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Decontamination of *Bacillus* Spores from Drinking Water Infrastructure with Physical Removal (Water Jet Pigging) and Assessment of Pipe Relining Technologies

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The contractor role did not include establishing Agency policy.

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Abbreviations

atm	atmosphere
BG	*Bacillus globigii*
BWS	bulk water sample
cfu	colony forming units
CT	chlorine concentration C, (mg/L) x contact time T, (min)
DPD	N,N-diethyl-p-phenylenediamine
ft	foot
gpm	gallons per minute
HPC	heterotrophic plate count
hr	hour
INL	Idaho National Laboratory
LOD	limit of detection
M	meter
min	minute
MPN	most probable number
psi	pounds per square inch
WSTB	Water Security Test Bed

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Executive Summary

The U.S. Environmental Protection Agency's (EPA) Homeland Security Research Program partnered with the Idaho National Laboratory (INL) to build the Water Security Test Bed (WSTB) at the INL test site outside of Idaho Falls, Idaho. The WSTB was built using an 8-inch diameter cement-mortar lined ductile iron drinking water pipe that had been previously taken out of service. The pipe was exhumed from the INL grounds and oriented in the shape of a small (450 feet long) drinking water distribution system. The WSTB can support drinking water distribution system research on a variety of topics including biofilms, water quality, sensors, and homeland security related contaminants. Since the WSTB is constructed of real drinking water distribution system pipes, research can be conducted under conditions which are representative to those in a municipal drinking water system (USEPA, 2016; USEPA, 2018).

This report summarizes the results of biological decontamination experiments performed at the WSTB. The experiments focused on removing and remediating *Bacillus globigii* spores adhered to the inner surface of the 8-inch water pipe. *B. globigii* spores are a non-pathogenic surrogate for *B. anthracis*, which is the causative agent of anthrax. Decontamination was undertaken with a technique known as pigging, or physical scouring of the inner pipe surface, followed by disinfection with free chlorine. The pigging decontamination technique used a Warthog® high pressure water jet nozzle, with the water jet scouring the internal pipe surface. In this technique, dubbed "Warthog pigging," water was pumped from a combination (Vactor®) truck through the Warthog nozzle at high flow and pressure (approximately 70 gpm and 2,300 psi, respectively). The water flow caused the nozzle to spin and discharge a high-pressure water jet that scoured the inner pipe surface.

After decontamination, two pipe relining technologies were also evaluated in separate experiments. The first relining technology evaluated was Oceanit DragX™ (Oceanit Laboratories Inc., Honolulu, HI), which is a proprietary thin (2 mil) spray on polymer coating. The second relining technology was cured in place pipe (CIPP). This technique works by inserting a resin saturated cloth tube into the existing iron pipe, filling it with hot water or steam to cure the resin, then draining the pipe, which leaves a hard, cured pipe inside the original pipe. Both the pigging and pipe relining techniques were implemented on individual sections of cement-mortar lined iron pipe and unlined iron pipe with corrosion.

The following is a summary of the results that came from the pigging and relining experiments performed at the INL WSTB:

- Warthog pigging (2,300 psi, 70 gpm) of an individual cement-mortar lined iron pipe section resulted in a 1.9-log reduction of the number of spores detected on the inner pipe surface. After pigging, chlorination of the water in the pipe at an initial concentration of 149 mg/L (111 mg/L after 18.25 hours) resulted in an additional 1.1-log inactivation of the spores adhered to the pipe inner surface, for a total reduction of 3.0-log.

- Warthog pigging (2,300 psi, 70 gpm) of an individual corroded iron pipe section resulted in a 4.9-log reduction of the number of spores detected on the inner pipe surface. After pigging, chlorination of the water in the pipe at an initial concentration of 82 mg/L (39

mg/L after 18.25 hours) resulted in an additional 0.9-log inactivation of the spores adhered to the pipe inner surface, for a total reduction of 5.8-log.

- Warthog pigging (2,300 psi, 70 gpm) followed by Oceanit DragX relining of an individual cement-mortar lined iron pipe section resulted in a 5.4-log reduction of the number of spores detected on the inner pipe surface (note that spores were only detected in 2 out of 6 pipe interior samples). After relining, chlorination of the water in the pipe at an initial concentration of 216 mg/L (133 mg/L after 22.15 hours) resulted in no spores detected on the interior pipe surface, or up to an additional 0.5-log inactivation of the spores adhered to the pipe inner surface, for a total reduction of ≥ 5.9-log.

- Warthog pigging (2,300 psi, 70 gpm) followed by Oceanit DragX relining of an individual corroded iron pipe section resulted in no spores detected on the inner pipe surface, or ≥ 6.5-log reduction. After relining, chlorination was still conducted. Chlorination of the water in the pipe at an initial concentration of 171 mg/L (122 mg/L after 22 hours) resulted in no detectable spores on the interior pipe surface.

- Warthog pigging (2,300 psi, 70 gpm) followed by CIPP relining of an individual cement-mortar lined iron pipe section resulted in a 4.0-log reduction of the number of spores detected on the inner pipe surface (note that spores were only detected in 2 out of 4 pipe interior samples after relining). After relining, chlorination of the water in the pipe at an initial concentration of 215 mg/L (69 mg/L after 16.75 hours) resulted in an additional 0.3-log inactivation of the spores adhered to the pipe inner surface, for a total reduction of 4.3-log. Spores were detected in 1 out of 4 post chlorination pipe interior samples, and were likely due to cross contamination.

- Warthog pigging (2,300 psi, 70 gpm) followed by CIPP relining of an individual corroded iron pipe section resulted in a 4.5-log reduction of the number of spores detected on the inner pipe surface (note that spores were only detected in 2 out of 4 pipe interior samples after relining). After relining, chlorination of the water in the pipe at an initial concentration of 210 mg/L (59 mg/L after 16.75 hours) resulted in an additional 0.8-log inactivation of the spores adhered to the pipe inner surface, for a total reduction of 5.3-log. Spores were detected in 1 out of 4 post chlorination pipe interior samples, and were likely due to cross contamination.

In summary, pigging with the Warthog nozzle followed by chlorination reduced spores on cement-mortar lined iron by 3.0-log, and by 5.8-log on corroded iron. Increased decontamination efficacy on corroded iron compared to cement-mortar lined iron was likely due to the fact that spores were adhered to the corroded iron matrix, which is almost completely removed during pigging process. After both relining processes were complete, spores were nearly undetectable. Any detectable spores present after relining (and chlorination) were likely due to cross contamination of spores from the surrounding area or carry over from the contaminated pipe. For pipe relining to be successful, cross contamination of contaminant would need to be controlled.

It is important to note that these physical scouring and pipe relining activities will require a longer time frame to implement than standard chlorination and flushing techniques. Excavation is required to access the pipeline for entry of the water jetting attachment and relining equipment. Specialty equipment like Vactor trucks are also required for water jetting activities and significant amounts of contaminated debris will be generated. Consideration should be given to supplying an alternate source of water to customers while these more extensive remedial efforts take place. Also, consideration should be given to disposal options for any debris removed by flushing or drag scraping the pipeline after water jetting. It is possible that significant amounts of biologically contaminated water and debris could result from water jetting.

Some utilities have successfully relined metal pipes with a thin coating of cement after pipe cleaning and debris removal. This relining step is necessary to prevent taste and odor complaints due to the exposure of the iron pipe surface. The results of the pipe rehabilitation have also been recorded with CCTV video monitoring equipment. Before implementing water jetting as a decontamination method, decision makers should think about worker safety and contamination of water and wastewater utility equipment. It is possible that utility equipment will be contaminated to the extent that it could not be readily used after decontamination is complete. These additional activities should be considered in practice, but were beyond the scope of this experiment.

1.0 Introduction

1.1 Background

The U.S. Environmental Protection Agency's (EPA) Homeland Security Research Program has partnered with the Idaho National Laboratory (INL) to build the Water Security Test Bed at INL near Idaho Falls, Idaho. The centerpiece of the Water Security Test Bed (WSTB) is an 8-inch diameter cement-mortar lined ductile iron drinking water pipe that had been taken out of service. The pipe was exhumed from the INL grounds and then oriented in the shape of a small drinking water distribution system. The WSTB has been fitted with service connections, fire hydrants, and removable coupons (excised sample materials) to collect samples from the pipe interiors (USEPA, 2016).

Experiments, focused on decontamination of *Bacillus globigii* spores that adhered to the inner surface of the 8-inch water pipe, have been conducted at the WSTB in previous years. *B. globigii* spores are a non-pathogenic surrogate for *B. anthracis*, which is the causative agent of anthrax. The standard protocol that most utilities follow in response to a bacterial contamination event involves chlorination and flushing and described in AWWA Standard C-651-05: Disinfecting of Water Mains (AWWA, 2005). Therefore, EPA's initial experiment using the full-scale WSTB used chlorine dioxide to decontaminate adhered spores. Two-log removal of *B. globigii* spores was observed with flushing and chlorine dioxide decontamination, which was less effective than anticipated based on previous pilot-scale experiments (Szabo et al, 2017a; Szabo et al, 2017b; USEPA, 2016). Chlorine dioxide is a powerful disinfectant, and it was not anticipated that other common drinking water disinfectants such as free chlorine or monochloramine would be more effective. Therefore, subsequent efforts at removing adhered *B. globigii* spores were focused on physical removal or scouring of the inner pipe surface, hereafter referred to as "pigging." Two technologies were selected: ice pigging and chain cutter pigging. Ice pigging was ineffective at removing spores. Physical scouring using a chain cutter nozzle followed by chlorination removed approximately 4.0-log spores from the inner pipe surface, but spores did remain on the inner pipe surface after decontamination (USEPA, 2018). These results led to further experiments on physical scouring and pipe relining, which are detailed in this report.

1.2 Project Objective

Previous experiments at the WSTB have shown that the standard chlorination and flushing methods were less effective than expected for adhered spores, and ice pigging was not an effective spore decontamination method (Szabo et al, 2017a; USEPA, 2018). The objectives of this project were to evaluate the effectiveness of: (1) a physical scouring (pigging) technology for removing B. *globigii* spores following intentional contamination of the WSTB; (2) two pipe relining technologies for encapsulating residual spores on the pipe inner surface after pigging; and (3) chlorination for residual spore destruction after pigging and pipe relining.

1.3 WSTB System Description

The primary feature of the WSTB is an 8-inch (20 cm) diameter cement-mortar lined ductile iron drinking water pipe oriented in the shape of a small drinking water distribution system. The

WSTB contains ports for service connections and a 15-foot (5 m) removable coupon section designed to sample the pipe interior to examine the results from contamination/decontamination experiments on the pipe wall. Figure 1 schematically depicts the main features of the WSTB.

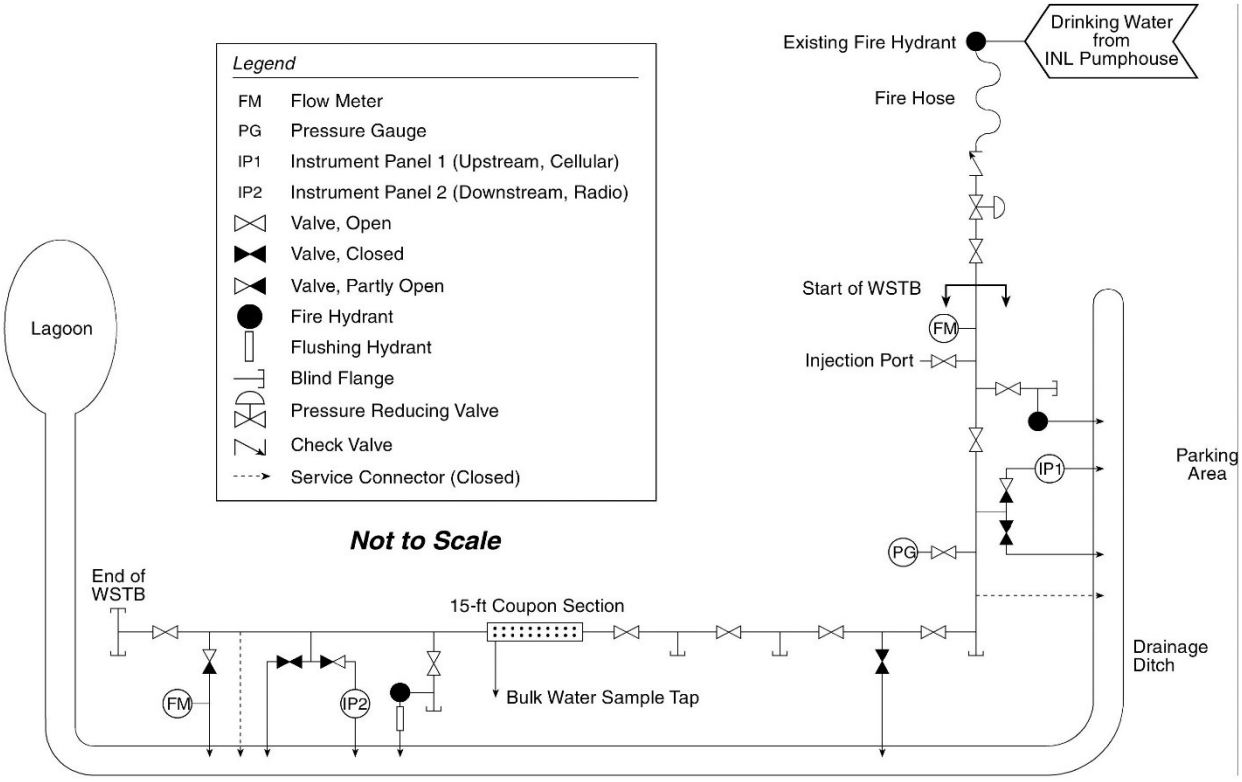

Figure 1: Schematic overview of Water Security Test Bed (WSTB).

Figure 2 shows the aerial view of the WSTB. The lower right corner shows the upstream and system inlet; the upper left corner shows the lagoon.

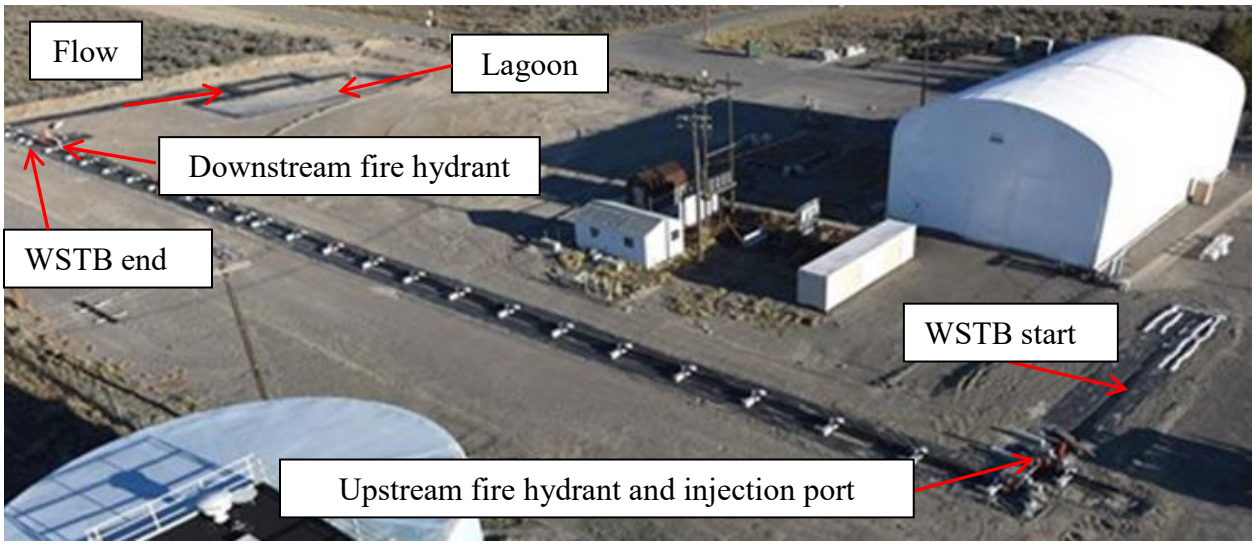

Figure 2: Aerial view of the Water Security Test Bed (WSTB).

Drinking water supplied to the WSTB is chlorinated ground water that also supplied the surrounding INL facilities. The WSTB incorporates approximately 450 feet (137 m) of 8-inch (20 cm) diameter cement-mortar lined ductile iron pipe. The 8-inch (20 cm) pipe system is constructed directly over the lined drainage ditch for spill/ leak containment (as shown in Figure 2). The total volume of the WSTB was estimated to be around 1,150 gallons (4,353 L). The effluent water from the WSTB system was discharged to a lined lagoon (Figure 3) which has a total water storage capacity of 28,000 gallons (105,980 L).

Figure 3: Water Security Test Bed discharge lagoon.

To examine pigging and pipe relining technologies, individual sections of pipe were set up next to the lagoon. The individual pipe setup is shown in Figure 4. Two types of pipe were pigged and relined. One was the same cement-mortar lined iron pipe used in the 450 ft WSTB pipe (each pipe was approximately 18 ft). The other was iron pipe with heavy corrosion on the interior (each pipe was approximately 10 ft). This pipe was obtained from the District of

Columbia Water and Sewer Authority (DC Water). All pipe surface samples taken from the individual pipes were direct scrapings of the inner surface. Further details on the contamination, pigging, pipe relining, and sampling processes are described in Section 2.

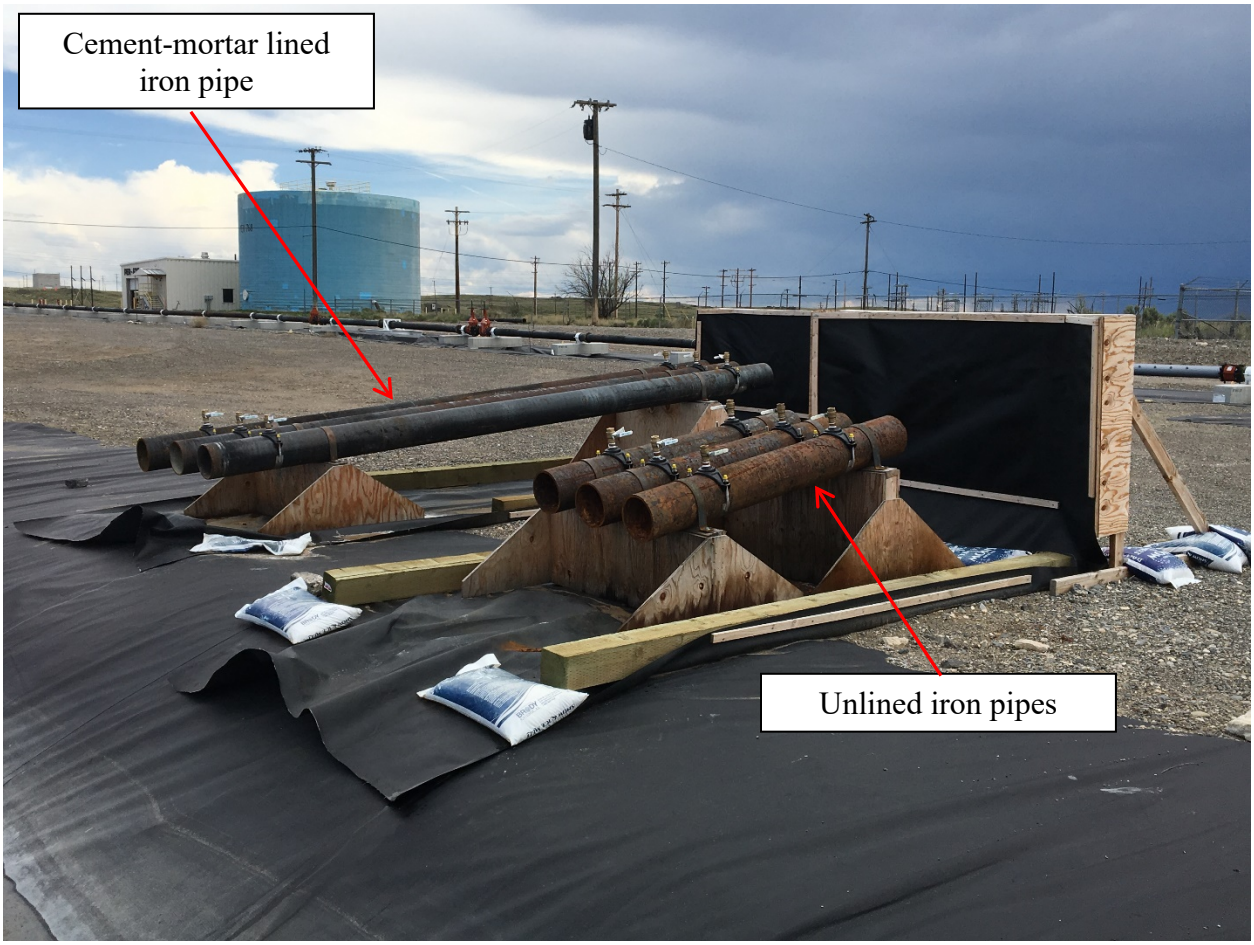

Figure 4: Individual pipe sections next to the Water Security Test Bed lagoon.

2.0 Description of Pigging and Pipe Relining Techniques

Historically, the term "pigging," in the context of pipeline cleanup operations, refers to the practice of using mechanical devices known as "pigs" to perform cleanup activities. The original mechanical pigs used for cleaning pipes were made from straw wrapped in wire. This device would make a squealing noise when scraping the pipe walls and traveling through the pipe, which led to the process being called pigging. In general, pipeline cleaning operations using pigs are accomplished by launching the pig at an upstream location and pushing the pig down the pipe until it reaches a downstream receiving station for retrieval.

In industrial applications, soft foam pigs are most commonly used for pipe cleaning applications. The soft pigs are constructed using flexible open cell polyurethane foam materials (or other materials with similar properties) topped with select external wrapping that is suited for individual application. The soft pigs are slightly oversized and designed to form a "sliding seal"

in the pipe. When pushed through the pipe, the soft pig can mechanically scrape and remove product buildup, foreign matter and loose sediment from the pipe walls. In general, soft pigs are not appropriate for drinking water pipes due to the interior roughness of those pipes.

Physical scouring of drinking water pipe interiors can be performed using a variety of nozzles or metal tips that are attached to a high-pressure hose. These pigs are activated by pumping water at high pressure and flow through the nozzles. Pigs of this type have been used for at least 35 years (Beck et al, 1983). Past pigging research at the WSTB used a chain cutter nozzle, where a spinning chain scours the pipe interior (USEPA, 2018). In this study, a nozzle was used that produces a high-pressure water jet (or spray) that hits the pipe interior at an angle.

It was not practical to implement different relining methods within the long 440 ft WSTB pipeline, so three separate smaller lengths of piping were set up at the test bed to evaluate pipe relining. There are many different pipe relining materials and methods. For the purposes of this study two representative pipe relining technologies were also implemented in the three separate sections of pipe. One method was cured in place pipe (CIPP), which is a common pipe rehabilitation method where a new pipe is inserted into an old pipe and cured in place, usually through heat treatment. A CIPP material by Permaliner was used for this relining experiment. The new pipe then becomes the inner surface of the old pipe, and can provide structural integrity, if needed. A second relining method (Oceanit DragX®; Oceanit Laboratories Inc., Honolulu, HI) was a spray on coating, where a new non-structural lining is sprayed onto the inner surface of the pipe. DragX is a proprietary nanocomposite technology that creates a durable, low-friction internal pipe surface. After coating, the new surface is approximately 2 mil (0.002 inches or 0.051 mm).

There are advantages and disadvantages to both pipe relining methods. The CIPP method adds structural strength and integrity to the pipe after curing that cannot be provided by the spray-on liner. However, each individual service connection to the CIPP must be re-cut after the liner cures. This additional step is not required for the spray on liner method. A detailed description of each lining process is provided in the following sections.

2.1 Water Jet Pigging

The nozzle shown in Figure 5 is the Warthog WHR Switcher (Stone Age Tools, Durango, CO), and was used to scour the internal surface of the pipe. INL contracted Big Sky Industrial (Big Sky, Spokane, WA) to perform the pipe scouring work at the Water Security Test Bed. This nozzle is capable of being inserted into pipes from 6 to 18 inches in diameter and was designed to remove obstructions and blockages in pipes such as roots, debris and tuberculation (like iron corrosion). This type of pig is primarily used to clear wastewater piping clogged with persistent tree roots, however the field operation of the device was the same for drinking water pipe decontamination. When water flows into the rear end of the nozzle (at the left of Figure 5), the front end (right end of Figure 5) rotates, and water flows out in a high pressure jet through multiple openings at the head of the nozzle. After hitting the inner pipe surface, the high-pressure jets flow toward the rear end of the nozzle and helps propel the nozzle forward.

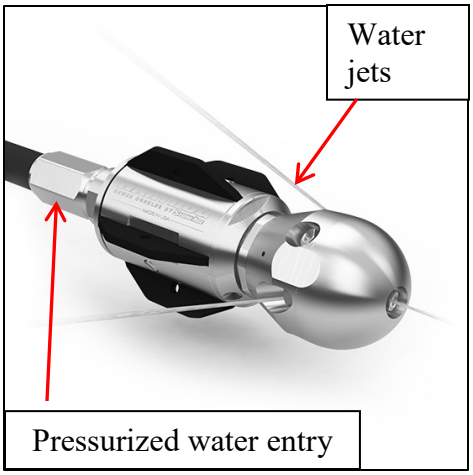

Figure 5: Warthog nozzle used for pipe scouring
(reproduced from https://stoneagetools.com/whr-switcher)

To achieve the appropriate amount of scouring action, water was supplied from a combination truck, which is shown in Figure 6. Big Sky provided the Vactor® truck and the operator for this pigging experiment. In the wastewater industry, combination trucks are commonly referred to as "Vactor trucks" after one of the manufacturers of these vehicles. Combination trucks have a dual function. The hose on the front can vacuum solids out of a sewer and pump them into the tank on the back. The truck can also store approximately 1,300 gallons (4,921 L) of potable water and pump it through a high pressure hose at up to 2500 psi (170 atm) and 80 gpm (302 L/min). Water at a flow of 70 gpm (265 L/min) and 2300 psi (157 atm) pressure was used to operate the Warthog nozzle inside of the pipe sections next to the WSTB lagoon. Figure 7 shows the Warthog nozzle installed at the end of the high pressure hose. The Warthog attachment was moved at approximately 1 ft /second during the jetting of the 440 foot long pipe. Two passes were made within the 440 foot pipe.

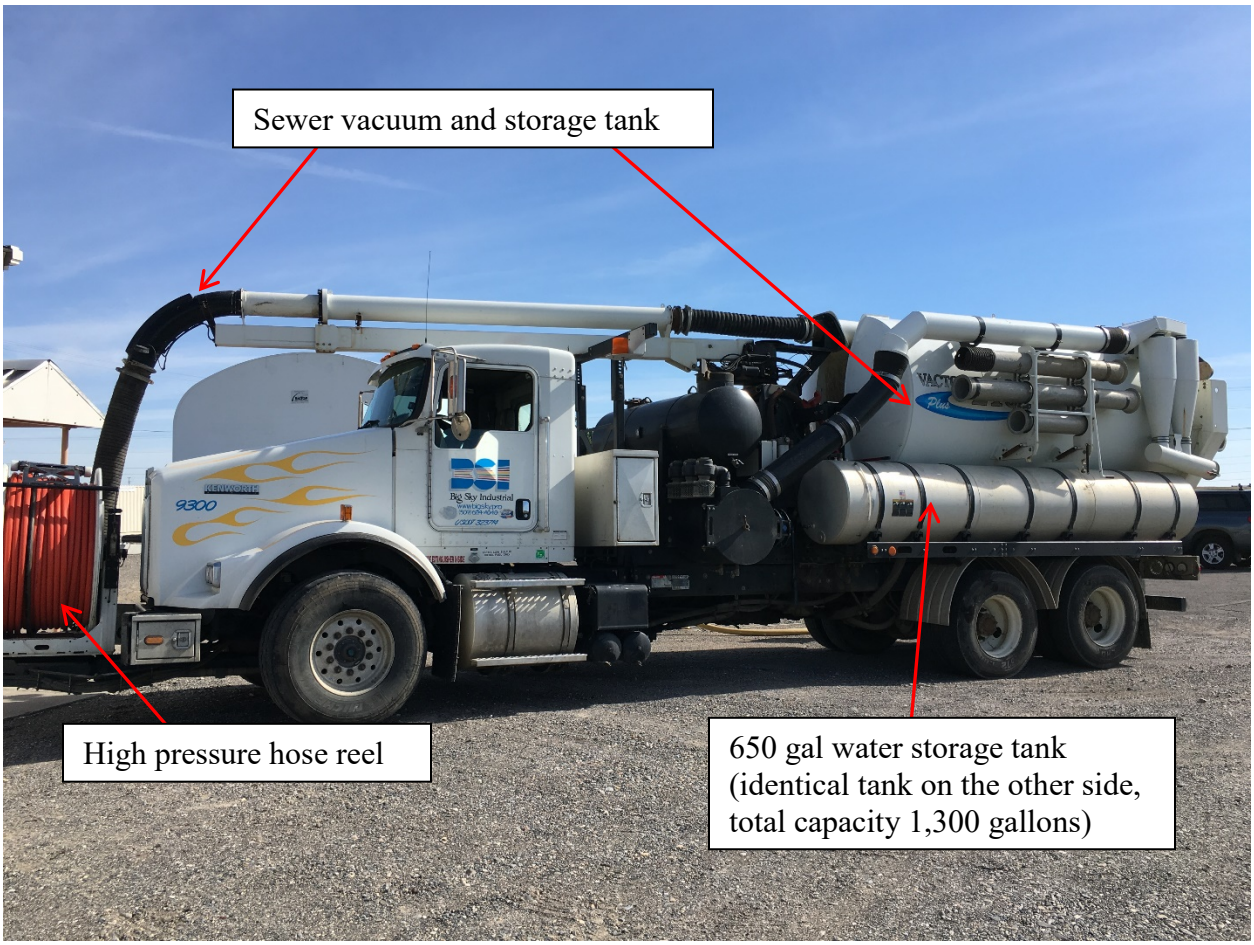

Figure 6: Combination (Vactor) truck.

Figure 7: Water jet nozzle attached to the combination truck high pressure hose.

Images showing the process of pigging the individual pipe section are shown in Figure 8 through Figure 10. After the combination truck was filled with water and the nozzle was installed on the hose, the nozzle was placed inside of an individual pipe section. When the high pressure water pump on the combination truck was turned on, the water began flowing through the nozzle, and the nozzle began spinning and spraying water. High pressure water exited through an opening in the rear of the chain cutter nozzle, and this pressurized water flow propelled the chain cutter down the pipe. The nozzle was operated at a pressure of 2,300 psi and a flowrate of 70 gpm. These are approximate values that might have varied during operation of the nozzle. Once pigging of a pipe was complete, the nozzle was pulled back through the pipe, inserted into another pipe, and the process repeated. Pigging was performed with one pass through the pipe. However, if visible corrosion or other adhered material was observed after one pass, a second pass with the nozzle was performed.

Figure 8: Water jet nozzle inserted into a pipe section.

Figure 9: Spray coming out of a pipe section as the water jet nozzle travels down the pipe.

Figure 10: Jet sprayer nozzle exiting a pipe section.

2.2 Pipe relining using spray on coating

Application of Oceanit DragX coating is illustrated in Figure 11 through Figure 13. The pipe was pigged with the water jet sprayer prior to coating (see section 2.3 for more detail), but the Oceanit site personnel scrubbed the pipe interior with a wire brush to remove any remaining debris. Then, the proprietary nanocomposite coating was mixed in a bucket. A hose was inserted into the bucket, and the coating was pumped to an air driven spin coater that was pulled through the pipe. The coating cured overnight and was visually inspected the next morning for trapped air bubbles or bare spots (none were detected).

Figure 11: Mixing the Oceanit DragX coating in a bucket.

Figure 12: Rotary air sprayer inserted into the pipe to apply the DragX coating.

Figure 13: DragX coated pipe after curing overnight.

2.3 CIPP application

The application of CIPP is illustrated in Figure 14 through Figure 18. First, a flexible fabric sock was unrolled and cut to the length of the pipe. The sock was then soaked in a proprietary resin, and the resin-soaked sock was pulled through the pipe section. The sock was then tied at one end, and hot water pumped into the sock so that it fully inflated and was forced against the iron pipe interior. Over approximately four hours, the hot water cured the liquid resin, which was transformed into a rigid lining. The CIPP was then drained and sawed off at the ends so that the new interior pipe was flushed with the iron pipe.

Figure 14: Flexible CIPP sock being cut to the length of the iron pipe.

Figure 15: Flexible CIPP fabric sock being soaked in resin.

Figure 16: Resin soaked CIPP sock being pulled through the iron pipe.

Figure 17: CIPP filled with hot water and in the process of curing.

Figure 18:Finished CIPP sawed off to the length of the iron pipe.

2.4 Contamination and Decontamination Protocols

Contamination and decontamination took place as follows:

Step 1 - Pipe conditioning (cultivation of biofilm)
Step 2 - Contamination (addition of *B. globigii* spores to WSTB pipes)
Step 3 - Decontamination (Pigging, chlorination and pipe relining)
Step 4 - Post pigging and relining disinfection

Step 1 - Pipe Preparation (cultivation of biofilm)
As shown in Figure 4, individual sections of pipe were used for pigging and relining experiments. Before contamination, baseline samples were taken for *B. globigii* spores and heterotrophic plate count (HPC). The pipes were wetted before these samples were taken, but HPC levels represented what was present on the recently wetted dry pipe.

Step 2 - Contamination (Addition of *B. globigii* Spores to WSTB pipes)
During contamination, caps were installed on each end of the pipe (Figure 19). The caps had two influent ports so that local tap water and *B. globigii* spores could be injected simultaneously (see arrows on Figure 19). Tap water was introduced through a garden hose, and the spores were pumped in. The mixing action of simultaneous filling ensured that the spores were mixed evenly throughout the bulk water phase in the pipe. Enough spores were injected to achieve approximately 5 x 10^5 cfu/mL in the pipe bulk water phase. After the pipe sections were filled, the spores were allowed to contact the pipe surfaces for 1 to 2 hours. The spore suspension was then drained (Figure 20), and the pipes were filled with local tap water until pigging was performed. Background water and pipe surface samples were taken before contamination, immediately after contamination, and then the morning of the day following contamination (immediately before pigging).

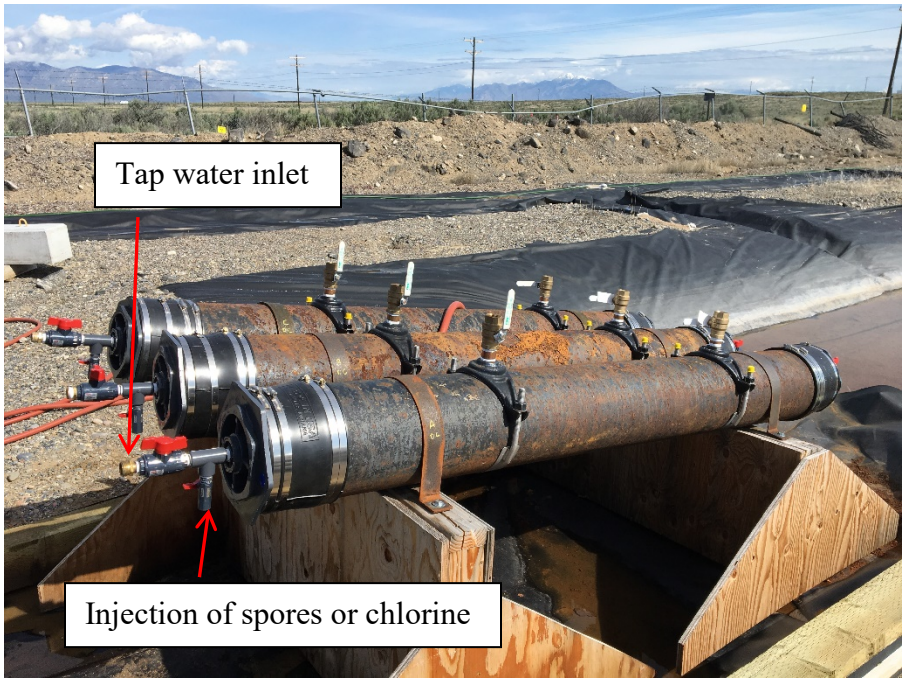

Figure 19: Caps inserted on individual pipes during contamination.

Figure 20: Draining the pipe sections.

Step 3 - Decontamination (Pigging, chlorination and pipe relining)
Pigging was performed as described in Section 2.1, and pipe relining as in Sections 2.2 and 2.3. Three pipes of each material (cement-mortar line iron and corroded iron) were used. One pipe of each material was pigged and chlorinated (see Step 4). The other two pipes of each material were pigged, relined (one with CIPP, one with DragX), and chlorinated (see Step 4).

Step 4 - Post pigging and relining disinfection
Following the completion of pigging or pipe relining, commercially available bleach (8.25% sodium hypochlorite) was injected into the pipe sections. Bleach was pumped into and mixed in the pipe sections in the same manner as the BG spores. In pipes that were pigged only, chlorination took place after pigging. In pipes that were relined, chlorination took place after relining. Aliquots of bleach were added to achieve a free chlorine concentration between 70 to 80 mg/L once the bleach mixed throughout the pipe bulk water phase. After overnight contact (16-20 hours), the pipe was emptied and flushed with clean tap water. Chlorination is a common method of pipe disinfection in the drinking water industry, which is why it was chosen for disinfection in this study. However, due to variations in pipe demand and volume of bleach added, the overnight chlorine concentrations differed from the target of 70 to 80 mg/L in some experiments. These results are described in the section 3.0.

2.5 Experimental Methods

Preparation and transport of *B. globigii* spores
Bacillus globigii spores were produced by mixing an inoculum of *B. globigii* spores with generic sporulation media and incubating with gentle shaking at 35 °C for 7 days. The *B. globigii* suspensions were heat-shocked and enumerated using the spread plate method with tryptic soy agar and membrane filtration (plating is described later in this section). The resulting prepared stock was shipped in separate 1 liter containers inside coolers (preserved at 4 ± 2 °C) to the site.

This suspension was pumped into the pipe sections during contamination (Section 2.4, Step 2).

Extraction of biofilm and spores from coupon and pipe surfaces for microbial analyses

Pipe surface samples were taken directly from the inner surface of the pipe sections. The biofilm, corrosion and spores were scraped from the surface using a disposable sterile surgical scalpel. An O-ring with an area of 0.371 square inches (2.4 square centimeters) was placed on the pipe wall, and the area inside the O-ring was scraped. This ensured that the same area was scraped for each sample. The extracted material was collected in a sterile sample bottle with a sodium thiosulfate tablet (for dechlorination of the water) and 100 mL of pre-filled carbon-filtered water. The extracted sample was transferred to a cooler at 4 ±2 ˚C. The samples were shipped cooled overnight to the EPA laboratory and analyzed upon receipt. After the pipes were relined, the same method was used to sample the pipe surfaces, except that a sterile cotton swab on a wooden stick was used. Using a scalpel on the relined surfaces would have scraped off the relined surface, exposing the spore contaminated surface underneath.

Enumeration of *B. globigii* and Heterotrophic Plate Count

Upon receipt in the lab, samples containing *B. globigii* spores were heat-shocked at 80˚C for 10 minutes and analyzed using the Standard Methods Spread Plate Method 9215 (APHA, 2005). Tryptic soy agar plates were used for *B. globigii* spores. *B. globigii* plates were incubated at 35˚ to 37˚C for 24 hours. Heterotrophic plate count samples were analyzed using the IDEXX SimPlate® method (Westbrook, ME) according to Standard Methods 9215E (APHA, 2005). Plates were incubated at 35˚ ± 0.5˚ C for 45 to 72 hours. When needed, samples were serially diluted (*B. globigii* and HPC) or membrane filtered (*B. globigii*).

Bulk water samples

The BWS for *B. globigii* were collected using the grab sampling technique in 100 mL sterile sample bottles with a sodium thiosulfate tablet. The bulk water sampling port in the WSTB coupon section was opened and the water was drained for 15 seconds prior to collection of 100 ml of water from the WSTB.

Free Chlorine

During decontamination experiments, 100 ml grab samples were collected from the pipe sections. The water was drained for 15 seconds prior to collection of 100 ml of water from the WSTB. Samples were collected in a clean glass laboratory beaker and analyzed for free chlorine using a portable Hach® colorimeter Hach, Loveland, CO). The sample was immediately processed for free chlorine using the Hach Method 10102 using N,N-diethyl-p-phenylenediamine (DPD) at the WSTB site. Samples were diluted in distilled water as needed.

2.6 Quality Control and Data Quality

2.6.1 Quality Control

Quality control samples for the contaminant reference method included continuing duplicate samples, controls and laboratory blanks. The data quality objectives for each of these quality control samples are provided in Table 1. The acceptable ranges limit the error introduced into

the experimental work. All analytical methods operated within the QC requirements for controls and laboratory blanks in Table 1. Note that duplicate samples for *B. globigii* refer to a duplicate analysis of one sample. All *B. globigii*, HPC and free chlorine samples were collected in duplicate.

Table 1: Quality Control Data Quality Objectives

Measurement	QC Check	Frequency	Acceptance Criteria	Corrective Action
B. globigii	Positive control using stock	Once per experiment	±10 fold of the spiking suspension	Investigate laboratory technique. Change stock organisms and use new set of media plates. Re-analyze the spiking suspension and change it if necessary.
B. globigii	Negative Control using sterile buffer	Once per experiment	0 CFU/plate	Investigate laboratory technique. Use a new lot. Re-analyze.
B. globigii	Negative control for heat shock	Once per experiment	0 CFU of vegetative cell/plate	Investigate the hot water bath. Heat samples for longer period.
B. globigii	Duplicate	Once per experiment	≤20% variation	Consider other dilutions. Reanalyze.
B. globigii	Field blank (an open bottle of sterile water in the vicinity of the BWS location)	Every 5 BWS	0 CFU/plate	Determine if background values impact results.
HPC	Negative Control	Before every set of measurements	No fluorescent wells	Re-analyze sterile buffer and change it if necessary.
HPC	Positive Control	Once per experiment	Fluorescent wells	Investigate laboratory technique. Re-analyze.
HPC	Duplicate	Once per experiment	Duplicate plates much agree within 5%	Investigate laboratory technique. Re-analyze.
Free Chlorine	Manufacturer DPD color standards kit	Once per experiment	As specified by the color standards kit	Clean the colorimeter measuring cell. Clean the DPD standards vials and recheck.

2.6.2 Data Quality

At least 10% of the data acquired during the evaluation were audited. These data include the biofilm/BG spore measurements and water quality measurements. The data was traced from the initial acquisition, through analysis, to final reporting, to ensure the integrity of the reported results. All calculations performed on the data undergoing the audit were checked. No significant adverse findings were noted in this audit.

2.6.3 Deviations

When conducting scrape samples from the interior of the drinking water, and o-ring was used to isolate the area to be sampled (see "Extraction of biofilm and spores from coupon and pipe surfaces for microbial analyses" in Section 2.5). Scraping within the o-ring area was meant to standardize the pipe surface area that was sampled. The tip of a scalpel was to trace the sampled area inside the o-ring. It was observed in the field that the traced area was not always an exact circle. Therefore, the area sampled may have varied between samples. It was not possible to precisely quantify this variation. However, it was estimated that the sampled area could have varied by 5% between samples. This should be considered when interpreting the data.

3.0 Experimental Results

3.1 Water Jet (Warthog) Pigging

The background HPC concentration on the cement-mortar lined and corroded iron inner pipe surfaces were analyzed via two scrape samples. These samples were removed after wetting the pipes with tap water, but before contamination with spores and decontamination with pigging. Mean HPC values from the two scrape samples from cement-mortar lined and corroded iron pipes were 3.9 x 10^5 most probable number (MPN)/cm^2 and 2.4 x 10^5 MPN/cm^2, respectively. These results indicate that viable biofilm was present on the pipe walls prior to the initiation of the tests.

The pigging decontamination technique known as "Warthog pigging" uses a Warthog® high pressure water jet nozzle, with the water jet scouring the internal pipe surface. Water jetting is more commonly used in sewer cleaning and root and clog removal than drinking water applications. The Vactor truck hosing and Warthog attachment would be amenable to disinfection with a strong bleach solution. A dedicated Vactor and warthog may be needed for drinking water systems if resources allow. Figure 21 and Figure 22 graphically summarizes the data obtained from the Warthog pigging experiments. The *B. globigii* spore values obtained from the pipe wall samples have been converted to colony forming units per square centimeter (CFU/cm^2). For all bars in Figure 21 and Figure 22, the "n" value shown in the legend represents the number of coupons samples taken during that phase of the experiment. The bar represents the average of those coupons, and the error bars represent standard deviation. The limit of detection (LOD) in the figures was calculated as follows: The scrapings from the sampled surface went into 100 ml of sterile buffer. Then 22.2 ml of the buffer suspension containing the coupons scrapings were membrane filtered in duplicate three sample volumes (0.1mL, 1mL, and 10mL). If one spore was contained in the filtered 22.2 ml, that scales up to 4.5 per 100 ml. When that value was normalized by the coupon area 2.4 cm^2, this yields a value of 1.9 CFU/cm^2. Note that the same LOD applies to Figures 23 to 26 in Sections 3.2 and 3.3.

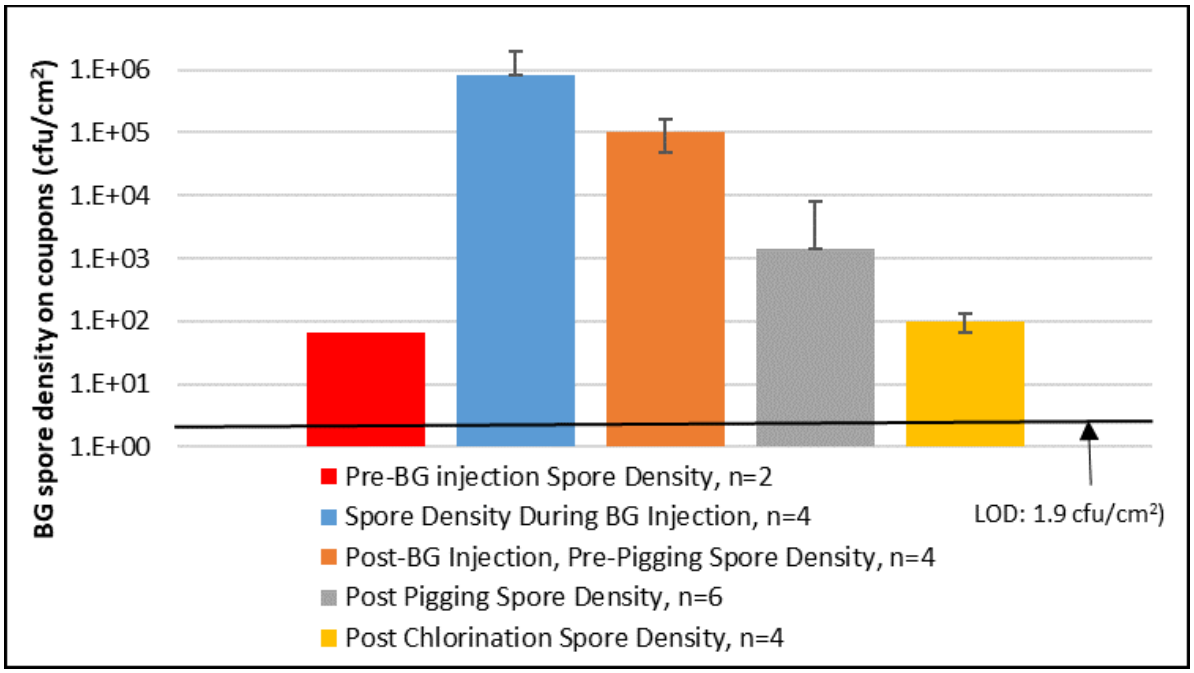

Figure 21: Decontamination of *Bacillus globigii* (BG) from the cement-mortar lined iron pipe section with the Warthog nozzle.

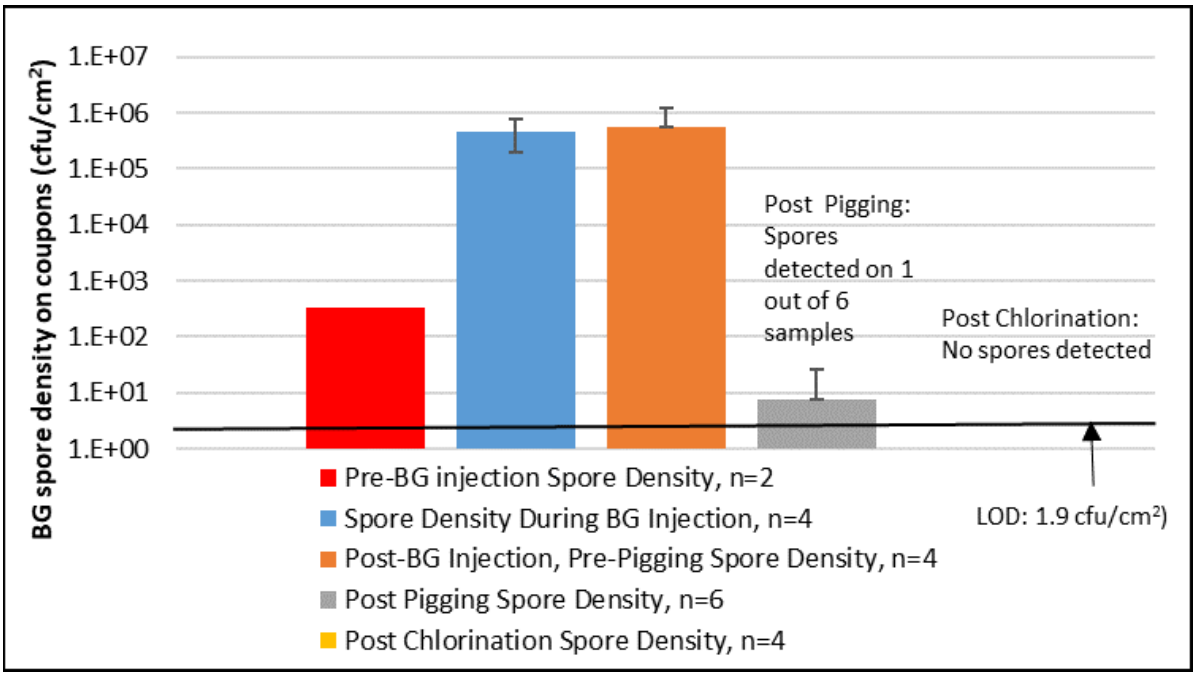

Figure 22: Decontamination of *Bacillus globigii* (BG) from the corroded iron pipe section with the Warthog nozzle.

The first bar (pre-BG injection spore density) in Figure 21 and Figure 22 reflect samples taken before contamination with spores. In both figures, spores are present. The pipes were not in contact with spores before contamination. However, previous experiments may have

contaminated the surrounding area with spore forming bacteria. The pipe sat open on the site for approximately 4 weeks before experiments began. Therefore, it is possible that spore contaminated dirt or dust blew into the pipes, and spores were not washed off when the pipes were wetted for HPC sampling.

The second bar (spore density during BG injection) represents the number of viable spores detected on the pipe surface immediately after spore contamination. The bulk water phase had 6.6×10^5 and 3.3×10^5 CFU/mL during contamination in the cement-mortar and corroded iron pipe, respectively. The pipes were contaminated, drained, sampled, and then filled with tap water until pigging took place the next day. The third bar (Post-BG injection) represents the number of viable spores attached to the pipe surface immediately before pigging took place. Any decrease between the second and third bar represents the number of spores that came off of the pipe surface or were inactivated between contamination and immediately before pigging. The fourth bar (Post pigging BG spore density) represents the number of viable *B. globigii* spores attached to the pipe surface after pigging. The last bar (Post chlorination spore density) shows the number of viable spores recovered from pipe surface after chlorination.

Figure 21 shows the Warthog pigging and decontamination results for the cement mortar lined pipe. Pigging with the Warthog nozzle resulted in 1.9 log removal of spores from the pipe surface. Chlorination resulted in an additional 1.1 log reduction, for a combined total of 3.0 log reduction. Figure 22 shows the Warthog pigging and decontamination results for the corroded iron pipe. Pigging with the Warthog nozzle resulted in 4.9 log removal of spores from the pipe surface. Chlorination resulted in an additional 0.9 log reduction, for a combined total of ≥5.8 log reduction. No viable spores were detected on the corroded iron pipe surface after chlorination.

During the chlorination phase, aliquots of chlorine bleach were added to the pipe sections with the goal of achieving 70 to 80 mg/L free chlorine. In the cement-mortar pipe, the initial free chlorine concentration was 149 mg/L. After 18.25 hours of contact, the free chlorine concentration was 111 mg/L. These values yield a bulk phase CT (chlorine concentration, C, in mg/L and contact time, T, in minutes) of 183,960 mg-min/L. CT is calculated by plotting concentration (y-axis) vs time (x-axis) and determining the area under the curve. In the corroded iron pipe, the initial free chlorine concentration was 82 mg/L. After 18.25 hours of contact, the free chlorine concentration was 39 mg/L. These values yield a bulk phase CT of 112,850 mg-min/L. No viable spores were detected in the bulk water phase after the bleach had been flushed from the pipe and tap water restored.

Comparing the results in Figure 21 and Figure 22 shows that pigging with the Warthog nozzle was more effective in the corroded iron pipe than the cement-mortar lined pipe. This is likely due to the fact that the spores adhered to the iron corrosion layer on the surface of the pipe. This iron corrosion layer was removed during pigging to the extent that only bare iron was visible after pigging. A similar level of surface removal was not observed in the cement-mortar lined pipe. Similar results were observed when using a chain cutter nozzle for pigging in previous experiments (USEPA, 2018). However, when using disinfectants alone, decontamination of spores adhered to corroded iron was more difficult compared to cement-mortar (Szabo et al, 2017). It should also be noted that spores detected on the pipe surface before contamination were not detected after pigging and chlorination.

3.2 Warthog pigging with Oceanit DragX pipe relining

The background HPC concentration on the cement-mortar lined and corroded iron inner pipe surfaces were analyzed via two scrape samples. These samples were removed after wetting the pipes with tap water, but before contamination with spores and decontamination with pigging. Mean HPC values from the two scrape samples from cement-mortar lined (Figure 23) and corroded iron pipes (Figure 24) were 5.1 x 10^5 most probable number (MPN)/cm^2 and 2.9 x 10^5 MPN/cm^2, respectively. These results indicate that viable biofilm was present on the pipe walls prior to the initiation of the tests.

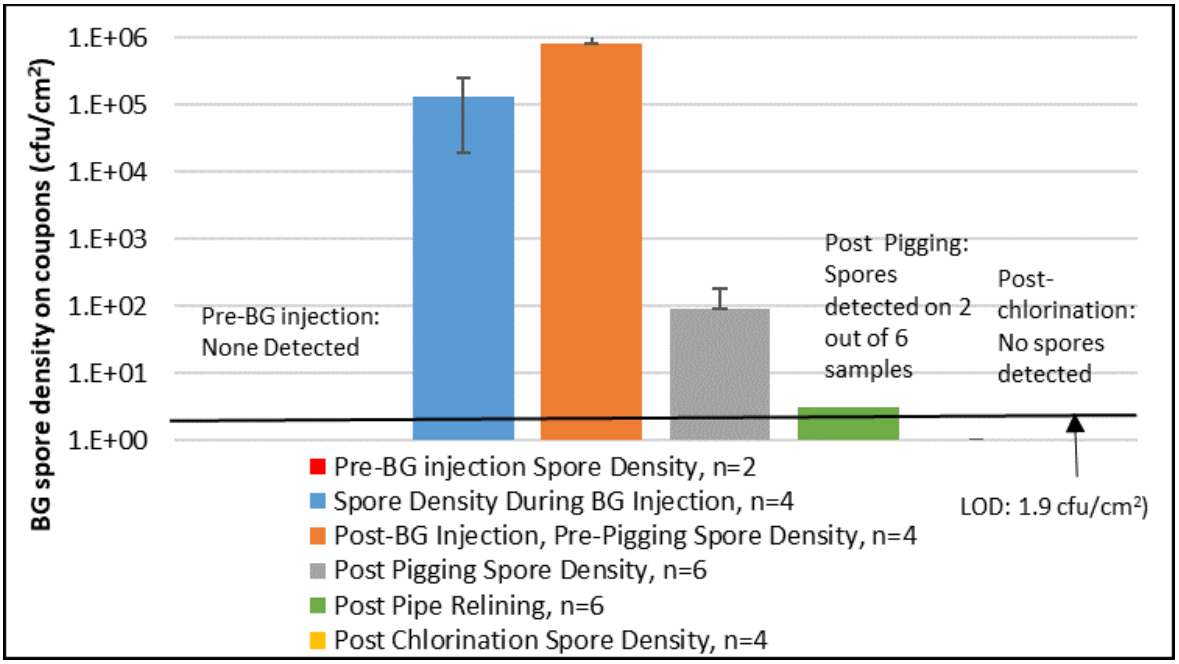

Figure 23: Decontamination of *Bacillus globigii* (BG) from the cement-mortar lined iron pipe section with the Warthog nozzle and Oceanit DragX relining.

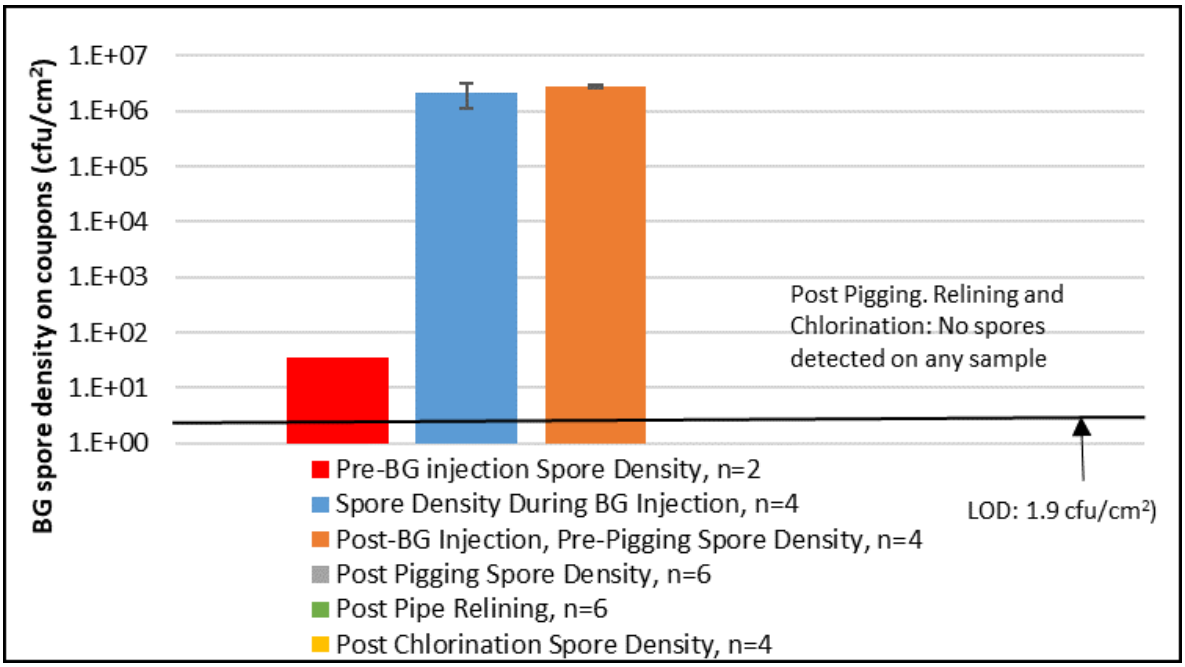

Figure 24: Decontamination of *Bacillus globigii* (BG) from the corroded iron pipe section with the Warthog nozzle and Oceanit DragX relining

The first bar (pre-BG injection spore density) in Figure 23 and Figure 24 reflect samples taken before contamination with spores. In Figure 24, spores are present. The pipe was not in contact with spores before contamination. However, previous experiments may have contaminated the surrounding area with spore forming bacteria. The pipe sat open on the site for approximately 4 weeks before experiments began. Therefore, it is possible that spore contaminated dirt or dust blew into the pipe, and spores were not washed off when the pipes were wetted for HPC sampling.

The second bar (spore density during BG injection) represents the number of viable spores detected on the pipe surface immediately after spore contamination. The bulk water phase had 5.3 x10^5 and 6.2 x10^5 CFU/mL during contamination in the cement-mortar and corroded iron pipe, respectively. The pipes were contaminated, drained, sampled, and then filled with tap water until pigging took place the next day. The third bar (Post-BG injection) represents the number of viable spores attached to the pipe surface immediately before pigging took place. Any decrease between the second and third bar represents the number of spores that came off of the pipe surface between contamination and immediately before pigging. The fourth bar (Post pigging BG spore density) represents the number of viable *B. globigii* spores attached to the pipe surface after pigging. The fifth bar (Post pipe relining) summarizes the number of viable *B. globigii* spores recovered from the inner pipe surface after relining. The last bar (Post chlorination spore density) represents the number of viable spores recovered from pipe surface after chlorination. Note that these bars are absent from Figure 24 since no spores were detected on these samples.

Figure 23 shows the Warthog pigging and Oceanit DragX relining results for the cement mortar lined pipe. Pigging with the Warthog nozzle resulted in 4.0 log removal of spores from the pipe surface. Relining with DragX reduced the number of viable spores detected by 1.4 log. Chlorination resulted in an additional 0.5 log reduction, for a combined total of ≥5.9 log

reduction. No viable spores were detected on the corroded iron pipe surface after chlorination. Figure 22 shows the Warthog pigging and Oceanit DragX relining results for the corroded iron pipe. Pigging with the Warthog nozzle resulted in ≥ 6.5 log removal of spores from the pipe surface. No spores were detected on the lined pipe surface after relining or chlorination.

During the chlorination phase, aliquots of chlorine bleach were added to the pipe sections with the goal of achieving 70 to 80 mg/L free chlorine. In the relined cement-mortar pipe, the initial free chlorine concentration was 216 mg/L. After 22.15 hours of contact, the free chlorine concentration was 133 mg/L. These values yield a bulk phase CT of 281,141 mg-min/L. In the corroded iron pipe, the initial free chlorine concentration was 171 mg/L. After 22 hours of contact, the free chlorine concentration was 122 mg/L. These values yield a bulk phase CT of 214,073 mg-min/L. No viable spores were detected in the bulk water phase after the bleach had been flushed from the pipe and tap water restored.

The results in Figure 23 and Figure 24 show that after pigging, relining with Oceanit DragX and chlorination, no spores were detected on the inner pipe surface. However, the degree to which each decontamination process affected the adhered spores differed between the two pipe materials. Before lining with DragX, pigging with the Warthog nozzle resulted in 4.0 log removal of the spores (Figure 23). However, in Figure 21, only 1.9 log spore removal was observed in the cement-mortar lined pipe that was pigged in the same manner. This shows that pigging effectiveness can differ between two pipes of the same material.

After relining with DragX, spores were only detected in two out of six swab samples taken from the lined surface. It is possible that spores penetrated or diffused through the spray on coating, but these spores could also be the result of cross contamination from the site or from the pipe during the coating process. No spores were detected after chlorination. In the iron pipe, no spores were detected after pigging, likely because they were removed with the corrosion material. This data suggests that relining is needed more for cement lined pipes than unlined pipes which have been pigged by this method. Pigging alone was not sufficient to remove all BG spores from the cement lined pipe even after the chlorination step, so this type of pipe might require further remediation or relining.

3.3 Warthog pigging with CIPP pipe relining

The background HPC concentration on the cement-mortar lined and corroded iron inner pipe surfaces were analyzed via two scrape samples. These samples were removed after wetting the pipes with tap water, but before contamination with spores and decontamination with pigging. Mean HPC values from the two scrape samples from cement-mortar lined (Figure 25) and corroded iron pipes (Figure 26) were 2.4 x 105 most probable number (MPN)/cm2 and 2.8 x 105 MPN/cm2, respectively. These results indicate that viable biofilm was present on the pipe walls prior to the initiation of the tests.

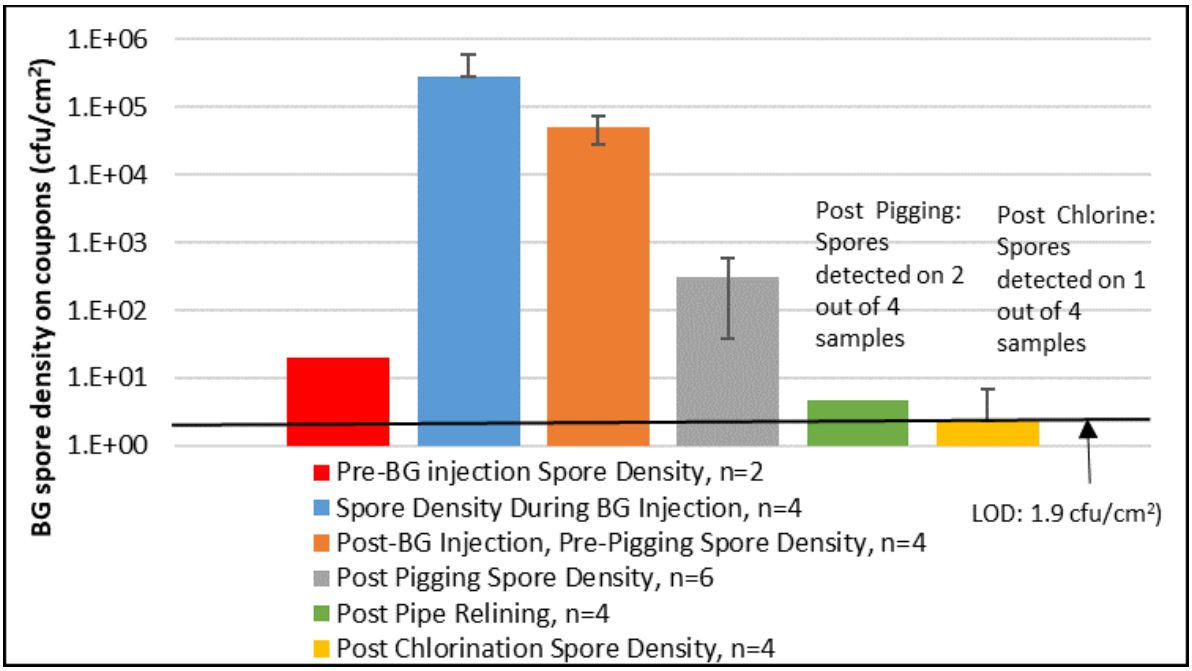

Figure 25: Decontamination of *Bacillus globigii* (BG) from the cement-mortar lined iron pipe section with the Warthog nozzle and CIPP relining

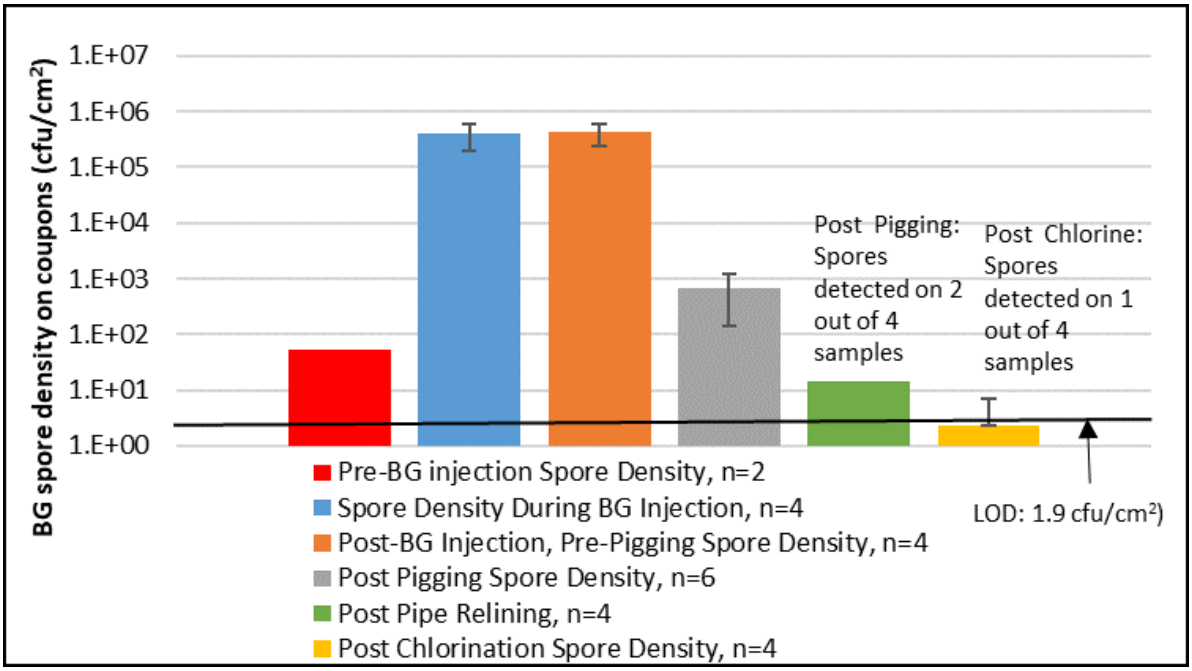

Figure 26: Decontamination of *Bacillus globigii* (BG) from the corroded iron pipe section with the Warthog nozzle and CIPP relining

The first bar (pre-BG injection spore density) in Figure 25 and Figure 26 reflect samples taken before contamination with spores. In both figures, spores are present. The pipes were not in contact with spores before contamination. However, previous experiments may have contaminated the surrounding area with spore forming bacteria. The pipes sat open on the site

for approximately 4 weeks before experiments began. Therefore, it is possible that spore contaminated dirt or dust blew into the pipe, and spores were not washed off when the pipes were wetted for HPC sampling.

The second bar (spore density during BG injection) represents the number of viable spores detected on the pipe surface immediately after spore contamination. The bulk water phase had 1.3 $x10^6$ and 6.9 $x10^5$ CFU/mL during contamination in the cement-mortar and corroded iron pipe, respectively. The pipes were contaminated, drained, sampled, and then filled with tap water until pigging took place the next day. The third bar (Post-BG injection) represents the number of viable spores attached to the pipe surface immediately before pigging took place. Any decrease between the second and third bar represents the number of spores that came off the pipe surface between contamination and immediately before pigging. The fourth bar (Post pigging BG spore density) represents the number of viable *B. globigii* spores attached to the pipe surface after pigging. The fifth bar (Post pipe relining) summarizes the number of viable *B. globigii* spores recovered from the inner pipe surface after relining. The last bar (Post chlorination spore density) represents the number of viable spores recovered from pipe surface after chlorination.

Figure 25 shows the Warthog pigging and CIPP relining results for the cement mortar lined pipe. Pigging with the Warthog nozzle resulted in 2.2 log removal of spores from the pipe surface. Relining with CIPP reduced the number of viable spores detected by 1.8 log. Chlorination resulted in an additional 0.3 log reduction, for a combined total of 4.3 log reduction. Viable spores were found in one out of four swab samples taken from the inner pipe surface after chlorination. Figure 26 shows the Warthog pigging and CIPP relining results for the cement mortar lined pipe. Pigging with the Warthog nozzle resulted in 2.8 log removal of spores from the pipe surface. Relining with CIPP reduced the number of viable spores detected by 1.7 log. Chlorination resulted in an additional 0.8 log reduction, for a total reduction of 5.3 log. Viable spores were found in one out of four swab samples taken from the pipe surface after chlorination.

During the chlorination phase, aliquots of chlorine bleach were added to the pipe sections with the goal of achieving 70 to 80 mg/L free chlorine. In the relined cement-mortar pipe, the initial free chlorine concentration was 215 mg/L. After 16.75 hours of contact, the free chlorine concentration was 69 mg/L. These values yield a bulk phase CT of 307,715 mg-min/L. In the corroded iron pipe, the initial free chlorine concentration was 210 mg/L. After 16.75 hours of contact, the free chlorine concentration was 59 mg/L. These values yield a bulk phase CT of 304,778 mg-min/L. No viable spores were detected in the bulk water phase after the bleach had been flushed from the pipe and tap water restored.

The results shown in Figure 25 and Figure 26 suggest that pigging, relining with CIPP and chlorination are effective at yielding an inner pipe surface with substantially fewer adhered spores. In both types of pipe, spores were detected in 1 out of 4 sample after chlorination. The CIPP lining is approximately 1.3 cm (0.5 in) thick and resembles a plastic or PVC pipe. It is unlikely that spore could transfer or diffuse through this material. The presence of spores on the CIPP surface is likely due to cross contamination from the surrounding site, or transfer from the pipe itself to the surface during CIPP installation. Installing the CIPP requires more handling and manipulation of the impregnated sock material as compared to the spray on pipe lining. It was noted that there were dirty or “greasy” spots on the CIPP surface that were sampled, and it is

possible that these areas could harbor spores. This could have made cross contamination of the CIPP relined pipe more likely than the pipe relined with the Oceanit method.

3.4 Results Summary Tables

Table 2 shows a summary of the total BG log reduction after the three decontamination methods on cement-mortar lined iron pipe and unlined ductile iron pipe. Table 2 is meant to be a quick summary of the overall effectiveness of each decontamination method.

Table 2: Summary of total BG spore log reduction from each decontamination method tested on two different pipe types.

Decontamination Method	Cement-Mortar Lined Iron Pipe Total Log Reduction	Unlined Iron Pipe Total Log Reduction
Warthog Pigging followed by chlorination	3.0	≥5.8
Warthog pigging following by Oceanit DragX then chlorination	≥5.9	≥6.5
Warthog pigging following by CIPP relining then chlorination	4.3	5.3

Table 3 shows the log reduction for each individual process in the three decontamination methods. Showing the effectiveness of each decontamination process side by side displays important points about their implementation in the field. First, Warthog pigging was performed on three cement-mortar lined ductile iron, and three unlined ductile iron pipes. However, the data in Table 3 shows that pigging alone was not equally effective on each pipe of the same type. BG spore log reduction ranged from 1.9 to 4.0 on cement-mortar lined iron pipe, and 2.8 to ≥6.5 on unlined iron pipe. This comparison shows that the decontamination effectiveness of pigging may be influenced by the number of initial spores adhered, but also possibly by how well the operator was able to pig the pipe, as well as factors that are unknown. However, the ranges listed above for each type of pipe could be used as a range of effectiveness for pigging with a jet spray type pig.

It should also be noted that after relining and chlorination, spores were still sometimes detected on the lined pipe surface. It is doubtful that this is due to spores penetrating through the lining. As noted earlier, the presence of spores is likely due to cross contamination from the surrounding site, or transfer from the original pipe to the lining surface during installation. In this study, spores were not detected on the Oceanit lining, but were detected on the CIPP lining. It is unclear if this result is a function of the lining itself or if it is a coincidence. However, the data suggest that both pipe relining technologies have the potential to be effective.

Table 3: Summary of the BG spore log reduction for each step the decontamination processes on two different pipe types.

		Log Reduction					
Pipe Type	Adhered Spore Density Before Pigging (cfu/cm^2)	After Warthog Pigging	+Oceanit DragX Relining	+CIPP Relining	+Chlorination	Total Log Reduction	# of spore positive sample after final decon method
Cement-Mortar Lined Iron Pipe	1.0×10^5	1.9			1.1	3.0	3/4
	8.3×10^5	4.0	1.4		≥0.5	≥5.9	0/4
	5.1×10^4	2.2		1.8	0.3	4.3	1/4
Unlined Iron Pipe	5.7×10^5	4.9			≥0.9	≥5.8	0/4
	8.3×10^5	≥6.5	N/A		N/A	≥6.5	0/4
	4.2×10^5	2.8		1.7	≥0.8	5.3	1/4

Darkened boxes indicate that the decontamination procedure was not used.
BG, *Bacillus globigii;* CIPP, cured in place pipe; N/A: not applicable as spores were not detected.

4.0 Conclusions

Decontaminating adhered *Bacillus* spores from drinking water infrastructure can be challenging. This study examined the ability of pigging, or physical scouring of the inside of pipes, as well as pipe relining followed by chlorination, to reduce the number of viable *Bacillus* spores that were detectable on the inner pipe surface. A summary of the three different decontamination processes on two different pipe types are as follows:

- Warthog pigging (2,300 psi, 70 gpm) of an individual cement-mortar lined iron pipe section resulted in a 1.9-log reduction of the number of spores detected on the inner pipe surface. After pigging, chlorination of the water in the pipe at an initial concentration of 149 mg/L (111 mg/L after 18.25 hours) resulted in an additional 1.1-log inactivation of the spores adhered to the pipe inner surface, for a total reduction of 3.0-log.

- Warthog pigging (2,300 psi, 70 gpm) of an individual corroded iron pipe section resulted in a 4.9-log reduction of the number of spores detected on the inner pipe surface. After pigging, chlorination of the water in the pipe at an initial concentration of 82 mg/L (39 mg/L after 18.25 hours) resulted in an additional 0.9-log inactivation of the spores adhered to the pipe inner surface, for a total reduction of 5.8-log.

- Warthog pigging (2,300 psi, 70 gpm) followed by Oceanit DragX relining of an individual cement-mortar lined iron pipe section resulted in a 5.4-log reduction of the number of spores detected on the inner pipe surface (note that spores were only detected in 2 out of 6 pipe interior samples). After relining, chlorination of the water in the pipe at an initial concentration of 216 mg/L (133 mg/L after 22.15 hours) resulted in no spores detected on the interior pipe surface, or up to an additional 0.5-log inactivation of the spores adhered to the pipe inner surface, for a total reduction of ≥ 5.9-log.

- Warthog pigging (2,300 psi, 70 gpm) followed by Oceanit DragX relining of an individual corroded iron pipe section resulted in no spores detected on the inner pipe surface, or ≥ 6.5-log reduction. After relining, chlorination of the water in the pipe at an initial concentration of 171 mg/L (122 mg/L after 22 hours) still resulted in no spores detected on the interior pipe surface.

- Warthog pigging (2,300 psi, 70 gpm) followed by CIPP relining of an individual cement-mortar lined iron pipe section resulted in a 4.0-log reduction of the number of spores detected on the inner pipe surface (note that spores were only detected in 2 out of 4 pipe interior samples after relining). After relining, chlorination of the water in the pipe at an initial concentration of 215 mg/L (69 mg/L after 16.75 hours) resulted in an additional 0.3-log inactivation of the spores adhered to the pipe inner surface, for a total reduction of 4.3-log. Spores were detected in 1 out of 4 post chlorination pipe interior samples, and their presence was likely due to cross contamination.

- Warthog pigging (2,300 psi, 70 gpm) followed by CIPP relining of an individual corroded iron pipe section resulted in a 4.5-log reduction of the number of spores detected on the inner pipe surface (note that spores were only detected in 2 out of 4 pipe interior samples after relining). After relining, chlorination of the water in the pipe at an initial concentration of 210 mg/L (59 mg/L after 16.75 hours) resulted in an additional 0.8-log inactivation of the spores adhered to the pipe inner surface, for a total reduction of 5.3-log. Spores were detected in 1 out of 4 post chlorination pipe interior samples, and were likely due to cross contamination.

Pigging with the Warthog nozzle followed by chlorination reduced spores on cement-mortar lined iron by 3.0-log, and by 5.8 log on corroded iron. Increased decontamination efficacy on corroded iron compared to cement-mortar lined iron was likely due to spores being adhered to the corroded iron matrix, which as almost completely removed during pigging process. After both relining process were complete, spores were nearly undetectable. Any detectable spores present after relining (and chlorination) were likely due to cross contamination of spores from the surrounding area or carry over from the contaminated pipe. For pipe relining to be successful, cross contamination would need to be controlled.

Should a biological contamination scenario occur, a technique like pipe lining or replacement could be implemented to ensure that human exposure to spores via drinking water does not occur. Pigging, relining and chlorination can substantially reduce the number of spores adhered to drinking water infrastructure, which may make further remedial actions easier. It should also be considered that pigging generates contaminated waste and wash water, which must be treated or disposed of properly. First responders and decision makers should weigh the burden of contaminated water and waste generation against the decontamination efficiency of pigging, chlorination and pipe relining.

It should also be noted that the skill and experience of the operators applying either pigging or pipe relining techniques are important. There is an art to “working the pigs” effectively through the pipeline, or successfully applying a pipe coating. The speed of the nozzle is controlled by the operator and certain sections of pipe may require several passes or rework as the pig progresses

through the pipe. The degree of decontamination resulting from pigging or pipe relining can vary depending on the skill of the operator.

The authors acknowledge that the decontamination and rehabilitation methods used in this report require more time and resources than typical chlorination and flushing response actions. These methods also require more specialized equipment and expertise, and would be more expensive to implement. Worker safety, contamination of utility owned equipment, and disposal of contaminated water and debris are other areas that need to be considered before implementing water jet pigging as a decontamination method. However, in areas where flushing and chlorination are ineffective, and pipe replacement is challenging, water jet pigging and/or pipe relining may be the only decontamination option.

All of the pipe decontamination and rehabilitation methods described in this report were intended for use on larger diameter (e.g. 4 inches or larger) drinking water utility owned piping. However, any contamination event that impacts the larger utility owned pipes under the street will likely impact the end users of the water supply. Additional research is needed to assist home owners and post service connection water customers with decontamination of their service lines, home plumbing and appliances. These pipe diameters are often 1 inch or less with numerous bends and valving. Several technologies are emerging for service line relining, and these relining methods should be tested as a way to contain residual spore contamination. Finally, it should be noted that a hole must be drilled in the Permaliner used in this study in order to insert a new home or building water service connection. It is possible that contamination trapped between the Permaliner and pipe wall could be released when a new service connection is cut. Research into how to avoid service connection contamination when installing a new service connection should be conducted.

5.0 References

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