CONSIDERATIONS FOR DECONTAMINATING HDPE SERVICE LINES BY FLUSHING

1. With continuous/intermittent flushing, how much water will we consume?
2. Similarly, what is the slowest rate we can flush, given a certain pipe size?

PURPOSE

This document is not intended to design or endorse any particular approach to high-density polyethylene (HDPE) service line decontamination or to endorse any particular decontamination goal. The purpose of this document is to illustrate the scientific and technical ability to address the two main questions regarding HDPE service line decontamination, along with important caveats regarding this information. The information in this document may help decision-makers take more informed actions regarding their site-specific needs; however, it is incumbent upon those decision-makers to establish the desired goals and operational parameters for any analysis to provide meaningful guidance.

SUMMARY

The decontamination goals*:

- Goal A: The drinking water will never exceed 0.5 ppb benzene in the utility service line (before it reaches the customer meter) regardless of stagnation time.
- Goal B: The drinking water will only exceed 0.5 ppb benzene in the utility service line (before it reaches the customer meter) after 72 hours (3 days) of stagnation time.

**The two goals presented here are examples that will ultimately need to be established by the decision-makers. These goals were proposed here to help demonstrate the ability of the analysis tools and the range of operational implications. As the goal changes, the corresponding data demonstrated in this document will also change.*

Definitions:

- Stagnation time: The duration of time the water sits in the pipe system prior to sampling.
- While other compounds that pose a health risk may be present, only benzene was considered.
- GPM: Gallons per minute water flow rate.
- GPD: Gallons per day water flow rate.
- MGD: Million gallons per day flow rate.
- Continuous Flushing: Water being flushed through a pipe every second of every day.
- Intermittent Flushing: Water being flushed through a pipe once per time period. For the purposes of this document the time period is 72 hours (3 days).

QUESTION #1: How much water will we consume?

The volume of water in gallons used to flush a SINGLE SERVICE LINE* has been estimated in Tables 1 and 2. The volume of water needed is directly related to the required flushing time, where volume (V) = flow rate (Q) multiplied by time (t). The required flushing time will depend on the degree the HDPE pipe is contaminated.

> **For the purpose of this document, a service line is assumed to be 1-in diameter HDPE pipe.*

Example – 20 ppb benzene:

For a condition where 20 ppb benzene is found in the water, the following holds.

Decontamination Goal A: 0.5 ppb benzene is never detected

- about 195 days of continuous flushing and about 570,180 gallons would be used per pipe
- about 213 days is needed for intermittent flushing and 141 gallons would be used per pipe

Decontamination Goal B: 0.5 ppb benzene can be found in the water system only when a stagnation period >72 hr occurs

- about 104 days of continuous flushing and 304,096 gallons would be used per pipe
- about 141 days is needed for intermittent flushing and 93 gallons would be used per pipe

Water use estimate for flushing decontamination of 2 of the 7 Pressure Zones (assuming all lines are similarly contaminated such that 20 ppb benzene was uniformly detected in all service line sample results)

- For continuous flushing and Decontamination Goal A:
  - If all 1,223 service lines in A-zone were flushed, about 697,000,000 gallons of water would be used
  - If all 2,779 service lines in C-zone were flushed, about 1,585,000,000 gallons of water would be used.

- For intermittent flushing and Decontamination Goal A:
  - If all 1,223 service lines in A-zone were flushed, about 172,000 gallons of water would be used
  - If all 2,779 service lines in C-zone were flushed, about 392,000 gallons of water would be used.

QUESTION #2: What is the slowest flow rate we can flush a 1-in diameter HDPE service line to remove benzene?

- Benzene will travel out of the plastic pipe into the clean water.
- Benzene removal is fastest when the concentration of benzene in the water at the pipe surface is zero, which is to say that clean water is in contact with the pipe surface.
- If water in the pipe flows fast enough, it completely mixes all the water in the pipe, therefore keeping clean with in contact with the pipe surface. This mixing occurs because of a process known as “turbulent” flow, which requires much higher flow rates than a mere trickle which sets up a process known as “laminar flow” which is assumed will not rapidly remove benzene from the pipe surface after it leaches out from the pipe wall.

- The water temperature was assumed to be 20°C (40°F) [per PID]. Colder water would cause a greater flow rate to be needed to achieve turbulent flow.
- A 2.03 GPM flow rate or greater PER SERVICE LINE is estimated to be sufficient to achieve the desired turbulent flow. This may seem like overly accurate number but is derived from the underlying science, so is used for the calculations shown.

Table 1. Time in Days Needed PER SERVICE LINE to Decontaminate by Water Flushing, based on the concentration of benzene measured before flushing begins. Flushing is with 2.03 GPM of benzene-free (0.0 ppb) water.

Initial measurement concentration (C_2)	Goal A (never above 0.5 ppb)		Goal B (only exceed 0.5 ppb after 72 hours of stagnation)	
	Continuous	Intermittent (once/72 hrs)	Continuous	Intermittent (once/72 hrs)
100 ppb	286	312	195	240
50 ppb	246	270	156	198
20 ppb	195	213	104	141
10 ppb	155	171	66	99
5 ppb	116	129	33	60
2 ppb	64	74	8	20

Table 2. Volume of Water Flushed in Gallons PER SERVICE LINE to Decontaminate by Water Flushing, based on the concentration of benzene measured before flushing begins. Flushing is with 2.03 GPM of benzene-free (0.0 ppb) water.

Initial measurement concentration (C_2)	Goal A (never above 0.5 ppb)		Goal B (only exceed 0.5 ppb after 72 hours of stagnation)	
	Continuous	Intermittent (once/72 hrs)	Continuous	Intermittent (once/72 hrs)
100 ppb	836,264	206	570,180	158
50 ppb	719,304	178	456,144	131
20 ppb	570,180	141	304,096	93
10 ppb	453,220	113	192,984	65
5 ppb	339,184	85	96,492	40
2 ppb	187,136	49	23,392	13

ASSUMPTIONS

There are many assumptions, which will impact the accuracy of the calculated volume and decontamination/ recovery time. They include, but are not limited to:

1. It was assumed that the pipe was initially contaminated by contaminated water sitting in the pipe for 12 weeks prior to any actions being taken (i.e., the contamination entered the pipe in November 2018). The longer the contaminated water sits in the pipe, the more contaminated the pipe becomes. Although at some time, the pipe will approach an equilibrium and become as contaminated as it can be. 12 weeks was estimated to be close to maximum contamination level of the pipe.
2. Benzene was the only chemical considered in this assessment. Other volatile organic compounds (VOC) (naphthalene, styrene, toluene, xylenes, etc.) have been detected in the water and have health-based drinking water exposure limits. They may travel into and out of HDPE pipe slower or faster than benzene.
3. The calculations above assume ZERO benzene in the flushing water (i.e., in the water mains). Field data demonstrates that portions of the water mains are likely similarly contaminated (17.3 ppb maximum to date for the total of 5 hydrant water samples). This raises a concern that the water from water mains that will be used for flushing may contain some VOCs. However, this is not uniformly true as evidenced by the service line and hydrant samples that have produced no detectable benzene at or above the 0.5 ppb detection limit of the analytical method. The presence of benzene in this flush water will slow the decontamination process, even at low levels such as 0.1 ppb or 0.49 ppb, especially as contamination in the service line pipe approaches the decontamination goal. This will also increase the volume of water used, as well as time needed to remove benzene from the HDPE pipes. Reliable estimates are not currently available for how much these times increase, and this factor may be more important for intermittent flushing which uses much less water than continuous flushing.
4. It should be further noted that as flushing proceeds, the contaminated portions of the water mains will similarly decontaminate, reducing this concern throughout the process.
5. The diffusion and partition coefficients for benzene in HDPE used in calculations are taken from Feng Mao, et al. *Modeling benzene permeation through drinking water high density polyethylene (HDPE) pipes* (2015). It is possible the coefficient for the specific HDPE service lines at the site could be different from these values.
6. The size of the service line (1 in diameter, 50 ft long), does not represent all service lines in the PID area. Lengths can be >150 ft and <20 ft; diameters can be 3/4 in diameter.] It is possible to estimate flushing times and volumes for other diameters; it was assumed 80% of the service lines in place are 1 in diameter.
7. It is likely that not all service lines are contaminated to the same degree. Based on the limited number of testing to date, it is difficult to estimate how many are and are not contaminated, and to what degree they are contaminated.
8. Not all service lines are HDPE. Some are copper tubing, copper and brass pipe, galvanized and steel pipe, and polybutylene (PB) pipe/tubing.
   a. The decontamination models are created for contaminated HDPE service lines. Benzene will interact differently with the different pipe materials.
   b. Based on our current understanding, HDPE pipe is more likely to become contaminated than PVC pipe. According to Feng Mao, et al. *Permeation of organic contaminants through PVC pipes* (2009), PVC pipe has been reported to resist contaminated by benzene unless the concentration of benzene exceeds around 1,000 mg/L. However, the PVC pipe used in that study may not represent PVC pipe at the site.
   c. PB pipe is also likely to be contaminated, but the number of PB service lines in use is unknown.

    d. High VOC concentrations, however, have been detected in some copper service lines. This may be related to existing gaskets in different piping materials.
9. Water meters used by the PID contain a variety of plastic components in contact with the drinking water. These plastic components can also likely become contaminated and leach contaminants into water.
10. As of March 2019, PID has not flushed all of their service lines yet because of the scale of activity. Most A-Zone service lines have been flushed at least once, and approximately 30% in B-zone.
11. There is no sanitary sewer to receive the water. The flushing water, which can contain disinfectant residual, goes to storm drains, direct to run-off, or into septic tanks. The implications on proper functioning of these receivers should be considered. For example, will septic tanks overflow or will discharges reach water bodies and/or tributaries.
12. An estimated 10,600 service lines exist in the PID service area, shown below by Zone letter.
    a. A = 1,223, B = 2,186, C = 2,799, D = 2,452, E = 1,196, F = 563, G = 61
13. We assume that benzene will diffuse through the pipe wall and out the outer wall into the soil. Benzene and other hydrocarbons in soil have previously shown to permeate HDPE pipe and contaminate drinking water elsewhere. If the soil or other substances surrounding the pipe are impermeable, then the time to decontaminate the pipe will be greater than shown above.

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SUPPORTING INFORMATION

1. As mentioned above, benzene was the only chemical considered in answering the two questions. Though, similar phenomena for benzene fate with HDPE plastic pipes applies to other VOCs, but rates and extent of contamination can vary significantly with the specific VOC.
2. For contaminated drinking water pipes, where VOCs have penetrated the pipe, removal of the VOCs from the pipe, is dependent on several factors. The suggestions below are made assuming diffusion of VOC through the outer wall occurs. The models here discuss contaminated HDPE drinking water pipes. Models have not yet been developed for pipes made of other materials.
3. For the fastest VOC removal from contaminated (HDPE) drinking water pipe at constant temperature, the VOC that penetrated into the pipe wall must be leached and flushed away. The lower the VOC concentration in the water at the surface of the pipe, the faster the removal rate of the VOC during flushing, although this is difficult to estimate currently.
4. As the service lines are flushed, the water mains (which provide the water used during flushing) will also be inherently flushed at the same time. The VOC values in the flushing/decontamination water should decrease over time.
5. To achieve zero VOC concentration at the pipe surface during flushing, the water has to be flowing fast enough to maximize leaching/diffusion from the pipe. The colder the water, the greater the water viscosity, and a higher flow rate is needed to achieve the desired effect during VOC removal. (For those familiar with fluid mechanics, the “turbulent” or “transitional” flow regimes may be acceptable whereas the “laminar” flow regime is less likely to be acceptable. Thus, there may be a range of flow rates that may be acceptable. The flow rate mentioned above is viewed as a precautious estimate, granted there is a tradeoff between the minimum flow rate to cause turbulence and water conservation.)

CALCULATIONS

To compare an intermittent flush approach (short flushing events repeated at regular and frequent intervals) to a continuous flush approach (leaving a valve open for an extended period of time), we made several calculations. In both approaches, turbulent flow regimes are used.

1. *Estimate how much flushing time would be needed per pipe to replace the water volume (for intermittent approach), and what flow rate is required for continuous flow.*

- A 1 in diameter pipe that is 50 ft long will hold about 2 gallons of water. We have thus used 2 gallons for each intermittent flush. However, to ensure that the water is completely replaced, we recommend a longer flush, e.g. of 5-10 gallons, which could provide a factor of safety. These volumes could also be practical to measure with a 5 gallon bucket. The estimated water volumes for only 2 gallons of water are included above.
- For a 1 in diameter pipe at 68°F (20° C), the flow rates were calculated based on what is known in fluid mechanics as the “Reynolds” number, Re of 4,000. This Reynolds number is considered to cause optimal removal of benzene from the pipe because it generates the desired mixing effect to introduce water with lower concentrations of benzene to the interior pipe wall where the chemical exchange occurs. The exact Reynolds number is unknown and may vary, but this variance is not expected to change the flow rate by very much.

- An important variable, however, is the temperature of the water being supplied to the pipe. This may or may not be the same as the ground temperature.
    - If the water temperature is lower, a higher flow rate is needed to achieve the desired flow rate based on a Re of 4000.
        - At 68 °F, a flow rate is 1.27 GPM
        - At 50 °F, a flow rate is 1.71 GPM
        - At 40 °F, a flow rate is 2.03 GPM

- These flow rates are calculated by simple fluid mechanics which ignore the rate of diffusion of benzene through water, which essentially has the effect of lowering the required flow rates.
- However, how much this lowers the flow rate is complicated to calculate, so given other uncertainties, like the temperature, a value of 2.03 GPM was assumed to err on the side of caution, although may be substantially less depending on season, and could increase by ~25% if it were near freezing (32 °F)
- You could also add a safety factor for flushing although this equates to a greater water usage.
- Mid-process samples could be collected to verify that decontamination is tracking along the predicted decontamination curve.

2. *Estimate Amount of Water Flushed PER SERVICE LINE*

Continuous flush approach

2.03 GPM is used here based on item 1 above. The warmer the water, the less flow rate would be needed. The 2.03 GPM flow rate is based on a 40°F water temperature.

$$\frac{2.03\text{ gallons}}{\text{minute}}\,\text{x}\,\frac{60\text{ minutes}}{1\text{ hour}}\,\text{x}\,\frac{24\text{ hour}}{\text{day}} = 2{,}924\,\frac{\text{gallons}}{\text{day} - \text{pipe}}$$

Intermittent (3-day) flush approach

The more frequently the pipes are flushed during the intermittent flushing approach, the more VOCs can be removed from the pipes, to a limit beyond which flushing more frequently does not help (which is why the intermittent approach can achieve similar contaminant removal as continuous flushing). For example, flushing once daily would result in greater removal than flushing once monthly. Thus, while more frequent flushing interval may decrease overall time, it is recognized that there are practical, logistical constraints on how frequently the water utility can flush pipes--given there are so many of them. From a practical standpoint, one flush is assumed every 3 days. We also used a 2 gallon flush, the approximate volume of a 50 ft,1 in diameter service line, but a longer flush (5 or 10 gallons, perhaps measured by 5-gallon buckets) could add a factor of safety.

$$\frac{2\ gallons}{flush}\,x\,\frac{1\ flush}{3\ days} = 0.66\,\frac{gallons}{day - pipe}$$

3. *Apply this to the "A" pressure zone, also called "A-Zone", All water goes through 1 pump station*

There are 6 pressure zones total, A-G

A-Zone has 1,223 service lines. Let's assume all are HDPE (i.e., highly likely to be contaminated).

If flushed all A-Zone service lines at the same time, how much water would be flushed per day?

$$2{,}924\,\frac{gallons}{day-pipe}\,x\;1{,}223\;AZone\;pipes = 3{,}580{,}000\,\frac{gallons}{day}\;\;(or\;3.58\;MGD)$$

If intermittent 3-day flush approach was applied, how much water would be flushed per day?

$$0.66\,\frac{gallons}{day}\,x\;1{,}223\;AZone\;flushing\;locations = 808\,\frac{gallons}{day}$$

All water going into A-zone must go through the pump station. The pump station can handle 3.024 MGD. So, this pump station would not be able to handle all of the demand of flushing, at the same time as other demands by customers. However, it may be difficult for the utility to flush all lines at the same time; rather a staggered approach may be more practical.

4. *Apply this to the "C" pressure zone, also called "C-Zone", Zone with most service lines.*

C-Zone has 2,799 service lines (Zone with most lines). Let's assume all are HDPE.

If flushed all C-Zone service lines at the same time, how much water would be flushed per day?

$$2{,}924\,\frac{gallons}{day-pipe}\,x\;2{,}779\;CZone\;pipes = 8{,}125{,}000\,\frac{gallons}{day}\;\;(or\;8.125\;MGD)$$

If intermittent 3-day flush approach was applied, how much water would be flushed per day?

$$0.66\,\frac{gallons}{day}\,x\;2{,}779\;CZone\;flushing\;locations = 1{,}835\,\frac{gallons}{day}$$

In 2014, the PID's maximum water treatment plant production capacity was estimated to be 15 MGD. So, it should be able to technically handle this demand, if all lines were flushed simultaneously (even if this were practical)

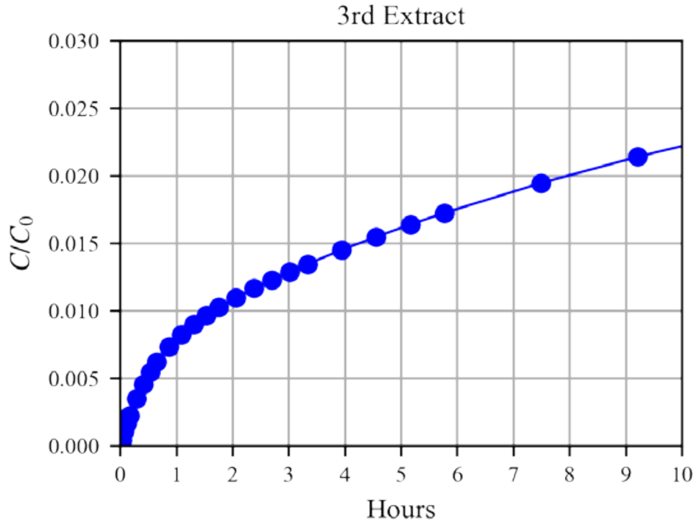
OTHER FACTS, THOUGHTS, AND MAJOR ASSUMPTIONS

Paradise Irrigation District Specific

- The water treatment plant's average production capacity was 15 MGD in 2014 and is reported to be 18 MGD max (per PID)
- The pump station in A-zone has a maximum capacity of 2,100 GPM which is 3.024 MGD. All A-zone water must go through this single pump station (per PID)
- Water that goes into B-G pressure zones does not pass through the pump station.
- Before the fire, the typical water treatment plant production was 2.5 to 8 MGD (per PID)
- After the fire the typical production is around 2.5 to 4 MGD (per PID)
- Average assumed Utility service line pressure: 70 psi
    - Some are <40 psi and others are >100 psi

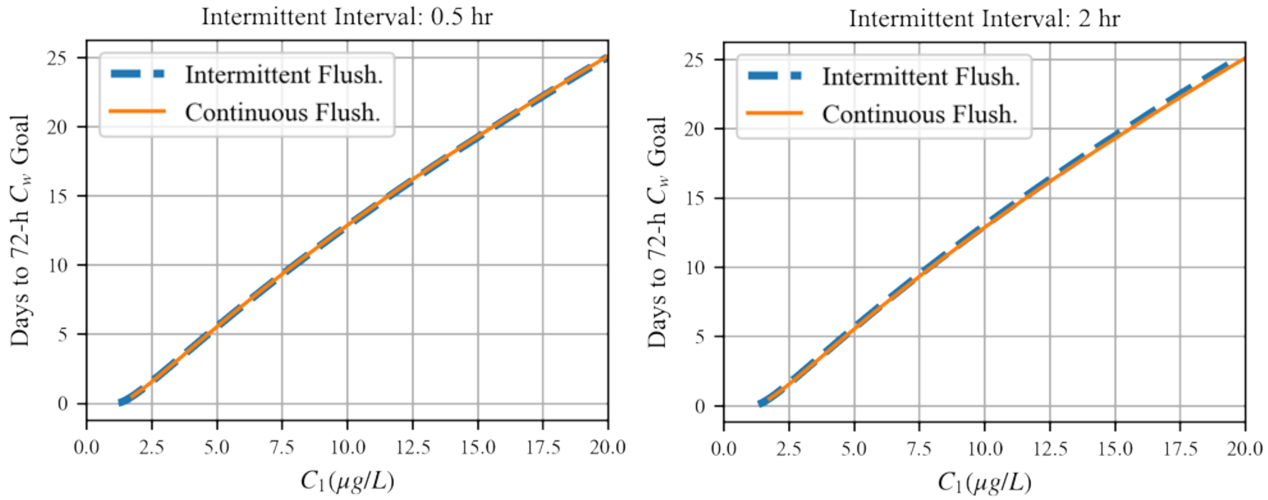
More thoughts on required flushing velocity (and intermittent flushing frequency)

Looking at the stagnant desorption kinetics of a hypothetical third stagnation after the incident, we can get some idea of when the benzene flux from the pipe wall into the water would be affected if we flush too slowly (that is, if we allow our residence time to be too long).



Based on the extraction kinetics, we might expect the flushing efficacy to remain near maximum if the residence time is less than half an hour.

We can examine this by setting the intermittent flushing interval to half an hour in the model and comparing to the predictions for the continuous flushing curve.



Indeed, with the intermittent flushing interval set to half an hour, the intermittent flushing curve follows the continuous flushing curve almost exactly. However, increasing the interval to two hours causes the curves to separate. It follows that if the water in the service lines is completely cycled every two hours, flushing efficacy should be preserved. However, these lower flow rates might not be sufficient to optimize removal of benzene from the pipe wall based (see discussion of above of how flow rates were calculated based on underlying principles of fluid mechanics, i.e., the Reynolds number.

To illustrate this further, based on the half-hour residence time from the figure above, flow rates as low as 0.04 GPM (based on a 25 ft of 1 in diameter pipe) may be sufficient to allow the benzene ample time to diffuse out of the pipe and into the flowing water from the standpoint of merely exchanging the volume of water. Therefore, the 2.03 GPM used in the worked examples is expected to be sufficient from a benzene diffusion standpoint.

Additional Considerations

- Contaminants follow with the water flow. When the backflow/ back siphonage (or low pressure at mains) happens, the contamination from one service line may travel to neighbors' service lines, resulting in ‘cross-contamination’ of service lines. Backflows occur for a variety of reasons, and damage to water systems can led to conditions that create backflows, although backflows can occur in undamaged systems, e.g., sudden water flow changes, water withdrawals, pump trips, fire hydrant exercises, etc. in the system.

- An additional source of contaminant movement is the natural tendency for chemicals to diffuse through water. For instance, if you place a chemical at one end of a stagnant pipe, eventually, it will reach the other end—just like an odor on one side of a room eventually makes its way to the other. The rate of movement of benzene in water as it moves down the length of the pipe, has been known for 50 years, as a function of temperature and benzene concentration. The end result is that it is about an inch per day of benzene moving through the water, maybe inches at higher temperatures. A very slow flow of water moving in the service line should contradict the diffusion of the benzene during this passive cross contamination unless a physical barrier (i.e., corporation stop) can be utilized to isolate contaminated water.