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Impact of Hydrocarbons on PE/PVC Pipes and Pipe Gaskets

Subject Area:
Infrastructure Reliability

EXECUTIVE SUMMARY

Plastic pipes have been used increasingly for the conveyance of drinking water in water listribution systems and, in many countries, plastic pipes are the preferred materials. Plastic naterials commonly used for the distribution of drinking water include polyvinyl chloride (PVC), olyethylene (PE), and polybutylene (PB). One of the factors for the increased use of plastic ipes is the ease of installation and handling of plastic pipes. In addition, plastic pipes are highly lurable and offer good resistance to the chemicals used in water treatment, such as chlorine. In nany urban areas, plastic pipes may come into contact with contaminated soils as a result of eaks from underground storage tanks, chemical spills, and improper disposal of used chemicals. hese pollutants from leaking storage tanks and contaminated soils can and have posed serious ireats to the longevity and structural integrity of plastic pipes and elastomeric gaskets which, in irn, can affect the water quality in the distribution system. Although there are research studies nd case studies documenting the permeation of organic compounds through plastic pipes and lastomeric gaskets, there is still a lack of understanding of the performance of PE and PVC pipe iaterials and elastomeric gaskets in hydrocarbon-contaminated soils commonly encountered un-er field conditions.

ESEARCH OBJECTIVES

The overall objective of this project was to study the impact of petroleum-based ydrocarbons on PE and PVC pipes, and elastomeric gaskets. The specific objectives of this oject were:

i. Conduct a survey of water utilities to obtain information on the types of pipe materials and gasket materials used for mains and service connections, permeation incidents, and successful use of plastic pipes (PE/PVC) or gasketed pipes in contaminated areas.
ii. Conduct hydrocarbon permeation experiments using the pipe-drum or pipe-bottle apparatus for PE/PVC pipes under simulated environmental conditions.
iii. Develop predictive laboratory tests that may predict the performance of plastic pipe materials in soils contaminated with petroleum-based hydrocarbons.
iv. Conduct experiments under simulated environmental conditions to assess the performance and failure of gasket materials exposed to hydrocarbon contamination.

PROACH

The research approach consisted of four major tasks: Task 1 – Survey and case histories, sk 2 - Laboratory material testing under simulated field conditions, Task 3 - Predictive pipe terials tests, and Task 4 - Gasket material tests.

In Task 1, a survey instrument was developed and sent to water utilities requesting ormation such as total miles of mains, miles of each type of pipe, total number of service inections and types of pipes, types of gasket materials, number of incidences of permeation of ins and service connections, and successful use of plastic pipes or any gasketed pipes in itaminated areas. In Task 2, information collected from the survey was used in the development of laboratory experiments that simulated field conditions. In this task, pipe-bottle apparaes ere developed to test permeation of PE and PVC pipes by benzene, toluene, trichloroethylene (TCE) and gasoline. In addition, pipe-bottle experiments were conducted using aqueous saturated solutions of benzene, toluene, TCE and gasoline. Three predictive tests: gravimetric sorption test, moving front test and near infrared spectroscopy were tested to assess their suitability as predictive test methods to assess susceptibility of pipes to permeation by hydrocarbons. Task 4 consisted of testing ductile iron pipes with five different gasket materials and PVC pipe with two different gasket materials in pipe-drum apparatuses. Contamination conditions included free product gasoline, 100% saturated aqueous gasoline solutions, and dilute aqueous solutions of gasoline. In this report, a 20% saturated aqueous solution of a solvent or gasoline, for example, refers to an aqueous solution with concentration equal to 20% of the concentration of a solution saturated with the solvent or gasoline. In this task, the effect of hydrostatic pressure on hydrocarbon permeation was also investigated.

CONCLUSIONS

A summary of the various tasks, major findings and recommendations is provided in Table E1. Details of the conclusions of the research are described below.

Survey and Case Histories

Eighteen percent of the total miles of mains reported were PVC, 16% were ductile iron, and 66% reported others, which included cast iron, steel asbestos-cement and concrete pipes. Only 0.18% of the total mains reported were PE pipes. With respect to the total number of service lines, PE and PVC pipe accounted for 6% and 5%, respectively.

The overall impact of permeation on the water industry is relatively small. Reports of permeation incidents involving potable water distribution are rare, with reports of one incident per 14,000 miles of mains and 0.9 incidents per million service connections in this survey.

Twenty-eight out of the 151 utilities (19%) reported having a protocol for selecting pipe and gasket materials for use in contaminated areas. Of the 28 utilities, 10 reported protocols specifying ductile (DI) pipe with resistant gaskets (either nitrile (NBR) or fluoroelastomer rubber (FKM); 8 reported protocols specifying DI with no mention of gasket type; 4 reported "no plastic", which could mean using DI in contaminated areas; 2 reported using steel, and 4 reported other approaches. No utility reported specifying plastic pipes in contaminated areas.

Data obtained from the survey was not sufficient to draw conclusions regarding the thresholds of contamination that would result in hydrocarbon permeation and require a utility to choose more resistant pipe or gasket materials.

Hydrocarbon Permeation of PE pipes

Laboratory experiments indicated that PE pipe is rapidly permeated by gasoline and solvents, whether in groundwater, in soil pore vapor, or as the free product. Benzene was the first of the BTEX compounds (benzene, toluene, ethylbenzene and xylene) to permeate PE pipe from water contaminated with gasoline, with the first detectable concentrations exceeding the EPA's 5 μg/L MCL for all experiments. Equations were derived to predict the concentration of contaminants in PE pipes for various external contaminant concentrations during continuous flow and after periods of stagnation. For a given contaminant in soil water, smaller pipes are more vulnerable

Table E.1 Summary of Tasks, Experiments, and Findings

Chapter	Description	Findings	Recommendations
Chapter 2	Survey and Case Histories	• Total miles of mains reported: 18% - PVC, 16% - ductile iron, 0.18% - PE, 66% - others (cast iron, steel, asbestos-cement, and concrete pipes). • No. of service connections reported: 6% - PE, 5% - PVC • One permeation incident per 14,000 miles of mains and 0.9 incidents per million service connections • 28 out of 151 utilities reported having a protocol for selecting pipe/gaskets for use in contaminated areas: 10 - DI pipe with resistant gaskets (either NBR or FKM); 8 - DI with no mention of gasket type; 4 - no plastic, 2 – steel, 4 – other approaches	
Chapter 3	Permeation of PE Pipes	• Gasoline permeates rapidly through PE pipes at all saturation concentrations and contaminated soils conditions • Permeation rate is a function of aqueous or vapor concentration of the hydrocarbons • Depending on hydrocarbon concentrations in soil water and soils and pipe size, water flow (no stagnation) may dilute benzene concentration to below MCL	• No level contamination at which PE pipe is resistant to permeation of gasoline, chlorinated solvents or aqueous solutions of gasoline • Corrective action should be taken
Chapter 4	Permeation of Ungasketed PVC pipes	• Premium gasoline (and, therefore, groundwater or soils saturated with gasoline) - no permeation of PVC pipes • Pure toluene, benzene and TCE – permeation of PVC pipes • saturated vapors of toluene, benzene and TCE – permeation of PVC pipes • Saturated aqueous solutions of benzene, toluene, or TCE – permeation of PVC pipe if activity > 0.60	• PVC pipes impervious to gasoline and gasoline-saturated solutions • PVC pipes permeated by saturated aqueous solutions of benzene, toluene, and TCE • Decontamination of PVC not feasible – must replace permeated pipe
Chapter 5	Predictive Tests (Sorption, Moving Front and Near Infrared (NIR) Reflectance)	• Of the three predictive tests (sorption, moving front and near infrared spectroscopy), the moving front test is the most suitable for PVC pipes and provides information on permeation rates • For single compound concentrations $\leq$ 40% (v/v) of benzene, toluene, or TCE in reference fuel, sorption (permeation) was insignificant and moving fronts were not formed. • No moving fronts were formed in $\leq$ 60% (v/v) saturated aqueous solutions of benzene, toluene, or TCE • Premium gasoline fortified with toluene - no moving front observed for $\leq$ 32.2% (v/v) total BTEX, moving fronts formed for $\geq$ 43.1% (v/v) total BTEX • No moving fronts for $\leq$ 40% (v/v) of multi-component BTEX mixtures in reference fuel. Fronts formed for $\geq$ 60% (v/v)	• PVC pipes can tolerate an activity of 0.40 (40% aqueous solutions of benzene, toluene and TCE) without permeation (without including safety factor and impact of other environmental conditions) • PVC pipes impervious to dilute aqueous solutions of benzene, toluene, and TCE, commonly encountered in the field • PVC pipes compatible with sum of individual BTEX activities $\leq$ 0.40 (activities are additive)

(continued)

Table E.1 Summary of Tasks, Experiments, and Findings (Cont'd)

Chapter	Description	Findings	Recommendations
Chapter 6	Permeation of Gasketed (Tyton®) DI Pipe	• Gaskets exposed to premium gasoline: EPDM permeated in 35 days, CR in 50 days, SBR in 50 days (4", benzene – avg. 2.72 mg/j/d), NBR in 124 days (4", benzene – 0.159 mg/j/d) (FKM (very low BTEX detected – probably leakage) • SBR gaskets permeated when exposed to gasoline-saturated water (210 days) and 50% saturated (240 days) • No permeation observed for SBR gasket in 20% and 5% saturated aqueous solutions of gasoline • No permeation of NBR gaskets observed for any level of gasoline contamination in water • No correlation between permeation and hydrostatic pressure in pipe	• SBR and NBR gaskets may be used (without exceeding benzene MCL) under all conditions of gasoline contamination with minimal average flow in pipe (no stagnation) • Under conditions of stagnation in contact with free product gasoline, NBR gaskets may be used (without exceeding benzene MCL). • SBR and NBR gaskets compatible with any level of gasoline in groundwater • NBR gaskets most cost effective choice when a gasket material resistant to gasoline is desired.
Chapter 7	Permeation of Gasketed (Rieber) PVC pipes	• Permeation of premium gasoline observed within 21 days for SBR (2", benzene avg. 0.73 mg/j/d) and NBR gaskets (2", benzene avg. 0.19 mg/j/d). • No permeation after 9 months for SBR and NBR gaskets in gasoline-saturated water • NBR rubber compound used for Rieber gaskets is about 3x more permeable than NBR rubber compound used in Tyton gaskets (75 W% vs 24% W% sorption).	• SBR or NBR gaskets may be used (without exceeding benzene MCL) in direct contact with gasoline with a minimal average flow in pipe • After 8 hours of stagnation in direct contact with gasoline, benzene MCL exceeded in pipes ≤ 24" using SBR and pipes ≤ 10" using NBR gaskets. • SBR or NBR gaskets compatible with any level of gasoline in groundwater (without exceeding MCL)

than larger pipes and the risk of exceeding EPA MCLs is much higher during periods of stagnation than during continuous flow. Laboratory experiments showed that, due to sorption, the organic content of soils can lower the concentration of hydrocarbon contaminants in the soil pore water. But once the organic adsorption capacity of the soil is exceeded, the organic content of the soil makes no difference in the permeation since the steady state permeation rates in PE pipes are dependent on the external bulk concentrations regardless of the soil types.

Permeation of PVC Pipe by Hydrocarbons

Pipe-Bottle Experiments

Pipe-bottle experiments showed that PVC pipes were rapidly permeated by pure benzene (20 days), toluene (16 days), and TCE (6.5 days). PVC pipes were also rapidly permeated by saturated vapors of benzene (31 days), toluene (28 days) and TCE (13 days). Pipe-bottle experiments also indicated that 100% aqueous saturated solutions of TCE and benzene permeated the PVC pipes at 168 and 250 days, respectively, while permeation by aqueous saturated solutions of toluene was predicted to occur after about 12 months of exposure. However, the pipe-bottle experiments indicated that PVC pipes were impervious to premium gasoline and gasoline-saturated water for over two years of exposure and, therefore, can be used in soils contaminated with gasoline, regardless of the level of contamination. An explanation for this resistance to permeation is that the activities of swelling compounds such as benzene, toluene, and xylene in premium gasoline were insufficient to soften the PVC material. The activity of total BTEX in gasoline for the pipe-bottle experiments was approximately 0.25.

Predictive Test – Gravimetric Sorption Test

Using the gravimetric sorption test, sorption of premium gasoline by PVC pipes was found to be negligible with less than 1% weight gain – implying that no permeation occurred. Sorption was insignificant for concentrations of toluene ≤ 40% (v/v) in NIST reference fuel – implying that no permeation of toluene occurred at these concentrations. With aqueous solutions of benzene, toluene, and TCE, the weight gains for 60% saturated aqueous solutions and below were less than 2% after 8 months of exposure. Sorption of the 20% saturated aqueous solutions was found to be statistically similar to that of the control experiment - implying that sorption was negligible for contaminant levels below 20% saturated aqueous solutions of benzene, toluene, and TCE.

Predictive Test – Moving Front Test

The moving front test developed in this study is a precise and rapid test that directly measures the progression of permeation caused by swelling in a PVC pipe. By measuring the moving front rates for 58 PVC pipe specimens from five different manufacturers in 48-hr toluene tests, the moving front test was found to be a useful tool for comparing the relative susceptibility of PVC pipes to permeation.

In experiments with PVC pipes exposed to various concentrations of benzene, toluene, and TCE in NIST reference fuel, no moving front was observed when the volume % of toluene was 40% or below. Moving fronts were observed at 100% and 80% saturated aqueous solutions of toluene, but no moving fronts at 60%, 40%, and 20% saturated aqueous solutions of benzene, toluene, or TCE after 12 months of exposure.

Moving fronts did not form during two years of exposure of PVC pipes to pure gasoline or to aqueous saturated solutions. Premium gasoline fortified with toluene did not cause a moving front to form in PVC pipe when the concentrations of total BTEX and toluene (v/v) were at or below 32.2% and 21.2%, respectively. Moving fronts were formed when total BTEX was between 43% and 45% by volume and toluene was at or above 30.8% by volume, a concentration of toluene that is more than double that typically found in premium gasoline.

The moving front tests showed that premium gasoline did not have sufficient toluene or other BTEX compounds to initiate a moving front. Experiments with toluene in NIST reference fuel and toluene-fortified gasoline showed that a concentration of more than 40% (v/v) toluene was required to initiate a moving front. This is well above the concentration of toluene or total BTEX in premium gasoline. Experiments with mixtures of BTEX compounds in reference fuel showed that the initiation of a moving front in PVC pipe is not dependent on the concentration of a single compound but is dependent on sum of the concentrations (i.e., activities) of the BTEX compounds. A moving front will not form in PVC pipe unless the total BTEX is greater that 40% (v/v).

PVC pipes that become permeated with hydrocarbons should be replaced (if they have not burst due to loss of physical strength) because remediation of the pipe material is not feasible.

Predictive Test –Near Infrared (NIR) Reflectance Spectroscopy

NIR spectroscopy was found to be a useful screening tool for predicting pipe permeation susceptibility and for tracking the permeation process of pure solvents such as benzene and toluene in PVC pipes. NIR spectra of unexposed and exposed pipes and laboratory reference data such as percent weight gain, weight gain per unit length and advance of the moving front were needed to establish a database for a given model of NIR spectrometer. Calibration models developed, however, are limited to the types of PVC pipes within the database and may not be able to predict with certainty for the types of PVC pipes not in the database.

Permeation of Gaskets by Hydrocarbons

Ductile Iron Pipes and Tyton® Gaskets

Using pipe-drum experiments with 4-inch DI joints, permeation was observed for ethylene propylene diene monomer (EPDM) after 35 days of exposure to gasoline, and after 50 days for neoprene (CR) and styrene butadiene rubber (SBR). NBR and FKM were the most resistant to permeation with permeation after 124 days for NBR while very low concentrations of BTEX were detected for FKM without a sudden breakthrough of BTEX, which was probably attributable to leakage, not permeation.

Upon exposure to gasoline-saturated water (about 168 mg/L total BTEX), breakthrough was observed through the SBR gasket after 210 days. Upon exposure to a 50% saturated aqueous solution of gasoline, breakthrough was observed after 240 days. No permeation was observed through SBR gaskets exposed to 20%, and 5% saturated aqueous solutions of gasoline.

No permeation through NBR gaskets was observed for any level of gasoline contamination in water.

Experiments with 4-inch DI pipe joints using SBR Tyton® gaskets exposed to free product premium gasoline for different hydrostatic pressures (0, 20, 40, and 60 psig) indicated that there was no correlation between permeation and hydrostatic pressure in the pipe.

In a service line where periods of stagnation occur, the 5 μg/L MCL for benzene was predicted to be exceeded during an 8-hour stagnation period for SBR gaskets in contact with free product gasoline. For the same conditions, the benzene MCL in the pipe-water was predicted to not be exceeded for DI pipe using NBR gaskets. For SBR Tyton® gaskets exposed to gasoline in groundwater, even groundwater that is saturated with gasoline, the EPA MCL for benzene would probably not be exceeded in the pipe water even for 8 hours of stagnation.

With a minimal average water flow, benzene in the pipe water was predicted to not exceed the MCL for DI pipes with SBR Tyton® gaskets exposed to gasoline, even under the worst conditions of gasoline contamination.

PVC Pipes and Rieber Gaskets

Permeation of gasoline through PVC pipes with SBR and NBR Rieber gaskets was rapid with breakthrough of benzene in 21 days. The MCL for benzene (5 μg/L) was exceeded at breakthrough.

After 8 hours of stagnation in contact with free product gasoline, the concentration of benzene in pipes of diameters up to 24 inches using SBR gaskets was predicted to exceed the CL. Under the same conditions, the MCL would be exceeded in pipes of diameters up to 10 inches using NBR gaskets. In pipes of diameters ≥12 inches with NBR Rieber gaskets, the concentration of benzene was not predicted to exceed the MCL. Flow estimations indicate that minimal average water flow would be sufficient to dilute the benzene to less than the MCL for both SBR and NBR gaskets when exposed to free product gasoline. Therefore, in typical gasketed PVC pipes with full water flow, the concentration of benzene was predicted to not exceed the MCL due to dilution.

After 9 months of testing, there was no permeation of BTEX through either SBR or NBR gaskets exposed to any level of gasoline contamination in water (including 100%, 75%, 50%, or 10% saturated aqueous solutions of gasoline).

RECOMMENDATIONS

PE Pipe

For practical purposes, there is no level contamination at which PE pipe is resistant to permeation by gasoline, chlorinated solvents, or aqueous solutions of gasoline or chlorinated solvents. Corrective action should be taken whenever there is a known spill of gasoline or organic solvents in the vicinity of a PE service line. Regardless of whether there is a taste or odor complaint, it is most likely that the MCL for benzene will be quickly exceeded in the potable water since the taste and odor threshold level for benzene in potable water is well above the MCL for nzene.

PVC Pipe

PVC pipe is impervious to gasoline. Where gasoline is the only source of hydrocarbon contamination and a choice is to be made between PVC or DI pipe, engineering considerations other than permeation should govern the selection of pipe materials. However, if conditions of stagnation and contact with free product are anticipated, selection of DI pipe with NBR gaskets is preferable, as discussed below.

PVC pipe is impervious to benzene, toluene, and TCE at concentrations in water that are commonly encountered in the field. Based on the laboratory experiments, moving fronts were not observed for less than 60% aqueous solutions of benzene, toluene, and TCE but weight gains of 2% in the sorption test were observed for 60% aqueous solutions of toluene and TCE.

AWWA standards relating to plastic pipes and gasketed pipes include a statement regarding permeation by hydrocarbons directing utilities to consult with manufacturers before selecting pipe or gasket materials to be used in contaminated or potentially contaminated areas. PVC pipe manufacturers commonly refer customers to the Uni-Bell PVC Pipe Association for guidance regarding use of PVC pipes in contaminated areas. The current criteria for compatibility of PVC pipe recommended by the Uni-Bell PVC Pipe Association are activities of 0.25 for benzene and toluene and activities of 0.10 for chlorinated solvents. These criteria were based on sorption experiments involving exposure of thin films of pure PVC polymer powders to solvents in the vapor phase and exposure of PVC sheets pressed from pure powders to the solvents.

The laboratory results reported here indicate that PVC pipes can tolerate a higher activity than that specified by Uni-Bell and that the impact of the individual activities of BTEX compounds is additive. PVC pipe is compatible with benzene, toluene, ethylbenzene, and xylenes (BTEX) in groundwater, provided that the sum of the activities of the individual compounds does not exceed 0.40 and no other swelling solvents are present in significant concentrations. This guidance includes a margin for safety since laboratory results showed that BTEX activities (or TCE activity) must exceed 0.60 activity for a moving front to form and permeation to occur. Activity in this case means the concentration of a compound expressed as a decimal fraction of its maximum solubility in water or vapor. PVC is compatible with TCE in groundwater provided that the activity of TCE does not exceed 0.40 and no other swelling solvents are present in significant concentrations. Mixtures of TCE and BTEX were not studied in this project.

Tyton® Gaskets

SBR Tyton® gaskets may be used (without exceeding the MCL for benzene) in DI water mains under all conditions of gasoline contamination as long as there is at least minimal average flow in the main (at least 0.24 gpm in 4-inch pipe) and conditions of stagnation do not occur. Under conditions of stagnation, as for a service line in direct contact with free product gasoline or soil vapor from a nearby layer of free product, NBR gaskets may be used (without exceeding the MCL for benzene). NBR Tyton® gaskets are the most cost effective choice when a gasket material resistant to gasoline is desired.

The guidance offered in this report is based on the assumption that water is safe to drink if the U.S. EPA maximum contaminant levels (MCLs) are not exceeded for any contaminant. Sufficient information is given in this report for utilities to perform the equivalent calculations for lower contaminant levels. It should be noted that the EPA's maximum contaminant level goal (MCLG) for benzene is 0 µg/L.

Rieber Gaskets

Both SBR and NBR Rieber gaskets may be used (without exceeding the MCL for benzene) in PVC water mains in direct contact with free product gasoline provided there is a minimum average water flow (at least 0.037 gpm in 2-inch pipe). For conditions of 8-hour stagnation in contact with free product gasoline, the MCL was predicted to be exceeded for pipes using SBR Rieber gaskets up to 24 inches in diameter and for NBR Rieber gaskets up to 10 inches in diameter. Either SBR or NBR Rieber gaskets may be used (without exceeding the MCL for benzene) for PVC pipes exposed to gasoline-saturated water.

FUTURE RESEARCH

This study has extended previous research by conducting laboratory experiments for concentrations that were similar to field conditions by using various aqueous solutions of gasoline, benzene, toluene and TCE. In addition, this study has developed a predictive test method (moving front) for PVC pipes and has assessed the utility of NIR spectroscopy.

The moving front test can be easily used to test aged PVC pipes and to study whether aging increases susceptibility. Since it is difficult to obtain aged pipes and their history, a deliberate attempt should be made to age the pipes in the laboratory. This could include burying and exposing pipes to soils of different pHs, for different period of times, and exposure to sunlight/ultraviolet light. These pipes could then be tested using the moving front test and the progression of the moving front would provide information on the susceptibility of the pipe under different aging conditions.

The research has focused on some of the major hydrocarbons encountered in the field such as BTEX in gasoline, and chlorinated solvents such as TCE. Testing should continue by using the predictive test methods and pipe-bottle apparatuses to assess the permeation of similar light aromatic compounds such as ethylbenzene, xylenes, and chlorinated solvents such as tetrachloroethylene (PCE), dichloroethylene (DCE), tetrachloroethane (PCA), and trichloroethane (TCA) to determine whether these chemicals behave in a manner similar to benzene, toluene and TCE. While the impact of on permeation of mixtures of BTEX compounds was studied in this project, future research should investigate permeation by mixtures of chlorinated solvents and by mixtures of chlorinated solvents and BTEX compounds.

Of interest is a further understanding of the pathway of contamination or the permeation process through the Tyton® and Rieber gaskets. The Tyton® and Rieber gaskets were designed to provide a tight joint to prevent water leakage under hydrostatic pressures and may not be optimized in its design to minimize permeation from the outside. Further research should focus on using better visualization or analytical tools to examine exposure areas, the path of travel for the contaminants, and modeling the permeation by using equivalent gasket dimensions. By building a better mathematical model, permeation can be estimated for different materials if the diffusion coefficients are determined using one or more of the predictive test methods.

There is a need for a more definite predictive test method to assess the permeability of gasket materials. The gravimetric sorption test method serves as a rapid method but does not provide sufficient data to provide relative magnitudes of the permeation rates.