EPA's Water Security Test Bed

INTRODUCTION

The U.S. Environmental Protection Agency (EPA) is the lead federal agency responsible for working with water utilities to protect water distribution systems from contamination and to clean up systems that become contaminated. Intentional and unintentional contamination of distribution systems can result in large amounts of water and miles of infrastructure that must be cleaned to return the system to service.

Advancing the science and engineering of decontaminating pipe systems and of safely disposing of high-volumes of contaminated water are high priorities for the EPA. The Agency homeland security researchers developed the first-of-its-scale water security test bed (WSTB). The first phase of the test bed, constructed at the Department of Energy's (DOE) Idaho National Laboratory (INL), replicates a section of a typical municipal drinking water piping system with roughly 450 feet of pipe and two fire hydrants laid out in an "L" shape. The eight-inch cement mortar lined ductile iron pipes, used for the construction of the WSTB section were excavated after twenty years of use for water conveyance (Figure 1). These pipes allow for technology testing in an environment that simulates a typical operating water distribution system. Researchers built the WSTB above ground for easy access during experiments, for leak detection, and for spill containment to protect the groundwater.

Figure 1. Cement mortar lined, ductile iron pipes, and auto-flushing hydrant.

The purpose of conducting research at the WSTB facility is to evaluate infrastructure decontamination technologies previously tested by the EPA's Homeland Security Research Program (HSRP) at the bench- and pilot-scale. Using this simulated full-scale distribution system allows for injection of contaminants that cannot be tested in operating municipal water facilities. HSRP researchers can then evaluate decontamination methodologies to determine those that are best suited for use by water utilities. The WSTB facility also enables testing of portable water treatment technologies for the effective management of the contaminated water that is discharged from the contaminated pipeline into a 28,000-gallon lagoon. Lastly,

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decontamination of premise plumbing and household appliances can be evaluated in an adjacent building at the site (Figure 2).

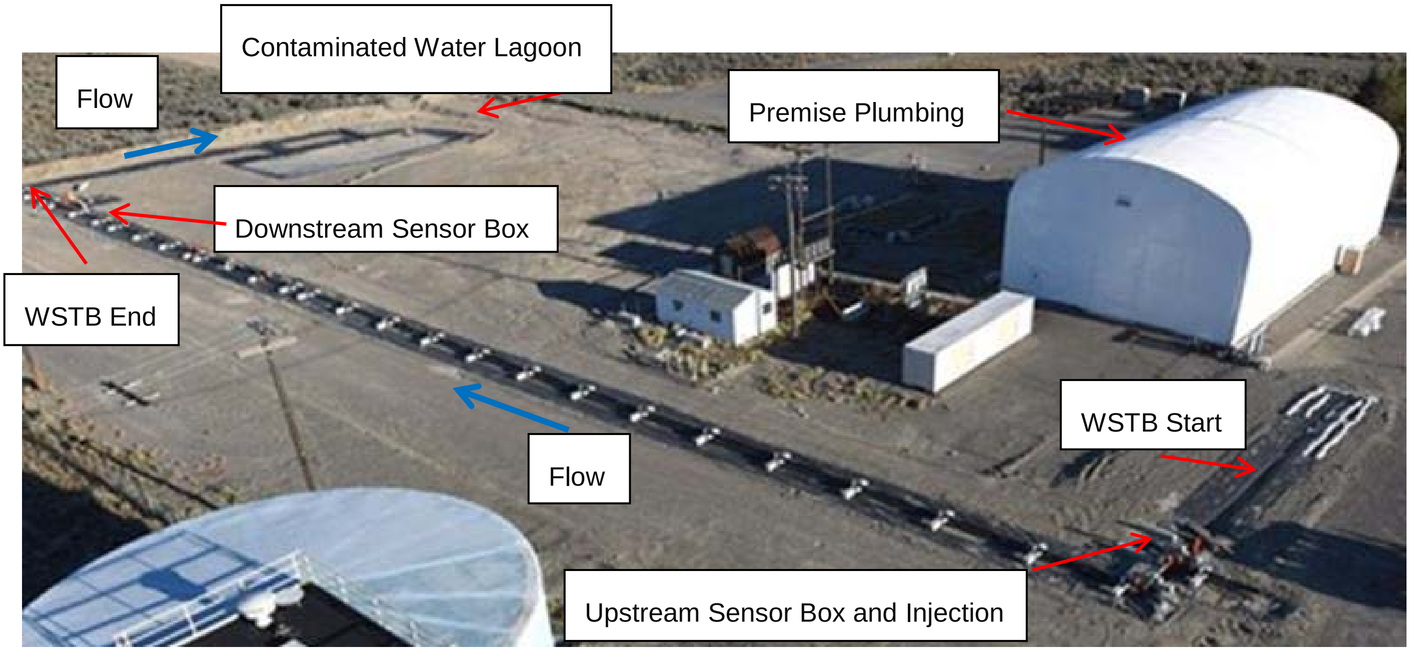

Figure 2. Water security test bed (WSTB) and capability within the Idaho National Laboratory site.

BACKGROUND

Homeland Security Presidential Directive [9 (HSPD-9, 1/30/2004),] and **Presidential Policy Directive 21** [(PPD-21, 2/12/2013)] tasked EPA with responsibilities for water infrastructure protection. In accordance with these directives, the HSRP has been conducting research to help utilities protect against contamination incidents and help utilities rapidly detect and respond to such incidents.

The WSTB full-scale facility has broad applicability for research into water system decontamination. The facility provides for the injection of biological, chemical (including crude oil), and radiological contaminants. The researchers are evaluating technologies and methodologies to determine their efficacy for treating the water, and for decontaminating the ductile iron pipe walls, water infrastructure appurtenances, premise plumbing and household appliances. Researchers at the WSTB facility also conduct testing of full-scale innovative portable water treatment technologies to treat contaminated water that is discharged. Effective management of contaminated water (from clearwells, the distribution system, or contaminated water from indoor and outdoor remediation activities) is needed to improve emergency response, shorten response time, and improve preparedness. These studies can also inform acceptance of such waters by water resource and recovery facilities (e.g., wastewater treatment facilities). Research at the facility can also support cyber security defense and mitigation approaches for water infrastructure operational technology. Support for field-testing of water quality detection sensors and real-time modeling software is also possible. The WSTB facility is expandable to support research by other organizations and training for emergency personnel and first responders.

WSTB Capability

The WSTB facility is equipped with sensors to detect contamination and injection points for the introduction of contaminant simulants and decontamination agents. Removable coupons (excised samples) are installed within the piping (Figure 3) and can be analyzed to determine the adherence of contaminants to the pipe walls and to evaluate the efficacy of decontamination efforts on pipe material and biofilm. A lined lagoon (28,000 gal) is constructed to contain water flushed from the test bed.

At 200 feet, a 1-inch sevice connection line is connected to an adjacent building and provides water to multiple types of household plumbing and home appliances. This allows for testing the persistence of contaminants on these household appliances and on different premise plumbing pipe material. Self-help methods to decontaminate these appliances are also evaluated.

Figure 3. Coupon sampling at the water security test bed pipe.

INFRASTRUCTURE DECONTAMINATION EXPERIMENTS

Response to Microbiological Contamination in the Pipes

Bacillus atrophaeus subsp. *globigii* (BG) is a surrogate for *Bacillus anthracis*, the causative agent of anthrax. BG spores are considered a resilient and conservative surrogate for most microbiological water infrastructure contaminants. BG spores were injected into the WSTB pipe and the persistence of the spores on the pipe material was evaluated. Chlorine dioxide decontamination was chosen from successful pilot-scale decontamination experiments at EPA's Test and Evaluation Facility in Cincinnati, Ohio. The number of BG spores was reduced by about 6-log in the water, which was consistent with the pilot-scale experiment. However, even with a higher concentration of chlorine dioxide at the field-scale, WSTB pipe wall decontamination was not as effective as expected from the pilot-scale experiments. The chlorine dioxide (100 mg/L) decontamination in the WSTB for 24 hours resulted in residual spores remaining adhered to the cement-mortar pipe surface. There was only a 2-log reduction at the WSTB as compared to a 4-log reduction at the pilot-scale. This was likely due to high chlorine dioxide demand from the pipe, higher temperature for the over-ground pipes, and inefficient transport of the disinfectant into dead end spaces. BG spores were found in the pipe months after the experiment ended, even following draining of the pipe during the winter and subsequent filling the next spring. The viability of the spores was not assessed. Testing of pipe cleaning technologies will be conducted in future experiments.

Response to Chemical Contamination in the Pipes

The WSTB pipe was contaminated with the subnatant fraction of Bakken crude oil that had been dissolved and mixed with local river water for 12 hours. This was meant to simulate an oil spill on a water body. Decontamination was performed by flushing with clean water first, as typically done by a water utility, followed by the addition of a surfactant. Persistence of the oil on the pipe material was evaluated. Data collected during the crude oil contamination experiment suggest that flushing the pipe with clean water was an effective decontamination method for the Bakken crude oil. With clean water flushing, benzene detected in the WSTB pipe from the oil contamination quickly dropped below the EPA prescribed drinking water Maximum Contaminant Levels (MCLs). No total petroleum hydrocarbons or toluene, ethylbenzene and xylene components were detected in the water. A surfactant was injected because it was assumed that oily components could persist in the water phase or on the infrastructure surfaces. Online sensor data and visual observation of foaming in the water samples indicated that the surfactant may have persisted in the dead-end portions of the WSTB pipe for weeks after the initial injection. Successful flushing with water makes surfactant addition ultimately unnecessary for Bakken crude oil contaminations. This lingering foaming should be taken into consideration if a surfactant is used during decontamination of a chemical in a drinking water distribution system.

Treatment Effectiveness of Microbiological Contamination in Water

BG spore contaminated water was collected in the lagoon. Four mobile disinfection technologies were tested for their ability to disinfect large volumes of biologically contaminated “dirty” water from the WSTB. The four technologies evaluated included: (1) Hayward Saline C™ 6.0 chlorination system, (2) advanced oxidation process (AOP) ultraviolet (UV)-ozone system (Figure 4 below), (3) Solstreme™ UV water treatment system, and (4) WaterStep chlorinator. Treatment effectiveness, capital cost, ease and speed of deployment, and operation were documented. Results from the water treatment experiments indicate that disinfection of large volumes of water contaminated with BG spores is feasible. All treatment units achieved at least 4-log removal of spores from the lagoon water over the course of the experiments, with some units achieving 7-log reduction. Treated water volumes ranged from 1,250 to 5,000 gallons (4,732 to 18,927 L) with experiments ranging from 5.5 hours to 1 day. It is likely that larger volumes of water may need to be disinfected in a real world scenario, which would need the scale up of portable units, or the use of multiple units. Data generated from this study demonstrate the challenge of disinfection of contaminated water in the field due to the disinfectant demand present in real world wash water, the potential for low temperature, and disinfectant dissipation due to sunlight.

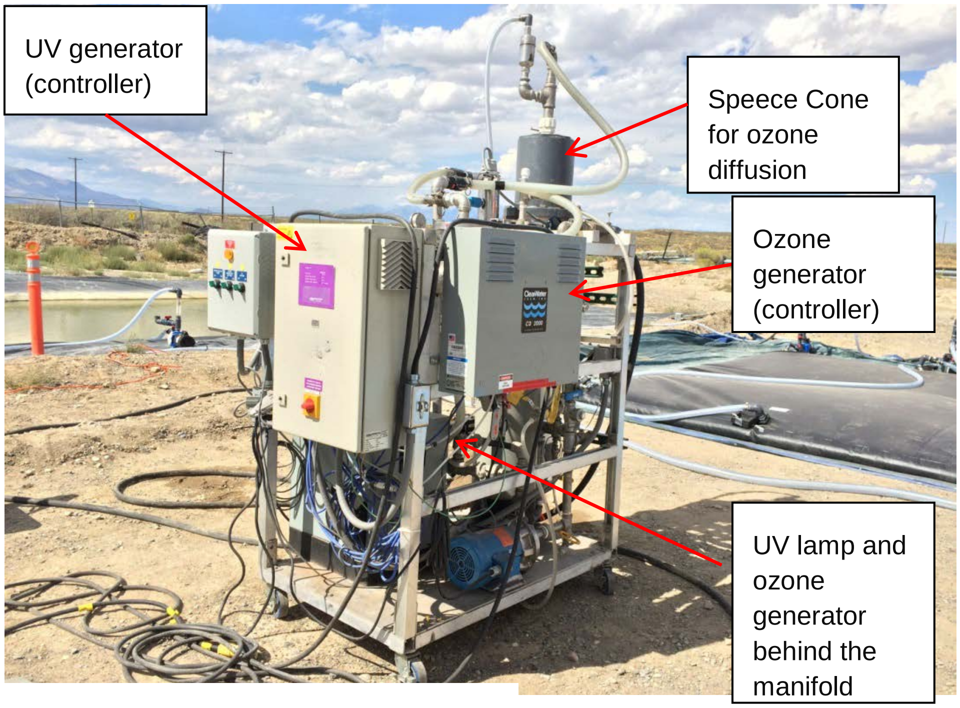

Figure 4. Mobile ozone/UV system.

Perfluorinated Compound Contamination

The portable on-site treatment of water contaminated with fire-fighting foam that contains perfluorinated compounds was tested at the WSTB lagoon. Approximately 10,000 gallons of chlorinated ground water from the WSTB well was contaminated with 5 gallons of 3M Light Water™ aqueous firefighting foam (AFFF) containing perfluorinated compounds. EPA evaluated the performance of 2 treatment technologies (1) Rembind™, an engineered powdered carbon treatment media and (2) Filtrasorb®, a more traditional granular activated carbon media. Preliminary results indicate that both systems were effective at reducing the perfluorinated compounds in excess of 99.99%. However, the commercially available Remind material was too fine to allow flow through it, and it had to be mixed with sand to allow adequate flow, an important operational finding. The traditional granular activated carbon did not require any manipulation and was ready to use in the field when it arrived at the site.

PREMISE PLUMBING and APPLIANCES DECONTAMINATION

Contamination of premise plumbing and appliances with BG spores and Bakken crude oil, followed by disinfection with pH adjusted bleach and/or flushing was evaluated at the building adjacent to the WSTB pipeline. Approximately 200 feet of 1-inch copper service line connects the WSTB 8-inch pipeline to the building. This service line feeds the building where there are multiple 6-inch sections of PVC, copper, and PEX (crosslinked polyethylene) home plumbing, which are then connected to a water heater, refrigerator, washing machine, dishwasher, and utility sink as shown in Figure 5. The choice of disinfectant is to investigate an approach that could be easily used by the homeowners.

BG Spores

The BG spores were injected for an hour into the 1-inch copper service line just before the three different premise plumbing pipe sections and appliances. Interestingly, some spores were found in the cold water influent from the WSTB 8” pipeline before the experimental injection. These BG spores are likely left over from past experiments in the big pipe and further highlights the resilience of the spores and how critical and difficult it is to completely decontaminate water infrastructure. After the BG spore contamination, decontamination proceeded by first draining the hot water heater and then refilling with a solution of 4 gallons of bleach and 4 gallons of vinegar into 47 gallons of uncontaminated tap water. The bleach solution flowed through all of the pipe sections and entered all of the appliances with a contact time of 1 hour. The cold water utility sink tap was flushed for 20 min, the hot water heater was drained, refilled and flushed with hot water for 20 min, and all of the appliances were run once. The same procedure was followed the next day but without the chlorination.

After chlorination and flushing, BG spores were not found at the taps, but some were found in the hot water heater and appliances. The next day, 5 to 50 BG spores/100ml (measured as colony forming units (CFUs)/100 ml) were still found in the appliances and coming out of the taps, especially the hot water tap, which is supplied by the hot water heater. The chlorination and flushing resulted in a consistent 6-8 log removal of spores from the water in the plumbing pipes and appliances. The remaining spores were likely caught in places that the chlorination and flushing could not reach adequately. Or, as mentioned previously, the large pipeline could continue to contribute as a source of contamination. The data show that flushing and chlorination do a good job removing a vast amount of the contamination, but it is possible that low numbers of spores can linger in premise plumbing systems for longer periods of time.

Figure 5. Premise plumbing and appliances

The 6-inch sections of copper, PEX and PVC coupons were swabbed and sampled before contamination and again after chlorination and flushing. About a 2.3-log reduction on the PVC and copper were observed and a 4-log reduction on the PEX. Similarly, lingering spores were found after decontamination in the appliances, which could be from residual spores adhered to the plumbing pipes or from dead spaces in the plumbing system where flushing was ineffective or chlorine could not reach.

Bakken Crude Oil

As in the large WSTB pipeline experiment, the "subnatant" water below the oil was injected for an hour and was flushed through all of the plumbing and appliances. Decontamination followed in order with (1) flushing the cold water tap (and refrigerator water) for 20 minutes, (2) then draining the water heater, refilling and flushing the hot water plumbing for 20 minutes, and 3) running the appliances for one cycle. Sampling and flushing was repeated the next day.

As in the 8-inch pipe experiment, large spikes of benzene were detected following injection. After the first flushing/draining and thereafter, the levels dropped to the pre-injection baseline level. Flushing was effective in decreasing the benzene levels to below the drinking water MCL.

Total petroleum hydrocarbons (made up of gas range organics, oil range organics and diesel range organics) were also analyzed. There are no drinking water MCLs for these, but some very low levels of some of the constituents were measured in the dishwasher and refrigerator water, possibly due to either adherence to the plumbing material in those appliances and then leaching or a remnant of the contaminant injection. No oily smell was detected following the second day of flushing. Toluene, ethylbenzene, and xylene were also analyzed and any residual amounts found were also well below the drinking water MCLs.

FUTURE EXPERIMENTS

Additional experiments are planned to:

- Finish biological decontamination approaches that will include physical scouring of pipes
- Evaluate decontamination of additional classes of chemical contaminants
- Decontaminate pipes and appurtenances from radioactive contaminants
- Continue evaluations and commercialization of innovative water treatment unit processes
- Evaluate cyber-attacks on system instrumentation, communications, and computer-based systems for remote monitoring and control

In the event that additional resources/partners become available, the WSTB facility can be expanded to provide a more complex hydraulic and operational network as shown below in Figure 6. This expansion can be done with similar pipes from the original excavation and from pipes from other partners or collaborators.

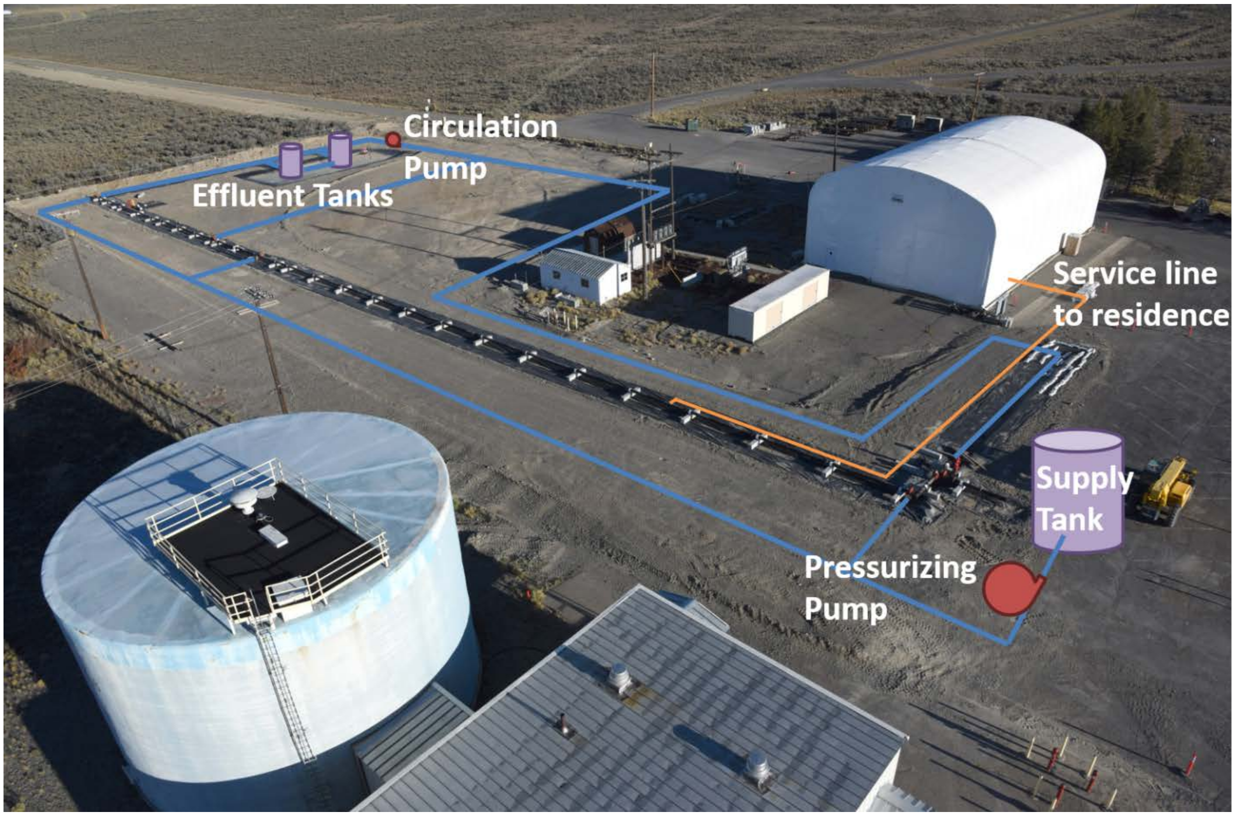

Figure 6. Future of the WSTB facility.

This would enable additional experiments involving:

- Evaluations and applications of innovative real-time water quality detection instrumentation and incident mitigation
- Distribution system network modeling
- Software calibration and verification
- Additional cyber experiments in a more complex configuration
- First responder, emergency personnel training, and homeowner self-help approaches

OUTREACH

EPA is opening up the test bed research capability to additional potential collaborators such as agencies within the DOE, Department of Defense, the Department of Homeland Security, universities, water utilities, and foundations interested in water security research. EPA is also considering partners' needs as they build out the test bed to include service connections and other types of pipe commonly found throughout water distribution systems.

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