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Uptake and Release of Benzene from Stagnant Drinking Water Pipes

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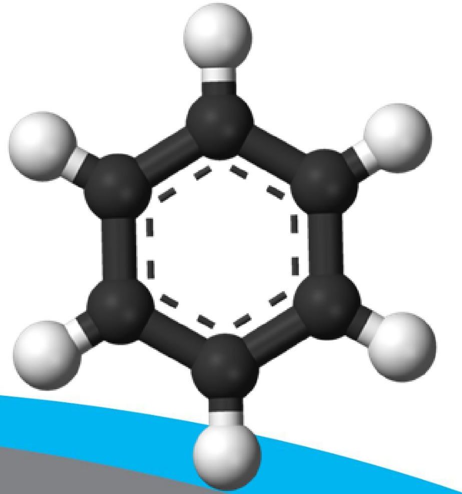
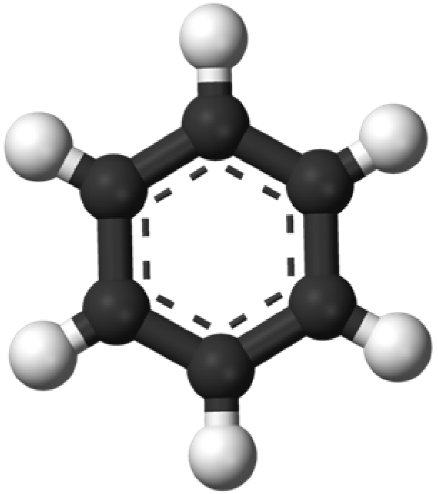
Project Background

- Hazardous chemicals, including benzene, were found in drinking water systems affected by wildfires.
- Some Examples in California:
  - Santa Rosa (2017-2018)
  - Paradise (2018-2019)
  - Riverside Grove (2020)
- High density polyethylene (HDPE) service lines and crosslinked polyethylene (PEX) pipes in buildings are permeable to benzene.
- Permeated pipes can complicate sampling and decontamination strategies.



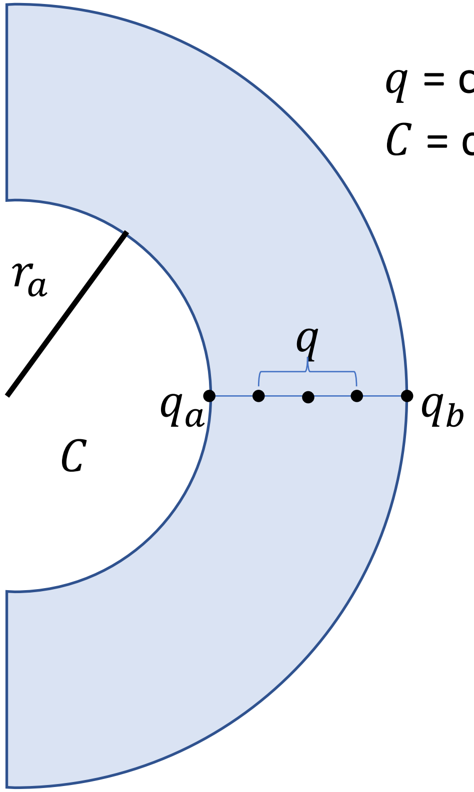
Benzene and Polyethylene Pipes

- Benzene can penetrate polyethylene pipe walls.
- Polyethylene can act as a reservoir for benzene.
- Benzene movement through polymers is (relatively) slow.
  - Resistance to decontamination by flushing.
  - False negative sampling from recently flushed pipes.
- Can this behavior be quantified?



Diffusion In Pipe Walls

- Fick's laws can be applied to radial diffusion in pipes.
- Applies to "rubbery" polymers such as polyethylene and polypropylene.
- Critical parameters:
    - Diffusion coefficient (D): how quickly benzene travels through a polymer.
    - Partition coefficient ($K_{p,w}$): the preference for benzene to be in a polymer instead of water.
- Exact mathematical solutions for simplified permeation models do not perform well for wildfire contamination.
- A numerical approximation was needed.



q = concentration in pipe wall
C = concentration in bulk water

$$\frac{\partial q}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD\frac{\partial q}{\partial r}\right)$$

$$\frac{\partial q_a}{\partial t} = 2D\frac{K_{p,w}}{r_a}\frac{\partial q_a}{\partial r}$$

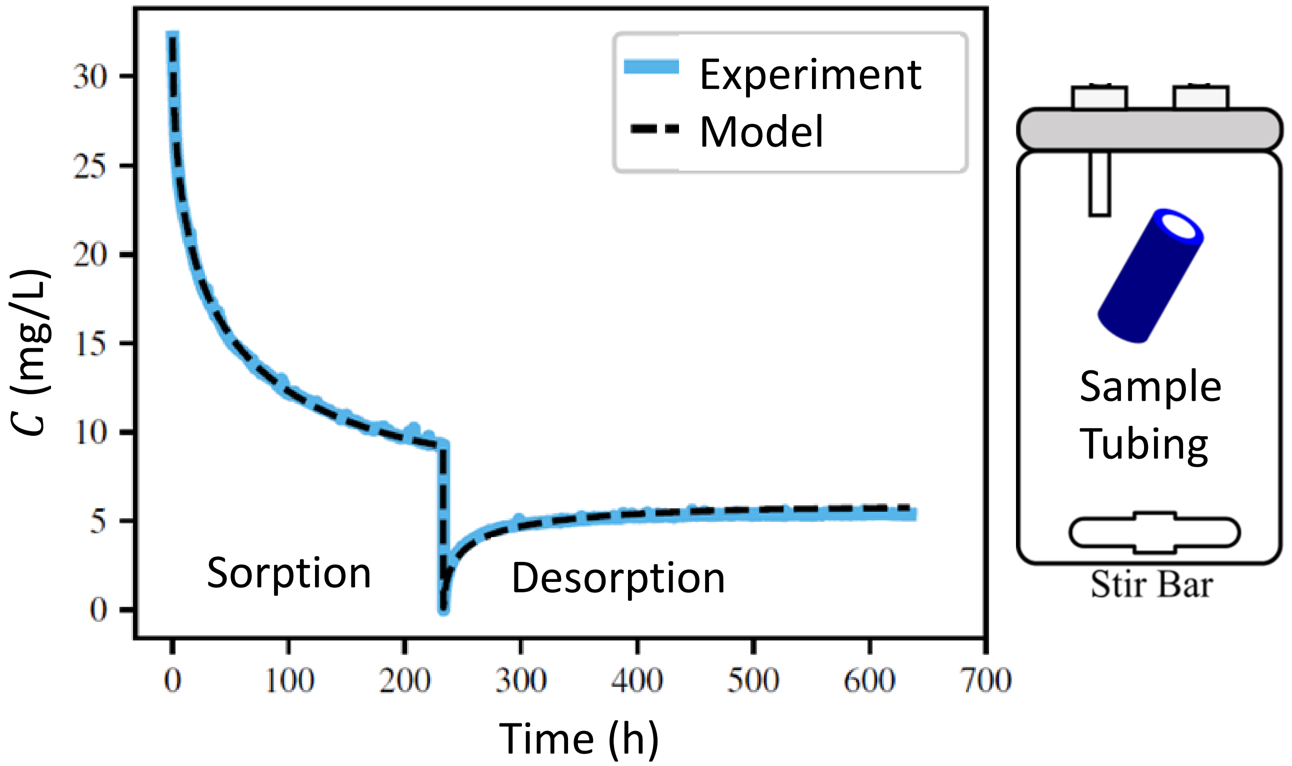
$$q_b = 0$$

$$q_a = CK_{p,w}$$

$$\frac{\partial C}{\partial t} = \frac{1}{K_{p,w}}\frac{\partial q_a}{\partial t}$$

Numerical Model

- Haupert and Magnuson (2019) developed a diffusion model for stagnant pipes.
- Premise plumbing is typically stagnant much of the time.
- Service lines also have long periods of stagnation.
- Model demonstrated on toluene and PEX.
- Can be adapted to benzene and PEX plumbing or HDPE service lines with appropriate diffusion and equilibrium parameters.



Gathering Parameters

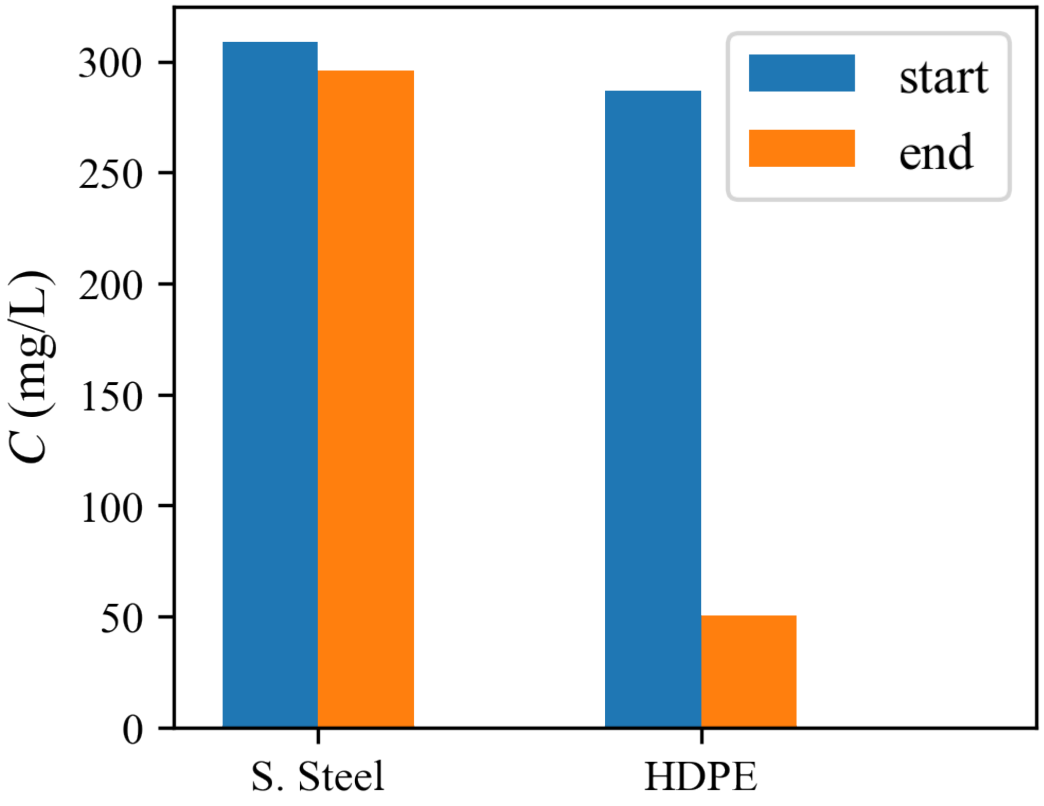
- Diffusion and equilibrium parameters for pipes are scarce.
- Mao et al. (2015) provides them for a single set of HDPE pipes.
- Parameter variability among pipes of different polyethylene types and sources is unknown.
- Research at the EPA T&E facility aims to address the data gap.
- Collaboration with EPA Region 9 as part of a RARE project.
- Pipe samples from affected sites were collected and shipped to EPA by the California Water Control Boards.

Laboratory Experiments

- Partitioning
  - Determine $K_{p,w}$.
  - Use pipe shavings for rapid equilibrium.
- Serial Extractions
  - Determine D.
  - Validate model.
  - Seal contaminated water inside pipes for 2, 4, or 8 weeks.
  - After contamination, refresh water daily and observe leached concentrations.

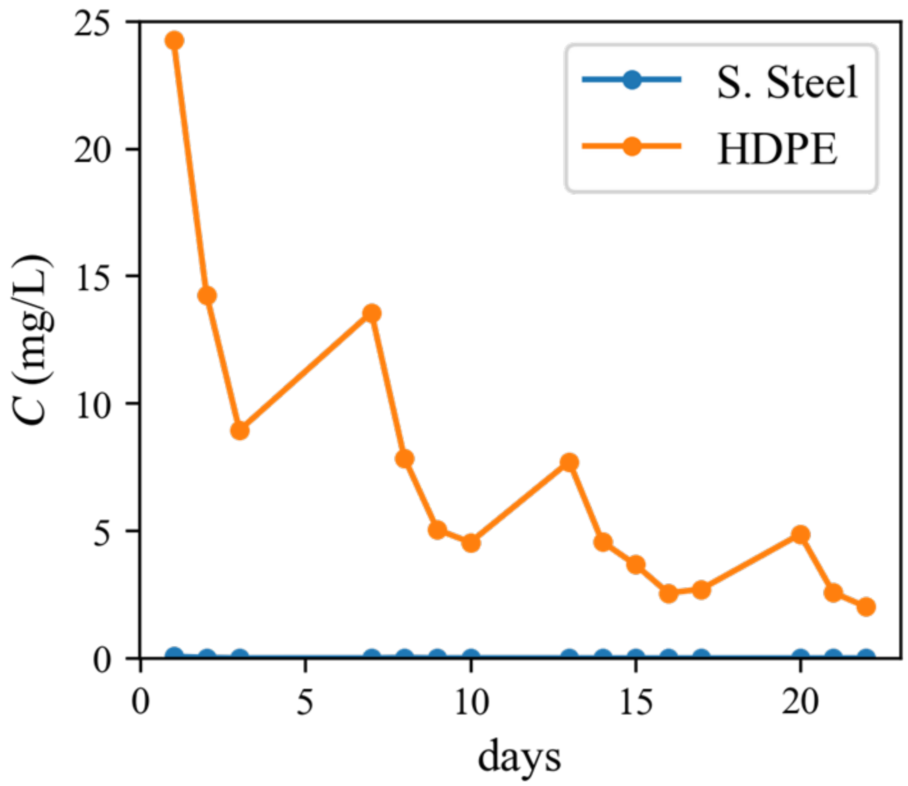
Benzene Uptake

- Sealed pipe segments are contaminated with benzene solution (~300 mg/L).
- After 8 weeks, concentration in stainless steel pipe only decreased by 4%, comparable to experimental error.
- Contrast: after only 2 weeks, concentration in HDPE pipe decreased by 82%.



Benzene Release

- Benzene in water is measured at the end of contamination period.
- Water is measured and changed daily (except weekends and holidays).
- Longer stagnation times allowed more benzene release.
- Release from (pristine) copper and stainless-steel pipes was much smaller than HDPE pipes (typically less than 0.01 mg/L).

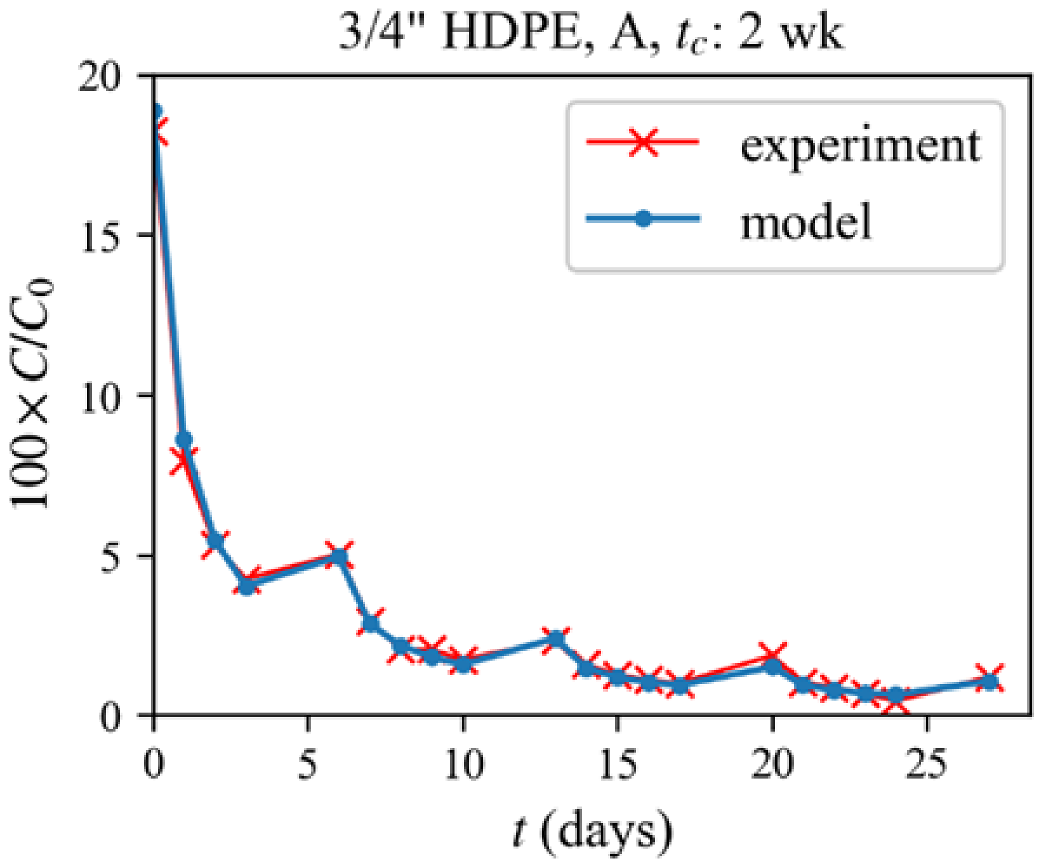


Model Improvement

- Model implemented in Python, using Numpy and Scipy libraries.
- Original solution, based on finite differences, was slow.
- Parameter estimation was difficult and time consuming.
- Changing to a collocation method (Carey and Finlayson, 1975) resulted in 100x speed up.
- Faster code enabled model fits of experimental data.

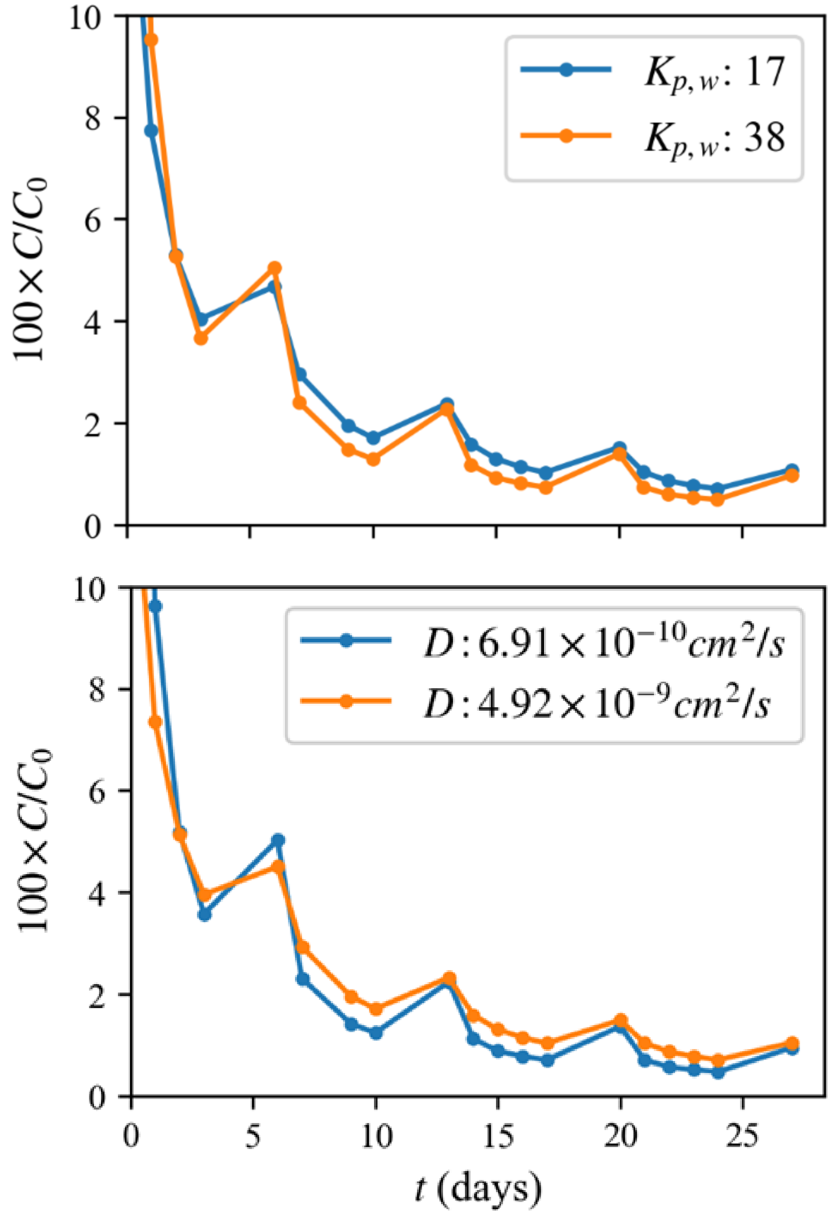
Model Fit Results

- Model was able to match data from the experiment.
- C_0 = initial concentration.
- Partition coefficients did not vary greatly (min:23, max:26) across pipes studied (HDPE and PEX-b).
- Fitted D for all studied HDPE pipes were within a factor of 2 of Mao's estimates.
  - Varied with size and manufacturer, but with no clear pattern.
  - Tests changing only contaminant contact time found same diffusion coefficients.
  - Suggests material or process variability in pipe manufacturing.



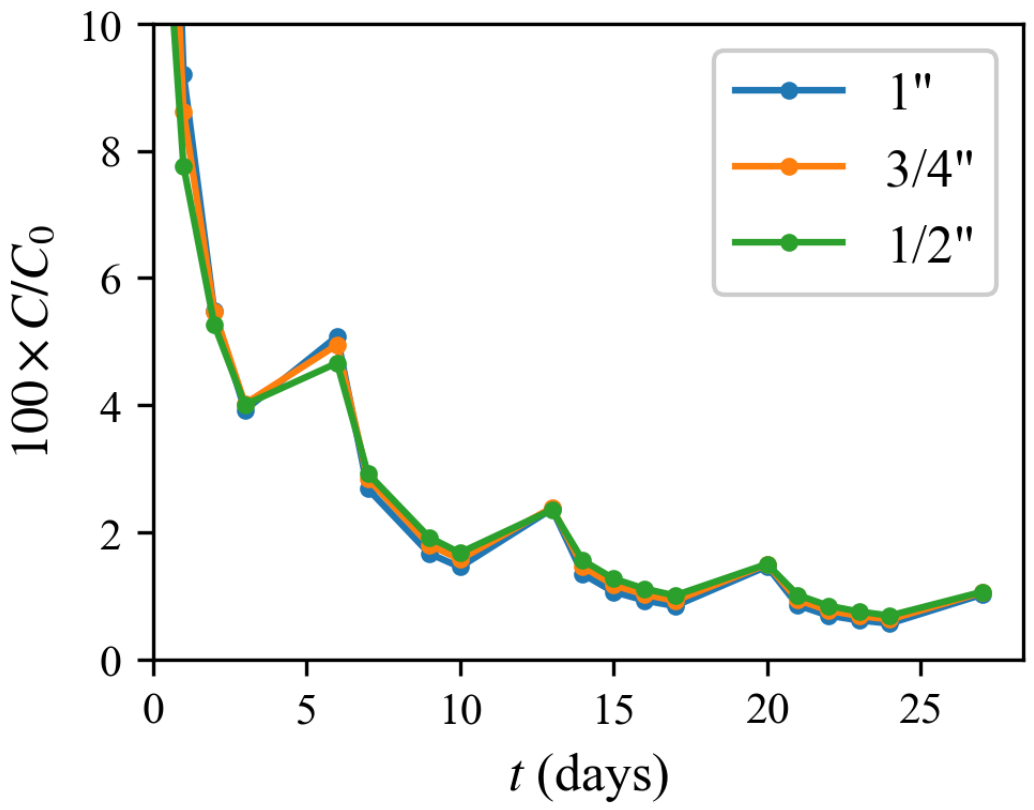
Parameter Sensitivity

- Even with variance in D larger than found in experiments, model still predicts similar long-term behavior.
- Long term behavior is likely more operationally relevant than results of the first couple of flushes.
- Sensitivity analysis of $K_{p,w}$ lead to similar conclusions.
- For scenarios like the ones in this study, model results should be robust against small errors in parameters.



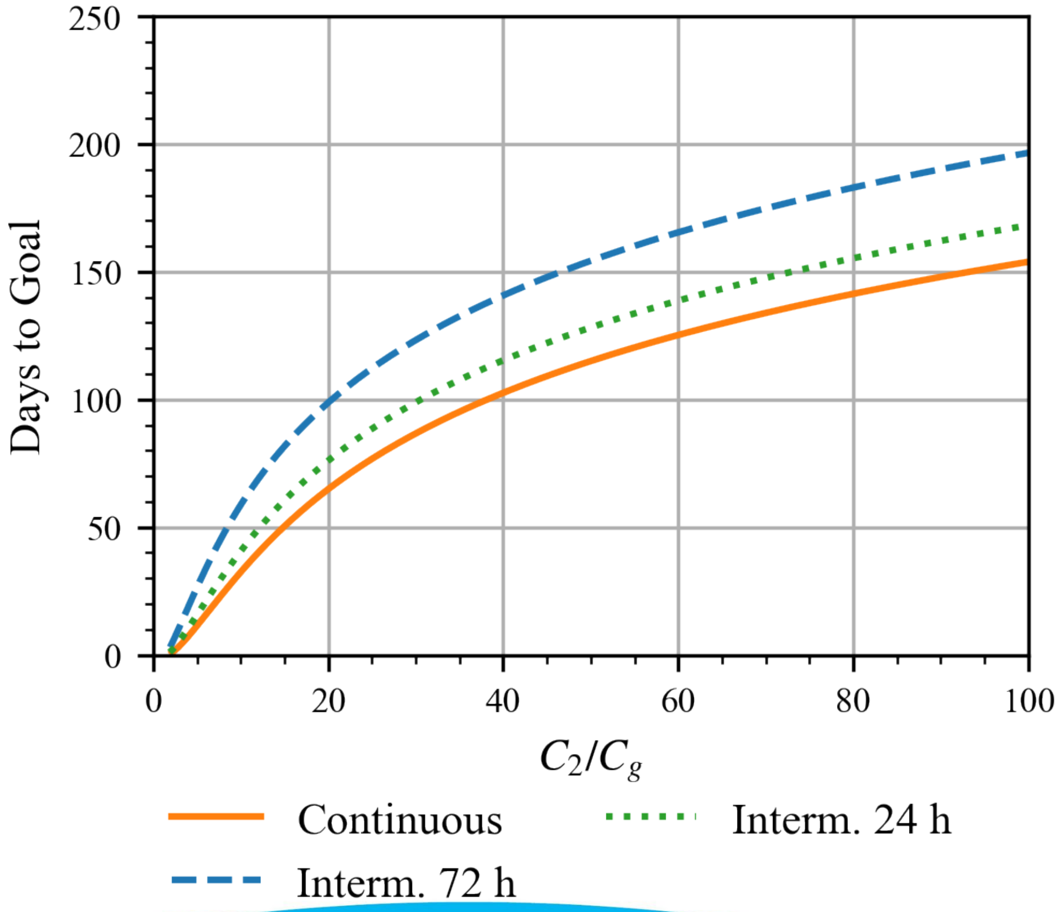
Pipe Size

- Pipes of different sizes and thicknesses are expected to differ for the first couple of extractions.
- However, they should have similar long-term behavior, which is likely of more operational interest.
- Precise knowledge of pipe dimensions may not be critical for some applications.



Modeling Example: Decontamination

- Compare performance of flushing strategies for specific scenarios for cost benefit analysis.
- 12-week contamination, 1” HDPE pipe.
- C_2: First measurement of contamination after incident.
- C_g: Goal concentration for 72-h stagnation.
- Example strategies:
  - Flushing briefly once every three days.
  - Flushing briefly once every day.
  - Flushing continuously
- Intermittent flushing uses much less water (about 98% less).
- However, doing so increases overall decon time.



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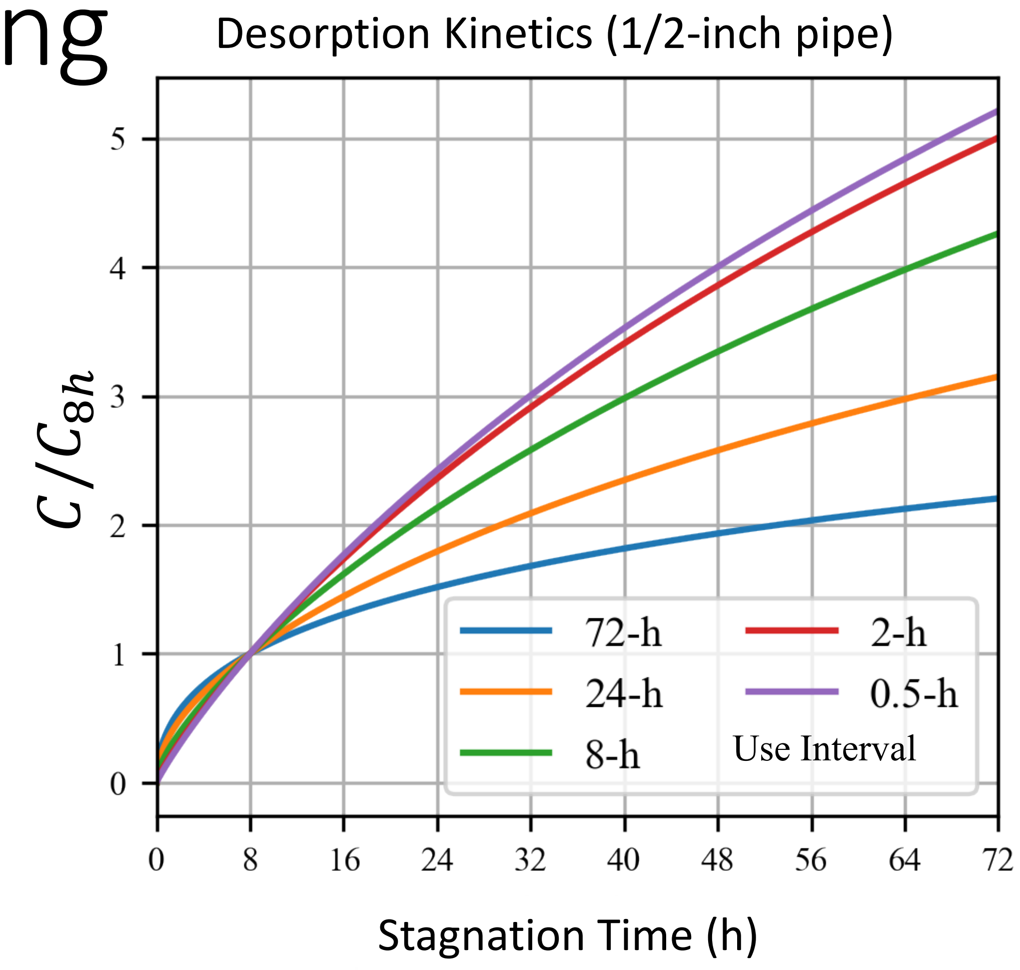
Modeling Example : Sampling

- Long stagnation times are inconvenient for occupied buildings.
- Given a concentration at 8-h stagnation (C_{8h}), what is the expected concentration at longer times?
- Depends on how frequently water is used.
- Example: 3 months of contamination and 6 months of use at regular intervals.
- Using water every half hour is roughly equivalent to running water continuously.
- Frequent water use reduces concentration at shorter stagnation times due to removal of benzene near the inner surface.



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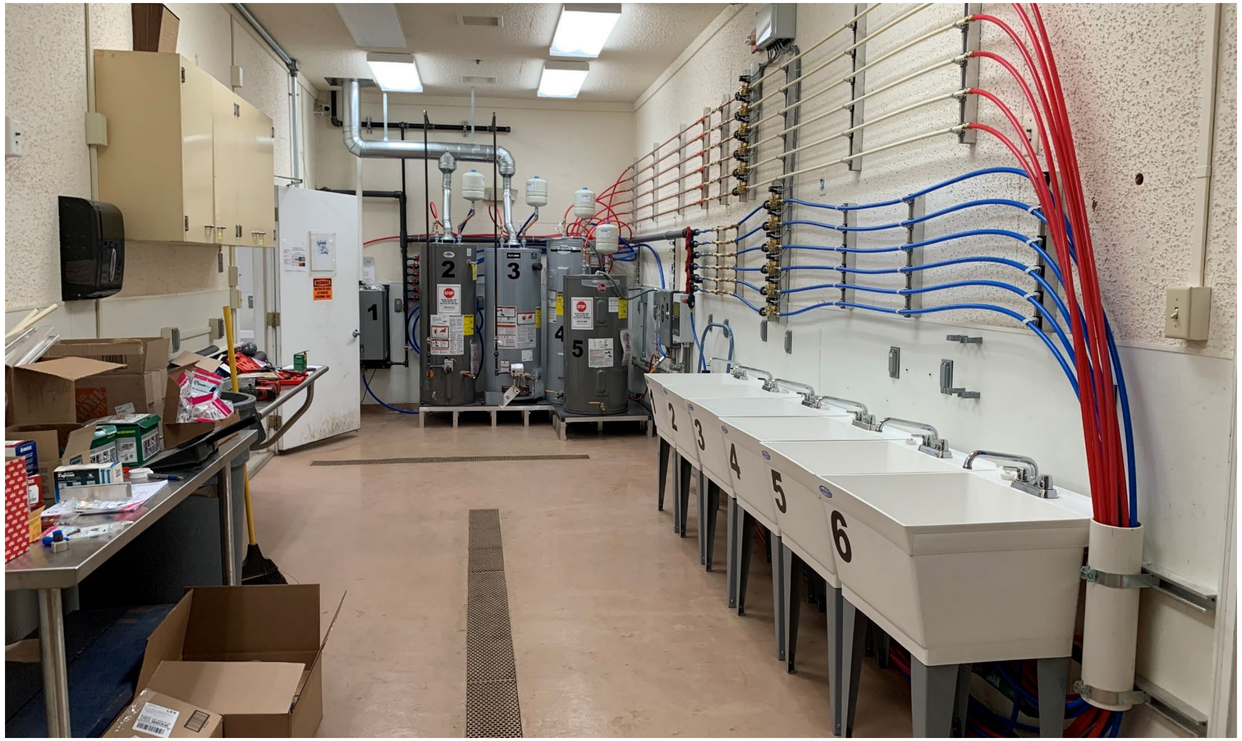
Discussion and Future Work

- Can apply modeling to specific contamination and water use patterns.
  - Interpret sampling results.
  - Inform cost/benefit analysis for decontamination.
- Can model contaminants other than benzene if parameters are measured or can be estimated.
- Additional data/experiments are needed to determine effects of:
  - Water chemistry
  - Pipe condition

Image provided by the California Division of Drinking Water.

Full Scale Premise Plumbing – T&E Facility



- Examine effect of water heaters on chemical and microbial water quality parameters.
- Evaluate decontamination and treatment methods for chemical and microbial contaminants.
- Control and prevent biofilm formation withing pipes and fixtures to reduce exposure to associated contaminants.

EPA Homeland Security Research Program
https://www.epa.gov/emergency-response-research/water-security

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Additional Resources

- EPA factsheet with recommended practices for addressing contamination of drinking water after wildfires: https://www.epa.gov/waterutilityresponse/build-wildfire-resilience
- Decision support framework for selecting decontamination technology for contaminated pipes: Haupert, et al. *Journal of Hazardous Materials Advances.* https://doi.org/10.1016/j.hazadv.2021.100013

Diffusion in plastic pipes can impact sampling and decontamination strategies.

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Additional Image Credits

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- Benzene molecule: Public Domain
- HDPE pipes: https://commons.wikimedia.org/wiki/File:Polyethylene_Pipe_lengths.jpg
- Damaged pipe, service line sampling: Provided by the California Division of Drinking Water