Improving Safety of Crude Oil and Regional Water System Pipeline Crossings

Final Report

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DISCLAIMER

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LIST OF ABBREVIATIONS

ASTM	American Standard Testing Methods
BTEX	Benzene Toluene Ethylbenzene Xylene
DI	Ductile Iron
DSG	Dakota Supply Group
GC/MS	Gas Chromatograph/ Mass Spectrometer
HDPE	High Density Polyethylene
MCL	Maximum Contaminant Level
MEK	Methyl Ethyl Ketone
mg/L	Milligrams per liter
PB	Polybutalene
PE	Polyethylene
psi	Pounds per square inch
PVC	Polyvinyl chloride
NBR	Nitrile Butadine Rubber
SBR	Styrene Butadine Rubber
TCE	Trichlorethylene
TOC	Total Organic Carbon
TPH	Total Petroleum Hydrocarbon
VOC	Volatile Organic Carbon
WEERC	Water and Environmental Engineering Research Center

CHAPTER 1. INTRODUCTION

1.1 General

New pipelines are being constructed across Midwestern states to convey crude oil from Canada to refineries in the United States of America. Two such pipelines are the Keystone pipeline (in operation) and the Keystone XL pipeline (proposed). In South Dakota these pipelines cross over regional water system pipelines that play a significant role in public, agricultural and industrial water supply. Proper design of the pipeline crossings will protect both pipeline systems, the water system pipelines from potential crude oil releases and the crude oil system pipelines from potential damage due to repairs of the water pipelines in the event of a water main break.

Crude oil released near a water pipeline may collect around the water pipe or joint. Crude oil contains organic compounds that may impact the strength or permeate through materials used in water pipelines. For example, various concentrations of benzene, toluene, and trichloroethylene were found to permeate water system components (Ong et al., 2008). According to Ong et al. (2008) premium gasoline did not permeate through polyvinyl chloride (PVC) under the conditions of their study, but permeation did occur through the joint coupling used in their study. The joint coupling gaskets were the point of permeation. Most regional rural water pipelines in South Dakota are constructed with jointed PVC pipe, and if hydrocarbons from a crude oil release permeated through a PVC water pipe, the quality of potable water in the system may be affected. The pipe material may swell and soften due to contaminant permeation (Ong et al., 2008). If a pipe becomes soft its structural integrity may be compromised leading to potential failure. However, no testing was done by Ong et al. (2008) to find the structural effects of crude oil on plastic pipe and pipe components.

Ten State Standards section 8.1.2 (Great Lakes Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, 2007) states that where distribution systems are installed in areas of ground water contaminated by organic compounds, (a) pipe and joint materials which do not allow permeation of the organic compounds shall be used, and (b) non-permeable materials shall be used for all portions of the system including, pipe, joint materials, hydrant leads, and service connections. Based on a survey conducted as part of this work, most water systems preferred encasing their water carrier pipe at the location where the two pipes crossed. The casing pipe would protect the water carrier pipe from a crude oil release. In the event of a water pipe failure, the failed water pipe could be replaced without excavating near the crude oil pipeline, protecting the oil pipe against accidental rupture. To enable improved crossing safety, for the purpose of this work the water carrier pipe was assumed to be encased with a plastic casing.

1.2 Objective

The purpose of this project was to provide information that will be used to recommend water pipe casing materials for design of future crude oil pipeline and rural water pipeline crossings. To accomplish this objective, plastic materials were selected as the best option for the casing pipe, given their favorable characteristics for directional bore construction, historical use as a casing material, and familiarity to pipeline construction contractors. Three types of plastic casing options were envisioned 1) fusible polyvinyl chloride (PVC), 2) restrained joint PVC, and 3) fusible high density polyethylene (HDPE). To examine the compatibility of materials in the event of a crude oil release, PVC joint couplings, PVC pipe, high density polyethylene (HDPE) pipe, and gaskets were tested for their resistance to permeation by crude oil. The strength characteristics of the joint couplings and pipe segments were also tested after they were submerged in crude oil saturated granular soil. The pipe segments and gaskets were also submerged in de-chlorinated tap water or water saturated soil as a control.

1.3 Scope

The scope of this work included a literature review, a survey of the characteristics of Keystone pipeline crossings with rural water system pipelines, and experimental work to examine the compatibility of crude oil with candidate casing materials. The literature review provided a review of design practices for water pipelines in the presence of petroleum pipelines, a basis for selecting experimental methods and a basis against which to compare the experimental results. The pipe crossing survey provided a review of alternatives used for the design of crossings. The experimental work included strength and permeability tests.

American Society of Testing and Materials (ASTM) based structural strength tests were conducted on the PVC and HDPE pipe, and pipe joint gaskets that were exposed to crude oil or de-chlorinated tap water. These strength tests included compression tests on the PVC and HDPE pipe and tensile tests on PVC and HDPE pipe and polyisoprene and nitrile butadiene rubber (NBR) gasket samples. Specimens exposed to de-chlorinated tap water were considered a control, and results from pipe specimens exposed to crude oil were compared with the strength results of pipe exposed to water.

Tensile tests were conducted on NBR and polyisoprene gaskets submerged in each crude oil and in de-chlorinated tap water. The results from the gasket samples submerged in water provided a control. The results were evaluated to see if the increase in weight due to permeation related to the tensile strength of the gaskets and permeation through the gasketed joints.

Permeation tests were also conducted on the PVC pipe, PVC joint couplings, and HDPE pipe segments. The pipe segments and joint couplings were submerged in granular soil saturated with either crude oil or water. Total petroleum hydrocarbon and total organic carbon tests were conducted on water contained inside the pipes and joint couplings to determine if permeation occurred. The test results from the joint couplings soaked in water were compared with the results from the joint couplings soaked in crude oil.

The test results were summarized relative to the desirable qualities of casing materials used for crossings, and a crossing method was recommended.

CHAPTER 2. LITERATURE REVIEW AND SURVEY

2.1 Introduction

Literature was reviewed to provide background information pertaining to interactions between petroleum hydrocarbons and plastic pipe or coupling gaskets. Factors affecting permeation through pipe components were investigated and summarized. The results of a survey of South Dakota rural water system pipe crossing experiences and a survey of state regulatory agency design standards and practices are presented.

2.2 Surveys of Water Pipe Permeation when Exposed to Hydrocarbons

Two surveys were located that examined water pipe behavior under hydrocarbon exposure. In a national survey conducted by Ong et al. (2008), permeation incidents were defined as occasions when customer experiences a taste, odor, or illness from drinking water or when the result of laboratory analysis of a water sample collected from an affected pipe exceeded U.S. EPA maximum contaminant levels (MCLs). PVC pipe accounted for 18% of the 83,360 miles of mains reported by survey respondents. Ductile iron and PE pipe accounted for 16% and 0.18% of the miles of main reported, respectively. The other 66% was reported as either cast iron, steel, asbestos cement, and concrete pipes. The respondents only considered 0.54% of the length of mains to be at risk of permeation by organic contaminants. Of the 6 reported permeation incidents, 4 involved PVC pipe material, 1 asbestos cement, and 1 cast iron. Three of the permeation incidents involved gasoline, 1 involved chlorinated solvents, and 2 involved unknowns.

The second survey was conducted by Thompson and Jenkins (1987). They found 43% of the reported permeation incidents in the U.S. involved polybutylene (PB) pipe, 39% involved polyethylene (PE) pipe, and 15% involved PVC pipe. From these results, plastic pipe appears to have experienced more permeation incidents than other pipe types.

2.3 Effects of Surrounding Soil Type on Permeation

Water pipe may be installed by directional boring or by cut and cover methods. While pipe installed by directional boring is likely surrounded by native soil, cut and cover soil backfill may be either native soil, or a granular soil bedding material. The soil type may impact the concentration and availability of hydrocarbon compounds in a release event. Vonk et al. (1986) found that hydrological aspects or biological degradation may lead to a decrease of the concentration of organic contaminant in soil, and sorption of organics on soil particles can amount to a minor fraction of the measured concentration.

Holsen et al. (1991) found that petroleum contaminants will permeate more slowly through a soil containing a high amount of organic carbon than through a soil of low organic carbon content. The results of the pipe bottle and soil column tests indicated that the permeation rate is controlled by the concentration of organic chemical in the soil-pore. According to Holsen et al. (1991), experimentally determined or empirically predicted partition coefficients between the soil and water can predict the soil-pore concentration for a particular organic chemical if the amount of organic chemical, initial water mass, and soil mass are known.

If petroleum contamination is anticipated near a water pipe, Holsen et al. (1991) suggests that at a minimum, native soil should be used as backfill material, because it generally has a higher organic content and lower permeability than sand. The use of native soil over sand will not completely protect the pipe from contact with organic chemicals. However, the organic carbon in the soil will adsorb some of the organic chemicals, lowering the amount of organics that may come in contact with the pipe. The native soil will also be more compact, providing less pore space for organic chemical movement.

2.4 Factors Affecting Permeation through Plastic

Several authors have investigated the influence of chemical and physical factors on permeation of hydrocarbons through plastic. Major factors include the petroleum hydrocarbon structure, its concentration or activity, and the structure of the plastic pipe.

Vonk (1986), and Berens (1985) stated that the activity of a compound rather than its concentration should be used to predict the susceptibility of pipe material to permeation by organic compounds. Berens (1985) assigned pure liquid compound an activity of one and used the pure liquid as the reference state. Vonk (1986) defined activity equal to one when the concentration of a compound was equal to its maximum solubility in water. Vonk (1986) used aqueous solubility to define activity in the context of permeation theory as follows:

$$\boldsymbol{\alpha_i = \frac{C_w}{C_{w,m}} \qquad or \qquad \alpha_i = \frac{C_v}{C_{v,m}}} \qquad \textit{Equation 2.1}$$

Where: α_i= activity (0≤ $\alpha_i \leq 1$) (not to be confused with chemical activity coefficient),

C_w= concentration in water (mg/L),

$C_{w,m}$ = maximum (saturated) solubility in water (mg/L),

C_v = concentration in the vapor phase (mg/L), and

$C_{v,m}$ = maxima (saturated concentration in the vapor phase (mg/L).

Vonk (1986) postulated several ranges of activity that would impact the permeation mechanism. He stated that if the concentration of a compound outside the pipe was less than 0.1 times the maximum concentration in water or vapor phase, then Fick's laws of diffusion would describe the permeation of the organic compounds through the pipe. However, the diffusion coefficients of organic compounds through rigid PVC pipe are small enough that Fickian diffusion would be negligible. Thus, permeation through plastic pipe not only depends on the speed of diffusion, but also the solubility of the organic molecules in the polymer (Olson, 1987). Vonk (1986) stated that organic compounds whose concentration is just below saturation (say, 0.8 times the maximam concentration) have the ability to soften and permeate through PVC pipe. This mechanism for permeation is named the "moving front". The "moving front test" can be used as a predictive test to estimate when the organic compound would break through the inner pipe wall (Vonk, 1986).

In the intermediate concentration range, between 0.1 and 0.8 times the maximam concentration, Vonk (1986) stated that no significant permeation occurs at concentrations up to about 0.25 times the maximum concentration in the water or vapor phase. This value was found by performing gravimetric sorption tests with solvents on thin films of pure PVC polymer. After the concentration of these organic compounds reaches above 0.25 times the maximal concentration, there is no deviation from Fickian diffusion.

The type of hydrocarbon also influences permeation through plastic. For compounds which soften PVC somewhat less readily, such as BTEX compounds, the activities indicated for Fickian diffusion according Berens (1985) are ≤0.25. Berens (1985) stated that concentrations of toluene in air or groundwater at 0.25 activity would be considered extremely high levels of environmental pollution, yet they are still in the range in which permeation through PVC pipe walls is vanishingly slow, enabling PVC to be an effective barrier under these conditions.

Even though Berens (1985) used pure solvent to describe unit activity and Vonk (1986) used the concentration when a solvent is at its maximum solubility in water to describe unit activity, the two values are the same. The two values are equal since the vapor pressure of a saturated solution equals the vapor pressure of the solvent (Ong et al., 2008). Based on the studies of Vonk (1986) and Berens (1985), even though the reference states of the activity were different, the values of the activities found to permeate PVC pipe would be similar.

2.5 Impacts of Pipe Structure and Type on Permeation

According to Vonk et al. (1986) two independent physical processes - one being partition equilibrium established at the surface of the polymer, and the other that diffusion occurs within the polymer - determines permeation in plastics. PVC and polyethylene (PE) pipe have different characteristics that control the occurrence of diffusion because of fundamental differences in their polymer structures. PE pipe has a high degree of mobility between the polymer chains. PVC pipe has limited flexibility in the polymer chains. Therefore, permeation occurs through the more mobile polymer chains of PE pipe, than the relatively immobile polymer chains of PVC pipe. The dissimilarity of permeation mechanisms between PE and PVC pipe is due to these structural differences (Vonk et al. 1986, Selleck et al. 1991). According to Holsen et al. (1991) polybutylene (PB) pipe is even more permeable than PE pipe. Leseman (1986) also found that PB pipe would be permeated by gasoline.

2.6 Coupling Gasket Permeation

Several types of rubber gaskets have been tested for their ability to withstand permeation by different solvents or gasoline mixtures. They were typically tested in two ways, one by submerging the gasket or a piece of the gasket in the contaminating liquid and measuring the weight gain, and second by rate of sorption through the gasket installed in a coupling (Glaza and Park, 1992). During weight gain tests, the gasket materials were submerged in the contaminating liquids, and thickness and weight measurements were taken at regular intervals. The sample was removed from the contaminating liquid, wiped dry with an absorbent towel, and then measurements were taken (Glaza and Park, 1992). The sorption test was conducted placing de-ionized water in gasketed pipe segments submerged in the contaminating liquid, and the de-ionized water was analyzed for contaminants at regular time intervals (Glaza and Park, 1992).

The results from research done by Glaza and Park (1992) concluded that jointed piping should not be used where the possibility of contact with VOC-contaminated soils is high because the gasketed joints were susceptible to permeation. Although metal pipe such as ductile iron is resistant to permeation, the gasketed couplings joining ductile iron pipe are susceptible to permeation. Permeation through the couplings might go unreported due to the low concentration that may not exceed the taste or odor threshold.

In the study by Glaza and Park (1992), styrene-butadiene (SBR), nitrile, and special nitrile gaskets were tested for permeation. Gasketed pipe segments were submerged in the contaminating liquids, and water inside the pipe was tested periodically to see if permeation had occurred. Each type of gasket experienced permeation by gasoline constituents, mineral spirits, MEK and toluene. The gasketed pipes soaked in gasoline took 10 months to experience significant levels of permeation. Both types of nitrile gaskets were more resistant to permeation by the benzene in the gasoline than the SBR gaskets. The gasketed pipes immersed in a mixture of mineral spirits, MEK, and toluene took 4 months to experience significant permeation. The special nitrile gasketed pipe was more resistant to permeation by methyl ethyl ketone (MEK) followed by the SBR gasketed pipe and then the nitrile gasketed pipe. MEK was the first to permeate due to its small molecular size (Glaza and Park, 1992).

In a water distribution system, water is typically continuously flowing through pipes as a result of water demand (unless the pipe is in a branched system or near a dead-end). Convection and diffusion through flowing water in pipes will be the primary means of transport of contaminant that has permeated through the water pipe gasket. When permeating through a gasket, diffusion of the contaminant would occur radially inward toward the center of the pipe as well as in the direction the water is traveling. For Fick's second law to be valid, it may be assumed that the contamination is instantaneously diffused across the cross-sectional area of the pipe at the gasket. In the case of steady state mass flux into a substance, the concentration can be found by using both distance from the source and time (Glaza and Park, 1992). Glaza and Park (1992) used Equation 2.2 to model this scenario;

$$C_{x,t} = \frac{Mx}{4DA_c\sqrt{\pi}} \int_0^{4Dt/x^2} u^{-1/2} e^{-1/u} du \qquad \textit{Equation 2.2}$$

in which M is the rate of mass input, x is the distance from the source of diffusant, D is the diffusion coefficient in the liquid, A_c is the cross-sectional area of pipe, and t is the time elapsed after exposure. The diffusion coefficient for benzene in water would be difficult to determine because it depends on temperature, pressure, and other chemicals present in the water. A diffusion coefficient of 1.02 x 10^{-5} cm^2/s in water at 20 degrees Celsius was determined for a low concentration of benzene in water. That same diffusion coefficient was used for methyl ethyl ketone (MEK) as well (Glaza and Park, 1992). Using this theory, the estimated average benzene concentrations in pipe water near a gasket were 550, 40, and 20 micrograms per liter for SBR, nitrile and special nitrile, respectively. These values are all above the benzene maximum contaminant level (MCL) of 5 micrograms per liter. The predicted MEK concentration near a gasket were 30,200, 17,600, and 17,500 micrograms per liter for SBR, nitrile, and special nitrile gaskets, respectively (Glaza and Park, 1992).

Ong et al. (2008) studied permeation through Reiber gaskets. The Reiber joint is a common bell and spigot joint used in water systems, where the pipe bell has the gasket placed in it during the manufacturing and belling process. According to Rahman and Alchin (2005) some advantages the Rieber joints offer are a high resistance to water infiltration and exfiltration, preventing leakage when axial joint deflection takes place within allowable limits, and withstanding high internal pressure and vacuum.

Findings from research performed on Rieber joint systems showed the Rieber gasket materials were susceptible to permeation of organics. Ong et al. (2008) simulated field conditions which varied from subsurface gasoline spills and gasoline-contaminated groundwater of various levels of contamination. Field conditions were simulated using Silica sand (Granusil 4030). The sand was placed in the pipe-drum apparatuses which consisted of a 20-L drum with holes drilled through the lid and bottom. The PVC pipe was placed through the drum, and the connections were sealed with Loctite epoxy putty. The pipes were filled by pumping water from top to bottom using a Masterflex pump. SBR gasketed pipe experienced breakthrough of benzene in about 21 days when exposed to premium gasoline. Breakthrough occurred in NBR gasketed pipe in 21 days as well.

When compared to sorption in gasoline, weight gain by the gaskets due to sorption of hydrocarbons in gasoline-saturated aqueous solution was much slower (Ong et al., 2008). This longer equilibrium sorption period may be due to the mass transfer limitations the water provided. The BTEX solvents had to first disperse through the aqueous solution, and then move through the "stagnant water film" surrounding the outer surface of the gaskets (Ong et al., 2008).

2.7 PVC Pipe Permeation by Organic Solvents

Ong et al. (2008) performed an environmental simulation experiment where PVC pipe was exposed to gasoline. Holes were drilled in both sides of a glass bottle and the pipe was secured in the holes of the glass bottle. The PVC pipe was covered in Silica sand (Granusil 4030), and the sand was saturated with gasoline. Over the 2 years the pipe was exposed to pure commercial gasoline no BTEX compounds permeated through the pipe wall to be found in the pipe water (Ong et al., 2008).

PVC pipe specimens were also exposed to BTEX hydrocarbons in the same pipe drum apparatuses as described earlier. One-inch diameter schedule 40 PVC pipe specimens were exposed to pure BTEX liquids, water saturated organic solvents, and vapor forms of benzene, toluene, and TCE (Ong et al., 2008). Water placed in these pipes was regularly tested for organic content permeation. When exposed to pure forms of the organic solvents, PVC pipe was permeated in 6.5 days by TCE, 16 days by toluene, and 20 days for benzene. At the time of breakthrough the permeation rate was constant (Ong et al., 2008). The pipes swelled and softened due to permeation of the pure forms of organic solvents. When PVC pipe was exposed to organic vapors breakthrough of TCE vapor, toluene vapor, and benzene vapor occurred in roughly 13, 28, and 31 days, respectively (Ong et al., 2008). The delayed permeation time as compared to when the pipe was exposed to pure forms of organic solvents may be due to the effect of mass transfer of the contaminants coming in contact with the pipe wall. Lastly when PVC pipe was exposed to water saturated organic solvents the breakthrough times for TCE and benzene was approximately 168 days and 250 days, respectively.

Based on these experiments the following conclusions can be made. PVC pipes are rapidly permeated by pure and vapor forms of organic solvents. Organic solvents saturated in a water solution can permeate PVC pipes, but the breakthrough times were much longer than those of PVC pipe exposed to pure organic solvents.

American Water Works Association (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 Association for guidance regarding use of PVC pipes in contaminated areas (Ong et al., 2008). 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 (Ong et al., 2008). 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 (Ong et al., 2008).

The laboratory results from the study done by Ong et al. (2008) indicated that PVC pipes can tolerate a higher activity than that specified by Uni-Bell PVC Association and the impact of the individual activities of BTEX compounds is additive. PVC pipe is compatible with BTEX hydrocarbons 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 substantial concentrations (Ong et al., 2008). (Activity in this case means the concentration of a compound expressed as a decimal fraction of its maximum solubility in water or vapor). The 0.4 total activity value includes a margin for safety since Ong et al. (2008) laboratory results showed that BTEX activities must exceed 0.60 activity for a moving front to form and permeation to occur. Ong et al. (2008) also concluded that PVC was compatible with TCE in groundwater provided that activity of

TCE did not exceed 0.40 and no other swelling solvents are present in substantial concentrations. Mixtures of TCE and BTEX were not studied in their project (Ong et al., 2008).

2.8 Polyethylene Pipe Permeation

Ong et al. (2008) prepared pipe permeation apparatuses made of one liter glass bottles with PE pipe installed horizontally through holes drilled in the glass. The connections between the pipe and glass jars were sealed with Loctite epoxy putty, and the ends were closed with Teflon plugs. The Teflon plugs had holes drilled in them and brass plugs were installed so water could be added and drawn from the pipes for analysis.

These pipe permeation apparatuses were used to test the effects of pure gasoline, gasoline-contaminated groundwater, and unsaturated gasoline-contaminated soil on the PE pipe. In the experiment used to determine if pure gasoline would permeate PE pipe, the pipe drum apparatuses were filled with silica sand saturated with premium gasoline. The BTEX compounds of the gasoline quickly permeated the PE pipe. Breakthrough occurred within approximately one week. When PE pipe was exposed to gasoline-contaminated ground water at four levels of contamination (100%, 50%, 10%, and 1% by volume), permeation rapidly occurred through the PE pipe even with the most diluted solution. Benzene and toluene were the first to permeate followed by ethylbenzene and xylene.

Based on their experiments, Ong et al. (2008) concluded that PE pipe is not resistant to permeation by gasoline, chlorinated solvents, or aqueous solutions of gasoline or chlorinated solvents at any concentration. Ong et al. recommended that whenever there is a known spill of gasoline or organic solvents in the vicinity of a PE service line, corrective action should be taken. The taste and odor threshold level for benzene in drinking water is well above the MCL for benzene. Therefore, even if there is not a taste or odor complaint, benzene concentrations in the potable water pipe would have probably reached the MCL (Ong et al., 2008).

Thompson and Jenkins (1987) and Vonk (1986, 1985) researched the effects of non-polar organic compounds on PE pipe. Vonk (1985) exposed PE pipe to aqueous and vapor forms of compounds. PE pipes were inserted horizontally through a glass bottle that was filled with drinking water and organic compounds. The water in the pipes and in the glass jar were tested to find the total amount of chemical penetrated into and through the pipe. Vonk (1985) found that PE pipe was rapidly permeated, and that Fick's Laws described permeation of organic compounds through PE pipe.

Vonk (1986) performed additional experiments where PE pipe was exposed to unsaturated solutions of different organic compounds in water, and organic vapors. Glass jars were used again in the same manner as the previous experiment conducted by Vonk (1985). Vonk (1986) concluded the constant rate of permeation for most organic compounds investigated happened in roughly 60 days, but diphenyl took 400 days to reach stationary state permeation. Another conclusion was that the permeation rate of the experimental organic compounds was almost equal through HDPE and LDPE pipe.

2.9 Review of Crossing Design Practices

Several resources were used to gather information that defined current design practices and regulatory approaches for water pipelines located in close proximity to petroleum pipelines or tanks. These resources included a survey of state regulatory agencies conducted by the Iowa Department of Natural Resources (2007), an additional survey of plan approval agencies conducted by project personnel, and a survey of rural water systems conducted by project personnel. The results of these surveys are summarized below.

2.9.1 Iowa Department of Natural Resources Survey

The Iowa Department of Natural Resources (2007) conducted a survey of state agencies to determine if they evaluated the impact of petroleum on plastic water lines in their underground storage tanks, leaking underground storage tanks, or other programs that may be involved in remediating or permitting plastic water lines. The following paragraphs summarize the responses from the survey.

Four of the 25 states interviewed have specified procedures for assessing the impacts of petroleum on plastic water lines (Iowa DNR, 2007). Indiana enables the underground storage tank program or the remedial programs that address petroleum releases to evaluate impacts of petroleum on plastic water lines. Risk-Based Corrective Action (RBCA) procedures are used by Iowa’s underground storage tank program to evaluate impacts to plastic water lines. They evaluate exposure pathways including via the soil to plastic water line, groundwater to plastic water line, and soil leaching to groundwater to plastic water line. If plastic water lines are within a simulated or actual plume, regulations require the plastic lines to be removed, the site remediated, and pipe replaced with non-plastic material. Missouri’s Tanks Section of the Hazardous Waste Program requires the responsible party to evaluate the impact of petroleum on plastic water lines. If contamination could contact water lines, further evaluation is used to determine if contaminants could enter the water system through pipe walls or joints. South Dakota Guidance indicates the procedure if ground water or soil above Tier 1 action level contamination above the maximum contaminant level is in contact or next to a water line a tap sample must be collected. In addition, free product or product saturated soil can never be left in contact with a waterline.

Seven of the 25 states interviewed handled potential permeation incidents on a site-specific basis. Illinois has a regulation that indicates water main and service lines shall be protected from hydrocarbon diffusion through any material used in construction, but the type of protection used is depends on the contamination situation. However, Illinois currently has no routine evaluation performed in hydrocarbon release situations. Delaware does not anticipate any changes to construction specifications, but should an unexpected contamination occurrence happen, the plastic water line would need to be replaced with ductile steel with nitrile rubber gaskets in the contaminated area. Maryland experienced water contamination issues dealing with plastic water lines and responded to them on a site-specific basis. Michigan follows Ten State Standards (Iowa DNR, 2007) which indicates ductile iron pipe with viton or nitrile gaskets be used in areas that are susceptible to petroleum product release. Montana and Nebraska assesses each situation of petroleum contamination on a site-specific basis. Oklahoma does not consider the plastic water line type in the evaluation of risk for exposure at petroleum storage tank release site.

2.9.2 Survey of State Design Standards

Thirteen states were surveyed by SDSU personnel in 2009 to summarize state design standards or regulations enforced for crossings of water pipe lines and crude oil pipe lines. These results can be seen in Table 2.1 (continued on the following page).

Table 2.1. Survey of state regulations and recommendations for pipe crossings.

Kansas - Dept. of Health and Environment: (785) 296-1500 • At least 25 ft. distance between potable water lines and pollution sources. • Under no circumstances shall a water line be extended through an area that is a real or potential source of contamination to the water supply. • Under no conditions shall the encasement of a water line be considered adequate protection of a water line or water supply for the purpose of extending the water line through a potential source of contamination. • Relative to pipe crossings (not specific to petroleum): When a water line must be sleeved within a pipe to protect it at pipeway crossings, the water line must be sleeved with seamless, jointless pipe or equal or greater mechanical strength for a distance of at least 10 ft. beyond the crossing in both directions, kept separate from the sleeve pipe with plastic spacers or wooden skids, and spaces at the end of the pipes must be made watertight with flexible boot type end seals.
Missouri - Dept. of Natural Resources: (573) 751-6892 • Standards on sewer and water: 18 in. vertical, 10 ft. horizontal separation with a full length of pipe on each side of the crossing to avoid joints being near the crossing
Louisiana - Dept. of Health and Hospitals: Jake Causey (225) 342-9500 • Currently no standards in place. Louisiana follows 2003 Ten State's Standards and no specific standard for crossing petroleum lines exists.
Arkansas - Dept. of Health: David Pool (501) 661-2623 • No standards for petroleum lines, but if a water line crosses near a petroleum tank that is leaking or has leaked in the past, ductile iron pipe is to be used instead of plastic pipe for the water line
Iowa - Dept. of Natural Resources: Roy Ney (515) 725-0282 • Forming a commission to address standards for leaking petroleum storage tanks. They are hoping to pass standards on gaskets and pipe materials. In regards to water lines, they are concerned about corrosion in petroleum lines, but no casing standards exist currently.
New Mexico - Environmental Dept.: Mike Huber (505) 660-3834 • 10 ft. horizontal separation from outside of pipe to outside of pipe for hazardous liquids. Crossing is prohibited.

Nebraska - Dept. of Environmental Quality: David Chambers (402) 471-2186 • If a gasoline or petroleum storage tank leak occurs, the contaminated soil must be removed and ductile iron pipe is to be used on any water line if it passes by the tank.
Minnesota - Dept. of Health: Lucas Martin (651) 201-5000 • Standards on sewer and water: 18 in. vertical separation with a full length of pipe on each side of the connection to avoid joints near the crossing, and 10 ft. horizontal separation
North Dakota - Health Dept. – Environmental: (701) 328-5210 • Currently no standards in place.
Arizona - Dept. of Environmental Quality: (602) 771-23000 Reference: Engineering Bulletin No. 10 – Chapter 8: Distribution Systems • Standards on sewer and water: horizontal separation of at least 6 ft. If a sewer crosses a water line and the sewer is >2 ft below the water line, no extra protection is required. At all other crossings the sewer shall be constructed of ductile iron with mechanical joints, or approved equal, for a distance of at least 6 ft. in each direction perpendicular to the water line. As an alternate, the sewer shall be encased in concrete of 6 in. minimum thickness for the same distance.
Wyoming - Dept. of Environmental Quality: (307) 777-7781 • Currently no standards in place.
Illinois – EPA: Chris Korhmann: (217) 782-3397 • When a water line crosses a hazardous liquid line, ductile iron is to be used for the water line, and hydrocarbon resistant gaskets, such as nitrile, are to be used. The ductile iron pipe should be installed for 25 ft. on each side of the crossing. Pipe should conform to ANSI/AWWA C111/A21.11.
Colorado - Dept. of Public Health and Environment: (303) 692-3500 • Standards on sewer and water: 10 ft. horizontal and 18 in. vertical separation

Based on the results of the survey summarized in Table 2.1, states have not adopted a uniform standard design for pipe crossings. One state specifically recommended casing the water pipe, whereas several other states recommended using ductile water line in areas of contamination. Of the 13 states surveyed, 7 states have specified a vertical and horizontal distance of separation between the water pipe line and "contamination source" pipe line. Seven states either had no standard for the crossing design or referred to the design practice for crossing sewer lines.

2.9.3 Survey of South Dakota Pipe Crossing Designs

One of the tasks of this project was to conduct a survey of rural water systems regarding the design aspects of crude oil/water pipeline crossings in their systems. Six rural water systems whose distribution systems were crossed by the Keystone pipeline were contacted. The responses from these systems are summarized in Table 2.2.

Several crossing characteristics were reported by the systems. The water carrier pipe diameters in the seventy crossings ranged from 1.5 to 18 inches. Five of the six systems encased the carrier pipe with a casing pipe whose diameter was typically two to four inches larger than the carrier pipe. Four systems used Yelomine PVC as the casing pipe, selected because of its relatively low cost, does not need cathodic protection, and it could be used in directional boring installations. One system used C900 fused-joint PVC pipe as the casing material to avoid issues with potential permeation of the joint gaskets. One system used steel casing for its largest diameter crossing because it was felt the steel casing provided the best protection.

Table 2.2. A summary of crossing characteristics of rural water systems crossed by the Keystone pipeline.

Rural Water System	**Number of crossings**	**Water Pipe diameters**	**Water Pipe material**	**Casing material**	**Casing Provider**	**Casing diameter**	**Total Casing length**	**Vertical Distance from water pipe to oil pipe**
A	14	1.5" - 8"	Yelomine PVC	Yelomine PVC	Winwater Works Company	2"-4" greater than water pipe	300 ft	7 ft
B	4	2" - 12"	Yelomine PVC	Yelomine PVC, Steel	DSG	2"-4" greater than water pipe	300-340 ft	6 ft
C	7	1.5" - 4"	Yelomine PVC	Yelomine PVC	DSG	2"-4" greater than water pipe	100 ft	7 ft
D	11	2" - 6"	Yelomine PVC	C900 fused PVC	Underground Solution	fused pipe, 2"-4" greater than water pipe	200 ft	10 - 12 ft
E	13	2" - 12"	Yelomine PVC	Yelomine PVC	DSG	2 sizes larger than water diameter	100 ft	10 - 20 ft
F	21	1.5" - 18"	original PVC, Yelomine PVC, ductile iron	none				18 in

Several systems reported the details of the casing design. Generally, centering blocks or spacers were used to keep the water pipe centered in the casing, and rubber boots with stainless steel clamps were fastened to the end of the casing and to the carrier pipe to prevent foreign material from entering the casing ends. The casing lengths ranged from 100 – 340 feet to ensure the ends of the casing were beyond the Keystone pipeline right of way and to provide enough casing length to allow sufficient curvature to achieve the desired vertical separation distance between the casing and the crude oil pipeline.

The vertical distance between the crude oil pipeline and the water pipe ranged between 18 inches and 20 feet. One system chose to use the 18-inch separation distance between water and sewer criteria found in Section 8.8.3 of Ten State's Standards (cite reference). This system chose not to case the water carrier pipe, assuming that the cost to case the water pipe was greater than the cost of installing a new pipe if the original water pipe needed repair. The separation distance between the top of the cased water pipe and the bottom of the crude oil pipe ranged between 7 – 20 feet for rural water systems that chose to case their pipelines.

2.10 Assumed Crossing Design and Resulting Factors that Influenced the Study of the Impacts of Crude Oil on Plastic Pipe and Pipe Components

The design of a safe crossing of crude oil and water system pipes generated the need for this study. The highest priority of the crossing design was to develop a safe crossing that would protect the integrity of crude oil pipeline and the water pipeline. Since the crude oil pipeline was installed above the water lines for most of the Keystone pipeline crossings in South Dakota, this configuration was assumed for the crossing design. Given this configuration, the crossing design must protect the water pipeline from potential effects of a crude oil release from the crude oil pipeline. Likewise, the design must protect the crude oil pipeline from potential excavation damage due to maintenance activities on the water pipe, should it need repair under the crude oil pipeline.

Given the review of history of the Keystone pipe crossing designs and review current design standards in Section 2.9, the assumed crossing design configuration involved encasing the water carrier pipe in a plastic casing pipe. The casing pipe should protect the water carrier pipe from a crude oil release and enable a water carrier pipe in need of repair to be replaced by withdrawal and reinsertion through the casing pipe. Plastic pipe was chosen for the casing due to its: a) low cost relative to steel, b) corrosion resistance and lack of need for cathodic protection, c) amenability to installation by directional boring methods, and d) familiarity of use by water utilities and their contractors.

The major concern regarding the use of plastic pipe as the carrier pipe was the potential impact of a crude oil release on the pipe structural integrity and potential for crude oil permeation through the pipe or pipe joint. No studies of the impacts of crude oil on the strength and permeability of plastic pipe or its components were found in the literature. However, several studies of the impacts of petroleum products on PVC and PE pipe, and gasketed PVC and ductile iron pipe joints were found in the literature and were summarized in Sections 2.2 through 2.8. The impacts of the compounds found in liquid petroleum products (gasoline and diesel) on pipe components included: a) petroleum products were found to impact the strength and permeate through polyethylene pipe, b) petroleum products were found to permeate through PVC pipe, although the rate of permeation was much slower than through PE pipe - the rate being strongly affected by the structure of the compound and its strength, and c) pipe joint gaskets are far more susceptible to permeation (than the pipe wall) by petroleum products, and the rate of permeation was directly related to the gasket material.

Due to the lack of direct experimental evidence of the impacts of crude oil on plastic pipe and joint components, experiments were conducted to determine the influence of crude oil on the strength and permeability of plastic pipes that were potential candidates for the pipe casing to be used in the pipeline crossings.

CHAPTER 3. METHODS AND MATERIALS

3.1 Introduction

The primary objective of the experiments conducted in this project was to examine the influence of crude oil on candidate pipe components for casing the water pipe as it crosses under a crude oil pipe. Based on characteristics favorable to their use as casings, Certa-Lok Yelomine PVC and HDPE pipe were chosen as candidate pipe materials. Experiments were developed to examine the effects of crude oil on the strength and permeation characteristics of 2-inch Yelomine PVC pipe, PVC pipe couplings and gaskets, and 2-inch HDPE pipe. The pipe, couplings, and gaskets were tested by exposure to three different samples of crude oil and de-chlorinated tap water (as a control). Comparisons between the results were made between specimens exposed to crude oil versus de-chlorinated water. The experiments were patterned after those of Ong et al., (2008), and American Society of Testing and Materials methods. The experiments are generally described below, followed by a detailed description of each experimental procedure.

Experiments were conducted to examine the potential for permeation of crude oil through the pipe couplings or straight pipe segments. The permeation tests consisted of submerging the Certa-Lok Yelomine PVC jointed pipe and straight lengths of PVC and HDPE pipe in tanks containing sand saturated with the oil or water. The pipe ends extended beyond the tanks and were capped. Valves were placed on the pipes/couplings so the pipes could be filled with Nano-pure (demineralized and organic free) water and samples could be withdrawn as needed. After a period of exposure, water quality tests were performed on the water samples drawn from the pipes/couplings to determine if petroleum hydrocarbons permeated through the plastic pipe or joints into the water.

A weight-gain method (ASTM D 543-06) was used to test the sorption of oil into the joint gasket material. Two gasket materials provided by CertaLok were tested for weight gain. In the weight-gain test, gaskets were soaked in each of the three crude oils and in water. Their weights were recorded at given time intervals to determine the rate of weight gain, which was then compared to examine the rate of oil or water sorption.

Structural integrity tests were performed on PVC and HDPE pipe segments to determine the impacts of exposure (to oil) on structural strength. Straight lengths of PVC and HDPE pipes were submerged in crude oil saturated sand and de-chlorinated water and compression and tensile strength tests were performed on the samples at time intervals. The ASTM D-2412 parallel plate method was used to test the pipe strength under compression. Tensile test was performed using dog-bone (shaped) samples cut from pipe segments following ASTM D 638-08.

Strength tests were also conducted on each of the two types of gaskets. Both types of gaskets were soaked in glass jars containing one of the crude oil specimens or de-chlorinated tap water. Periodically, gaskets were removed and tested for tensile strength using ASTM D-1414. Tensile strength results were correlated with weight gain results.

The experimental and analytical procedures used to test components of this study are described in detail in the following sections.

Given the variety of crude oil compositions shipped from the oil resourced in Canada, three crude oil samples were obtained for this study. The samples were representative of crude oils shipped through the Keystone pipeline. In respect for the proprietary nature of crude oil compositions, the samples are hereafter labeled Crude Oil-A, Crude Oil-B, and Crude Oil-C.

3.2 Pipe/Coupling Permeation Test

The pipe and pipe coupling permeation tests were performed to observe if contaminants would permeate through either the pipe wall or pipe couplings. Ong et al. (2008) conducted similar experiments using gasoline and BTEX compounds of several concentrations. Pipe couplings and straight lengths of pipe were tested for the permeability in an acrylic tank apparatus described below and depicted in Figures 3.1 through 3.5.

Two-inch diameter CertaLok joint couplings were assembled in each tank, along with straight lengths of PVC and HDPE pipe, and the pipe ends protruded through holes drilled in the tank, as seen in Figures 3.1 and 3.5. PVC caps were solvent-welded to the pipe ends. Valves sealed with Teflon tape were inserted into tapped holes in the end caps. One valve was positioned at the bottom of one end and the second valve was positioned at the top of the other end of the pipe to enable filling the pipe and draining water from the pipe. Loctite Plastic Epoxy and Loctite Epoxy Putty were used to seal the PVC pipe and HDPE pipe to the acrylic tank.

Seven acrylic tank apparatuses were created. Six tanks contained crude oil saturated sand (two for each of the three crude oil types) and a single tank contained water saturated sand. All acrylic tanks contained 100 pounds of Silica sand (Granusil 4030) saturated with liquid so a layer of free product liquid existed above the sand. Acrylic tanks containing Oil-A were fitted with three PVC joint couplings and two straight PVC pipe segments, as seen in Figure 3.4. A coupling can be seen in Figure 3.6. One tank contained NBR gaskets, and the other tank contained polyisoprene gaskets in the joint couplings.

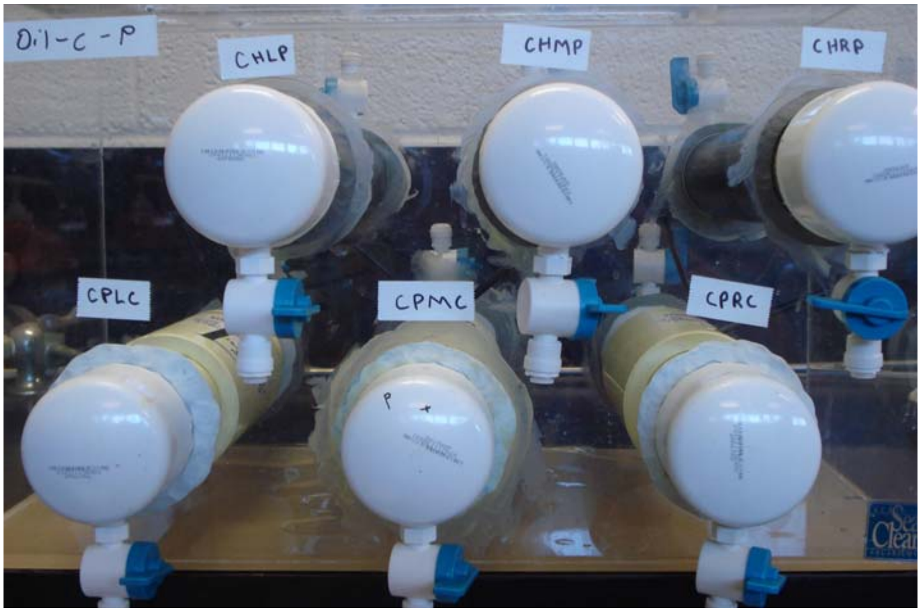

Figure 3.1. Acrylic Tank used to perform permeation study on Polyisoprene couplings and HDPE pipe using Oil-C.

Four acrylic tanks were constructed with three couplings and three straight pipe segments in them, as seen in Figure 3.2 – two tanks each for Oil-B and Oil-C. The couplings were placed in the bottom row and the straight pipes were placed in the top row. One tank contained three couplings with NBR gaskets and three PVC pipe segments, while the other tank contained three couplings with polyisoprene gaskets and three HDPE pipe segments. Dimensioned diagrams of the tanks containing de-chlorinated water, Oil-B and Oil-C are shown in Figures 3.2 and 3.3. The dimensions of acrylic tank apparatuses containing Oil-A are shown in Figure 3.4. In all the oil-filled acrylic tanks the joint couplings are on the bottom row, and the straight pipe segments are on the top row.

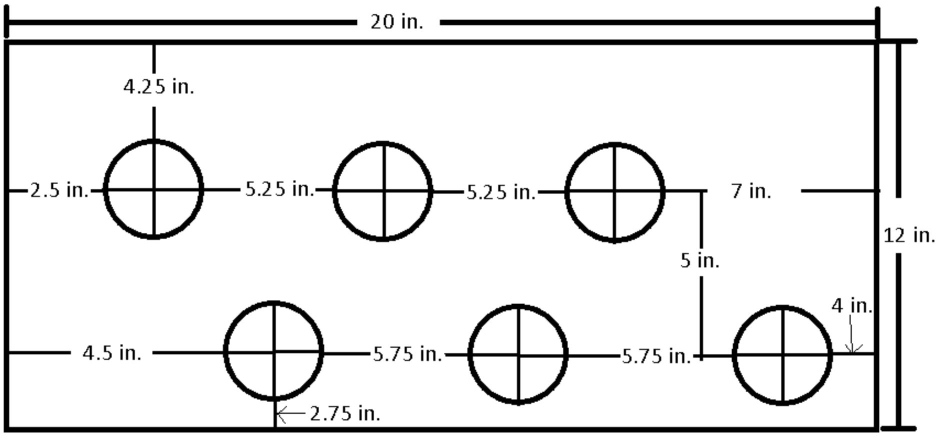

Figure 3.2. Front view of Oil-B and Oil-C tank apparatus used in the permeation test.

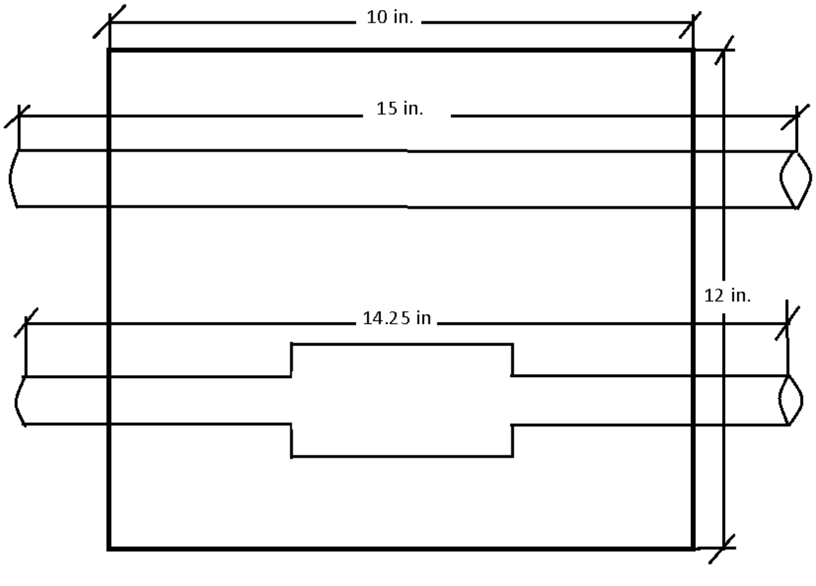

Figure 3.3. Side view Oil-B and Oil-C tank apparatus used in the permeation test.

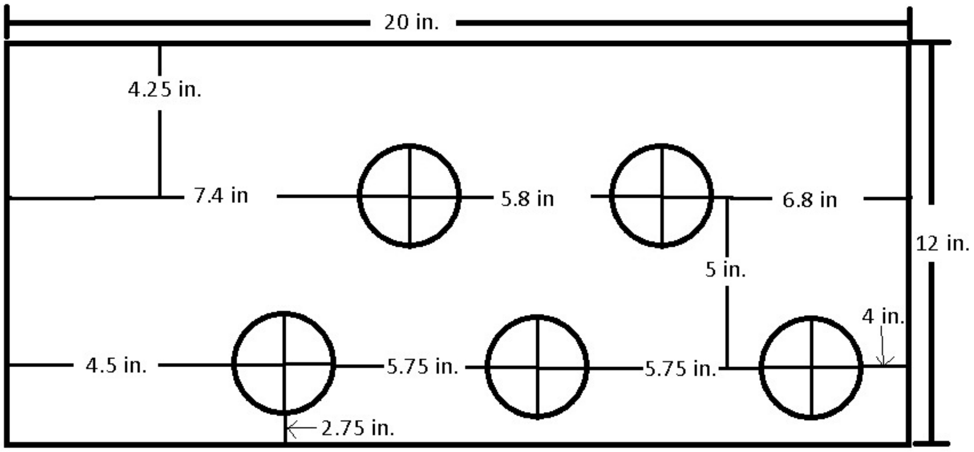

Figure 3.4. Front view of Oil-A tank apparatus used in the permeation test.

The final tank contained sand saturated with de-chlorinated water and 6 CertaLok restrained joint apparatuses, 3 with NBR gaskets (top row), and 3 with polyisoprene gaskets (bottom row). This tank was considered a control representing a situation of a pipe in the saturated zone absent crude oil.

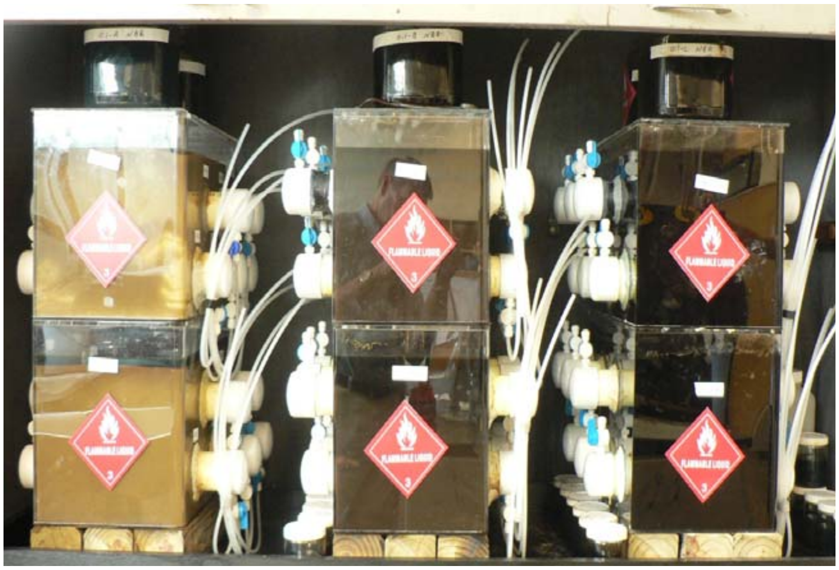

Figure 3.5. The six permeation apparatuses containing Oil-A (left tanks), Oil-B (middle tanks), and Oil-C (right tanks).

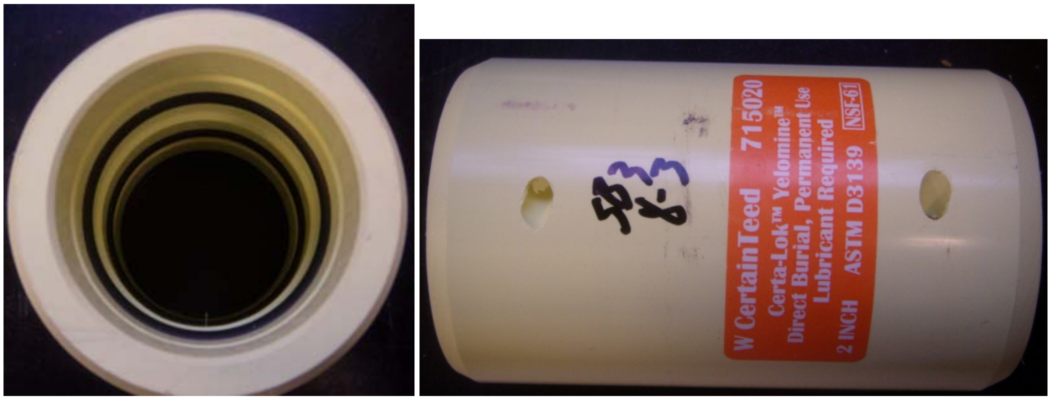

Figure 3.6. A joint coupling with Polyisoprene gaskets (permanent coupling).

Permeation of hydrocarbons from the oils through the pipe rigs was examined by measuring the concentrations of organic matter in water contained in the pipe rigs. Initially, each pipe rig was filled with high purity water (organic free, 18 megohm water obtained from the Nanopure water purification system in the South Dakota State University Water and Environmental Engineering Research Center (WEERC) Laboratory, hereinafter called Nanopure water). At given intervals the Nano-pure water was drained from the rigs and analyzed for organic concentrations. Samples of water from each pipe rig were analyzed for TOC by the WEERC laboratory using Standard Method 5310B (APHA, AWWA, WEF 2005). The remaining Nano-pure water from the three pipe rigs with like gaskets (in each tank) was composited, as was the Nano-pure water from common pipe segments soaking in the same crude oil. Aliquots of the consolidated composited samples were submitted to the South Dakota State Health Laboratory in Pierre, SD for total petroleum hydrocarbons analysis by gas chromatography/mass spectroscopy using EPA SW-846 Method 8015B.

3.3 Gasket Weight Gain Tests

Weight gain tests were conducted on the NBR and polyisoprene gaskets used in the 2-inch CertaLok restrained joint Yelomine pipe couplings. An example of the installed gasket is shown in the left picture of Figure 3.6.

To conduct the gasket sorption test, gaskets were placed in separate glass jars containing 150 mL of crude oil, as seen in Figure 3.7. At regular intervals, the gaskets were then removed from the oil, wiped clean with a paper towel, and weighed on the AND model FR-200 analytical balance, recording weight to the 0.0001 gram resolution. Weight gain tests of both gasket types (NBR and polyisoprene) were conducted in the three crude oil samples and in water (as a control).

Figure 3.7. On the left is a polyisoprene gasket in de-chlorinated water and on the right is a polyisoprene gasket in Oil-A.

3.4 Pipe and Gasket Structural Strength Experiments

According to Ong et al. (2008) organic solvents at high activities will permeate PVC and HDPE pipe, resulting in potential loss of structural integrity. Since the organic concentration of the crude oil samples was unknown, strength tests were conducted to examine potential impacts of crude oil on the potential plastic casing components.

The 10.5-inch long pipe test segments were cut from 20 foot sections of Yelomine and HDPE pipe purchased from Dakota Supply Group in Sioux Falls, SD. The pipe segments were capped on one end, filled with tap water, and then capped on the other end. The PVC caps were solvent welded on the ends of the PVC pipe segments and glued using silicon glue on the ends of the HDPE pipe segments. The pipe segments were immersed in each type of crude oil saturated Silica sand (Granusil 4030). The mixture ratio was 30 pounds of sand to 10 liters of crude oil. Figure 3.8 shows a 5-gallon pail with pipe specimens immersed in Oil-C saturated sand. Each pail held 11 pipe specimens, and was covered and sealed with a snap lock lid. Control pipe specimens were also prepared and immersed in de-chlorinated tap water. At specified time intervals, four pipe specimens were removed from each crude oil type and from water, one for tension testing and the other three for compression tests.

Figure 3.8. 10.5 inch pipe specimens immersed in sand and Oil-C.

3.4.1 Pipe Compression Test

The pipe compression test was performed following ASTM D2412. Three pipe specimens were washed with hot soapy water to remove excess crude oil, and then wiped dry with paper towels. Holes were drilled in each end cap to drain the water inside the pipe. Then the end caps were cut off, and the pipe was cut with a radial arm saw to the required 6 ±1/8 inch lengths, examples of which can be seen in Figure 3.9. Eight equally spaced thickness measurements were made, and the outside diameter was measured at 3 points, 1.5 inches from each end of the pipe, and then the middle. The average outside diameter and thickness was measured to the nearest 0.001 inches, using a micrometer.

Once these measurements were completed, the pipe specimen was placed between the parallel plates inserted into the MTS 810 compression test machine.

The pipe segment was positioned with its longitudinal axis parallel to the loading plates and centered laterally in the testing machine, as can be seen in Figure 3.10. The machine was set to compress the specimen at a rate of 0.5 ± 0.02 in/min, until the specimen deflection reached 30% of the average inside diameter, according to ASTM D2412. The load-deflection measurements were recorded intermittently relative to the movement of the loading plates.

Figure 3.9. Six-inch pipe specimens used in the parallel plate compression test.

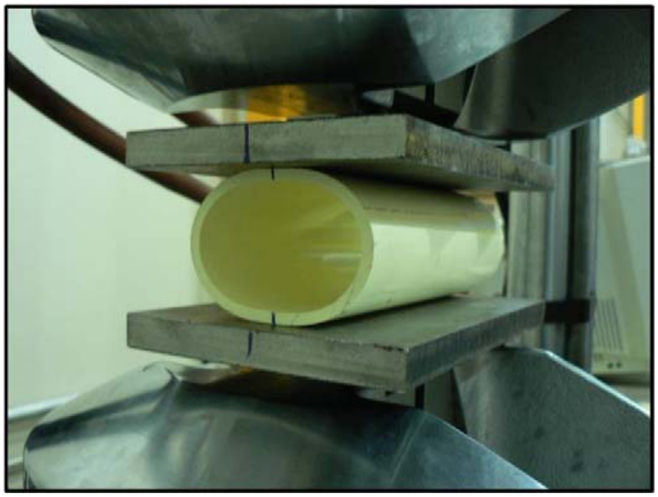

Figure 3.10. Performing the parallel plate loading compression test, using the MTS 810 machine.

3.4.2 Pipe Tensile Test

At the same time intervals used for the compression test, an additional pipe specimen was retrieved from the saturated sand container, dewatered, washed, dried and cut into 1/3 sections longitudinally, as seen in Figure 3.11. The end caps were then removed, as can be seen in Figure 3.12. Specimens were then cut from the three sections using a precision high-pressure jet cutter at Brookings Industrial Machine and Engineering. The “dog-bone” test specimen can be seen in Figure 3.13.

ASTM D 638-08 states the dog-bone test specimen has a total length of 6.5 inches long, with a 2 inch gauge length, and the gauge thickness is 1/2 inch. Figure 3.13 shows the dog-bone specimen after being cut from the pipe segment. Width and thickness measurements at the midpoint of the gage length and within 5 mm of each end of the gage length were taken before testing was performed.

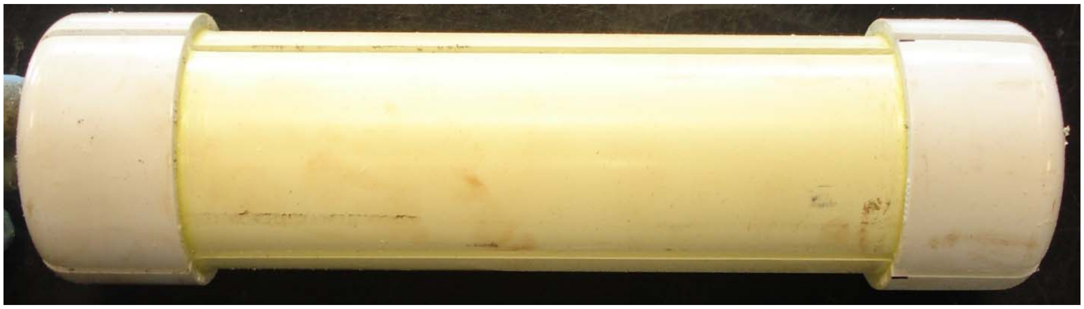

Figure 3.11. Pipe segment being cut longitudinally for tensile testing.

Figure 3.12. After being cut longitudinally the end caps were removed.

Figure 3.13. A dogbone is cut out of each 1/3 section of pipe to be tensile tested.

The specimens were brought to the METLab (Materials Evaluation and Testing Laboratory) at SDSU, and placed vertically in the grips of the MTS (Materials Testing System) Insight machine as shown in Figure 3.14 which shows the tension test in progress. The grips were then tightened evenly and firmly to the degree necessary to prevent slippage of the specimen during the test, but not to the point where the specimen was compromised. The rate of tension testing was set at 0.2 in/min ± 25%, following ASTM D 638-08. The MTS Insight Machine recorded load, elongation, stress, and strain readings. The yield strength of the specimen was determined from these readings.

The yield strength was found by observing the greatest axial load achieved by test specimen, which was taken as the tensile strength. Average tensile strength of the three dog-bone specimens was calculated to represent the tensile strength of the pipe wall at the time the test was run.

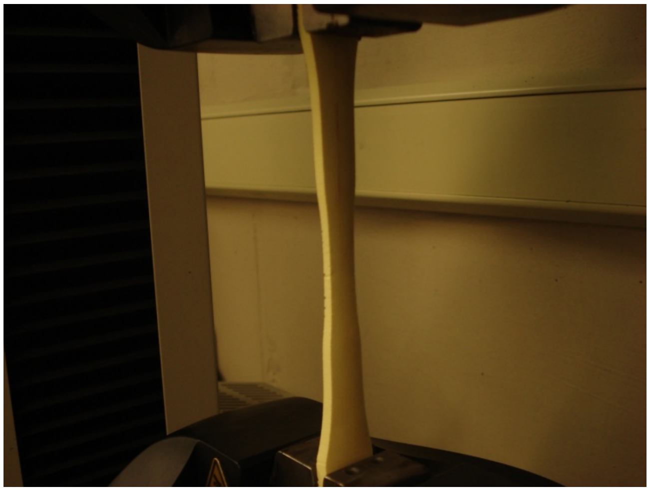

Figure 3.14. Performing tensile test on a dogbone specimen.

3.4.3 Gasket Strength Testing

Tensile strength tests were conducted on the NBR and polyisoprene gaskets. These gaskets were submerged in each liquid (three oil and one water), removed at specified time intervals and tested for tensile strength. Four jars contained NBR gaskets and four contained polyisoprene gaskets.

To conduct the tensile test at given time, five gaskets were removed from each container. After they were wiped dry with paper towels, the thickness of each gasket was measured, and they were then placed in separate plastic containers to be transported to the METLab for tensile tests. Tensile test jigs were constructed according to ASTM D1414. The jig was inserted in the upper jaw and one in the lower jaw of the test machine. The gasket was placed on the bearing of each jig (see Figure 3.15), and the jigs were separated by the MTS machine until the gasket broke.

The tension head speed was set for 20 ±2 in/min. Force measurements were recorded by the machine until failure.

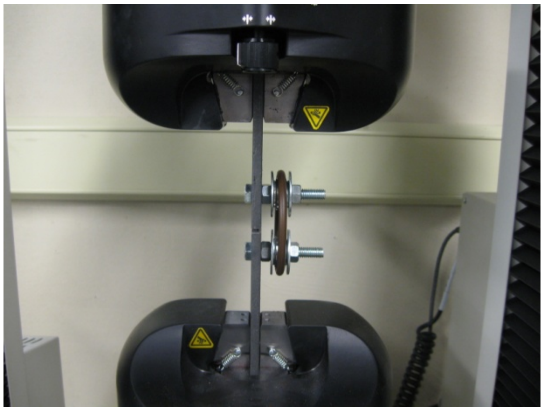

Figure 3.15. Starting point for the gasket tensile test.

3.5 Statistical Analysis

Statistical analyses were performed on the gasket and pipe tensile, pipe compression, and TOC data. The statistical results can be seen found in each Appendix associated with the experimental results. The computer program SAS was used for the ANOVA method to find if they means of results for the various tests exposing the components to oil and water were significantly different. If the p-value was greater than the alpha value (0.05), then the mean values would be considered not significantly different. Appendix H displays the calculations used to find the 95% confidence interval for the TPH permeation data.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Introduction

The literature review, regulatory review and pipe crossing design survey reported in Chapter 2 provided information leading to the recommendation of using a plastic pipe to encase the water system pipeline at the crude oil/water pipeline crossings. Fusible HDPE and PVC pipe as well as restrained joint PVC pipe were selected as possible candidates for the casing materials because of their amenability to directional bore installation, familiarity to pipe installation contractors, and potential to protect the water carrier pipe in the event of a crude oil release. However, the literature provides no documentation the structural and permeability characteristics of the selected casing materials when directly exposed to a crude oil release.

Structural and permeation tests were conducted to provide data to assess the impacts of crude oil on the characteristics of the casing materials. Structural tests were conducted on the PVC pipe, HDPE pipe, and gaskets that were submerged in granular soil saturated with either crude oil or de-chlorinated tap water. These structural tests include compression and tensile tests on the pipe, and tensile tests on gaskets. The specimens in de-chlorinated tap water were considered a control, and results from specimens soaked in crude oil were compared with specimens submerged in water. ASTM standard procedures were followed while conducting the analysis of pipe and gasket strength. Pipe compression and pipe tensile strength were examined over time to see whether these characteristics were influenced by contact with oil or water.

Sorption tests were performed to see if the gasket weight increased due to permeation, and if that weight gain affected the strength of the gaskets. Correlations were also completed between percent strength loss and percent weight gain.

Permeation tests were also conducted on the PVC pipe, PVC joint couplings containing both NBR or polyisoprene gaskets, and HDPE pipe segments. The pipe segments and joint couplings were submerged in a saturated mixture of sand and crude oil or water. Total petroleum hydrocarbon and total organic carbon tests were conducted on water contained inside the pipes and joint couplings to determine if permeation had occurred. The test results from the joint couplings soaked in water were compared with the results from the joint couplings soaked in crude oil. Also, the TPH test results from the two gasket types were compared to see if significant difference in permeation of organics existed between joints submerged in the 3 oil types and water. The TOC permeation results of like joints and like pipes soaked in the crude oils and water were compared.

4.2 Pipe Strength Tests

4.2.1 Pipe Tensile Strength Tests

Tensile strength tests were performed on pipe segments exposed to crude oil for 24 weeks. Pipe segments were exposed to a sand and crude oil or water saturated mixture for a given amount of time before being removed for testing. The tensile tests were performed to examine impacts of crude oil on the compressive strength of PVC or HDPE pipe. The average results of the rupture strength (in pounds per square inch, psi) for the three tensile strength tests for each day's set of samples are found in Table A.1, Appendix A.

The results of the tensile tests of PVC pipes exposed to oil were compared with those exposed to water (control). The averaged results of the failure strength of the three samples tested at each time interval over the 24-week testing duration are plotted in Figures 4.1 through 4.3. To qualitatively identify and compare trends in tensile strength over time in these figures, linear regression trend lines are plotted for the pipes exposed to oil (dashed line) and for the pipes exposed to water (solid line).

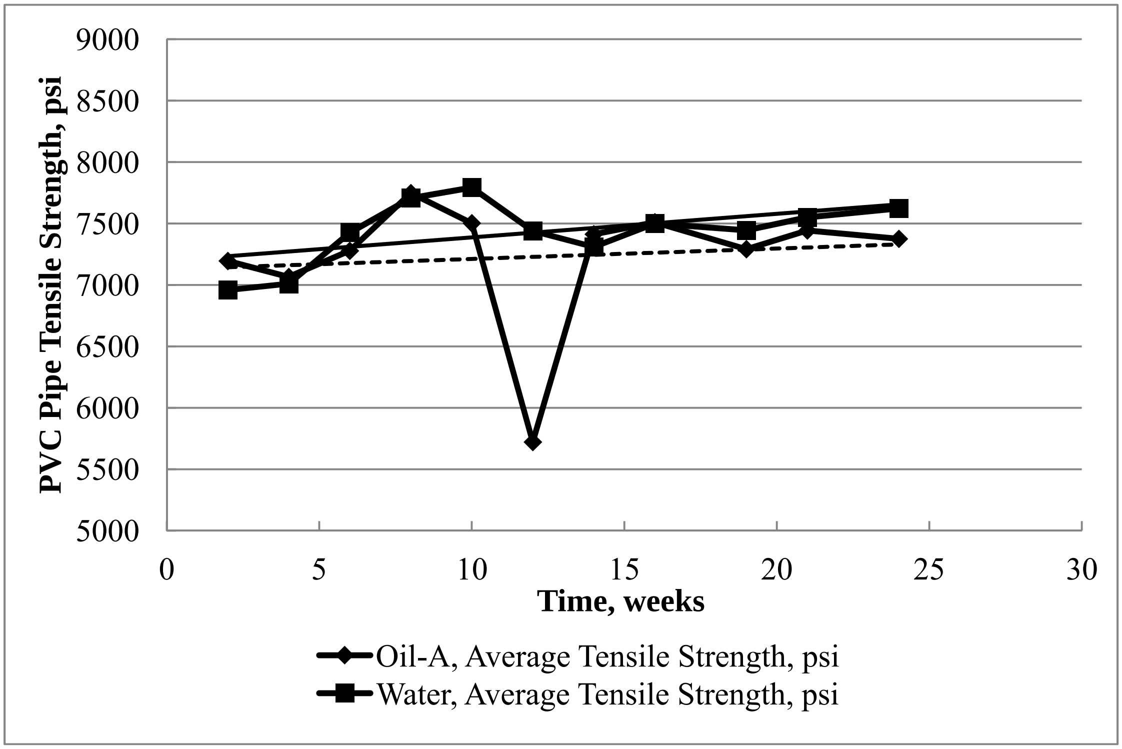

Figure 4.1. Average tensile strength of PVC pipe exposed to Oil-A or water.

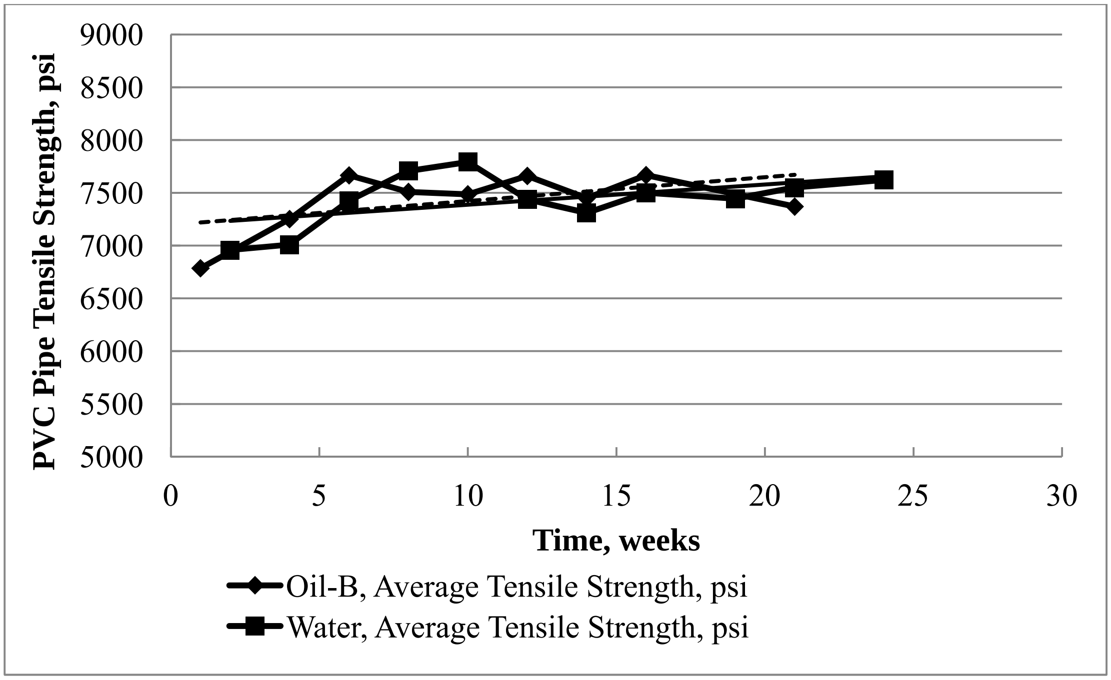

Figure 4.2. Average tensile strength of PVC pipe exposed to Oil-B or water.

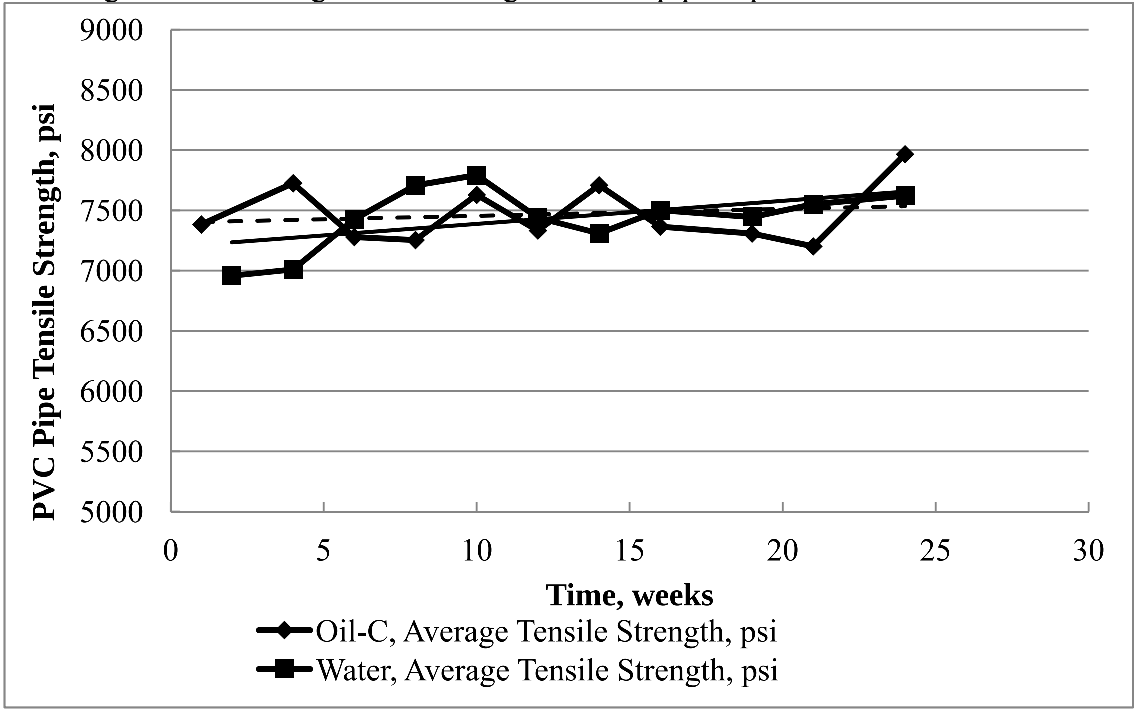

Figure 4.3. Average tensile strength of PVC pipe exposed to Oil-C or water.

The slopes of the trend lines for the tensile strength of PVC pipe coupons exposed to the three crude oil samples and to water all increased slightly over the duration of the test period. Statistical analysis were completed to determine if significant differences existed between the average tensile strength of PVC pipe soaked in the 3 oil types, and de-chlorinated water. These analyses can be seen in Appendix A. The computer program SAS was used to analyze the data with the analysis of variance (ANOVA) procedure using Duncan's Multiple Range Test. This determined whether the means of the tensile strength data for each treatment were significantly different. The Duncan test indicated no significant difference between the average tensile strength of pipe samples exposed to the 3 crude oils or exposed to water.

Figure 4.4 shows the impact of Oil C on the tensile strength of HDPE pipe. As the time of exposure increased, the average tensile strength decreased slightly. No HDPE pipe was submerged in water, therefore dry unexposed HDPE pipe was used as a control so statistical analysis could be performed on the data. The tensile strength data and statistical analysis can be found in Appendix A. The Duncan test indicated a significant difference between the tensile strength of the unexposed HDPE pipe and the average tensile strength of HDPE pipe exposed to Oil C.

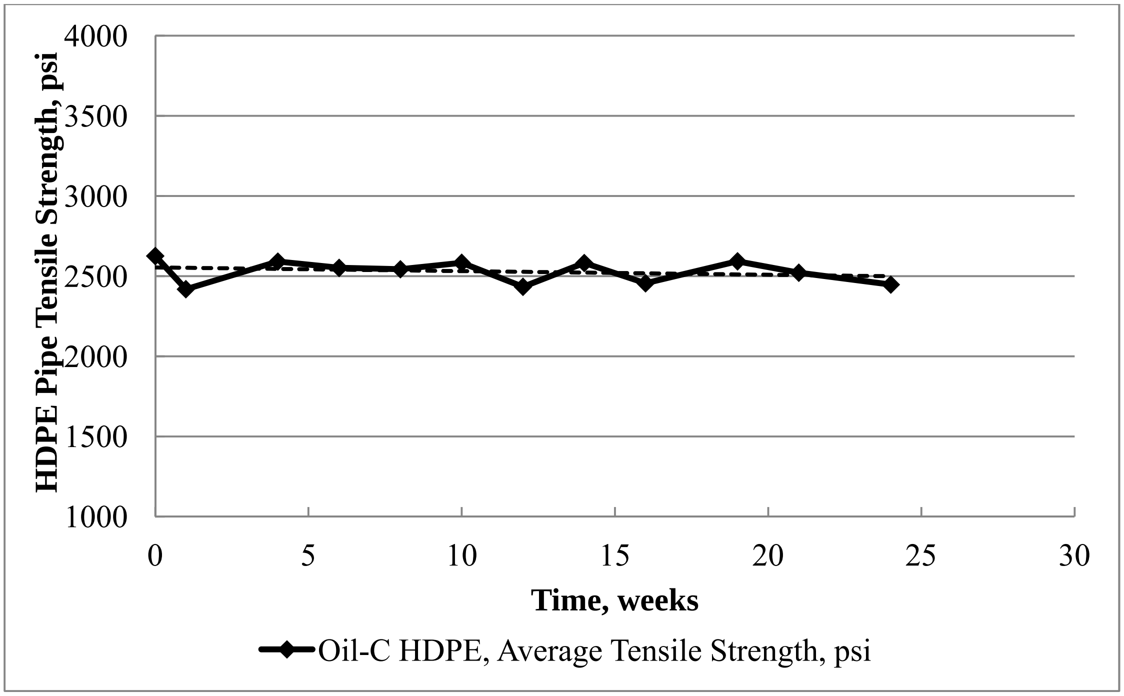

Figure 4.4. Average tensile strength measurements of HDPE pipe exposed to Oil-C.

4.2.2 Pipe Compression Strength Tests

Compression strength tests were conducted on pipe specimens submerged in crude oil for 24 weeks. Pipe segments were exposed to a sand and crude oil or water saturated mixture for a given amount of time before being removed for testing. The compression tests were performed on the exposed pipes to examine any impacts of crude oil or water on the compressive strength of PVC or HDPE pipe. The averaged results of the failure strength (in pounds of force, lbf) for the three compressive strength tests for each day's set of samples are found in Table B.1, Appendix B.

The results from the compression tests of PVC pipes exposed to oil were compared with those exposed to water (control). The averaged results of the failure strength of samples tested at each time interval over the 24-week testing duration are plotted in Figures 4.5 through 4.7. To qualitatively identify and compare trends in compressive strength over time in these figures, linear regression trend lines are plotted for the pipes exposed to oil (dashed line) and for the pipes exposed to water (solid line).

Based on the data plotted in Figures 4.5 through 4.7, exposure of oil and water appear to have a similar impact on the compressive strength of the PVC pipe. For each crude oil, the compressive strength varied by approximately 50 pounds, and, based on the slopes of the regression lines, appeared to increase slightly over the test duration. Pipes exposed to Oil B appeared to achieve greater increase in compressive strength as compared to Oils A and C. The compressive strength of pipes exposed to water increased in a manner similar to the crude oils.

As with the pipe tension test data, the Duncan's Multiple Range Test was also conducted on the on the means of the compression strength data. Each pipe sample test result was used in the calculation of the mean compressive strength, and the Duncan's Multiple Range test also considers the variations around the mean at the 95% confidence interval. The ANOVA results are found in Table B.3 of Appendix B. The statistical test results indicate no difference between the mean compressive strengths of the PVC pipes exposed to the three oils and the water.

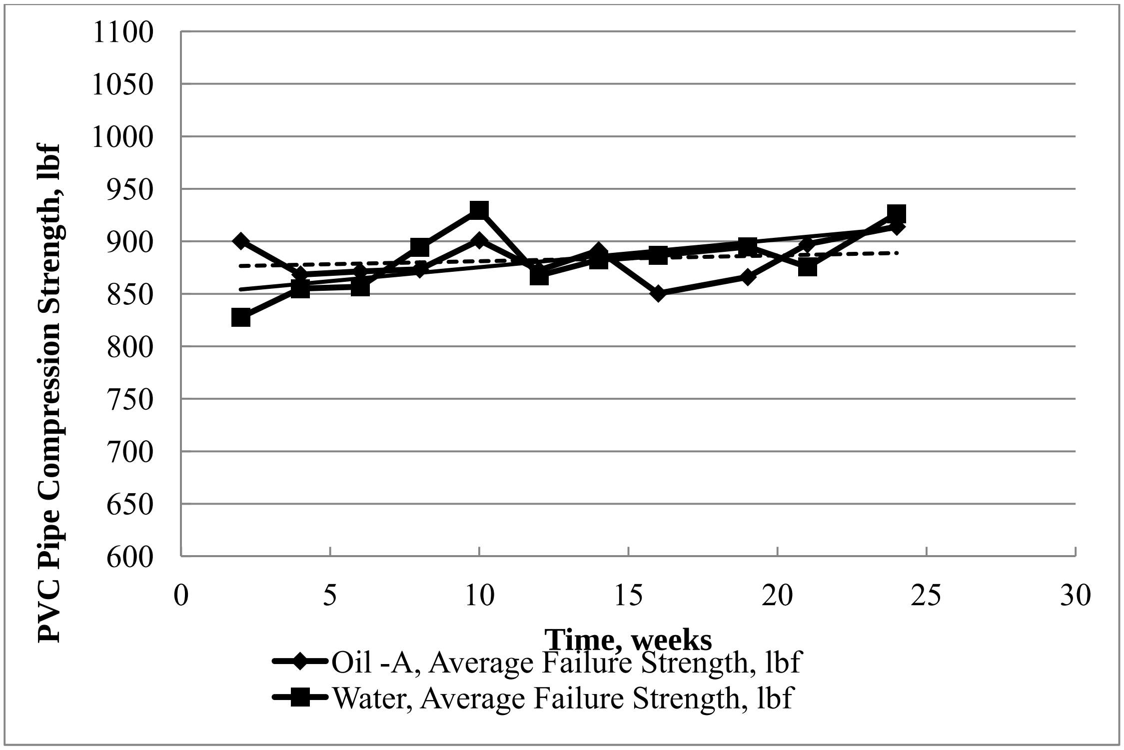

Figure 4.5. Compression strength of pipe exposed to water or Oil-A.

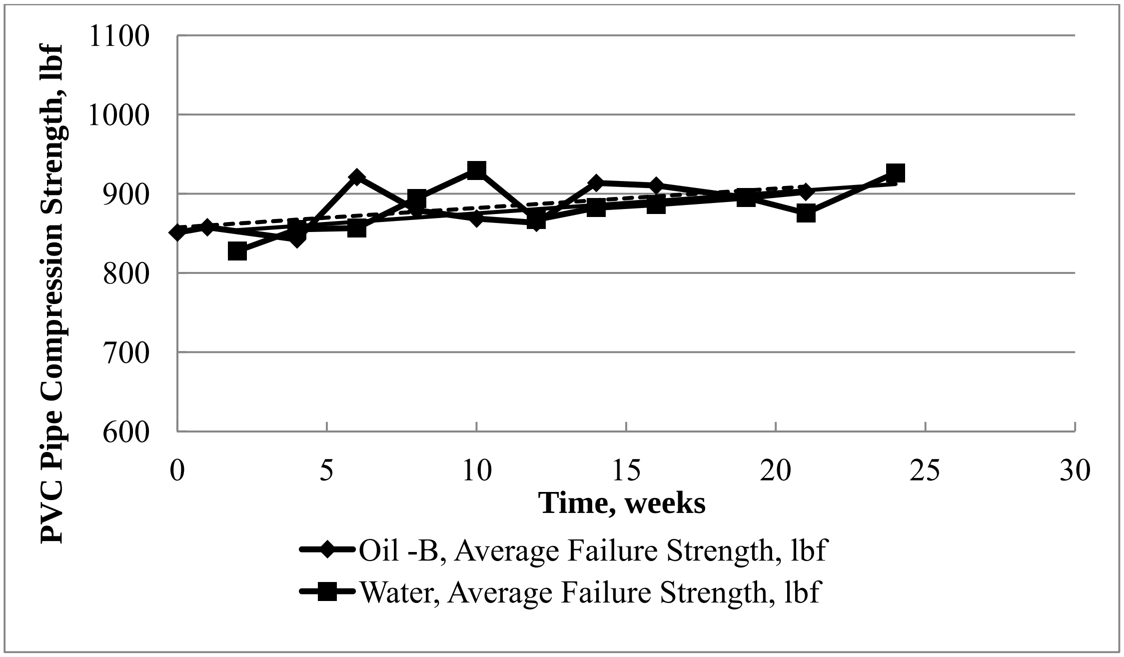

Figure 4.6. Compression strength of pipe exposed to water or Oil-B.

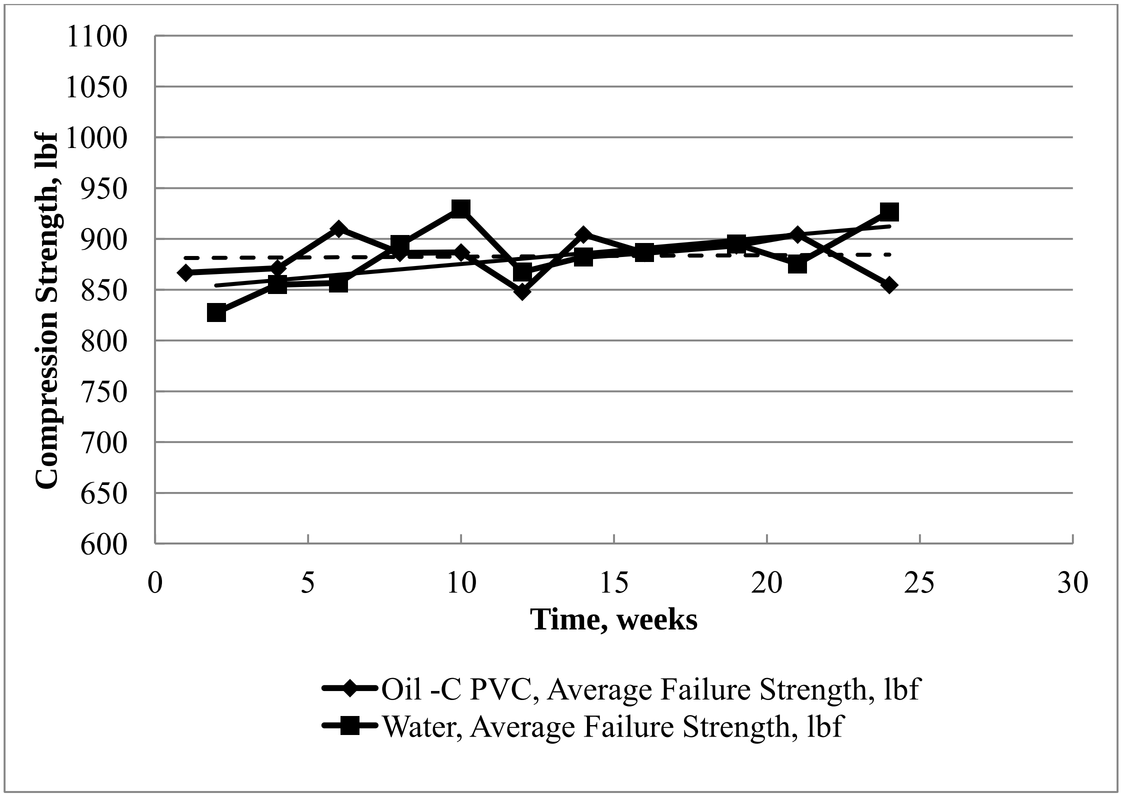

Figure 4.7. Compression strength of pipe exposed to water or Oil-C.

The results of parallel plate compression tests on HDPE pipes exposed to Oil-C are plotted in Figure 4.8. Since no HDPE pipe samples were exposed to water, the compressive strength of the exposed pipe can only be compared with the compressive strength of the unexposed pipe to examine the impact of exposure. A trend line (least squares linear regression method) was plotted using the data in Figure 4.8 to enable a qualitative judgment of the trend in the compressive strength.

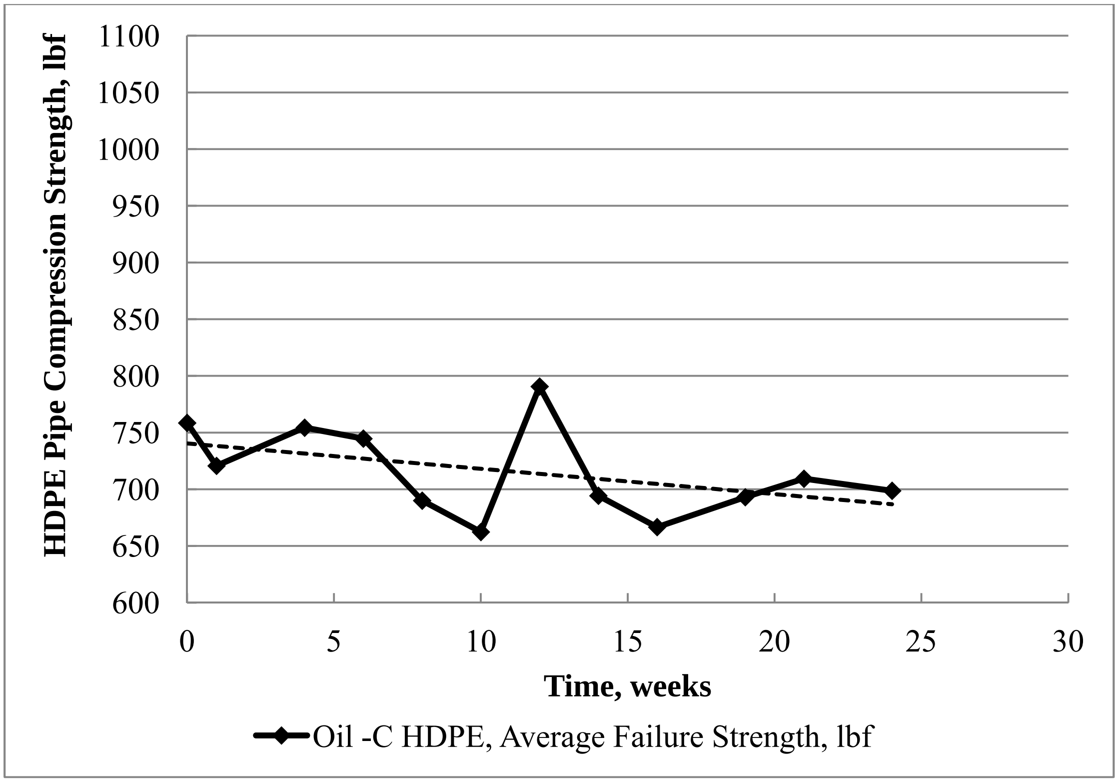

Figure 4.8. Compression strength measurements of HDPE pipe exposed to Oil-C.

Based on the slope of the regression line, it appears the compression strength of the HDPE pipe decreases with exposure time. The compressive strength appeared to decrease approximately 50 pounds (force) over the 24-week exposure time. This 50 pound decrease was equivalent to approximately 7 percent of the original strength of the HDPE pipe. The Duncan multiple range test was used to compare the mean strength of the unexposed pipe samples with the mean strength of the pipe samples exposed to Oil-C (see results in Table B.2, Appendix B). The means of the unexposed pipe compressive strength were found to be significantly different from the compressive strength of the exposed pipe.

4.2.3 Summary of the Pipe Strength Test Results

The tensile compressive strengths of PVC pipes exposed to crude oils and water increased slightly over the 24-week exposure period, although there was no statistical difference between the mean compressive strength of the samples exposed to the crude oils or the water. The tensile and compressive strength of the HDPE pipe exposed to Oil-C decreased slightly over the 24-week exposure period and the average tensile and compressive strengths of the exposed HDPE pipe were statistically different from the averaged compressive strengths of the unexposed HDPE pipe.

Relative to the use of PVC as a casing pipe in the crossing design, these data indicate the tensile and compressive strengths of the pipe would not be compromised in a 24-week time period. However, since the tensile and compressive strengths of the HDPE pipe decreased slightly over the same time period, its use as a casing pipe is less favored relative to PVC pipe.

4.3 Gasket Tests

4.3.1 Gasket Sorption Tests

Sorption tests were conducted on polyisoprene and NBR gaskets available from the manufacturer for the restrained joint pipe couplings. For each gasket type, the sorption experiment consisted of submerging three gaskets in the liquid (water or crude oil). At given time intervals the gaskets were weighed, and the average weight of the three gaskets was recorded. Percent weight gain was calculated and recorded (Appendix C). The sorption data are plotted in Figure 4.9.

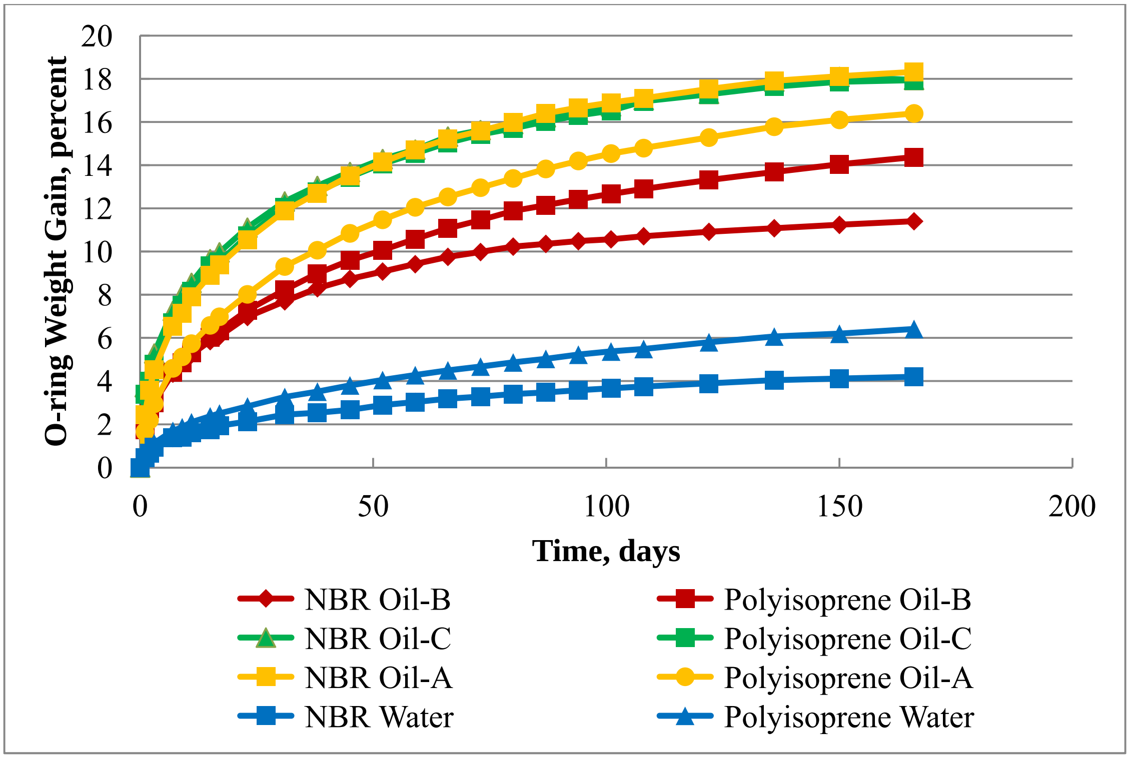

Figure 4.9. Average percent weight gain of gaskets submerged in crude oil and water.

The gaskets immersed in oil exhibited substantially higher percent weight gain than the gaskets immersed in water. After 166 days of immersion in water the NBr and polyisoprene gaskets weight gains were 4.2 and 6.4 percent, respectively. The weight gains of polyisoprene gaskets immersed in crude oil ranged between 14.4 and 17.9 percent, and the weight gains of NBR gaskets immersed in crude oils ranged between 11.3 and 18.3 percent. The gaskets submerged in Oil-B exhibited the lowest average percent weight gain of the gaskets submerged in crude oil, and the gaskets immersed in Oil-A and Oil-C exhibited similar values of average percent weight gain. Polyisoprene gaskets gained more weight than NBR gaskets submerged in Oil-B, NBR gaskets gained more weight than polyisoprene gaskets submerged in Oil-A, and both types of gaskets gained weight when submerged in Oil-C. The absorption of oil by rubber gaskets indicated by weight gain is not surprising, since gasoline BTEX absorption by rubber gaskets has been demonstrated in the literature. These data indicate the gaskets used for the restrained joint casing have the potential to adsorb crude oil. This absorption may impact the gasket strength and permeation characteristics.

4.3.2 Gasket Tensile Tests

Gasket tensile tests were performed on NBR and polyisoprene gaskets that were submerged in crude oil and water to examine the impacts of exposure on the strength of the gaskets. The averaged tensile strength of five gaskets was recorded at each time interval and was plotted as a function of time in Figures 4.10 through 4.12. Since the tensile strength data varied substantially from test to test, least squares trend lines were plotted through the data to identify trends. The solid regression lines represent polyisoprene data, and the dashed lines represent NBR data.

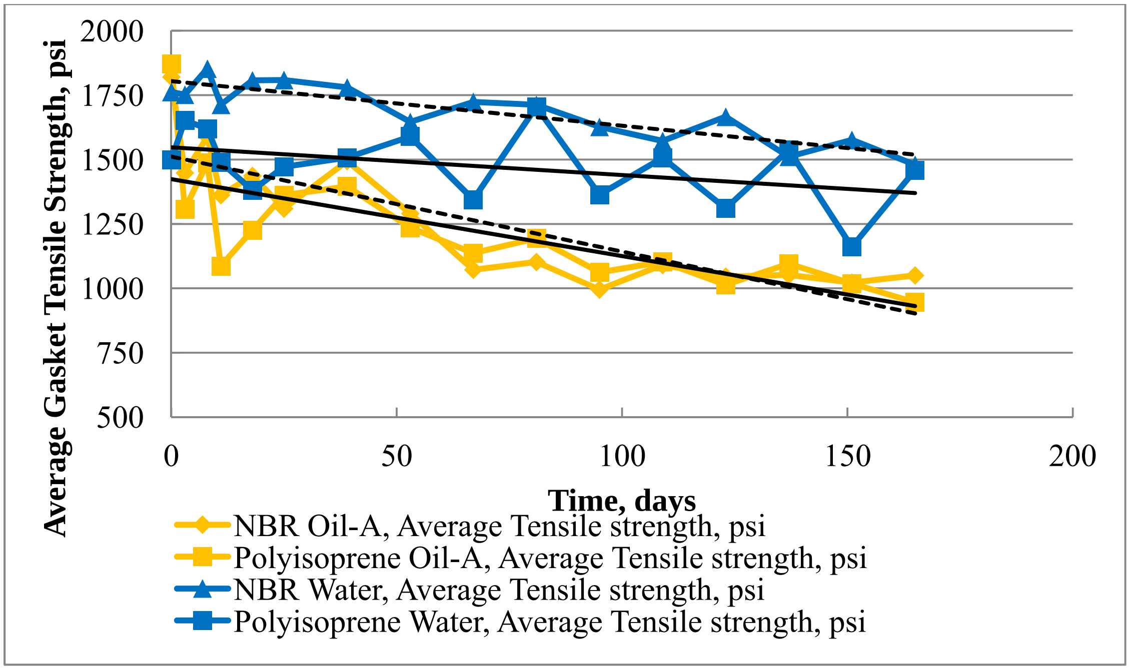

Figure 4.10. Average tensile strength of gaskets submerged in water and Oil-A.

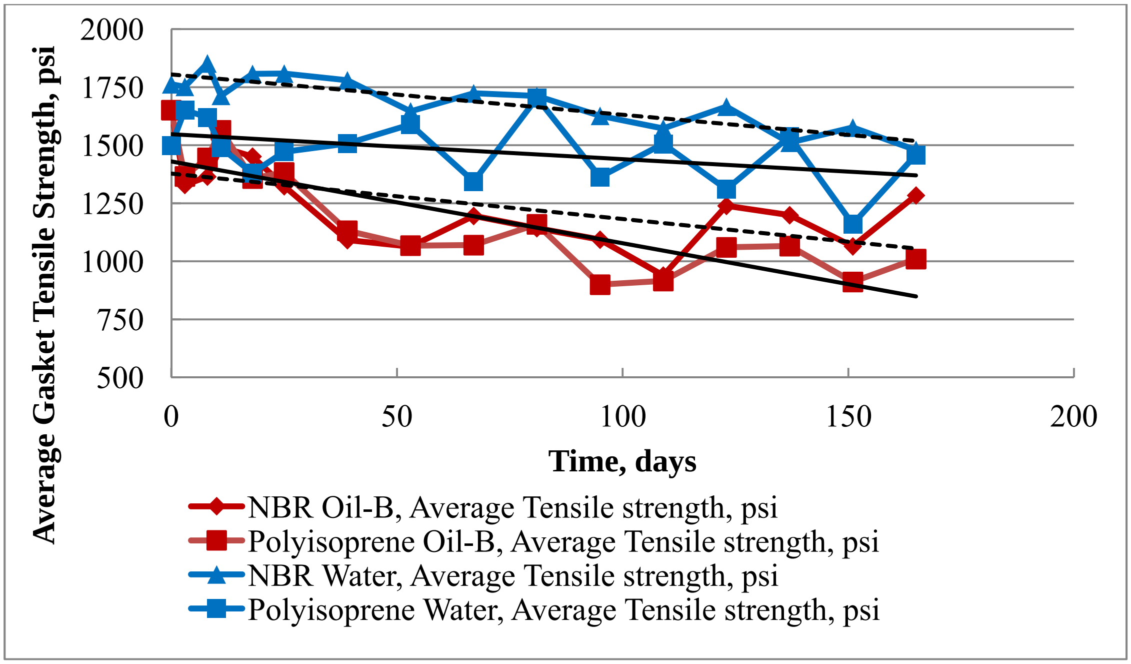

Figure 4.11. Average tensile strength of gaskets submerged in water and Oil-B.

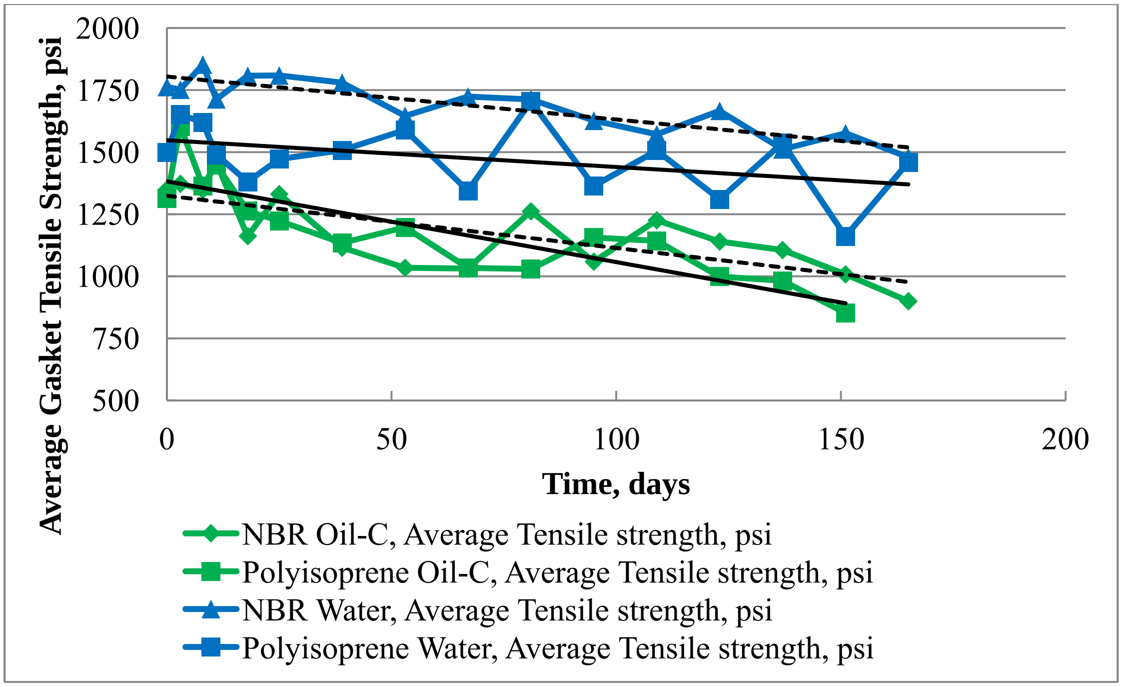

Figure 4.12. Average tensile strength of gaskets submerged in water and Oil-C.

The gaskets submerged in crude oil exhibited a greater decrease in average tensile strength than those submerged in de-chlorinated water so the final tensile strengths of gaskets submerged in crude oil was substantively lower than the gaskets submerged in water. Duncan's multiple range tests were conducted to examine the differences between the tensile strengths of the gaskets immersed in each liquid. The results of the statistical tests are found in Tables D.3 and D.4 of Appendix D. The mean yield strength of the NBR gaskets submerged in water was 1,687 psi, whereas the mean yield strengths of the gaskets submerged in Oils A, B, and C were 1,261, 1,245, and 1,183 psi respectively, representing a loss in strength (compared to water) of 25%, 26%, and 30%. The Duncan's test indicated the strengths of NBR gaskets submerged in water were significantly different from those submerged in the oils. The mean yield strength of the polyisoprene gaskets submerged in water was 1,475 psi, whereas the mean yield strengths of the gaskets submerged in Oils A, B, and C were 1,221, 1,191, and 1,183 psi respectively, representing a loss in strength (compared to water) of 17%, 19%, and 20%. The Duncan's test indicated the strengths of polyisoprene gaskets submerged in water were significantly different from those submerged in the oils.

4.3.3 Summary of Gasket Test Results

Experiments were conducted to examine the impacts of contact with crude oil and water on the characteristics of gaskets used in restrained joint PVC pipe that is a candidate for water carrier pipe casing at pipeline crossings. Gaskets submerged in crude oil exhibited greater tensile strength loss and weight gain than gaskets submerged in water. A comparison of percent tensile strength loss and percent weight gain is provided in Table 4.1. The percentage tensile loss in this table were calculated by subtracting the average tensile strength or weight gain of gaskets submerged in the oils from the average tensile strengths or weight gains of gaskets submerged in water, dividing the result by the average tensile strengths or weight gains of gaskets submerged in water, and finally multiplying the result by 100. The percent weight gains were those recorded from the final day of the weight gain experiments.

Table 4.1. Summary of Percent Weight Gain and Percent Tensile Strength Loss

	Water	Oil-A	Oil-B	Oil-C
	NBR			
Average Tensile Strength, psi	1687	1261	1245	1183
Loss in Tensile Strength, percent		25	26	30
Percent Weight Gain	4.2	18.3	11.3	18.0
	Polyisoprene			
Average Tensile Strength, psi	1475	1221	1191	1183
Loss in Tensile Strength, percent		17	19	20
Percent Weight Gain	6.4	16.8	14.4	17.9

As seen from the results in Table 4.1, there is a direct relationship between weight gain and loss in tensile strength. Absorption of oil into the gasket material is related to a loss in tensile strength of the material. Although the gaskets are not undergoing tension in their function as a gasket material, this loss of strength characteristic is an indication of the impact of contact with crude oil on the structural properties of the gasket material.

4.4 Permeation Tests

A desireable property of the casing pipe is to resist permeation by hydrocarbons in the event of a petroleum release at a pipe crossing. To test this characteristic, permeation tests of candidate casing components were conducted as described in Chapter 3. Experiments were conducted to examine the impacts of contact with crude oil on permeation of crude oil compounds through the walls and joint couplings of candidate pipe casing materials. Total petroleum hydrocarbon tests and total organic carbon tests were conducted on water samples contained in un-jointed (straight) and jointed pipes that were submerged in oil saturated granular media.

4.4.1 Total Petroleum Hydrocarbon Test Results

Total petroleum hydrocarbon (TPH) data collected from pipes and joint couplings during the permeation tests are found in Appendix E. The data were plotted to observe trends in the data that would indicate permeation. TPH data for the pipe components exposed to water saturated granular media were viewed as the control. If the TPH data trend for pipe components exposed to oil saturated granular media departed or deviated from the baseline established by the control, permeation of hydrocarbons was likely occurring. Due to variations in the TPH data, 95% confidence interval bands were calculated and plotted along with the experimental data. Example calculations of the 95% confidence interval can be found in Appendix I. The time (date) to permeation of the jointed pipe segments was observed as the day when the lower 95% confidence interval of the crude oil data departed from the upper 95% confidence interval of the water data. Since no water soaked PVC or HDPE pipe segments were used as a control, the time of breakthrough of the pipe segment data was observed as the day when the concentration showed a consistent departure from the trend of initial data points.

Permeation tests were conducted using un-jointed pipe segments to determine the effectiveness of fusible PVC and HDPE for limiting permeation of hydrocarbons if the casing pipe was surrounded by crude oil in the event of a release. The results of the permeation tests for un-jointed PVC pipe are shown in Figure 4.13.

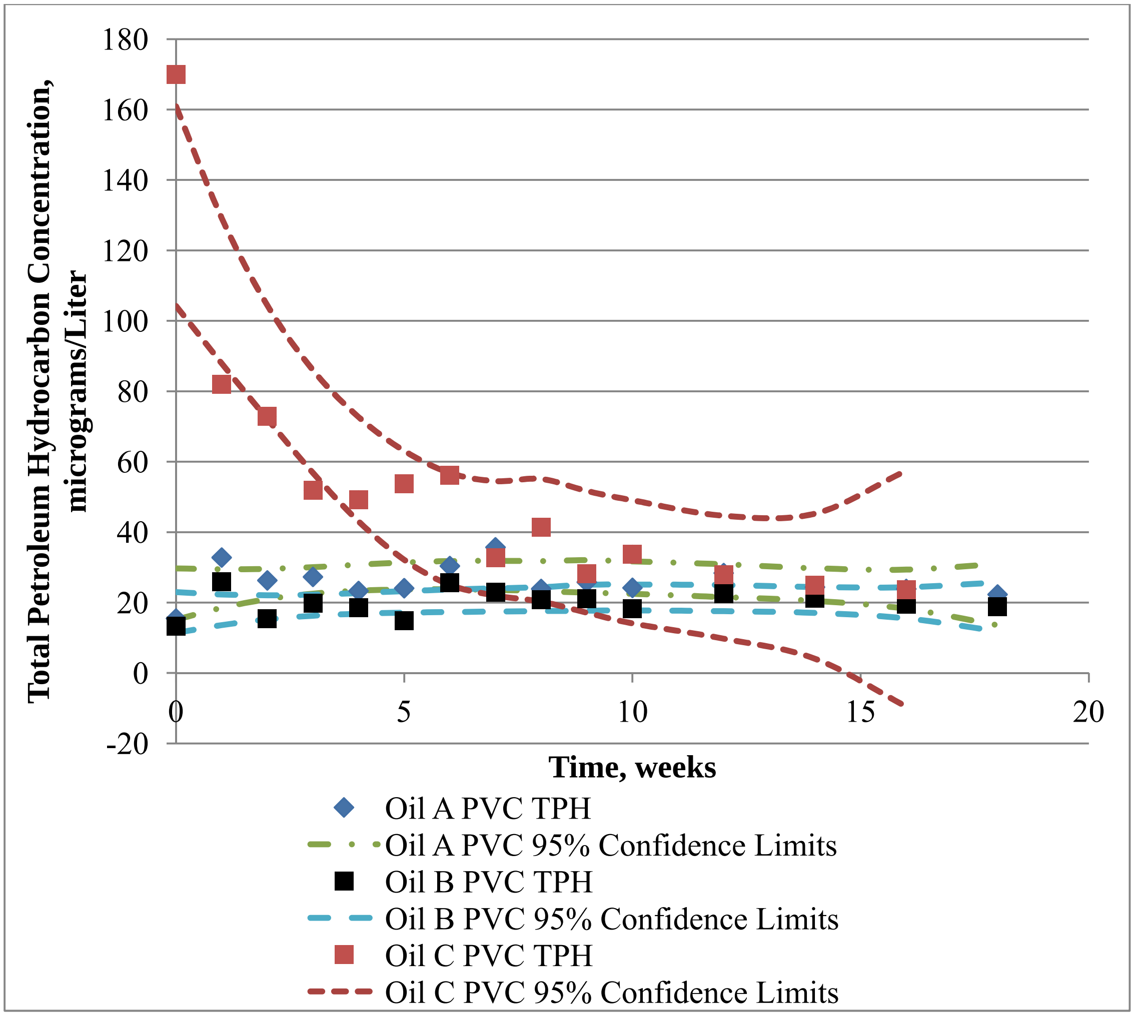

Figure 4.13. TPH water samples from all the straight PVC pipe segments.

As seen in Figure 4.13, the TPH concentrations from water contained in un-jointed pipes exposed to Oil-A and Oil-B ranged between 15 and 40 micrograms per liter, and did not depart from this range. This TPH concentration range represents a background concentration that is emanating from the pipe walls during the 7-day time period that Nanopure water was exposed to the pipe wall between water sample collections. The Oil-C TPH values were initially very high relative to the other two oils. However the TPH concentrations decreased with time until they reached the concentrations exhibited by pipes exposed to Oil-A and Oil-B. It is suspected the Oil-C concentrations were initially high due to contamination from excess solvent weld solvent and adhesive.

The results of TPH analyses conducted water samples from un-jointed HDPE pipes exposed to granular media saturated with Oils B and C are compared with water samples collected un-jointed PVC pipes exposed to the same oils in Figure 4.14. As indicated by the departure of data from the initially low TPH concentrations, TPH permeated though the walls of the HDPE pipe. Oil-B TPH permeated through the wall of the HDPE pipe in approximately 12 weeks, and Oil-C TPH permeated through the HDPE pipe wall in approximately 9 weeks.

TPH permeability through the pipe wall is a criterion for selection of the casing pipe material. In the event of an oil release, the casing for the water carrier pipe protects the carrier pipe from contamination by hydrocarbon vapors until the contaminated soil is removed. As indicated by the TPH permeability data produced in these experiments, PVC pipe is a valid candidate for casing material, since permeation did not occur through the pipe wall over the 18 week experiments conducted in this study. However, HDPE pipe is less desireable than PVC as a casing material, since TPH permeated through the HDPE pipe wall in a range of 9 to 12 weeks. Two-inch diameter pipes were used in the experiments, and pipes of other diameters would have a range of wall thicknesses that

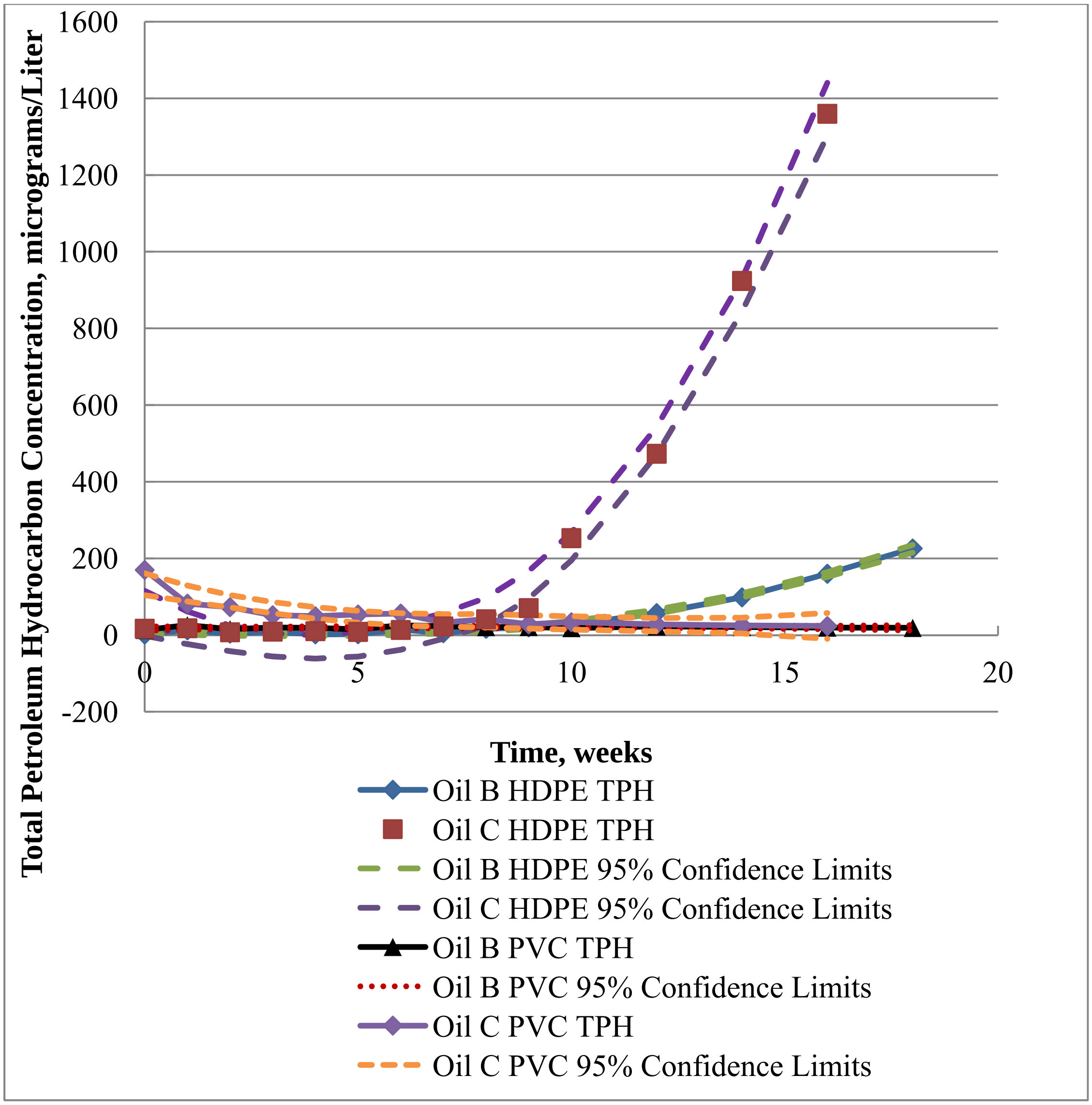

Figure 4.14. Comparison of un-jointed PVC and HDPE TPH results.

would influence time of permeation. However, the resistance to permeation of crude oil hydrocarbons by PVC and lack of resistance to permeation of crude oil by HDPE is verified by the experimental results.

Restrained joint PVC pipe was also suggested as a candidate casing material. As discussed in the literature, gaskets used for sealing joints in couplings are susceptible to permeation. The restrained joint pipe manufacturer provided polyisoprene and NBR gaskets for testing of restrained joint in this study. The results of permeability tests of pipe segments containing restrained joints with these gasket materials are discussed using data plots similar to those presented above for the straight pipe segments. Data for un-jointed and jointed PVC pipe exposed to Oil-A and water saturated granular media are presented in Figure 4.15. A clearer image of the Oil-A and water data for the NBR gasketed joint are shown in Figure 4.16.

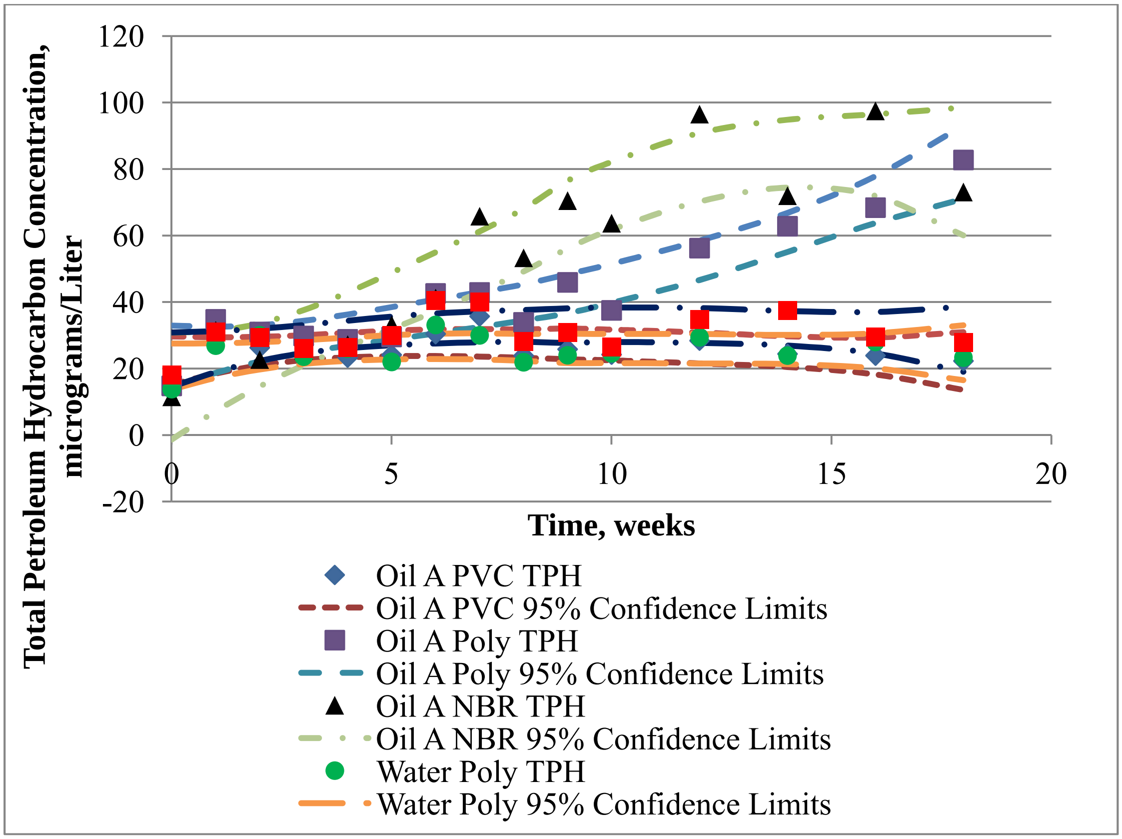

Figure 4.15. TPH test results for permeability experiments with Oil-A.

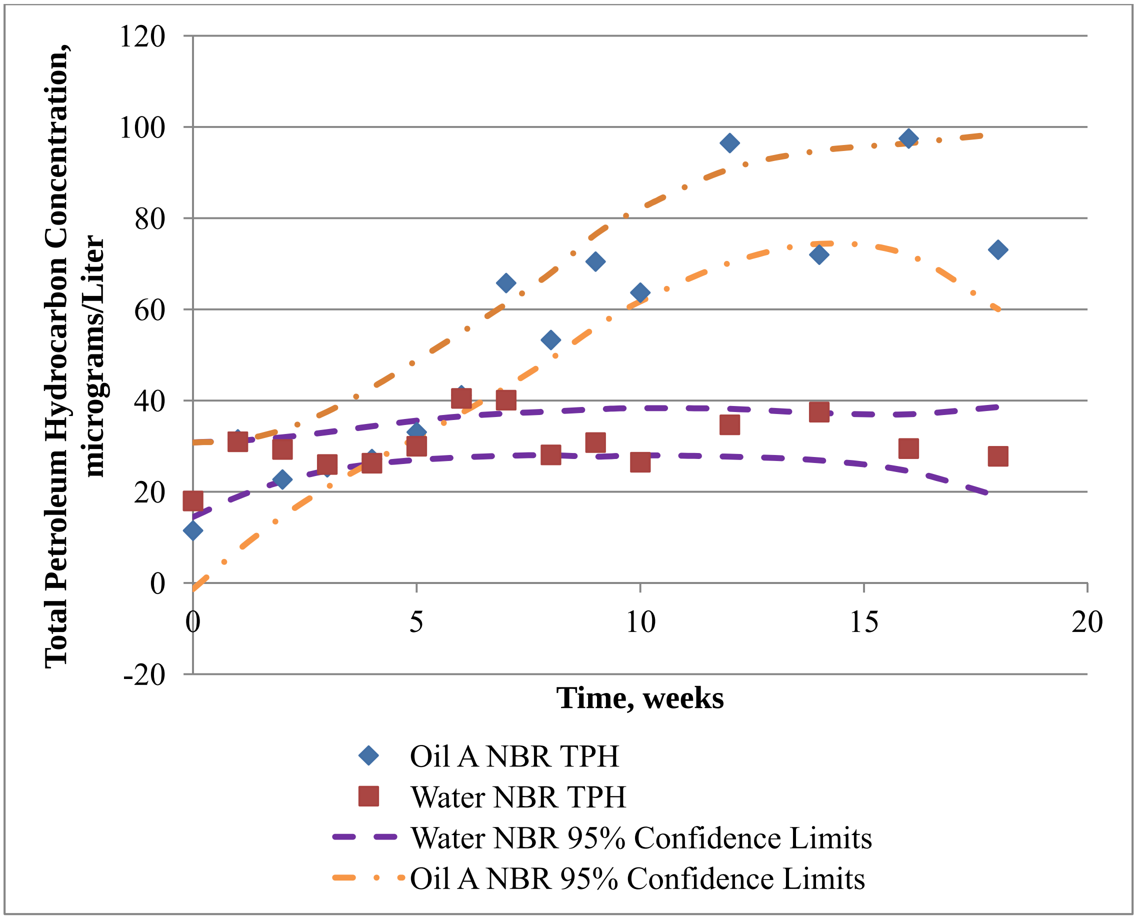

Figure 4.16. TPH test results for permeability experiments for NBR gasketed joints exposed to water and Oil-A

As indicated in Figures 4.15 and 4.16, the TPH concentrations of jointed pipes with polyisoprene and NBR gaskets exposed to water saturated granular media remain in a range between 20 and 40 micrograms per liter. This range is similar to the TPH concentration range for the permeability test of Oil-A on un-jointed pipe. However, the TPH concentrations for jointed pipes with polyisoprene gaskets (Oil-A Poly TPH) and with NBR gaskets (Oil-A NBR TPH) increase as they permeate through the joints. This joint permeation is likely due to absorption of components of the crude oil that also occurred during the gasket weight gain tests. Absorption of hydrocarbons by the gaskets represents a pathway for diffusion of crude oil compounds through the joint into the water. Based on these data and using the criteria to identify the time to permeation mentioned previously, the estimated time for TPH from Oil-A to permeate the polyisoprene and NBR gasket joint was 6 weeks for both materials.

Permeation test data NBR and polyisoprene restrained joints exposed to Oil-C and water are shown in Figure 4.17.

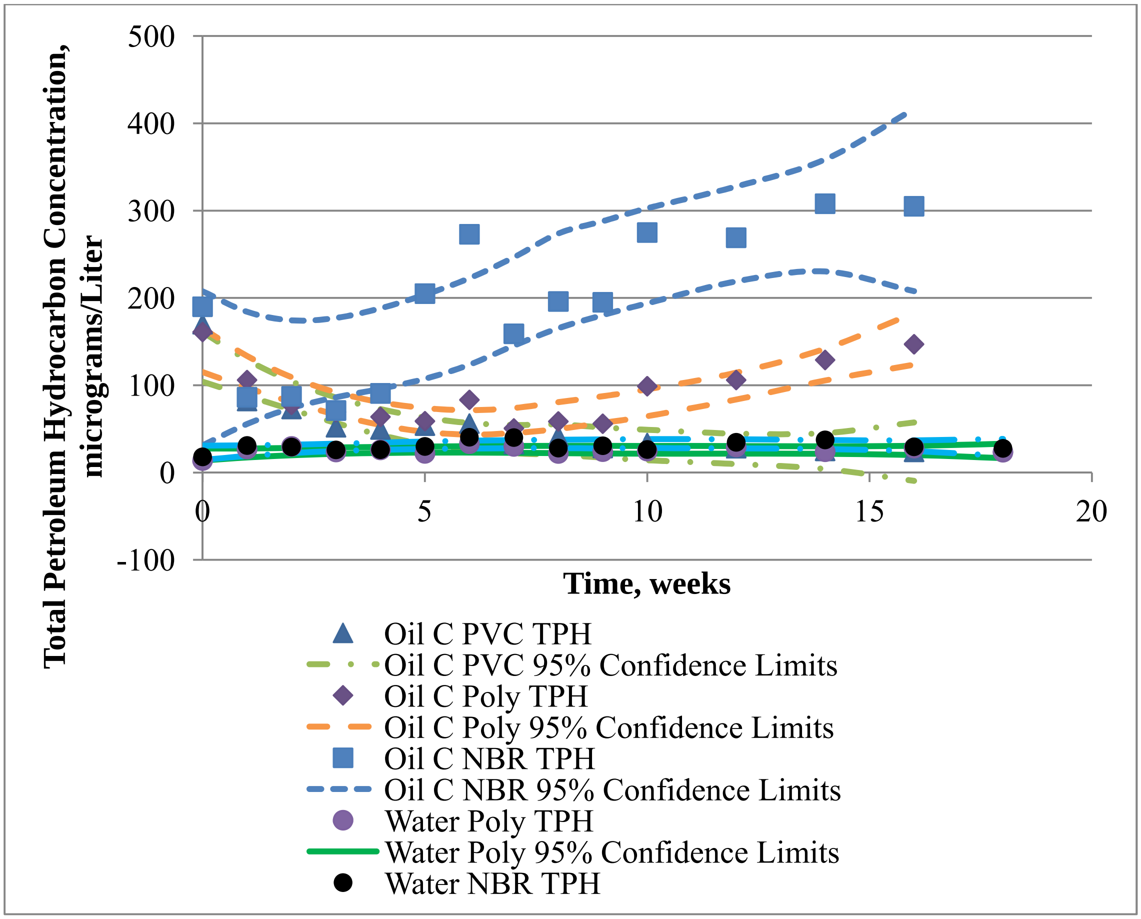

Figure 4.17. TPH test results for permeability experiments with Oil-C.

As occurred with gasketed joints exposed to Oil-A, TPH concentrations permeated through both the NBR and polyisoprene gasketed joints exposed to soil saturated with Oil-C. High initial THP concentrations in the NBR gasketed couplings were likely due to solvent weld residues. The time to TPH permeation of the polyisoprene gasketed joint exposed to Oil-C was approximately 10 weeks, where the time to TPH permeation of the NBR gasketed joint was approximately 4 weeks.

To facilitate comparison of Oil-B permeation data with those of the other crude oils and water, Figure 4-18 compares the permeation data of the polyisoprene gasket jointed pipe for Oil-B with that of water and Oil-A, and Figure 4-19 compares the permeation data of the NBR gasket jointed pipe for Oil-B with that of water and Oil-C.

Both the NBR and the polyisoprene gasketed joints exhibited permeation by TPH compounds from Oil-B. Time to permeation for the NBR gasketed joint was estimated at 12 weeks, whereas the time to permeation for the polyisoprene gasketed joint was estimated at 4 weeks.

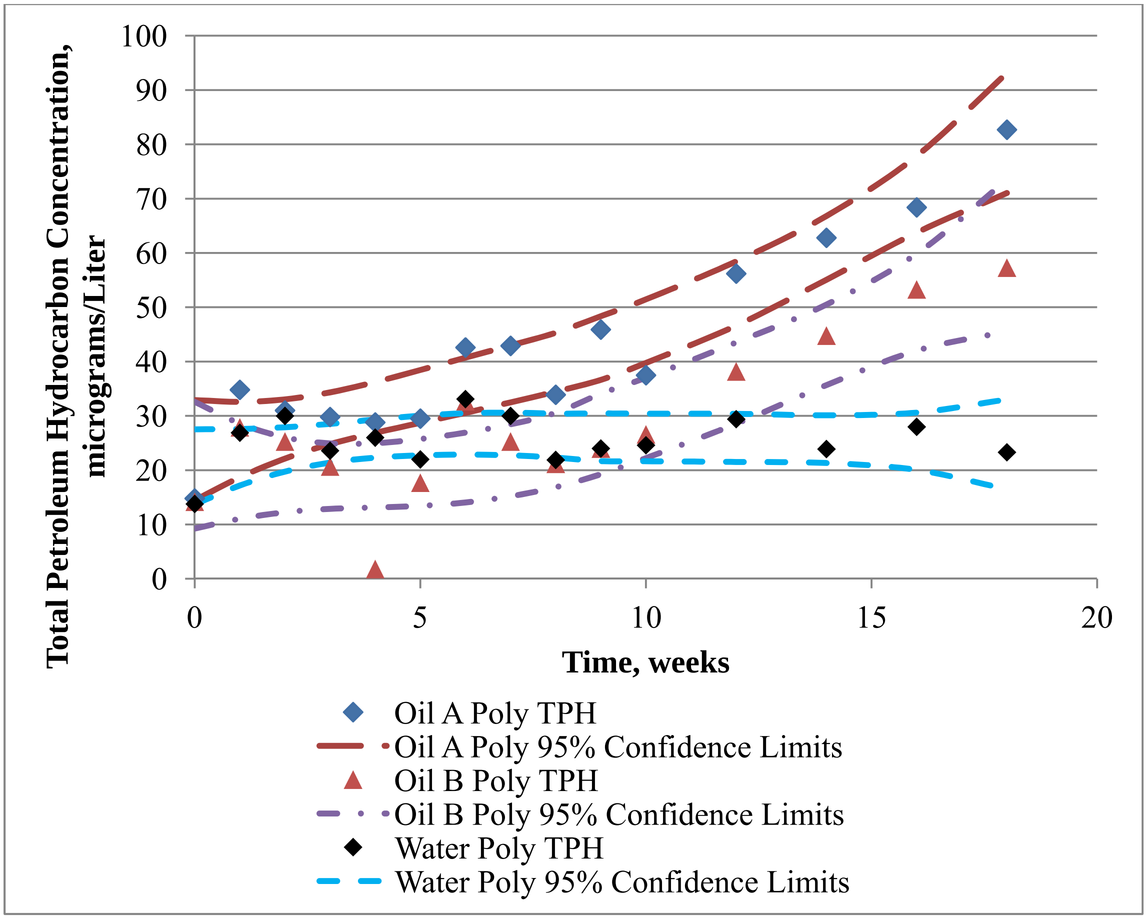

Figure 4.18. Comparison of TPH permeation test data for polyisoprene gasketed joints exposed to Oil-A, Oil-B and Water.

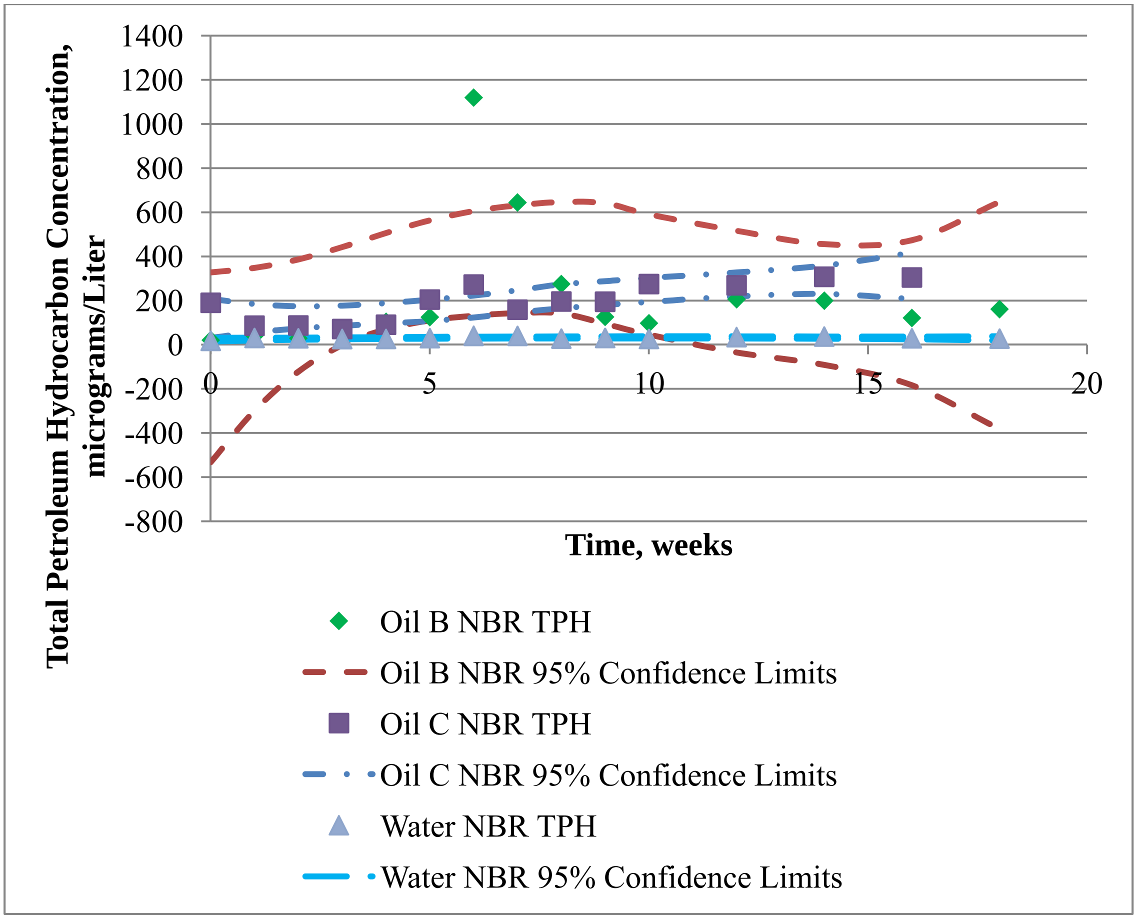

Figure 4.19. Comparison of TPH permeation test data for NBR-gasketed joints exposed to Oil-B, Oil-C and Water.

4.4.2 Total Organic Carbon Test Results

While the TPH test examined the concentrations of purgeable (volatile) organic carbons that may permeate through the pipe joints or walls, the Total Organic Carbon test was performed to examine whether non-purgeable organic carbon could permeate through the pipe couplings or PVC/HDPE pipes. Trace amounts of total organic carbon in the nanopure water sampled during the permeability tests would indicate the potential for contaminants permeating through the joint couplings. These experiments are described in detail in Chapter 3. Data from the TOC analyses are found in Appendix F.

Figures 4.20 through 4.22 represent the results of TOC analyses from permeation experiments of un-jointed pipe exposed to oil and water saturated granular media. Total organic carbon concentrations measured in the nanopure water extracted from straight lengths of PVC pipe exposed to all three oils were greater than one mg/L during the initial weeks of the permeation experiments. The TOC concentration gradually decreased to less than 0.5 mg/L. On the other hand, the TOC concentrations measured in nanopure water extracted from the straights lengths of HDPE pipe did not exhibit the initial high TOC concentrations. The single high TOC result for the HDPE pipe data in Figure 4.21 is likely due to a sample that was contaminated during sample collection, and not due to permeation through the pipe wall, since prior and following TOC results were low.

It is presumed that PVC pipe was leaching organic carbon from the pipe materials into the water, initially at a high rate, and gradually settling to a low rate as the pipe wall came to equilibrium with the water. HDPE pipe did not exhibit as substantial leaching characteristic, but rather exhibited a rather constant TOC concentration in the nanopure water as the experiment advanced. This leaching of organic compounds from the PVC pipe wall overshadowed concentrations of hydrocarbons that may have permeated through the pipe wall. As a result, the TOC test results were not useful to detect permeation of petroleum hydrocarbons through the pipe wall.

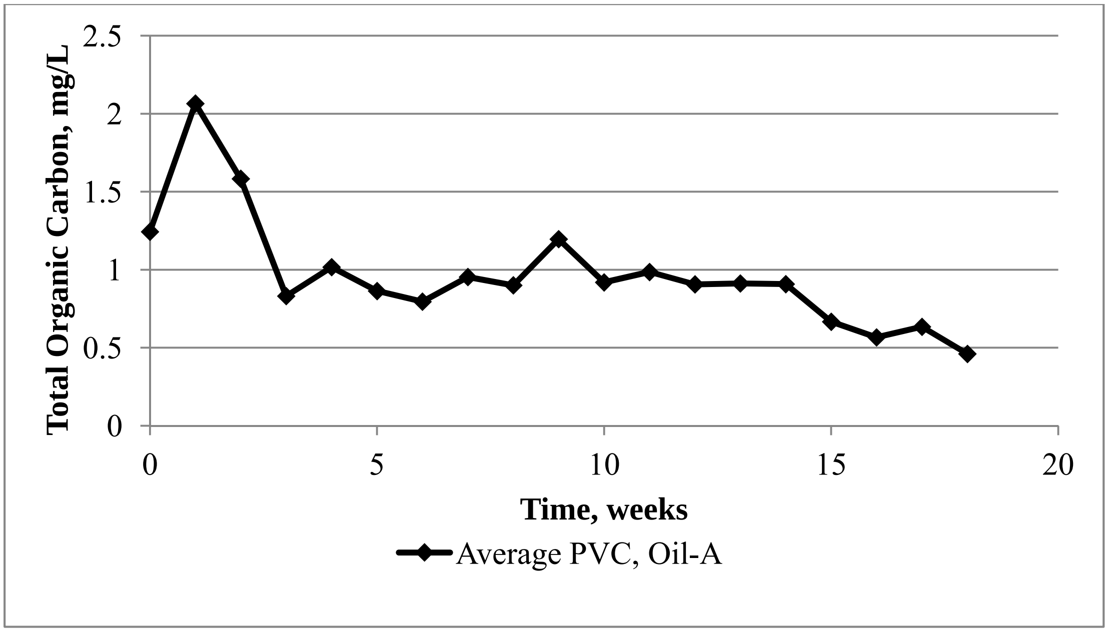

Figure 4.20. TOC results from permeation experiments on PVC pipe exposed to Oil-A.

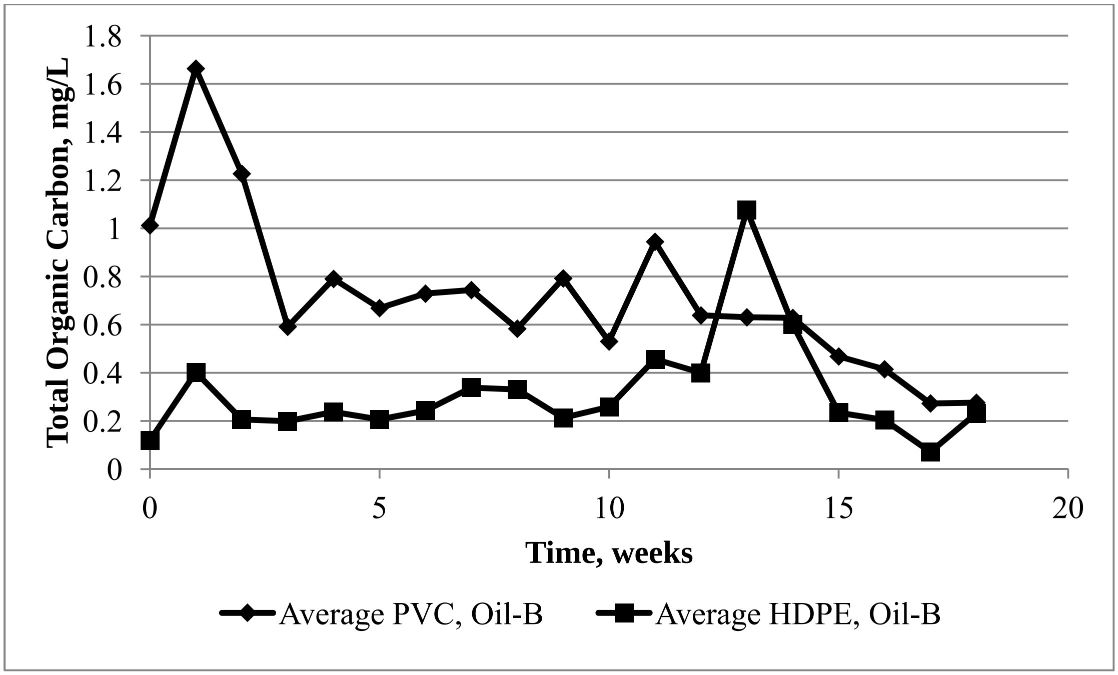

Figure 4.21. TOC results from permeation experiments on PVC and HDPE pipe exposed to Oil-B.

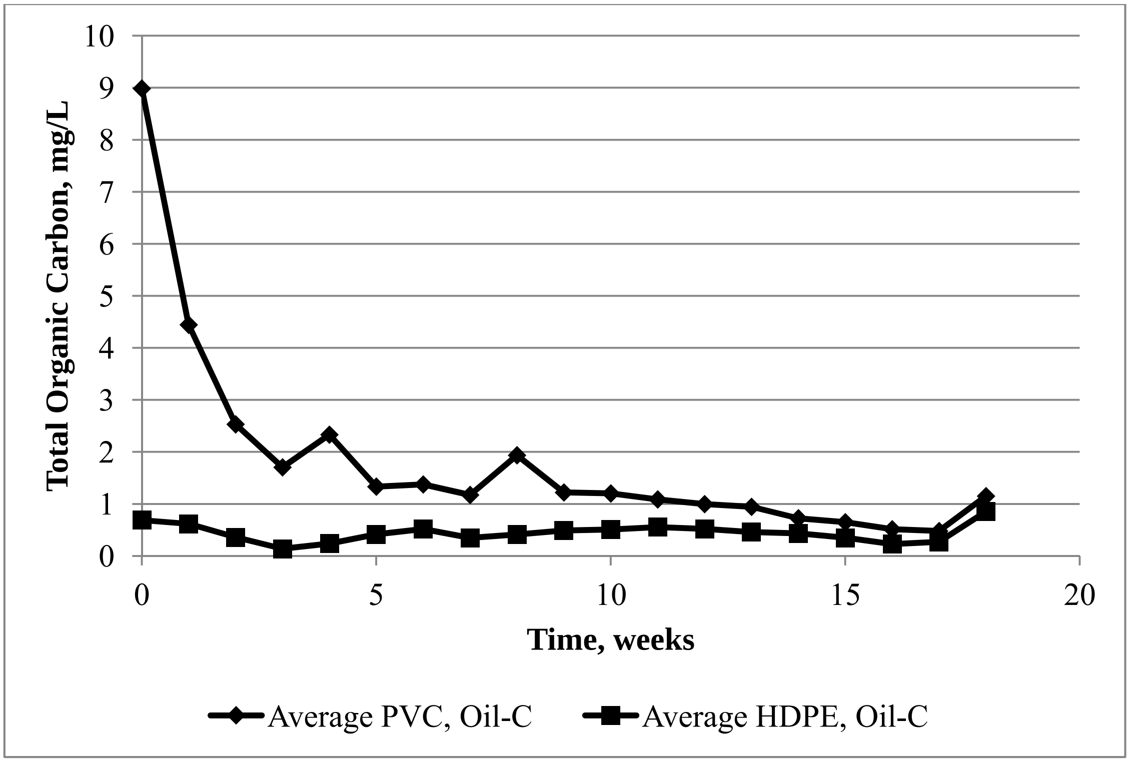

Figure 4.22. TOC results from permeation experiments on PVC and HDPE pipe exposed to Oil-C.

TOC measurements were also recorded for nanopure water samples extracted from the jointed pipe sections immersed in granular media saturated with the crude oils and water. Data from these experiments are also found in Appendix F. Representative plots of the data are displayed in Figure 4.23 for polyisoprene gasket jointed PVC pipe exposed to Oil-A and water, and in Figure 4.24 for NBR gasket jointed PVC pipe exposed to Oil-A and water. The week 11 spurious result for the Oil-A data in Figure 4.22 was likely due to sample contamination during the sample collection effort.

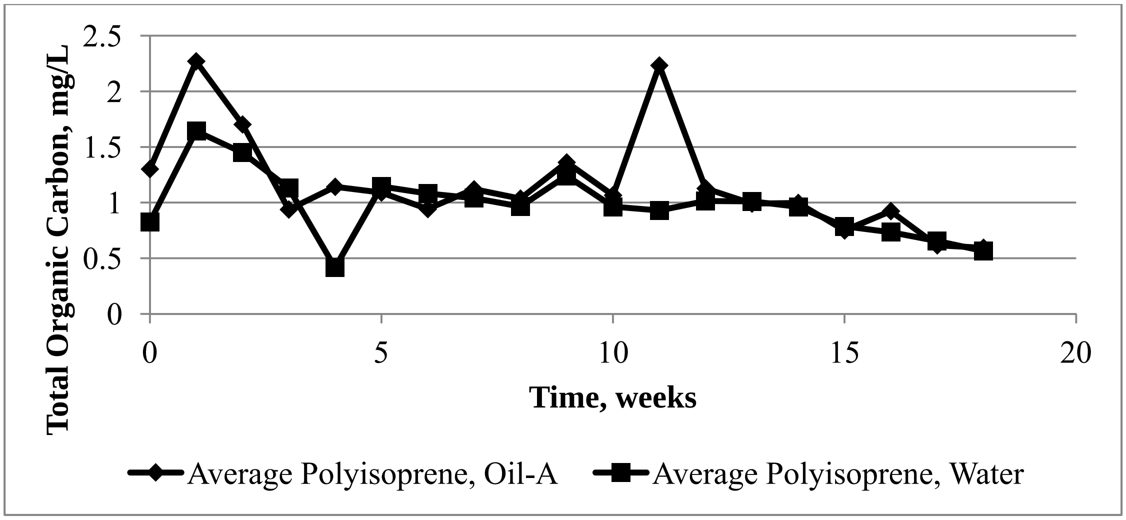

Figure 4.23. TOC results from permeation experiments on polyisoprene gasket jointed pipes exposed to crude Oil-A and water.

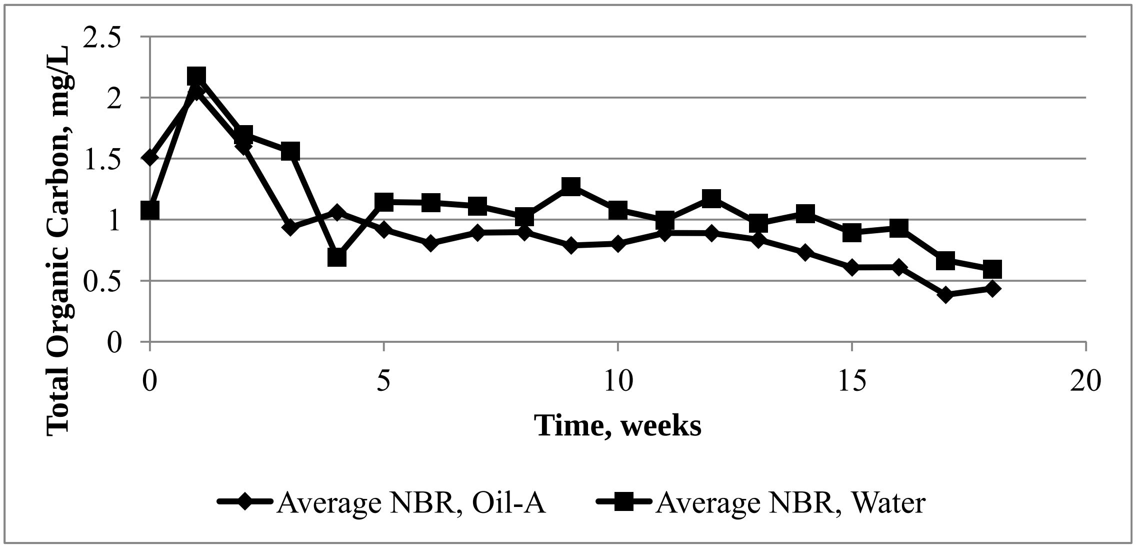

Figure 4.24. TOC results from permeation experiments on NBR gasket jointed pipes exposed to crude Oil-A and water.

Similar to the results of the un-jointed PVC pipe permeation tests, the TOC concentrations of the jointed PVC pipe permeation experiments decreased throughout the duration of the test. The NBR and polyisoprene jointed pipe segments exposed to oil saturated granular media exhibited the same trend as those exposed to water saturated granular media. Additionally, like trends were exhibited irrespective of oil type.

The interpretation of the TOC permeation data for the jointed PVC pipe segments is identical to that of the un-jointed PVC pipe segments. Organic compounds leaching from the PVC pipe material contributed TOC concentrations to the water as the nanopure water was held in the pipe during each 7-day exposure cycle. With increasing time of exposure, the concentration of these organic compounds decreased. This background concentration due to PVC leaching was far greater than concentrations of any non-purgeable petroleum hydrocarbons that may have permeated through the joint. Therefore the TOC measurements during the experiments were not useable to assess permeation through the joints (or walls) of the pipe.

4.4.3 Summary of Pipe Joint Permeation Test Results

The results of the restrained joint pipe segment permeation experiments that both NBR and polyisoprene gaskets enabled permeation of total petroleum hydrocarbons through the pipe joints exposed to crude oil saturated granular media. The time to permeation exhibited by the experiments are summarized in Table 4.2.

Table 4.2. Time to Permeation of TPH through Pipe Joints.

Oil Sample	Polyisoprene Gasket Joint	NBR Gasket Joint
A	6 weeks	6 weeks
B	12 weeks	4 weeks
C	10 weeks	4 weeks
Average	9 weeks	5 weeks

The average time to permeation of TPH through the polyisoprene gasket joints was 9 weeks whereas the average time to permeation through NBR joints was 5 weeks. Since permeation through the casing pipe in the event of a crude oil release is not a desirable event, the restrained joint PVC pipe is a less desireable alternative than the fusible joint PVC pipe alternative. Gasket permeation is likely a result of absorption and diffusion of the petroleum hydrocarbons into and through the gasket material, also indicated by the weight gain test results summarized in Section 4.3 of this report.

TOC analyses conducted during the permeation experiments failed to detect permeation. Organic carbon compounds leaching from the pipe into the water caused high TOC concentrations to dissolve into the water. These high TOC concentrations masked low concentrations of non-purgable organic carbon that would indicate permeation through the pipe wall or gasket material.

CHAPTER 5. EXECUTIVE SUMMARY

The objective of this study was to recommend design elements to improve the safety of crossings of crude oil pipelines and regional water system pipelines. Safety improvements were considered to protect the crude oil pipeline during repairs to the water pipeline at the crossing and to protect the water system pipeline from a crude oil release at the crossing.

5.1 Basis for Crossing Design

To conceive alternatives to the design of the crossing, state regulatory requirements and the design characteristics of existing crossings of the Keystone pipeline with regional rural water system pipelines were reviewed. Resulting from these reviews, the assumed crossing design configuration involved encasing the water carrier pipe in a plastic casing pipe. The casing pipe should protect the water carrier pipe from a crude oil release and enable a water carrier pipe in need of repair to be replaced by withdrawal and reinsertion through the casing pipe. Plastic pipe was chosen for the casing due to its: a) low cost relative to steel, b) corrosion resistance and lack of need for cathodic protection, c) amenability to installation by directional boring methods, and d) familiarity of use by water utilities and their contractors.

The major concern regarding the use of plastic pipe as the casing pipe was the potential impact of a crude oil release on the pipe structural integrity and potential for crude oil permeation through the pipe or pipe joint. No studies of the impacts of crude oil on the strength and permeability of plastic pipe or its components were found in the literature. However, several studies of the impacts of petroleum products on PVC and PE pipe, and gasketed PVC and ductile iron pipe joints were found in the literature and were summarized in Sections 2.2 through 2.8 of this report. The impacts of the compounds found in liquid petroleum products (gasoline and diesel) on pipe components included: a) petroleum products were found to impact the strength and permeate through polyethylene pipe, b) petroleum products were found to permeate through PVC pipe, although the rate of permeation was much slower than through PE pipe - the rate being strongly affected by the structure of the compound and its strength, and c) pipe joint gaskets are far more susceptible to permeation (than the pipe wall) by petroleum products, and the rate of permeation was directly related to the gasket material.

5.2 Experimental Approach

Due to the lack of direct experimental evidence of the impacts of crude oil on plastic pipe and joint components, experiments were conducted to determine the influence of crude oil on the strength and permeability of plastic pipes that were potential candidates for the pipe casing to be used in the pipeline crossings. Candidate casing pipe configurations examined experimentally were fusible PVC, fusible HDPE, and restrained joint PVC. Three crude oil samples were obtained to represent the types of oil shipped through the Keystone pipeline.

5.3 Impacts of Crude Oil on Pipe Strength Characteristics

Pipe strength tests were conducted using ASTM methods to examine the impacts of an oil release on pipe strength characteristics. To simulate a release of oil that saturated the soil surrounding the casing pipe, pipe segments were submerged in oil-saturated sand and tested at intervals of time over a 24-week period to determine the impact of crude oils on the tensile and compression strength characteristics of the pipe. Additional pipes were exposed to water as a control against which the pipes submerged in oil could be compared.

The tension and compression test results indicated no difference between the strength of PVC pipes exposed to oil and the strength of pipe exposed to water. The tensile and compressive strength of PVC pipes exposed to water and the three oils slightly increase over the 24-week period. On the other hand, the strength of HDPE pipe slightly decreased over the 24-week period.

Relative to the use of PVC as a casing pipe in the crossing design, the experimental results indicate the tensile and compressive strengths of the pipe would not be compromised in a 24-week time period. However, since the tensile and compressive strengths of the HDPE pipe decreased slightly over the same time period, its use as a casing pipe is less favored relative to PVC pipe.

5.4 Impacts of Crude Oil on Pipe Gasket Characteristics

Restrained joint pipe potentially considered for the casing material is supplied with either polyisoprene or nitrile butadiene rubber (NBR) gaskets. Since the literature review indicated gasket materials in pipe joints provide a potential route for permeation of petroleum hydrocarbons, the impacts of crude oil on the material properties of gasket materials was examined. The impacts of exposure of the gasket materials to oil and water were examined by conducting gasket tensile strength tests and weight gain tests on polyisoprene and NBR gaskets exposed to the three oils and to water (as a control). NBR and polyisoprene gaskets submerged in crude oil exhibited greater tensile strength loss and weight gain than gaskets submerged in water. Absorption of oil into the gasket material was related to a loss in tensile strength of the material. Although the gaskets are not undergoing tension in their function as a gasket material, this loss of strength characteristic is an indication of the impact of contact with crude oil on the structural properties of the gasket material.

5.5 Permeation of Crude Oil through Pipe Wall and Joints

To examine the potential for permeability of crude oil through the pipe walls and joints, un-jointed pipe samples and jointed pipe samples were submerged in crude oil-saturated sand. Using specifically designed valves, the pipes were filled with Nanopure (organic free, demineralized) water. The water was drained after 7-days and the permeability of hydrocarbons through the pipe/joints was measured by testing the samples of water drawn from the pipes for total petroleum hydrocarbons and total organic carbon. This experiment was repeated on a 7-day cycle for 18 weeks.

Hydrocarbons did not permeate through the wall of PVC pipe during the test period, whereas hydrocarbons did permeate through the wall of the HDPE pipe within 9 weeks. Additional experiments that were conducted to examine permeation through pipes with restrained joints containing polyisoprene rubber gaskets found permeation to occur after nine weeks of contact with crude oil. Crude oil hydrocarbons permeated through joints containing nitrile butadiene rubber gaskets after 5 weeks of contact with crude oil.

5.6 Recommendations for Crossing Design Elements

The experiments provided information that helps engineers and managers select pipe materials for the casing pipe used for crude oil/rural water pipe crossings. Three alternative materials were suggested, restrained joint PVC, fusible HDPE, and fusible PVC pipe. As shown in Table 5.1, favorable experimental results for pipe strength tests would allow all three pipe types to be used as the casing. However, consideration of the joint permeability experimental results would reject the use of restrained joint PVC pipe, and pipe wall permeability experimental results would reject the use of fusible HDPE as the casing pipe.

Table 5.1. Factors affecting pipe selection for the casing at crude oil/rural water pipe crossings.

Decision Parameter	Restrained Joint PVC	Fusible HDPE	Fusible PVC
Pipe Tensile Strength	Accept	Accept ? (slight strength decrease)	Accept
Pipe Compressive Strength	Accept	Accept ? (Slight strength decrease)	Accept
Pipe Wall Permeability	Accept	Reject	Accept
Joint Permeability	Reject	Jointless	Jointless
Overall	Reject	Reject	Accept

Considering the overall performance of the three pipe materials in tests of compatibility between crude oil and the candidate pipe components in this study, the fusible PVC is the best alternative for casing a rural water system pipe located under a crude oil pipeline. Under the conditions of experiments conducted in this study, fusible PVC maintained its strength characteristics when exposed to crude oil, exhibited resistance to permeation through pipe walls, and due to its jointless construction, did not exhibit permeation through joints as was experienced by the restrained joint PVC pipe samples.

Other design characteristics of crossings include the cased length of the rural water pipe, the vertical separation distance between the crude oil pipeline and the diameter of the casing. Decisions about these factors are specific to each crossing site, and depend on such factors as the width of the crude oil pipeline right of way, the amount of bend in the casing required to achieve the vertical separation distance between the crude oil pipeline and the water pipeline, and the type of soil in the area of the crossing.

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APPENDIX A. PIPE TENSILE STRENGTH DATA

Table A.1. Results of Pipe Tensile Experiments

(Table provides averaged pipe tensile strength (pounds per square inch, psi) of tests on three pipe coupons. Nine unsoaked HDPE samples were tested to find the average initial value to be used as the control.)

Week	Water PVC Pipe	Oil-A PVC Pipe	Oil-B PVC Pipe	Oil-C PVC Pipe	Oil-C HDPE Pipe
0					2625.9
1				7382.2	2419.0
2	6958.3	7195.3	6785.8		
4	7009.9	7065.4	7251.7	7724.9	2591.4
6	7425.3	7277.7	7665.8	7278.4	2552.0
8	7706.8	7747.9	7509.1	7253.5	2543.3
10	7792.1	7502.6	7486.1	7628.5	2583.8
12	7439.1	5721.2	7660.4	7332.0	2434.0
14	7309.3	7412.9	7449.1	7708.0	2582.2
16	7501.3	7510.5	7668.0	7364.9	2456.0
19	7444.9	7291.1		7306.8	2592.8
21	7550.2	7443.6	7370.2	7200.9	2521.8
24	7622.7	7375.3	7325.4	7965.4	2447.5

Table A.2. Statistical Analysis of HDPE pipe tensile strength mean values

(Results of the ANOVA Procedure using Duncan's Multiple Range Test were used to determine if the average failure strength of HDPE pipe in each oil type was significantly different from the average failure strength of unsoaked HDPE pipe during the 24 week testing period.)

Means with the same letter are not significantly different.			
Duncan Grouping	Mean	N	Submergence Liquid
A	2625.67	9	No Submergence Liquid
B	2520.27	33	Oil-C Soaked HDPE

Table A.3. Statistical Analyses of PVC Pipe tensile strength mean values

(Results of the ANOVA Procedure using Duncan's Multiple Range Test were used to determine if the average failure strength of PVC pipe in each oil type was significantly different from the average failure strength of PVC pipe soaked in water during the 24 week testing period.)

Means with the same letter are not significantly different.			
Duncan Grouping	Mean	N	Submergence Liquid
A	7467.78	33	Oil-C
A	7432.72	33	Water
A	7417.15	30	Oil-B
A	7403.23	33	Oil-A

APPENDIX B. AVERAGE PIPE COMPRESSION DATA

Table B.1. Results of Parallel Plate Pipe Compression Experiments

(Table provides averaged failure strength (pounds of force, lbf) of tests on three pipe samples tested. Six unsoaked HDPE samples were tested to create a control.)

Week	Water PVC Pipe	Oil-A PVC Pipe	Oil-B PVC Pipe	Oil-C PVC Pipe	Oil-C HDPE Pipe
0					758.5
1				866.7	720.7
2	827.7	900.3	851.0		
4	855.0	868.3	857.7	871.0	754.3
6	856.7	871.3	842.3	910.0	744.7
8	894.3	873.3	921.0	886.3	690.0
10	929.3	901.0	879.0	886.7	662.3
12	867.3	872.3	868.7	848.0	790.7
14	882.3	891.3	863.3	904.3	694.3
16	886.7	850.3	913.7	886.3	666.7
19	895.0	866.0	910.3	893.7	693.0
21	875.7	897.3	895.0	904.3	709.3
24	926.3	914.0	902.3	854.7	698.7

Table B.2. Statistical Analysis of HDPE pipe compression strength mean values

(Results of the ANOVA Procedure using Duncan's Multiple Range Test were used to determine if the average compression strength of HDPE pipe in each oil type was significantly different from the average failure strength of unsoaked HDPE pipe during the 24 week testing period.)

Means with the same letter are not significantly different.			
Duncan Grouping	Mean	N	Submergence Liquid
A	758.5	6	No Submergence Liquid
B	710.9	33	Oil-C Soaked HDPE

Table B.3. Statistical Analysis of PVC pipe compression strength mean values (Results of the ANOVA Procedure using Duncan's Multiple Range Test were used to determine if the average compression strength of PVC pipe soaked in each oil was significantly different from the average failure strength of water soaked HDPE pipe during the 24 week testing period.)

Means with the same letter are not significantly different.			
Duncan Grouping	Mean	N	Submerging Liquid
A	884.061	33	Oil-C
A	882.333	33	Oil-A
A	881.485	33	Water
A	879.152	33	Oil-B

APPENDIX C. GASKET PERCENT WEIGHT GAIN DATA

Table C.1. Average Percent Weight Gain of NBR Gaskets Soaked in Oil or Water

(Table provides average percent weight gained by NBR gaskets submerged in their respective liquids. The average was taken from three test samples.)

Average Percent Weight Gain				
Day	NBR Water	NBR Oil-A	NBR Oil-B	NBR Oil-C
0	0	0	0	0
1	0.5	2.5	1.8	3.7
2	0.7	3.6	2.4	4.4
3	0.9	4.5	3.0	5.3
7	1.4	6.6	4.3	7.3
9	1.4	7.1	4.9	8.0
11	1.6	7.9	5.2	8.6
15	1.8	8.9	5.8	9.7
17	1.9	9.4	6.1	10.0
23	2.1	10.5	6.9	11.1
31	2.4	11.9	7.7	12.3
38	2.5	12.7	8.3	13.1
45	2.7	13.5	8.7	13.7
52	2.9	14.2	9.0	14.3
59	3.0	14.7	9.4	14.8
66	3.2	15.2	9.7	15.4
73	3.3	15.6	9.9	15.7
80	3.4	16.0	10.2	15.9
87	3.5	16.4	10.3	16.3
94	3.6	16.7	10.4	16.5
101	3.7	16.9	10.5	16.8
108	3.7	17.1	10.7	17.1
122	3.9	17.5	10.9	17.3
136	4.0	17.9	11.0	17.9
150	4.1	18.1	11.2	18.1
166	4.2	18.3	11.3	18.0

Table C.2. Average Percent Weight Gain of Polyisoprene Gaskets Soaked in Oil or Water

(Table provides average percent weight gained by polyisoprene gaskets submerged in their respective liquids. The average was taken from three test samples.)

Average Percent Weight Gain				
Day	Polyisoprene Water	Polyisoprene Oil-A	Polyisoprene Oil-B	Polyisoprene Oil-C
0	0	0	0	0
1	0.6	1.7	1.8	3.4
2	0.8	2.5	2.7	4.0
3	1.1	3.2	3.0	4.8
7	1.7	4.9	4.4	6.7
9	1.9	5.4	4.9	7.5
11	2.1	5.9	5.3	8.2
15	2.4	6.8	6.0	9.3
17	2.5	7.2	6.3	9.5
23	2.8	8.2	7.3	10.7
31	3.3	9.4	8.2	12.0
38	3.5	10.2	9.0	12.8
45	3.8	11.0	9.6	13.5
52	4.0	11.6	10.1	14.1
59	4.3	12.2	10.6	14.5
66	4.5	12.7	11.1	15.0
73	4.7	13.2	11.5	15.4
80	4.9	13.6	11.9	15.7
87	5.0	14.0	12.1	16.0
94	5.2	14.4	12.4	16.3
101	5.4	14.8	12.7	16.5
108	5.5	15.1	12.9	17.0
122	5.8	15.6	13.3	17.3
136	6.1	16.1	13.7	17.6
150	6.2	16.4	14.0	17.9
166	6.4	16.8	14.4	17.9

APPENDIX D. GASKET TENSILE TEST DATA

Table D.1. NBR Gasket Tensile Strength Data

(Table provides average tensile strength (pounds per square inch) of tests on five gaskets tested each time.)

Average Tensile Strength of NBR Gaskets				
Day	NBR Water	NBR Oil-A	NBR Oil-B	NBR Oil-C
0	1762.7	1820.8	1648.5	1349.5
3	1751.9	1448.0	1329.1	1372.7
8	1852.7	1589.3	1364.7	1348.6
11	1713.0	1361.9	1492.6	1458.6
18	1807.5	1436.8	1451.4	1161.9
25	1808.9	1309.4	1323.8	1331.2
39	1780.0	1494.0	1091.5	1115.2
53	1646.1	1290.6	1063.7	1034.2
67	1723.9	1072.2	1195.7	1030.8
81	1712.5	1102.3	1142.7	1261.6
95	1626.9	995.3	1093.4	1059.0
109	1572.0	1090.9	939.5	1225.7
123	1666.4	1045.5	1239.1	1140.2
137	1511.1	1051.8	1199.0	1105.8
151	1576.4	1022.1	1064.7	1007.7
165	1479.5	1050.1	1284.1	899.8

Table D.2. Polyisoprene Gasket Tensile Strength Data

(Table provides average tensile strength (pounds per square inch) of tests on five gaskets tested at each time interval.)

Average Tensile Strength of Polyisoprene Gaskets				
Day	Polyisoprene Water	Polyisoprene Oil-A	Polyisoprene Oil-B	Polyisoprene Oil-C,
0	1498.3	1871.32	1651.28	1313.1
3	1651.96	1307.63	1365.9	1604.02
8	1619.9	1488.1	1445.9	1364.9
11	1489.42	1086.68	1564.76	1449.22
18	1380.48	1225.84	1356.86	1263.08
25	1471.94	1361.76	1382.92	1223.2
39	1507.72	1395.46	1132	1133.94
53	1589.26	1235.96	1067.74	1197.28
67	1344.22	1136.72	1070.2	1033.7
81	1704.22	1193.6	1159.52	1028.9
95	1363.60	1062.06	899.74	1156.08
109	1506.24	1102.96	915.62	1142.46
123	1310.3	1013.46	1060.54	998.86
137	1537.64	1095.74	1065.84	982.02
151	1160.7	1018.8	911.62	852.1
165	1458.96	945.6	1010.32	

Table D.3. Statistical Analysis of NBR Gasket Tensile strength mean values

(Results of the ANOVA Procedure using Duncan's Multiple Range Test were used to determine if the average tensile strength of NBR gaskets submerged in each liquid was significantly different.)

Means with the same letter are not significantly different.				
Duncan Grouping		Mean	N	Submergence Liquid
	A	1686.98	80	Water
	B	1261.31	80	Oil-A
C	B	1245.22	80	Oil-B
C		1183.4	80	Oil-C

Table D.4. Statistical Analysis of Polyisoprene Gasket Tensile strength mean values.

(Results of the ANOVA Procedure using Duncan's Multiple Range Test were used to determine if the average failure strength of polyisoprene gaskets in each liquid were significantly different.)

Means with the same letter are not significantly different.			
Duncan Grouping	Mean	N	Submergence Liquid
A	1474.68	80	Water
B	1221.35	80	Oil-A
B	1191.3	80	Oil-B
B	1182.86	75	Oil-C

APPENDIX E. TPH PERMEATION TEST DATA

Table E.1. TPH Permeation Data for NBR Gasketed PVC Couplings Exposed to Water, Oil-A and Oil-C.

(Table provides total petroleum hydrocarbon analysis results in micrograms per liter from consolidated water samples collected from three NBR gasketed couplings exposed to sand saturated with the respective liquid.)

NBR Coupling TPH Analysis Results			
	Water	Oil-A	Oil-C
Date	Result, micrograms/L		
4/5/2011	18	11.5	
4/12/2011	31	31.5	190
4/19/2011	29.3	22.7	86.3
4/26/2011	26	25.4	87.3
5/3/2011	26.3	27.2	71.1
5/10/2011	30	33.1	90.7
5/17/2011	40.5	41.2	205
5/24/2011	40.1	65.8	273
5/31/2011	28.1	53.3	159
6/7/2011	30.8	70.5	196
6/14/2011	26.5	63.7	195
6/28/2011	34.7	96.5	275
7/12/2011	37.5	72	269
7/26/2011	29.5	97.5	308
8/9/2011	27.8	73.1	305

Table E.2. TPH Permeation Data for NBR Gasketed PVC Couplings Exposed to Oil-B.

(Table provides total petroleum hydrocarbon analysis results in micrograms per liter from consolidated water samples collected from three NBR gasketed couplings exposed to sand saturated with Oil-B. A mass balance needed to be performed on the NBR gasketed coupling data due to excessive permeation of the middle coupling (BNMC).)

Oil-B NBR Coupling TPH Analysis Results			
	Result, micrograms/L		
			BNMC
Date	Left and right coupling results		Middle coupling results
4/5/2011		21.3	
4/12/2011		40.5	
4/19/2011		29.6	
4/26/2011		46.9	
5/3/2011		104	
5/10/2011		125	
5/17/2011		1120	
5/24/2011	42.5	644.7	1880
5/31/2011	38.1	275.3	762
6/7/2011	37.5	126.2	308
6/14/2011	39.4	97.6	217
6/28/2011	50.3	206.2	526
7/12/2011	60.1	199.7	486
7/26/2011	62.2	121.5	243
8/9/2011	69	161.4	351

Table E.3. TPH Permeation Data for Polyisoprene Gasketed PVC Couplings Exposed to Water and Crude Oil.

(Table provides total petroleum hydrocarbon analysis results in micrograms per liter from consolidated water samples collected from three polyisoprene gasketed couplings exposed to sand saturated with the respective liquid.)

Polyisoprene Coupling				
	Water	Oil-A	Oil-B	Oil-C
Date	Result, micrograms/L			
4/5/2011	13.8	14.8	14.2	
4/12/2011	26.9	34.8	27.9	161
4/19/2011	30	31	25.3	106
4/26/2011	23.6	29.8	20.7	77.6
5/3/2011	26	28.8	1.8	69.4
5/10/2011	22	29.5	17.7	63.8
5/17/2011	33.1	42.6	32.7	58.9
5/24/2011	30	42.9	25.3	83.3
5/31/2011	21.9	33.9	21.2	50.7
6/7/2011	24	45.9	24	58.6
6/14/2011	24.6	37.5	26.6	56
6/28/2011	29.4	56.2	38.2	98.9
7/12/2011	23.9	62.8	44.8	106
7/26/2011	28	68.4	53.3	129
8/9/2011	23.3	82.7	57.3	147

Table E.4. TPH Permeation Data for Straight PVC Pipes Exposed to Crude Oil.

(Table provides total petroleum hydrocarbon analysis results in micrograms per liter from consolidating the water samples from three PVC pipe samples exposed to sand saturated with the respective liquid.)

Straight PVC Pipe			
	Oil-A	Oil-B	Oil-C
Date	Result, micrograms/L		
4/5/2011	15.5	13.3	
4/12/2011	32.8	25.9	170
4/19/2011	26.3	15.4	82
4/26/2011	27.3	19.8	72.9
5/3/2011	23.3	18.6	51.9
5/10/2011	24.1	14.9	49.3
5/17/2011	30.4	25.6	53.8
5/24/2011	35.7	22.9	56.2
5/31/2011	23.9	20.8	32.8
6/7/2011	25.8	21.1	41.4
6/14/2011	24.2	18.3	28.2
6/28/2011	28.4	22.5	33.8
7/12/2011	24.4	21.2	27.9
7/26/2011	23.9	19.6	24.9
8/9/2011	22.3	18.8	23.7

Table E.5. TPH Permeation Data for Straight HDPE Pipes Exposed to Oil-C

(Table provides total petroleum hydrocarbon analysis results in micrograms per liter from consolidating the water samples from three HDPE pipe samples exposed to sand saturated with Oil-C.)

Straight HDPE Pipe		
Date	Result micrograms/L	
4/5/2011	1.7	
4/12/2011	12.3	16.7
4/19/2011	4	18
4/26/2011	9	7.42
5/3/2011	1.8	9.2
5/10/2011	2.36	10.2
5/17/2011	14.2	8.5
5/24/2011	5.1	13.4
5/31/2011	16.3	22.8
6/7/2011	20.3	41.3
6/14/2011	26.7	70.4
6/28/2011	57.5	253
7/12/2011	98.6	473
7/26/2011	160	924
8/9/2011	226	1360

APPENDIX F. TOC PERMEATION TEST DATA

Table F.1. TOC Permeation Data from Polyisoprene Gasketed PVC Couplings Exposed to Water and Crude Oil

(Table provides averaged Total Organic Carbon concentration results (milligrams per liter) of tests on samples taken from three coupling segments exposed to sand saturated with the respective liquid.)

Polyisoprene Coupling TOC Concentration Data				
	Water	Oil-A	Oil-B	Oil-C
	mg/L	mg/L	mg/L	mg/L
Date				
4/5/2011	0.825	1.302	1.224	
4/12/2011	1.643	2.270	1.887	8.015
4/19/2011	1.449	1.703	1.327	4.886
4/26/2011	1.130	0.938	0.660	2.839
5/3/2011	0.416	1.142	0.794	1.445
5/10/2011	1.144	1.090	0.812	2.501
5/17/2011	1.081	0.942	0.608	1.231
5/24/2011	1.041	1.120	0.783	1.416
5/31/2011	0.966	1.036	0.675	1.471
6/7/2011	1.241	1.362	0.794	1.788
6/14/2011	0.963	1.066	0.945	1.333
6/21/2011	0.930	2.233	0.801	1.205
6/28/2011	1.015	1.128	0.661	1.209
7/5/2011	1.011	0.991	0.783	1.015
7/12/2011	0.963	0.997	0.628	1.044
7/19/2011	0.786	0.750	0.497	0.954
7/26/2011	0.734	0.924	0.421	0.793
8/2/2011	0.654	0.616	0.293	0.591
8/9/2011	0.565	0.594	0.291	1.005

Table F.2. TOC Permeation Data from NBR Gasketed PVC Couplings Exposed to Water and Crude Oil

(Table provides averaged Total Organic Carbon concentration results (milligrams per liter) of tests on samples taken from three coupling segments exposed to sand saturated with the respective liquid.)

NBR Coupling Average TOC Concentration Data				
	Water	Oil-A	Oil-B	Oil-C
	mg/L	mg/L	mg/L	mg/L
Date				
4/5/2011	1.080	1.510	1.815	
4/12/2011	2.175	2.047	2.619	7.986
4/19/2011	1.699	1.600	1.819	4.523
4/26/2011	1.560	0.937	0.985	1.935
5/3/2011	0.691	1.060	1.218	1.964
5/10/2011	1.145	0.919	1.114	2.153
5/17/2011	1.139	0.807	0.946	1.476
5/24/2011	1.111	0.893	0.952	1.541
5/31/2011	1.024	0.897	0.887	1.506
6/7/2011	1.270	0.789	1.039	1.690
6/14/2011	1.080	0.803	0.890	1.771
6/21/2011	0.997	0.892	0.951	1.367
6/28/2011	1.173	0.889	0.947	1.358
7/5/2011	0.969	0.836	0.992	1.613
7/12/2011	1.048	0.732	0.779	1.322
7/19/2011	0.896	0.609	0.711	0.895
7/26/2011	0.930	0.611	0.497	0.859
8/2/2011	0.666	0.384	0.490	0.753
8/9/2011	0.593	0.436	0.509	0.749

Table F.3. TOC Permeation Data from PVC Pipe Exposed to Crude Oil

(Table provides averaged Total Organic Carbon concentration results (milligrams per liter) of tests on samples taken from three pipe segments exposed to sand saturated with the respective liquid.)

Straight PVC Pipe TOC Concentration Data			
	Oil-A	Oil-B	Oil-C
	mg/L	mg/L	mg/L
Date			
4/5/2011	1.244	1.013	
4/12/2011	2.065	1.664	8.986
4/19/2011	1.583	1.227	4.444
4/26/2011	0.831	0.592	2.530
5/3/2011	1.017	0.790	1.704
5/10/2011	0.863	0.669	2.332
5/17/2011	0.796	0.729	1.333
5/24/2011	0.954	0.744	1.375
5/31/2011	0.900	0.583	1.174
6/7/2011	1.196	0.792	1.936
6/14/2011	0.919	0.530	1.221
6/21/2011	0.986	0.945	1.202
6/28/2011	0.906	0.639	1.087
7/5/2011	0.912	0.631	0.997
7/12/2011	0.908	0.628	0.945
7/19/2011	0.667	0.468	0.724
7/26/2011	0.566	0.415	0.649
8/2/2011	0.634	0.273	0.514
8/9/2011	0.460	0.276	0.479

Table F.4. TOC Permeation Data from HDPE Pipe Exposed to Crude Oil

(Table provides averaged Total Organic Carbon concentration results (milligrams per liter) of tests on samples taken from three pipe segments exposed to sand saturated with the respective liquid.)

Straight HDPE Pipe		
	Oil-B	Oil-C
	mg/L	mg/L
Date		
4/5/2011	0.120	
4/12/2011	0.402	0.689
4/19/2011	0.206	0.617
4/26/2011	0.199	0.360
5/3/2011	0.238	0.138
5/10/2011	0.206	0.238
5/17/2011	0.243	0.417
5/24/2011	0.339	0.518
5/31/2011	0.331	0.347
6/7/2011	0.213	0.414
6/14/2011	0.258	0.491
6/21/2011	0.457	0.508
6/28/2011	0.401	0.554
7/5/2011	1.076	0.522
7/12/2011	0.600	0.459
7/19/2011	0.235	0.435
7/26/2011	0.204	0.350
8/2/2011	0.072	0.229
8/9/2011	0.232	0.271

APPENDIX G. PIPE THICKNESS DATA

Table G.1. Average Thickness of PVC or HDPE Pipes Soaked in Oil or Water

(Table provides results of pipe thickness measurements taken before destructive tests were conducted. The average of eight thickness measurements are presented below. These thickness values were used along with standard sample dimensions to calculate the pipe cross-sectional areas required for strength calculations. The results also indicate that exposure to the crude oils did not substantially impact the pipe thickness during the exposure times of the experiments.)

Average Pipe Thickness					
Week	Water	Oil-A	Oil-B	Oil-C PVC	Oil-C HDPE
2	0.150	0.152	0.151	0.150	0.229
4	0.150	0.151	0.150	0.150	0.230
6	0.150	0.151	0.151	0.151	0.231
8	0.150	0.151	0.150	0.151	0.232
10	0.150	0.151	0.150	0.150	0.231
12	0.150	0.150	0.151	0.151	0.231
14	0.150	0.150	0.151	0.150	0.230
16	0.150	0.150	0.150	0.152	0.231
19	0.150	0.151	0.151	0.150	0.232
21	0.150	0.152	0.152	0.152	0.232
24	0.150	0.153	0.152	0.152	0.232

APPENDIX H. CONFIDENCE INTERVALS

The 95% confidence interval was found by using the following equation

$$P[(\mu-1.96\sigma/\sqrt{n}) < \hat{Y} < (\mu+1.96\sigma\sqrt{n})] = 0.95$$

These sample calculations were performed on the tensile tests of PVC pipe soaked in Oil-A.

$\mu = 561.21$

$\sigma = 14.948$

$n = 33$

$$561.21-1.96*14.948/\sqrt{33} < \hat{Y} < 561.21+1.96*14.948/\sqrt{33} =0.95$$

$$556.1099 < \hat{Y} < 566.3101$$

$$556.1099/566.3101 = 0.98$$