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Pilot-Scale Tests and Systems Evaluation for the Containment, Treatment, and Decontamination of Selected Materials From T&E Building Pipe Loop Equipment

Office of Research and Development
National Homeland Security Research Center

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Pilot-Scale Tests and Systems Evaluation for the Containment, Treatment, and Decontamination of Selected Materials From T&E Building Pipe Loop Equipment

by

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5050 Section Avenue
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for

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Any opinions expressed in this report are those of the authors and do not necessarily reflect the official positions and policies of EPA. Any mention of products or trade names does not constitute recommendation for use by EPA.

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List of Acronyms

AA	atomic absorption
AwwaRF	American Water Works Association Research Foundation
ATI	Analytical Technology, Inc.
cells/mL	cells per milliliter
CFU/cm^2	colony forming units per square centimeter
cPVC	chlorinated polyvinyl chloride
CT	[chlorine concentration] X [contact time]
DRO	Diesel Range Organics
DSS	distribution system simulator
EPA	United States Environmental Protection Agency
EQL	estimated quantification limit
fps	feet per second
GC/FID	Gas Chromatograph/Flame Ionization Detector
gpm	gallons per minute
GRAS	generally regarded as safe
HDPE	high-density polyethylene
HPC	heterotrophic plate count
HSPD	Homeland Security Presidential Directive
ICP	inductively coupled plasma
in^2	square inches
Kow	Octanol-Water Partition Coefficient
L	liter
mg/coupon	milligrams per coupon
mg/L	milligrams per liter
mL	milliliter
NHSRC	National Homeland Security Research Center
NRMRL	National Risk Management Research Laboratory
NSF	National Sanitation Foundation
NTU	Nephelometric Turbidity Unit
ORD	Office of Research and Development
ORP	oxidation-reduction potential
PDD	Presidential Decision Directive
PE	Professional Engineer
PL	Project Leader
psi	pounds per square inch
ppm	parts per million
PVC	polyvinyl chloride
QA	quality assurance
QC	quality control
QAPP	Quality Assurance Project Plan
Re	Reynolds number
SCADA	Supervisory Control and Data Acquisition
SBRT	SBR Technologies, Inc. (subcontractor to Shaw Environmental, Inc.)
Shaw	Shaw Environmental, Inc.
SOP	standard operating procedure
STL	Severn Trent Laboratories

List of Acronyms

TOC	total organic carbon
T&E	Test & Evaluation
µg/L	micrograms per liter
µm	micrometer
WA	Work Assignment
WAM	Work Assignment Manager
WSWRD	Water Supply and Water Resources Division
w/v	weight/volume

1.0 Introduction

This summary report has been prepared for the U.S. Environmental Protection Agency (EPA) National Risk Management Research Laboratory (NRMRL) to fulfill the requirement for a summary report for the research study performed as described in Section 2.3 of the Work Plan for Work Assignment No. 2-12 (WA 2-12) under EPA Contract No. EP-C-04-034.

This report summarizes the pilot-scale evaluations conducted at the EPA Test and Evaluation (T&E) Facility between April 2005 and January 2007 to investigate removal of sodium arsenite, mercuric chloride, *Bacillus subtilis*, diesel fuel (No. 2), and chlordane from water distribution systems. The report covers the purpose of the study, detailed experimental test conditions and methods, analytical results, and observations. It also incorporates technical reviewer comments from American Water Works Association Research Foundation (AwwaRF) and Sandia National Laboratories on the draft summary reports that Shaw prepared for contaminant-specific evaluations conducted under this Work Assignment.

1.1 PURPOSE OF STUDY

The safety and security of water supplies has come under reassessment in the past year. Issues ranging from public safety and health, ecological concerns, and national security are under consideration. The terrorist attacks on the United States on September 11, 2001, and the subsequent delivery of anthrax-contaminated letters through the mail raised concerns about protecting U.S. citizens and the nation's critical infrastructure. Presidential Decision Directive 63 (PDD 63) designates EPA as the lead for securing the national water infrastructure. Therefore, the Agency is working to be proactive in the anticipation, detection, and identification of the threat of deliberate or accidental con-tamination of our water supplies. This proactive approach shall be to prevent, respond to, mitigate and/or treat contamination of our essential national resources. EPA has developed strategies to deter, detect, treat, and respond to physical, biological, chemical, radiological, and cyber attacks on U.S. water supplies, utilities, or systems. This preparation includes understanding the interdependencies among the national water infrastructure and other critical U.S. infrastructure. The Agency is guided in its efforts by the requirements of the Bioterrorism Act of 2002 (107-188). EPA is further guided in this effort by Homeland Security Presidential Directive 9 (HSPD-9), which was signed on February 4, 2004. This research also supports the National Homeland Security Research Center (NHSRC) under other directives, including Critical Infrastructure Identification, Prioritization, and Protection (HSPD-7), which was signed on December 17, 2003, and Biodefense for the 21st Century (HSPD-10), which was signed on April 28, 2004.

One of EPA's more important challenges in dealing with a contamination threat is how to treat, contain, and dispose of contaminated water. Depending on where the contaminant is introduced, this may involve actions within source waters, drinking water treatment plants, distribution systems, or points downstream. Any material (including the water) may need to be disposed of properly. Furthermore, the physical infrastructure of the water distribution system will require decontamination before it is reused. To evaluate the efficacy of various decontamination methods, a series of pilot-scale tests were conducted, using the pipe loop system located at the T&E Facility, in Cincinnati, Ohio.

1.2 PROJECT OBJECTIVES

The decontamination study had the following primary goals:

1. Quantitative determination of the potential of target contaminants for persistence in a dynamic drinking water distribution system. The key objectives were to:
   - Determine the adherence tendency of five contaminants to drinking water distribution pipe surfaces
   - Investigate the effect of different pipe materials on the adherence of contaminants to the pipe surface
   - Examine the effect of different flow regimes (laminar and turbulent) on the fate of contaminants and their adherence to pipe surfaces
2. Quantitative determination of the efficacy of various decontamination methods for removing contaminants from a drinking water distribution system. The key objectives were to:
   - Evaluate several decontamination methods for their effectiveness in removing different contaminants from a drinking water distribution system
   - Determine the optimal decontamination condition (e.g., flow rate, reagent concentration, pH) of each decontamination method for each contaminant
   - Investigate the effect of pipe materials on the performance of the decontamination technique

2.0
Experimental Methodology

2.1 EXPERIMENTAL DESIGN OVERVIEW

A list of target contaminants for the decontamination research was developed based on EPA NHSRC's Water Contaminant List and AwwaRF's Contaminant List. Sodium arsenite, mercuric chloride, *Bacillus subtilis*, diesel fuel (No. 2), and chlordane were selected as the target contaminants for the study. Chlordane was not included in the initial pilot-scale test plan because its use has been banned for the past twenty years and it has been very difficult to find suppliers of the commercial form of chlordane. Also, there was concern over using a banned pesticide like chlordane in the pilot-scale decontamination study, and it was thought that it would be more applicable to use off-the-shelf contaminants. However, chlordane was one of the contaminants investigated in AwwaRF's laboratory-scale decontamination study. Chlordane is a very "sticky" chemical, as shown by its high Kow value (adsorption coefficient), and would pose a challenge for decontamination. Therefore, AwwaRF selected chlordane as one of the "most-difficult-to-treat" chemicals in their laboratory-scale experiments. In order to perform a comparison with AwwaRF's laboratory-scale results, EPA/Shaw Team added chlordane to the list of target contaminants for the pilot-scale decontamination study. In December 2006, Shaw was successful in obtaining small quantities of chlordane for the pilot-scale evaluation from the Ohio Hamilton County Household Hazardous Waste Collection site. This summary report includes the adherence and decontamination tests conducted for the five different target contaminants.

Each of the pilot-scale adherence/decontamination experiments was initiated with integration of used "real-world" pipe sections (coupons) into the existing drinking water distribution system simulator (DSS) at the U.S. EPA T&E Facility. Figure 2-1 presents a schematic of the DSS incorporating the 1-inch "real-world" pipe sections. Figure 2-2 is a photograph of the DSS located at the EPA T&E Facility, in Cincinnati, Ohio. Biofilm was cultivated within the DSS over one to two weeks, using an accelerated biofilm cultivation strategy. Upon confirmation of the biofilm development in the pipe loop, the target contaminant was injected into the DSS. The DSS was operated in a recirculation mode at the designated flow rate condition. After a two-day contact period, the coupons (real-world pipe materials) were sampled to determine the adherence of contaminant to the pipe loop materials. Upon completion of the adherence study, a designated decontamination approach was evaluated. After decontamination, the coupon walls were analyzed for residual, adsorbed contaminant. Figure 2-3 depicts the overall experimental strategy for the planned tests.

Figure 2-1 Schematic of Pipe Loop Distribution System Simulator (DSS) With Integrated Real-World Pipe Sections

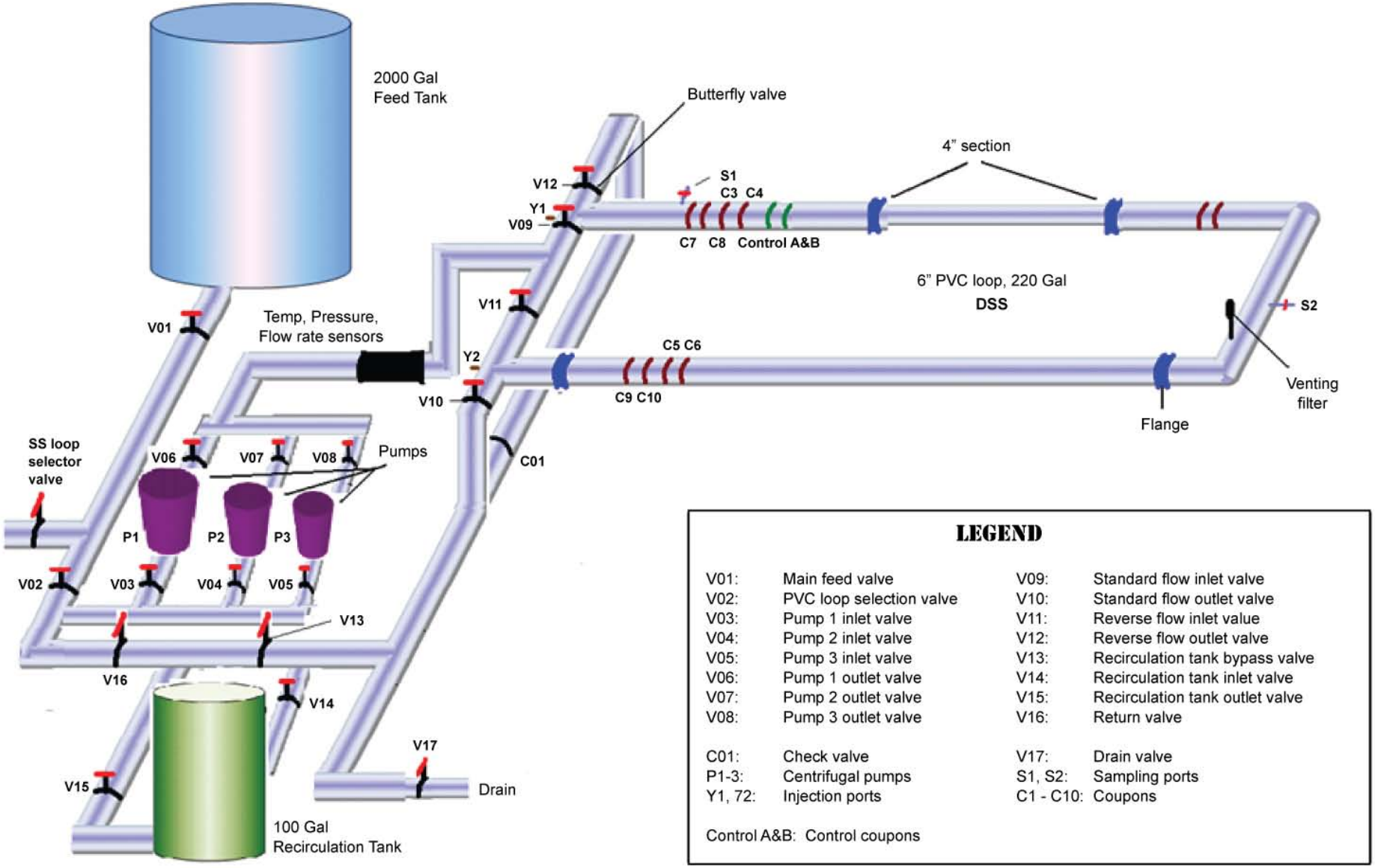
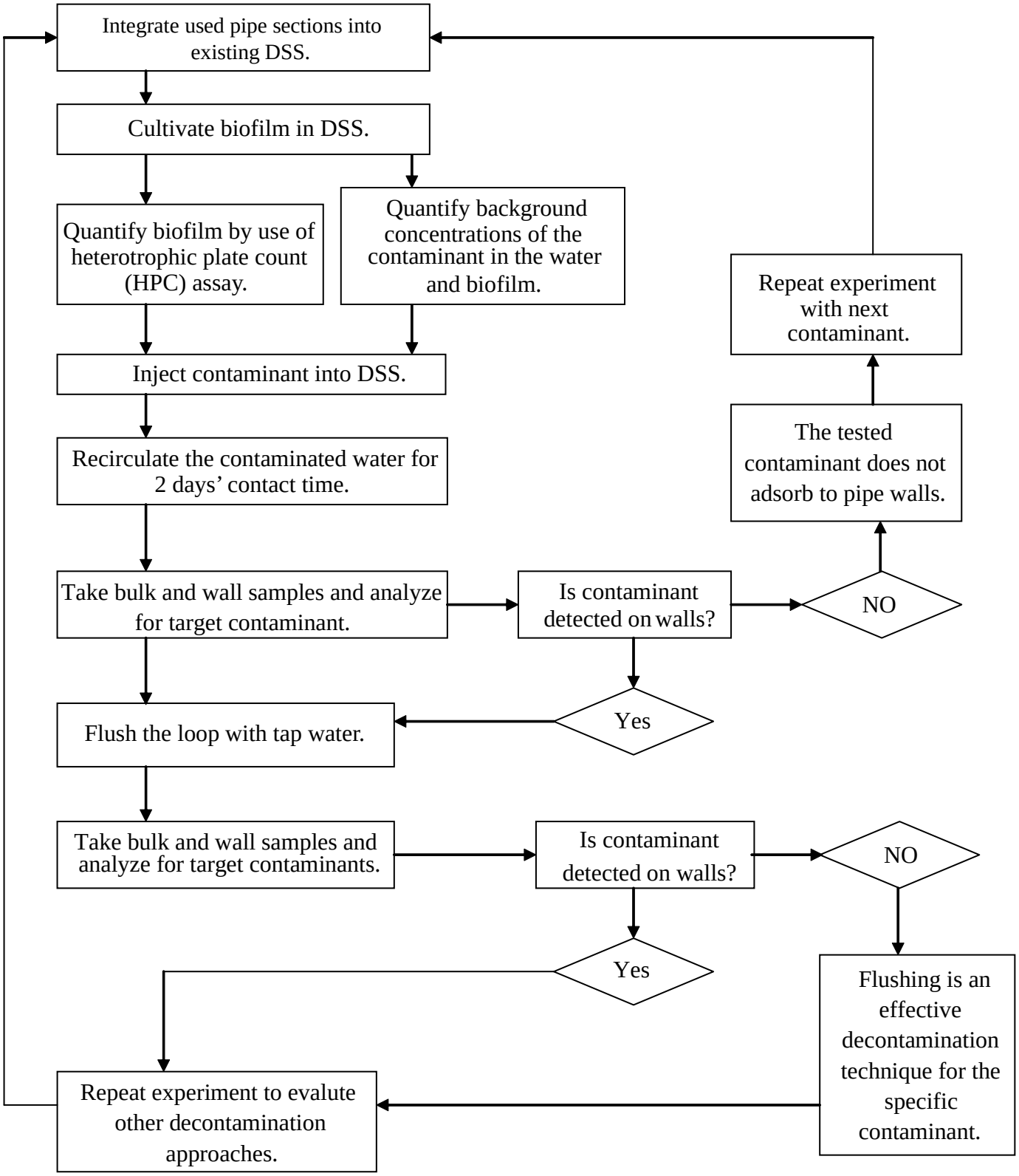


Figure 2-2 Photograph of Pipe Loop DSS Located at the EPA T&E Facility

Figure 2-3 Overall Experimental Strategy for Decontamination Pilot-Scale Tests



2.2 EXPERIMENTAL VARIABLES

Table 2-1 presents a list of primary experimental design parameters for conduct of the adherence/decontamination studies on arsenic, mercury, *Bacillus subtilis*, diesel fuel (No. 2), and chlordane.

Table 2-1 Experimental Design Parameters

Parameters	Selected Materials / Conditions	
Target contaminants	Sodium arsenite, mercuric chloride, *Bacillus subtilis*, diesel fuel (No. 2), chlordane	
Pipe material evaluated	Cement-lined ductile iron (from 5-year-old T&E Facility pipe loop system)	
Biofilm	Biofilm cultivated on pipe wall[a]	
DSS operating parameters	Flow mode: recirculation	
	Flow rates: 1, 15, 60 gallons per minute	
	Temperature: ambient high-bay temperature	
	pH: pH of Cincinnati tap water ~8.5	
	Free chlorine at start of study: ~1.0 milligram per liter (mg/L)	
Contact time for contaminant adherence study	2 days after injection of contaminant into pipe loop system	
Concentration of target contaminant within loop	10 mg/L of mercury, arsenic, and diesel fuel (No. 2), chlordane (as alpha+gamma chlordane, 40 mg/L as technical chlordane)	
	10^4 cells/mL of *Bacillus subtilis*	
Decontamination approaches evaluated	**Arsenic:**	Baseline water flushing (2.5 fps flow rate)
		Low-pH (i.e., pH 4) flushing
		Phosphate buffer flushing
		Acidified potassium permanganate flushing
		NSF Standard 60 Products flushing:
		NW-310/NW-400 flushing
		Floran Biogrowth Remover/Catalyst flushing
		Floran Top Ultra/Catalyst flushing
	Mercury:	Baseline water flushing (2.5 fps flow rate)
		Low-pH (i.e., pH 4) flushing
		Acidified potassium permanganate flushing
	Bacillus subtilis:	Baseline water flushing (2.5 fps flow rate)
		Shock chlorination
	Diesel fuel:	Baseline water flushing (2.5 fps flow rate)
		Surfonic TDA-6 flushing
	Chlordane:	Surfonic TDA-6 flushing

[a] Target Heterotrophic Plate Count (HPC) of greater than 10^4 colony forming units per square centimeter (CFU/cm^2).

The experimental test run ID and the corresponding flow rate, velocity, Reynolds number (Re), and decontamination approach are tabulated in Table 2-2.

Table 2-2 List of Test Run ID, Adherence Test Flow Rate, Velocity, Reynolds Number, and Decontamination Approach

Contaminant	Test Run ID	Adherence Test			Decontamination Approach
		Flow rate (gpm)	Velocity in 6" Diameter Pipe Section (fps)	Re in 6" Diameter Pipe Section	
Arsenic	As F1	1	0.011	521	Water flushing
	As F15	15	0.17	7808	Water flushing
	As F60	60	0.69	31232	Water flushing
	As pH4	60	0.69	31232	Low-pH flushing
	As Phos	60	0.69	31232	Phosphate buffer flushing
	As KMnO4	60	0.69	31232	Acidified potassium permanganate flushing
	As NW	60	0.69	31232	NW-310/NW-400 flushing
	As Floran I	60	0.69	31232	Floran Biogrowth Remover/ Catalyst flushing
	As Floran II	60	0.69	31232	Floran Top Ultra/Catalyst flushing
Mercury	Hg F1	1	0.011	521	Water flushing
	Hg F15	15	0.17	7808	Water flushing
	Hg F60	60	0.69	31232	Water flushing
	Hg pH4	60	0.69	31232	Low-pH flushing
	Hg KMnO4	60	0.69	31232	Acidified potassium permanganate flushing
Bacillus subtilis	BS F60	60	0.69	31232	Water flushing
	BS CT30K	60	0.69	31232	Shock chlorination
Diesel fuel (No. 2)	DRO F60	60	0.69	31232	Water flushing
	DRO TDA	60	0.69	31232	Surfonic TDA-6 flushing
Chlordane	ChLD TDA	60	0.69	31232	Surfonic TDA-6 flushing

2.3 CONTAMINANTS SELECTED FOR EVALUATION

Five contaminants were selected for the pilot-scale contamination/decontamination tests. The contaminants and a summary of their known behaviors in drinking water systems are provided in Table 2-3. These contaminants were chosen to represent common chemical and biological agents that are potential threats to the water supply as indicated in the table. Although chlordane was not initially selected for evaluation, because it is currently a banned chemical in the United States, it was later included to provide a comparison with the results from other laboratory-scale AwwaRF studies.

Table 2-3 Contaminants Selected for Study

Contaminant	Properties of Contaminant
Mercuric chloride (representing a heavy metal mercury)	o Water soluble o Fungicide
Sodium arsenite (representing an inorganic poison arsenic)	o Very water soluble o Chlorine oxidizes arsenite (AsO_2^-) to arsenate (AsO_4^{3-})
Bacillus subtilis (representing a biological spore or cell)	o *Bacillus subtilis* is a gram-positive, rod-shaped, and endospore-forming aerobic bacterium. It is found in soil and rotting plant material and is a GRAS (Generally Regarded as Safe) microorganism o Typical size: 2- to 3-micrometer (µm) length, 0.5-µm width o May be killed by chlorine
Diesel fuel (No. 2) (representing a sticky industrial organic contaminant)	o The major components: ➢ alkanes (estimated to be 65–85 percent by weight) ➢ alkenes (common in converted products such as catalytic cracker fractions) ➢ aromatics (estimated to be 10–30 percent by weight) o Very low water solubility o Significant tendency to adsorb to pipe surfaces o Does not degrade rapidly in water o Chlorination: unknown
Chlordane (representing a toxic organic chemical)	o Organochlorine insecticide: termite control o Use has been banned since 1988 o Very low water solubility: 0.056 mg/L o High log Kow: 6.0 o Very persistent and hard to remove o Does not degrade rapidly in water o Can exit aquatic systems by adsorbing to sediments or by volatilization o Volatilization half-life for chlordane in lakes and ponds is less than 10 days o Chlorination: unknown o Loses its chlorine in presence of alkaline reagents

2.4 PILOT-SCALE DRINKING WATER DISTRIBUTION SYSTEM SIMULATOR (DSS)

A pilot-scale clear polyvinyl chloride (PVC) DSS (refer to Figure 2-1 and Figure 2-2) was used in the decontamination study experiments. The main components of the clear PVC DSS are a 2000-gallon reservoir used to supply water to the PVC pipe loop, approximately 75 feet of clear PVC pipe (6-inch diameter except for a 4-inch-diameter section that is ~10 feet long), a 100-gallon recirculation tank (in line with the main pipe), water pumps, and the associated valves and electronic control devices necessary to operate the system. The total volume in the DSS (including the 100 gallons in the recirculation tank) is approximately 220 gallons. The interior surface area of the loop including the recirculation tank (available for adsorption) is approximately 25,000 square inches (in^2).

The whole DSS is of clear PVC pipe construction except for ten real-world pipe coupons (coupon #1 through coupon #10 in Figure 2-1). As shown in Figure 2-4, the real-world pipe coupons employed in the current study were machined out of used cement-lined ductile iron pipe sections scavenged from an old drinking water distribution simulator within the T&E Facility, which has been in service for five years. The cement-lined ductile iron pipes used in this study did not have an asphalt seal coat. They were originally purchased from U.S. Pipe and intended for use in drinking water distribution systems. Each coupon has a 6-inch inside diameter and is 1 inch in width. Two control coupons (control coupons A and B in Figure 2-1) were also integrated into the DSS during each experiment. These control coupons were cut from a clear PVC section. All twelve coupons were sacrificed after each run, and "new" coupons were reintegrated in the following test run.

The DSS is equipped with sensors that continuously measure the basic water quality parameters of pH, turbidity, free chlorine, conductivity, and oxidation-reduction potential (ORP). Total organic carbon (TOC) on grab samples was measured in the T&E Facility laboratory using a Teledyne Tekmar Phoenix 8000 TOC analyzer.

2.5 BIOFILM CULTIVATION

The unique clear PVC loop system at the T&E Facility was newly fabricated in 2003 and the pipes in the loop have been in limited service; therefore, there is little biofilm buildup on the inside surfaces. To effectively study the adsorption of contaminants on pipe walls, it is essential to ensure that there is a viable biofilm on the pipe wall surfaces. The biofilm could influence adsorption of the contaminant on the pipe wall and play a role in the metabolism, biodegradation, or detoxification of the contaminant.

Shaw conducted a review of the literature (Batte et al., 2003; Butterfield et al., 2002; Camper et al., 1996; Cloete et al., 2003; Chu et al., 2004; Hansen et al., 2002; Lawrence et al., 2000; Pozos et al., 2004; Wasche et al., 2002; Wijeyekoon et al., 2004) and identified a biofilm cultivation protocol for this study. Based on this protocol, a viable biofilm can be formed on the pipe surfaces within one to two weeks by augmenting the water in the loop with low concentrations of carbon, nitrate, and phosphate under laminar flow conditions.

According to this protocol, the DSS loop was used as a tubular reactor, and carbon, nitrate, and phosphate were introduced into the loop through the recirculation tank to result in final concentrations of 100 µg/L each of nitrate and phosphate and 1000 µg/L of carbon. The carbon source contained equimolar concentrations on the basis of carbon of acetate, sodium benzoate, propionaldehyde,

Figure 2-4 Cement-lined Ductile Iron Coupon (Real-World Pipe Coupon)

p-hydroxybenzoic acid and ethanol. Sodium nitrate and sodium phosphate were used as the source of nitrate and phosphate, respectively. The water was dechlorinated for the biofilm cultivation, and the water in the loop was recirculated using a centrifugal pump at a flow rate of 4 gpm.

During the biofilm cultivation, bulk water samples were collected on a daily basis and the daily bacterial growth in bulk water was monitored through heterotrophic plate count (HPC) analyses until it reached pseudo steady-state. One coupon sample was taken out of the system at steady-state for checking the extent of biofilm formation. The biofilm sample (scraped off the pipe wall) was suspended in sterile water, homogenized, and subjected to an HPC count to determine the formation of biofilm in the pipe walls. Based on the literature review, a bacterial cell count of 10^4 CFU/cm^2 or higher is considered to adequately represent a viable biofilm population in the pipe loop system.

Because the pipe sections in the DSS were made of clear PVC pipe, the interior of these sections was exposed to light, and it was likely that algae contributed to the biofilm content in the clear pipe section. However, the sections where coupons were located were covered by black rubber sleeves; therefore, a dark environment was provided for coupon samples, which would have reduced the growth of algae on the coupon surfaces. A comparison of biofilm composition for the clear pipe section vs. dark coupon section was out of the project scope, and such a comparison was not performed for this study.

Biofilm was cultivated on coupons after the coupons were installed in the clear PVC DSS, and the biofilm cultivation was conducted prior to each test.

2.6 INJECTION OF CONTAMINANTS

Each of the target contaminants was injected by use of a 1-L capacity pressurized (~20 psi) syringe fabricated at the T&E Facility for this purpose to reach a target contaminant concentration (10 mg/L for arsenic, mercury, diesel fuel, and alpha+gamma chlordane, and 10^4 cells/mL for *Bacillus subtilis*). Water-soluble chemicals, such as mercuric chloride and sodium arsenite, were dissolved in deionized water. (To maintain a reasonable injection volume, 1 liter of deionized water was used.) Diesel fuel (No. 2) and chlordane have limited solubility in water; however, they were also mixed in 1 liter of deionized water for consistency. *Bacillus subtilis* was suspended in the growth medium (i.e., Tween 20) in which it was prepared. The concentrated contaminant solution was injected into the PVC pipe loop through the injection port shown on Figure 2-1, using the pressurized syringe.

2.7 DSS OPERATING CONDITIONS

The DSS was operated in a recirculation mode for prolonged contact with the contaminant. Shaw performed experiments in both laminar and turbulent flow ranges. Shaw performed some calculations to estimate the effect of pipe diameter and flow rate on contaminant mass transfer coefficients, which reflect the rate at which a constituent would be transported from the bulk phase to the pipe wall. These calculations show that the mass transfer coefficients increase with Reynolds Number (Re). The flow is laminar if Re < 2300, transient in the range 2300 < Re < 4000, and turbulent when 4000 < Re. The flow rates that Shaw tested in the adherence tests included 1 gpm, 15 gpm, and 60 gpm. The water was at ambient temperature (13–32 °C), and the pH was the same as Cincinnati tap water (~8.5). The flow rates and the basic water quality parameters were monitored continuously during the experiments.

The DSS design permits direct control over only the flow rate and the chlorine level. For these experiments, flow was set at one of the three rates by adjusting the pump speed to achieve the desired flow rate as measured by the electronic flow meter (magnetometer) installed in the loop. The chlorine level was set to 1.0±0.1 mg/L prior to injection by manually adjusting the chlorine level in the feed tank and monitoring the concentration by use of the ATI A15/62 free chlorine meter.

Temperature, pH, turbidity, and all other water quality parameters were not controlled.

2.8 SAMPLING METHODOLOGY

Coupon samples and samples of the bulk liquid and were collected for each test run. All liquid samples were collected as grab samples at the liquid sampling port shown in Figure 2-1. For each test run, duplicate liquid samples were collected for contaminant analyses during and/or after each adherence and decontamination test. Duplicate coupon samples were collected at each location to meet the quality control (QC) duplication requirement. The bulk liquid samples provide an indication of the concentration of the contaminant in the bulk water. The coupon samples provide the most useful information for this study.

Ten used-pipe coupon sample locations are identified in Figure 2-1. Assuming fast and complete mixing of injected contaminants within the loop, operation in the recirculation mode creates an equal opportunity for adsorption of the contaminant anywhere on the ten coupons. Four of the coupons are located within 3 feet of the injection point. The other set of coupons are located 52 feet from the injection point.

The sampling schedule for each test run is outlined in Table 2-4. There were three sampling events for each injection of a contaminant: two coupon samples were collected just prior to contaminant injection to establish the baseline concentration of the contaminant on the walls (coupon #1) and determine biofilm availability (coupon #2) before addition of chlorine to the DSS, four coupon samples were sacrificed after a contact period of two days to determine adherence on the pipe walls, and the remaining four coupon samples were sacrificed after employing a specific decontamination procedure to quantify residual contaminant on the pipe walls. Two control coupons (A and B) cut from a clear PVC section were sampled after the two-day contact period for the analyses of the target contaminant on the PVC pipe loop material.

Sensors installed on the DSS provided continuous measurements of basic water quality parameters, i.e., pH, turbidity, free chlorine, conductivity, and ORP. These parameters can provide an indication of the fate of the injected species and the effect on the chemistry of the drinking water. For example, free chlorine demand and ORP will provide evidence of reactions that are occurring, and specific conductance may detect the presence of dissolved inorganic species. TOC analyses were performed manually using grab samples. TOC analyses can provide evidence on the fate of an organic contaminant. These basic measurements minimize the need for expensive laboratory analyses during the two-day contact period. Sensor data were continuously logged during all experimental phases by use of an existing supervisory control and data acquisition (SCADA) system.

Table 2-4 Sampling Schedule for Various Phases of Testing

Event		Time	Location	Sample Number and Type, Including QC	Purpose of Measurement	Continuously Monitored Parameters
Baseline		Just prior to injection	Coupon #1 and #2	Coupon #1	Background: contaminant on walls	pH, ORP, Specific conductance, Free chlorine, Total chlorine, Turbidity
				Coupon #2	Quantify biofilm development	
			Liquid sampling port	Duplicate water samples (grab)	Background: contaminant in liquid phase	
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	Liquid sampling port	Duplicate water samples (grab)	Verify presence of contaminant in the loop	pH, ORP, Specific conductance, Free chlorine, Total chlorine, Turbidity
		1 day after injection	Liquid sampling port	Duplicate water samples (grab)	Determine fate of injected contaminant	
		2 days after injection	Liquid sampling port	Duplicate water samples (grab)	Determine fate of injected contaminant	
	After 2-day contact period	After draining loop	Control coupon	Control coupon A	Comparison to adherence of the same contaminant on PVC pipe loop material	Not applicable
				Control coupon B	Duplicate	
			Coupon #3, #4	Coupon #3	Contaminant on pipe wall	
				Coupon #4	Duplicate	
			Coupon #5, #6	Coupon #5	Contaminant on pipe wall	
				Coupon #6	Duplicate	
Decontamination Study		Prior to draining loop	Liquid sampling port	Duplicate water samples (grab)	Presence of contaminant in decontamination fluid	pH, ORP, Specific conductance, Free chlorine, Total chlorine, Turbidity
		After draining loop	Coupon #7, #8	Coupon #7	Contaminant on pipe wall	Not applicable
				Coupon #8	Duplicate	
			Coupon #9, #10	Coupon #9	Contaminant on pipe wall	
				Coupon #10	Duplicate	

TOTAL SAMPLE COUNT PER TEST RUN:	**12 COUPON SAMPLES AND 10 WATER SAMPLES**

2.9 SAMPLE EXTRACTION AND ANALYSES

The DSS was drained prior to removing the coupons. Once drained, the coupons were removed from the DSS and immediately rinsed with deionized water with the aid of a squirt bottle. This step was necessary to remove contaminated water that might still be in contact with the coupon. Each coupon was placed in a small glass casserole dish. The interior surface of ductile iron pipes is primarily composed of rust and biofilm. The extraction procedure was designed to remove both of these layers to maximize recovery.

Biofilm was scraped off the coupon with a sterilized toothbrush, using autoclaved water. The extraction solvent was recovered by pouring the contents of the dish into an 8-ounce autoclave glass jar. The biofilm was quantified by use of a bacterial counting technique. The HPC method (Standard Method 9215 B) was modified as specified in the Hach test kits based on the SimPlate™ Technique for HPC developed by IDEXX Laboratories, Inc. This IDEXX HPC method was approved by EPA on October 29, 2002, as found in 40 CFR Part 141.

Arsenic/mercury was extracted from the coupon surface by physical scrubbing with a toothbrush, using 10% (w/v) nitric acid solution and deionized water. The extraction solvent was recovered by pouring the contents of the dish into a 1L HDPE sample bottle with appropriate preservative (nitric acid for arsenic and mercury samples). The bulk liquid and coupon extraction fluid samples were submitted to a commercial laboratory [Severn Trent Laboratories (STL)] to perform the sample analyses on arsenic/mercury. Arsenic was analyzed by inductively coupled plasma (ICP) according to U.S. EPA methods SW 846 3005A/6010B. Mercury was analyzed by atomic absorption (AA) according to U.S. EPA method SW 846 7470A.

Bacillus subtilis was extracted from the coupon surface by physical scrubbing with a toothbrush, using autoclaved water. The extraction solvent was recovered by pouring the contents of the dish into a 250-mL sterile sample bottle with appropriate preservative (sodium thiosulfate). In analyzing for spores, the bulk liquid and coupon extraction fluid samples were subjected to heat treatment to inactivate the indigenous vegetative bacterial cells. During the heat treatment, the hot water bath was filled with 50:50 deionized water and tap water, and the temperature was set at 90 °C. *B. subtilis* samples, along with positive and negative controls, were introduced into the water bath and incubated for a period required to reach the bath water temperature of 80 °C, followed by an additional 12 minutes of incubation time after the water temperature reached 80 °C. Positive and negative controls were prepared by spiking sterile buffer with *B. subtilis* and *E. coli*, respectively. The absence of any colonies for negative control confirms the effectiveness of heat shock. The recovery of *B. subtilis* from positive control confirms the viability of injection suspension. The surviving bacterial spores in the samples were filtered through a 0.45 μm membrane filter and analyzed by cultural methods that permit the spore to germinate and produce bacterial cells. A detailed description on the quantification of *Bacillus subtilis* in water samples is provided in the Standard Operation Procedure (SOP) for Enumeration of *Bacillus subtilis* Water Samples (SOP No.: T&E SOP 021.00.R0), which was developed by Shaw in August 2005.

Diesel fuel was extracted from the coupon surface by physical scrubbing with a brass brush, using 250 mL of methylene chloride/acetone (1:3 volume ratio) mixture and 250 mL of acetone. The extraction solvent was recovered by pouring the contents of the dish into a 1-L amber glass sample bottle with appropriate preservative (sodium thiosulfate). The bulk liquid and coupon extraction fluid samples were submitted to a commercial laboratory (DataChem Laboratories) to perform the sample analyses on Diesel Range Organics (DRO).

The term "diesel fuel" incorporates a broad range of petroleum products that vary significantly in chemical composition. The major components of diesel fuel include alkanes (estimated to be 65 to 85 percent by weight), alkenes (common in converted products such as catalytic cracker fractions), and aromatics (estimated to be 10 to 30 percent by weight of No. 2 diesel fuel). When assessing the nature and extent of contamination by diesel fuel, it is important to use analytical methodologies that distinguish the diversity and complexity of diesel fuel's chemical components. Determination of diesel fuel components by gas chromatography is well established in the petroleum industry and environmental community. This method enables the elimination of interferences and provides both qualitative and quantitative information on the chemical components of diesel fuel. DRO was analyzed by GC/FID according to U.S. EPA method SW 846 8015B.

Chlordane was extracted from the coupon surface by physical scrubbing with a brass brush, using 250 mL of a hexane/acetone (1:3 volume ratio) mixture and 250 mL of acetone. The extraction solvent was recovered by pouring the contents of the dish into a 1-L amber glass sample bottle with appropriate preservative (sodium thiosulfate). The bulk liquid and coupon extraction fluid samples were submitted to a commercial laboratory (STL) to perform the sample analyses on chlordane. Chlordane was analyzed by GC/ECD according to U.S. EPA Method SW 846 3520/8081A.

Technical chlordane consists of over 50 compounds, including the stereoisomers *cis*- and *trans*-chlordane, chlordane, heptachlor, and nanochlor (Howard, 1991). *Cis*-chlordane (lα,2α,3aα,4ß,7ß,7aα) is also known as alpha-chlordane; *trans*-chlordane (1α,2ß,3aα,4ß,7ß,7aα) is commonly known as gamma-chlordane. For chlordane sample analyses, laboratories usually analyze for these two isomers as well as the concentration of total technical chlordane.

2.10 DECONTAMINATION APPROACH

Based on the literature review, Shaw selected several decontamination technologies for each target contaminant to evaluate their decontamination effectiveness and associated testing issues. The decontamination methods evaluated in this research included both physical (e.g., water flushing) and

chemical (e.g., low-pH flushing, potassium permanganate flushing, etc.) cleaning processes. As water flushing is the most cost-effective and most widely used technique, this was the baseline decontamination method in the research program. Shaw coordinated with AwwaRF to ensure that effective decontamination techniques identified in the AwwaRF laboratory-scale studies were given priority.

2.10.1. Decontamination of Arsenic

Various decontamination techniques were evaluated to investigate removal of arsenic from the pilot-scale water distribution system. As mentioned above, the first (baseline) decontamination method applied was simple water flushing. The simple flushing approach consisted of recirculating tap water within the DSS at a high flow rate of 210 gpm (corresponding to 2.5 fps for 6-inch diameter pipe) for a duration of two hours.

Shaw performed a literature review to identify other potential decontamination techniques for arsenic. Low-pH flushing and phosphate buffer flushing were identified as alternative decontamination approaches. Low-pH conditions can increase the solubility of metals in water; therefore, low-pH flushing was expected to increase the removal of arsenic from the drinking water pipe surfaces (Ellison et al, 2002). The low-pH flushing approach consisted of recirculating low-pH water (i.e., pH 4, adjusted by hydrochloric acid) within the DSS at a flow rate of 60 gpm (corresponding to 0.7 fps for 6-inch diameter pipe) for a duration of four hours, followed by simple water flushing at a flow rate of 210 gpm for a duration of ten minutes in a single-pass mode.

Phosphate buffer has been proven to be effective for extraction of arsenic from sediment and/or soil samples (Bruce and Martens, 1997; Gonzalez et al, 2003). Arsenic (V) anions ($H_2AsO_4^-$ and $HAsO_4^{2-}$) form strong surface complexes at the mineral-water interfaces and undergo ligand exchange with $H_2PO_4^-$ and HPO_4^{2} -anions. The phosphate buffer flushing approach consisted of recirculating 1 mM phosphate buffer solution (50:50 KH_2PO_4:K_2HPO_4) within the DSS at a flow rate of 60 gpm (i.e., 0.7 fps for 6-inch diameter pipe) for a duration of four hours, followed by simple water flushing at a flow rate of 210 gpm for a duration of ten minutes in a single-pass mode.

The fourth decontamination approach used for arsenic was acidified potassium permanganate flushing. Acidified potassium permanganate is a very strong oxidant that is widely used in the metal sample digestion. It can significantly increase the solubility of metals. Also, acidified potassium permanganate can destroy biofilm in the drinking water distribution system. Bench-scale drinking water pipe decontamination studies conducted by Battelle confirmed the high removal efficiency of acidified potassium permanganate flushing for mercury from various types of drinking water pipe surfaces (Chattopadhyay and Fox, 2006). Therefore, it was speculated that this method would also be effective in removal of arsenic from cement-lined ductile iron pipe surfaces. The acidified potassium permanganate flushing approach consisted of recirculating an acidified potassium permanganate (1% sulfuric acid/0.4% potassium permanganate) solution within the DSS at a flow rate of 60 gpm for a duration of four hours, followed by simple water flushing at a flow rate of 210 gpm for a duration of ten minutes in a single-pass mode.

Besides the aforementioned chemical decontamination techniques, some commercially available decontamination reagents were also evaluated for their effectiveness in removal of arsenic from the pilot-scale water distribution system. NSF Standard 60 Products were identified as the potential decontamination reagents for this evaluation. The NSF Standard 60 Drinking Water Treatment chemicals are environmentally friendly products that have successfully been used in drinking water treatment to stabilize water quality and extend the lifetime of valuable infrastructure (NSF Product and Service Listing, 2006). Various NSF Standard 60 Pipe Cleaning Aid Products are available in the market. After contacting all of the NSF-certified manufacturers/vendors, Shaw identified and procured three different combinations of NSF Standard 60 products, i.e., NW-310/NW-400 (manufactured by Johnson Screens, Inc.), Floran Biogrowth Remover/Catalyst, and Floran Top Ultra/Catalyst (manufactured by Floran Technologies, Inc.) as representative decontamination reagents for arsenic. These pipe-cleaning aid products are being used in commercial applications for cleaning of drinking water pipes and/or wells. Accordingly, experiments were conducted using NSF Standard 60 Pipe Cleaning Aid Products as the potential decontamination approach to removing arsenic from water distribution systems.

In the NW-310/NW-400 flushing experiment, after the two-day contact period of contaminant adherence, the PVC pipe loop was refilled with fresh tap water. About 5.5 gallons (2.8 liters) of NW-310 and 0.2 gallons (0.7 liters) of NW-400 were then poured into the recirculation tank to reach the final concentration of NW-310 and NW-400 in the loop (about 3 percent and 0.1 percent by weight, respectively). The water containing NW-310/NW-400 was then recirculated in the loop for six hours at a flow rate of 60 gpm. Upon completion of the NW-310/NW-400 water recirculation, the pipe loop was drained. This was followed by simple water flushing of the system at 210 gpm for ten minutes in a single-pass mode. Coupon samples were taken and analyzed for contaminants after the decontamination to investigate the decontamination efficiency of this technique.

Two separate decontamination tests were conducted using the combination of Floran Technologies Products, Biogrowth Remover/Catalyst, and Top Ultra/Catalyst. During each test run, about 1.1 gallons of each component (Biogrowth Remover/Catalyst or Top Ultra/Catalyst) were poured into the recirculation tank to reach the final concentration of each component in the loop, i.e., 0.5% by volume. According to the manufacturer's suggestion, the flow should be ceased upon complete mixing of each component in the loop, and an overnight incubation time should be provided at zero flow rate. However, in the course of the decontamination test with Biogrowth Remover/Catalyst, a significant amount of foam was produced during the incubation with stagnant

loop water, which resulted in an overflow of the recirculation tank. Therefore, for this test scenario, a flow rate of 25 gpm was provided during the incubation. Upon completion of the incubation, the pipe loop was drained, followed by simple water flushing of the system at 210 gpm for ten minutes in a single-pass mode. Coupon samples were taken and analyzed for contaminants after the decontamination to investigate the decontamination efficiency of these techniques.

2.10.2. Decontamination of Mercury

Three types of decontamination methods were evaluated for removal of mercury from drinking water distribution systems: (baseline) water flushing, low-pH flushing, and acidified potassium permanganate flushing. The procedure for each decontamination method used for mercury was the same as that used for arsenic, as described in Section 2.10.1. The selection of these three decontamination techniques was based on Shaw's literature review and the test results from AwwaRF's laboratory-scale studies and Battelle's bench-scale studies (Welter et al., 2006; Chattopadhyay and Fox, 2006). Simple water flushing was tested as the baseline decontamination approach. Low-pH flushing was chosen based on the literature review (Ellison et al, 2002). The acidified potassium permanganate decontamination method was proven very effective in removal of mercury from the drinking water pipe surfaces in Battelle's bench-scale studies (Chattopadhyay and Fox, 2006) and hence was applied in the pilot-scale mercury decontamination test.

2.10.3. Decontamination of Bacillus subtilis

Two decontamination approaches were evaluated in this study to investigate removal of *Bacillus subtilis* from water distribution systems: baseline simple water flushing and shock chlorination. The procedure for baseline water flushing is described in Section 2.10.1.

Shock chlorination is a very traditional method used to inactivate microorganisms and surrogates in drinking water systems. Rose et al. (2005) and Rice et al. (2006) studied chlorine inactivation of various bacterial agents under different Chlorine Concentration X Contact Time (CT) conditions. It was reported that 2–3 log removal of *Bacillus* species was achieved using shock chlorination. The mean CT values for *Bacillus globigii* (from hundreds to thousands) were higher than the mean values of the other *Bacillus* species tested (*i.e., anthracis, cereus, and thuringiensis*). Whitney et al. (2003) performed a literature review on the various techniques for the inactivation of *Bacillus* spores, and they reported 4 log removal of *Bacillus subtilis* using 0.05% of sodium hypochlorite at pH 7 at 20 °C with 30 minutes contact time. AwwaRF's laboratory-scale decontamination test on *Bacillus thuringiensis* indicated that shock chlorination with a CT value of 30,000 mg/L-min achieved less than 2 log removal of *Bacillus thuringiensis* from the old, heavily tuberculated galvanized pipe surfaces (Welter et al., 2006). The significantly high CT value from the AwwaRF study demonstrates the challenge associated with decontamination of microbial contaminants from the pipe surfaces as compared to removal from bulk water.

Based on the literature review results, Shaw applied the shock chlorination decontamination approach to inactivate *Bacillus subtilis* from the cement-lined ductile iron pipe surfaces using a CT value of 30,000 mg/L-min. The shock chlorination approach consisted of flushing the DSS with an increased chlorine concentration (i.e., free chlorine concentration of 200 mg/L) at a flow rate of 60 gpm (i.e., 0.7 fps in 6-inch pipe) in a recirculation mode for a duration of 2.5 hours to reach a CT value of 30,000 mg/L-min, followed by simple water flushing at a flow rate of 210 gpm (i.e., 2.5 fps in 6-inch pipe) for a duration of ten minutes in a single-pass mode.

2.10.4. Decontamination of Diesel Fuel

Two different decontamination methods, simple water flushing and surfactant flushing, were investigated for removal of diesel fuel from drinking water pipe surfaces. Simple water flushing was tested as the baseline decontamination method.

The surfactant, Surfonic TDA-6, was identified based on AwwaRF's laboratory-scale test conducted on chlordane (Welter et al., 2006). The AwwaRF study indicated that Surfonic TDA-6 is a very effective surfactant for removing chlordane from the drinking water pipe surfaces. Therefore, Surfonic TDA-6 was applied during the current pilot-scale decontamination of diesel fuel from the drinking water pipe surface. The Surfonic TDA-6 flushing consisted of flushing the pilot-scale DSS with 5% Surfonic TDA-6 solution at a flow rate of 60 gpm (i.e., 0.7 fps in 6-inch pipe) in a recirculation mode for a duration of 24 hours, followed by simple water flushing at a flow rate of 210 gpm (i.e., 2.5 fps in 6-inch pipe) for a duration of 10 minutes in a single-pass mode.

2.10.5. Decontamination of Chlordane

The chlordane decontamination study was performed using Surfonic TDA-6 as the decontamination agent. A large variety of surfactants were screened initially in the AwwaRF's bench-scale decontamination study (Welter, et al., 2006) by a simple procedure to test their ability to dissolve chlordane. Based on the initial screening of surfactants, the AwwaRF Project Team identified three surfactants — Surfonic TDA-6, Surfonic N-60, and Empicol LZV — for further testing in their bench-scale pipe decontamination protocol. The test results indicated that Surfonic TDA-6 and Surfonic N-60 are the most promising decontamination reagents for removal of chlordane from various types of pipe surfaces. Surfonic N-60 was out of stock from the manufacturer's (Huntsman Petrochemical Corporation) warehouse during Shaw's scheduled test for chlordane. Therefore, Surfonic TDA-6 was selected for testing in the pilot-scale chlordane decontamination study. The Surfonic TDA-6 flushing protocol for chlordane was identical to that employed for diesel fuel as described in the previous subsection.

3.0 Results and Discussions

3.1 PRELIMINARY TEST RESULTS ON COUPON SAMPLE EXTRACTION

To quantify the contaminant recovery from the proposed sample extraction procedure, Shaw conducted an independent bench-scale study in which two real-world cement-lined ductile iron pipe coupons were exposed to 50 mg/L of arsenic/mercury diluted in 15 gallons of dechlorinated water in a stainless steel container. The coupons were separately exposed to arsenic/mercury for two days. The water was continuously stirred during this period. After the two-day contact time, coupon samples were removed from the system and collected for arsenic/mercury analyses. The coupon samples were subjected to the same sampling and extraction procedures that would be applied in the pilot-scale decontamination experiments. Duplicate bulk water samples were also collected in the beginning and at the end of the experiment for arsenic/mercury analyses. Based on a mass balance calculation on the bench-scale procedure, the arsenic/mercury recovery efficiency of the extraction procedure could be determined. Table 3-1 presents the experimental results obtained from the bench-scale experiment. As can be seen from the table, the proposed sampling and extraction procedure recovered 67 percent and 68 percent of arsenic and mercury, respectively, from the coupons. It was assumed that arsenic/mercury removed from the bulk solution was all adsorbed to the coupons. As the project objectives could be met with such high recoveries, Shaw applied this extraction procedure during the pilot-scale experiments.

3.2 PILOT-SCALE CONTAMINATION/ DECONTAMINATION TEST RESULTS

3.2.1. Biofilm Cultivation

To simulate the real-world drinking water distribution system pipe conditions, biofilm was cultivated on the inner surfaces of the pilot-scale DSS prior to each adherence/decontamination test, using the Shaw-developed biofilm cultivation protocol. During the period of biofilm cultivation, bulk water samples were collected on a daily basis to monitor the daily bacterial growth in bulk water through HPC analyses until it reaches pseudo steady-state. One coupon sample was taken out of the system at steady-state for the confirmation of biofilm formation. A bacterial cell count of 10^4 CFU/cm^2 was considered satisfactory for coupons to be used in the following adherence/decontamination tests.

It was observed from the HPC analytical results that the bacterial cell counts all exceeded the recommended limit for viable biofilm growth (HPC levels ranged between 10^4 CFU/cm^2 and 10^6 CFU/cm^2) after one to two weeks of biofilm development in the system, indicating that a viable biofilm was developed prior to the injection of contaminant for each test run.

As mentioned previously, specific nutrients were added to loop water to enhance the growth of general heterotrophic bacteria. Dr. Anne Camper of Montana State University (Camper, et al, 1996) provided the project team with the recommendation that water with a C:P:N ratio of 1000:100:100 µg per liter be used to enhance the growth of heterotrophic bacteria and a minimum of 10^4 CFU/cm^2 of HPC be cultivated for confirmation of satisfactory biofilm development. This guideline was used as general criteria for biofilm cultivation and contaminant adherence. Nutrients were added to achieve a representative biofilm for contaminant adherence within a short time. The addition of nutrients may have caused growth of certain selective organisms, but it was beyond the scope of the study to identify the profile of the biofilm. Since the loop system was decontaminated after each adherence event, the biofilm thickness was minimized.

Table 3-1 Arsenic/Mercury Recovery From the Bench-Scale Experiments

	Initial contaminant concentration in bulk water (mg/L)	Final contaminant concentration in bulk water (mg/L)		Contaminant adsorbed to coupon surface (mg/coupon)		% adsorption (calculation based on bulk water mass balance)[a]	% adsorption (based on sampling and analytical measurements on the coupon)[b]	% extraction recovery[c]
		Sample 1	Sample 2	Coupon 1	Coupon 2			
Arsenic	52.4	39.6	37.3	324	194	27%	18%	67%
Mercury	49.2	10.9	11.5	812	637	77%	53%	68%

[a] % adsorption = {[Initial concentration in bulk water (mg/L)] - [Final concentration in bulk water (mg/L)]} / [Initial concentration in bulk water (mg/L)] *100

[b] % adsorption = [Mass of contaminant adsorbed to coupon surface (measured)] / [Initial mass of contaminant in bulk water] *100

[c] % extraction recovery = [% adsorption (based on sampling and analytical measurements on the coupon)] / [% adsorption (calculated based on bulk water mass balance)] *100

In the first pilot-scale test run (Run ID: As F1), the free chlorine level in the water flowing to the DSS was set at 1.1 mg/L just prior to the injection of arsenic by manually adjusting the chlorine level in the supply water and monitoring the concentration by use of the ATI free chlorine meter. However, it was observed that immediately after introducing the supply water into the pipe loop, the free chlorine decreased to 0.70 mg/L, eventually stabilizing around 0.30 mg/L before injection. This is due to the high chlorine demand in the DSS from the biofilm developed in the loop. As a result, for the first test run, the initial free chlorine level for the arsenic adherence study was 0.3 mg/L, which was lower than the target level of 1.0±0.1 mg/L free chlorine level (as planned originally). To resolve this problem, for the second test run (Run ID: As F15), after one to two weeks of biofilm cultivation in dechlorinated water, the pipe loop water was drained and refilled with supply water with free chlorine of ~1.0 mg/L to condition the biofilm in high chlorine water before injection. The pipe water was partially recirculated until the free chlorine in the loop was stabilized at 1.0±0.1 mg/L, which took two to three days. In order to ensure that the biofilm was not damaged by exposure to high chlorine water, one coupon sample was taken out for HPC analysis after the conditioning of biofilm in high-chlorine water. It was observed that the HPC counts per unit surface area of the coupon decreased slightly (from 2.2×10^5/cm^2 to 1.8×10^5/cm^2) but remained above the recommended limit for viable biofilm growth. This was confirmed in another test run (Run ID: As F60) in which the HPC counts on the coupon surface reduced from 7.0×10^5/cm^2 to 1.1×10^5/cm^2 after chlorination. Therefore, all the following test runs were performed according to this adjusted biofilm cultivation strategy.

3.2.2. Pilot-scale Contaminant Adherence Test Results

3.2.2.1. Arsenic Adherence Test Results

Arsenic adherence tests were conducted at three different flow rate conditions, (incorporating both the laminar and turbulent flow regime) using the pilot-scale clear PVC DSS to evaluate the effect of flow rate on the adsorption of arsenic on the drinking water pipe surfaces.

The analytical results for the bulk water and coupon samples collected from the pilot-scale adherence studies for arsenic at the three different flow rates are summarized in Tables 3-2, 3-3, and 3-4, respectively. The analytical data for each test run is also presented in Appendix A.

The bulk water sampling port is located approximately 35 feet downstream of the contaminant injection port. Therefore, the time taken for the arsenic to reach the sampling port varied with the different flow rates applied as shown by concentrations in bulk water samples collected five minutes after contaminant injection. However, for all three scenarios, it showed complete contaminant mixing in the pipe loop system one day after injection, as shown by the target arsenic concentration in the bulk water at this time point.

Prior to the experiment, there was concern that the adsorptive properties of the PVC pipe within the DSS might swamp the contaminants in water at an initial contaminant concentration of 10 mg/L. Therefore, the bulk water samples were collected at the designated intervals during the experiments to reveal whether the contaminant was in contact with the coupons. This information ensures that the coupons are exposed to the contaminant during the two-day contact period. As can be seen from Tables 3-2, 3-3, and 3-4, the presence of the contaminants in the bulk water samples collected just prior to the conclusion of each adherence experiment (i.e., two days after the injection) confirmed the availability of contaminant within the system.

The arsenic analytical measurements on the coupons were converted to mass of arsenic adsorbed per unit surface area of the coupon (mg/in^2) based on the surface area of each coupon sample (19 in^2). The results are presented in Figure 3-1 for the three different flow rates that were investigated in the study. Although the deposition of arsenic on individual coupons varied, the experimental results indicate that arsenic adsorbs to cement-lined ductile iron pipe surfaces regardless of the velocities of the water flow. However, as can be seen from the figure, the amount of arsenic that adsorbs to the cement-lined ductile iron pipe surfaces increases with flow rate, with the highest adherence at the flow rate of 60 gpm evaluated in this study. This is possibly due to the increased mass transfer coefficients at higher flow rates. The figure also shows that the effect of coupon locations within the DSS on the arsenic adsorption capacity is not very obvious. In lower flow rate conditions (i.e., for flow rates of 1 gpm and 15 gpm), the coupons closer to the injection port tended to have more arsenic deposition than the coupons farther from the source; while the opposite result was observed for the higher flow rate (i.e., 60 gpm). However, overall, the effect of coupon location on the arsenic adherence on cement-lined ductile iron pipe surfaces is not very significant, indicating complete contaminant mixing under recirculation condition in the pipe loop during the two-day contact time. It can also be seen in Figure 3-1 that arsenic has a stronger tendency to adsorb to the surfaces of cement-lined ductile iron pipe than to the PVC surfaces.

Table 3-2 Experimental Results From Test Run ID: As F1 (Adherence Test Flow Rate: 1 gpm)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Arsenic concentration (mg/L)	Coupon ID	Arsenic concentration (mg/coupon)
Baseline		Just prior to injection	As F1 T0	ND	Coupon #1	0.029
			As F1 T0 Dup	ND	Coupon #2[a]	4.3 x10^5 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	As F1 T5M	ND		
			As F1 T5M Dup	ND		
		1 day after injection	As F1 T1D	10.4		
			As F1 T1D Dup	8.7		
		2 days after injection	As F1 T2D	9.6		
			As F1 T2D Dup	9.5		
	After 2-day contact period	After draining loop			Control coupon A	0.24
					Control coupon B	0.097
					Coupon #3	1.0
					Coupon #4	2.1
					Coupon #5	1.5
					Coupon #6	1.6

[a] Coupon #2 was taken for HPC analysis to check the biofilm development.

Table 3-3 Experimental Results From Test Run ID: As F15 (Adherence Test Flow Rate: 15 gpm)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Arsenic concentration (mg/L)	Coupon ID	Arsenic concentration (mg/coupon)
Baseline		Just prior to injection	As F15 T0	0.0042	Coupon #1	0.052
			As F15 T0 Dup	0.0034	Coupon #2[a]	1.8 x10^5 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	As F15 T5M	2.6		
			As F15 T5M Dup	1.6		
		1 day after injection	As F15 T1D	9.3		
			As F15 T1D Dup	9.3		
		2 days after injection	As F15 T2D	9.3		
			As F15 T2D Dup	9.3		
	After 2-day contact period	After draining loop			Control coupon A	0.37
					Control coupon B	0.18
					Coupon #3	2.1
					Coupon #4	2.8
					Coupon #5	0.81
					Coupon #6	1.5

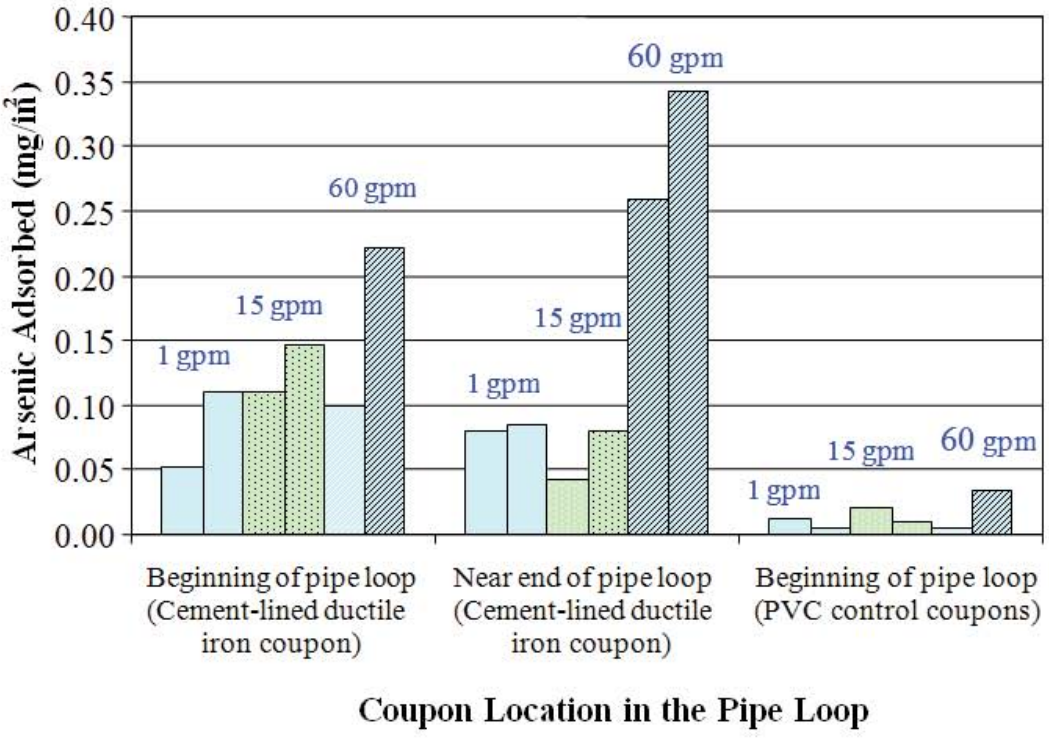
[a] Coupon #2 was taken for HPC analysis to check the biofilm development.

Table 3-4 Experimental Results From Test Run ID: As F60 (Adherence Test Flow Rate: 60 gpm)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Arsenic concentration (mg/L)	Coupon ID	Arsenic concentration (mg/coupon)
Baseline		Just prior to injection	As F60 T0	0.0036	Coupon #1	0.024
			As F60 T0 Dup	0.0052	Coupon #2[a]	1.1 x10^5 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	As F60 T5M	9.6		
			As F60 T5M Dup	10.4		
		1 day after injection	As F60 T1D	9.5		
			As F60 T1D Dup	8.8		
		2 days after injection	As F60 T2D	8.9		
			As F60 T2D Dup	8.9		
	After 2-day contact period	After draining loop			Control coupon A	0.11
					Control coupon B	0.64
					Coupon #3	1.9
					Coupon #4	4.2
					Coupon #5	4.9
					Coupon #6	6.5

[a] Coupon #2 was taken for HPC analysis to check the biofilm development.

Figure 3-1 Arsenic Adherence Study Results (Flow Rates: 1, 15, 60 gpm)



Also monitored were basic water quality parameters, including TOC, pH, ORP, free chlorine, turbidity, conductivity, and temperature. As expected, free chlorine readings decreased upon injection of sodium arsenite due to the reaction of arsenite with free chlorine. The reaction between arsenite and chlorine is shown below:

AsO_2^- (Arsenite) + Cl2 → AsO_4^{3-} (Arsenate) + $2Cl^-$

Correspondingly, ORP readings also decreased due to the consumption of free chlorine (oxidant) in water.

Temperatures fluctuated over time due to the effect of ambient high-bay temperature change at the T&E Facility.

Turbidity readings fluctuated significantly over the whole experimental period. The turbidity readings are inconclusive due to the interference of bubbles generated on the sensor.

The other water quality parameters, i.e., pH, specific conductance, and TOC, did not show any considerable change following the arsenic injection.

3.2.2.2. Mercury Adherence Test Results

Mercury adherence tests were also performed at three different flow rates conditions, i.e., 1 gpm, 15 gpm, and 60 gpm. The analytical results for the bulk water and coupon samples collected from the pilot-scale decontamination studies for mercury at the three different flow rates are summarized in Tables 3-5 through 3-7. For all three scenarios, complete contaminant mixing was observed in the pipe loop system one day after injection, as shown by the steady mercury concentration in the bulk water after this time point. As can be seen from Tables 3-5, 3-6, and 3-7, the results of the bulk water samples collected just prior to the conclusion of each adherence experiment (i.e., two days after the injection) confirmed the availability of contaminant within the system. This information ensures that the coupons were exposed to the contaminant during the two-day contact period.

Figure 3-2 presents the mass of mercury adsorbed per unit surface area of the coupon (mg mercury/in^2) as a function of flow rates, coupon locations, and coupon materials. The experimental results indicate the varying degree to which mercury adsorbs to cement-lined ductile iron pipe surfaces at different water flow rate conditions. As can be seen from the figure, the amount of mercury that adsorbs to the cement-lined ductile iron pipe surfaces increases with flow rate, with the highest adherence at the flow rate of 60 gpm evaluated in this study. This result conforms to the findings obtained from the arsenic adherence test. Figure 3-2 shows that the effect of coupon locations within the DSS on the mercury adsorption capacity is not significant, further indicating complete contaminant mixing in the pipe loop during the two-day contact time. Figure 3-2 also shows that mercury has a stronger tendency to adsorb to the surfaces of cement-lined ductile iron pipe than to the PVC surfaces.

Table 3-5 Experimental Results From Test Run ID: Hg F1 (Adherence Test Flow Rate: 1 gpm)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Mercury concentration (mg/L)	Coupon ID	Mercury concentration (mg/coupon)
Baseline		Just prior to injection	Hg F1 T0	0.00005	Coupon #1	0.00036
			Hg F1 T0 Dup	0.000068	Coupon #2[a]	2.8 x10^6 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	Hg F1 T5M	0.000075		
			Hg F1 T5M Dup	0.000079		
		1 day after injection	Hg F1 T1D	9.3		
			Hg F1 T1D Dup	8.9		
		2 days after injection	Hg F1 T2D	9.6		
			Hg F1 T2D Dup	9.5		
	After 2-day contact period	After draining loop			Control coupon A	0.49
					Control coupon B	0.048
					Coupon #3	4.0
					Coupon #4	2.2
					Coupon #5	1.2
					Coupon #6	3.3

[a] Coupon #2 was taken for HPC analysis to check for biofilm development.

Table 3-6 Experimental Results From Test Run ID: Hg F15 (Adherence Test Flow Rate: 15 gpm)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Mercury concentration (mg/L)	Coupon ID	Mercury concentration (mg/coupon)
Baseline		Just prior to injection	Hg F15 T0	0.0016	Coupon #1	0.073
			Hg F15 T0 Dup	0.0016	Coupon #2[a]	1.4 x10^3 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	Hg F15 T5M	9.6		
			Hg F15 T5M Dup	4		
		1 day after injection	Hg F15 T1D	10.7		
			Hg F15 T1D Dup	8.4		
		2 days after injection	Hg F15 T2D	8.1		
			Hg F15 T2D Dup	7.8		
	After 2-day contact period	After draining loop			Control coupon A	0.083
					Control coupon B	2.3
					Coupon #3	9.6
					Coupon #4	12.7
					Coupon #5	4.3
					Coupon #6	8.1

[a] Coupon #2 was taken for HPC analysis to check for biofilm development.

Table 3-7 Experimental Results From Test Run ID: Hg F60 (Adherence Test Flow Rate: 60 gpm)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Mercury concentration (mg/L)	Coupon ID	Mercury concentration (mg/coupon)
Baseline		Just prior to injection	Hg F60 T0	0.003	Coupon #1	0.093
			Hg F60 T0 Dup	0.0025	Coupon #2[a]	3.3 x10^6 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	Hg F60 T5M	11		
			Hg F60 T5M Dup	10.5		
		1 day after injection	Hg F60 T1D	9.7		
			Hg F60 T1D Dup	9.7		
		2 days after injection	Hg F60 T2D	8.8		
			Hg F60 T2D Dup	9.4		
	After 2-day contact period	After draining loop			Control coupon A	0.078
					Control coupon B	0.94
					Coupon #3	25.5
					Coupon #4	37.8
					Coupon #5	50.8
					Coupon #6	23.8

[a] Coupon #2 was taken for HPC analysis to check for biofilm development.

Figure 3-2 Mercury Adherence Study Results (Flow Rates: 1, 15, 60 gpm)

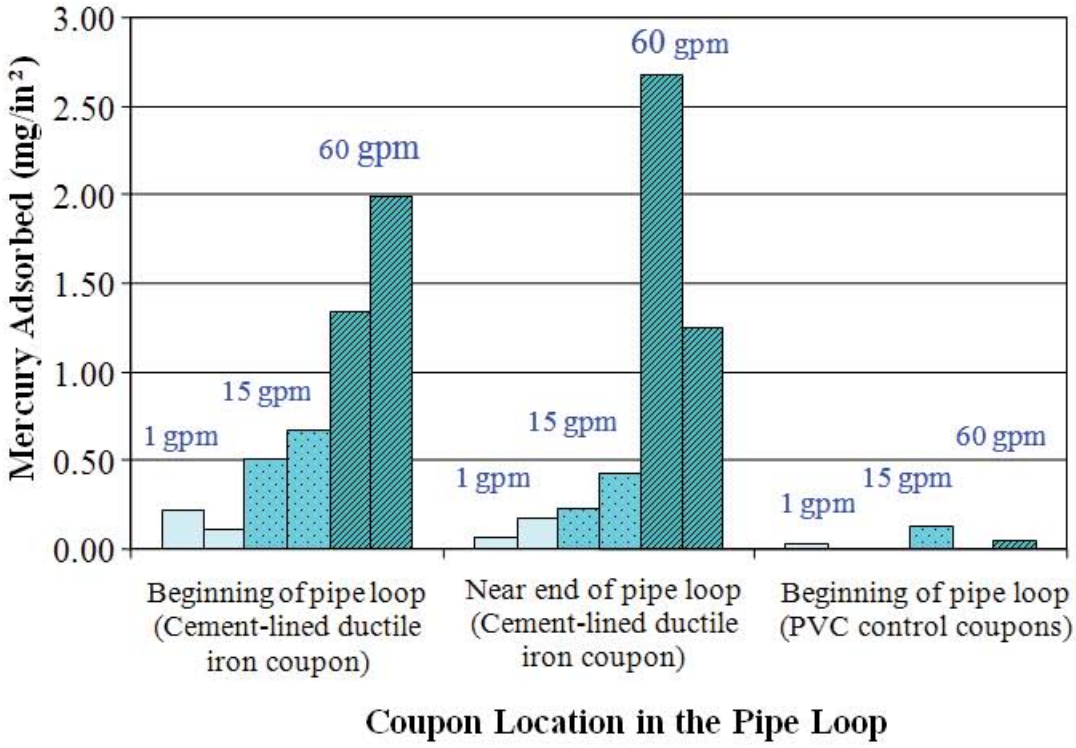


Figure 3-3 compares the adherence of mercury and arsenic to the cement-lined ductile iron and clear PVC pipe surfaces at the three different flow rate conditions. As can be seen, mercury has significantly stronger adherence to cement-lined ductile iron pipe surfaces compared to arsenic. The experimental results also indicate that there is no considerable difference between the adsorption of mercury and arsenic on clear PVC pipe coupons.

Also monitored were basic water quality parameters, including TOC, pH, ORP, free chlorine, turbidity, conductivity, and temperature.

Free chlorine measurements decreased gradually upon injection of mercuric chloride. In mercuric chloride, mercury (II) exists as the most oxidized form of mercury species; therefore, it cannot be further oxidized by chlorine. As such, the decrease of chlorine is attributed to the chlorine demand from biofilm in the loop.

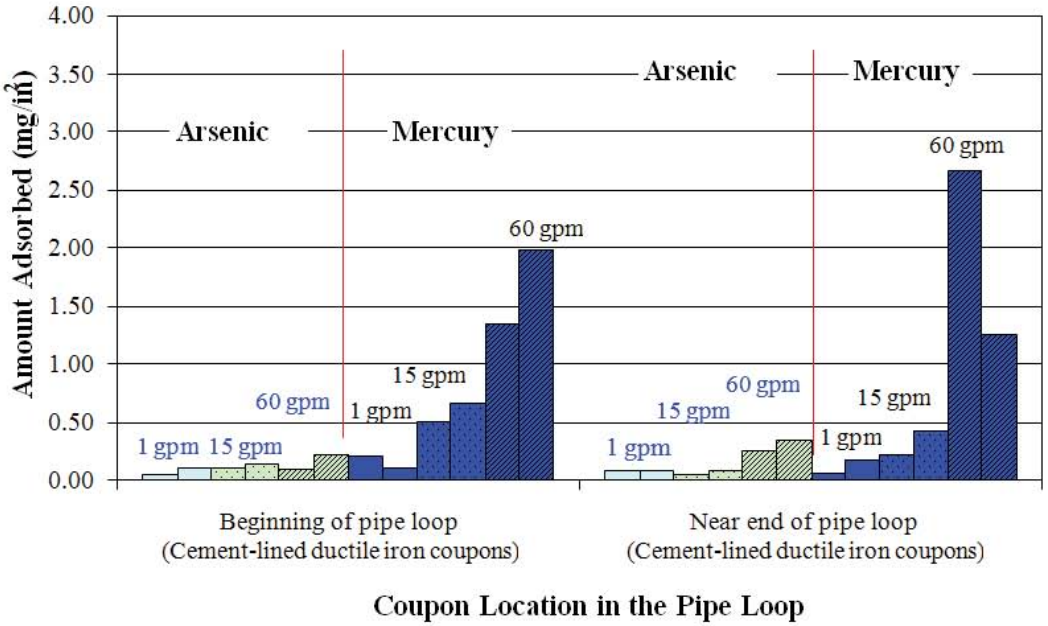
Correspondingly, ORP readings also decreased due to the consumption of free chlorine (oxidant) in water.

The injection of mercuric chloride resulted in a decrease of pH in the pipe loop system.

Temperatures fluctuated over time due to the effect of ambient high-bay temperature change at the T&E Facility.

The other water quality parameters, i.e., specific conductance, turbidity, and TOC, did not show any considerable change following the mercury injection.

Figure 3-3 Comparison of Arsenic and Mercury Adherence to Cement-lined Ductile (Iron Pipe Surfaces at Various Flow Rate Conditions)



3.2.2.3. *Bacillus subtilis* Adherence Test Results

A *Bacillus subtilis* adherence test was conducted at a flow rate of 60 gpm. From the previous experiments, which were aimed at evaluating the effect of flow rate on adherence of inorganic contaminants (e.g., arsenic and mercury) to the pipe surfaces, it was found that the amount of contaminant that adsorbs to the cement-lined ductile iron pipe surfaces increases with flow rate, with the highest adherence at the flow rate of 60 gpm evaluated (corresponding to turbulent flow). Therefore, the flow rate of 60 gpm was established for the adherence test of *Bacillus subtilis*.

The analytical results for the bulk water and coupon samples collected from the pilot-scale adherence test for *Bacillus subtilis* are summarized in Table 3-8. As can be seen, the injected *Bacillus subtilis* showed complete mixing in the pipe loop system five minutes after injection, as shown by the steady *Bacillus subtilis* concentration in the bulk water after this time point. It was also found that the concentration of *Bacillus subtilis* in the bulk water decreased over time probably due to the strong adherence of *Bacillus subtilis* to both PVC and cement-lined ductile iron surfaces. However, the results of the bulk water samples collected just prior to the conclusion of each adherence experiment (i.e., two days after the injection) confirmed the availability of *Bacillus subtilis* within the system. This information indicates that the coupons were exposed to the contaminant during the whole two-day contact period.

The *Bacillus subtilis* adherence test results are also presented in Figure 3-4. As can be seen from the figure, *Bacillus subtilis* showed similarly strong adherence to both the cement-lined ductile iron and clear PVC pipe surfaces as shown by the same order of magnitude of adherence (i.e., ~10^4 cells/in^2) on these two types of surfaces.

Also monitored were basic water quality parameters, including TOC, pH, ORP, free chlorine, turbidity, conductivity, and temperature.

TOC readings increased slightly upon injection of *Bacillus subtilis* probably due to the organic content of the sporulation media.

Upon injection of *Bacillus subtilis*, free chlorine readings decreased gradually due to the chlorine demand from *Bacillus subtilis* and sporulation media and biofilm in the loop.

Correspondingly, ORP readings also decreased gradually due to the consumption of free chlorine (oxidant) in water.

Temperatures fluctuated over time due to the effect of ambient high-bay temperature change at the T&E Facility.

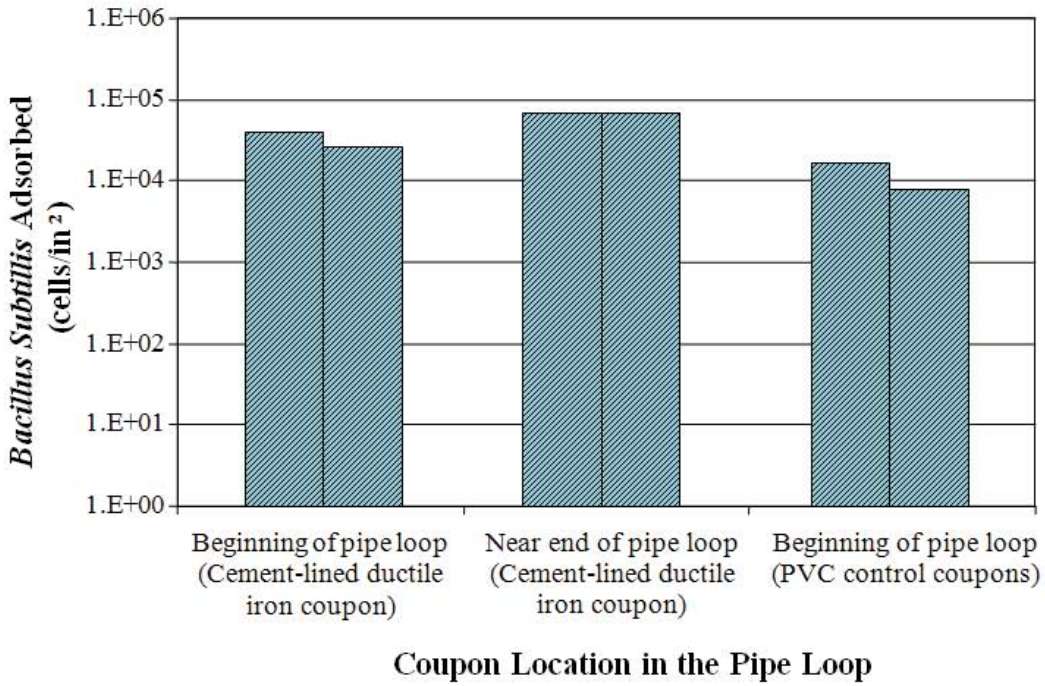
The other water quality parameters, i.e., pH, specific conductance, and turbidity, did not show any considerable change following the *Bacillus subtilis* injection.

Table 3-8 Experimental Results From Test Run ID: BS F60 (Adherence Test Flow rate: 60 gpm)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	*Bacillus subtilis* concentration (cells/mL)	Coupon ID	*Bacillus subtilis* concentration (cells/in²)
Baseline		Just prior to injection	BS F60 T0	0	Coupon #1	16
			BS F60 T0 Dup	0	Coupon #2[(a)]	5.3 x10⁵ cells/ cm²[(a)]
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	BS F60 T5M	880		
			BS F60 T5M Dup	900		
		1 day after injection	BS F60 T1D	720		
			BS F60 T1D Dup	800		
		2 days after injection	BS F60 T2D	330		
			BS F60 T2D Dup	410		
	After 2-day contact period	After draining loop			Control coupon A	1.8E+04
					Control coupon B	7.1E+03
					Coupon #3	4.6E+04
					Coupon #4	3.3E+04
					Coupon #5	5.5E+04
					Coupon #6	5.6E+04

[(a)] Coupon #2 was taken for HPC analysis to check the biofilm development.

Figure 3-4 *Bacillus subtilis* Adherence Study Results (Flow Rate: 60 gpm)



3.2.2.4. Diesel Fuel Adherence Test Results

A flow rate of 60 gpm was established for the pilot-scale adherence test of diesel fuel. The analytical results for the bulk water and coupon samples collected from the adherence test of diesel fuel are summarized in Table 3-9.

As can be seen, the injected diesel fuel showed complete mixing in the pipe loop system five minutes after injection, as shown by the target diesel fuel concentration in the bulk water at this time point. It was also found that the concentration of diesel fuel in the bulk water decreased significantly over time due to the strong adherence of diesel fuel to both PVC and cement-lined ductile iron pipe surfaces. The bulk water samples collected just prior to the conclusion of the adherence experiment (i.e., two days after the injection) showed very low or nondetectable levels of diesel fuel. This information indicates that the coupons might not have been exposed to diesel fuel during the last day of the adherence test and the adherence of diesel fuel to the pipe surfaces could be stronger if higher diesel fuel concentrations were applied in the bulk water during the adherence test.

The diesel fuel adherence test results are also presented in Figure 3-5. As can be seen from the figure, diesel fuel showed strong adherence to both the cement-lined ductile iron pipe and clear PVC pipe surfaces. Diesel fuel appeared to have stronger adherence to the cement-lined ductile iron pipe surfaces (1.1- 1.5 mg/in^2) than to the clear PVC pipe surfaces (0.5-0.8 mg/in^2).

Also monitored were basic water quality parameters, including TOC, pH, ORP, free chlorine, turbidity, conductivity, and temperature.

As expected, TOC readings increased slightly upon injection of diesel fuel.

Upon injection of diesel fuel, free chlorine readings decreased gradually due to the chlorine demand from diesel fuel.

Correspondingly, ORP readings also decreased gradually due to the consumption of free chlorine (oxidant) in water.

Turbidity increased significantly upon the injection of diesel fuel, and 10–12 hours later, the turbidity gradually decreased probably due to the decrease of diesel fuel concentration in the loop water. (Some diesel fuel might have reacted with chlorine, and some might have adsorbed to the pipe surfaces.)

Temperatures fluctuated over time due to the effect of ambient high-bay temperature change at the T&E Facility.

The other water quality parameters, i.e., pH and specific conductance, did not show any considerable change following the diesel fuel injection.

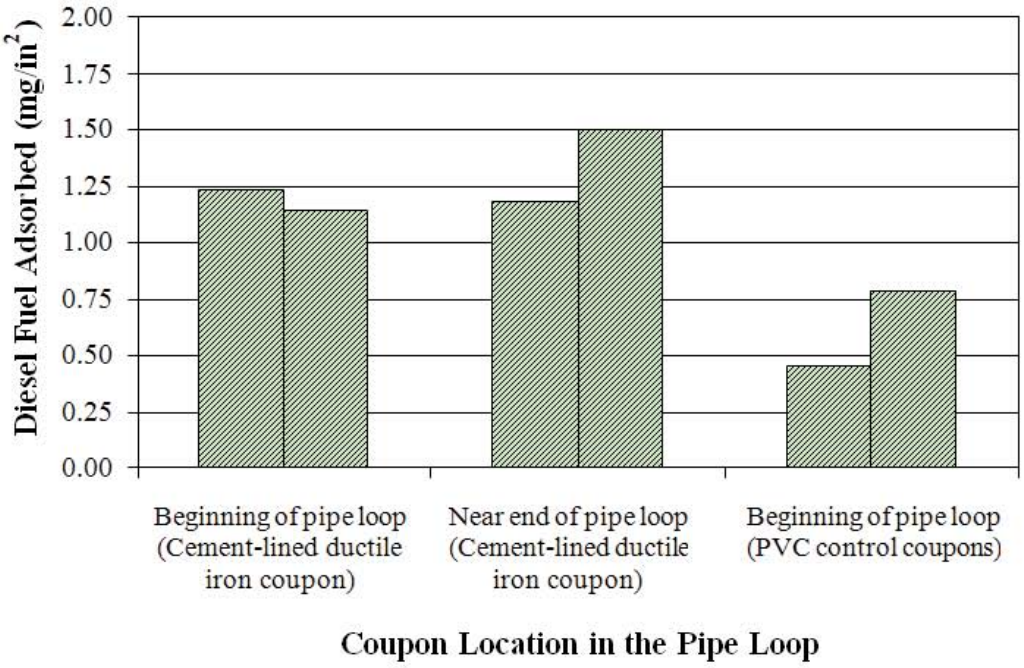
Table 3-9 Experimental Results From Test Run ID: DRO F60 (Adherence Test Flow rate: 60 gpm)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Diesel fuel concentration (mg/L)	Coupon ID	Diesel fuel concentration (mg/coupon)
Baseline		Just prior to injection	DRO F60 T0	ND	Coupon #1	14.0[a]
			DRO F60 T0 Dup	ND	Coupon #2[b]	4.8 x 10^5 cells/ cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	DRO F60 T5M	13.1		
			DRO F60 T5M Dup	11.1		
		1 day after injection	DRO F60 T1D	3.9		
			DRO F60 T1D Dup	1.3		
		2 days after injection	DRO F60 T2D	ND		
			DRO F60 T2D Dup	0.7		
	After 2-day contact period	After draining loop			Control coupon A	8.7
					Control coupon B	14.8
					Coupon #3	23.5
					Coupon #4	21.7
					Coupon #5	22.4
					Coupon #6	28.5

[a] Diesel Range Organics were detected for coupon #1. However, according to the chromatograph, these compounds were not diesel fuel compounds.

[b] Coupon #2 was taken for HPC analysis to check the biofilm development.

Figure 3-5 Diesel Fuel Adherence Test Results (Flow Rate: 60 gpm)



3.2.2.5. Chlordane Adherence Test Results

A chlordane adherence test was conducted using a flow rate of 60 gpm. The analytical results for the bulk water and coupon samples collected from the adherence test of chlordane are summarized in Table 3-10.

As mentioned previously, each sample was analyzed for technical chlordane, alpha-chlordane, and gamma-chlordane, and the analytical results are reported as the concentration of technical chlordane as well as the summation of alpha- and gamma-chlordane in Table 3-10. Based on the bulk water sample results, the summation of alpha- and gamma-chlordane accounted for ~30 percent of technical chlordane, which was the same percentage as that in the chlordane stock solution obtained from the Ohio Hamilton County Household Hazardous Waste collection site.

As can be seen from Table 3-10, the summation of alpha- and gamma-chlordane concentration in bulk water five minutes after injection ranged from 4.6 to 5.5 mg/L, which was much less than the target concentration of 10 mg/L, possibly due to the adherence of chlordane immediately after the injection before it was completely mixed in the pipe loop. In fact, the quick adherence of chlordane was confirmed by the significantly higher adherence of chlordane on the coupons at the beginning of the pipe loop as compared to those at the end of the pipe loop, which is discussed in detail in the following paragraph. It was also found that the concentration of chlordane in the bulk water decreased significantly after one day of contact time possibly due to the adherence of chlordane to the pipe surfaces plus some loss of chlordane by reacting with chlorine in water. The bulk water samples collected just prior to the conclusion of the adherence experiment (i.e., two days after the injection) showed significantly decreased concentration of chlordane (both technical chlordane and alpha-/gamma-chlordane); however, it also confirmed the availability of chlordane within the system, although the chlordane level was very low. This information indicates that the coupons were exposed to the contaminant during the whole two-day contact period.

The chlordane adherence test results are also presented in Figure 3-6. As can be seen from the figure, chlordane showed strong adherence to both the cement-lined ductile iron pipe and clear PVC pipe surfaces. Chlordane appeared to have much stronger adherence to the cement-lined ductile iron pipe surfaces (adsorbed alpha- and gamma-chlordane: 1.3 – 1.8 mg/in^2) than to the clear PVC pipe surfaces (adsorbed alpha- and gamma-chlordane: 0.3 mg/in^2). It was also observed that the effect of coupon location within the DSS on the chlordane adsorption is significant for cement-lined ductile iron pipe. The adherence of chlordane on the coupons located in the beginning of the pipe loop (near the chlordane injection port) was more than twice that at the end of the pipe loop, indicating that chlordane adheres to the pipe surfaces very quickly upon injection.

Also monitored were basic water quality parameters, including TOC, pH, ORP, free chlorine, turbidity, conductivity, and temperature.

As expected, TOC readings increased slightly upon injection of chlordane.

Upon injection of chlordane, free chlorine readings decreased gradually due to the chlorine demand from chlordane.

Correspondingly, ORP readings also decreased gradually due to the consumption of free chlorine (oxidant) in water.

Turbidity increased significantly upon the injection of chlordane solution because the chlordane solution injected was a thick amber liquid.

Temperatures fluctuated over time due to the effect of ambient high-bay temperature change at the T&E Facility.

The other water quality parameters, i.e., pH and specific conductance, did not show any considerable change following the chlordane injection.

Figure 3-6 Chlordane Adherence Test Results
(Flow Rate for Adherence Study: 60 gpm Decontamination: Surfonic TDA-6 Flushing)

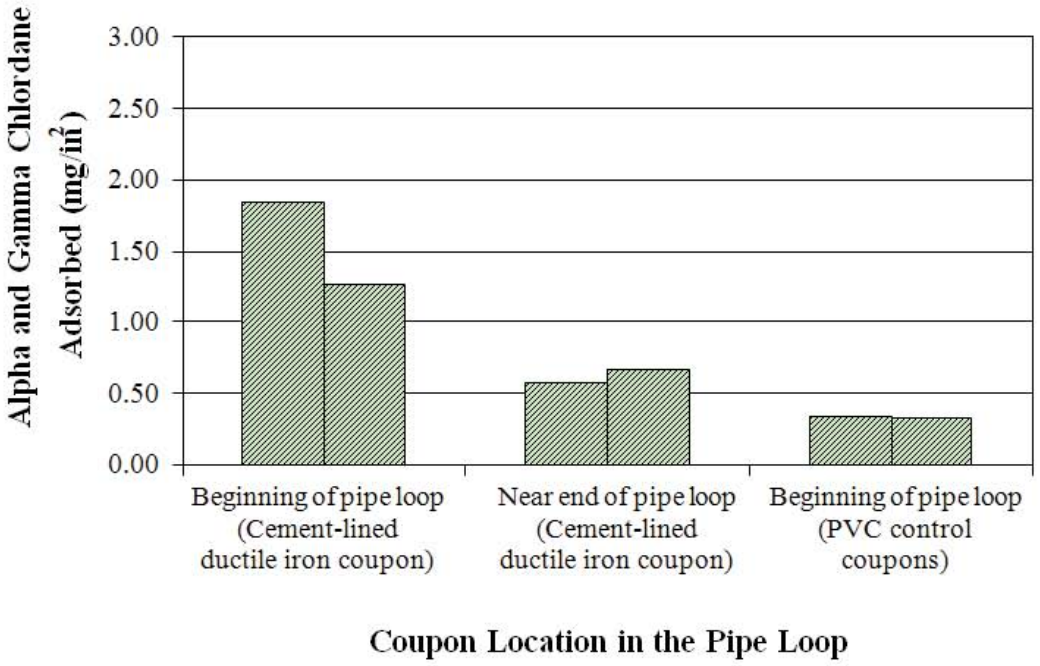


Table 3-10 Experimental Results From Test Run ID: ChLD TDA (Adherence Test Flow rate: 60 gpm)

Event		Sampling Time	Bulk Water Samples			Coupon Samples		
			Sample ID	Technical chlordane concentration (mg/L)	Alpha + Gamma chlordane concentration (mg/L)	Coupon ID	Technical chlordane concentration (mg/coupon)	Alpha + Gamma chlordane concentration (mg/coupon)
Baseline		Just prior to injection	ChLD TDA T0	ND	ND	Coupon #1	ND	ND
			ChLD F60 T0 Dup	ND	ND	Coupon #2[a]	1.3 x 10^6 cells/cm^2	
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	ChLD TDA T5M	15	4.6			
			ChLD TDA T5M Dup	18	5.5			
		1 day after injection	ChLD TDA T1D	11	3.4			
			ChLD TDA T1D Dup	3.8	1.13			
		2 days after injection	ChLD TDA T2D	5.6	1.76			
			ChLD TDA T2D Dup	5.6	1.76			
	After 2-day contact period	After draining loop				Control Coupon A	34	6.5
						Control Coupon B	31	6.4
						Coupon #3	180	35
						Coupon #4	130	24
						Coupon #5	60	11
						Coupon #6	68	12.8

[a] Coupon #2 was taken for HPC analysis to check the biofilm development.

3.2.3. Pilot-scale Decontamination Test Results

As described in the previous section, all contaminants tested, i.e., arsenic, mercury, *Bacillus subtilis*, diesel fuel, and chlordane showed strong adherence to cement-lined ductile iron pipe surfaces. *Bacillus subtilis* has similar adsorption capacity on both the PVC pipe surfaces and on the cement-lined ductile iron pipe surfaces. Diesel fuel and chlordane also showed considerable amount of adherence to the clear PVC pipe surfaces. To identify appropriate decontamination technologies for each of these contaminants, various decontamination methods were tested in this study. As described in the overall experimental strategy in Figure 2-3, each decontamination test was initiated with an adherence test, using the target contaminant, followed by a designated decontamination technique.

3.2.3.1. Arsenic Decontamination Test Results

A total of seven different decontamination approaches were investigated for removal of arsenic from the pilot-scale water distribution system: baseline water flushing, low-pH flushing, phosphate buffer flushing, acidified potassium permanganate flushing, NW-310/NW-400 flushing, Floran Biogrowth Remover/Catalyst flushing, and Floran Top Ultra/Catalyst flushing. The arsenic decontamination test results for each of these decontamination methods are presented below.

(1) Baseline water flushing

Three runs of baseline water flushing tests were performed on arsenic following three scenarios of arsenic adherence tests that applied three different flow rates, i.e., 1 gpm, 15 gpm, and 60 gpm. The test results are plotted in Figures 3-7, 3-8, and 3-9 for the three different test scenarios, respectively. As can be seen from the figures, water flushing of the pipe loop at 210 gpm, i.e., 2.5 fps, did not consistently remove arsenic from the cement-lined ductile iron pipe surfaces. The variation from test to test is very high, e.g., in Scenario 1 and 3, the water flushing removed some of the arsenic from the pipes; in Scenario 2, no arsenic removal was observed.

Figure 3-7 Arsenic Simple Water Flushing Test Results From Scenario 1
(Flow Rate for Adherence Study: 1 gpm Decontamination: Simple Water Flushing @ 210 gpm)

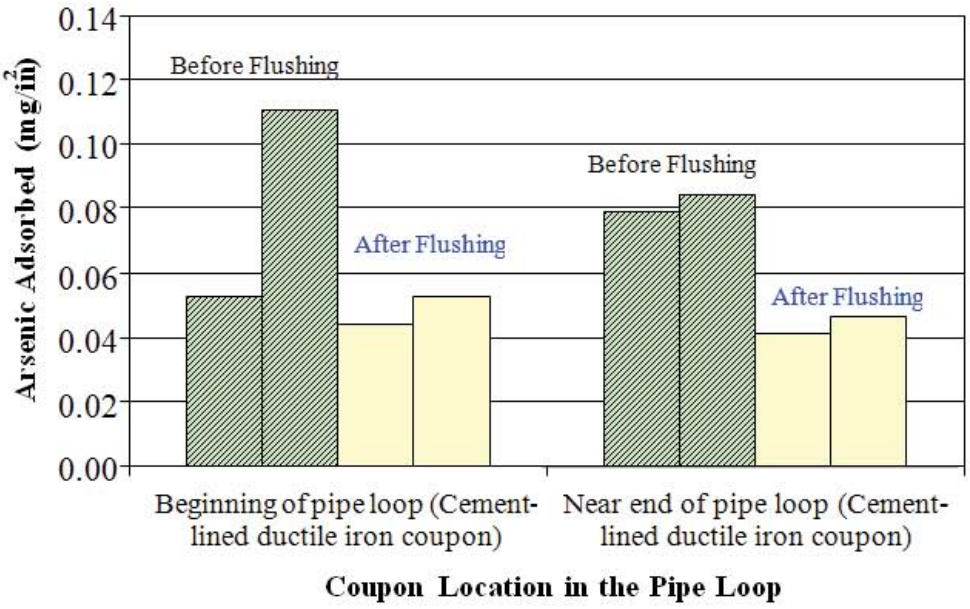


Figure 3-8 Arsenic Simple Water Flushing Results From Scenario 2
(Flow Rate for Adherence Study: 15 gpm Decontamination: Simple Water Flushing @ 210 pgm)

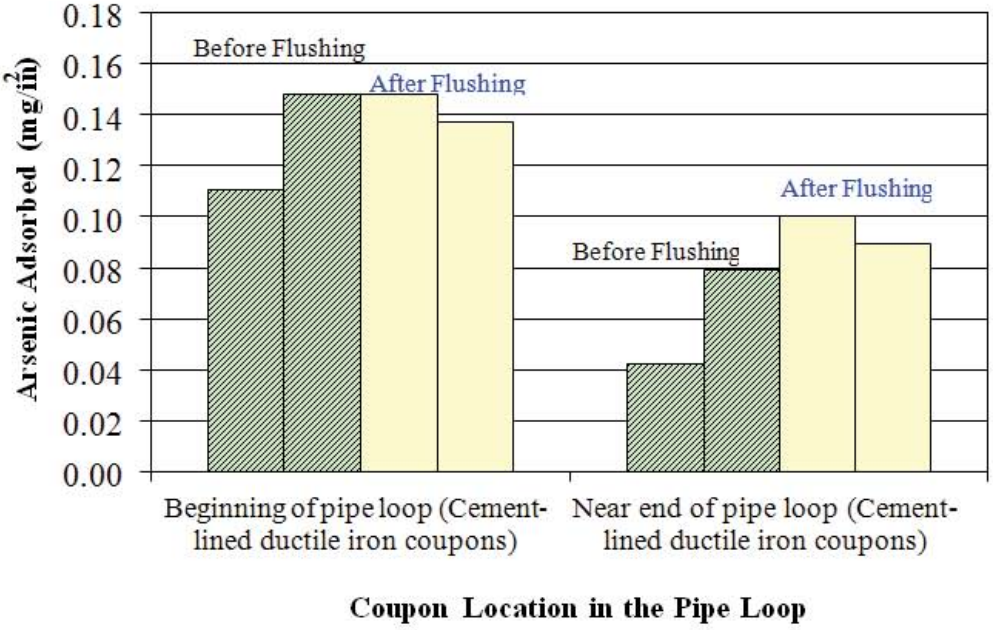
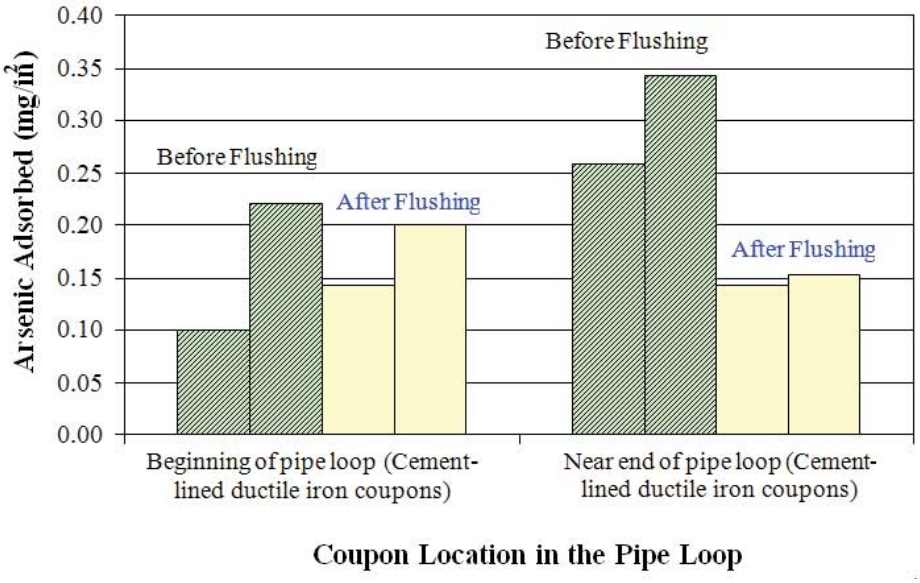


Figure 3-9 Arsenic Simple Water Flushing Results From Scenario 3
(Flow Rate for Adherence Study: 60 gpm Decontamination: Simple Water Flushing @ 210 gpm)



The decontamination efficiency of simple water flushing is calculated for each test scenario by comparing the arsenic remaining on coupons in the same location before and after the flushing. The results are shown in Tables 3-11, 3-12, and 3-13 for the adherence test flow rates of 1 gpm, 15 gpm, and 60 gpm, respectively. According to the calculations, the decontamination efficiency obtained for arsenic ranged from -55 to 51 percent. As can be seen, the data from individual coupons were highly varied (most possibly due to the variations in the coupons and the extraction procedure). However, the experimental results indicate that overall the simple water flushing of the pipe loop at 2.5 fps is a marginally effective decontamination technique for removing arsenic from drinking water distribution systems.

Table 3-11 Decontamination Efficiency of Simple Flushing for Arsenic Calculated From Test Run ID: As F1 (Flow Rate for Adherence Study: 1 gpm Decontamination: Simple Water Flushing @ 210 gpm)

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Arsenic adsorbed (mg/coupon)	1.0	2.1	1.5	1.6
	Average (mg/coupon)[1]	1.6		1.6	
After flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Arsenic remaining on coupon after flushing (mg/coupon)	0.84	1.0	0.78	0.88
	Average (mg/coupon)[1]	0.92		0.83	
Decon Efficiency (%)[2]		41%		46%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

Table 3-12 Decontamination Efficiency of Simple Flushing for Arsenic Calculated From Test Run ID: As F15 (Flow Rate for Adherence Study: 15 gpm Decontamination: Simple Water Flushing @ 210 gpm)

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Arsenic adsorbed (mg/coupon)	2.1	2.8	0.81	1.5
	Average (mg/coupon)[1]	2.5		1.2	
After flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Arsenic remaining on coupon after flushing (mg/coupon)	2.8	2.6	1.9	1.7
	Average (mg/coupon)[1]	2.7		1.8	
Decon Efficiency (%)[2]		-10%		-55%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

Table 3-13 Decontamination Efficiency of Simple Flushing for Arsenic Calculated From Test Run ID: As F60 (Flow Rate for Adherence Study: 60 gpm Decontamination: Simple Water Flushing @ 210 gpm)

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Arsenic adsorbed (mg/coupon)	1.9	4.2	4.9	6.5
	Average (mg/coupon)[1]	3.1		5.7	
After flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Arsenic remaining on coupon after flushing (mg/coupon)	2.7	3.8	2.7	2.9
	Average (mg/coupon)[1]	3.3		2.8	
Decontamination Efficiency (%)[2]		-7%		51%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

(2) Low-pH flushing

From the previous arsenic adherence experiments, which were aimed at evaluating the effect of flow rate on adherence of arsenic to the pipe surfaces, it was found that the amount of arsenic that adsorbs to the cement-lined ductile iron pipe surfaces increases with flow rate, with the highest adherence at the flow rate of 60 gpm evaluated. This is attributed to the increased mass transfer coefficients at higher flow rates. Therefore, the flow rate of 60 gpm was established for the adherence of the contaminants during the evaluation of the decontamination efficiency of low-pH flushing.

Figure 3-10 shows the results of the low-pH flushing for arsenic. As can be seen, the low-pH flushing did not dramatically remove arsenic from the cement-lined ductile iron pipe surfaces.

The decontamination efficiency of low-pH flushing is calculated by comparing the arsenic remaining on coupons in the same location before and after the flushing. The results are shown in Tables 3-14. The experimental results indicate that low-pH flushing of the pipe loop is a marginally effective decontamination technique for removing arsenic from the drinking water distribution system. The decontamination efficiency obtained for arsenic was 6 percent and 36 percent for the two coupon locations tested in this study, respectively. It was concluded from the test result, that decontamination efficiency for arsenic from cement-lined ductile iron pipe surfaces was not improved by using low-pH flushing as compared to simple water flushing.

Figure 3-10 Low-pH (pH 4) Flushing Results for Arsenic Decontamination (Flow Rate for Adherence Study: 60 gpm Decontamination: pH 4 Flushing)

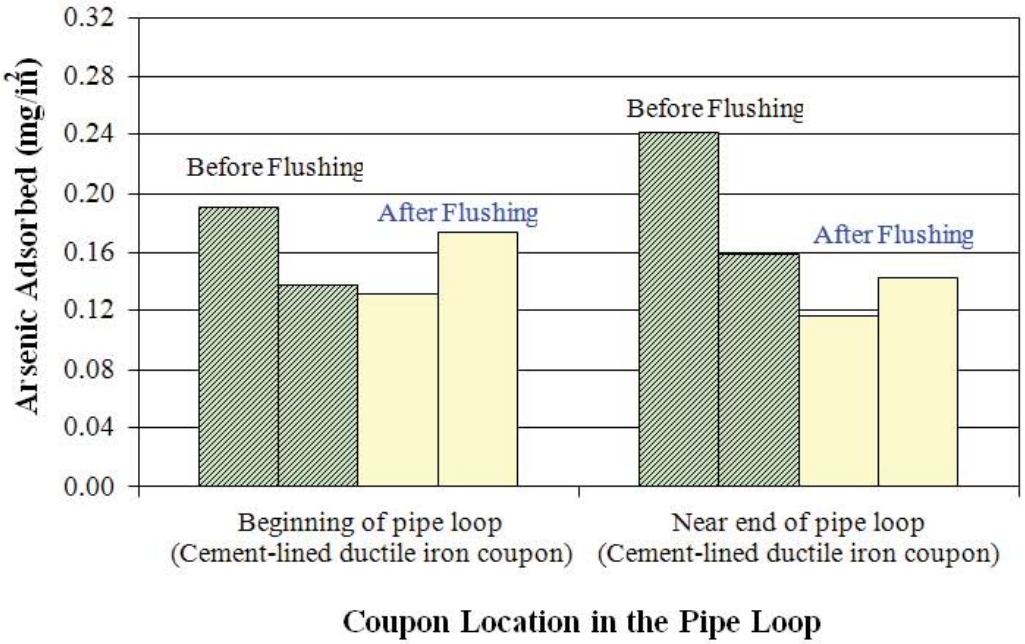


Table 3-14 Decontamination Efficiency of Low-pH Flushing for Arsenic

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Arsenic adsorbed (mg/coupon)	3.6	2.6	4.6	3.0
	Average (mg/coupon)[1]	3.1		3.8	
After flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Arsenic remaining on coupon after flushing (mg/coupon)	2.5	3.3	2.2	2.7
	Average (mg/coupon)[1]	2.9		2.5	
Decon Efficiency (%)[2]		6%		36%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

(3) Phosphate buffer flushing

The previous arsenic decontamination indicated that simple water flushing at 2.5 fps could remove only up to ~51 percent of adsorbed arsenic from the cement-lined ductile iron pipe surfaces. Furthermore, the decontamination efficiency for arsenic from cement-lined ductile iron pipe surfaces was not improved by using low-pH flushing. Therefore, phosphate buffer flushing was applied to determine whether this technique could achieve higher arsenic removal efficiency. The test result is presented in Figure 3-11. As can be seen from the figure, phosphate buffer flushing did not show any removal of arsenic from the cement-lined ductile iron pipe surfaces.

The decontamination efficiency of phosphate buffer flushing is also calculated by comparing the arsenic remaining on coupons in the same location before and after the decontamination. The results are shown in Tables 3-15. A negative decontamination efficiency was observed for phosphate buffer flushing, indicating that phosphate buffer flushing is not an effective decontamination technique for removing arsenic from drinking water distribution systems.

Figure 3-11 Phosphate Buffer Flushing Results for Arsenic Decontamination (Flow Rate for Adherence Study: 60 gpm Decontamination: Phosphate Buffer Flushing)

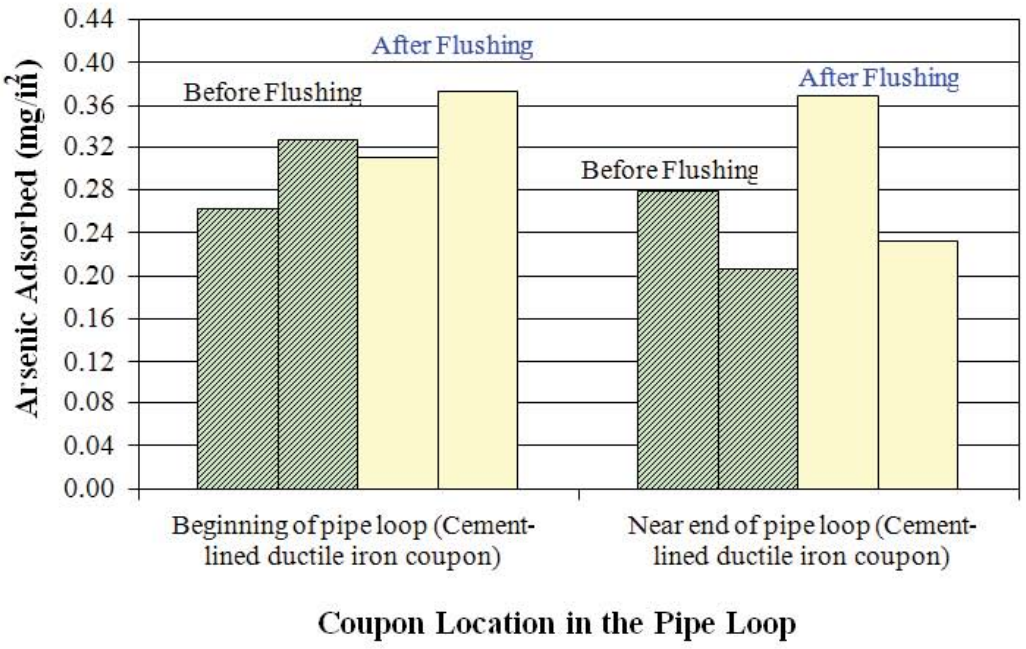


Table 3-15 Decontamination Efficiency of Phosphate Buffer Flushing for Arsenic

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before phosphate buffer flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Arsenic adsorbed (mg/coupon)	5.0	6.2	5.3	3.9
	Average (mg/coupon)[1]	5.6		4.6	
After phosphate buffer flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Arsenic remaining on coupon after flushing (mg/coupon)	5.9	7.1	7.0	4.4
	Average (mg/coupon)[1]	6.5		5.7	
Decontamination Efficiency (%)[2]		-16%		-24%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

(4) Acidified potassium permanganate flushing

Acidified potassium permanganate flushing is a more aggressive chemical decontamination technique compared to the previously applied decontamination approaches for arsenic. As the decontamination methods tested previously did not show significant removal efficiency for arsenic, this method was chosen in order to achieve improved decontamination efficiency.

Figure 3-12 presents the results obtained from the acidified potassium permanganate flushing test on arsenic. As can be seen from the figure, the acidified potassium permanganate flushing consistently removed approximately half of the adsorbed arsenic from the cement-lined ductile iron surfaces. The decontamination efficiency calculated for acidified potassium permanganate flushing, 54 percent to 61 percent (as shown in Table 3-16), indicated that the acidified potassium permanganate flushing is the most efficient decontamination approach (among the techniques evaluated) for removing arsenic from the cement-lined ductile iron pipe surfaces. This is possibly attributed to the enhanced solubility of arsenic in the presence of acid (pH of ~2) and permanganate in the solution.

Figure 3-12 Acidified Potassium Permanganate Flushing Results for Arsenic Decontamination
(Flow Rate for Adherence Study: 60 gpm
Decontamination: Acidified Potassium Permanganate Flushing)

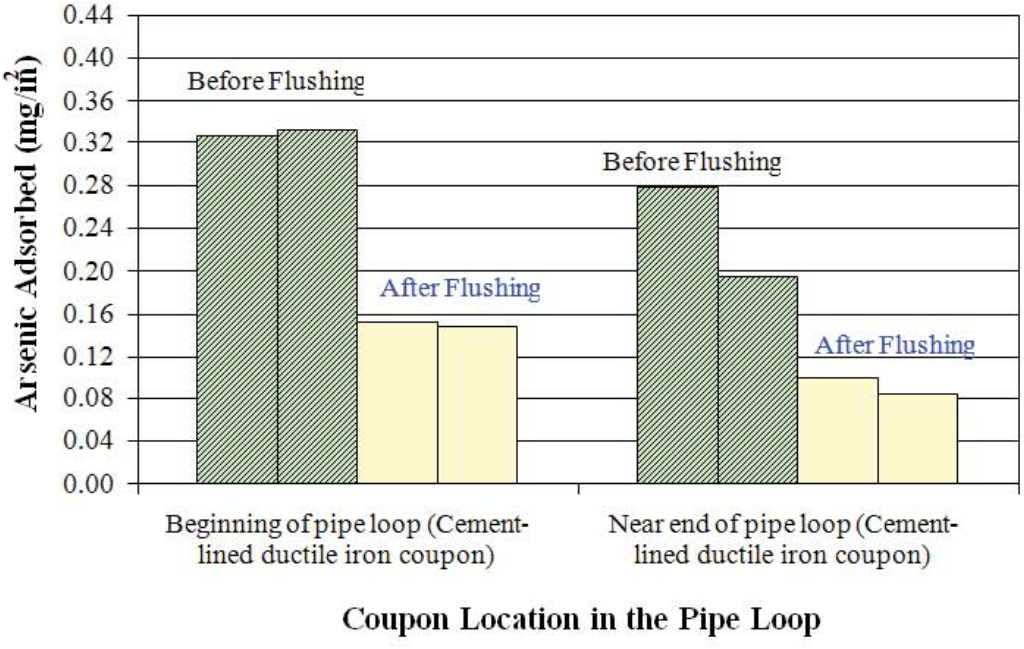


Table 3-16 Decontamination Efficiency of Acidified Potassium Permanganate Flushing for Arsenic

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before phosphate buffer flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Arsenic adsorbed (mg/coupon)	6.2	6.3	5.3	3.7
	Average (mg/coupon)[1]	6.3		4.5	
After phosphate buffer flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Arsenic remaining on coupon after flushing (mg/coupon)	2.9	2.8	1.9	1.6
	Average (mg/coupon)[1]	2.9		1.8	
Decontamination Efficiency (%)[2]		54%		61%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

(5) NSF Standard 60 Pipe Cleaning Aid Products Flushing (NW-310/NW-400 flushing, Floran Biogrowth Remover/Catalyst, and Floran Top Ultra/Catalyst)

NSF Standard 60 Pipe Cleaning Aid Products decontamination is a follow-up study to the baseline simple flushing, low-pH flushing, phosphate buffer flushing, and acidified potassium permanganate flushing experiments conducted for arsenic. The previous test results indicated that the highest arsenic removal efficiency was observed with acidified potassium permanganate flushing, which removed up to 61 percent of arsenic from the cement-lined ductile iron pipe surfaces. The other decontamination approaches presented no removal or low removal of arsenic from drinking water distribution systems. The NSF Standard 60 Pipe Cleaning Aid Products were identified for decontamination of arsenic as they were proven as a very effective technique for the cleaning of drinking water pipes and wells. In this study, Shaw conducted three separate decontamination tests using the combination of NW-310/NW-400, Floran Biogrowth Remover/Catalyst, and Floran Top Ultra/Catalyst.

The results are presented in Figures 3-13, 3-14, and 3-15 for the three different NSF Standard 60 Pipe Cleaning Aid Products decontamination approaches that were investigated in the study. As can be seen from the figures, approximately half of the adsorbed arsenic was removed from the cement-lined ductile iron surfaces after the application of NSF Standard 60 Pipe Cleaning Aid decontamination procedure.

The decontamination efficiencies of three different NSF Standard 60 products decontamination procedures are calculated by comparing the arsenic remaining on coupons in the same location before and after the decontamination. The results are shown in Tables 3-17, 3-18, and 3-19, respectively. As shown in Tables 3-17, 3-18, and 3-19, the NSF Standard 60 Products decontamination methods appear to be efficient approaches to removing arsenic from the cement-lined ductile iron pipe surfaces. Compared to the decontamination technologies tested previously on arsenic (except for the acidified potassium permanganate flushing), the decontamination efficiency was improved by using the NSF Standard 60 Products as the decontamination reagents. As far as the decontamination efficiencies are concerned, there is no significant difference among the three different NSF Standard 60 products tested, i.e., the decontamination efficiencies are bracketed in the range of 46 percent to 67 percent. However, a comparison of the three test results indicates that the amount of arsenic adsorbed to the pipe surfaces from Test Run: As NW (1.4 – 2.7 mg of arsenic adsorbed per coupon) was less than that from Test Run: As Floran I and As Floran II (2.8 – 6.5 mg of arsenic adsorbed per coupon). The reason for such a difference is not very clear, since the adherence test condition was the same for all three tests. It is also noticed that the decontamination efficiency of the NSF Standard 60 Products flushing for arsenic is similar to that of the acidified potassium permanganate flushing. However, compared to the acidified potassium permanganate, the NSF Standard 60 Products are much more environmentally friendly; therefore, the NSF Standard 60 Products should be given higher priority in a real-world arsenic decontamination scenario.

Figure 3-13 NW-310/NW-400 Flushing Results for Arsenic Decontamination
Flow Rate for Adherence Study: 60 gpm Decontamination: NW-310/NW-400 Flushing)

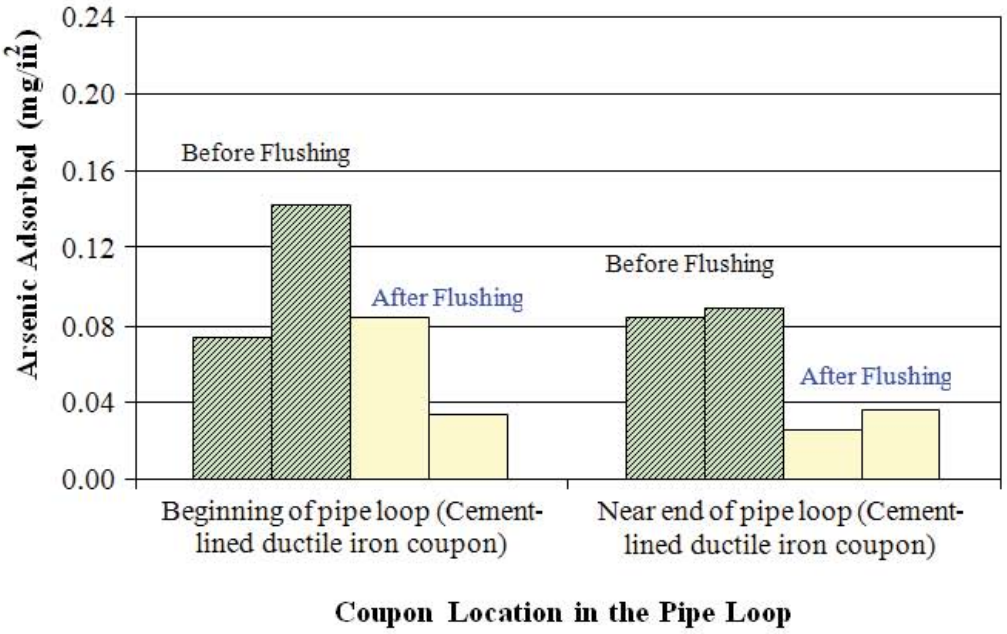


Figure 3-14 Floran Biogrowth Remover/Catalyst Flushing Results for Arsenic Decontamination
(Flow Rate for Adherence Study: 60 gpm)
Decontamination: Floran Biogrowth Remover/Catalyst Flushing

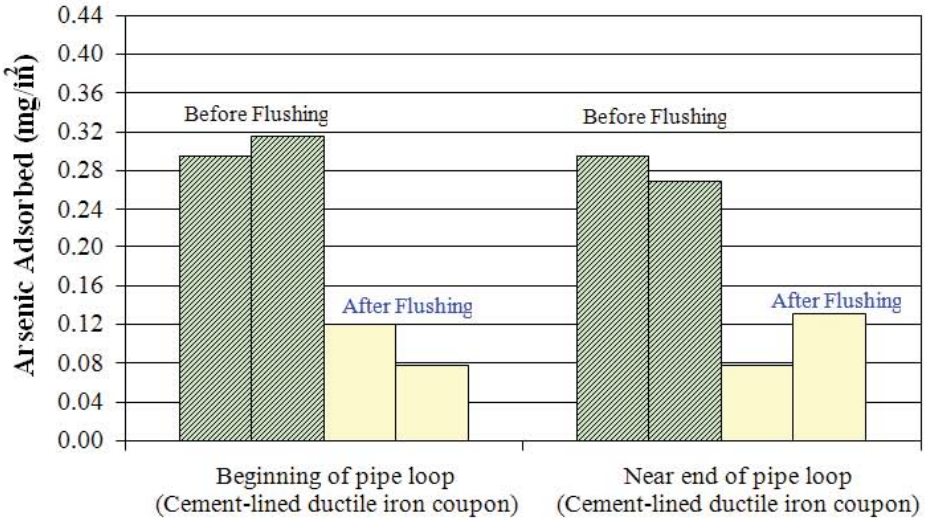


Figure 3-15 Floran Top Ultra/Catalyst Flushing Results for Arsenic Decontamination
(Flow Rate for Adherence Study: 60 gpm Decontamination: Floran Top Ultra/Catalyst Flushing)

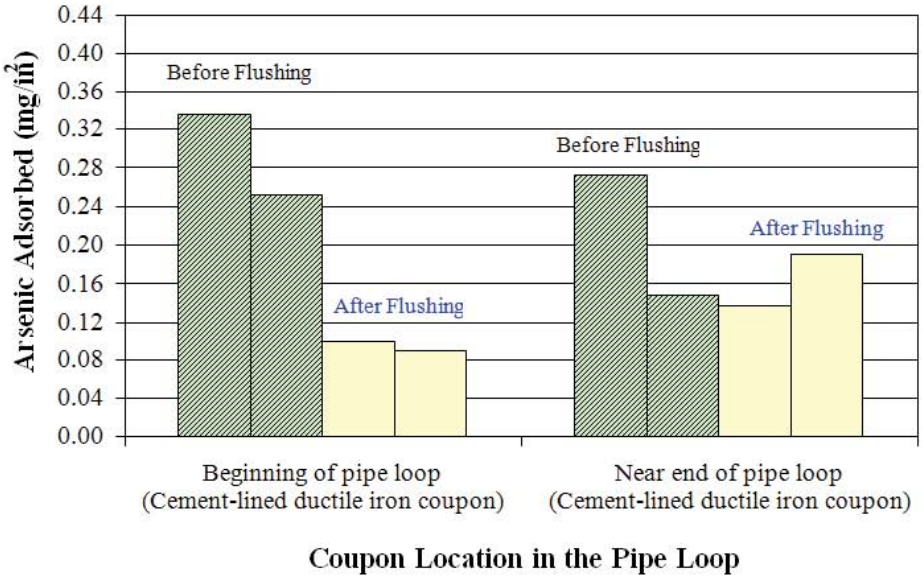


Table 3-17 Decontamination Efficiency of NW-310/NW-400 Flushing for Arsenic

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before phosphate buffer flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Arsenic adsorbed (mg/coupon)	1.4	2.7	1.6	1.7
	Average (mg/coupon)[1]	2.1		1.7	
After phosphate buffer flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Arsenic remaining on coupon after flushing (mg/coupon)	1.6	0.63	0.5	0.67
	Average (mg/coupon)[1]	1.1		0.6	
Decontamination Efficiency (%)[2]		46%		65%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

Table 3-18 Decontamination Efficiency of Floran Biogrowth Remover/Catalyst Flushing for Arsenic

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before phosphate buffer flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Arsenic adsorbed (mg/coupon)	5.6	6.0	5.6	5.1
	Average (mg/coupon)[1]		2.1	1.7	
After phosphate buffer flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Arsenic remaining on coupon after flushing (mg/coupon)	2.3	1.5	1.5	2.5
	Average (mg/coupon)[1]	1.9		2.0	
Decontamination Efficiency (%)[2]		67%		63%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

Table 3-19 Decontamination Efficiency of Floran Top Ultra/Catalyst Flushing for Arsenic

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before phosphate buffer flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Arsenic adsorbed (mg/coupon)	6.4	4.8	5.2	2.8
	Average (mg/coupon)[1]	5.6		4.0	
After phosphate buffer flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Arsenic remaining on coupon after flushing (mg/coupon)	1.9	1.7	2.6	3.6
	Average (mg/coupon)[1]	1.8		3.1	
Decontamination Efficiency (%)[2]		46%		65%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

3.2.3.2. Mercury Decontamination Test Results

Three different decontamination approaches were used for the mercury decontamination study: baseline water flushing, low-pH flushing, and acidified potassium permanganate flushing.

(1) Baseline water flushing

Three runs of baseline water flushing were conducted on mercury following three scenarios of mercury adherence tests that applied three different flow rates, i.e., 1 gpm, 15 gpm, and 60 gpm. The results are shown in Figures 3-16, 3-17, and 3-18 for the three test scenarios, respectively. As can be seen from the figures, water flushing of the pipe loop at 210 gpm (corresponding to 2.5 fps for 6-inch diameter pipe) did not result in considerable removal of mercury from the cement-lined ductile iron pipe surfaces. The variation from test to test and from coupon to coupon is very high, e.g., in Scenario 2 and 3, the water flushing removed some of the mercury from the pipes; while in Scenario 1, it did not remove mercury from the coupons located in the beginning of the pipe loop.

Figure 3-16 Mercury Simple Water Flushing Test Results
(Flow Rate for Adherence Study: 1 gpm Decontamination: Simple Water Flushing @ 210 gpm)

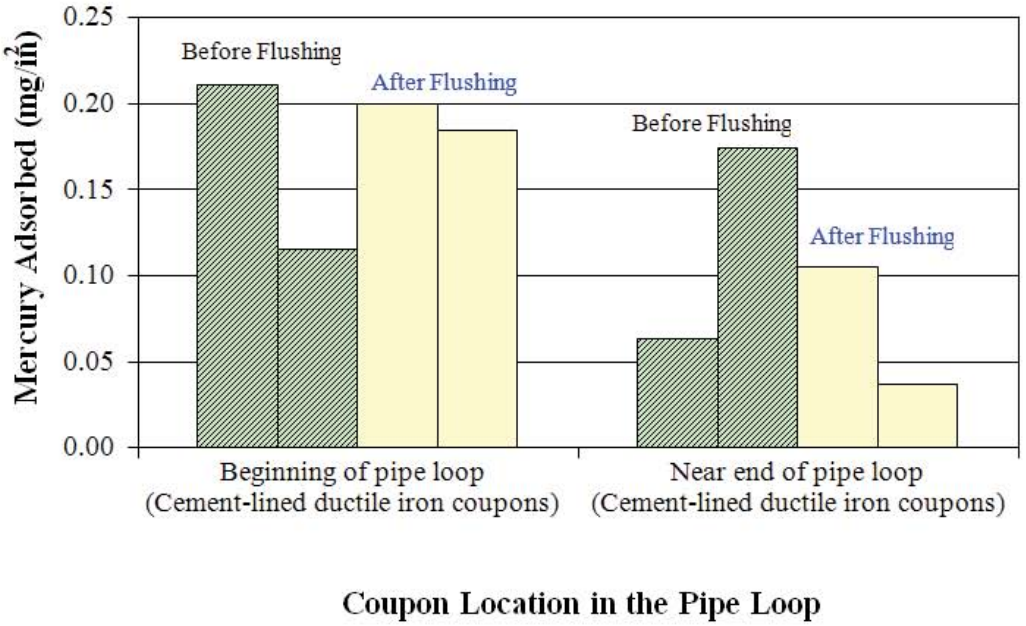


Figure 3-17 Mercury Simple Water Flushing Test Results
(Flow Rate for Adherence Study: 15 gpm Decontamination: Simple Water Flushing @ 210 gpm)

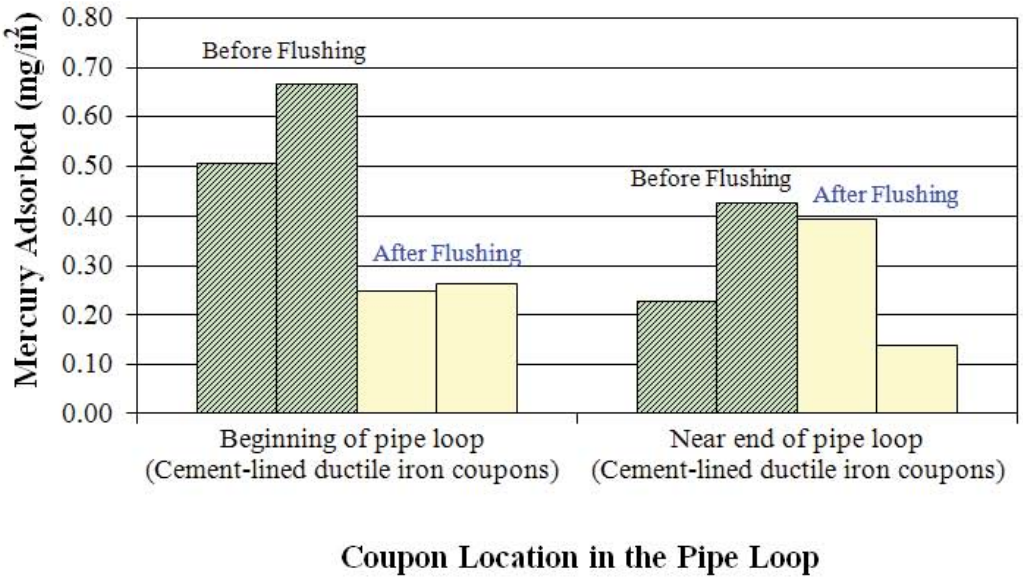
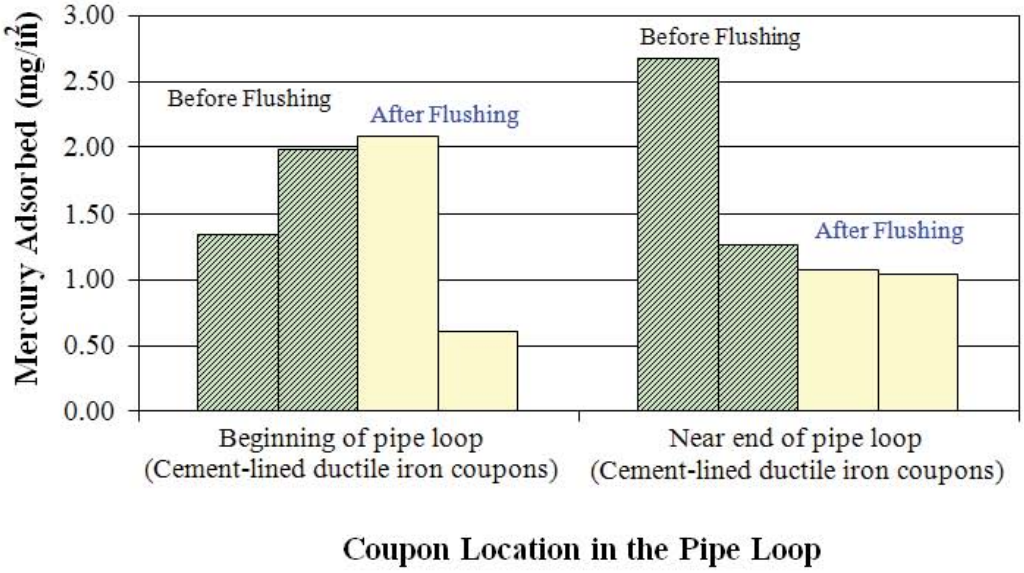


Figure 3-18 Mercury Simple Water Flushing Test Results
(Flow Rate for Adherence Study: 60 gpm Decontamination: Simple Water Flushing @ 210 gpm)



The decontamination efficiency of simple water flushing is calculated for each test scenario by comparing the mercury remaining on coupons in the same location before and after the flushing. The results are shown in Tables 3-20, 3-21, and 3-22 for the adherence test flow rates of 1 gpm, 15 gpm, and 60 gpm, respectively. According to the calculations, the decontamination efficiency obtained for mercury ranged between -18 percent and 57 percent. As can be seen, the data from individual coupons were highly varied (most possibly due to the variations in the coupons and the extraction procedure), and it was difficult to obtain a representative number for decontamination efficiency. However, the experimental results indicate that overall the simple water flushing of the pipe loop at 2.5 fps is a marginally effective decontamination technique for removing mercury from the drinking water distribution systems.

Table 3-20 Decontamination Efficiency of Simple Flushing for Mercury Calculated From Test Run ID: Hg F1 (Flow Rate for Adherence Study: 1 gpm Decontamination: Simple Water Flushing @ 210 gpm)

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Mercury adsorbed (mg/coupon)	4.0	2.2	1.2	3.3
	Average (mg/coupon)[1]	3.1		2.3	
After flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Mercury remaining on coupon after flushing (mg/coupon)	3.8	3.5	2.0	0.71
	Average (mg/coupon)[1]	3.7		1.4	
Decon Efficiency (%)[2]		-18%		40%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

Table 3-21 Decontamination Efficiency of Simple Flushing for Mercury Calculated From Test Run ID: Hg F15 (Flow Rate for Adherence Study: 15 gpm Decontamination: Simple Water Flushing @ 210 gpm)

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Mercury adsorbed (mg/coupon)	9.6	12.7	4.3	8.1
	Average (mg/coupon)[1]	11.2		6.2	
After flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Mercury remaining on coupon after flushing (mg/coupon)	4.7	5.0	7.5	2.6
	Average (mg/coupon)[1]	4.9		5.1	
Decon Efficiency (%)[2]		57%		19%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

Table 3-22 Decontamination Efficiency of Simple Flushing for Mercury Calculated From Test Run ID: Hg F60 (Flow Rate for Adherence Study: 60 gpm Decontamination: Simple Water Flushing @ 210 gpm)

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Mercury adsorbed (mg/coupon)	25.5	37.8	50.8	23.8
	Average (mg/coupon)[1]	31.7		37.3	
After flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Mercury remaining on coupon after flushing (mg/coupon)	39.6	11.4	20.4	19.9
	Average (mg/coupon)[1]	25.5		20.2	
Decontamination Efficiency (%)[2]		19%		46%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

(2) Low-pH flushing

To evaluate decontamination approaches that may have higher removal efficiency for mercury, a chemical decontamination approach, i.e., low-pH (pH 4) flushing was applied. The test results are presented in Figure 3-19, and the calculated decontamination efficiency is summarized in Table 3-23. From the results, it can be seen that the application of low-pH flushing could remove a small portion of mercury adsorbed to the cement-lined pipe surfaces; however, it did not significantly improve the decontamination efficiency as compared to simple water flushing.

Figure 3-19 Low-pH Flushing Results for Mercury Decontamination (Flow Rate for Adherence Study: 60 gpm Decontamination: pH 4 Flushing)

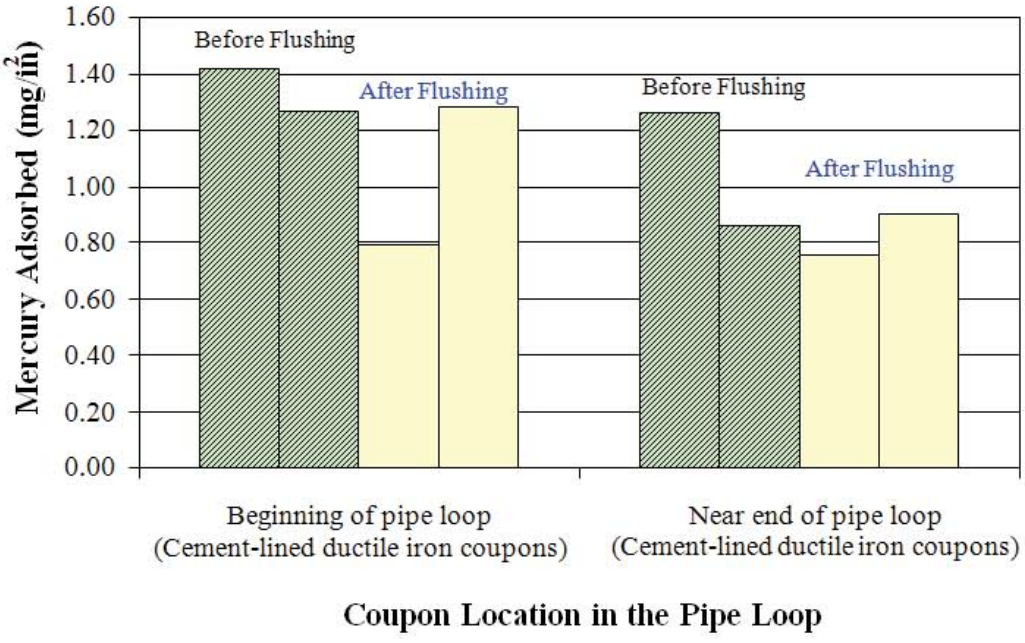


Table 3-23 Decontamination Efficiency of Low-pH Flushing for Mercury

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Mercury adsorbed (mg/coupon)	27.0	24.1	23.9	16.3
	Average (mg/coupon)[1]		25.6	20.1	
After flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Mercury remaining on coupon after flushing (mg/coupon)	15.0	24.3	14.4	17.2
	Average (mg/coupon)[1]	19.7		15.8	
Decon Efficiency (%)[2]		23%		21%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[0] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

(3) Acidified potassium permanganate flushing

To improve the decontamination efficiency for mercury, an aggressive chemical decontamination approach, i.e., acidified potassium permanganate flushing, was applied. The test results are presented in Figure 3-20, and the calculated decontamination efficiency is summarized in Table 3-24. From the results, it can be seen that acidified potassium permanganate flushing could remove a significant amount of mercury from the cement-lined pipe surfaces at two different coupon locations within the pipe loop. The decontamination efficiency ranged from 72 percent to 96 percent. This is the most effective decontamination technology evaluated during the pilot-scale decontamination study for mercury.

In mercuric chloride, mercury (II) exists as the most oxidized form of mercury species; therefore, it is obvious from a chemical perspective that the mechanism involved in the decontamination of mercury by acidified permanganate is not oxidation. It is rather the enhanced solubility of mercury in the presence of acid (pH of ~2) and permanganate in the solution. Similar results were observed in Battelle's bench-scale decontamination of mercury using acidified potassium permanganate (Chattopadhyay and Fox, 2006).

Figure 3-20 Acidified Potassium Permanganate Flushing Results for Mercury Decontamination
(Flow Rate for Adherence Study: 60 gpm
Decontamination: Acidified Potassium Permanganate Flushing)

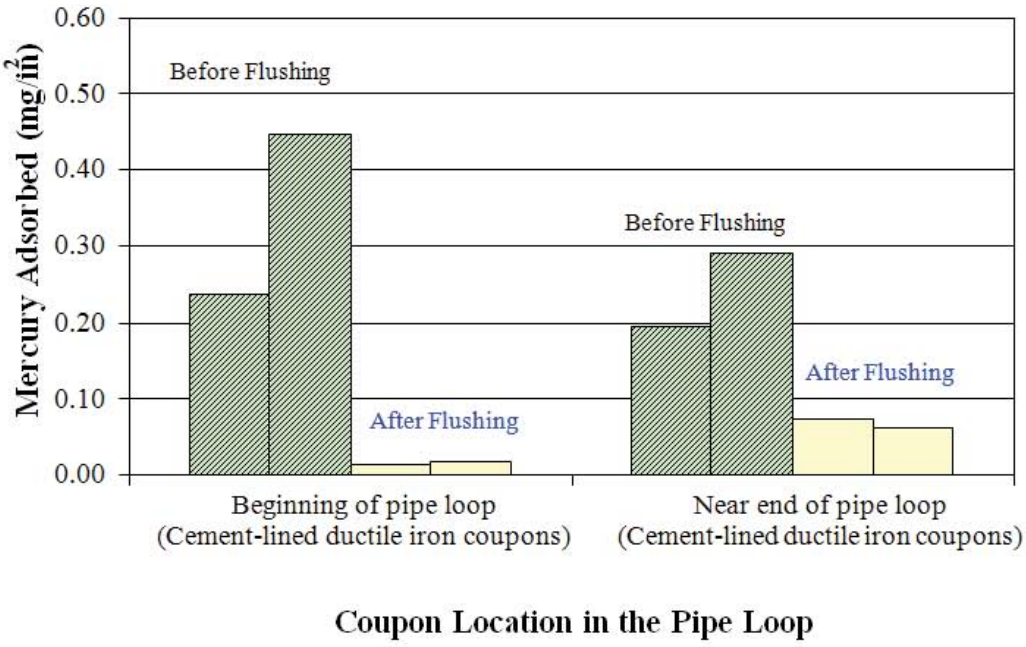


Table 3-24 Decontamination Efficiency of Acidified Potassium Permanganate Flushing for Mercury

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Mercury adsorbed (mg/coupon)	4.5	8.5	3.7	5.5
	Average (mg/coupon)[1]	6.5		4.6	
After flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Mercury remaining on coupon after flushing (mg/coupon)	0.25	0.33	1.4	1.2
	Average (mg/coupon)[1]	0.29		1.3	
Decon Efficiency (%)[2]		96%		72%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

3.2.3.3. *Bacillus subtilis* Decontamination Test Results

Two types of decontamination approaches were tested for the *Bacillus subtilis* decontamination study: baseline water flushing and shock chlorination. The results from these two decontamination tests are discussed in the following subsections.

(1) Baseline water flushing

Simple water flushing was evaluated for *Bacillus subtilis* as the baseline decontamination method, and the results are plotted in Figure 3-21. It is apparent that the baseline water flushing approach did not remove any *Bacillus subtilis* from the cement-lined ductile iron pipe surfaces. Table 3-25 presents the results in tabular format.

Figure 3-21 Simple Flushing Results for Bacillus subtilis Decontamination (Flow Rate for Adherence Study: 60 gpm Decontamination: Simple Water Flushing @ 210 gpm)

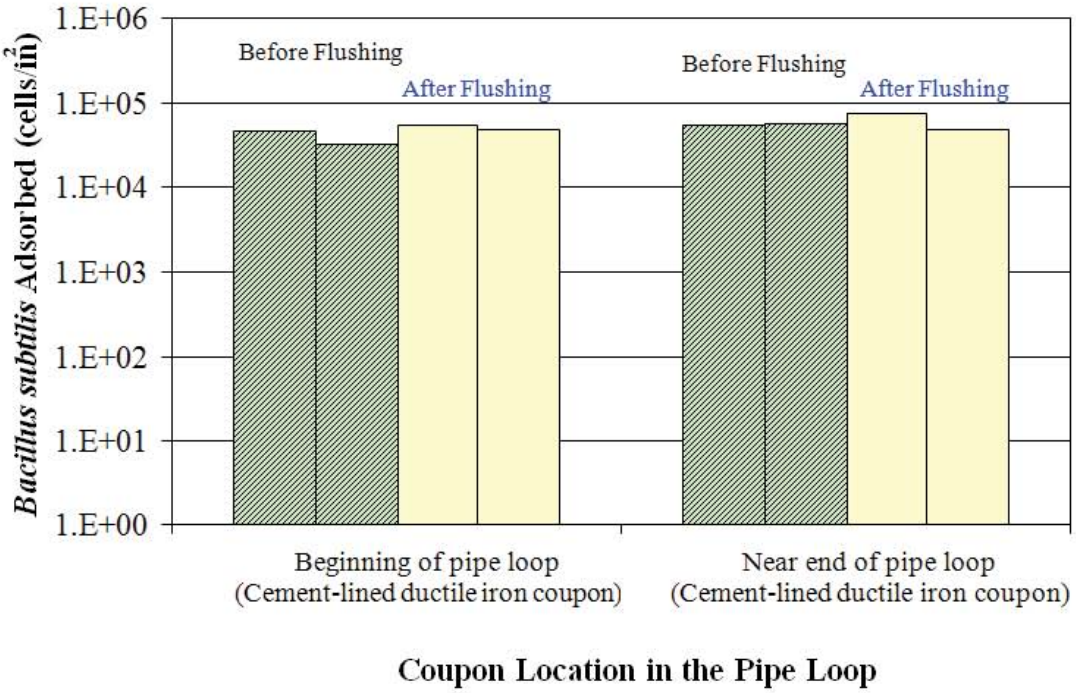


Table 3-25 Decontamination Efficiency of Simple Flushing for *Bacillus subtilis*

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Bacillus subtilis adsorbed (cells/in^2)	4.6E+04	3.3E+04	5.5E+04	5.6E+04
	Average (cells/in^2)[1]	4.0E+04		5.6E+04	
After flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Bacillus subtilis remaining on coupon after flushing (cells/in^2)	5.4E+04	4.8E+04	7.5E+04	4.9E+04
	Average (cells/in^2)[1]	5.1E+04		6.2E+04	
Decon Efficiency (%)[2]		-29%		-11%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

(2) Shock chlorination

Shock chlorination was performed at a free chlorine level of 200 mg/L with a contact time of two hours to reach the target CT value of 30, 000 m/L-min. The shock chlorination results for Bacillus subtilis are presented in Figure 3-22, and the calculated decontamination efficiency is shown in Table 3-26.

Because the cement-lined ductile iron pipe used in this study is quite smooth on the surfaces without corrosion tubercles, the chlorine demand from the pipe surfaces was not very significant, and the chlorine level could be maintained at the targeted value during the test. The test results indicated that the decontamination efficiency of shock chlorination for *Bacillus subtilis* ranged from 94 percent to 96 percent (i.e., 1.2 to 1.4 log removals). As mentioned previously, a literature review (Rose et al. (2005) and Rice et al. (2006)) indicated much higher Bacillus species removal (i.e., 2–3 log removals) from bulk water, using much lower CT values. Compared to these results, 96 percent inactivation (less than 2 log removal) of *Bacillus subtilis* from the cement-lined ductile iron pipe surfaces is not very promising, given the significantly higher CT value (30,000) applied in our study. Nevertheless, the relatively poor inactivation of *Bacillus subtilis* in our test is consistent with the AwwaRF's laboratory-scale test results for *Bacillus thuringiensis* (Welter et al., 2006), which demonstrates the difficulty of decontaminating microbes lodged on pipe surfaces. In addition, Szabo et al. (2007) also reported that similar experiments with high CT on corroded iron pipe did not remove *Bacillus* spores in the presence of free chlorine. As such, an increased CT value (e.g., higher chlorine concentration or longer contact time) might be necessary to achieve higher *Bacillus subtilis* inactivation efficiency.

Figure 3-22 Shock Chlorination Results for Bacillus subtilis Decontamination (Flow Rate for Adherence Study: 60 gpm Decontamination: Shock Chlorination)

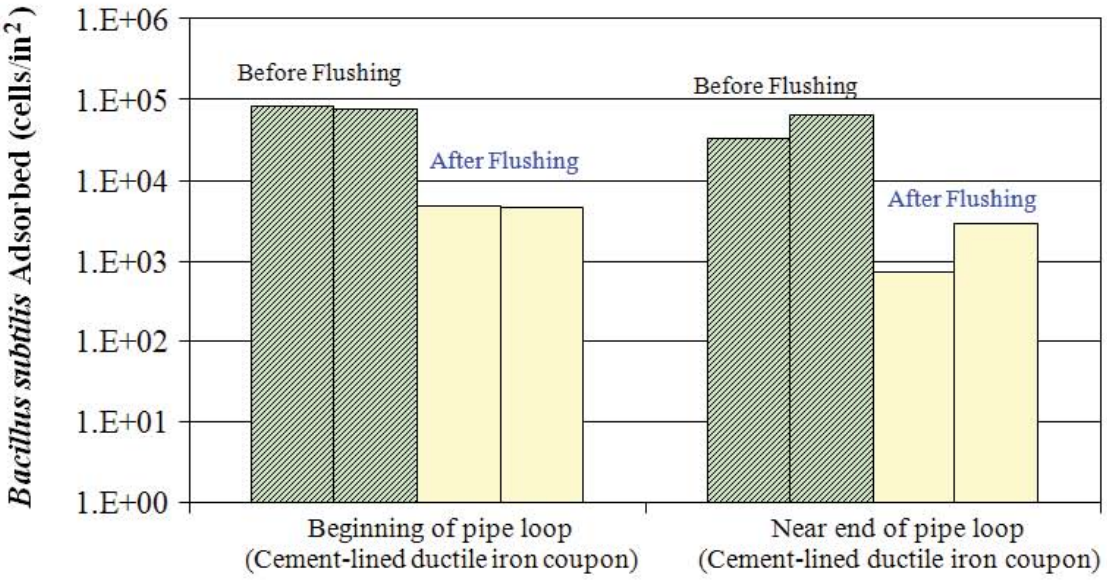


Table 3-26 Decontamination Efficiency of Shock Chlorination for *Bacillus subtilis*

Coupon Location		Beginning of pipe loop		Near end of pipe loop	
Before flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6
	Bacillus subtilis adsorbed (cells/in^2)	8.2E+04	7.7E+04	3.2E+04	6.5E+04
	Average (cells/in^2)[1]	7.9E+04		4.8E+04	
After flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10
	Bacillus subtilis remaining on coupon after decontamination (cells/in^2)	4.8E+03	4.3E+03	7.4E+02	2.8E+03
	Average (cells/in^2)[1]	4.6E+03		1.8E+03	
Decon Efficiency (%)[2]		94% (1.2 log removal)		96% (1.4 log removal)	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

3.2.3.4. Diesel Fuel Decontamination Test Results

Two different decontamination approaches were tested for diesel fuel decontamination: baseline water flushing and surfactant (Surfonic TDA-6) flushing. The results obtained from these two decontamination tests are discussed in the following subsections.

(1) Baseline water flushing

Simple water flushing was evaluated as the baseline decontamination method, and the results are plotted in Figure 3-23. It is apparent that the baseline water flushing approach removed diesel fuel from both the cement-lined ductile iron and clear PVC pipe surfaces. As shown in Table 3-27, the decontamination efficiency of the water flushing approach for diesel fuel is 36–38 percent for cement-lined ductile iron pipe and 74 percent for clear PVC pipe surface. Diesel fuel has stronger adherence to the ductile-iron pipe surfaces than to the clear PVC pipe surfaces. Simple water flushing proved to be an effective decontamination method to remove diesel fuel from the clear PVC pipe surfaces, while it was less effective for removal of diesel fuel from the ductile-iron pipe surfaces.

Figure 3-23 Simple Water Flushing Results for Diesel Fuel Decontamination
(Flow Rate for Adherence Study: 60 gpm Decontamination: Simple Water Flushing @ 210 gpm)

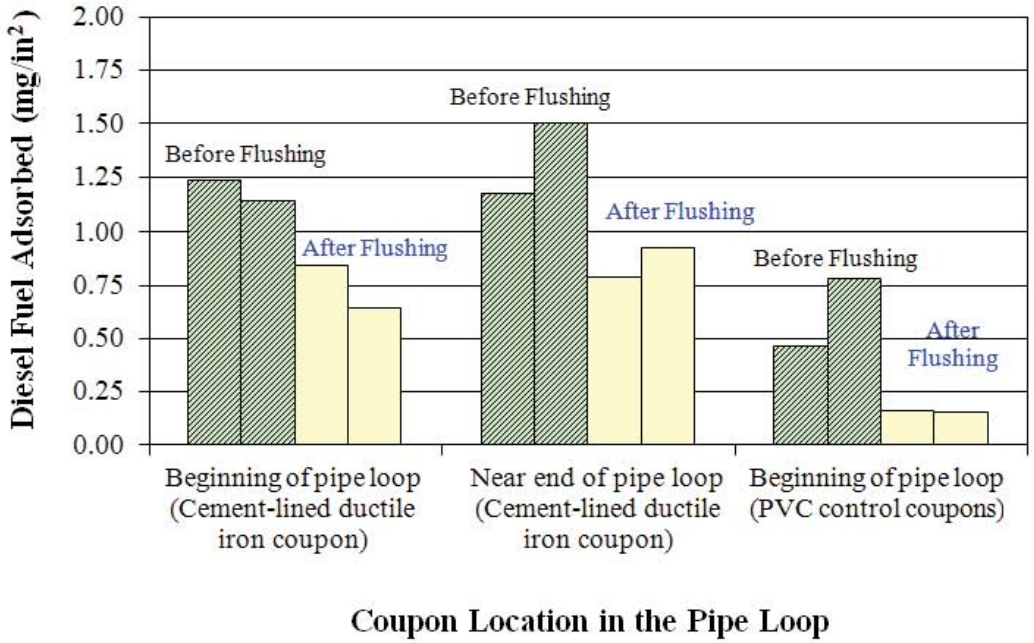


Table 3-27 Decontamination Efficiency of Simple Flushing for Diesel Fuel

Coupon Location		Beginning of pipe loop (Cement-lined Ductile Iron)		Near end of pipe loop (Cement-lined Ductile Iron)		Beginning of pipe loop (Clear PVC)	
Before flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6	Coupon #A	Coupon #B
	Diesel fuel adsorbed (mg/coupon)	23.5	21.7	22.4	28.5	8.7	14.8
	Average (mg/coupon)[1]	22.6		25.5		11.8	
After flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10	Coupon #C	Coupon #D
	Diesel fuel remaining on coupon after flushing (mg/coupon)	16.0	12.2	15.0	17.4	3.1	3.0
	Average (mg/coupon)[1]	14.1		16.2		3.1	
Decon Efficiency (%)[2]		38%		36%		74%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

(2) Surfactant (Surfonic TDA-6) flushing

Surfonic TDA-6 has been proven as a very effective decontamination reagent for removing chlordane from the drinking water pipe surfaces, according to AwwaRF's bench-scale study (Welter et al., 2006). Therefore, Surfonic TDA-6 was applied during the surfactant flushing of diesel fuel from the drinking water pipe surface.

The Surfonic TDA-6 decontamination test results for diesel fuel are presented in Figure 3-24, and the calculated decontamination efficiency is listed in Table 3-28. As can be seen from the results, Surfonic TDA-6 flushing is a very effective decontamination method for diesel fuel. After flushing with Surfonic TDA-6, there was no detectable diesel fuel on the cement-lined ductile iron coupon samples. Because the Surfonic TDA-6 compounds have interference with the diesel range organic (DRO) analysis, it is not feasible to calculate the actual decontamination efficiency of Surfonic TDA-6 flushing for diesel fuel from cement-lined ductile iron pipe surfaces. However, according to the input provided by DataChem Laboratories as well as the confirmation with GC analyses of these samples, it is ensured that there are no detectable diesel fuel compounds for the cement-lined ductile iron coupon samples after flushing. Therefore, the decontamination efficiency was calculated based on the initial diesel fuel adsorbed on coupons before flushing and the laboratory Estimated Quantification Limit (EQL). The Surfonic TDA-6 flushing approach showed >91 percent removal efficiency for diesel fuel from the cement-lined ductile iron pipe surfaces.

For PVC coupon samples, the Surfonic TDA-6 compounds did not show any interference for DRO analysis. However, these samples showed some peak integration issues with the C20–C34 range DRO analyses. (DRO result for each sample contains both the C10–C20 range DRO and C20–C34 range DRO.) Therefore, only C10–C20 range DRO values were considered during the calculation of decontamination efficiency. As most hydrocarbons in diesel fuel No. 2 belong to the C10–C20 range DRO, the decontamination efficiency calculated using the C10–C20 range DRO should be comparable to that calculated using the C10–C34 range DRO numbers. As can be seen from the results, Surfonic TDA-6 appears to be a very effective decontamination technique for removing diesel fuel from clear PVC pipe surfaces, as demonstrated by the removal efficiency of 78 percent for diesel fuel.

Figure 3-24 Surfonic TDA-6 Decontamination Results for Diesel Fuel Decontamination (Flow Rate for Adherence Study: 60 GPM Decontamination: Surfonic TDA-6 Flushing)

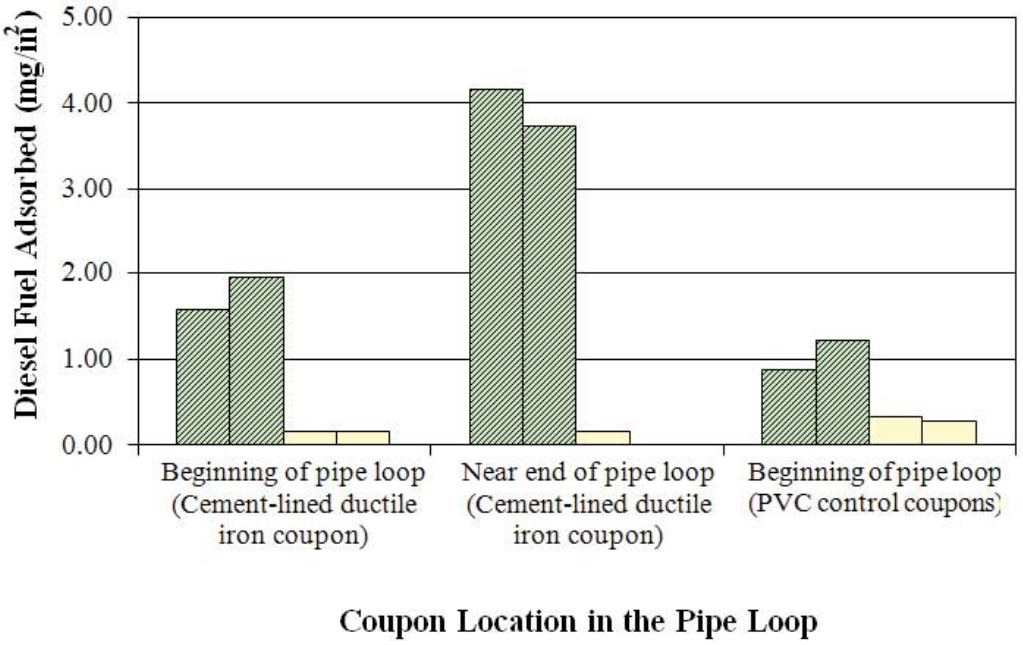


Table 3-28 Decontamination Efficiency of Surfonic TDA-6 Flushing for Diesel Fuel

Coupon Location		Beginning of pipe loop (Cement-lined Ductile Iron)		Near end of pipe loop (Cement-lined Ductile Iron)		Beginning of pipe loop (Clear PVC)	
Before flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6	Coupon #A	Coupon #B
	Diesel fuel adsorbed (mg/coupon)	30.0	37.5	79.0	70.9	17.0[5]	23.0[5]
	Average (mg/coupon)[1]	33.8	75.0	20.0			
After flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10	Coupon #C	Coupon #D
	Diesel fuel remaining on coupon after flushing (mg/coupon)	< 3.0[3]	< 3.0[3]	< 3.0[3]	NA[4]	5.0[5]	4.0[5]
	Average (mg/coupon)[1]	< 3.0		< 3.0		4.5	
Decon Efficiency (%)[2,6]		> 91%		> 96%		78%	

[1] The average numbers were rounded, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

[3] The DRO contamination in these samples is not diesel fuel. The identity of the compounds in these samples cannot be determined by GC/FID analysis, but from the information provided by DataChem Laboratories and from the chromatographs, it is probable that a high molecular weight surfactant is the source of the contamination.

[4] This sample appears to contain both diesel fuel contamination and the surfactant present in the previous samples. Therefore, a DRO number could not be determined for this sample.

[5] C20-C34 DRO analyses of Clear PVC coupon extraction samples showed some peak integration issues; therefore, only C10-C20 DRO numbers are used here.

[6] Because the diesel fuel compounds were not detected for the coupons after flushing, the decontamination efficiency was calculated based on the initial diesel fuel concentration on the coupons before the flushing and the Laboratory Reporting Limit for diesel fuel.

3.2.3.5. Chlordane Decontamination Test Results

Only one decontamination approach, i.e., surfactant (Surfonic TDA-6) flushing, was tested for the chlordane decontamination, to provide a comparison with the results from AwwaRF's laboratory-scale study. The results obtained from the Surfonic TDA-6 decontamination test for chlordane are discussed in the following subsection.

(1) Surfactant TDA-6 flushing

The Surfonic TDA-6 decontamination test results for chlordane are presented in Figure 3-25, and the calculated decontamination efficiency is listed in Table 3-29. As can be seen from the results, Surfonic TDA-6 effectively removed chlordane from both cement-lined ductile iron and clear PVC pipe surfaces. After flushing with Surfonic TDA-6, the amount of chlordane adsorbed on the coupon surfaces reduced significantly. The decontamination efficiency of Surfonic TDA-6 flushing for chlordane was calculated using the alpha and gamma chlordane values, and the results indicated that the Surfonic TDA-6 flushing is a very promising decontamination approach for chlordane. The decontamination efficiency ranged between 89 percent and 91 percent for the cement-lined ductile iron pipe material and was 99 percent for the clear PVC pipe material. The decontamination efficiency calculated by the technical chlordane values (not shown in Table 3-29) were the same as that calculated by the alpha and gamma chlordane values.

The excellent removal of chlordane by Surfonic TDA-6 observed in the pilot-scale decontamination test matches very well with AwwaRF's laboratory-scale test results. In the AwwaRF study, Surfonic TDA-6 was one of the three surfactants that showed very good removal of chlordane from chlorinated polyvinyl chloride (cPVC), heavily corroded galvanized iron, and epoxy-coated steel pipes with decontamination efficiencies of approximately 90 percent.

Figure 3-25 Surfonic TDA-6 Decontamination Results for Chlordane Decontamination (Flow Rate for Adherence Study: 60 gpm Decontamination: Surfonic TDA-6 Flushing)

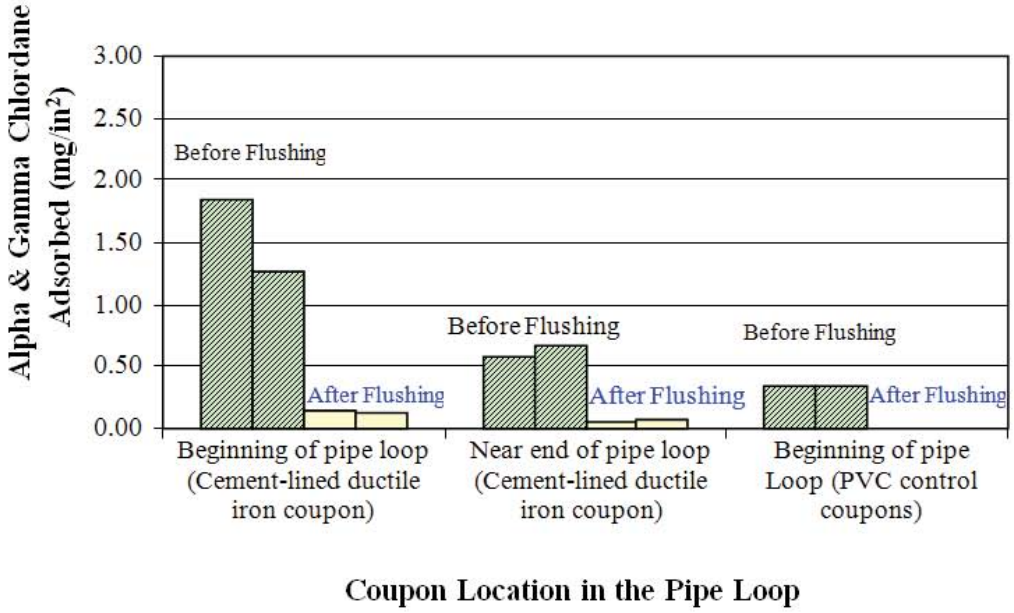


Table 3-29 Decontamination Efficiency of Surfonic TDA-6 Flushing for Chlordane

Coupon Location		Beginning of pipe loop (Cement-lined Ductile Iron)		Near end of pipe loop (Cement-lined Ductile Iron)		Beginning of pipe loop (Clear PVC)	
Before flushing	Coupon ID	Coupon #3	Coupon #4	Coupon #5	Coupon #6	Coupon #A	Coupon #B
	Alpha & Gamma chlordane adsorbed (mg/coupon)	35.0	24.0	11.0	12.8	6.5	6.4
	Average (mg/coupon)[1]	29.5		11.9		6.5	
After flushing	Coupon ID	Coupon #7	Coupon #8	Coupon #9	Coupon #10	Coupon #C	Coupon #D
	Alpha & Gamma chlordane remaining on coupon after flushing (mg/coupon)	2.9	2.4	1.2	1.4	0.025	0.080
	Average (mg/coupon)[1]	2.7		1.3		0.053	
Decon Efficiency (%)[2]		91%		89%		99%	

[1] The average numbers were rounded to two significant figures, consistent with the laboratory-reported numbers.

[2] The decontamination percent removals were calculated (i.e., generated by Excel), using the nonrounded average numbers, to represent a more accurate calculation. The resulting efficiency value was rounded to two significant figures.

3.2.3.6. Summary of Decontamination Test Results

Table 3-30 presents a summary of the performance of various decontamination techniques for the target contaminants tested in this study. Percent removals of each decontamination method for each contaminant are presented in Table 3-30. Because conduct of the pilot-scale adherence/decontamination tests is time-intensive and expensive, a single test run was conducted for each test condition. The variability in the decontamination effectiveness was assessed by the different coupons employed within the pipe loop system. As such, compared to the quantitative statements, a qualitative rating would be more appropriate in summarizing the effectiveness of the decontamination methods in this study. Therefore, qualitative ratings of the various decontamination methods are also indicated in Table 3-30.

For arsenic, mercury, and *Bacillus subtilis*, various decontamination methods were evaluated for the cement-lined ductile iron pipe material only. As can be seen from Table 3-30, for arsenic, baseline water flushing and low-pH flushing resulted in average removal of arsenic; while phosphate buffer flushing showed poor removal for arsenic. Acidified potassium permanganate flushing and flushing with several NSF Standard 60 Products showed good arsenic removal. For mercury, baseline water flushing and low-pH flushing showed average level of effectiveness as decontamination methods for mercury. Acidified potassium permanganate flushing was very effective in decontamination of mercury. Baseline water flushing resulted in no removal of *Bacillus subtilis*. Shock chlorination showed an average level of decontamination efficiency for *Bacillus subtilis*. For diesel fuel and chlordane, the performance of decontamination techniques was evaluated on both cement-lined ductile iron and the clear PVC pipe materials. As shown in Table 3-30, baseline water flushing showed average effectiveness in removal of diesel fuel from cement-lined ductile iron pipe surfaces, while it showed good removal of diesel fuel from the clear PVC pipe surfaces. The Surfonic TDA-6 flushing resulted in very high removal efficiencies for diesel fuel and chlordane from both cement-lined ductile iron and the clear PVC pipes surfaces.

Table 3-30 Performance of Decontamination Techniques for Various Target Contaminants

Contaminants	Decontamination Method	Decontamination Efficiency for Cement-lined Ductile Iron Pipe	Qualitative Performance Rating[1]
Arsenic	Water flushing	-7 – 51%	Average
	Low-pH	6 – 36%	Average
	Phosphate buffer	-24 – -16%	Poor
	Acidified potassium permanganate	54 – 61%	Good
	NW-310/NW-400	46 – 65%	Good
	Floran Biogrowth Remover / Catalyst	63 – 67%	Good
	Floran Top Ultra / Catalyst	23 – 68%	Average
Mercury	Water flushing	19 – 46%	Average
	Low-pH	21 – 23%	Average
	Acidified potassium permanganate	72 – 96%	Excellent
Bacillus subtilis	Water flushing	-29 – -11%	Poor
	Shock chlorination	94 – 96% (1.2-1.4 log removal)	Average
Diesel fuel	Water flushing	36 – 38%	Average
		74% (for clear PVC pipe)	Good
	Surfonic TDA-6	> 91%	Excellent
		78% (for clear PVC pipe)	Good
Chlordane	Surfonic TDA-6	89 – 91%	Excellent
		99% (for clear PVC pipe)	Excellent

[1] The qualitative performance ratings are defined in terms of percent/log removal as shown below:

For Chemical Contaminants	
< 20%	Poor
20–50%	Average
50–80%	Good
> 80%	Excellent

For Biological Contaminants	
< 1 log removal	Poor
1–2 log removal	Average
2–3 log removal	Good
> 3 log removal	Excellent

4.0 Conclusions

A pilot-scale experimental test program was conducted at the EPA T&E Facility over the past two years to investigate the potential of target contaminants (arsenic, mercury, *Bacillus subtilis*, diesel fuel, and chlordane) for adherence to drinking water pipe surfaces and to evaluate various decontamination approaches for removing target contaminants from the pipe surfaces.

The contaminant adherence study demonstrated that all the contaminants tested have a strong tendency to adhere to cement-lined ductile iron pipe surfaces. The adherence capacity of target contaminants to the clear PVC pipe surfaces varied significantly. Bacillus subtilis showed strong adherence to both the cement-lined ductile iron and clear PVC pipe surfaces. Diesel fuel and chlordane showed lower adherence to clear PVC pipe than to the cement-lined ductile iron pipe surfaces. Arsenic and mercury showed much stronger adherence to cement-lined ductile iron pipe surfaces than to the clear PVC pipe surfaces. It was also found that mercury has stronger adherence to cement-lined ductile iron pipe surfaces compared to arsenic.

Experiments studying the effects of flow rates on the adherence of contaminants to the pipe surfaces indicated that the inorganic contaminants tested (i.e., arsenic and mercury) adhere to the cement-lined ductile iron pipe surfaces at both flow regimes, laminar and turbulent. It was found that the adherence of arsenic and mercury to pipe surfaces is higher under turbulent flow conditions.

Various decontamination techniques were evaluated to assess their effectiveness in removing target contaminants from cement-lined ductile iron pipe and clear PVC pipe surfaces. From the decontamination tests performed for arsenic, it was found that acidified potassium permanganate and NSF Standard 60 Products flushing showed the most promise as effective decontamination methods for arsenic from cement-lined ductile iron pipe surfaces. Baseline water flushing and low-pH flushing resulted in average removals of arsenic.

Experiments evaluating the removal efficiency of various decontamination methods for mercury indicated that acidified potassium permanganate flushing is very effective in decontamination of mercury from the cement-lined ductile iron pipe surfaces. Baseline water flushing and low-pH flushing showed average removal of mercury from cement-lined ductile iron pipe surfaces.

The shock chlorination of *Bacillus subtilis* at a CT value of 30, 000 mg/L-min. showed an average level of effectiveness for removal of *Bacillus subtilis* from cement-lined ductile iron pipe surfaces. Baseline water flushing resulted in no removal of *Bacillus subtilis* from the cement-lined ductile iron pipe surfaces.

The decontamination tests conducted for diesel fuel indicated that Surfonic TDA-6 is a very effective decontamination reagent for diesel fuel from both cement-lined ductile iron and clear PVC pipe surfaces. Baseline water flushing showed lower effectiveness as a decontamination method for diesel fuel.

The result of the pilot-scale decontamination test performed for chlordane indicated that Surfonic TDA-6 is very effective for removal of chlordane from cement-lined ductile iron and clear PVC pipe surfaces. This result confirmed the findings from AwwaRF's laboratory-scale tests, which also demonstrated very high decontamination efficiency of Surfonic TDA-6 for the removal of chlordane from various types of pipe materials, including cPVC, heavily corroded galvanized iron, and epoxy-coated steel pipes.

The pilot-scale adherence/decontamination study provides valuable information on the adherence potential of various contaminants to drinking water pipe surfaces and the performance of a variety of decontamination techniques on real-world pipe materials under realistic conditions. Additional experiments are needed to obtain data on other pipe surface materials and to attain statistically significant data over a full range of operating conditions. And many of the conclusions drawn from this study are qualitative rather than quantitative. Modeling approaches are recommended to validate the test results attained from this study and to predict performance for other pipe materials/contaminant scenarios.

5.0
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Appendix A
Contaminant Adherence/Decontamination
Test Results Data

Table A-1 Experimental Results from Test Run ID: As F1
(Adherence study flow rate: 1 gpm, Decontamination: simple water flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Arsenic concentration (mg/L)	Coupon ID	Arsenic concentration (mg/coupon)
Baseline		Just prior to injection	As F1 T0	ND	Coupon #1	0.029
			As F1 T0 Dup	ND	Coupon #2[a]	4.3 x10^5 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	As F1 T5M	ND		
			As F1 T5M Dup	ND		
		1 day after injection	As F1 T1D	10.4		
			As F1 T1D Dup	8.7		
		2 days after injection	As F1 T2D	9.6		
			As F1 T2D Dup	9.5		
	After 2-day contact period	After draining loop			Control coupon A	0.24
					Control coupon B	0.097
					Coupon #3	1.0
					Coupon #4	2.1
					Coupon #5	1.5
					Coupon #6	1.6
Decontamination Study (Flushing)		Prior to draining loop	As F1 Decon	0.99		
			As F1 Decon Dup	0.97		
		After draining loop			Coupon #7	0.84
					Coupon #8	1.0
					Coupon #9	0.78
					Coupon #10	0.88

[a] Coupon #2 was taken for HPC analysis to check the biofilm development.

Table A-2 Experimental Results From Test Run ID: As F15
(Adherence study flow rate: 15 gpm, Decontamination: simple water flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Arsenic concentration (mg/L)	Coupon ID	Arsenic concentration (mg/coupon)
Baseline		Just prior to injection	As F15 T0	0.0042	Coupon #1	0.052
			As F15 T0 Dup	0.0034	Coupon #2[a]	1.8 x10^5 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	As F15 T5M	2.6		
			As F15 T5M Dup	1.6		
		1 day after injection	As F15 T1D	9.3		
			As F15 T1D Dup	9.3		
		2 days after injection	As F15 T2D	9.3		
			As F15 T2D Dup	9.3		
	After 2-day contact period	After draining loop			Control coupon A	0.37
					Control coupon B	0.18
					Coupon #3	2.1
					Coupon #4	2.8
					Coupon #5	0.81
					Coupon #6	1.5
Decontamination Study (Flushing)		Prior to draining loop	As F15 Decon	2.9		
			As F15 Decon Dup	3.0		
		After draining loop			Coupon #7	2.8
					Coupon #8	2.6
					Coupon #9	1.9
					Coupon #10	1.7

[a] Coupon #2 was taken for HPC analysis to check the biofilm development.

Table A-3 Experimental Results From Test Run ID: As F60
(Adherence study flow rate: 60 gpm, Decontamination: simple water flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Arsenic concentration (mg/L)	Coupon ID	Arsenic concentration (mg/coupon)
Baseline		Just prior to injection	As F60 T0	0.0036	Coupon #1	0.024
			As F60 T0 Dup	0.0052	Coupon #2[a]	1.1 x10^5 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	As F60 T5M	9.6		
			As F60 T5M Dup	10.4		
		1 day after injection	As F60 T1D	9.5		
			As F60 T1D Dup	8.8		
		2 days after injection	As F60 T2D	8.9		
			As F60 T2D Dup	8.9		
	After 2-day contact period	After draining loop			Control coupon A	0.11
					Control coupon B	0.64
					Coupon #3	1.9
					Coupon #4	4.2
					Coupon #5	4.9
					Coupon #6	6.5
Decontamination Study (Flushing)		Prior to draining loop	As F60 Decon	0.39		
			As F60 Decon Dup	0.57		
		After draining loop			Coupon #7	2.7
					Coupon #8	3.8
					Coupon #9	2.7
					Coupon #10	2.9

[a] Coupon #2 was taken for HPC analysis to check the biofilm development.

Table A-4 Experimental Results From Test Run ID: As pH4
(Adherence study flow rate: 60 gpm, Decontamination: pH 4 flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Arsenic concentration (mg/L)	Coupon ID	Arsenic concentration (mg/coupon)
Baseline		Just prior to injection	As pH 4 T0	ND[a]	Coupon #1	0.036
			As pH 4 T0 Dup	ND[a]	Coupon #2[b]	1.4 x10^5 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	As pH 4 T5M	9.4		
			As pH 4 T5M Dup	9.0		
		1 day after injection	As pH 4 T1D	8.4		
			As pH 4 T1D Dup	8.3		
		2 days after injection	As pH 4 T2D	7.9		
			As pH 4 T2D Dup	8.3		
	After 2-day contact period	After draining loop			Control coupon A	0.25
					Control coupon B	0.27
					Coupon #3	3.6
					Coupon #4	2.6
					Coupon #5	4.6
					Coupon #6	3.0
Decontamination Study (Flushing)		After low-pH water recirculation	As pH 4 Decon	1.1		
			As pH 4 Decon Dup	1.1		
		After simple water flushing	As pH 4 Decon 2	0.0077		
			As pH 4 Decon 2 Dup	ND		
		After draining loop			Coupon #7	2.5
					Coupon #8	3.3
					Coupon #9	2.2
					Coupon #10	2.7

[a] ND: nondetectable.

[b] Coupon #2 was taken for HPC analysis to check for biofilm development.

Table A-5 Experimental Results From Test Run ID: As Phos
(Adherence study flow rate: 60 gpm, Decontamination: phosphate buffer flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Arsenic concentration (mg/L)	Coupon ID	Arsenic concentration (mg/coupon)
Baseline		Just prior to injection	As Phos T0	ND[a]	Coupon #1	0.013
			As Phos T0 Dup	ND[a]	Coupon #2[b]	$2x10^6$ cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	As Phos T5M	9.5		
			As Phos T5M Dup	9.9		
		1 day after injection	As Phos T1D	9.0		
			As Phos T1D Dup	8.8		
		2 days after injection	As Phos T2D	8.3		
			As Phos T2D Dup	8.5		
	After 2-day contact period	After draining loop			Control coupon A	0.29
					Control coupon B	0.45
					Coupon #3	5.0
					Coupon #4	6.2
					Coupon #5	5.3
					Coupon #6	3.9
Decontamination Study (Phosphate Buffer Flushing)		After phosphate buffer flushing	As Phos Decon	1.3		
			As Phos Decon Dup	1.4		
		After draining loop			Coupon #7	5.9
					Coupon #8	7.1
					Coupon #9	7.0
					Coupon #10	4.4

[a] ND: nondetectable

[b] Coupon #2 was taken for HPC analysis to check for biofilm development.

Table A-6 Experimental Results From Test Run ID: As KMnO4
(Adherence study flow rate: 60 gpm, Decontamination: acidified permanganate flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Mercury concentration (mg/L)	Coupon ID	Mercury concentration (mg/coupon)
Baseline		Just prior to injection	As KMnO4 T0	ND	Coupon #1	0.15
			As KMnO4 T0 Dup	ND	Coupon #2[b]	2.9X10^5 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	As KMnO4 T5M	10.3		
			As KMnO4 T5M Dup	10.0		
		1 day after injection	As KMnO4 T1D	9.0		
			As KMnO4 T1D Dup	9.6		
		2 days after injection	As KMnO4 T2D	9.1		
			As KMnO4 T2D Dup	8.9		
	After 2-day contact period	After draining loop			Control coupon A	0.28
					Control coupon B	0.44
					Coupon #3	6.2
					Coupon #4	6.3
					Coupon #5	5.3
					Coupon #6	3.7
Decontamination Study (Acidified Potassium Permanganate Flushing)		After acidified potassium permanganate flushing	As KMnO4 Decon	1.3		
			As KMnO4 Decon Dup	0.87		
		After draining loop			Coupon #7	2.9
					Coupon #8	2.8
					Coupon #9	1.9
					Coupon #10	1.6

[a] Coupon #2 was taken for HPC analysis to check for biofilm development.

Table A-7 Experimental Results From Test Run ID: As NW
(Adherence study flow rate: 60 gpm, Decontamination: NW-310/NW-400 flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Arsenic concentration (mg/L)	Coupon ID	Arsenic concentration (mg/coupon)
Baseline		Just prior to injection	As NW T0	ND[a]	Coupon #1	0.073
			As NW T0 Dup	ND[a]	Coupon #2[b]	3.7X10^6 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	As NW T5M	8.9		
			As NW T5M Dup	9.1		
		1 day after injection	As NW T1D	8.2		
			As NW T1D Dup	8.0		
		2 days after injection	As NW T2D	7.8		
			As NW T2D Dup	8.0		
	After 2-day contact period	After draining loop			Control coupon A	0.26
					Control coupon B	0.46
					Coupon #3	1.4
					Coupon #4	2.7
					Coupon #5	1.6
					Coupon #6	1.7
Decontamination Study (NW-310/NW-400 Flushing)		After NW-310/NW-400 flushing	As NW Decon	1.2		
			As NW Decon Dup	1.5		
		After draining loop			Coupon #7	1.6
					Coupon #8	0.63
					Coupon #9	0.47
					Coupon #10	0.67

[a] ND: nondetectable

[b] Coupon #2 was taken for HPC analysis to check for biofilm development.

Table A-8 Experimental Results From Test Run ID: As Floran I
(Adherence study flow rate: 60 gpm, Decontamination: Floran Biogrowth Remover/Catalyst flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Arsenic concentration (mg/L)	Coupon ID	Arsenic concentration (mg/coupon)
Baseline		Just prior to injection	As Floran I T0	ND[a]	Coupon #1	0.073
			As Floran I T0 Dup	ND[a]	Coupon #2[b]	$8.7X10^5$ cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	As Floran I T5M	10.4		
			As Floran I T5M Dup	9.3		
		1 day after injection	As Floran I T1D	8.9		
			As Floran I T1D Dup	9.3		
		2 days after injection	As Floran I T2D	8.8		
			As Floran I T2D Dup	9.4		
	After 2-day contact period	After draining loop			Control coupon A	0.41
					Control coupon B	0.53
					Coupon #3	5.6
					Coupon #4	6.0
					Coupon #5	5.6
					Coupon #6	5.1
Decontamination Study (Floran Biogrowth Remover/ Catalyst Flushing) Catalyst Flushing		After Floran Biogrowth Remover/	As Floran I Decon	0.84		
			As Floran I Decon Dup	0.86		
		After draining loop			Coupon #7	2.3
					Coupon #8	1.5
					Coupon #9	1.5
					Coupon #10	2.5

[a] ND: nondetectable

[b] Coupon #2 was taken for HPC analysis to check for biofilm development.

Table A-9 Experimental Results From Test Run ID: As Floran II
(Adherence study flow rate: 60 gpm, Decontamination: Floran Top Ultra/Catalyst flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Arsenic concentration (mg/L)	Coupon ID	Arsenic concentration (mg/coupon)
Baseline		Just prior to injection	As Floran II T0	ND[a]	Coupon #1	0.046
			As Floran II T0 Dup	ND[a]	Coupon #2[b]	2.2X10^6 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	As Floran II T5M	9.9		
			As Floran II T5M Dup	10.2		
		1 day after injection	As Floran II T1D	9.2		
			As Floran II T1D Dup	8.5		
		2 days after injection	As Floran II T2D	8.6		
			As Floran II T2D Dup	8.6		
	After 2-day contact period	After draining loop			Control coupon A	0.48
					Control coupon B	0.40
					Coupon #3	6.4
					Coupon #4	4.8
					Coupon #5	5.2
					Coupon #6	2.8
Decontamination Study (Floran Top Ultra/Catalyst Flushing) Catalyst Flushing		After Floran Top Ultra/	As Floran II Decon	1.4		
			As Floran II Decon Dup	1.4		
		After draining loop			Coupon #7	1.9
					Coupon #8	1.7
					Coupon #9	2.6
					Coupon #10	3.6

[a] ND: nondetectable

[b] Coupon #2 was taken for HPC analysis to check for biofilm development.

Table A-10 Experimental Results From Test Run ID: Hg F1
(Adherence study flow rate: 1 gpm, Decontamination: simple water flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Mercury concentration (mg/L)	Coupon ID	Mercury concentration (mg/coupon)
Baseline		Just prior to injection	Hg F1 T0	0.00005	Coupon #1	0.00036
			Hg F1 T0 Dup	0.000068	Coupon #2[a]	2.8 x10^6 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	Hg F1 T5M	0.000075		
			Hg F1 T5M Dup	0.000079		
		1 day after injection	Hg F1 T1D	9.3		
			Hg F1 T1D Dup	8.9		
		2 days after injection	Hg F1 T2D	9.6		
			Hg F1 T2D Dup	9.5		
	After 2-day contact period	After draining loop			Control coupon A	0.49
					Control coupon B	0.048
					Coupon #3	4.0
					Coupon #4	2.2
					Coupon #5	1.2
					Coupon #6	3.3
Decontamination Study (Flushing)		Prior to draining loop	Hg F1 Decon	0.37		
			Hg F1 Decon Dup	0.44		
		After draining loop			Coupon #7	3.8
					Coupon #8	3.5
					Coupon #9	2.0
					Coupon #10	0.71

[a] Coupon #2 was taken for HPC analysis to check for biofilm development.

Table A-11 Experimental Results From Test Run ID: Hg F15
(Adherence study flow rate: 15 gpm, Decontamination: simple water flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Mercury concentration (mg/L)	Coupon ID	Mercury concentration (mg/coupon)
Baseline		Just prior to injection	Hg F15 T0	0.0016	Coupon #1	0.073
			Hg F15 T0 Dup	0.0016	Coupon #2[a]	1.4 x10^3 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	Hg F15 T5M	9.6		
			Hg F15 T5M Dup	4		
		1 day after injection	Hg F15 T1D	10.7		
			Hg F15 T1D Dup	8.4		
		2 days after injection	Hg F15 T2D	8.1		
			Hg F15 T2D Dup	7.8		
	After 2-day contact period	After draining loop			Control coupon A	0.083
					Control coupon B	2.3
					Coupon #3	9.6
					Coupon #4	12.7
					Coupon #5	4.3
					Coupon #6	8.1
Decontamination Study (Flushing)		Prior to draining loop	Hg F15 Decon	0.23		
			Hg F15 Decon Dup	0.28		
		After draining loop			Coupon #7	4.7
					Coupon #8	5.0
					Coupon #9	7.5
					Coupon #10	2.6

[a] Coupon #2 was taken for HPC analysis to check for biofilm development.

Table A-12 Experimental Results From Test Run ID: Hg F60
(Adherence study flow rate: 60 gpm, Decontamination: simple water flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Mercury concentration (mg/L)	Coupon ID	Mercury concentration (mg/coupon)
Baseline		Just prior to injection	Hg F60 T0	0.003	Coupon #1	0.093
			Hg F60 T0 Dup	0.0025	Coupon #2[a]	3.3 x10^6 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	Hg F60 T5M	11		
			Hg F60 T5M Dup	10.5		
		1 day after injection	Hg F60 T1D	9.7		
			Hg F60 T1D Dup	9.7		
		2 days after injection	Hg F60 T2D	8.8		
			Hg F60 T2D Dup	9.4		
	After 2-day contact period	After draining loop			Control coupon A	0.078
					Control coupon B	0.94
					Coupon #3	25.5
					Coupon #4	37.8
					Coupon #5	50.8
					Coupon #6	23.8
Decontamination Study (Flushing)		Prior to draining loop	Hg F60 Decon	0.63		
			Hg F60 Decon Dup	0.61		
		After draining loop			Coupon #7	39.6
					Coupon #8	11.4
					Coupon #9	20.4
					Coupon #10	19.9

[a] Coupon #2 was taken for HPC analysis to check for biofilm development.

Table A-13 Experimental Results From Test Run ID: Hg pH4
(Adherence study flow rate: 60gpm, Decontamination: pH 4 flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Mercury concentration (mg/L)	Coupon ID	Mercury concentration (mg/coupon)
Baseline		Just prior to injection	Hg pH 4 T0	0.0011	Coupon #1	0.024
			Hg pH 4 T0 Dup	0.0012	Coupon #2[a]	1.3 x10^5 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	Hg pH 4 T5M	9.6		
			Hg pH 4 T5M Dup	10.4		
		1 day after injection	Hg pH 4 T1D	9.7		
			Hg pH 4 T1D Dup	9.2		
		2 days after injection	Hg pH 4 T2D	7.6		
			Hg pH 4 T2D Dup	8.6		
	After 2-day contact period	After draining loop			Control coupon A	0.51
					Control coupon B	1.2
					Coupon #3	27.0
					Coupon #4	24.1
					Coupon #5	23.9
					Coupon #6	16.3
DecontaminationStudy (Flushing)		After low-pH water recirculation	Hg pH 4 Decon	0.86		
			Hg pH 4 Decon Dup	0.89		
		After simple water flushing	Hg pH 4 Decon 2	0.0035		
			Hg pH 4 Decon 2 Dup	0.010		
		After draining loop			Coupon #7	15.0
					Coupon #8	24.3
					Coupon #9	14.4
					Coupon #10	17.2

[a] Coupon #2 was taken for HPC analysis to check for biofilm development.

Table A-14 Experimental Results From Test Run ID: Hg KMnO4
(Adherence study flow rate: 60 gpm, Decontamination: acidified permanganate flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Mercury concentration (mg/L)	Coupon ID	Mercury concentration (mg/coupon)
Baseline		Just prior to injection	Hg KMnO4 T0	0.0014	Coupon #1	0.0093
			Hg KMnO4 T0 Dup	0.0012	Coupon #2[a]	1.2 X10^5 cells/cm^2
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	Hg KMnO4 T5M	9.0		
			Hg KMnO4 T5M Dup	5.2		
		1 day after injection	Hg KMnO4 T1D	18		
			Hg KMnO4 T1D Dup	6.3		
		2 days after injection	Hg KMnO4 T2D	5.3		
			Hg KMnO4 T2D Dup	6.8		
	After 2-day contact period	After draining loop			Control coupon A	0.47
					Control coupon B	0.12
					Coupon #3	4.5
					Coupon #4	8.5
					Coupon #5	3.7
					Coupon #6	5.5
Decontamination Study (Acidified Potassium Permanganate Flushing)		After acidified potassium permanganate Flushing	Hg KMnO4 Decon	0.58		
			Hg KMnO4 Decon Dup	0.53		
		After draining loop			Coupon #7	0.25
					Coupon #8	0.33
					Coupon #9	1.4
					Coupon #10	1.2

[a] Coupon #2 was taken for HPC analysis to check for biofilm development.

Table A-15 Experimental Results From Test Run ID: BS F60
(Adherence study flow rate: 60 gpm, Decontamination: simple water flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	*Bacillus subtilis* concentration (cells/mL)	Coupon ID	*Bacillus subtilis* concentration (cells/in^2)
Baseline		Just prior to injection	BS F60 T0	0	Coupon #1	16
			BS F60 T0 Dup	0	Coupon #2[(a)]	5.3 x10^5 cells/ cm$^{2(a)}$
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	BS F60 T5M	880		
			BS F60 T5M Dup	900		
		1 day after injection	BS F60 T1D	720		
			BS F60 T1D Dup	800		
		2 days after injection	BS F60 T2D	330		
			BS F60 T2D Dup	410		
	After 2-day contact period	After draining loop			Control coupon A	1.8E+04
					Control coupon B	7.1E+03
					Coupon #3	4.6E+04
					Coupon #4	3.3E+04
					Coupon #5	5.5E+04
					Coupon #6	5.6E+04
Decontamination Study (Flushing)		Prior to draining loop	BS F60 Decon	800		
			BS F60 Decon Dup	500		
		After draining loop			Coupon #7	5.4E+04
					Coupon #8	4.8E+04
					Coupon #9	7.5E+04
					Coupon #10	4.9E+04

[(a)] Coupon #2 was taken for HPC analysis to check the biofilm development.

Table A-16 Experimental Results From Test Run ID: BS CT30K
(Adherence study flow rate: 60 gpm, Decontamination: shock chlorination)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	*Bacillus subtilis* concentration (cells/mL)	Coupon ID	*Bacillus subtilis* concentration (cells/in²)
Baseline		Just prior to injection	BS CT30K T0	7	Coupon #1	17
			BS CT30K T0 Dup	5	Coupon #2[(a)]	7.6 x10^5 cells/ cm$^{2(a)}$
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	BS CT30K T5M	5300		
			BS CT30K T5M Dup	5400		
		1 day after injection	BS CT30K T1D	1000		
			BS CT30K T1D Dup	1200		
		2 days after injection	BS CT30K T2D	680		
			BS CT30K T2D Dup	950		
	After 2-day contact period	After draining loop			Control coupon A	5.7E+04
					Control coupon B	3.4E+04
					Coupon #3	8.2E+04
					Coupon #4	7.7E+04
					Coupon #5	3.2E+04
					Coupon #6	6.5E+04
Decontamination Study (Flushing)		Prior to draining loop	BS CT30K Decon	0		
			BS CT30K Decon Dup	0		
		After draining loop			Coupon #7	4.8E+03
					Coupon #8	4.3E+03
					Coupon #9	7.4E+02
					Coupon #10	2.8E+03

[(a)] Coupon #2 was taken for HPC analysis to check the biofilm development.

Table A-17 Experimental Results from Test Run ID: DRO F60
(Adherence study flow rate: 60 gpm, Decontamination: simple water flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Diesel fuel concentration (mg/L)	Coupon ID	Diesel fuel concentration (mg/coupon)
Baseline		Just prior to injection	DRO F60 T0	ND[a]	Coupon #1	14.0[b]
			DRO F60 T0 Dup	ND[a]	Coupon #2[b]	4.8 x 10^5 cells/ cm^2 [c]
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	DRO F60 T5M	13.1		
			DRO F60 T5M Dup	11.1		
		1 day after injection	DRO F60 T1D	3.9		
			DRO F60 T1D Dup	1.3		
		2 days after injection	DRO F60 T2D	ND		
			DRO F60 T2D Dup	0.7		
	After 2-day contact period	After draining loop			Control coupon A	8.7
					Control coupon B	14.8
					Coupon #3	23.5
					Coupon #4	21.7
					Coupon #5	22.4
					Coupon #6	28.5
		Prior to draining loop	DRO F60 Decon	3.5		
			DRO F60 Decon Dup	4.0		
Decontamination Study (Flushing)		After draining loop			Control coupon C	3.1
					Control coupon D	3.0
					Coupon #7	16.0
					Coupon #8	12.2
					Coupon #9	15.0
					Coupon #10	17.4

[a] ND: nondetectable

[a] Diesel Range Organics were detected for coupon #1. However, according to the chromatograph these compounds were not diesel fuel compounds.

[b] Coupon #2 was taken for HPC analysis to check the biofilm development.

Table A-18 Experimental Results From Test Run ID: DRO TDA
(Adherence study flow rate: 60 gpm, Decontamination: Surfonic TDA–6 flushing)

Event		Sampling Time	Bulk Water Samples		Coupon Samples	
			Sample ID	Diesel fuel concentration (mg/L)	Coupon ID	Diesel fuel concentration (mg/coupon)
Baseline		Just prior to injection	DRO TDA T0	ND[a]	Coupon #1	5.0[b]
			DRO TDA T0 Dup	ND[a]	Coupon #2[b]	3.9 x 10^6 cells/ cm^{2}[c]
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	DRO TDA T5M	11		
			DRO TDA T5M Dup	9.9		
		1 day after injection	DRO TDA T1D	1.8		
			DRO TDA T1D Dup	0.8		
		2 days after injection	DRO TDA T2D	ND		
			DRO TDA T2D Dup	0.7		
	After 2-day contact period	After draining loop			Control coupon A	22.3
					Control coupon B	28.6
					Coupon #3	30.0
					Coupon #4	37.5
					Coupon #5	79.0
					Coupon #6	70.9
Decontamination Study (Flushing)		Prior to draining loop	DRO TDA Decon	14500[d]		
			DRO TDA Decon Dup	14500[d]		
		After draining loop			Control coupon C	15.0[d]
					Control coupon D	14.0[d]
					Coupon #7	20.8[e]
					Coupon #8	24.0[e]
					Coupon #9	30.0[e]
					Coupon #10	45.0[f]

[a] ND: nondetectable

[b] Diesel Range Organics (DRO) were detected for coupon #1. However, according to the chromatograph these compounds were not diesel fuel compounds.

[c] Coupon #2 was taken for HPC analysis to check the biofilm development.

[d] C20-C34 DRO analyses of Clear PVC coupon extraction samples showed some peak integration issues; therefore, only C10-C20 DRO numbers are used here.

[e] The DRO contamination in these samples is not diesel fuel. The identity of the compounds in these samples cannot be determined by GC/FID analysis, but from the information provided by DataChem Laboratories and from the chromatographs, it is probable that a high molecular weight surfactant is the source of the contamination.

[f] This sample appears to contain both diesel fuel contamination and the surfactant present in the previous samples.

Table A-19 Experimental Results From Test Run ID: ChLD TDA
(Flow rate: 60 gpm)

Event		Sampling Time	Bulk Water Samples			Coupon Samples		
			Sample ID	Technical chlordane concentration (mg/L)	Alpha + Gamma chlordane concentration (mg/L)	Coupon ID	Technical chlordane concentration (mg/coupon)	Alpha + Gamma chlordane concentration (mg/coupon)
Baseline		Just prior to injection	ChLD TDA T0	ND[a]	ND[a]	Coupon #1	ND[a]	ND[a]
			ChLD F60 T0 Dup	ND[a]	ND[a]	Coupon #2[b]	1.3 x 10^6 cells/cm^2	
Adherence Study	During 2-day contaminant contact period	5 minutes after injection	ChLD TDA T5M	15	4.6			
			ChLD TDA T5M Dup	18	5.5			
		1 day after injection	ChLD TDA T1D	11	3.4			
			ChLD TDA T1D Dup	3.8	1.13			
		2 days after injection	ChLD TDA T2D	5.6	1.76			
			ChLD TDA T2D Dup	5.6	1.76			
	After 2-day contact period	After draining loop				Control Coupon A	34	6.5
						Control Coupon B	31	6.4
						Coupon #3	180	35
						Coupon #4	130	24
						Coupon #5	60	11
						Coupon #6	68	12.8
Decontamination Study (Surfonic TDA-6 Flushing)		Prior to draining loop	ChLD TDA Decon	11	3.4			
			ChLD TDA Decon Dup	12	3.6			
		After draining loop				Control Coupon C	0.09	0.025
						Control Coupon D	0.23	0.08
						Coupon #7	14	2.9
						Coupon #8	12	2.4
						Coupon #9	6.9	1.18
						Coupon #10	7.4	1.37

[a] ND: nondetectable

[b] Coupon #2 was taken for HPC analysis to check the biofilm development

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