THREE DECADES OF REMEDIATION AT THE CDOT MTL:

A MODEL FOR ADAPTIVE MANAGEMENT

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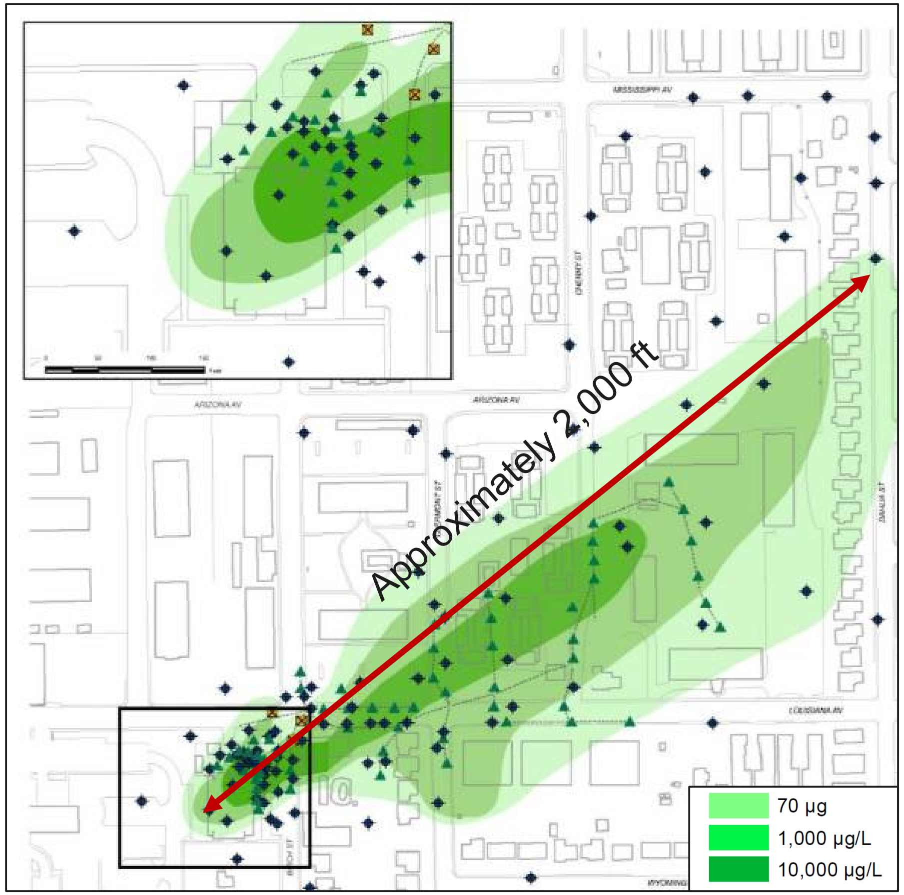
Site History and Conditions

- 1957 to 2006: Materials testing laboratory
- 1972 to 1987: 2 waste solvent USTs
  - DNAPL
  - 1,1,1-TCA, TCE, methylene chloride, and 1,4-dioxane
  - Degradation product 1,1-DCE primary driving COC
- 1990s: characterization, interim remedy
- 2001-current: Full-scale remedy

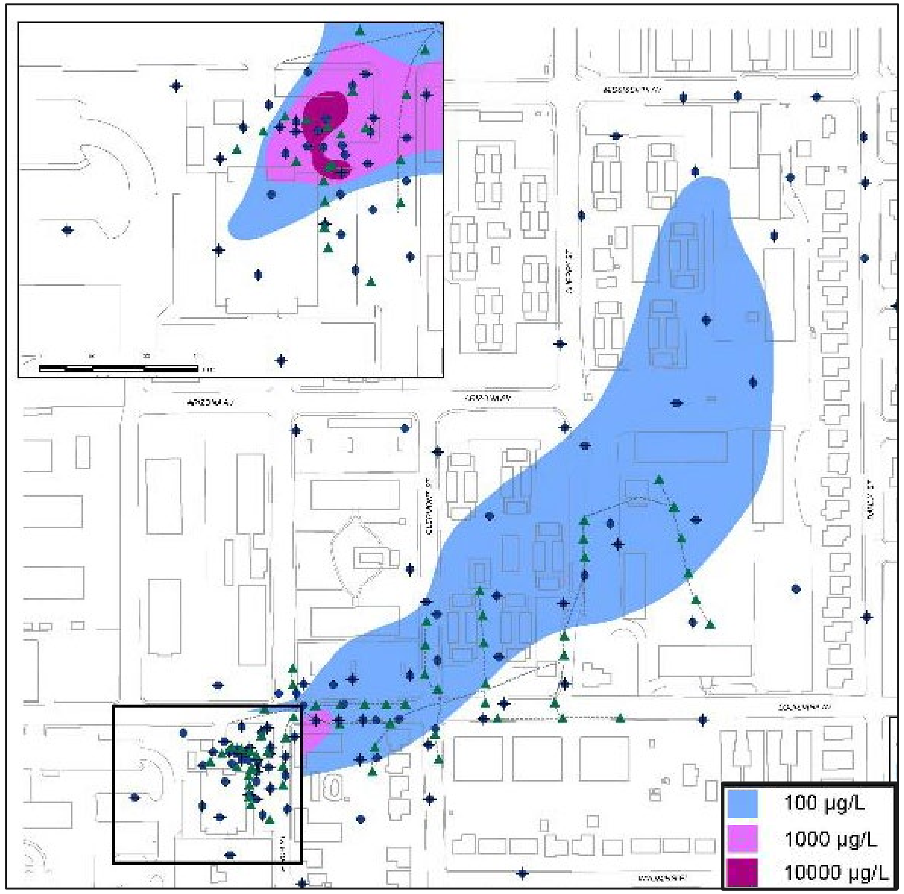
- Highly fractured and weathered sandstones, siltstones, and claystones
- Low bulk hydraulic conductivity <10^{-4} cm/s

Baseline Plumes in Shallow WBZ

1,1-DCE (2001)



1,4-Dioxane (2006)



Initial Remedy, Corrective Measures Study (1998)

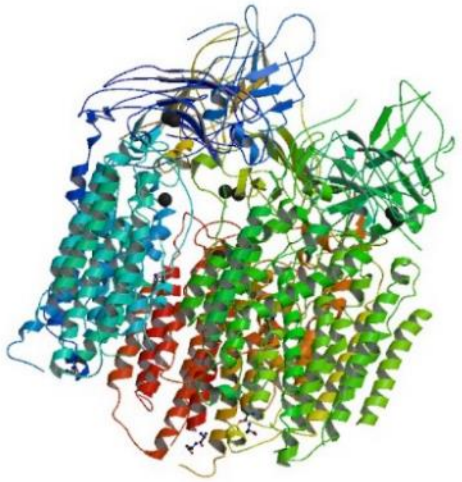
On-site/Source Area: Pump and Treat + SVE

- ~20 extraction wells; 2-5 gpm total flow
- Remediation timeframe: *indefinite*

Off-site: Aerobic enhanced bioremediation (AB) and MNA

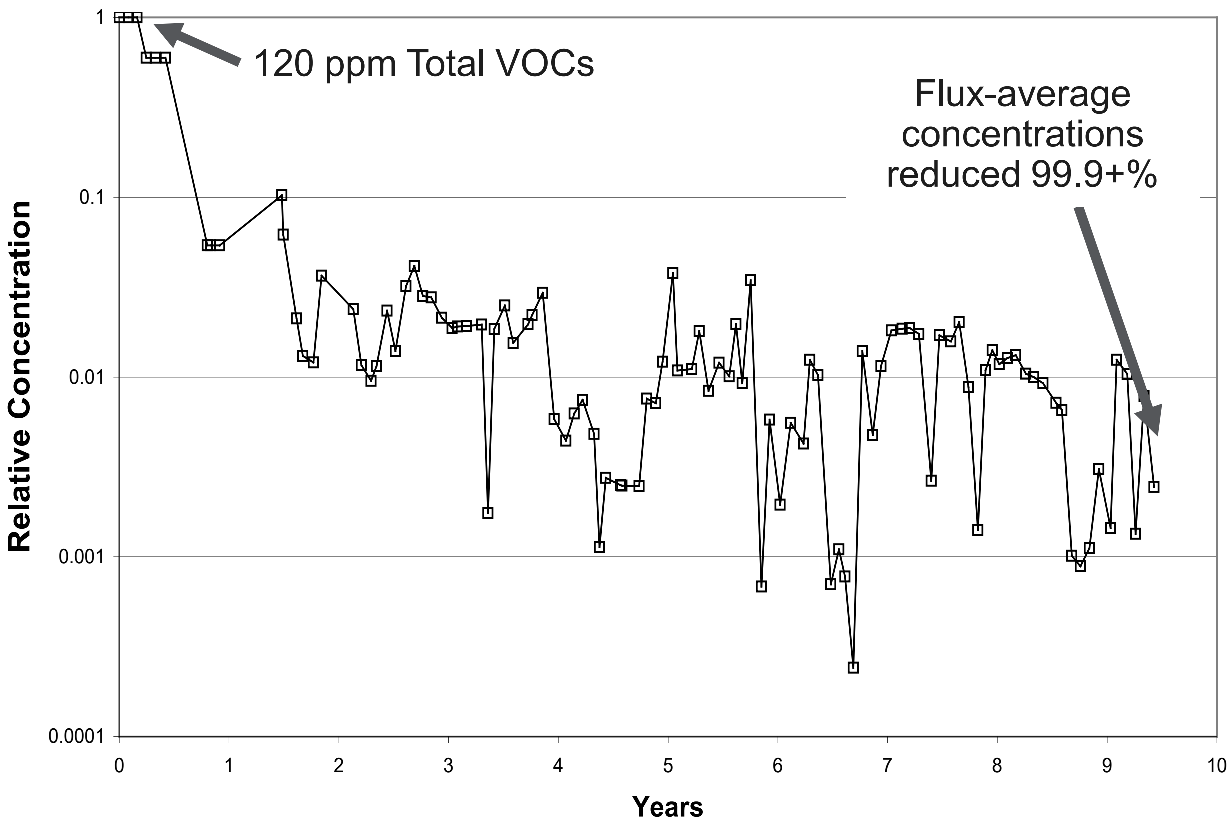
- AB selected over anaerobic approach due to concerns about vinyl chloride (VC) generation
- Enzymes (methane monoxygenase [sMMO]) produced by methanotrophs cometabolically destroy COCs
- Methanotroph growth supported by dissolved oxygen (electron acceptor) and methane (carbon source)
- Predicted remediation timeframe: *12 years*

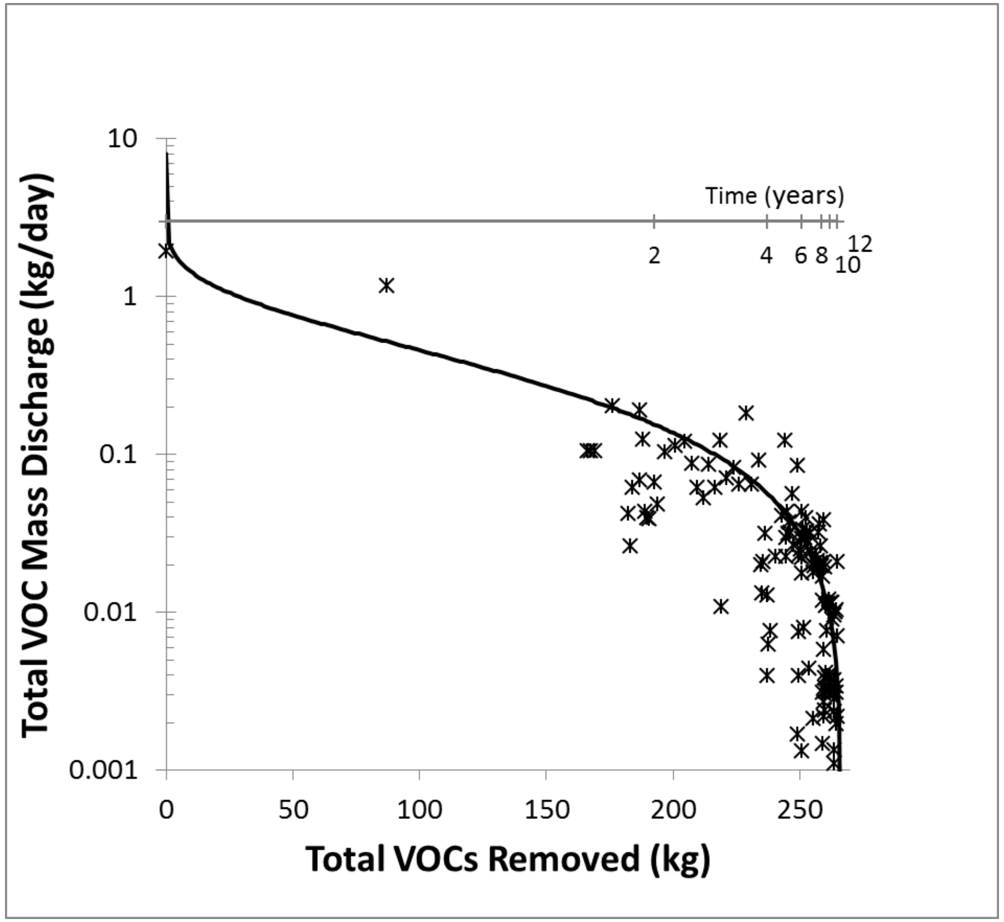
1,4-Dioxane not considered in remedy because presence was not known



methane monoxygenase
(http://chemwiki.ucdavis.edu/)

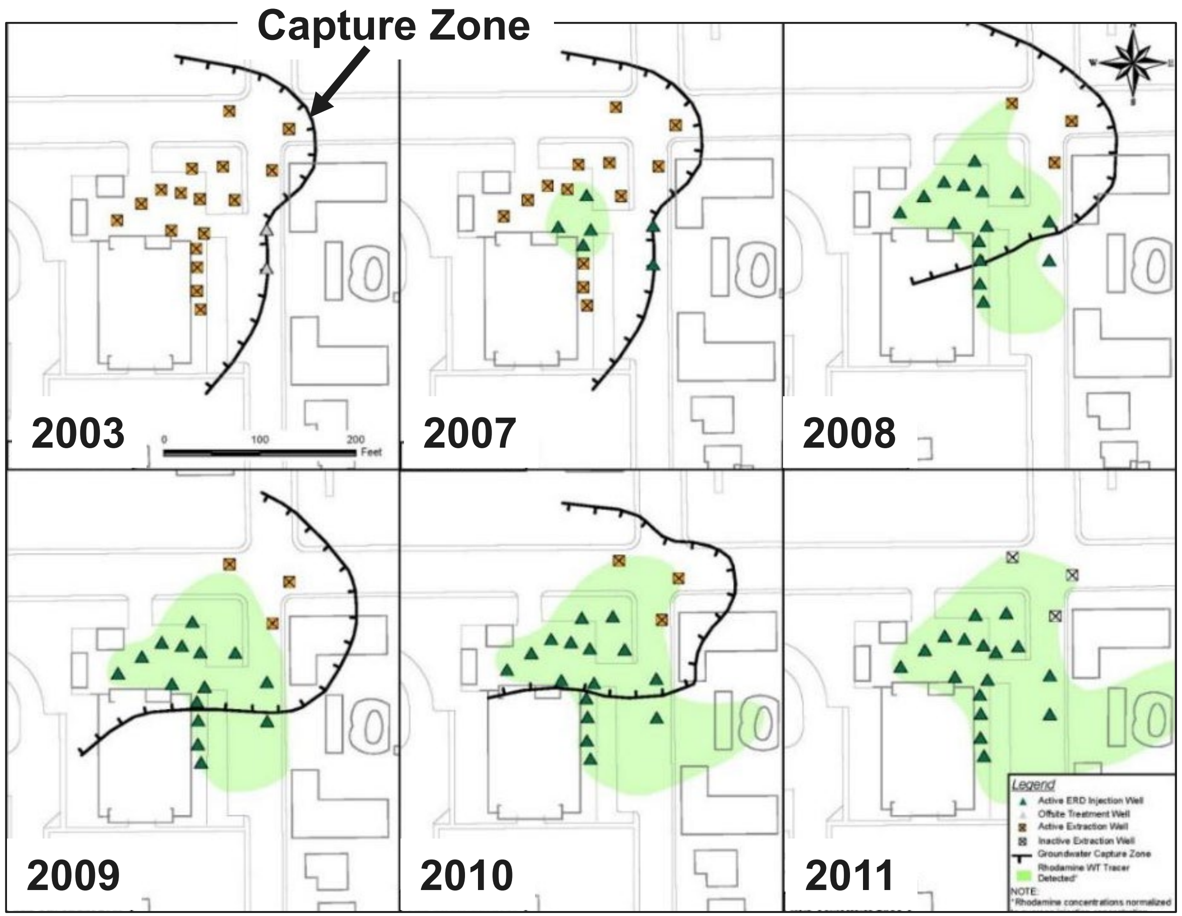
Source Zone P&T Performance (1998-2008)





Conversion from P&T to ERD (2003-2011)

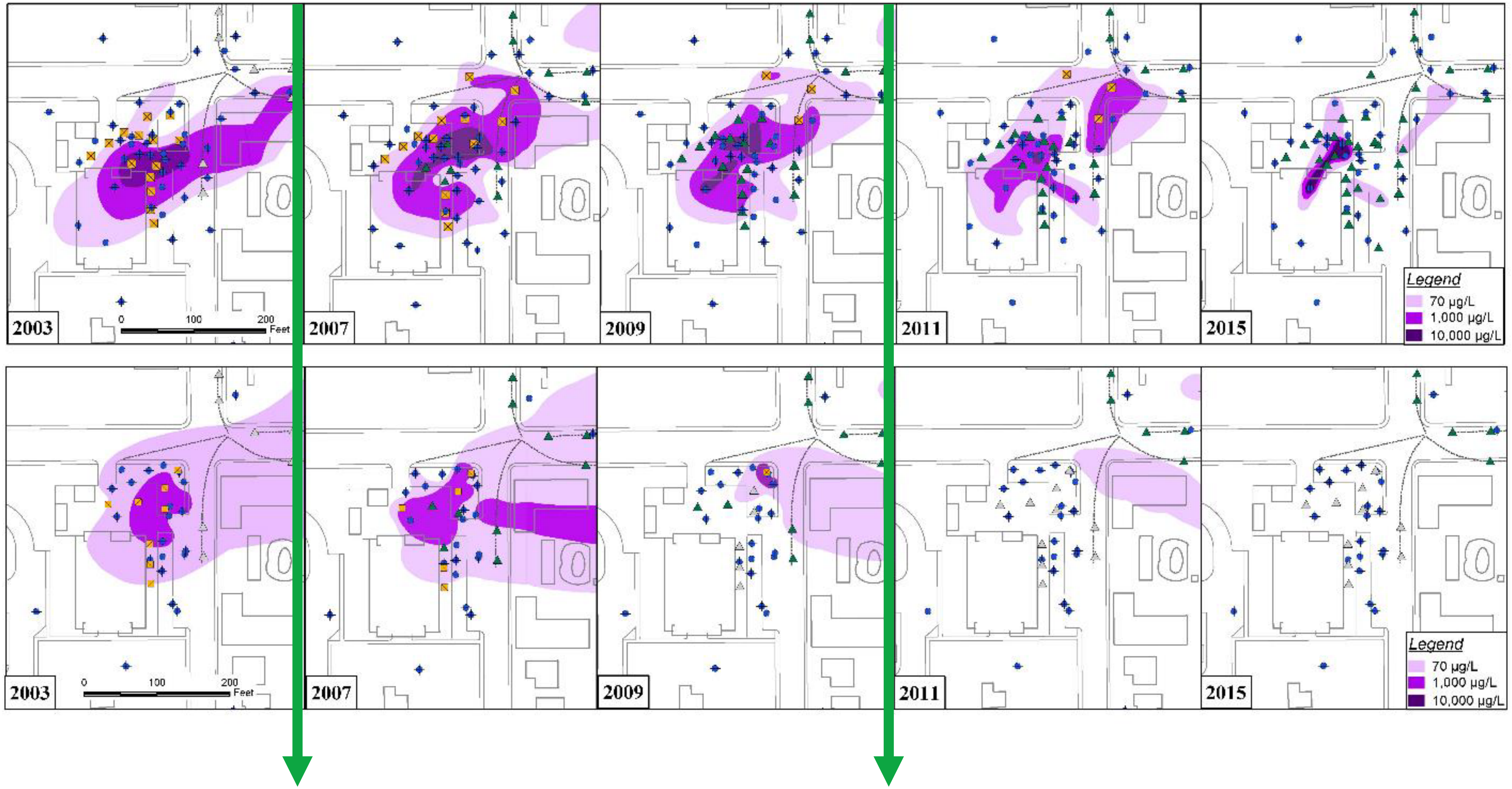
- October 2003: ERD pilot test initiated
- 2007-2009: ERD expanded to 90% of source zone
  - Hydraulic capture maintained
  - Tracer continuously added
- 2011: P&T terminated



Source Zone P&T + ERD Performance (2003-2015)

1,1-DCE in Shallow Groundwater

1,1-DCE in Deeper Groundwater

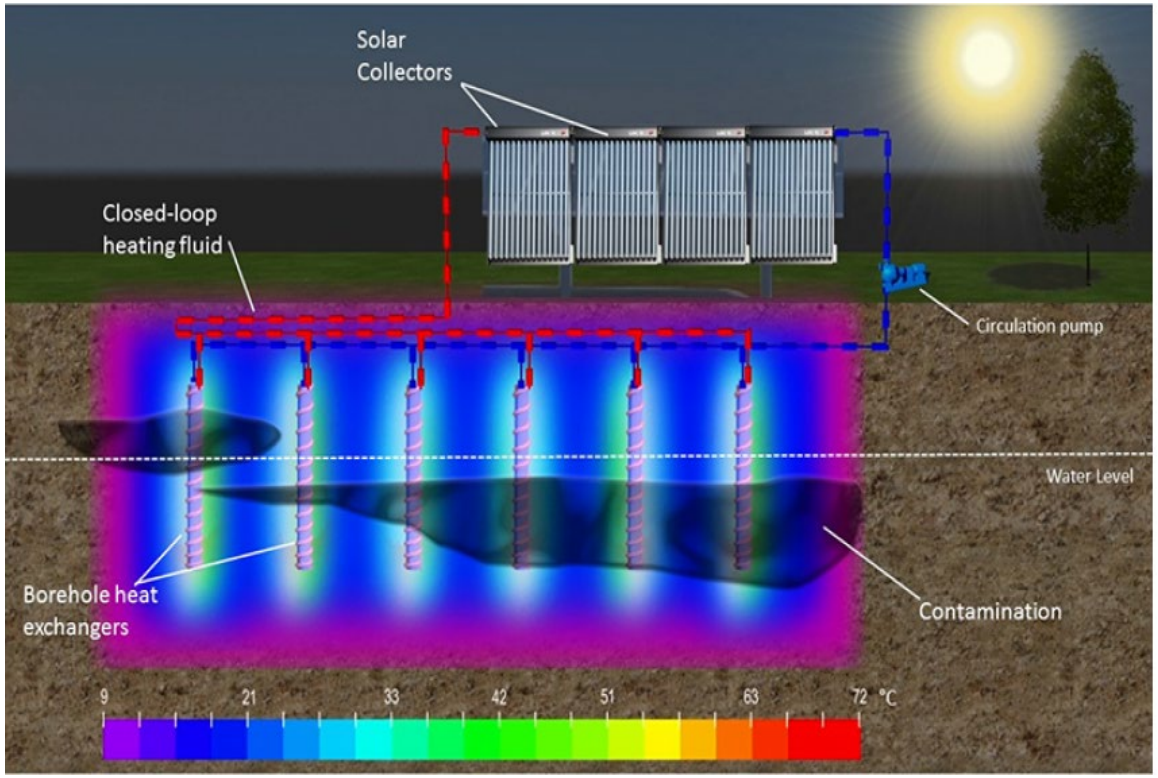


Source-Zone ERD Initiated

P&T System Shut Down

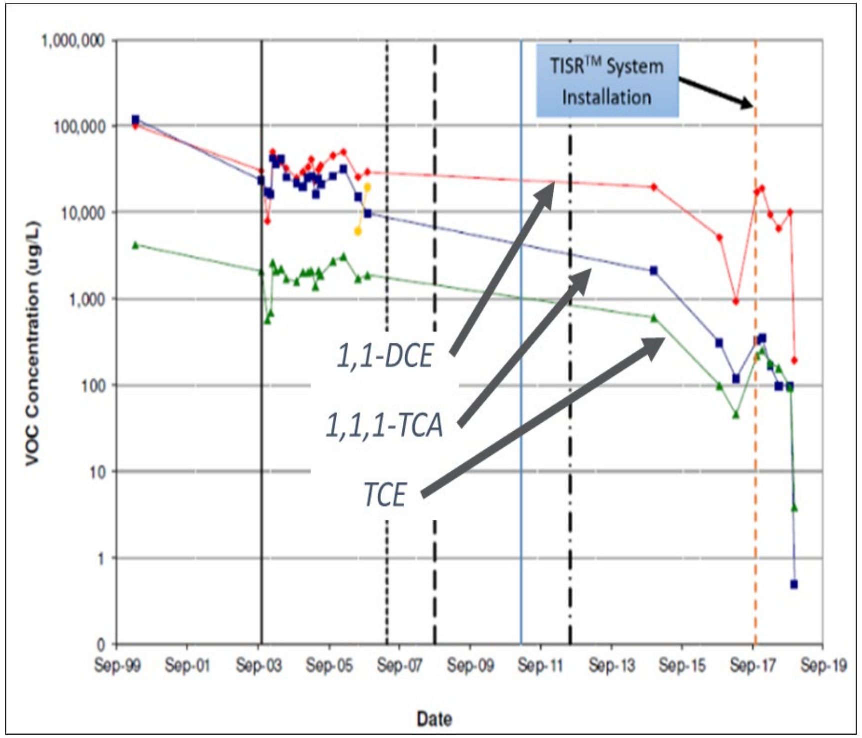
Thermal In-Situ Sustainable Remediation (TISR^{SM})

- Heat is collected and transferred to subsurface via closed-loop borehole heat exchangers
- Elevated temperature enhances biodegradation, hydrolysis, volatilization, and dissolution, desorption, and back diffusion



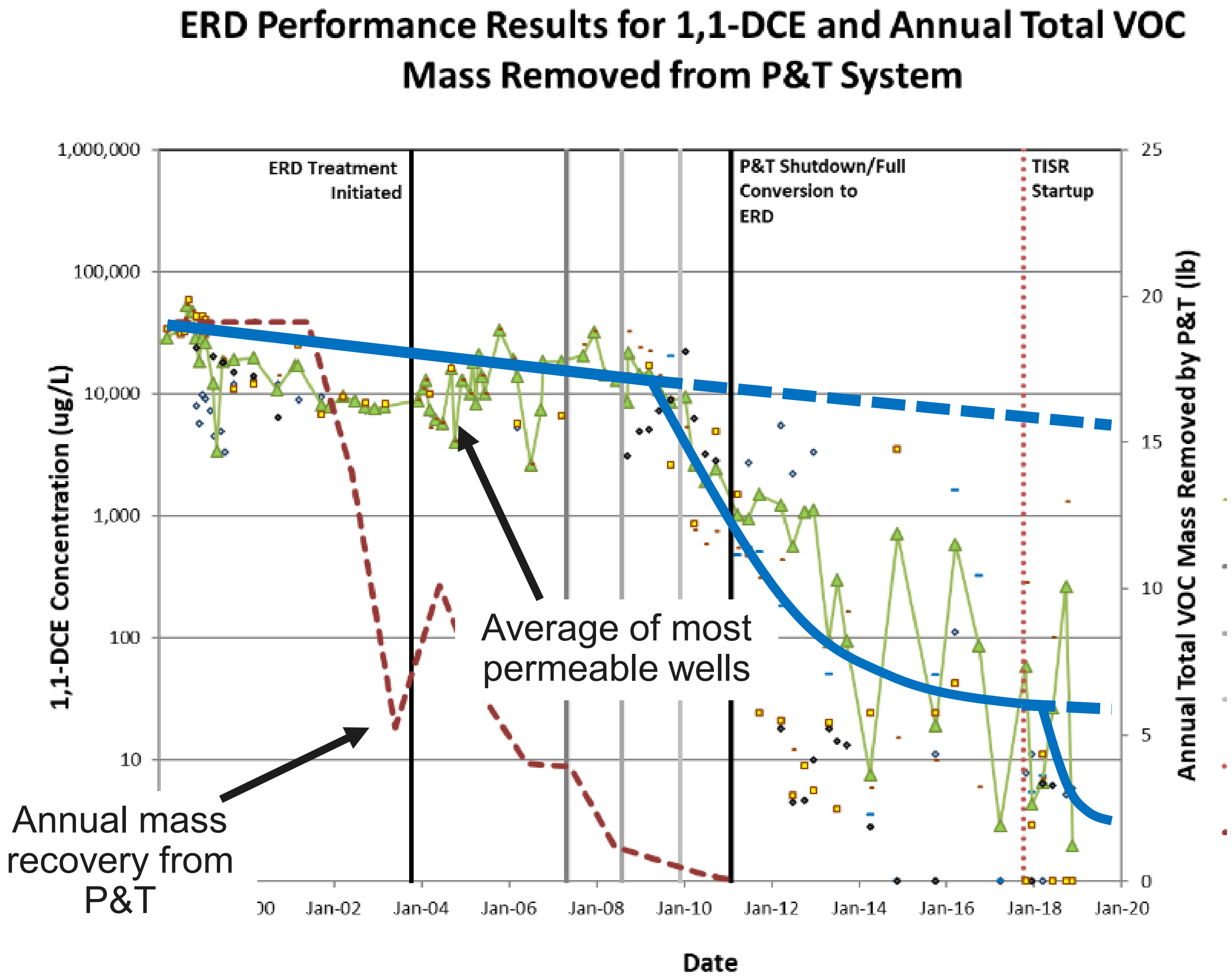
System Manifold

Borehole Heat Exchanger



Source Zone Current Conditions

- Full transition from hydraulic capture to ERD
- TISR "bolted on" in 2018 to accelerate pace
- Concentrations reduced from near-solubility concentrations to low ppb and ND
- Remediation timeframe reduced by 10+ years
- Estimated lifecycle savings of $2-4M
- No active remediation anticipated after 2019



Aerobic Biodegradation (AB) System (2001-2008)

- 2001: Start-up
- Large-scale injection system
  - 82 hydrofractured injection wells, 3 treatment buildings
  - Dissolved methane and oxygen
  - Tracers (Br, SF_6)
- System operation
  - Continuous injections initially
  - Switched to pulsed injections
  - 0.1 to 0.5 gpm per well

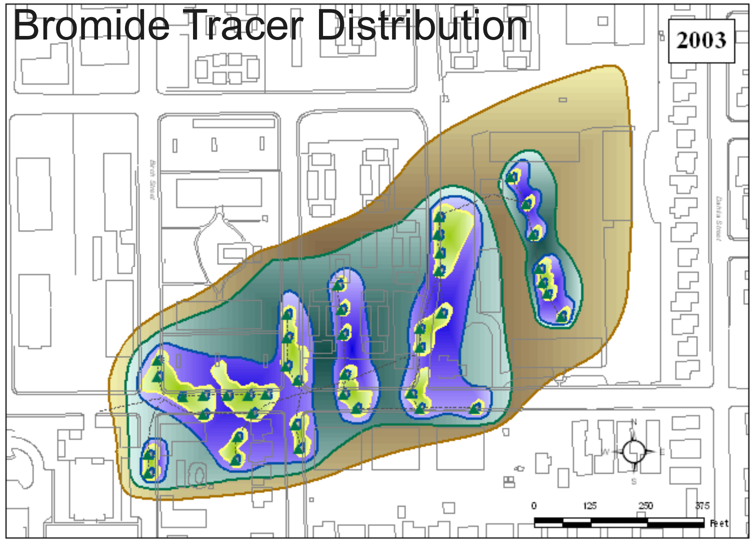
AB System Summary

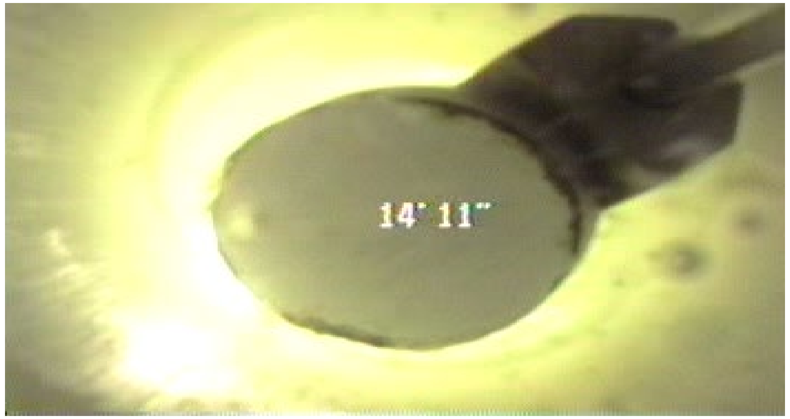
Successful treatment of COCs,

- <u>However</u>, pace would not achieve goals in the target timeframe/cost despite several efforts to optimize the system

Reagent distribution limited by

- Low solubility of methane
- Short half-life of methane (10-20 days)
- Injectability
  - Low baseline injection capacity
  - Biofouling!

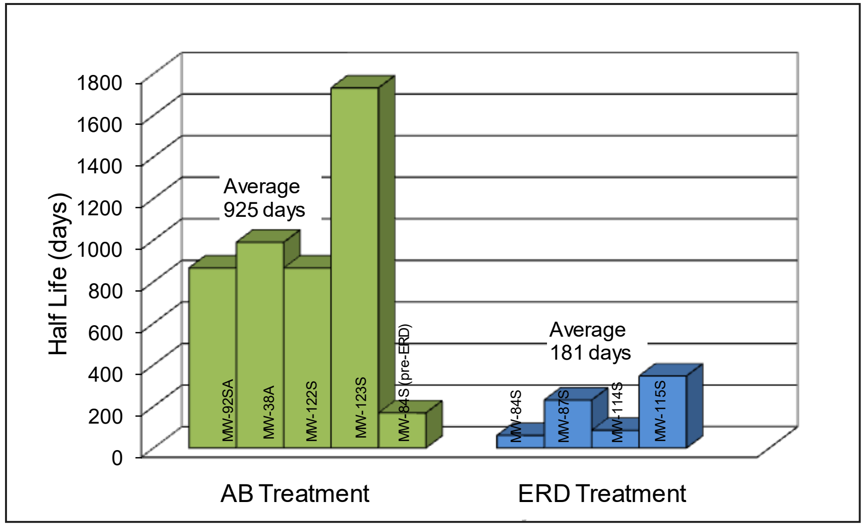




Off-site Anaerobic ERD Pilot Testing (2005-2008)

1. ***Is large-scale system redox conversion possible within a reasonable timeframe?***
2. ***Can remedial timeframes be achieved under and anaerobic ERD approach?***
3. ***Are full-scale lifecycle costs less?***

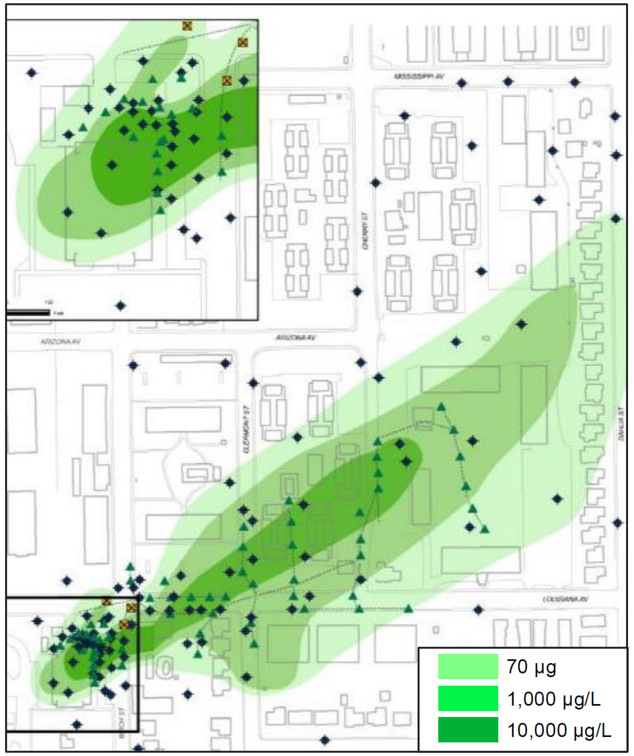
- Only 3-4 month “lag time” to convert to anaerobic conditions compared to other nearby sites in same geologic unit
- Full dechlorination achieved at all wells, apparent half-lives ~80% shorter
- Estimated lifecycle cost savings $3-5M



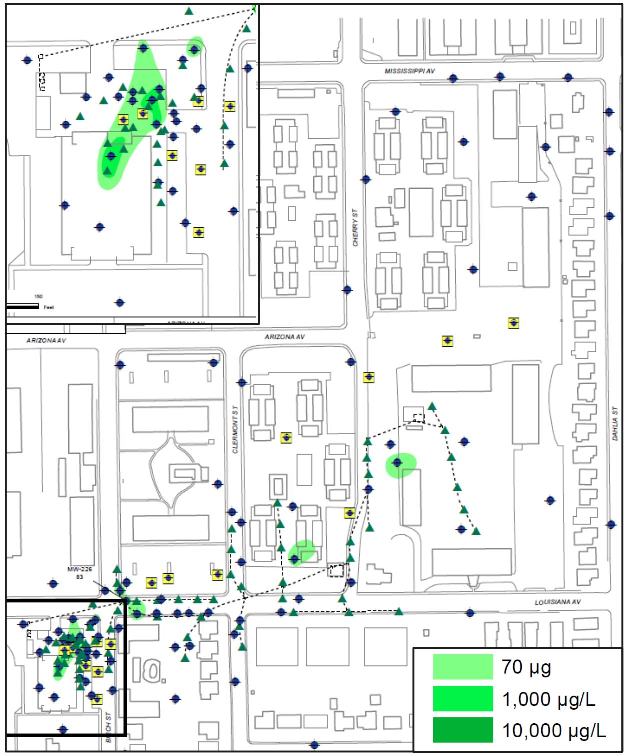
Full-Scale Off-Site ERD System (2008-2013)

- Full-scale conversion utilizing existing infrastructure
- Upgrades to automate injections at 78 wells
- Injection volumes: 1,000 to 4,000 gal/well 2-4 times/year
- Dosage ranges between 1 and 3% molasses
- 80% less annual injection volume

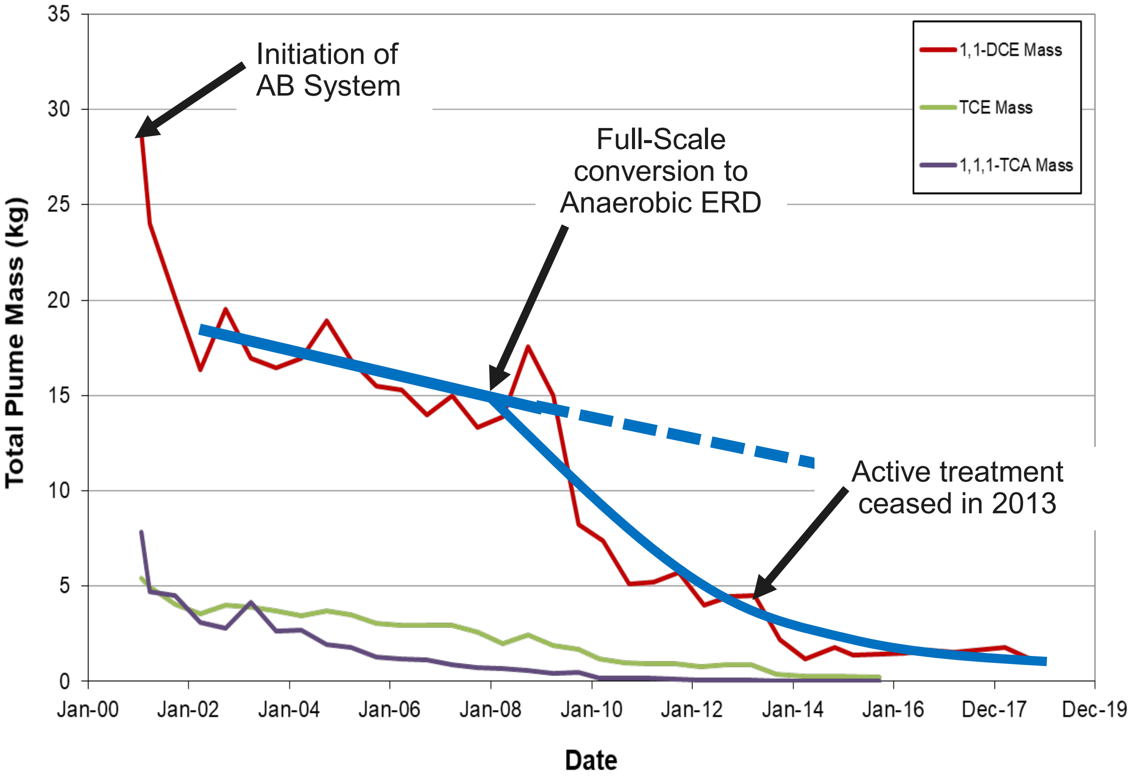
1,1-DCE Plume



2001

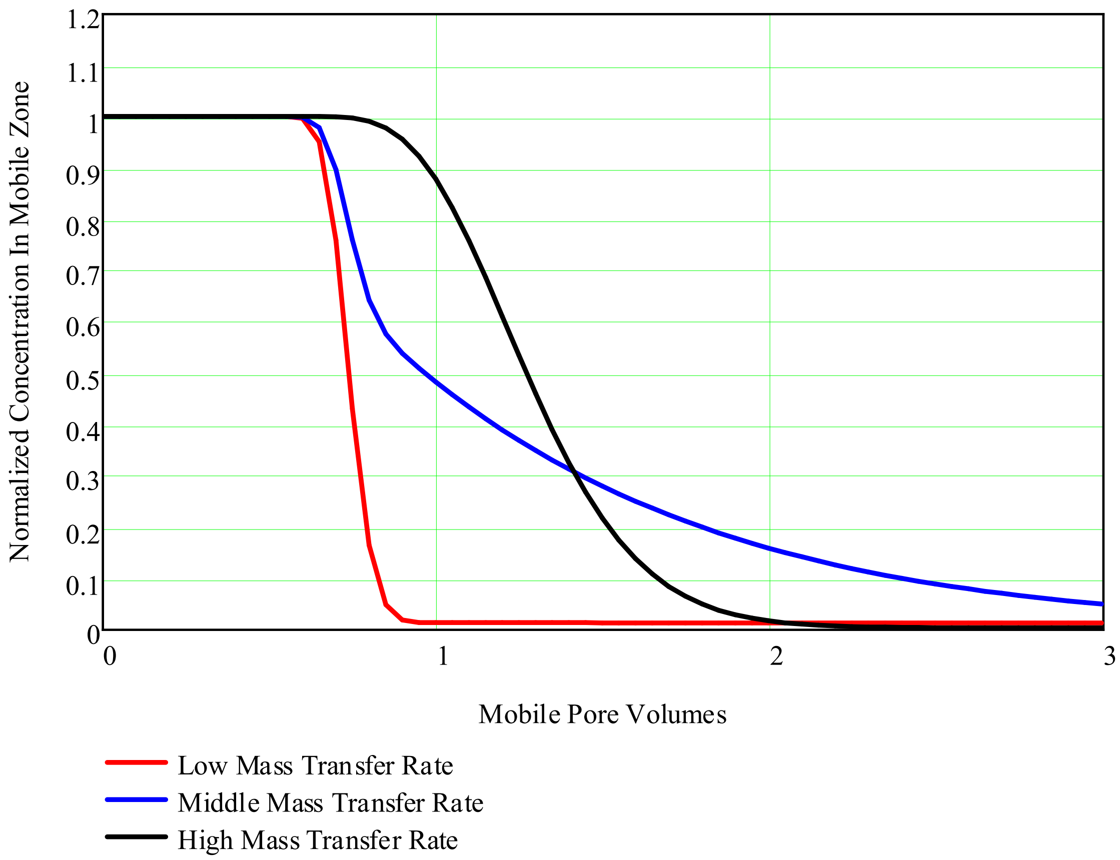


2018



Fractured Sedimentary Rock and No Rebound?

- Low effective mass transfer rate coefficient
  - Bulk matrix has very low permeability and accessible porosity (matrix is often dry)
  - Low matrix surface-area-to-volume r
- Low back diffusive flux is minimal relative to
  - Continued enhanced biodegradation
  - Abiotic transformation by reduced iron minerals
  - Dilution



Residential Indoor Air Program

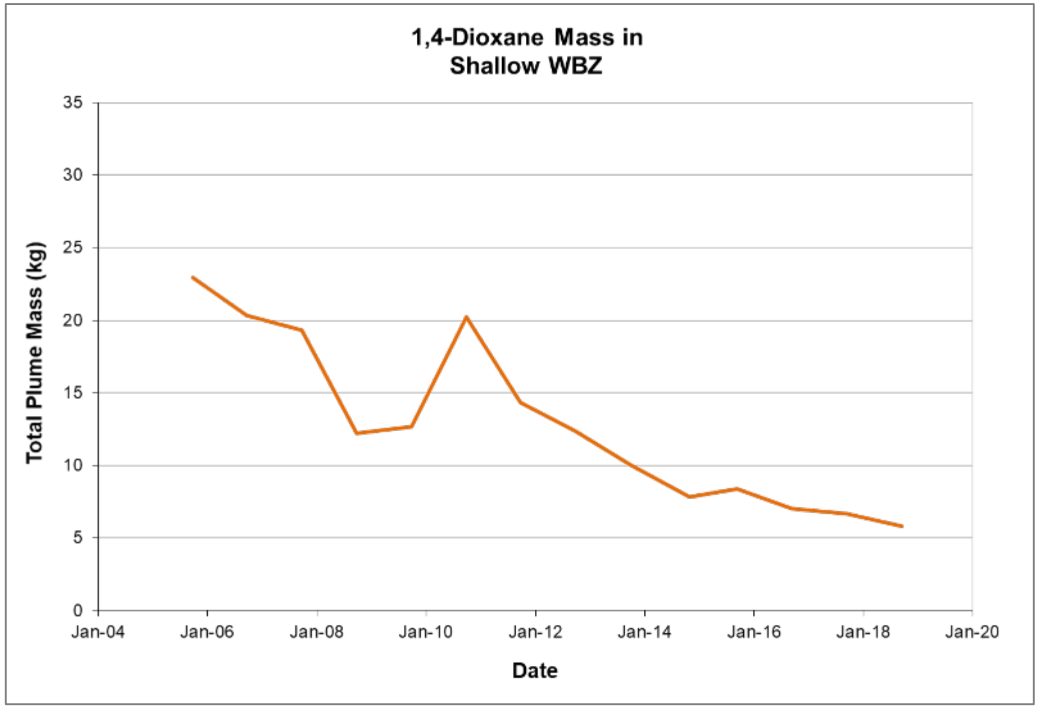
- 1995: Vapor Intrusion concerns (1,1-DCE and TCE)
- 1997: Interim action plan implemented
  - Temporary relocation of 12 residents
  - Indoor Air Mitigation Systems in 14 apartment buildings, 12 townhomes, and 21 single-family homes
- Quarterly monitoring at up to 135 residences

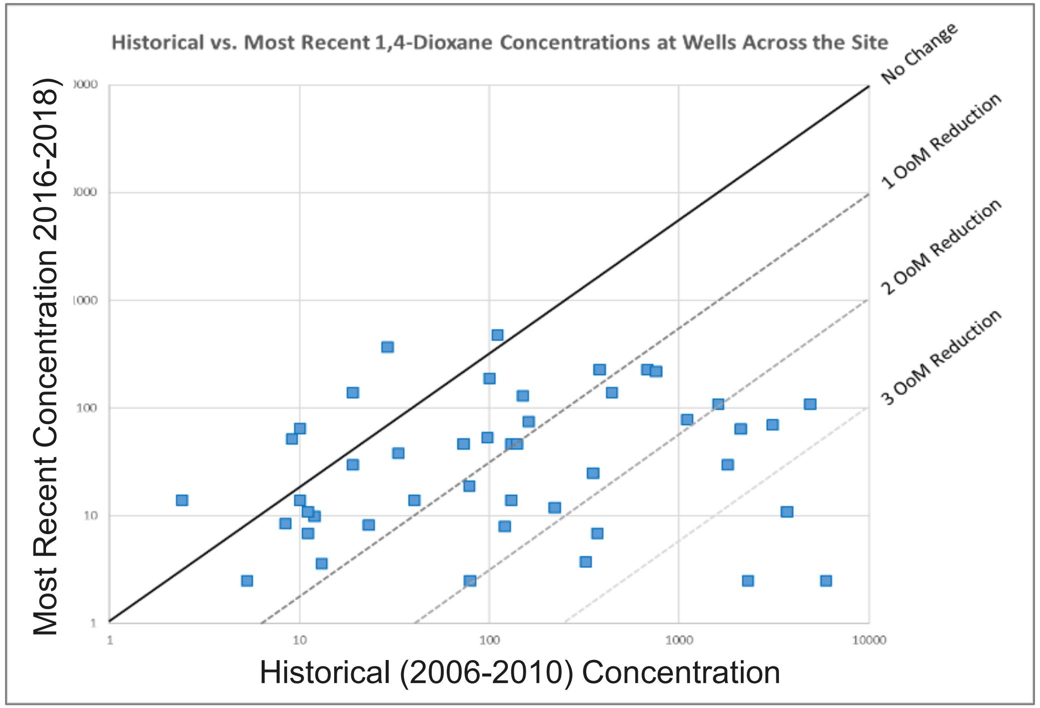
- 2005-2007: Initial Round of System shutdowns
  - Confirmatory sampling conducted post-system shutdown
- 2012-2013: Final round of system shutdowns
  - All off-site locations well below IA goals
- 2014: No Further Action (NFA) for Off-site Indoor Air Program

"…This is the first VI-site closure that I am aware of. Again, congratulations to you and everyone involved, and thank you for sharing this with me."
Henry Schuver, USEPA Headquarters – Vapor Intrusion Expert

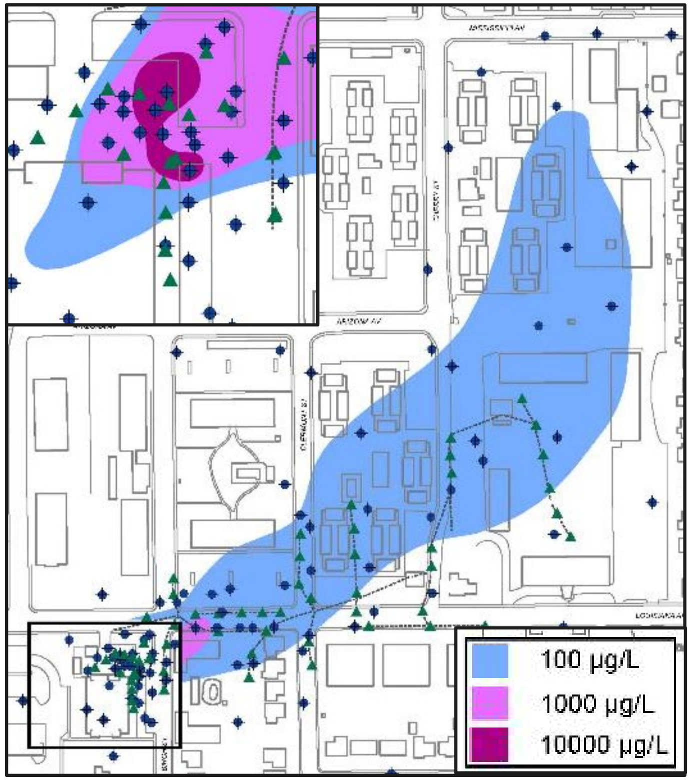
1,4-Dioxane Mass and Concentrations Changes

- Biodegradation rates were not quantifiable in microcosm tests or field isotope study
- However, long-term monitoring verified destructive mechanisms clearly present
- Monitoring-only approved in 2015

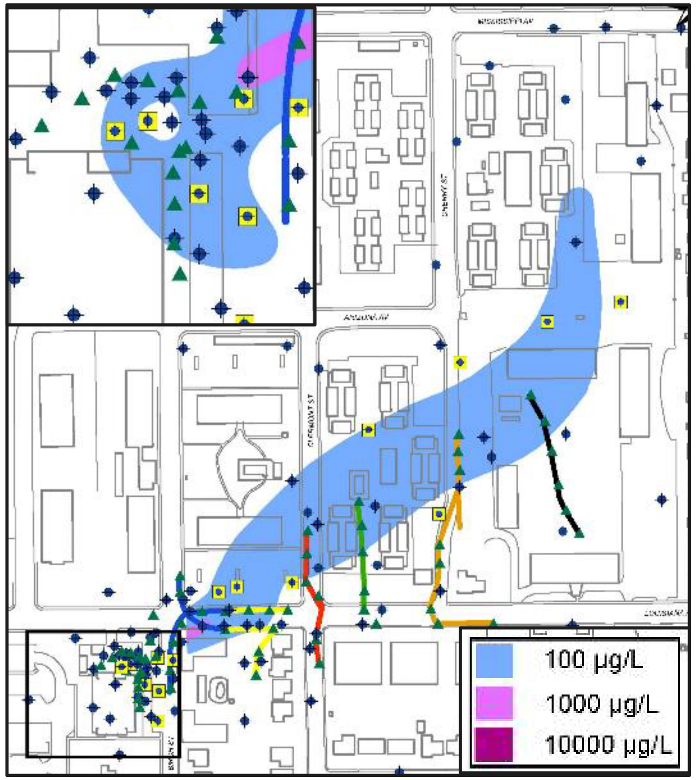




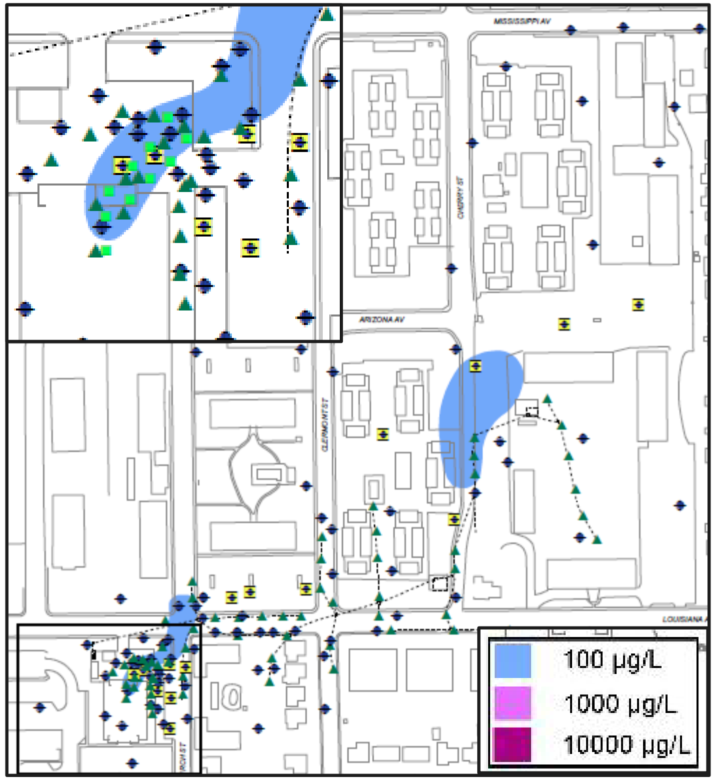
1,4-Dioxane Plume Through Time



2006

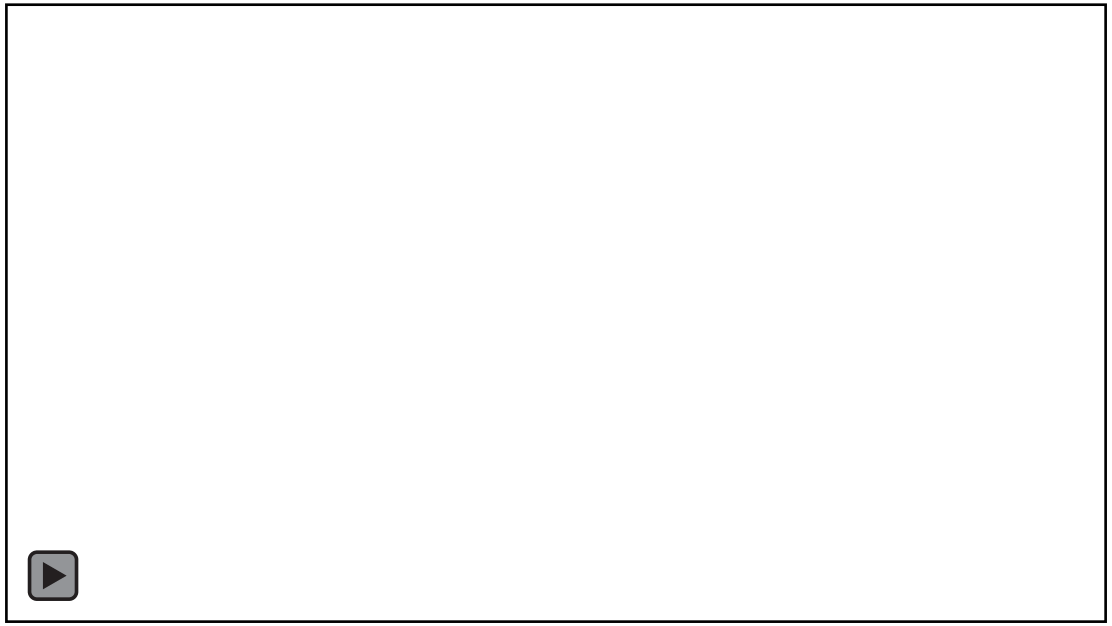


2015



2018

Regulatory Agency Engagement and Perspective



"The Department congratulates CDOT for the work it has done these last 17 years investigating, mitigating and remediating the contamination that was responsible for the intrusion of vapors into buildings overlying the footprint of the ground water plume. We consider this to be a major accomplishment of national importance, because this was the premier vapor intrusion site that made EPA and other states aware of the importance of evaluating this exposure pathway."

Walter Avramenko, Former Haz. Waste Corrective Action Unit Leader, CDPHE

Summary

- Source concentrations and mass discharge has been greatly reduced; active remediation expected to end in 2019
- 95+% VOC mass reduction in the off-site plume
- No significant rebound: fractured sandstone can be remediated
- Vapor intrusion risk off-site has been eliminated through effective groundwater treatment
- Active treatment in the source area and across the entire site expected to be complete in 2019
- Stable/reducing 1,4-Dioxane plume supports long term monitoring-only strategy

Key Takeaways

1. ***The project lifecycle highlights the value of adapting the remedial strategy based on observed remedial performance, new site information, and developments in remediation technologies.***
2. ***Successful remedy optimization requires a commitment to performance goals, on-going engagement of technical experts, and stakeholder collaboration and agility.***