NIST Technical Note 1605

Contaminant Accumulation and Removal in Building Plumbing Systems

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National Institute of
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September 2008

ABSTRACT
This report summarizes the results of measurements conducted to evaluate the accumulation and removal of water-borne contaminants in building plumbing systems. In particular, tests were conducted at the Building and Fire Research Laboratory (BFRL) Plumbing Test Facility, which emulates a full-scale building water supply system in a controlled laboratory setting. The measurement results highlighted the difficulty in removing contaminants that have been introduced into building plumbing systems, even for relatively simple configurations such as straight pipe sections, and particularly for large water tanks such as water heaters. Simple flushing with cold tap water may require very long flush times to remove persistent contaminants such as diesel fuel and strychnine, and while capable of substantially reducing the number of spores in a water supply system, may benefit from supplementary decontamination procedures such as flushing with hot water, cleaning solutions or hyper-chlorination

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1. INTRODUCTION

This report summarizes the results of measurements conducted to evaluate the accumulation and removal of water-borne contaminants in building plumbing systems. In particular, tests were conducted at the Building and Fire Research Laboratory (BFRL) Plumbing Test Facility, which emulates a full-scale building water supply system in a controlled laboratory setting. The test facility includes water supply piping, fittings and fixtures that represent a five-story building, and incorporates a computer based control and data acquisition system which can be programmed to circulate water according to any desired profile. The facility also includes a measurement station for water tanks, such as water heaters.

The types of tests that were conducted involved introducing a water/contaminant mixture into the water distribution system, and allowing it to circulate and/or stand for a set period of time, followed by a flushing or cleaning operation. Pipe and water samples were collected at various stages of each test run, and then analyzed for the presence of accumulated contaminant. In this manner, the tendency of different contaminants to accumulate on exposed components of building plumbing systems could be determined, along with the effectiveness of flushing and cleaning procedures.

Screening tests on small samples of copper, galvanized iron, polyvinyl chloride (PVC), and rubber exposed to diesel fuel, gasoline, strychnine, cyanide, and phorate were done to explore which contaminants potentially posed the greatest problems for water appliances and building plumbing. From these tests, it was determined that diesel, strychnine and cyanide would be used in the water heater and pipe loop tests. In order to examine the effect of biological contaminants, Bacillus thuringiensis[1] (BT) spores were also examined in these large-scale tests.

2. BACKGROUND

If water-borne contaminants enter a building plumbing system, they represent a direct hazard to water consumers if the contaminants are consumed or otherwise come into human contact [1]. In addition to contaminants that remain in the water, and may eventually be flushed from the system, contaminants that come into contact with plumbing systems substrates, such as pipe surfaces, valves, tank walls and appliances, may accumulate on those surfaces. The possible accumulation methods include adsorption, absorption and sedimentation. If contaminants do accumulate within the plumbing system, they represent an additional danger, as they may be subsequently released into potable water. Therefore, it is important to know how, when and where contaminants accumulate in plumbing systems, as well as how to eliminate them from the system.

There are several notable features that are of importance when considering building plumbing systems and the potential for contaminant accumulation. First, pipe diameters are relatively small, typically ranging from ¼ to one inch[2], thus the ratio of exposed surface area to water

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[1] According to the US Environmental Protection Agency, "Bacillus thuringiensis is a naturally occurring soil bacterium that, when sprayed on plants, is toxic to certain pest insects."
http://www.epa.gov/oppbppd1/biopesticides/pips/regofbtcrops.htm

[2] The International System of Units has not been used in this publication when specifying piping diameters. This was done in order to be consistent with the piping identification system of the plumbing industry.

volume is high. Second, water flows tend to be intermittent, so contaminants will have ample time to interact with exposed surfaces before the contaminated water traverses the water supply system. Third, there tend to be many fittings such as elbows, valves and tees, as well as faucets and showerheads, which present potential accumulation locations, and flow obstructions that can inhibit the effectiveness of flushing [2]. In addition to these factors, most water distribution systems that have been in operation for some time will have biofilms, chemical deposits and corrosion on surfaces that can affect both the accumulation and removal processes [3, 4].

Large water tanks, such as water heaters, can be especially problematic, as they tend to collect sediments and are difficult to flush. Water-using appliances, such as dishwashers and clothes washers are a concern, but are not as critical an issue since they are not sources of human water consumption, and posses an inherent cleaning function that can be utilized for decontamination.

Flushing poses problems for building sanitary drains because the normal mode of water system flushing involves discharging the waste water down the drain. In addition, flushing will expose sink and tub surfaces to contaminants, which may require separate cleaning.

3. MEASUREMENTS
Raman spectroscopy was used to investigate contaminant accumulation and removal from building plumbing systems. Several different types of measurements were conducted, ranging from screening measurements on small samples to measurements on a full scale piping system and water heater tanks.

3.1 Screening Tests
Because conducting contamination tests of full scale plumbing systems is time consuming and potentially damaging to equipment, a series of small scale tests was conducted using a selection of chemical contaminants and plumbing system materials, to determine which combinations exhibited the greatest potential for contaminant accumulation. The contaminants tested included:

- Diesel fuel

- Gasoline

- Strychnine

- Cyanide

- Phorate

The material substrates tested were:

- Copper

- Galvanized iron

- PVC

- Rubber

High concentrations (mass fractions) of contaminants (see details in Table 1) were placed in small jars, and a small piece (coupon) of each of the test materials was separately placed in its own sealed jar of contaminant in order to prevent cross-contamination of the samples. Following a certain period of time which varied based on scheduling constraints, the test material was removed from each jar and evaluated for the presence of contaminant. This was followed by flushing with clean tap water for 1 h and a recheck for contaminant, and then another clean tap water flush for 24 h[3] and a final measurement. The flushing intervals were chosen so that the exponential decay of the contaminant would be captured by the measurement. The flushing methodology involved inserting the exposed coupon into a piece of flexible hose through which cold tap water was directed at a flow rate of approximately 0.25 L/s, corresponding to a Reynolds number of approximately 30,000.

These tests represent a somewhat severe exposure scenario, since the contaminant remains in contact with the substrate for an extended period of time, but one that might occur near the point of contaminant introduction in an actual event. Because our objective was to ensure the restoration of the potability of water in buildings, this worst-case analysis is appropriate.

Table 1   Contaminant Mass Fractions for Screening Tests

Contaminant	Diesel	Gasoline	Strychnine	Cyanide	Phorate
Concentration	100 %	100 %	0.5 %	1 %	100 %

The presence of contaminant on the exposed coupons was evaluated using a Raman spectrometer to look for the characteristic Raman spectral signatures associated with each of the contaminants. These signatures were determined by first obtaining Raman spectra of each contaminant, along with Raman spectra of each unexposed substrate material. Then, the Raman spectra of the exposed substrates were compared to the baseline and contaminant spectra, and the presence of the contaminant inferred by the observation of characteristic Raman peaks, and the magnitude of any contaminant accumulation estimated by measuring the height of specific characteristic peaks. Type B evaluations of the wavelength uncertainty and the intensity uncertainty for a 95 % confidence level were ± 0.1 cm^{-1} and ± 15 %, respectively. However, spatial variations in Raman intensity larger than 15 % for a given surface and contaminant condition were not uncommon.

Lacking specific calibration data to relate the dimensionless Raman peak intensity to mass or volume of contaminant, the contaminant accumulation values are best considered to be relative values. However, a later section will attempt to estimate the thickness of the layer of accumulated contaminant for some of the measurements. It should be noted that acceptable levels of residual contaminants within water supply systems are a public health matter that is

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[3] All times have a Type B uncertainty of ± 3 % for a 95 % confidence level.

beyond the scope of this analysis. However, estimation of residual contamination, and the methods for effectively removing contaminants, is the focus of this work.

3.2 Screening Test Results

Figure 1 presents measurement results for the diesel contaminant. used coupons of copper, PVC, iron, and rubber were soaked in 100 percent diesel fuel for approximately 140 h, except for the rubber, which was soaked for approximately 283 h. The data points furthest to the left represent the Raman intensity at the same selected wave number for the specimens immediately after soaking. The data points just to the right of those points correspond to the specimens having been flushed with cold water for 1 h. The data points to the far right were taken after approximately 24 h of flushing. Diesel fuel is clearly seen to stick to each of the substrates, particularly the used cast iron, PVC and copper coupons. The initial 1 h clean water flush was successful at reducing the diesel accumulation by about one order of magnitude, and while continued flushing removed additional diesel, the removal rate slowed noticeably. Residual diesel levels following 24 h of clean water flushing leveled off at about 4 % of the initial values. All flush times in this study were measured to within $\pm$ 5 minutes.

Figure 2 presents the results of measurements for gasoline exposure. Gasoline accumulation after initial exposure was greatest for copper, and least for iron, with PVC and rubber falling in the middle. Flushing only was effective for the rubber substrate, which showed a reduction to approximately 3 % of the initial level. Used coupons of the materials shown to the right of the graph were soaked in 100 % gasoline for approximately 24 h, except for the rubber, which was soaked for approximately 480 h. The data points furthest to the left represent the Raman
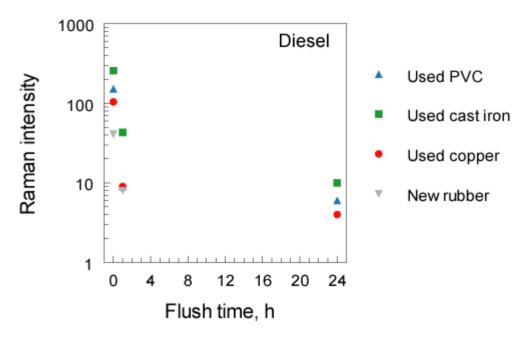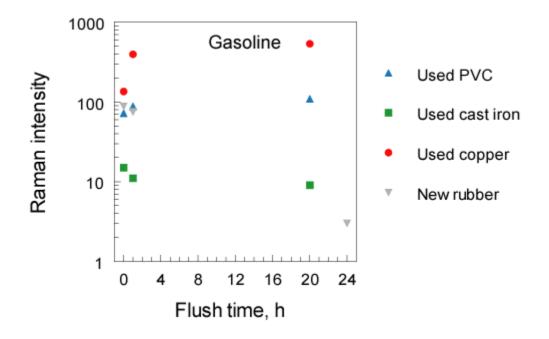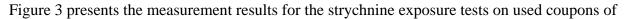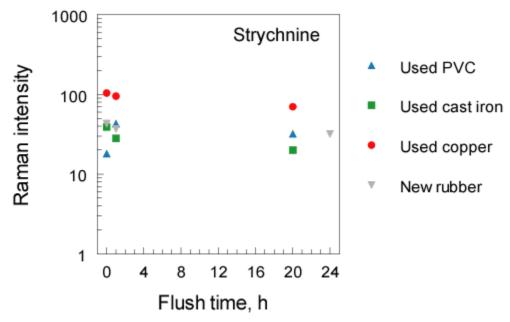

Fig. 1 *Diesel contamination of used coupons of copper, PVC, iron, and rubber were soaked in 100 % diesel fuel*

Fig. 2 *Gasoline contamination of used coupons of the materials shown to the right of the graph were soaked in 100 % gasoline*

intensity at a selected wave number for the specimens immediately after soaking. The data points just to the right of those points correspond to the contaminated specimens having been flushed with cold water for 1 h. The data points to the far right were taken after approximately 20 h of flushing, except for the rubber specimen, which was flushed for approximately 24 h.
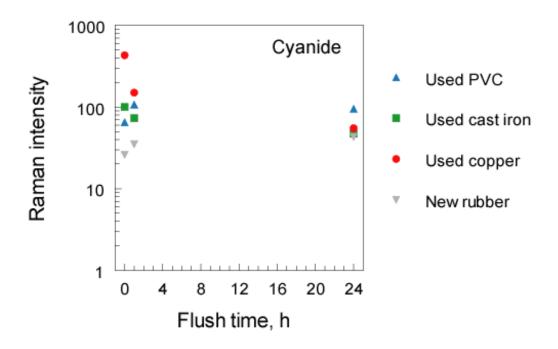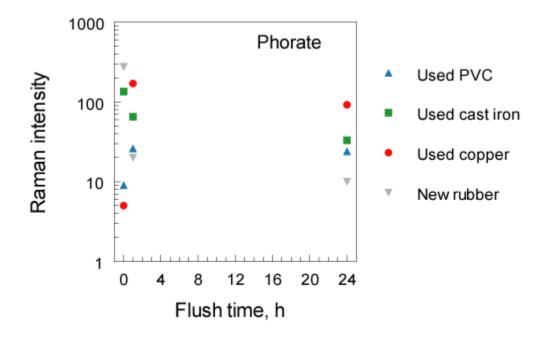
Figure 3 presents the measurement results for the strychnine exposure tests on used coupons of

Fig. 3 *Strychnine contamination of used coupons of the materials shown to the right of the graph were soaked in 100 % strychnine*

the materials shown to the right of the graph that were soaked in a 0.5 % mass fraction solution of strychnine in water for approximately 140 h, except for the rubber, which was soaked for approximately 480 h. The data points furthest to the left represent the Raman intensity at a selected wave number for the specimens immediately after soaking. The data points just to the right of those points correspond to the contaminated specimens having been flushed with cold water for approximately 1 h. The data points to the far right were taken after approximately 24 h of flushing. These results show that strychnine accumulated on all of the substrates, and flushing with tap water was not very effective in removing the residual contaminant because the after flushing Raman intensities are approximately within the uncertainties of the before flushing measurements.

Figure 4 presents measurement results for the cyanide exposure tests on used coupons of the materials shown to the right of the graph that were soaked in a 1 % mass fraction solution (10,000 ppm) of sodium cyanide for approximately 260 h, except for the rubber, which was soaked for approximately 480 h. The data points furthest to the left represent the Raman intensity at a selected wave number for the specimens immediately after soaking. The data points just to the right of those points correspond to the specimens having been flushed with cold water for approximately 1 h. The data points to the far right were taken after approximately 24 h of flushing. The greatest accumulation was on the copper sample, which also showed some reduction from flushing. The other samples accumulated less cyanide, but the levels were not substantially reduced by flushing.

Fig. 4 *Cyanide contamination of used coupons of the materials shown to the right of the graph were soaked in 100 % cyanide*

Fig. 5 *Phorate contamination of used coupons of the materials shown to the right of the graph were soaked in 100 % phorate*
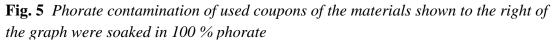
Figure 5 presents the measurement results for the phorate exposure tests on used coupons of the materials shown to the right of the graph that were soaked in a solution of 100 % phorate (a systemic insecticide, $C_7H_{17}O_2PS_3$) for approximately 144 h, except for the rubber, which was soaked for approximately 283 h. The data points furthest to the left represent the Raman intensity at a selected wave number for the specimens immediately after soaking. The data points just to the right of those points correspond to the specimens having been flushed with cold water for approximately 1 h. The data points to the far right were taken after 24 h of flushing. Due to its low solubility in water, phorate accumulation was observed to be non-uniform, a probable explanation for the low initial measured accumulations on copper and PVC (i.e., measurement area at a spot where a lower amount of phorate was present). Flushing with water was not effective at removing the accumulated phorate from the PVC and copper, but performed better on the rubber and cast iron, although still leaving significant residual amounts.

3.3 Full-Scale Pipe Loop Tests

The BFRL Plumbing Test Facility was used to measure contaminant accumulation and removal in full scale building plumbing systems. This facility has been described in detail previously [5,6], so the testing methodology is briefly summarized as follows:

1. Figure 6 shows a schematic of the test loop. Water/contaminant mixtures were prepared in a large tank shown in Fig. 6, and then circulated by pumping though a simulated three floor building plumbing system, which included measurement sections with small removable pieces of copper (3/4 and ½ inch) and PVC (½ inch) pipe. (Exception: For cyanide and strychnine, the pipe samples were exposed to the contaminant by suspension in a small

container, and then inserted into the pipe loop for flushing, so that the entire test loop would not be subject to contaminant exposure).

2. Pipe samples were removed after exposure for measurement using a Raman spectrometer.

3. The plumbing system was then flushed with clean, cold tap water, at a flow rate of 0.25 L/s at the pipe samples, and additional pipe samples removed periodically and measured.

4. At the conclusion of the flushing tests, all components of the pipe loop were thoroughly cleaned as needed with hot water and detergent.

Tests were conducted using diesel fuel, strychnine, sodium cyanide and Bacillus thuringiensis (BT) spores, but the sodium cyanide samples did not provide any useful results.
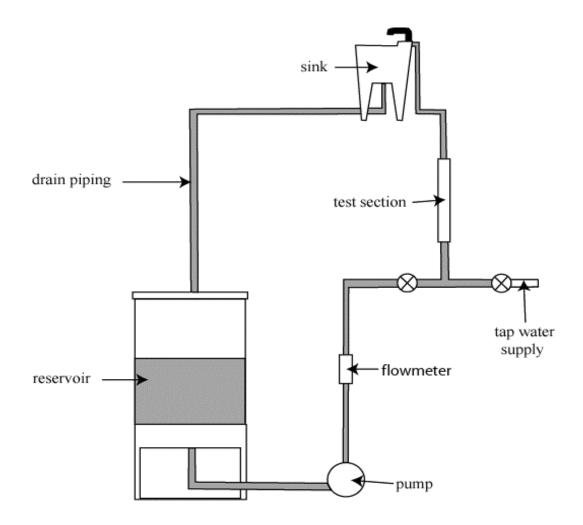

Fig. 6. Schematic of full scale test loop

3.3.1 Diesel Fuel

Figures 7 and 8 show diesel Raman contamination measurements in the pipe loop on copper and CPVC, respectively. Diesel fuel was mixed with water at a nominal concentration of 8.3 %, then circulated through the pipe loop and allowed to stand for eight days. The water lines were then flushed at a flow rate of 0.25 L/s at the pipe samples. Pipe samples were collected from Floor 1 (¾ inch copper pipe) and Floor 3 (½ inch CPVC) and Raman spectra were obtained for all of the samples taken. The measurements showed that flushing with cold tap water was not very effective at removing the accumulated diesel fuel from the pipe samples for either the copper (Fig. 7) or CPVC (Fig. 8) pipe at this flow rate for flushing times of 13 h, although there was some reduction for the CPVC pipe.

3.3.2 Strychnine

Figures 9 and 10 show Raman strychnine contamination measurements in the pipe loop on copper and CPVC, respectively. Samples were measured for Floor 1 (3/4 inch copper pipe) and Floor 2 (1/2 inch copper pipe). For Floor 2, no Raman spectrum was obtained for the sample taken before flushing began and reasonable spectra were only obtained for the samples taken after approximately1h and 2 h of flushing: The measurement results are shown in Fig. 9 for ¾ inch copper pipe and Fig. 10 for ½ inch copper pipe, which indicate that cold water flushing was not effective at removing the accumulated strychnine from the pipe samples.
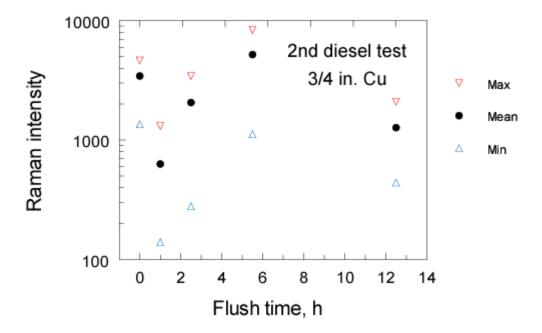

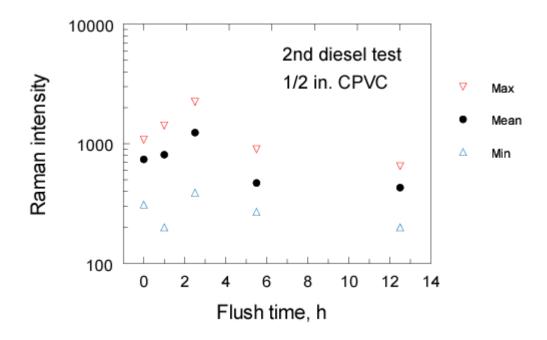**Fig. 7.** *Pipe loop measurements for copper pipe and diesel fuel*

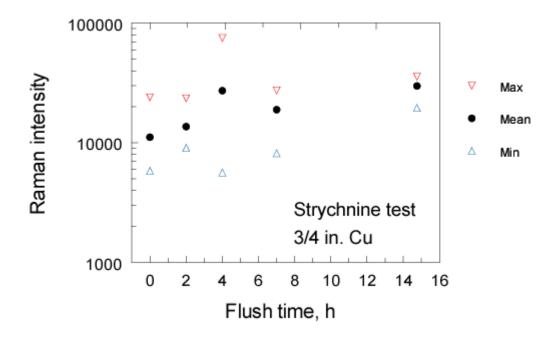**Fig. 8.** *Pipe loop measurements for CPVC pipe and diesel fuel*

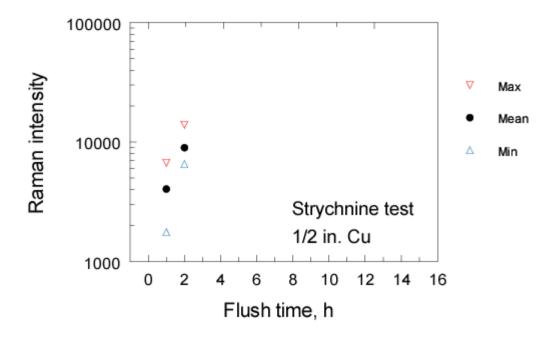**Fig. 9.** *Pipe loop measurements for ¾ inch copper pipe and strychnine*

Fig. 10. *Pipe loop measurements for ½ inch copper pipe and strychnine*

3.3.3 BT Spores

A solution containing BT spores was prepared in the following manner:

- Add 2 L reverse osmosis (RO) water to 3.7 L jug

- Add 4 mL 10 % Triton X-100[4], mix

- Mix bottle of Bonide (#4) and add 100 mL to jug and mix well

- Add 1.67 L RO water to jug and mix well again

- Titer jug

This solution was circulated through the pipe test loop and left overnight to soak, followed by flushing and sampling at 1 h, 3 h and 13.3 h.

Pipe samples were analyzed in the following manner:

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[4] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.
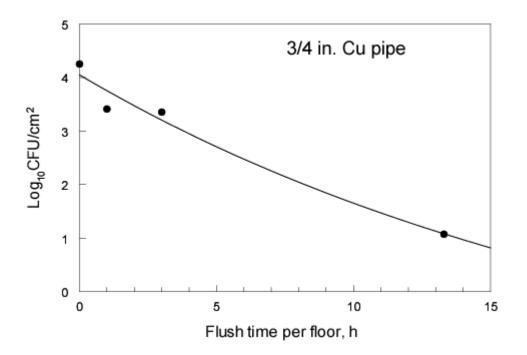
Fig. 11. *Pipe loop measurements for ¾ inch copper pipe and BT spores*

- Received samples and sampled the next day

- Remove pipe from tube and dip pipe in beaker with 100 mL RO water.

- Repeat 2 more times using a new beaker with 100 mL RO water.

- Scrape pipes using cell scraper into 5 mL PBS/Triton in 50 mL conical tubes

- Wash pipe 4 times with buffer in tube

- Vortex for 30 s

- Titer

The results of these measurements are shown in Figs. 11, 12 and 13 for the three floors, which had different pipe sizes and materials. The ¾ inch copper pipe (Fig. 11) showed less than a one log reduction after 3 h of flushing, and a three log reduction after 13.3 h of flushing. While this is a significant reduction, it is possible that the remaining spores could germinate and eventually reproduce, causing them to persist in the system.

Figure 12 shows the results for ½ inch copper pipe, which showed a 2.5 log reduction after a 3 h flush. The 13.3 h flush sample could not be analyzed.

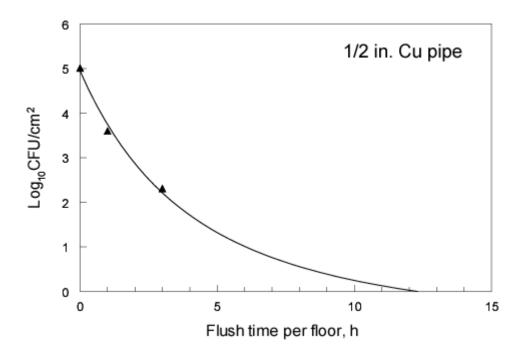**Fig. 12.** *Pipe loop measurements for ½ inch copper pipe and BT spores*

Figure 13 shows the results for the ½ inch CPVC pipe, which showed a 2 log reduction after 3 h of flushing, and a three log reduction after 13.3 h.

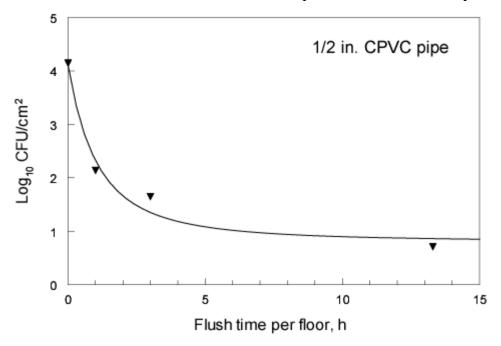While substantial reductions in the number of spores was observed, complete eradication would

Fig. 13. *Pipe loop measurements for ½ inch CPVC pipe and BT spores*

probably require additional decontamination procedures, such as hot water, shock chlorination and/or germination.

3.4 Water Heater Tests

Figure 14 shows a schematic of the hot water test apparatus that was used to conduct tests with used, nominally 50 gallon (189 L), water heaters using the following contaminants:

- Diesel fuel

- Strychnine

- Sodium Cyanide

- Bacillus thuringiensis (BT) Spores

As with the pipe loop tests, water/contaminant mixtures were made and added to empty water heater tanks, then allowed to soak, followed by flushing and/or draining and refilling with clean
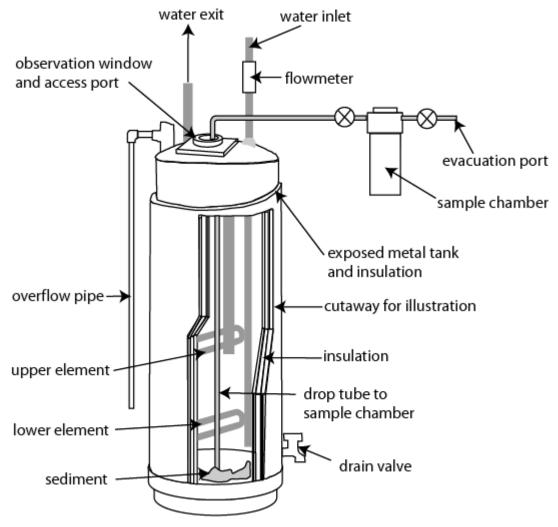
Fig. 14. *Schematic of water heater testing apparatus*

tap water. Periodic samples were taken of sediments from the bottom of the tanks and tank water. Except for the second diesel fuel test, the tank heating elements were not energized. In some cases, multiple Raman measurements were made on each sample or multiple samples, so data are shown as maximum, minimum and average readings. This occurred because contaminant accumulation was not uniform, and the measurement area of the Raman system is very small. The maximum readings are of greatest significance, given that it is necessary to ensure adequate removal of accumulated contaminants wherever they are located.

3.4.1 Diesel Fuel

Approximately 7.6 L of commercial diesel fuel were put into a used 50 gallon (189 L) water heater, which was then filled with cold water, resulting in a nominally 4 % solution. That solution was circulated from the drain to the cold water inlet for 8 h in order to mix the solution and to promote wetting of the tank interior and the sediment in the bottom of the tank by the diesel-water mixture. The tank was drained and a sediment sample extracted from the bottom of the tank. The tank was filled with cold water and allowed to stand for four weeks, at which time it was drained again, and another sediment sample was taken. The tank was re-filled with water, and flushed with clean cold water at approximately 0.13 L/s for a total of 24 h, corresponding to a water volume of approximately 10,900 L being passed through the tank. The tank was then drained, refilled and flushed with hot water at approximately 0.25 L/s for 1.25 h, followed by another sediment sample extraction. In order to attempt to clean the sediment more thoroughly, the tank was drained, approximately 1.4 L of powdered laboratory detergent were added to the tank, and the tank was filled with hot water and allowed to soak (no flushing) for 4 h and then drained before another sediment sample was taken.

Figure 15 shows the measured results for the testing sequence. The higher point to the left of the graph corresponds to the initial Raman spectrum for the sediment following the exposure. The lower point to the left of the graph was taken after the tank was drained and refilled, which showed little change in the Raman intensity. The data point to the right of the graph corresponds to a sediment sample taken after all of the flushing was completed. It is seen that the Raman intensity was somewhat lower than it originally had been but that it was only reduced to about 30 percent of the initial value. Following the cleaning operation, the sediment sample showed no characteristic Raman peak for diesel fuel.

These results suggest that simple draining and refilling of the hot water tank is not particularly effective at removing the diesel fuel, in large part because of the lack of solubility of diesel and its tendency to float on top of the water. A better approach might be to extract it from the top of the tank if possible, and avoid encouraging contact between the diesel fuel and the sediments at the bottom of the tank. While cold water flushing was not effective, cleaning with hot water and detergent was successful at removing all measureable traces of diesel from the tank. In practice, this method would require injecting the cleaning solution upstream of the tank, or through the drain valve.
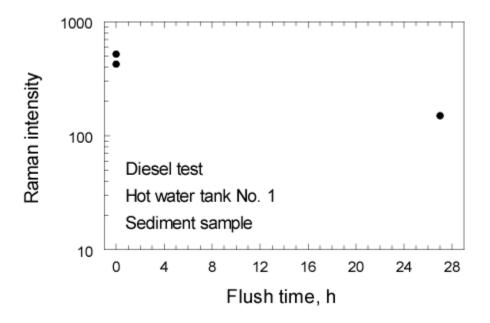
Fig. 15. *Measurement results for a hot water tank exposed to diesel fuel*

3.4.2 Diesel Fuel in Heated Hot Water Tank

Figure 16 shows the water heater test with diesel fuel while sampling from the outlet. For this test, the tank heating elements were energized so that the water was heated to approximately 60 °C. A heated hot water tank was used as representative of actual operation, although the process of flushing introduces cold water to the tank in any case. The tank was partially drained
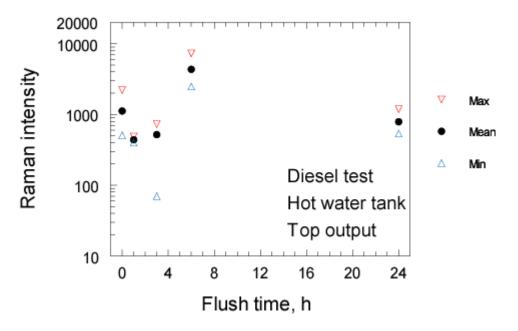

Fig. 16. *Heated water heater test with diesel fuel, sampling from the outlet*

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to allow the addition of diesel fuel at a concentration of 4 % by volume, which was then mixed using a circulating pump, and allowed to stand for 24 h. This was followed by flushing with clean tap water at 0.25 L/s for approximately 27 h, while periodic water samples were taken from the tank outlet and drain for analysis. Because the tank was sealed, it was not possible to collect sediment samples. Figures 16 and 17 indicate that flushing was only partially effective at removing the diesel contamination from the tank, as a significant amount of diesel remained present in water samples following 24 h of flushing. Another challenge associated with flushing hot water tanks is their large volume of water relative to flush water volumes, which causes small water velocities in the tank and correspondingly low removal rates.

3.4.3 Strychnine

Figure 18 shows the water heater test with strychnine.   Raman spectra were obtained for the sediment samples at 0 h, 1 h, 3 h, and 24 h of flushing at 0.13 L/s. Strychnine was still present in sediment samples after 24 h of flushing, at about 10 % of the initial levels.

3.4.4 Sodium Cyanide

The sodium cyanide was detected in the initial sediment sample following exposure, but was not detected in subsequent samples. However, other cyanide measurements suggested that cyanide was not stable in chlorinated water, and also reacted with substrates to form complexes that confounded measurements, so a definitive conclusion could not be reached.

3.4.5 BT spores

Figures 19 and 20 show the measured Colony Forming Unit/milliliter (cfu/ml) of BT spores in
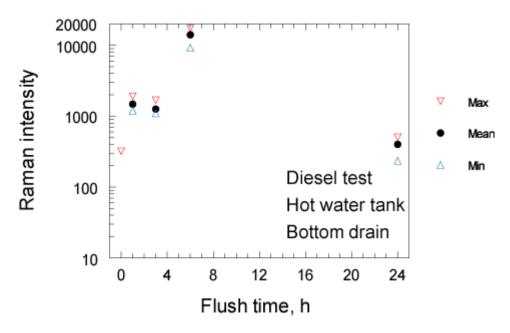

Fig. 17. *Heated water heater test with diesel fuel, sampling from drain*
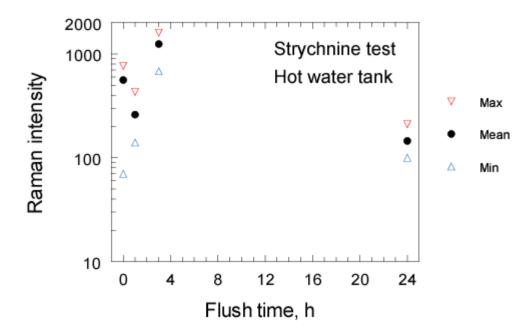
Fig. 18. *Water heater test with strychnine*

the water heaters. In this experiment, a concentrated solution of Bionide spores (an oil spore suspension) was used. Approximately 100 mL of concentrated Bionide was diluted to 3.7 L in RO water containing 0.01 % Triton X-100 and mixed well. The 50 gallon (189 L) water heater tank was filled one-half full and then the Bionide solution was added and the tank was filled up to the 50 gallon (189 L) mark. After allowing the tank to sit for 24 h, the tank was mixed with a rod and then flushed. After a total of 8 h of flushing (48 h after the spores were added) the sediment and water from the bottom of the tank was collected. To the sediment sample, 30 mL of PBS-Trition X100 was added. The anode, which was immersed during the experiment, was scrapped with a cell scrapper and washed with 20 mL of PBS-Triton X-100.
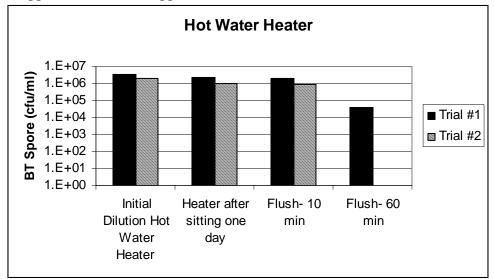

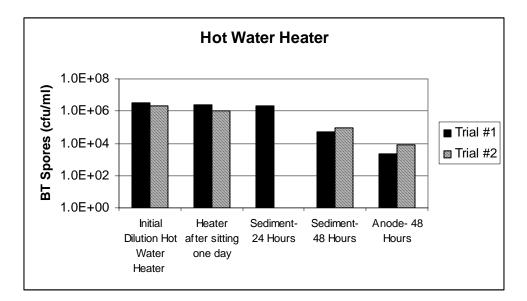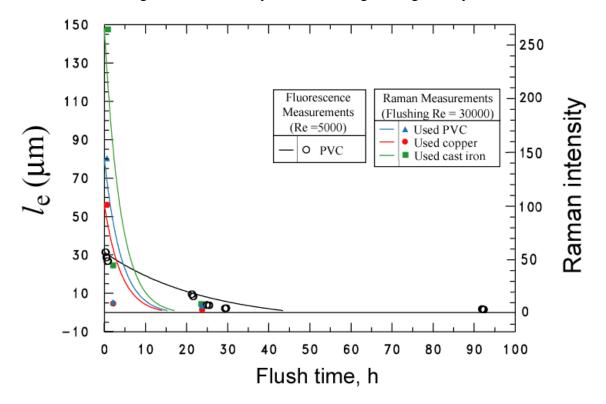**Fig. 19.** Water heater measurements with BT spores- water samples

Figure 20. Water heater measurements with BT spores- sediment and anode samples

The collected spores were diluted and spread on nutrient plates. The spore counts were determined by the average of two plates, which resulted in an estimated uncertainty of $\pm$ 25 % for a 95 % confidence level. The results showed the BT spore concentration remained the same in the water heater after it was allowed to sit for 24 h. In both trials, the spore concentration in the 10 minute flush was similar to the spore concentration in the tank. This means the majority of the spores were flushed out in the 10 minute flush sample. A 60 minute sample was taken in trial #1 and there was a 2 log decrease in the number of spores. However, the sample taken from trial #1 after 2.5 h of flushing revealed no spores. In the second trial, a sample was taken after 10 minutes of flushing and the next sample was taken after 100 minutes of flushing. The concentration in the 10 minute flush was similar to the initial concentration leading one to believe that spores were easily flushed out of the water heater. The next sample was taken at 100 minutes and there were no detectable spores in this flush sample, as is shown in Fig. 19.

Even though a significant number of spores were flushed out of the water heater, a number remained in the sediment. After 24 h in Trial #1 there was the same concentration of spores in the sediment as what was reported in solution. After 48 h of contact in both experiments, there was a log decrease in the number of spores, which resided in the residue. Additionally, there were some spores which remained on the anode (Trial #1) and sample of hot water tank wall (Trial #2) as seen in Fig. 20.

4. ESTIMATED CONTAMINANT LAYER THICKNESS

As mentioned earlier, the Raman measurements themselves do not provide absolute quantitative information about the magnitude of contaminant accumulation. In order to provide some estimates of contaminant layer thicknesses (l_e), static mass measurements were made using water and diesel fuel in order to associate the measured Raman intensities with film thicknesses. The water measurements are representative of dilute water/contaminant mixtures. The static measurements were made by comparing the mass of dry and wet tube samples before and after soaking them in liquid for 24 h. The initial film thickness that was associated to zero flushing time was calculated from the measured surface area and the mass of diesel adsorbed to the pipe surfaces. For diesel fuel, the copper and PVC tube samples had an adsorbed film thickness of 56 µm ± 6 µm and 47 µm ± 5 µm, respectively, while for water, the film thicknesses were 76 µm ± 8 µm and 47 µm ± 5 µm. Using these values, the thicknesses of the diesel layer for copper at the beginning of the screening tests (see Fig. 1) can be estimated to be 56 µm, which corresponds to a measured Raman intensity of 100. As flushing proceeds, the relative change in Raman intensity can be used to estimate the thickness of the remaining diesel layer. These results are plotted in Fig. 21, along with other measurement results obtained using an in situ fluorescence technique [7,8]. In those measurements, a diesel/water mixture was circulated until diesel accumulation reached a steady value, followed by flushing with clean tap water. It is interesting to note the similarity in initial measured film thicknesses for the two exposure techniques, although the static tests are somewhat higher. Removal of the accumulated diesel is faster for the screening tests, undoubtedly due to flushing at a higher Reynolds number.

Fig. 21. *Comparison of flushing test results using the fluorescent measurement technique and the Raman measurement technique, for different exposure conditions and flow*

5. CONCLUSIONS

The measurement results highlighted the difficulty in removing contaminants that have been introduced into building plumbing systems, even for relatively simple configurations such as straight pipe sections, and particularly for large water tanks such as water heaters. Simple flushing with cold tap water may require very long flush times to remove persistent contaminants such as diesel fuel and strychnine, and while capable of substantially reducing the number of spores in a water supply system, may benefit from supplementary decontamination procedures such as flushing with hot water, cleaning solutions or hyper-chlorination. While the properties of specific substrates may cause variations in contaminant accumulation and removal, these differences would likely be overshadowed by more important parameters such as flush water flow rates, plumbing system design and operation.

6. ACKNOWLEDGEMENTS

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