assumed pump efficiency of 75%.
- Calculate motor horsepower required based on an assumed motor efficiency of 90%.
- Compute motor electrical power required in kilowatts.
- Compute annual electrical energy required based on total hours per year and kWh per 100 feet required.
- Compute annual energy cost per 100 feet using an assumed cost of energy starting at \$0.07/kWh and increasing by \$0.01/kWh per decade.
- Determine total 100-year energy required by totaling annual energy requirements.
- Determine total 100-year energy cost by totaling annual energy costs.

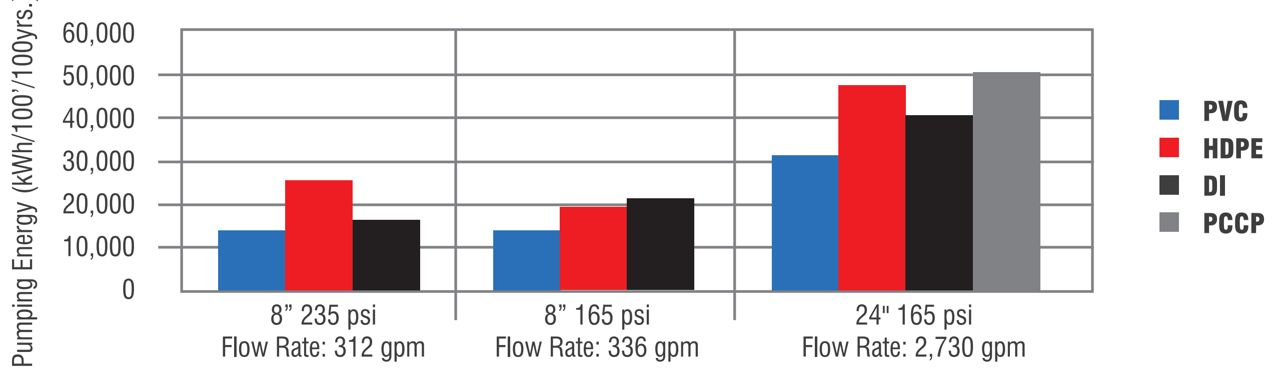
Note that comparisons cannot be made across PVC pipe pressure classes, since the flows are based on the internal diameter of each specific pressure class of pipe. Total 100-year pumping energy and cost per 100 feet for each pipe are shown in Table A.3. The results for the total 100-year pumping energy per 100 feet are shown graphically in Figure A.3. The results for the total pumping costs per 100 feet are shown graphically in Figure A.4.

TABLE A.3 : 100-YEAR PUMPING ENERGY PER 100 FEET AND 100-YEAR PUMPING COST PER 100 FEET OF PIPE

Pipe Material	Comparable PVC Size and Pressure Class					
	8" 235 psi		8" 165 psi		24" 165 psi	
	kWh/100'/100 yrs.	$/100'/100 yrs.	kWh/100'/100 yrs.	$/100'/100 yrs.	kWh/100'/100 yrs.	$/100'/100 yrs.
PVC	12,700	$1,500	13,100	$1,500	31,500	$3,600
HDPE	25,400	$2,900	19,400	$2,200	46,800	$5,400
DI	16,400	$1,900	20,200	$2,300	40,000	$4,600
PCCP	N/A	N/A	N/A	N/A	50,100	$5,800

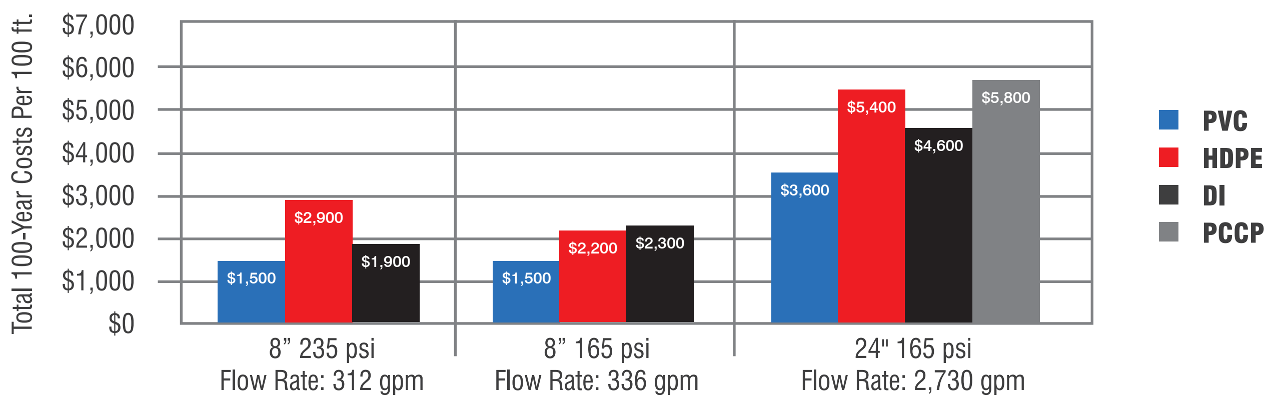
Note: Table assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

FIGURE A.3 : TOTAL 100-YEAR PUMPING ENERGY USE PER 100 FEET OF PIPE



Note: Graph assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

FIGURE A.4 : TOTAL 100-YEAR PUMPING ENERGY COSTS PER 100 FEET OF PIPE



Note: Graph assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

Pressure Pipe: Total Embodied Energy Calculations

The pumping energy over the 100-year design life is a major component of the total embodied energy of a pressure pipeline. This includes cradle-to-gate energy for pipe manufacturing, transportation and installation energy, energy associated with corrosion protection, pumping energy over the life cycle period, energy required for replacement if needed during the life cycle period and the energy related to lost water from leaks and repairs.

Not all life cycle energy is easy to quantify (such as energy for maintenance and repair). The embodied energy comparisons for the PVC pressure pipes are based on size and pressure class. The total 100-year embodied energy associated with the PVC pressure pipe comparisons in this study are summarized in Tables A.4, A.5 and A.6. Figures A.5, A.6 and A.7 illustrate the total 100-year life cycle embodied energy advantage of PVC pipe.

TABLE A.4 : 100-YEAR TOTAL EMBODIED ENERGY (MJ/100') FOR 8" PVC DR18 PC235 C900 COMPARISON

100-Year Life Cycle Activity	8" PVC DR18 Comparison		
	PVC DR18 PC235	HDPE 4710 DR9 PC250	DI CL51 PC350
Cradle-to-Gate	23,300	42,600	50,900
Final Transportation & Installation	4,100	4,700	5,300
Corrosion Protection	N/A	N/A	3,300
Total Cradle-Through-Installation	27,400	47,300	59,500
Replacement	N/A	47,300	59,500
100-Year Hydraulic Energy	45,700	91,400	59,000
Water Loss/100 Years	19	19	35
Total 100-Year Embodied Energy	73,100	186,000	178,000

FIGURE A.5 : 8" PVC DR18 EQUIVALENT PIPES: 100-YEAR TOTAL EMBODIED ENERGY

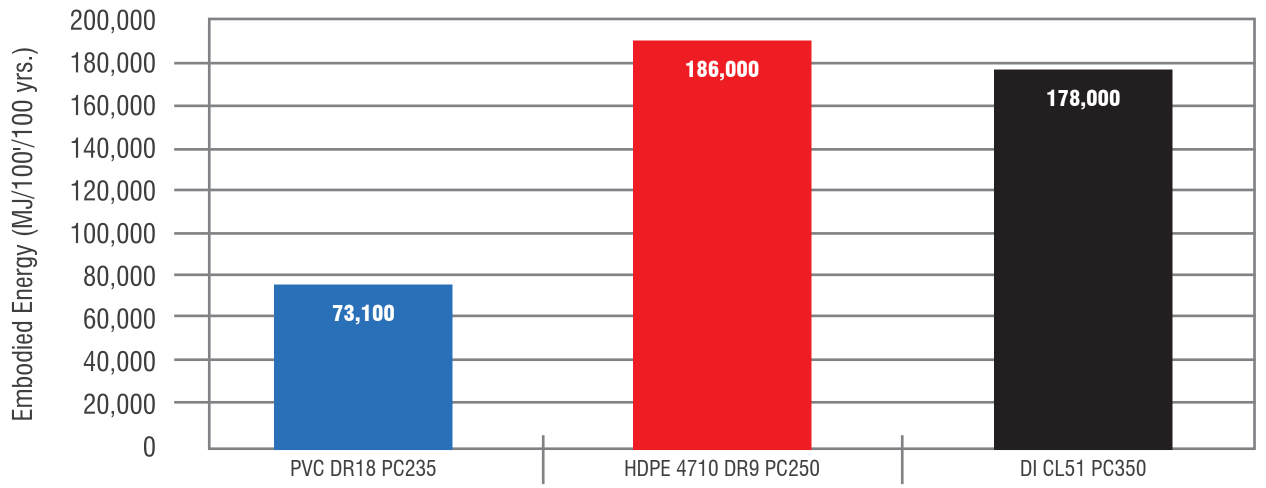


TABLE A.5 : 100-YEAR TOTAL EMBODIED ENERGY (MJ/100') FOR 8" PVC DR25 PC165 C900 COMPARISON

100-Year Life Cycle Activity	8" PVC DR25 Comparison		
	PVC DR25 PC165	HDPE 4710 DR13.5 PC160	DI CL51 PC350
Cradle-to-Gate	15,900	29,600	50,900
Final Transportation & Installation	4,000	4,400	5,300
Corrosion Protection	N/A	N/A	3,300
Total Cradle-Through-Installation	19,900	34,000	59,500
Replacement	N/A	34,000	59,500
100-Year Hydraulic Energy	47,000	70,000	72,700
Water Loss/100 Years	19	19	35
Total 100-Year Embodied Energy	66,900	138,000	191,700

FIGURE A.6 : 8" PVC DR25 EQUIVALENT PIPES: 100-YEAR TOTAL EMBODIED ENERGY

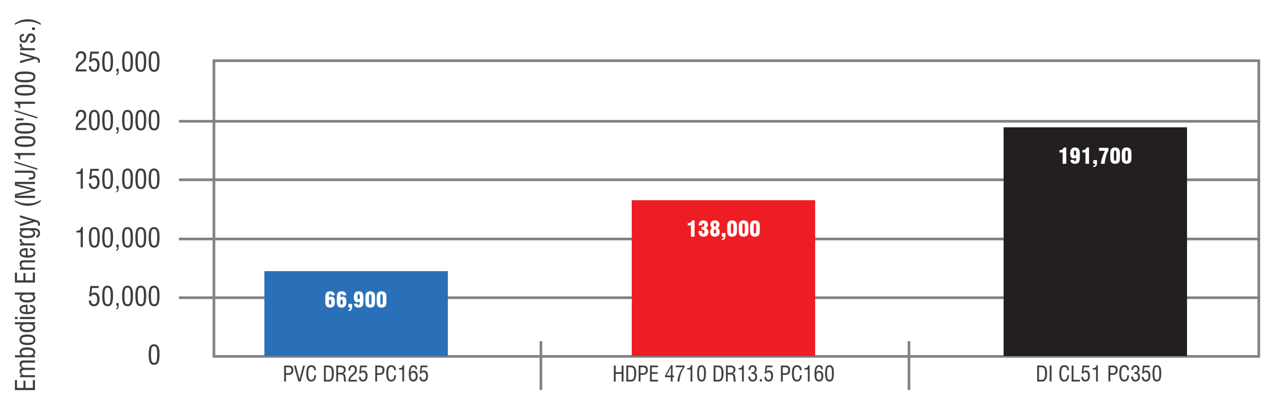
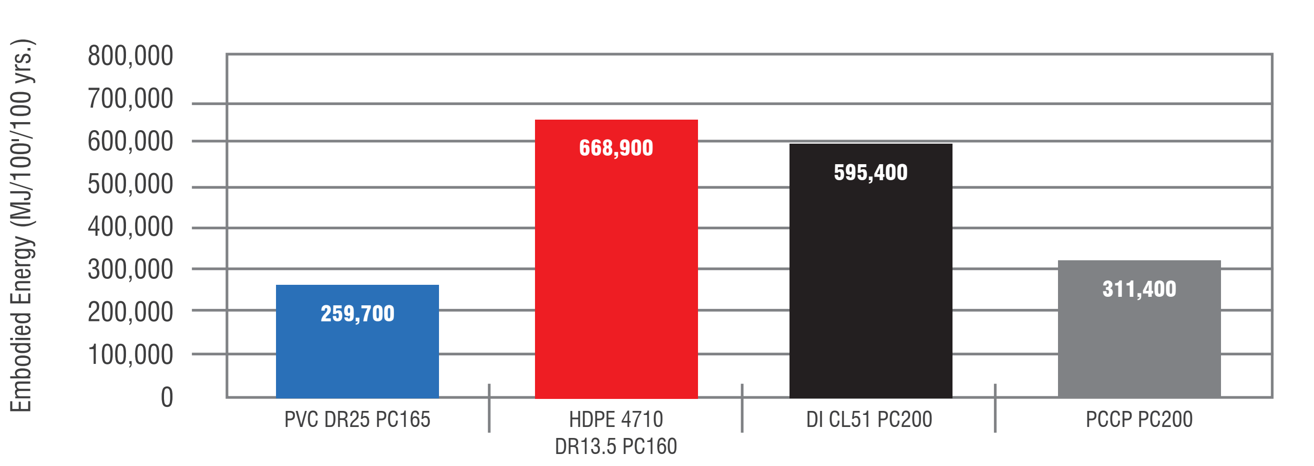


TABLE A.6 : 100-YEAR TOTAL EMBODIED ENERGY (MJ/100') 24" PVC DR25 PC165 C905 COMPARISON

100-Year Life Cycle Activity	24" PVC DR25 Comparison			
	PVC DR25 PC165	HDPE 4710 DR13.5 PC160	DI CL51 PC200	PCCP PC200
Cradle-to-Gate	137,900	240,800	206,600	53,500
Final Transportation & Installation	8,300	9,300	10,000	11,900
Corrosion Protection	N/A	N/A	8,900	N/A
Total Cradle-Through-Installation	146,200	250,100	225,500	65,400
Replacement	N/A	250,100	225,500	65,400
100-Year Hydraulic Energy	113,300	168,500	144,100	180,300
Water Loss/100 Years	160	160	310	340
Total 100-Year Embodied Energy	259,700	668,900	595,400	311,400

FIGURE A.7 : 24" PVC DR25 EQUIVALENT PIPES: 100-YEAR TOTAL EMBODIED ENERGY



GRAVITY PIPE

The capacity of a gravity pipe is determined by its flow rate for a given diameter at a given slope. Capacity comparisons for gravity pipes were based on the slope required to achieve a flow velocity of 2 feet per second (fps). For each gravity pipe type, the slope used for the comparison was set for the requirement to achieve the minimum flow for 2 fps. The pipe with the worst flow characteristics, in other words the pipe which required the steepest slope to achieve a minimum flow velocity of 2 fps, was used as the baseline for comparing all the other gravity pipes for each pipe type. With its smooth interior walls, PVC consistently had the greatest flow capacity for each pipe type on the slope determined. In some cases a smaller diameter PVC sewer pipe achieved similar or greater flows than larger competitive products, generating savings in embodied energy and costs.

Specifications for design of gravity pipe systems often use the least efficient pipes to set base values for flow coefficients and minimum slopes. This has the effect of reducing the advantages of more efficient materials like PVC pipe. These less efficient design standards, which include higher Manning's n and steeper minimum slope requirements, result in increased pipe size and add unnecessary costs to underground infrastructure projects.

▶ Gravity Pipe Total Embodied Energy Calculations

The total 100-year embodied energy calculations for gravity pipes include:

- Cradle-to-gate energy for the pipe manufacturing
- Transportation and installation energy
- Energy associated with the protection of corroding pipes
- Energy if a replacement is required during the life cycle period

The total 100-year embodied energy values for the gravity pipes used in this study are listed in Table A.7 and shown in Figures A.8 and A.9.

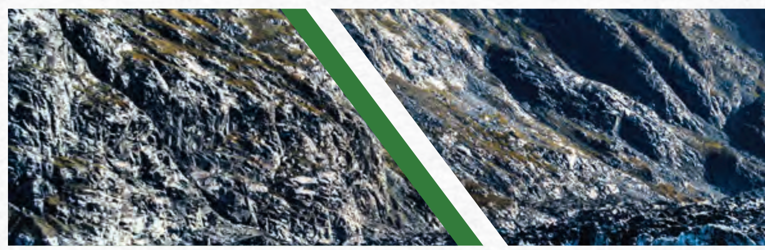


TABLE A.7 : GRAVITY PIPE TOTAL 100-YEAR EMBODIED ENERGY COMPARISONS INCLUDING REPLACEMENTS

PVC Size and Product	Comparable Products	Standard	100-Year Embodied Energy (MJ/100')
8" PVC PS46 F794 Profile Wall	8" PVC PS46	ASTM F794	9,800
	8" DI	ASTM A746	108,500
24" PVC PS46 F794 Profile Wall	24" PVC PS46	ASTM F794	57,400
	24" PP PS46	ASTM 2736	102,900
	24" HDPE PS34	ASTM 2306	101,200
	21" PVC PS46	ASTM F794	43,300
8" PVC PS46 SDR35 D3034 Solid Wall	8" PVC PS46	ASTM D3034	13,900
	8" DI	ASTM A746	108,500
	8" VCP	ASTM C700	38,400
24" PVC PS46 F679 Solid Wall	24" PVC PS46	ASTM F679	107,700
	24" DI	ASTM A746	376,000
	24" VCP	ASTM C700	193,800
	24" NRCP	ASTM C14	77,100
	21" PVC PS46	ASTM F679	83,100

Note: All ductile iron sewer pipes in this study are double cement-lined per AWWA C104.

FIGURE A.8 : TOTAL 100-YEAR EMBODIED ENERGY FOR 24" GRAVITY PIPE PRODUCTS

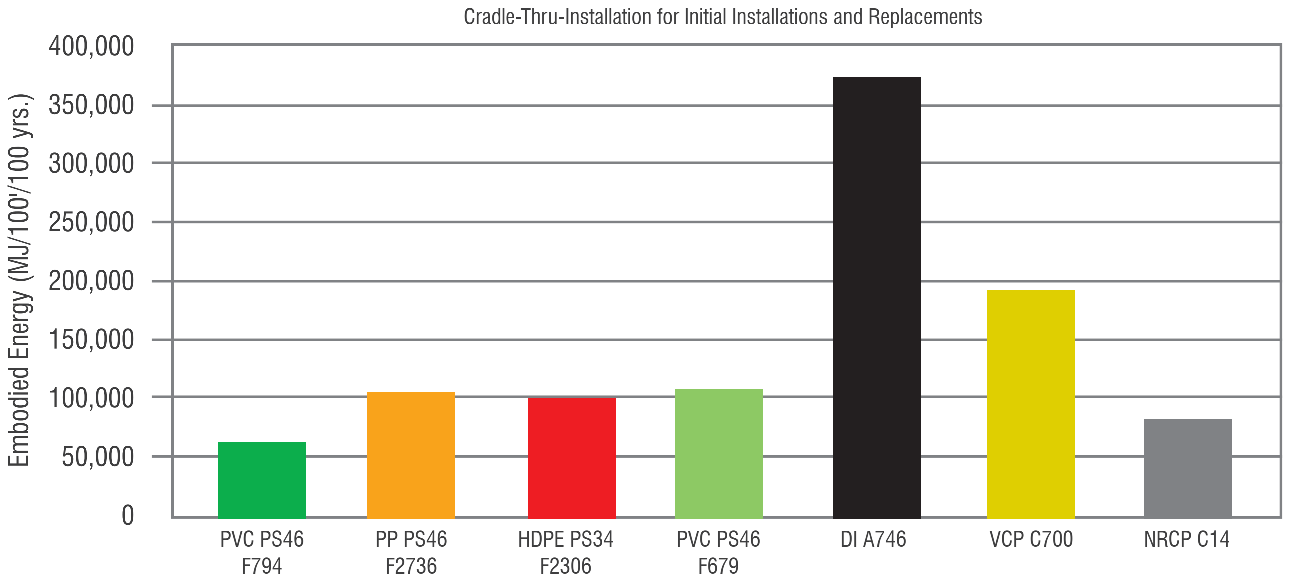
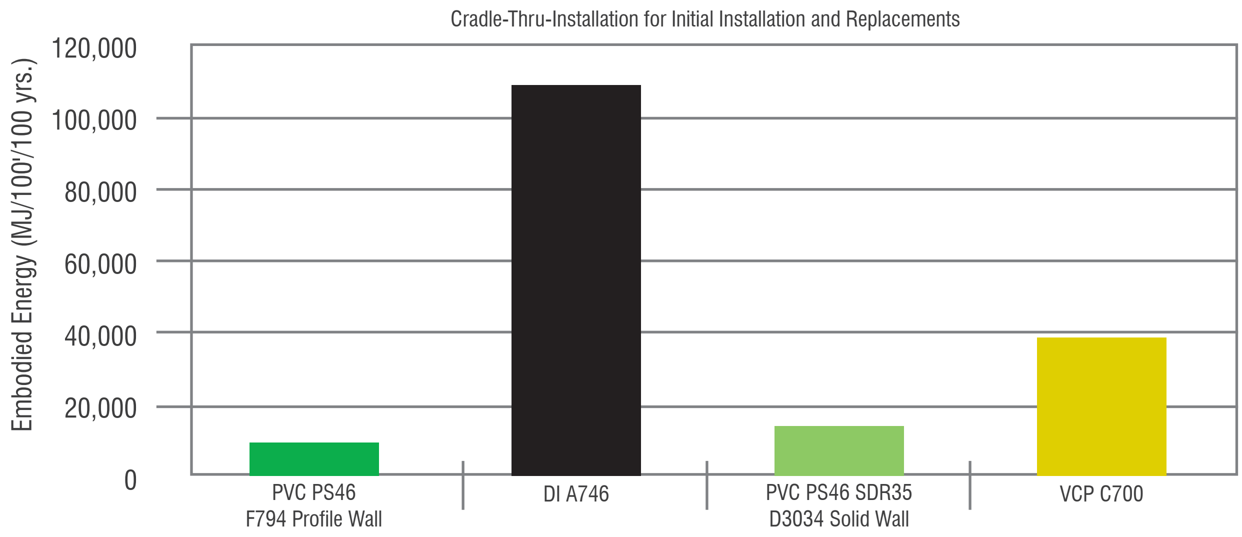


FIGURE A.9 : TOTAL 100-YEAR EMBODIED ENERGY FOR 8" GRAVITY PIPE PRODUCTS



Using the same slope as the pipe with the steepest slope required to achieve a flow velocity of 2 fps, volumetric flows for the other comparison pipes were calculated and compared. In addition, for the 24-inch pipe size options, the next size smaller PVC pipe was evaluated.

The flow-carrying capacities of the pipe materials compared were examined using the procedure described herein. The capacities based on the procedure are shown in Table A.8.

Figure A.10 demonstrates that 8-inch PVC PS46 ASTM F794 profile-wall pipe has a greater capacity than the 8-inch ductile iron ASTM A746 pipe. The 8-inch DI pipe has almost 20% less capacity than the 8-inch profile-wall PVC pipe on the same slope.

Figure A.11 shows that the 24-inch PVC ASTM F794 profile-wall pipe has greater flow capacity than the competitive profile-wall pipe products, 24-inch PP ASTM F2736 and 24-inch HDPE ASTM F2306. The PP and HDPE profile-wall pipes have 23% and 21% less capacity than the 24-inch profile-wall PVC pipe on the same slope, respectively. As part of the study, smaller PVC pipe products were compared to larger competitive pipe products. The 21-inch PVC profile-wall pipe has just slightly less capacity than PP and HDPE pipes on the same slope. In situations when the design flow is very close to the capacity of the PP and HDPE products, a smaller size of PVC pipe could meet the flow requirements with greater savings in embodied energy and costs.

Figure A.12 shows the comparison of 8-inch solid-wall gravity pipe products. As can be seen in Figure A.12, and as can be calculated from Table A.8, the commonly used 8-inch PVC ASTM D3034 solid-wall pipe has 25% more capacity than 8-inch DI pipe on the same slope. The 8-inch PVC also has over 56% more capacity than the 8-inch VCP pipe on the same slope. The 8-inch pipe size is the standard minimum size pipe in many sanitary sewer systems across the country because it allows room for cleaning and maintenance activities while providing adequate capacity for most residential and commercial development blocks. In scenarios where the flow is increasing because of the size of the collection area, the superior flow capacity of 8-inch PVC pipe may be able to serve a larger area before there is a need to increase the pipe size for additional flow capacity.

TABLE A.8 : GRAVITY PIPE FLOW COMPARISONS USING A COMMON SLOPE

Size and Wall Type	Pipe Product Description	Standard	n	Slope (ft./ft.)	Computed Velocity (ft./sec.)	Computed Flow (cfs)	Diff in Q (%)
24" Profile Wall Sewer	24” PVC PS46	ASTM F794	0.009	0.00067	2.6	7.98	0.0
	24” PP PS46	ASTM F2736	0.012	0.00067	2.0	6.17	-22.7
	24” HDPE PS34	ASTM F2306	0.012	0.00067	2.0	6.32	-20.8
	21” PVC PS46	ASTM F794	0.009	0.00067	2.4	5.72	-28.3
8" Profile Wall Sewer	8” PVC PS46	ASTM F794	0.009	0.0032	2.8	0.94	0.0
	8” DI PC350	ASTM A746	0.013	0.0032	2.0	0.76	-19.5
8" Solid Wall Sewer	8” PVC PS46 SDR35	ASTM D3034	0.009	0.0035	2.9	1.00	0.0
	8” DI PC350	ASTM A746	0.013	0.0035	2.1	0.80	-19.5
	8” VCP	ASTM C700	0.013	0.0035	2.0	0.64	-35.4
24" Solid Wall Sewer	24” PVC PS46	ASTM F679	0.009	0.00081	2.9	8.71	0.0
	24” DI PC250	ASTM A746	0.013	0.00081	2.1	7.01	-19.6
	24” VCP	ASTM C700	0.013	0.00081	2.0	5.80	-33.4
	24” NRCP	ASTM C14	0.013	0.00081	2.1	6.45	-25.9
	21” PVC PS46	ASTM F679	0.009	0.00081	2.7	6.36	-27.0

Note: All ductile iron sewer pipes in this study are double cement-lined per AWWA C104.

FIGURE A.10 : 8" PROFILE-WALL PVC GRAVITY PIPE FLOW COMPARISONS WITH EQUIVALENT SLOPE

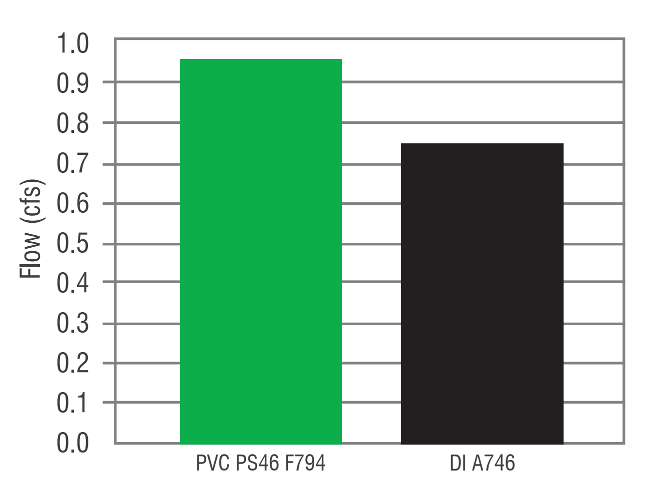


FIGURE A.11 : 24" PROFILE-WALL PVC GRAVITY PIPE FLOW COMPARISONS WITH EQUIVALENT SLOPE

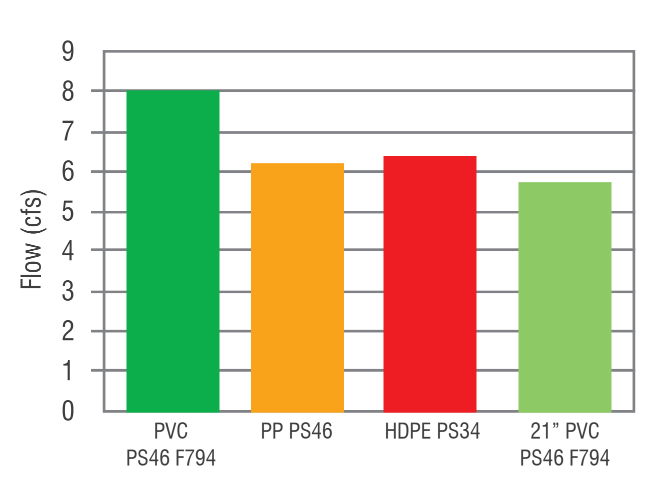


FIGURE A.12 : 8" SOLID-WALL PVC GRAVITY PIPE FLOW COMPARISONS WITH EQUIVALENT SLOPE

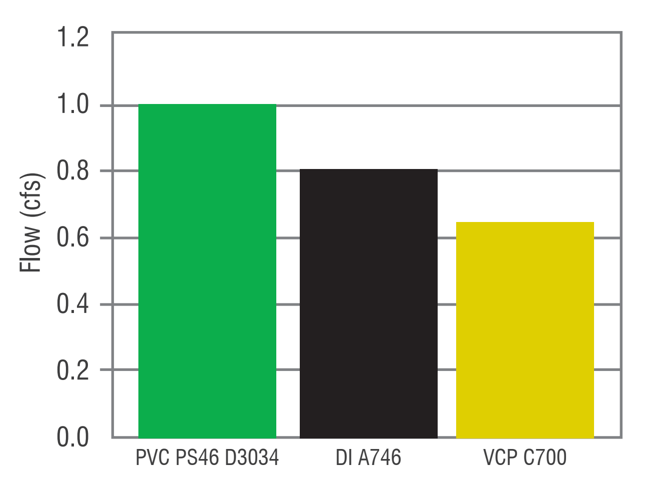


FIGURE A.13 : 24" SOLID-WALL PVC GRAVITY PIPE FLOW COMPARISONS WITH EQUIVALENT SLOPE

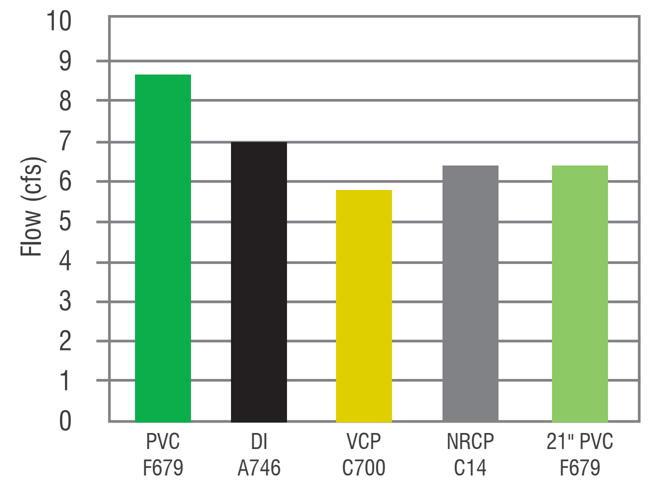


Figure A.13 compares PVC ASTM F679 pipe to other 24-inch solid-wall products. PVC has over 24% more capacity than DI pipe, over 50% more than clay pipe, and 35% more than non-reinforced concrete pipe (NRCP) on the same slope.

On the same slope, a 21-inch solid-wall PVC pipe has the following capacities relative to alternative 24-inch products:

- Only 9% less capacity than 24-inch DI pipe
- About 10% more capacity than 24-inch VCP
- Only 1% less capacity than 24-inch NRCP

A smaller PVC gravity pipe can have the same capacity as a larger competitive pipe product because of its superior flow characteristics. When sizing pipe, design engineers should look closely at the capacities of PVC pipe products based on their design attributes.

Since gravity pipes use no power, the energy use comes primarily from the embodied energy in the pipe from cradle through the installation. This energy, as well as the energy for new replacement pipes during the 100-year design life, can be quantified; however, there are many other instances where gravity pipes require or create energy use. Some of these include (but were not quantifiable) maintenance activities and the energy to treat infiltration flows.

▶ Infiltration Flows

Certain pipe materials can create a need for energy use to treat the surface and ground water that enters the pipes through leaking joints, cracked pipe and corrosion. The infiltration water can be more than four times the normal flows during rain events. Infiltration creates the need for a huge amount of embodied energy in up-sizing pipes to accommodate the additional flow capacity, in constructing storage capacity to store the extra flow, in adding pumping capacity and in treating the wastewater. There may be also additional costs in fines, administrative orders and capital improvements to prevent overflows of raw sewage. To date, research tying infiltration rates to specific pipe materials has not been available to quantify the huge amount of additional energy required due to infiltration. PVC pipe attributes, such as leak free joint and corrosion resistance, make it the logical choice for use as a sewer pipe product that does not create infiltration demand.

PIPE MATERIAL EMBODIED ENERGY SUMMARY

Table A.9 lists the cradle-to-gate (i.e., from raw materials through manufacturing, excluding final product transportation and installation) embodied energy for 100 feet of pipe for PVC and for each material that is similar in specification to the PVC products analyzed in the study. Understanding that each material result is derived from a different source with varying degrees of data quality, cradle-to-gate embodied energy values for the various pipe products can still be illustrated.

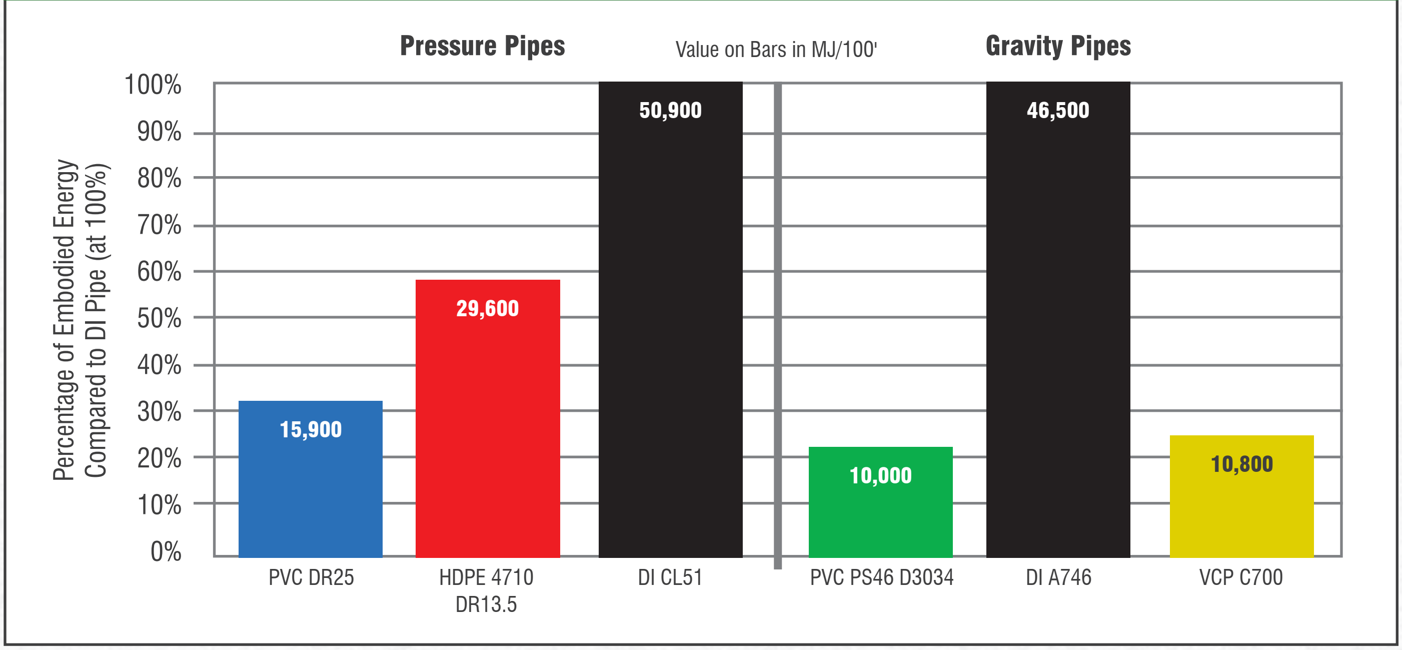
TABLE A.9 : SUMMARY OF CRADLE-TO-GATE EMBODIED ENERGY FOR PVC AND ALTERNATIVE PIPE MATERIALS

PVC Size and Product	Comparable Products	Standard	Embodied Energy (MJ/100 ft.)
8” PVC DR18 PC235 C900	8” PVC DR18	AWWA C900	23,300
	8” HDPE 4710 DR9	AWWA C906	42,600
	8” DI CL51	AWWA C151	50,900
8” PVC DR25 PC165 C900	8” PVC DR25	AWWA C900	15,900
	8” HDPE 4710 DR13.5	AWWA C906	29,600
	8” DI CL51	AWWA C151	50,900
24” PVC DR25 PC165 C905	24” PVC DR25	AWWA C905	137,900
	24” HDPE 4710 DR13.5	AWWA C906	240,800
	24” DI CL51	AWWA C151 AWWA C104	206,600
	24” PCCP PC200	AWWA C301	53,500
24” PVC PS46 F794 Profile Wall	24” PVC PS46	ASTM F794 AASHTO M304	49,700
	24” PP PS46	ASTM F2736	43,700
	24” HDPE PS34	ASTM F2306	42,900
8” PVC PS46 F794 Profile Wall	8” PVC PS46	ASTM F794 AASHTO M304	5,900
	8” DI	ASTM A746	46,500
8” PVC PS46 SDR35 D3034 Solid Wall	8” PVC PS46	ASTM D3034	10,000
	8” DI	ASTM A746	46,500
	8" VCP	ASTM C700	10,800
24” PVC PS46 F679 Solid Wall	24” PVC PS46	ASTM F679	98,600
	24” DI	ASTM A746	176,600
	24” VCP	ASTM C700	82,400
	24" NRCP	ASTM C14	21,300

Note: All ductile iron pressure pipes in this study are cement-lined per AWWA C104.
All ductile iron sewer pipes in this study are double cement-lined per AWWA C104.

Figure A.14 compares other pipe materials to the embodied energy of DI pipe which is set at 100% given that it has the highest embodied energy values. The embodied energy of PVC pipe is competitive when compared to DI pipe and other alternate materials. The 8-inch PVC DR25 pressure pipe is 69% lower in embodied energy than cement-lined DI pipes and 46% less than HDPE. If a pipe material is required to be replaced during the 100-year life cycle, the embodied energy of that material is increased accordingly. The total cradle-to-gate embodied energy for 8-inch PVC PS46 D3034 gravity pipe is 83% less than cement-lined DI pipe when replacements are considered during the 100-year design life.

FIGURE A.14 : CRADLE-TO-GATE EMBODIED ENERGY COMPARISONS FOR EQUIVALENT 8" PIPES (MJ/100')



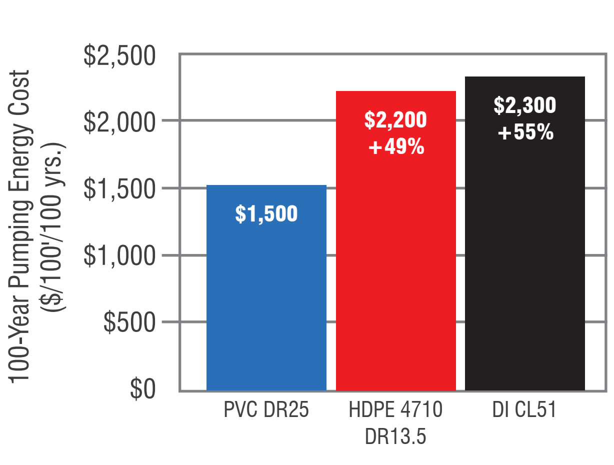
Note: Total 100-year embodied energy includes cradle-through-installation, required replacements and corrosion protection.

PUMPING ENERGY COMPARISONS OVER A 100-YEAR LIFE CYCLE

Water distribution systems require significant amounts of pumping energy to overcome frictional forces between the walls of the pipe and the flowing water. The energy required to pump water through PVC pipe remains constant over the life of the pipe, unlike metallic and concrete pipes. This generates overall life cycle cost savings and a lower carbon footprint compared to materials that require more pumping energy over time due to the roughening of their interior surfaces from corrosion and internal degradation.

In Figure A.15 8-inch PVC DR25 water pipe has a lower 100-year life cycle pumping cost per 100 feet because of its lower pumping energy demand than HDPE and ductile iron piping materials. The energy required to pump water through a pressurized pipe system over the life of the pipe is a significant source of potential environmental impacts.

FIGURE A.15 : PUMPING ENERGY COST OF 8" PVC DR25 EQUIVALENT PIPES OVER A 100-YEAR LIFE CYCLE



Note: Graph assumes replacement of HDPE and DI pipe at 50 years.

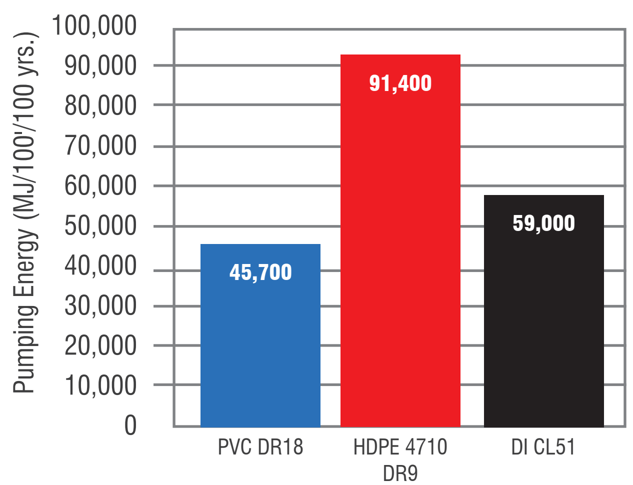
PVC pipe is not subject to corrosion, unlike iron and concrete pipes, or chemical oxidation which affects HDPE. Corrosion and chemical oxidation increase the risk of pipe failure and water loss and reduce the sustainability benefits for water utilities.

Corrosion affects 75% of water utilities.[166] Durability and corrosion resistance of a pipe greatly affect the life cycle environmental impacts. Ductile iron pipe may last as little as 11-14 years in moderately corrosive soils requiring it to be replaced many times over a 100-year period.[167] This increases the embodied environmental impacts of iron pipe by up to 9 times compared to PVC pipe.

The pumping energy represents between 24% and 75% of the total 100-year embodied energy depending on the size and pipe material. The smooth, inner wall of PVC pipe helps minimize that impact. The fact that PVC does not corrode means that PVC pipe has, over the piping system's design life, reduced pumping energy and reduced operational costs compared to corrosion-prone pipe materials. In addition, PVC pipe does not experience the increase in pipe friction and pumping energy over time that is characteristic of cement-lined pipes.

More utilities and local governments are implementing strategies to reduce greenhouse gas emissions as part of their long-term goals. Municipal water treatment and delivery systems require a significant amount of energy for moving water. Water and wastewater utilities often consume as much as 40% of a municipality's total energy consumption.[168] Choosing PVC pipe provides low embodied impacts and consistently smooth, non-corroding walls which help utilities and local governments minimize the energy (and GHGs) required in their water systems.

FIGURE A.16 : 8" PVC DR18 EQUIVALENT PIPES 100-YEAR PUMPING ENERGY

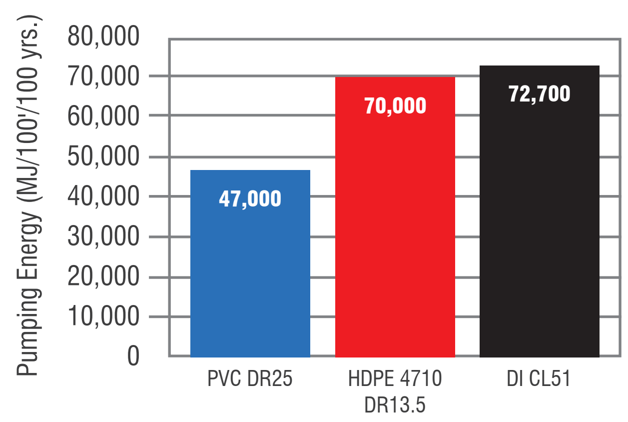


Note: Graph assumes replacement of HDPE and DI pipe at 50 years.

Loss of carrying capacity and higher pumping costs are due much more to the effects of iron pipe corrosion, leaks and tuberculation rather than minor internal diameter differences between iron and PVC pipes. HDPE pipe, on the other hand, has a much smaller internal diameter than either DI or PVC pipe, significantly impacting its pumping energy requirements over time.

Figure A.16 compares 8-inch PVC DR18 pipe with similar pressure class pipe materials. The deterioration of the cement-lining and corrosion of DI pipe causes greater pumping energy use over the life cycle than PVC pipe. Because of the lower tensile strength, HDPE pipe has thick walls and smaller internal diameter, resulting in a diminished conveyance area and increased pumping energy over the life cycle.

FIGURE A.17 : 8" PVC DR25 EQUIVALENT PIPES 100-YEAR PUMPING ENERGY



Note: Graph assumes replacement of HDPE and DI pipe at 50 years.

Figure A.17 illustrates the difference in the life cycle pumping energy required for 8-inch PVC DR25 pipe compared to DI and HDPE pipes. Again, the deterioration of the mortar lining and corrosion of the DI pipe and the smaller conveyance area of HDPE pipe result in higher life cycle pumping energy requirements and costs for those materials.

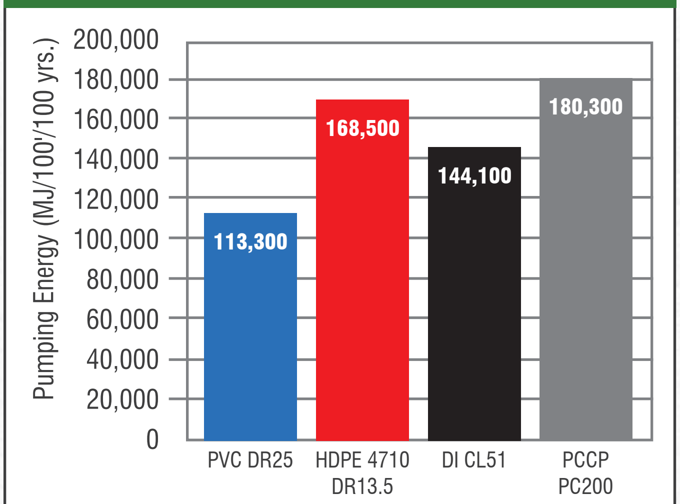
Figure A.18 compares 24-inch PVC DR25 pipe with similar pressure classes of DI, HDPE and PCCP piping. When the diameter and deterioration of friction factor of all pipe materials are considered, 24-inch PVC pipe is the clear, sustainable choice for efficiency in pumping energy.

The smooth walls, large diameters and lack of deterioration of the friction factor for PVC pipe results in more sustainable processes than just life cycle pumping energy. Pumping facilities are designed for the long-term pipeline capacity of the system that will be supplied by their discharge. Materials such as DI and PCCP may have a larger internal diameter and a respectable friction factor when new, but pumping facilities are not designed based on the capacity of new pipes. DI and PCCP may experience at least a 30% decrease in friction factor over their pipe lives. This can result in a 100% increase in the pump power required for the same flow as new pipe as for older pipelines.

Metrics Applied for Pressure Pipe Use-Phase Analysis

- PVC flow velocity was 2 feet per second
- Competitive pipe products were evaluated using same volumetric flow rate
- Actual diameters were used based on standards
- Friction losses were determined using realistic Hazen-Williams C factors
- Deterioration of C factor for each pipe material was included
- Use-phase energy was determined using pumping energy for comparison flow rate over 100 years
- Embodied energy calculations included cradle-through-installation, any required replacements, 100-year pumping and 100-year water loss energies

FIGURE A.18 : 24" PVC DR25 EQUIVALENT PIPES 100-YEAR PUMPING ENERGY



Note: Graph assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

The fact that PVC does not corrode means that PVC pipe has, over the piping system's design life, reduced pumping energy and reduced operational costs compared to corrosion-prone pipe materials.

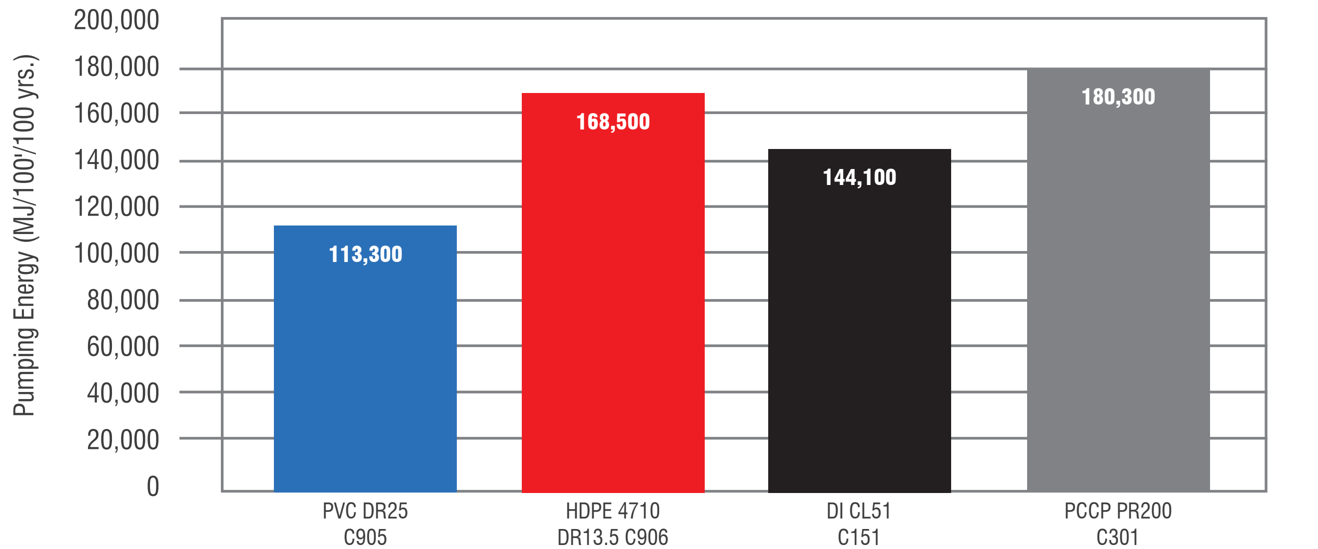
Total 100-Year Pumping Energy: Costs Over Time Using Differing Pipe Service Lives

A review of existing publicly available LCA literature shows that PVC pipe has lower embodied impacts and use stage impacts compared to other pipes. Pumping energy, however, is the largest component of the total 100-year life cycle embodied energy of a piping material. Therefore, pumping efficiency over time is critical. Figures A.19 and A.20 illustrate the differences in pumping energy of various pipe materials. Figure A.19 shows the pumping energy of 24-inch pipe based on the service life as determined in this study.

Figure A.20 demonstrates the increase in pumping energy beyond service life for corrosion-prone piping materials like DI and PCCP. Figures A.21 and A.22 show that using a pipe material beyond its service life results in higher pumping costs. This study has evaluated HDPE and DI pipe's longevity at 50 years and PCCP's at 75 years.

In Figures A.20, A.21 and A.22, the 50-year and 75-year bars take into account that new pipe is installed at 50 and 75 years, respectively, into the 100-year system design life. This resets the friction factor to that of new pipe at that time. For the 100-year bars, new pipe is not installed so the friction factor is not reset during the 100-year period.

FIGURE A.19 : 24" PVC DR25 EQUIVALENT PIPES 100-YEAR PUMPING ENERGY



Note: Graph assumes replacement of HDPE pipe at 50 years, DI pipe at 50 years and PCCP at 75 years.

FIGURE A.20 : 24" PVC DR25 EQUIVALENT PIPES TOTAL 100-YEAR PUMPING ENERGY USING DIFFERING PIPE LIVES

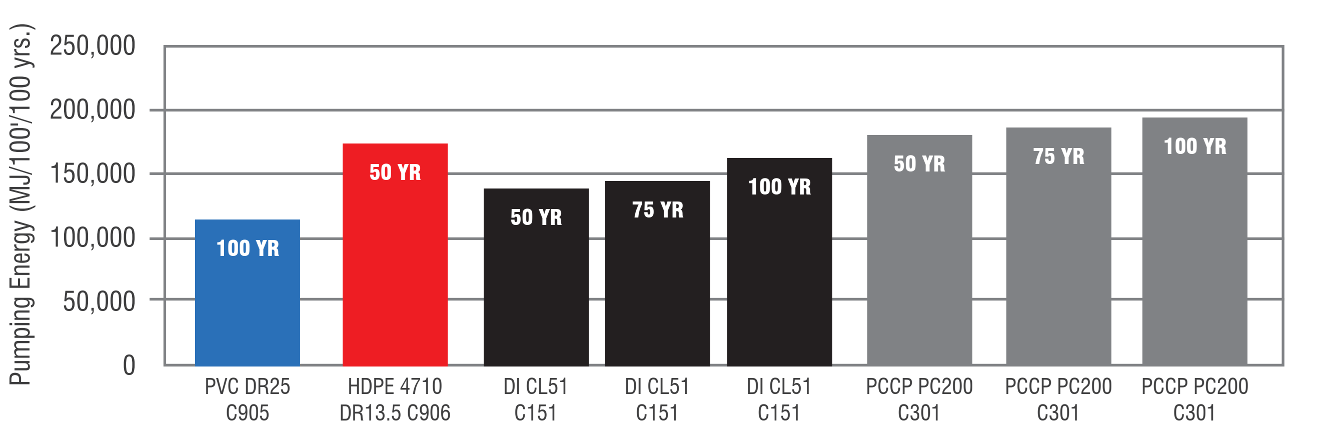


FIGURE A.21 : 8" PVC DR18 EQUIVALENT PIPES TOTAL 100-YEAR PUMPING COSTS USING DIFFERING PIPE LIVES ($/100'/100 YRS.)

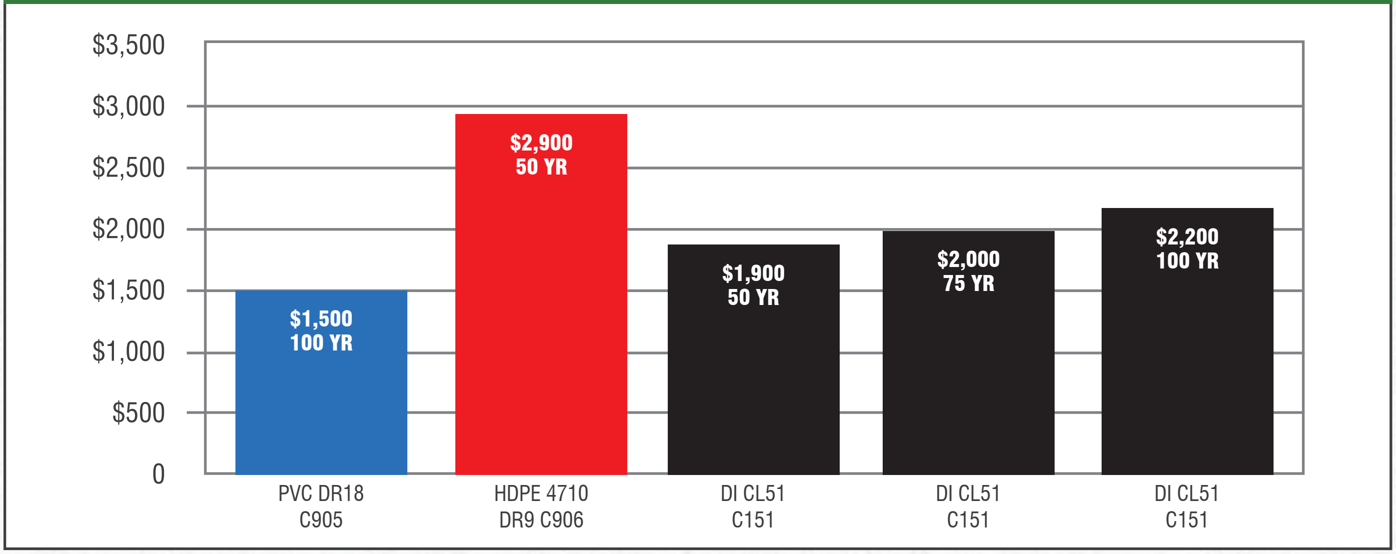
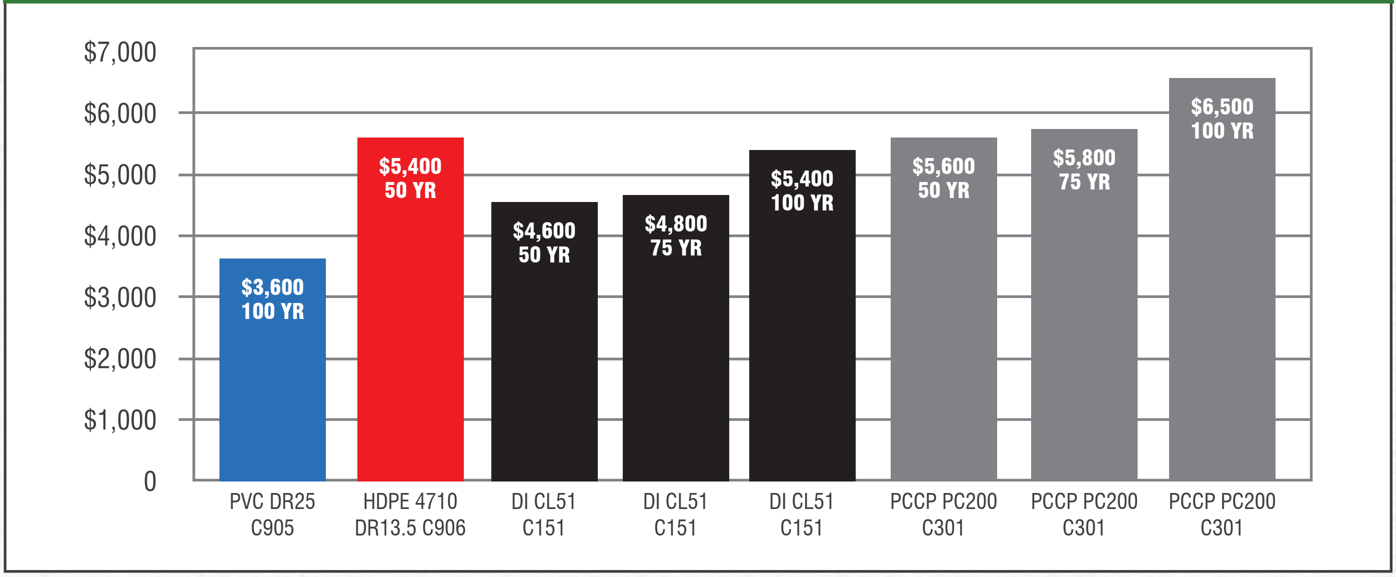


FIGURE A.22 : 24" PVC DR25 EQUIVALENT PIPES TOTAL 100-YEAR PUMPING COSTS USING DIFFERING PIPE LIVES ($/100'/100 YRS.)



Figures A.20, A.21 and A.22 use differing pipe lives/service lives for iron and concrete pipes to provide utility professionals with accurate comparative pumping energy and cost estimates for a 100-year period. This requires a redefinition of traditional notions of pipe service life. For much of the time that iron and concrete pipes have been considered to be "in service," they in fact were not since they were not performing as designed. For a good portion of the time they are in use, they are prone to water main breaks, water loss, water quality issues as well as higher maintenance and operating costs due to corrosion. This affects pumping efficiency significantly. As these pipes age, their internal walls become rougher, driving up pumping costs. Internal pipe wall degradation may begin almost immediately after ductile iron and concrete pipes are installed, resulting in decreasing pumping efficiency, higher energy use and higher pumping costs over time. This is not the case with PVC pipe which maintains its C factor over the 100-year period. Like iron and concrete pipes which may degrade and may not perform adequately after 50 years, HDPE with its lower factor of safety, strain creep and oxidation issues, may not perform adequately for the duration of the 50-year service, though it may maintain its pumping efficiency.[169 170]

Life Cycle Cost Comparisons Over a 100-Year Life Cycle

Looking at the total life cycle costs for a utility to purchase and maintain pipes, the following trends for varying pipe classes were analyzed for one hundred feet of pipe for a 100-year timeframe. Understanding that utilities maintain miles of pipe, these costs are compounded and increase quickly. Compared to other materials, PVC has minimal overall costs for the entire 100-year design life of a water system. Because HDPE and DI pipes may not last 100 years, replacement of the pipe may be required, increasing cost. If DI pipe is not replaced after its performance has significantly degraded, the increase in pumping and maintenance costs due to corrosion will increase the life cycle costs for that system. This estimate does not account for the costs to maintain a pipe material, such as adding additional internal and exterior linings, cathodic mitigation and other efforts that may have to be undertaken to allow the pipe last for the 100-year design life.

STUDY OF WATER MAIN CAST IRON (CI) AND DUCTILE IRON (DI) PIPE FAILURES

A large utility can experience in excess of 300 water main breaks per year. A University of Texas at Arlington study analyzed 31,560 water main pipe section failures of cast iron and ductile iron pipes over a period of 110 years.[171]

Pit-Cast Iron

Many of the original iron pipes, called pit-cast iron pipes, are experiencing corrosion failure today as pit-cast iron pipes installed in the early 1900s have long ago reached the end of their service lives. Cast iron was initially manufactured starting in the 1800s, but with major production beginning in 1914.[172] Originally cast iron pipe used a method that "joined these pipes [using] molten lead along with a rope (oakum)" with the bell and spigot joint.[173] The lead joints were widely used in cast iron pipes and still exist today in pipe systems older than 60 years.[174] A study with a water utility shows pit-cast gray iron pipe was installed from 1872 until 1945, with a significant number of installations from 1925 to 1931. Failure analyses revealed that 3,611 pipe section failures had a service life of more than 75 years, followed by 1,818 with a service life of 50-75 years; 1,676 had 25 to 50 years of service life, and only 20 failures had less than 25 years of service life."[175]

Gray Cast Iron

"The centrifugal cast gray iron pipe installations followed the pit-cast gray iron pipe of the 1920s and began volume production in the 1930s."[176] Centrifugal cast iron was thinner and stronger compared to pit-cast iron pipe. Cement lining and new sulfur-based leadite joining compound viz. plasticized sulfur cement were introduced in the same time period as joint materials. Leadite joints were eventually found to have increased splitting and corrosion compared to lead. Flexible rubber gasket joints were introduced in the 1950s as improved joints."[177]

"The water utility installed centrifugal cast gray iron pipe from 1946 until 1964 with a total of 17,364 installations, which exceeded the pit-cast gray iron pipe in a relatively shorter period of time. Complete information on 9,683 failures was available. Considering these failures, there are no pipe sections having a service life of more than 75 years. 2,641 had a service life between 50 and 75 years. A significant 6,812 centrifugal gray iron pipes had 25 to 50 years of service life and there were only 7 failures which had less than 25 years of service life."[178]

Ductile Iron Service Life Is Less Than 50 Years

"Ductile iron pipe material was introduced to the pipe industry in 1948, produced by 1955 and was in wide use by 1979. The installations for ductile iron pipes observed [from the water utility are] between 1953 to 1982. Considering these failures, no pipe sections had a service life of more than 75 years. 3% of the failures observed had a service life of 50-75 years, while 79% of failures had a service life of 25-50 years. Finally, 18% of the failures had less than 25 years of service life."[179]

"The pit-cast gray iron pipe performed better than the centrifugal cast gray iron pipe and ductile iron pipe as far as the service life is concerned. Pit-cast gray iron has corrosion as the main cause of failure, followed by transverse break failure, bell and spigot-lead joint failure, split pipe failure, and then lastly, bell and spigot leadite joint failure. For centrifugal cast gray iron pipe, transverse break failure is the main cause of failure, followed by corrosion, bell and spigot-lead joint failure, and split pipe failure. Some failures in mechanical lock-type and push-on type of joint was observed as well. Corrosion is the main cause in ductile iron pipe failure, followed by transverse break failure, and then mechanical lock-type joint failure."[180]

Based on the case study results, "6-inch, 8-inch, 12-inch and 16-inch cast iron and ductile iron pipe had the most number of failures during a 25-to-50-year service life."[181]

"The available data of different types of joints used for 31,258 cast iron and ductile iron pipes combined, an incredible amount of 25,977 bell and spigot lead joints representing about 83% of all joints, [were] used in the [water] utility."[182]

These results are confirmed by other surveys and studies where the average age of pipe failure (water main breaks) is 47 years,[183] and the fact that many utilities report that their new [ductile] iron pipes are failing at the same time as the older iron pipes.

Nations like Japan have a legally designated service life for iron water pipes which is set at 40 years in order to avoid the consequences of corrosion, water loss, water quality issues and public health concerns.[184]

Ductile Iron Has Thinner Pipe Walls

The service life of iron pipes is not the same as how long a pipe can be in the ground, i.e., for example "end of physical life." Before iron pipes reach the end of their physical life, they may have drastically put water quality at risk and have increased utility operational and maintenance costs significantly. The performance and economic analysis of a pipe also includes leakage which drives up pumping energy costs and may degrade water quality. Recent examples continue to demonstrate that 100 year old iron pipes present a significant burden on a community, as in the case where there is an 80% water loss.[185]

IRON PIPE CORROSION, LEACHING AND WATER QUALITY RISKS

Research related to other piping materials and corrosion supports the conclusions in this report. The cradle-to-gate potential environmental impacts of piping materials can vary greatly. Similarly, pipe performance characteristics can also greatly differ over the course of a piping system's service life. Certain types of pipe materials are susceptible to internal corrosion as the pipe ages. An electrochemical reaction involving metallic components of a pipe is the leading cause for internal corrosion. This corrosion increases the roughness of the interior surface of the pipe, which creates more friction (see Figure A.23) and requires more pumping energy over the service life of the system.[186]

More Chemicals (Corrosion Inhibitors) Are Used in Drinking Water When Iron Pipes Are Used

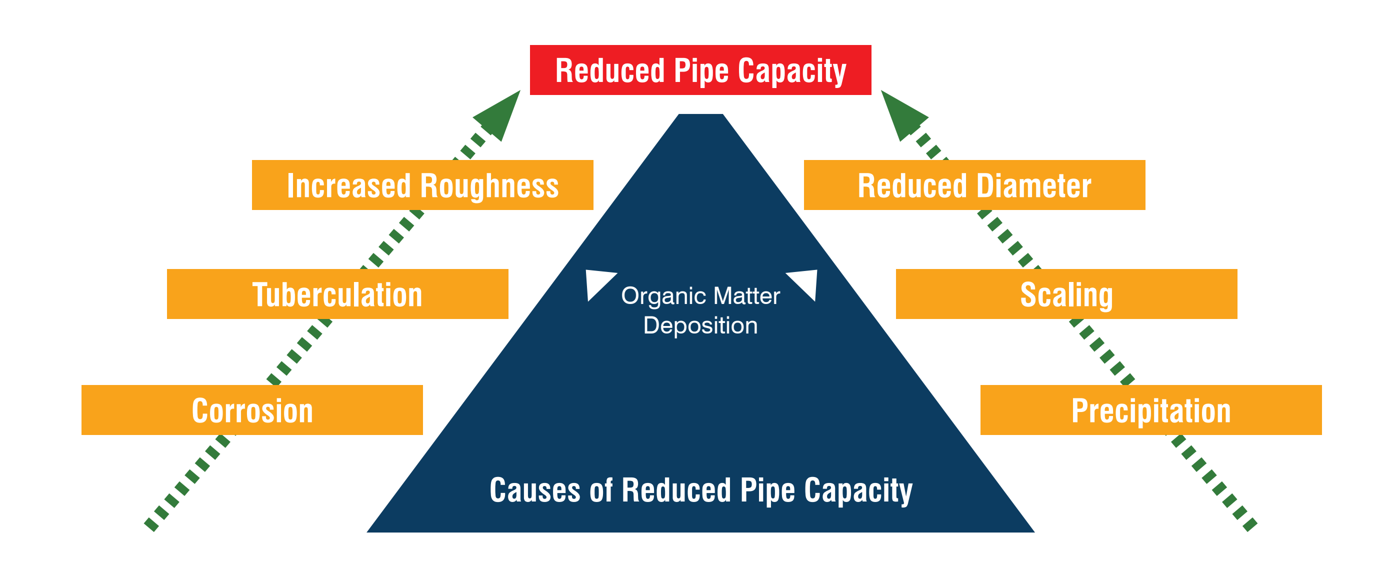
Chemical additives used for corrosion control include phosphates, silicates and those affecting the carbonate system equilibrium (amount of carbonate in the system) such as calcium hydroxide, sodium hydroxide, sodium bicarbonate and sodium carbonate. Corrosion inhibitors are commonly used to address the corrosion influence of acidic water treatment additives.[187]

Cement Lining Is a Potential Source of Heavy Metal Leaching

Distribution system infrastructure and appurtenances can react with the water they supply as well as the external environment. Cement-based materials include reinforced or prestressed concrete pipes, cement-mortar linings and asbestos-cement pipe. Two general components of cement-based materials include the aggregates and the binder. Several types of degradation of cement materials can occur in the presence of acidic waters or waters aggressive to calcium carbonate.[188 189 190 191 192 193]

Leaching is a mechanism that can result in the degradation of the distributed water. Leaching from cement linings can occur in soft, aggressive, poorly buffered waters. Under static conditions, metals such as aluminum, arsenic, barium, chromium and cadmium can leach from cement linings, even when materials certified to NSF/ANSI 61 are used and linings are applied.[194]

FIGURE A.23 : INTERNAL CORROSION AND TUBERCULATION OF WATER MAINS: CAUSES AND IMPACTS ON PERFORMANCE



A 1991 study investigated the deterioration of new cement linings under various water quality conditions.[195] Field testing demonstrated that aggressive water is capable of leaching cement compounds from these linings, causing significant increases in bulk solution pH, alkalinity and calcium. Studies of cement lined pipes in use for 10-20 years all showed degradation of the mortar lining in the form of leached elements.[196] Water which has a low ion content is aggressive to the calcium hydroxide in cements.[197] This means that the water delivered to consumers may not have the desired quality, due to a high pH caused by the leaching of calcium hydroxide. This also causes a gradual loss of capacity to protect the iron against corrosion. Losing calcium makes the lining less protective against corrosion because it lowers the pH value in the thin layer of water between the cement and the internal pipe wall.

A 1999 study included reviewing the installation of 7,200 feet of cement lined ductile iron pipe which caused aluminum levels in a water supply to increase from 5 µg/L to 690 µg/L over the course of 2 months.[202] More than two years later, aluminum continued to leach from the lining and produce water with over 100 µg/L of aluminum. This contributed to several illnesses and a 32% mortality rate at a receiving dialysis center. The water in contact with the pipe was seawater that had been desalinated and subsequently treated with coal-filtration, fluoridation and UV disinfection. The water was aggressive (maximum Langelier Index between –0.5 and –1.5), soft (hardness 15-20 mg/L as CaCO3) and of low alkalinity (no data) with high pH (8.5 to 9.5). The pipe had been lined with cement at the factory by a rotary centrifugal process. The extent of leaching is also strongly related to the contact time between the water and the cement lining.

Cement materials contain a variety of regulated inorganic chemicals, many of which are prone to leaching. A 1998 study conducted laboratory tests to determine the extent of leaching from ductile iron pipes lined in situ with Portland cement mortar. The pipes were lined and cured in accordance with ANSI/AWWA Standard C602-89, and subsequently, disinfected according to ANSI/AWWA C651-92. The test water was standard faucet water from a New Jersey utility. Under static conditions, barium, cadmium and chromium leached from the lining to a concentration higher than drinking water quality standards.[198]

High content of aluminum in cement is positive for protection properties of the lining, but simultaneously may lead to higher concentrations of aluminum in water flowing through freshly renovated pipes from cast iron or through new ductile iron water mains. The application of cement lining can also lead to aluminum leaching.[199]

Aluminum poses serious health risks to hemodialysis patients. The European Union defines a maximum aluminum concentration of 30 mg/L in water used for hemodialysis. The U.S. EPA has established a Secondary MCL range for aluminum of 50-200 mg/L.[200]

Aggressive, soft and poorly buffered (i.e., low alkalinity) waters promote aluminum leaching from cementitious materials. These are the same water quality conditions that are conducive to leaching of lead and copper. The impact of leaching calcium on pH and leaching of the aluminum from cement to the water is greater in pipes of small diameters. Demineralized water, which is aggressive against concrete, can cause high concentrations of calcium, aluminum and chromium in the water.[201]

Utilities are required to maintain optimal water quality parameters at the point of entry to the distribution system and at several locations within the distribution system to minimize lead and copper leaching at the tap. However, in recent findings related to Flint, MI and lead leaching, the EPA has found many instances nationwide where utilities were not properly testing for water quality. Dr. M. Edwards with Virginia Tech University, the scientist who first uncovered the lead leaching crisis in Flint, described water testing in some of America's largest cities as an "outrage."[203]

Polyphosphate corrosion inhibitors also attack and soften cement linings, thereby accelerating cementitious leaching. "These corrosion inhibitors can also chelate and complex with soluble calcium and aluminum."[204]

▶ Iron and Manganese from Iron Piping

There is growing concern about high levels of iron and manganese in water carried by iron pipe systems and it is clear that iron and manganese levels increase as drinking water passes through corroded iron pipes.[205] "Excess manganese interferes with the absorption of dietary iron. Long-term exposure to excess levels may result in iron-deficiency anemia… [It] can increase bacterial growth in water. Symptoms of toxicity mimic those of Parkinson's disease (tremors, stiff muscles) and excessive manganese intake can cause hypertension in patients older than 40. Significant rises in manganese concentrations have been found in patients with severe hepatitis and post hepatic cirrhosis, in dialysis patients and in patients suffering heart attacks."[206] High levels of manganese is also dangerous to young children and pregnant women.[207] "Iron is a potentially toxic heavy metal. In excess, it can cause cancer, heart disease, and other illnesses."[208] As well, iron corrosion has been shown to increase the leaching of lead into water.[209 210] A test sample recently taken in St. Joseph, LA found concentrations more than 230 times EPA's recommended level for iron in drinking water.[211]

Pipe Selection Implications

Additional water quality issues arise from the use of ductile iron pipe. There is a propensity for the cement lining to degrade from aggressive water and/or high velocities and crack and break off during tapping, deflection, installation and transport. Loss of lining brings potable water into contact with the iron pipe wall or substrate for which there is no health and safety test. Only the cement lining

in ductile iron pipe is certified to NSF/ANSI Standard 61 "Drinking Water System Components – Health Effects," the inside iron pipe wall is not. Also, the bell of ductile iron pipe is not lined, adding additional risk to public health.

Unlike concrete and DI pipes, PVC pipes do not corrode internally. The energy use with PVC will remain constant over a 100-year design life. Ductile iron pipe, however, will sustain degradation to the internal wall surfaces and be prone to corrosion, breaks and leaks which will increase the energy use and pumping cost over time. Ductile iron pipe will also have higher maintenance, repair and replacement costs. Most mains do not have high water pressure and, therefore, do not need excessive strength to overcompensate for a poorly designed or operated system. The Utah State University water main break study reported the average pressure to be 77 psi in municipal water distribution systems across North America and that most water pipe networks do not need excessive strength for their piping.[212] PVC pipes have lower water main breaks, fewer leaks and lower operating and maintenance costs compared to ductile iron pipes. This results in PVC pipes creating an environmentally stable and sustainable water quality condition which protects public health.

While DIPRA claims the benefits and long-term performance of thicker cast iron pipes, ductile iron pipes are significantly thinner and corrode both internally and externally. Studies show that iron pipe longevity is plummeting due to significant reductions in iron pipe wall thickness.[213] Key drivers for decision makers when selecting piping materials are soil corrosivity (corrosive soils affect 75% of our nation's water infrastructure)[214] and aggressive water. According to a 2011 study by the AWWA Water Research Foundation, ductile iron pipes with the thinnest walls (representing the majority of metallic pipe sold) in moderately corrosive soils have a life expectancy of only 11 to 14 years.[215] Pipes that fail prematurely from corrosion are not environmentally friendly or sustainable. NACE does not recognize the wrapping of ductile iron pipe in plastic as a corrosion control measure.

Iron Corrosion (Rusty/Red Water) Can Cause Lead Leaching in Water

Dr. M. Edwards and Dr. S. Masters at Virginia Tech University published an article titled *Increased Lead in Water Associated with Iron Corrosion* in 2015 describing water testing.[216] The article examines consumers complaining about red water, "rusty" water complaints and the overall lead level increase. The complaints prompted intensive field testing into the possible associations between higher particulate iron from the distribution system and particulate lead in the house plumbing. This raised the issue that sometimes iron corrosion could be strongly linked to lead corrosion. To the extent that iron pipe corrosion can increase lead release, reducing lead in water may require upgrades to potable, non-corrosive water infrastructure or iron corrosion control, as opposed to current approaches that focus exclusively on reducing lead solubility.

There was a significant interaction between water type, pH and the presence of iron in lead corrosion. There was greater than 150% more lead release with iron, which is likely due to the sorption and/or co-precipitation of lead onto detached iron particles. Iron-rich water flows into lead service lines, absorbs the lead and then releases it at consumer taps.[217]

Iron Corrosion (Rusty/Red Water) Can Deplete Water Disinfectants

Chloride is generally considered to be very corrosive to iron. For instance, chloride present in road salts applied in the winter causes the iron in cars and bridges to rust. Many utilities add a corrosion inhibitor chemical (orthophosphate) to water to help reduce the corrosion of metals such as iron and lead. Iron corrosion can cause serious problems when trying to meet federal drinking water standards because iron corrosion consumes chlorine and chlorine is needed to keep water safe. The high iron in the water can remove disinfectants like chlorine, allowing harmful bacteria to grow that can cause diseases such as Legionnaires' disease.[218] Virginia Tech Professor Dr. M. Edwards also contends that corrosion in water pipes provides nutrients, such as iron, which is a food source for pathogens like legionella.[219]

Health Impacts

Exposure to lead can cause a series of health impacts, particularly in children under the age of 6 and expectant mothers. In Flint, MI, between 6,000 and 12,000 children have been exposed to drinking water with high levels of lead. Lead exposure can impact learning ability as well as cause behavioral problems.[220]

Chlorine is added to the water to prevent growth of microorganisms that cause disease, and maintaining a chlorine residual is the best way to protect public health against pathogens.

Municipalities with corrosion issues and inadequate chemical controls could be exposing their customers to potential public health and safety issues beyond lead contamination. The outbreak of Legionnaires' disease in Flint which killed 10 people and affected 77 is believed to have occurred as a result of having no residual chlorine in the pipes to continue the disinfection process.[221] According to Dr. M. Edwards, without adequate levels of corrosion inhibitors in Flint's water system, the iron pipes leached high levels of iron, creating the conditions for bacteria to flourish that could have contributed to the Legionnaires outbreak.[222]

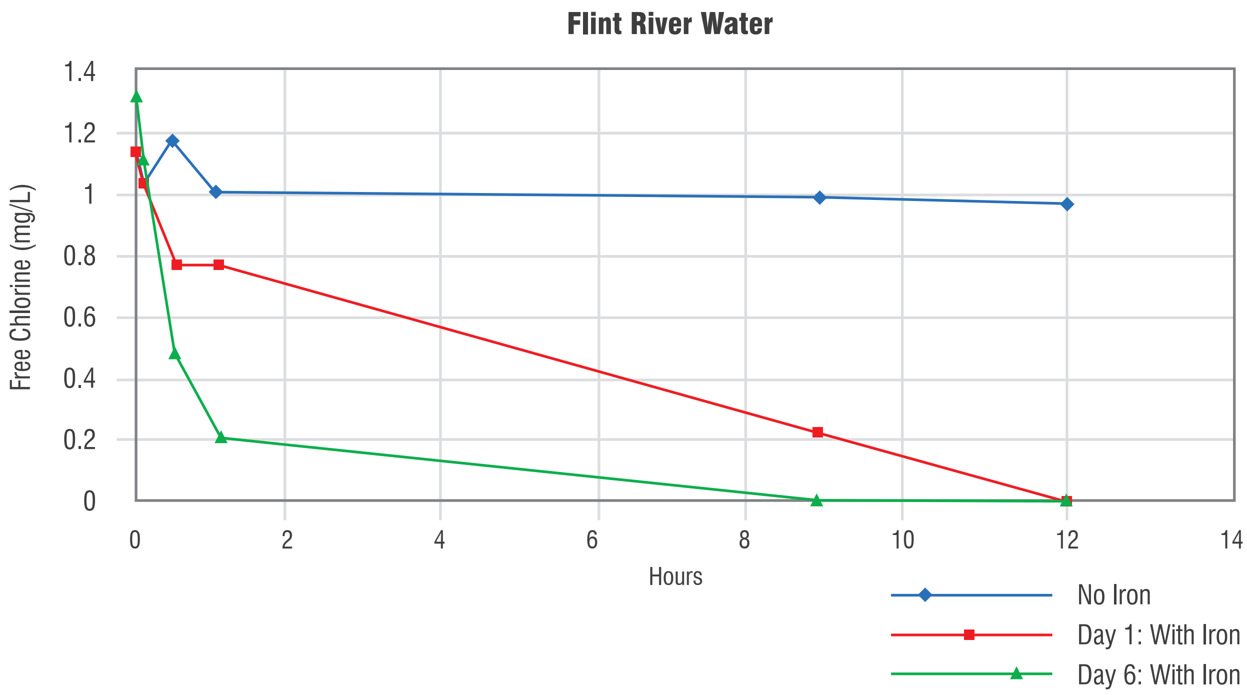
FIGURE A.24 : IRON CORROSION CAUSES "RED" OR RUSTY WATER

Iron Pipe Corrosion and Flint Water Quality Issues

Iron corrosion causes water to become a rusty/red color. In Flint, Michigan, residents had been complaining of "red" or discolored water. See Figure A.24 for an example of Flint drinking water affected by corrosion and Figure A.25 for examples of corroded iron water pipes dug up in Flint.[223] Iron in water can make it difficult for municipalities to meet federal standards because iron corrosion consumes chlorine which makes it more likely that bacteria will grow in the water. It is possible that, with the existing unlined iron pipe system in Flint and the relatively low water demand (due to declining population and loss of businesses) it will be very difficult to meet federal standards for minimum chlorine levels, regardless of what is done to treat the water.[224] See Figure A.26 for an example of how chlorine levels decrease when exposed to iron.[225]

FIGURE A.25 : CORRODED IRON PIPE SAMPLES FROM FLINT, MI

FIGURE A.26 : DECAYING OF FREE CHLORINE IN FLINT RIVER WATER WITH AND WITHOUT IRON



Source Water pH Can Change

Some natural source waters containing calcium and carbonate in the presence of manganese and iron can produce a protective film on an iron pipe surface. However, the formation and stability of the film can be easily compromised with the presence of acids and produce localized corrosion.[226] Water can turn acidic in a variety of ways including increased CO_2 levels, stagnant water and excess amounts of chlorine.[227] The water can undergo hydrolyses to form hydrochloric and hypochlorous acid. This process lowers the pH, strips any protective coatings on a metal surface and initiates pitting corrosion. Seasonal temperature, decreased water use and changing conditions can also lead to corrosion.[228]

SEWER PIPE LCA COMPARATIVE CASE STUDY

An independent study was published that utilizes LCA to analyze the environmental performance of four different piping materials in wastewater transportation infrastructure. This study was published in 2015 by Procedia Engineering and conducted by Purdue University as the *Comparative Life Cycle Analysis of Materials in Wastewater Piping Systems.*

"A comparative study of the production stages of different pipe materials was carried out and the characterization results obtained are shown in [Figure A.27]. The production stage was specifically chosen for the study because this phase had the maximum impact for literally all the four materials. The figure brings to light the impact of the production stage of the four materials (Ductile Iron, Concrete, "FRP" composite fiber reinforced polymer and PVC) on different environmental categories and are represented on a percentage scale. The production stage of ductile iron was found out to be the most deleterious, impacting almost all categories to the greatest extent except for eco–toxicity, which was hit the most by the production stage of concrete. In spite of the fact that ductile iron production stage has a considerable detrimental impact on ozone layer depletion, since polystyrene is utilized in FRP pipes production and hydrochlorofluorocarbons (HCFCs) is generated during the process, FRP production stage is considered as the most impactful stage on ozone layer deletion category. The production of FRP and PVC pipes also affected the environment but not as much as ductile iron."[229]

Among the four pipe types analyzed by Purdue University, ductile iron has the maximum environmental and health impacts, while PVC has the lowest, as seen in Figure A.28. Notably, ductile iron scored highest of all materials in the production of carcinogens. This study is consistent with the results of this *Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials.*

FIGURE A.27 : CHARACTERIZATION GRAPH FOR LIFE CYCLE COMPARISON FOR ALL PIPING MATERIALS

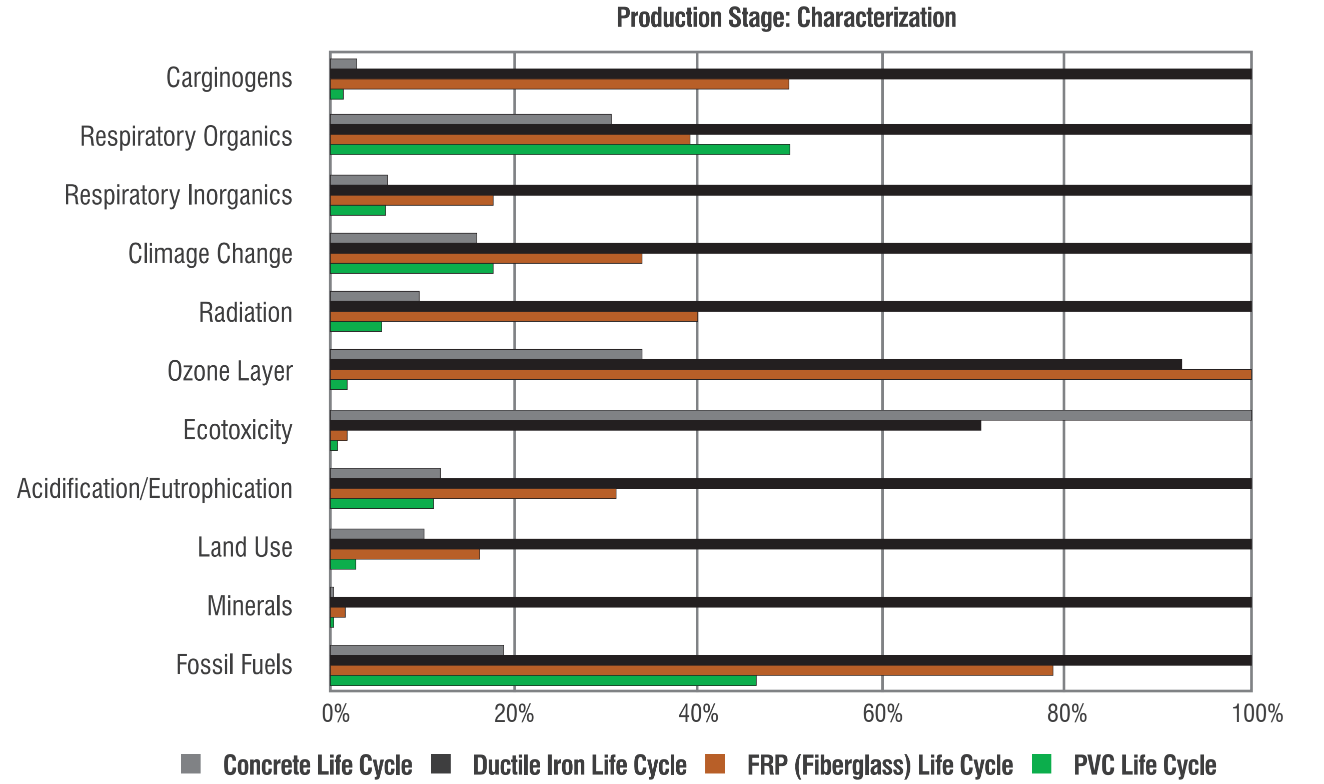
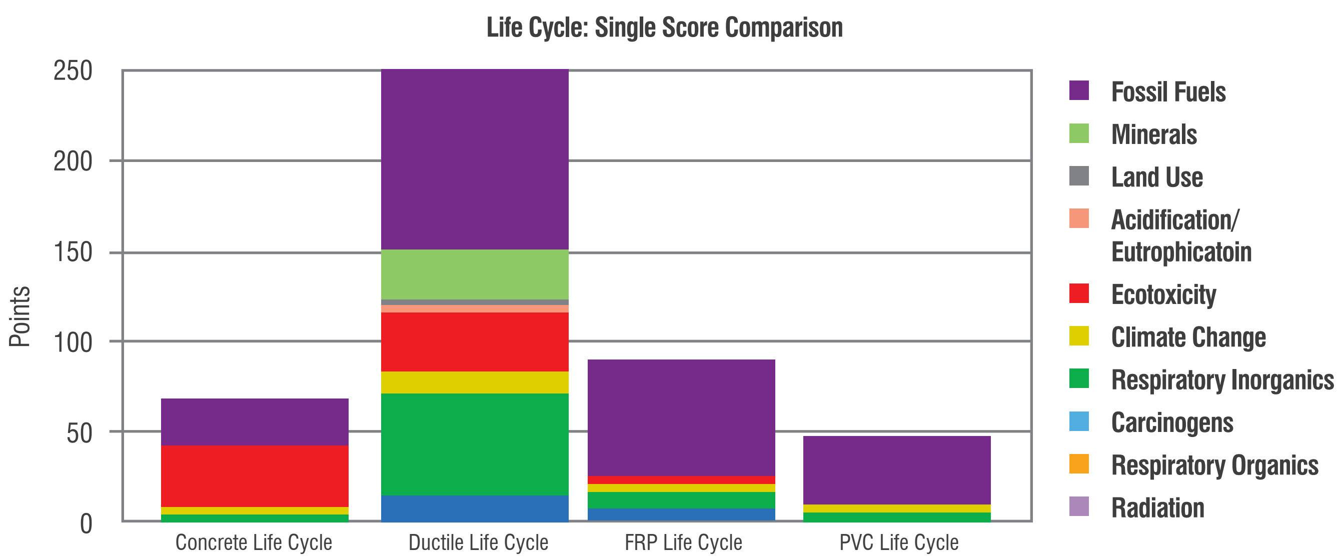


FIGURE A.28 : SINGLE SCORE GRAPH FOR LIFE CYCLE COMPARISON FOR ALL PIPING MATERIALS



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