

In Situ Remediation of Chlorinated Solvents in a Tight Matrix by Applying Low-intensity Electric Fields



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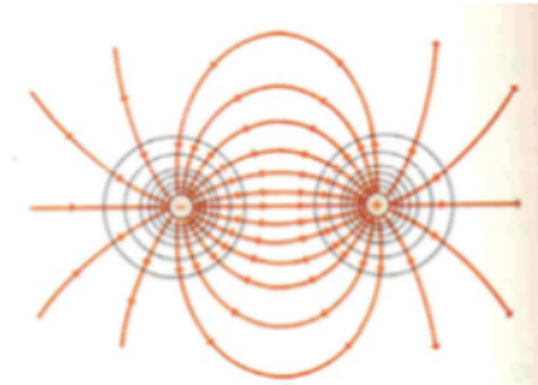
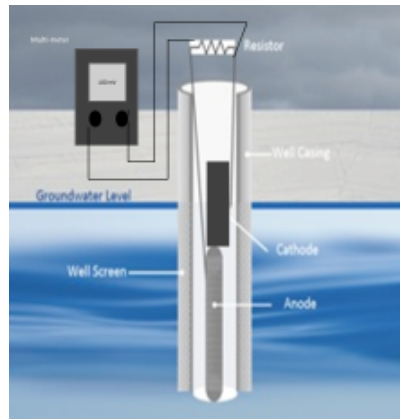
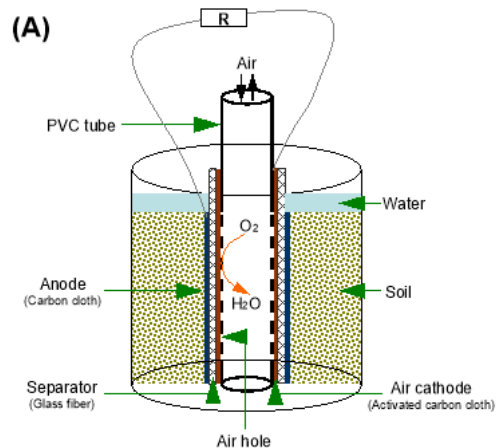
Advanced Environmental Technologies, LLC
Fort Collins, Colorado

ACKNOWLEDGEMENTS

SUBJECTS

- Paul Fallgren – Advanced Environmental Technologies, LLC
- Debbie Tuttle – City of Northglenn (retired)
- Richard Lesser – RE Solutions

- I. E-Redox[®]-I mechanisms
- II. Case studies of E-Redox[®]-I reduction of chlorinated solvents



Microbial-Electro-Chemistry Redox Technology (E-Redox)

1

Reactions via electron transport and shifts of matrix particle/water interface charges and configurations

2

Friendly for fine-grained lithology with higher electrical conductivities: silts & clays

E-Redox[®]

Boosts bio(oxidative)degradation

Abiotic redox reactions for COC destruction and desorption

E-Redox[®] (O-oxidation)

Desorption of mass into water phase

E-Redox[®] (I-Reduction)

Typical Petroleum
Hydrocarbons (e.g.,
BTEX)

Some PAHs

Other VOCs,
SVOCs, 1,4-
dioxane,
oxyanions
(e.g., As)

Certain Oxyanionic
Metals (e.g., CrVI)

Chlorinated
Solvents,
Some PFAS

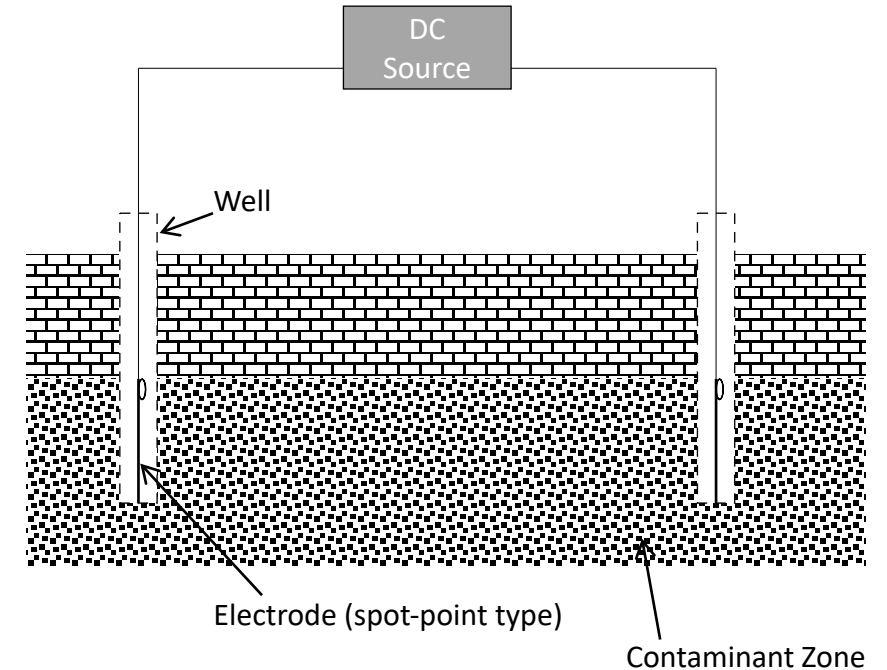
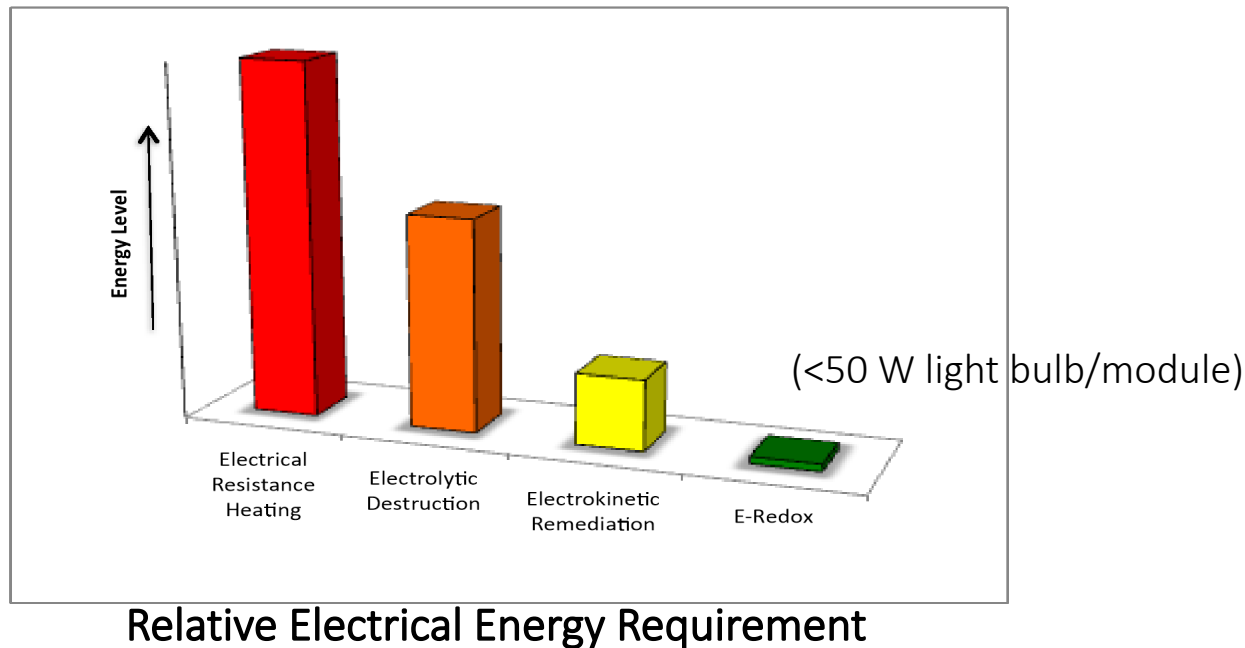
Nitrate/Nitrite,
Perchlorate

Nitro-aromatic
Compounds

PCBs

E-Redox[®] (I)

- Establishes a low-voltage/low-amperage static electric field in the contaminated matrix.
- Promotes reductive destruction and desorption of source compounds from soil into water



Patented by AET, 1st Field Application 2014
 Jin et al., 2008. Chem Eng J, 140:642
 Jin and Fallgren 2009, J Haz Mat, 153:127
 Luo et al., 2010. Chem Eng J, 160:185

E- Tools

	Typical Linear Current Density	Typical Linear Voltage Density	Current Loading	Main Reactions
Electrolytic Destruction (ER)	50 mA/cm	5000 mV/cm		Electrode surface/interface reactions, reactive barrier applications
Electrokinetic Migration (Remediation)		500 mV/cm	0.123-0.615 mA/cm ²	Movements of soluble constituents in the matrix
E-Redox	2 mA/cm	<50 mV/cm	0.002-0.006 mA/cm ²	Static electrical field by turning soil particles into “micro-capacitors” and disturbing solid-water interface charges and configurations

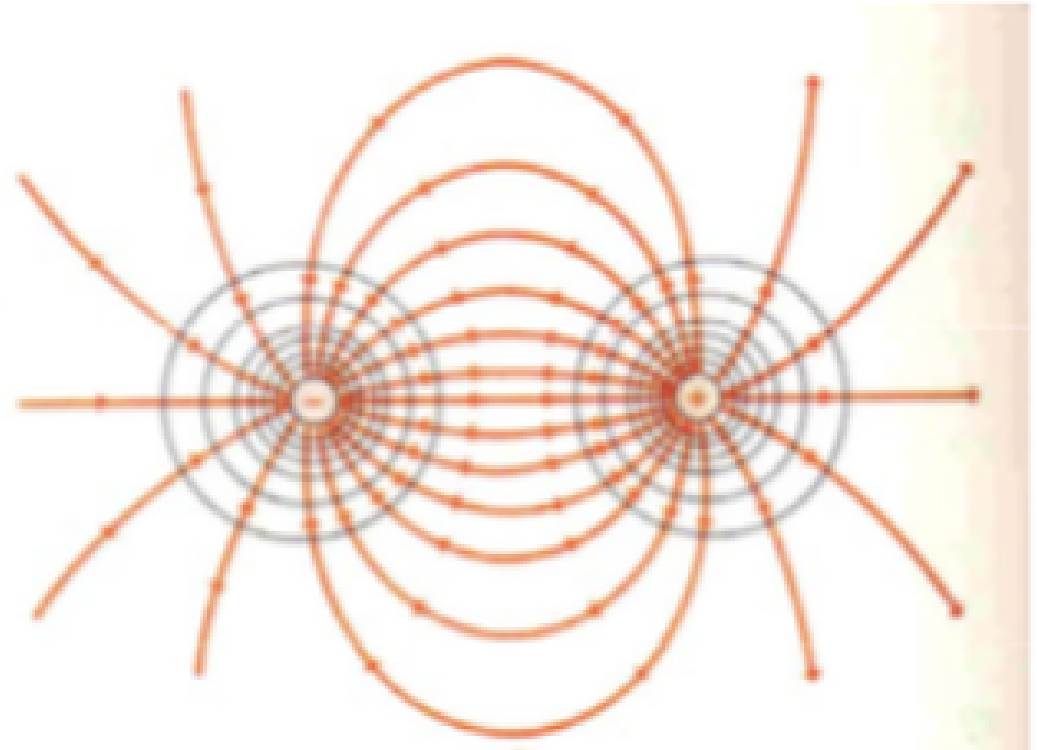
E-Redox: “microconductor”, “microcapacitor”, mechanism for redox reactions and mass desorption

- Soil particles in the influenced matrix act as micro-conductors, become polarized, and act as “micro-capacitors”* with constant charging and discharging cycles:
 - Abiotic reductive destruction of chlorinated solvents and oxyanions
 - Beneficial to biological dechlorination
 - Localized redox reactions destruct PFAS compounds
- Constant shifts of surface charge causes electrostatic and hydration repulsion, disturbs the “water cage” configuration and results in:
 - Desorption of contaminants from soil/solids into water
 - Elimination of “rebounds”

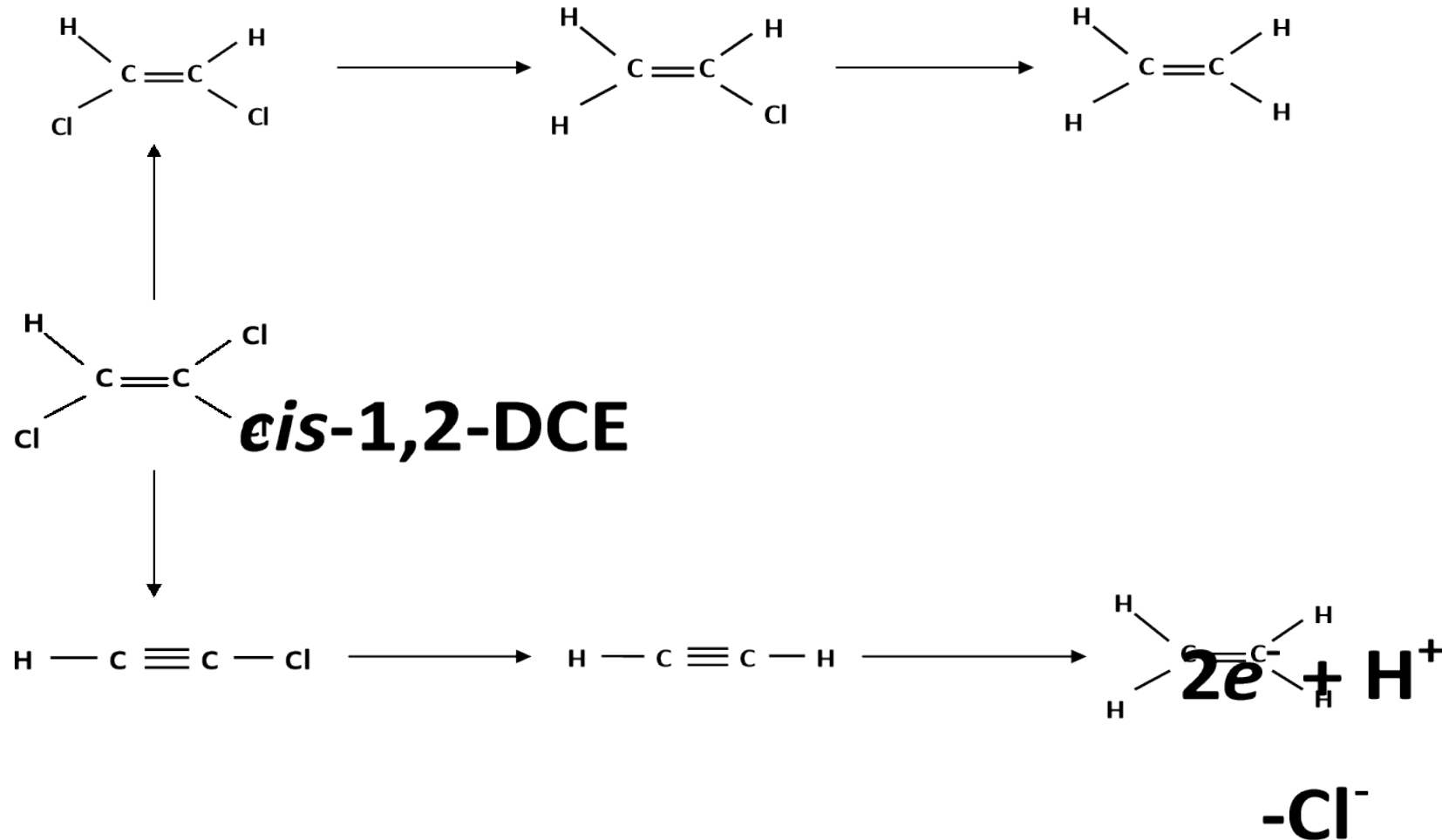
** Dietmar Rahner, Dresden U of Technology, 2002*

Static Electric Field

- Field data indicate a radius of influence (ROI) of ~25-30 ft in clay and silts; >50 ft for matrices with injection history of carbon, ZVI, or other conductive compounds
- Electrodes spacing: ~25 ft



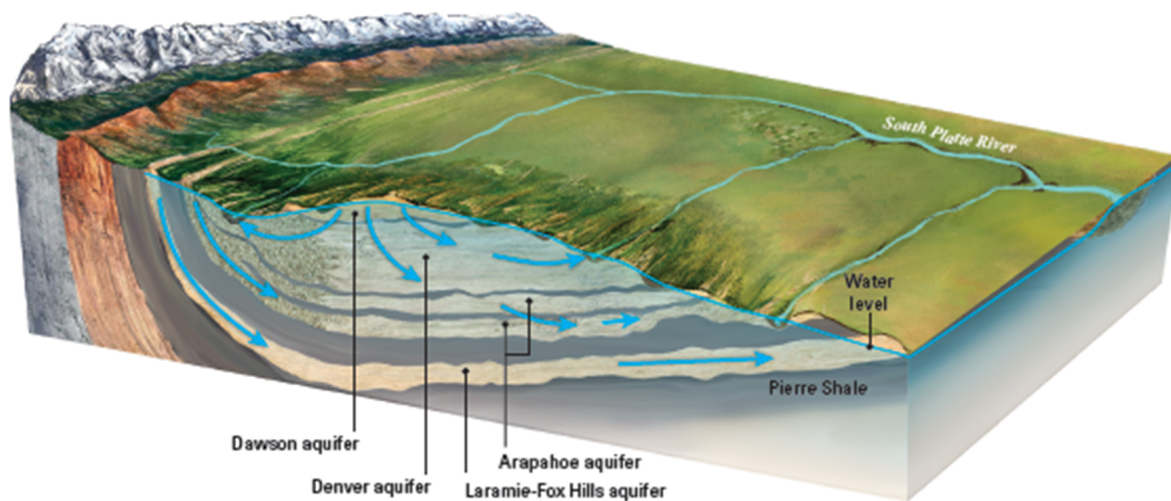
Reductive Pathways of Chlorinated Ethenes



*E-Redox® (I) primarily drives abiotic dechlorination (beta-elimination); however, the presence of the electric field also enhances opportunistic biotic reductive dechlorination and mass desorption

Denver Basin

- Formation along the Front Range (CO)
 - Includes the Denver Metro Area
- Material overlaying aquifers
 - Sandstone, mudstone, claystone, conglomerate
- Alluvial aquifers consist of clay and silty sandy clay
- Hydraulic conductivity and low groundwater flow velocity
 - challenging for in situ remediation involving delivery of physical reagents



Source: USGS



Source: USGS



FORMER SHOPPING CENTER, NORTHGLENN, CO

Location: Northglenn, CO

Site History: Former shopping center with dry cleaner

Site Owner: Northglenn Urban Renewal Authority (NURA)

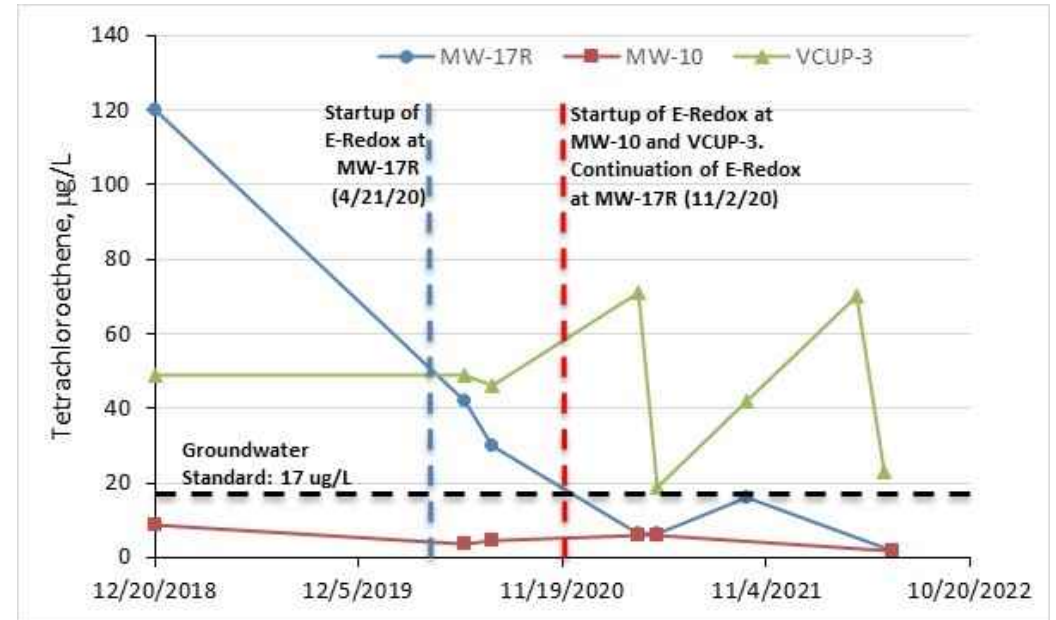
Main Contaminant: Tetrachloroethene (PCE)

Contaminated Matrix: Groundwater (alluvial, clay)

Remediation History: ISCO injections

Remedial Issues: Bedrock channels and DNAPL settling in bedrock depressions in residential area





E-Redox® units were decommissioned after <1-yr operation. The site was closed with a No Action Determination (NAD) granted by the Colorado Department of Public Health and Environment in September 2022

Alaska DOT Facility, Fairbanks, Alaska

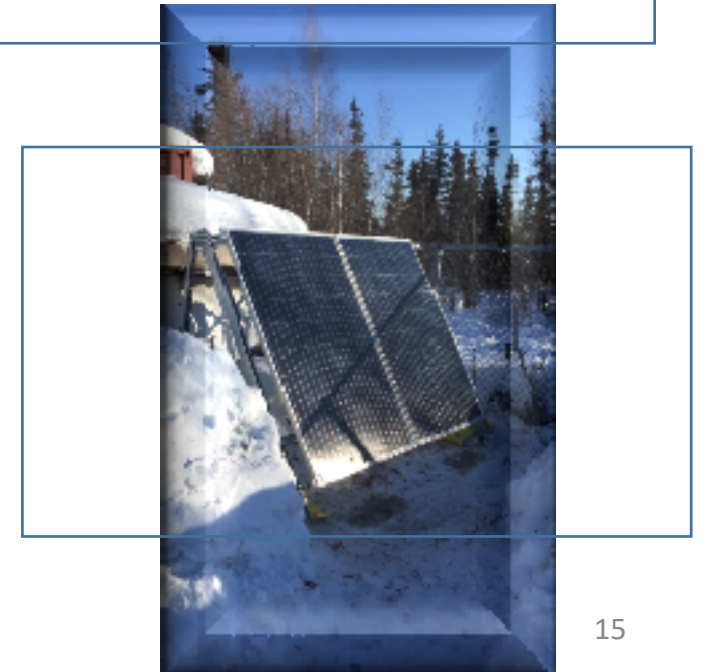


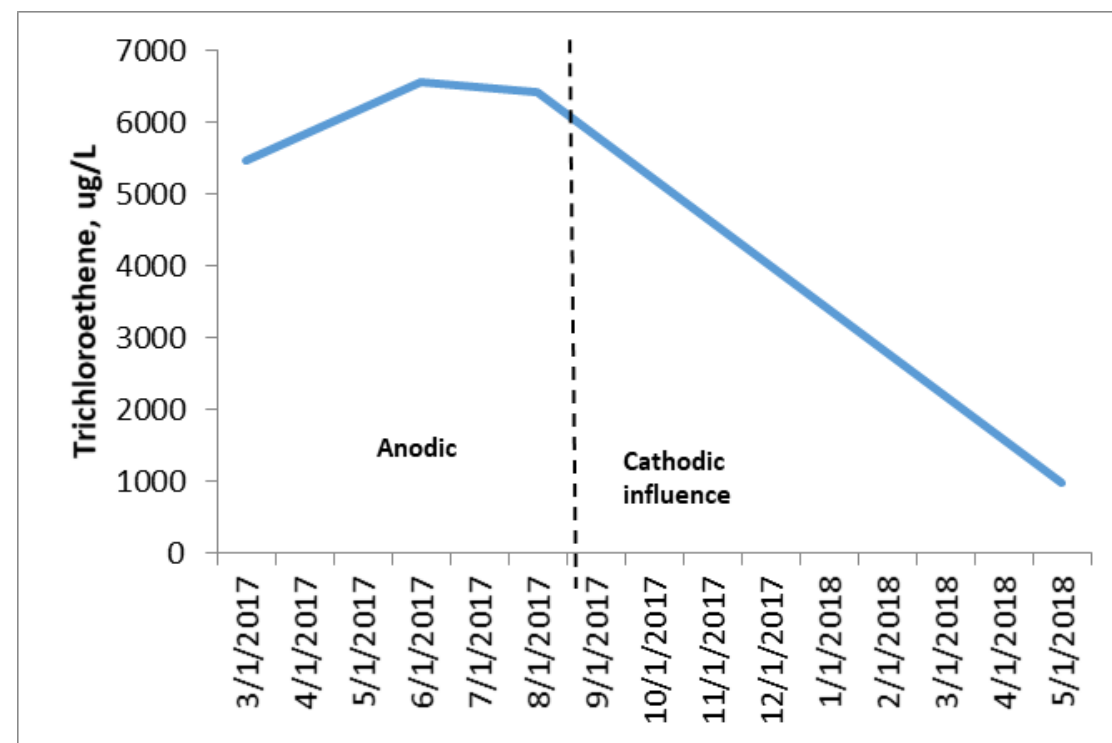
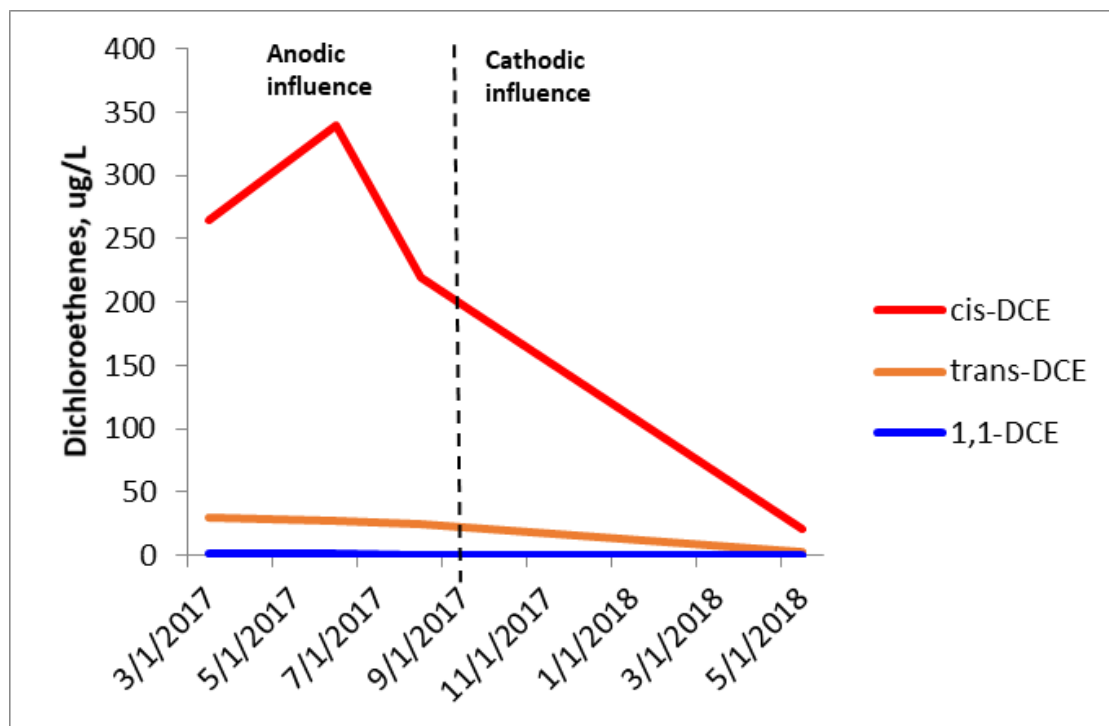
Location: DOT Service center, Fairbanks, AK

Contaminated Matrix:
Groundwater (alluvial, clay)

Main Contaminant: TCE
and DCEs

Previous Remediation:
unknown







Location: 29th Ave & Xavier, Former dry cleaner in Denver, CO

Contaminated Matrix: Saturated zone with clay

Primary Contaminants: PCE

Previous Remediation activities:

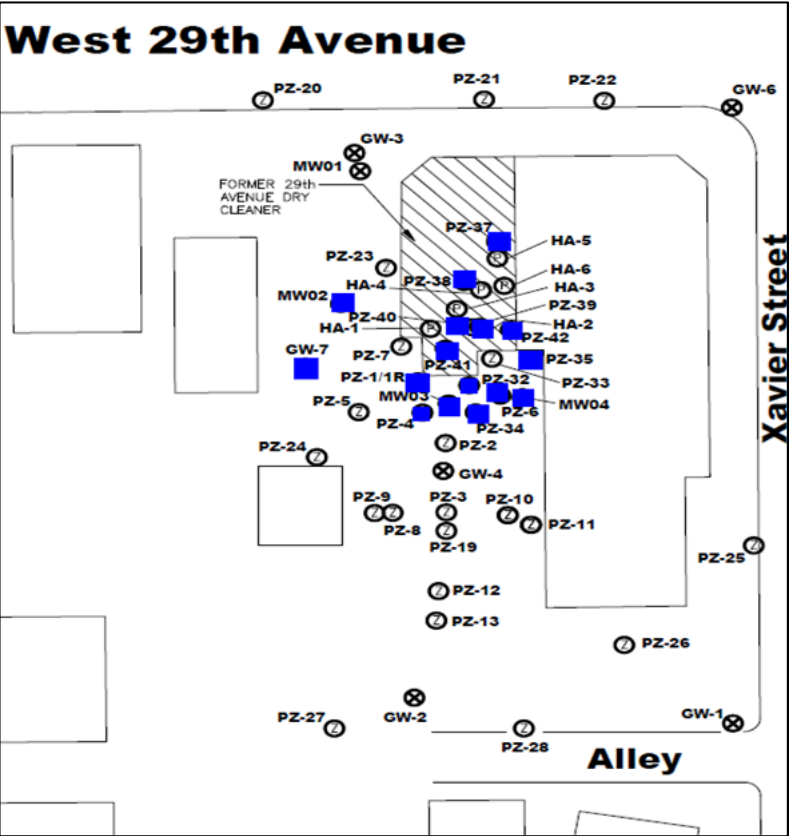
Source removal by excavation

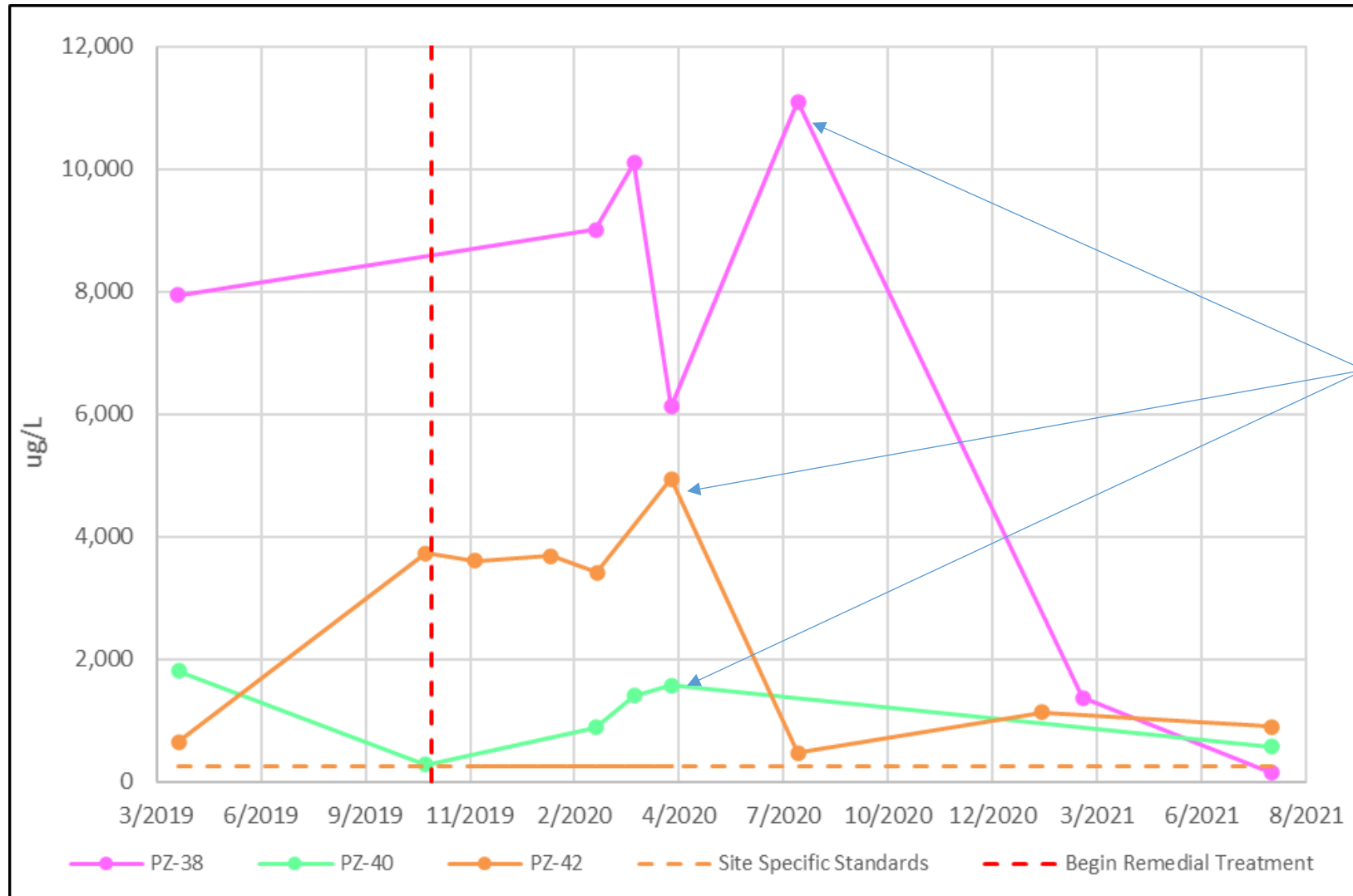
Injections of activated carbon
with metallic iron and sodium
permanganate

Downgradient PRB



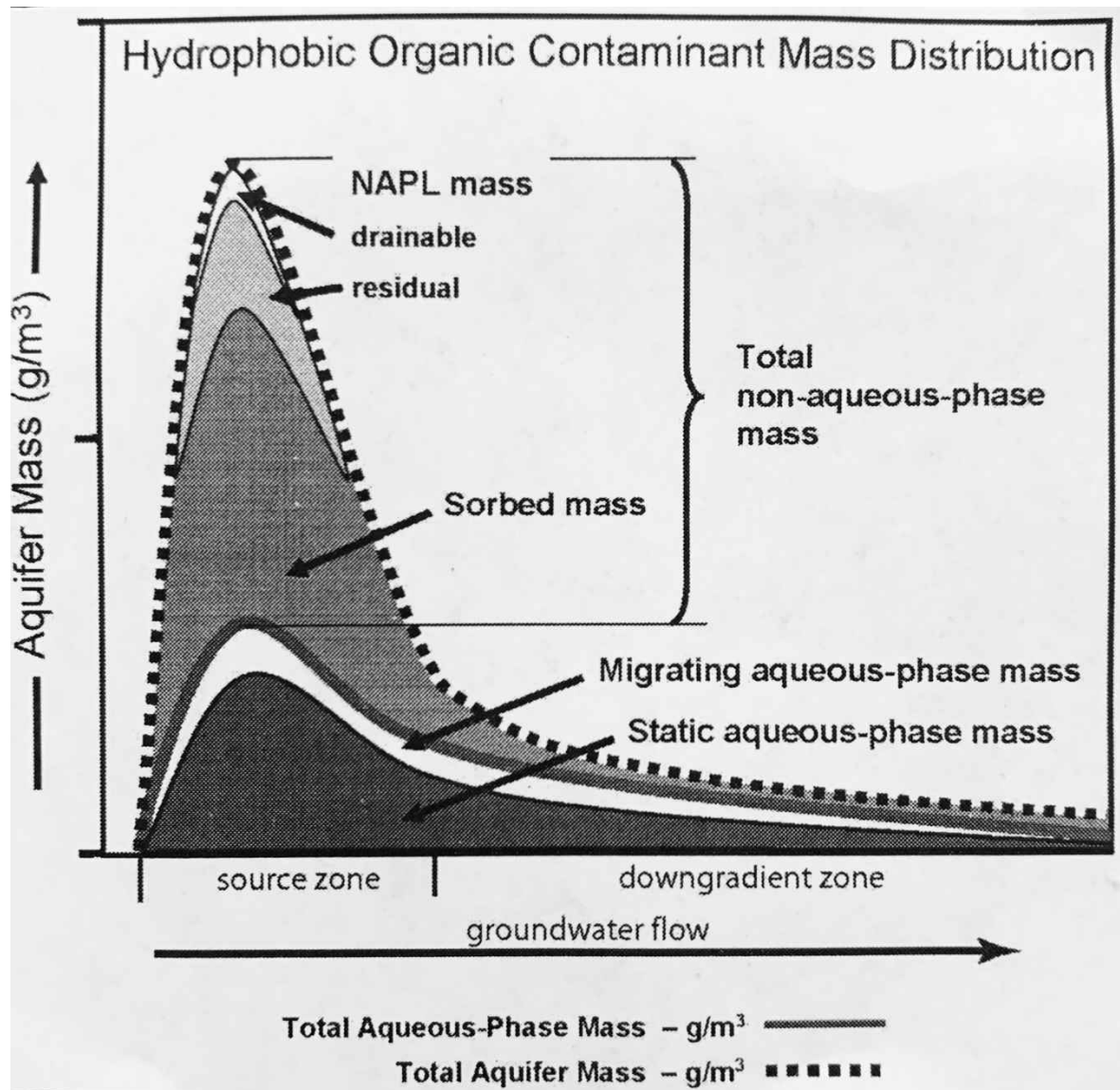
E-REDOX I (REDUCTION) IMPLEMENTATION



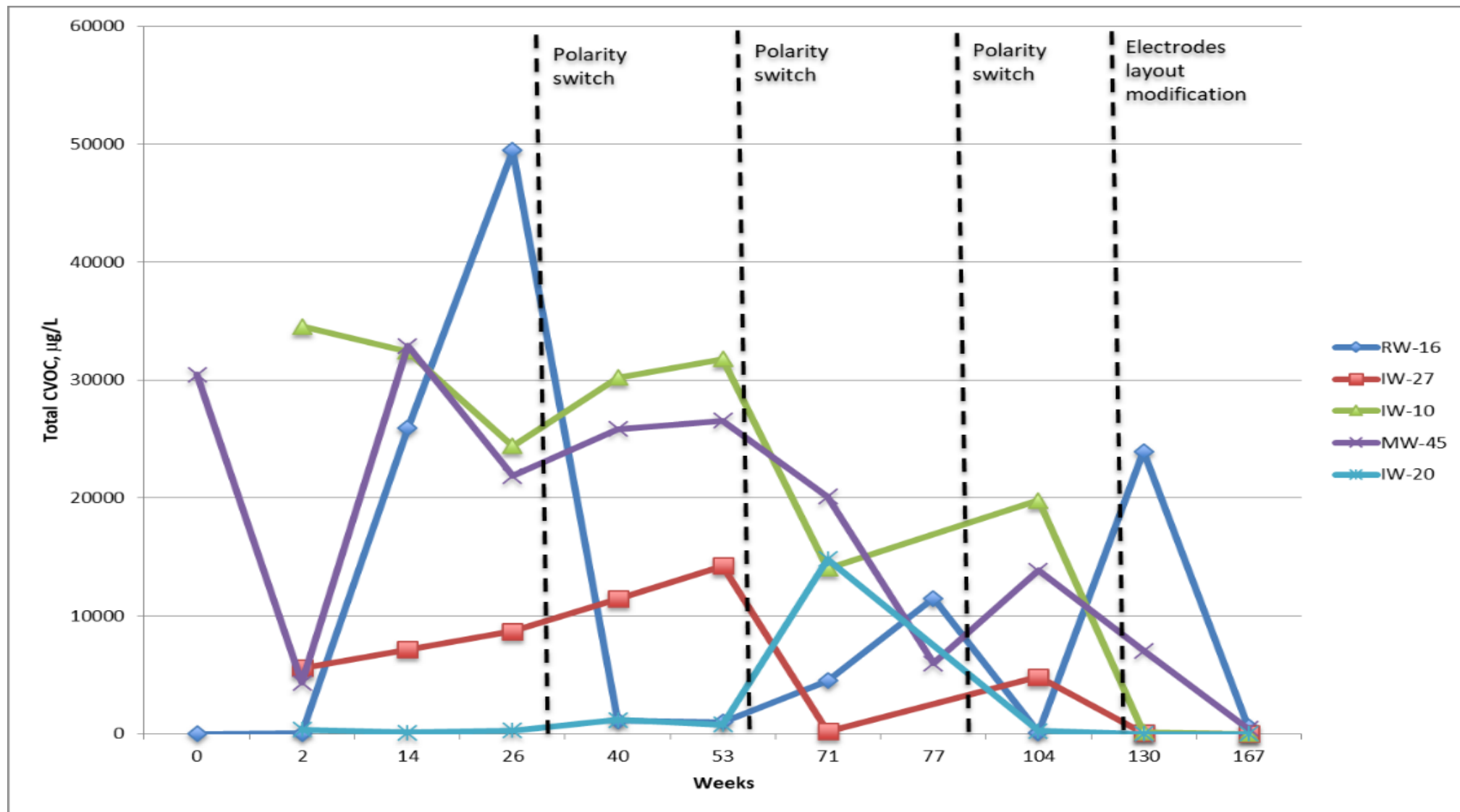


Spikes from polarity switches of the E-Redox I units to help desorb PCE from solids into groundwater

PCE Concentration Profiles in Key Monitoring Wells



E-Redox[®]-I facilitated desorption-reduction for faster mass removal and degradation



E-Redox[®]-I facilitated desorption-reduction for faster mass removal and degradation
(Charleston, SC)



E-Redox[®] (Reduction) Summary

- NOT EK
- Electron transport fit diverse matrices including clay and bedrock fracture
- Both abiotic and biological reductive (dechlorination and defluorination) reactions
- Electrical repulsion and shift in solid-water surface charges and cage configurations enhances desorption of COCs
- High electronegativity of electrons lowers redox potential instantly, favoring reductive reactions
- ROI of 25-50 ft; 30-50 W/unit, renewable power fits remote sites
- Integrates with other remediation technologies:
 - ZVI rejuvenation
 - Extends electron donor longevity
 - Rapidly establishes low redox condition for reductive remedies

THANK YOU!

E-Redox®



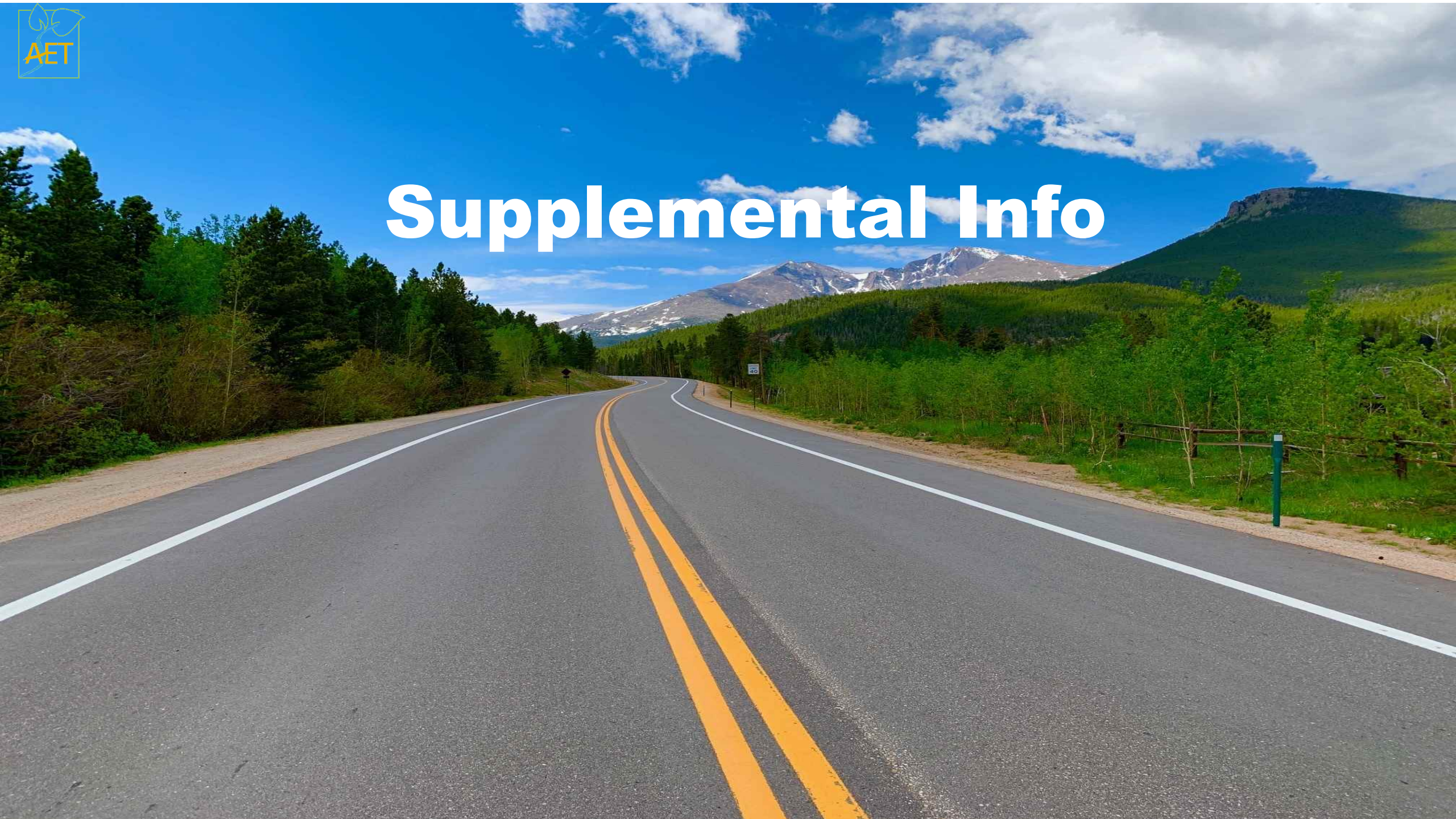
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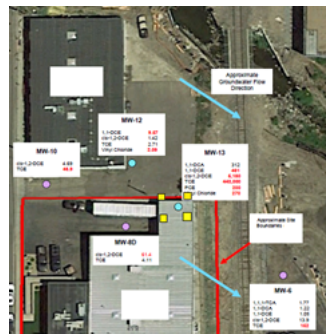


Supplemental Info

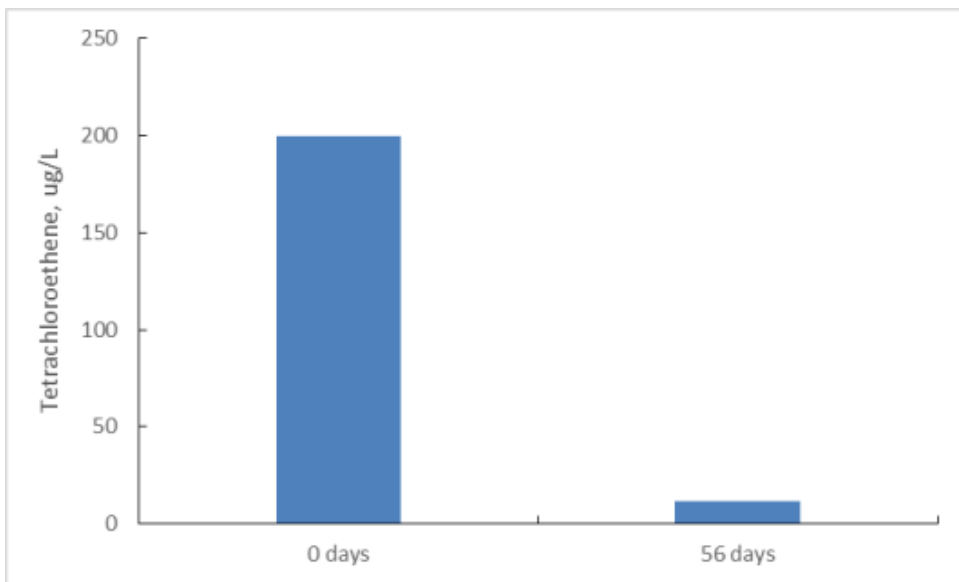


E-Redox[®] Enhanced Contaminant Desorption

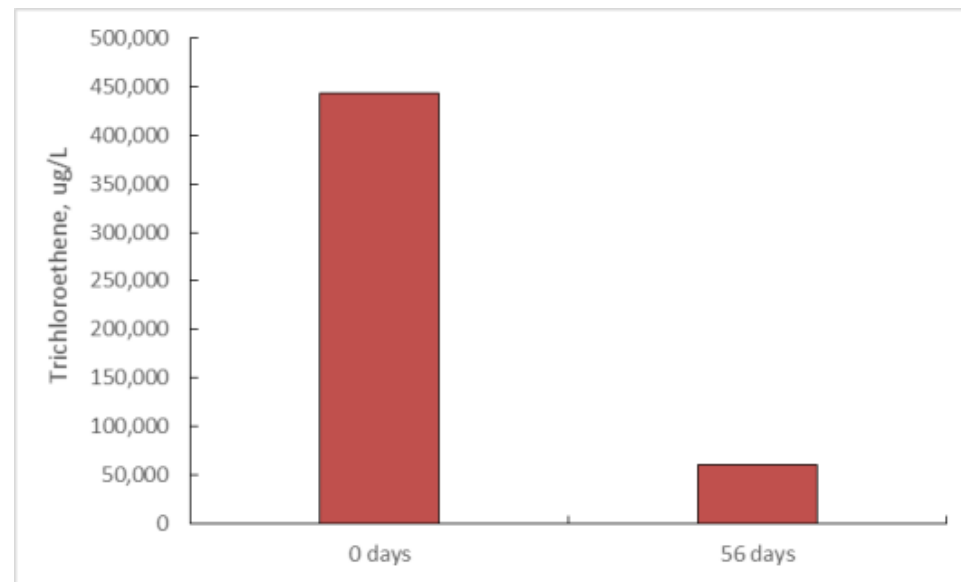
- Hydrophobic compounds are surrounded by water molecules forming a “cage” around compound
 - The water at the surface of mineral particle is more ordered than around the hydrophobic compound
 - This difference in order between sides of the compound causes the compound to adsorb onto mineral surface
- When applying electric field, the conditions at the surface changes which causes the compound to desorb
- Another mechanism for desorption may be increased order of water on the side of the compound that was originally less ordered, causing it to desorb from the compound surface
- Soil organic matter (SOM) has regions that are polar and non-polar
 - The non-polar regions will adsorb the compound more strongly than observed on mineral surface (which is why greater SOM will adsorb greater amounts of hydrophobic compounds)
 - When applying the electric field, non-polar regions tend to polarize which weakens the bond between the hydrophobic compound



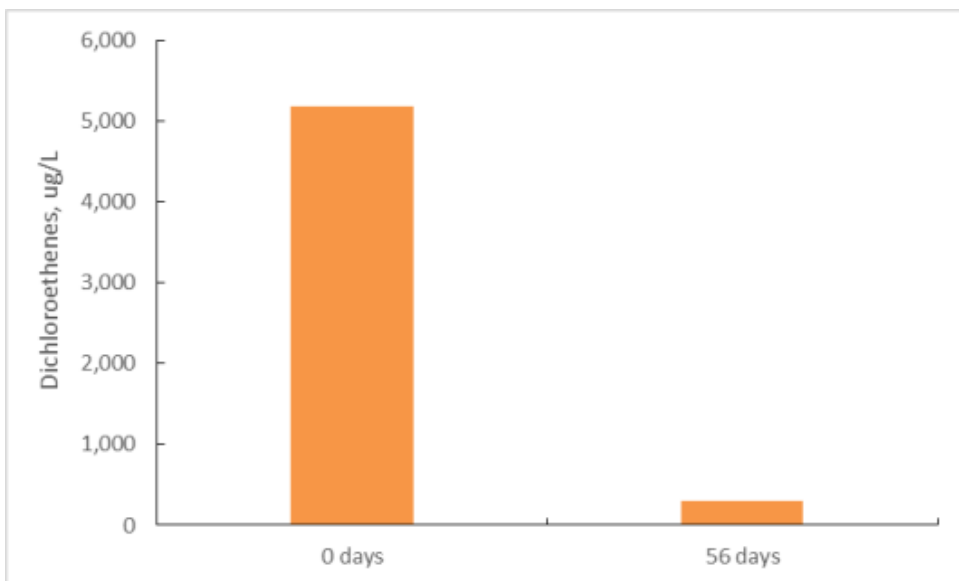
More CVOC Sites



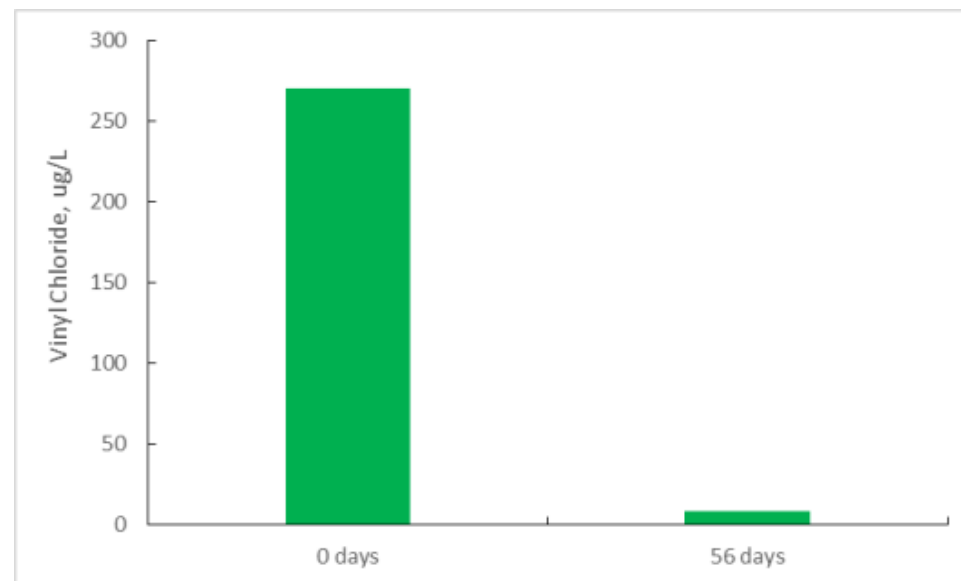
PCE (94% reduction)



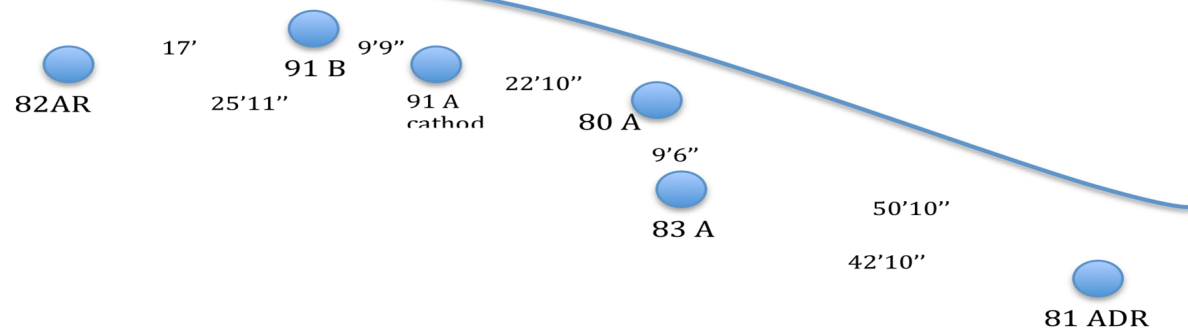
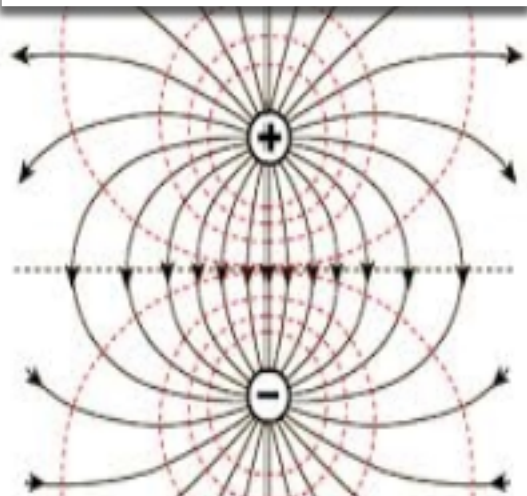
TCE (86% reduction)



DCEs (94% reduction)



VC (97% reduction)



ORP decreased >115 mV after 30 min and continued to decrease in the area with continued E-Redox-I operating

During the testing period of 4 hr, E-Redox-I system has a measurable ROI of >26 feet from either electrode outward

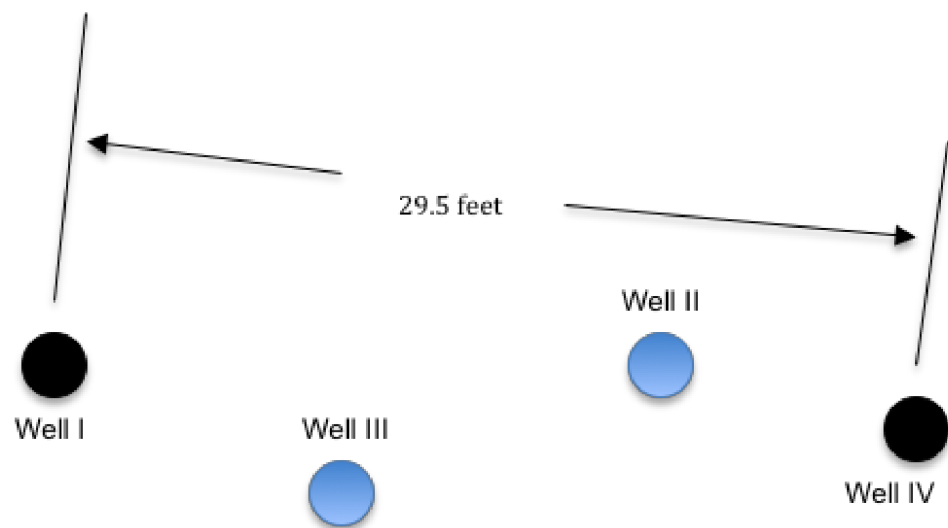
*Fallgren, P.H., Eisenbeis, J.J., Jin, S. 2018. *J. Environ. Sci. Health Part A* 53:517-523.



The background image is a wide-angle landscape photograph. It shows a series of rolling hills and mountains under a bright blue sky filled with scattered white clouds. The hills are covered in dry, yellowish-brown grass and some sparse green shrubs. In the foreground, there is a field of tall, dry grass. The overall scene depicts a natural, somewhat desolate environment.

Former Explosives Testing Site, San Bernardino, CA

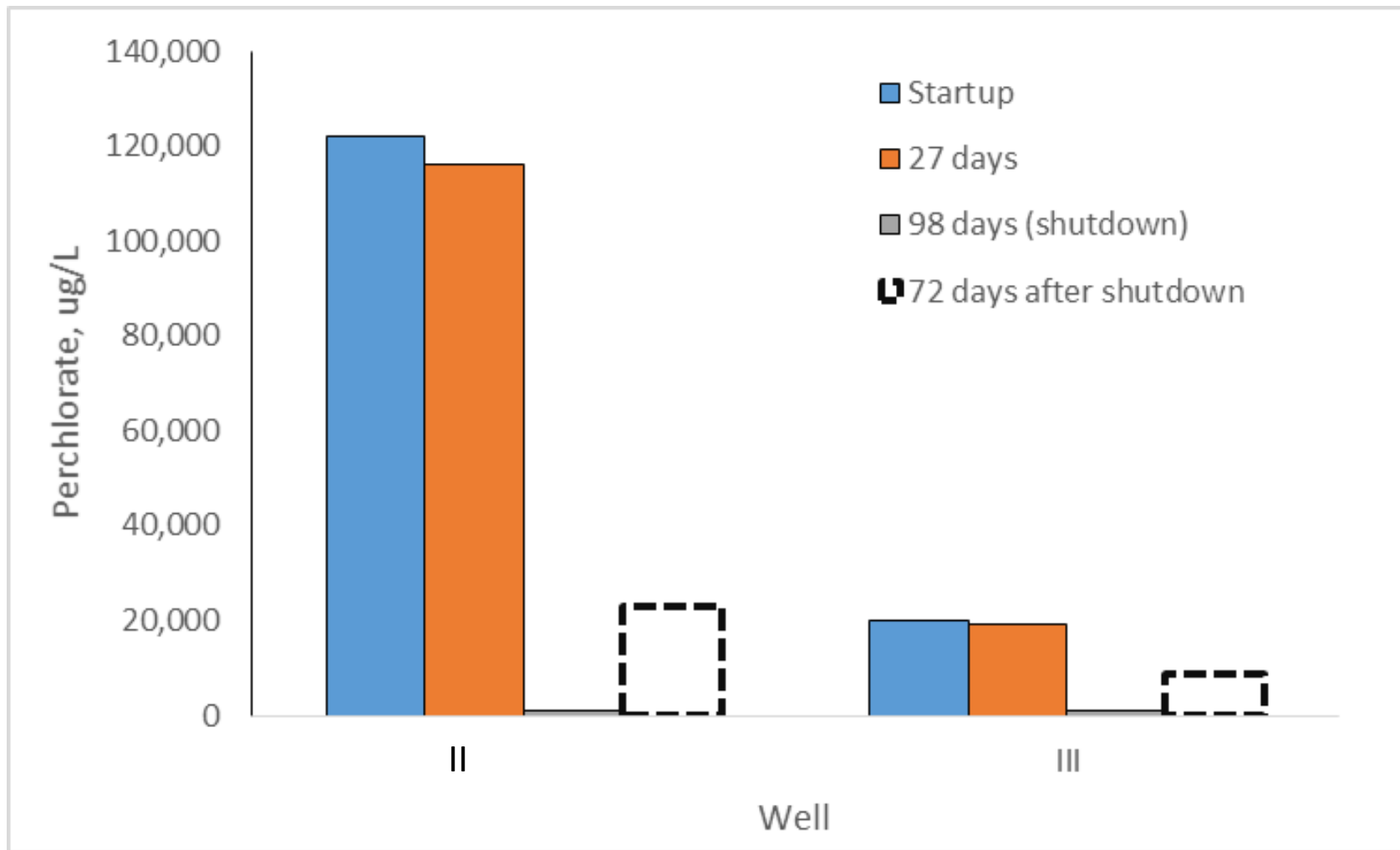
- Former explosives testing site
- Groundwater contaminants: primarily perchlorate
- Past remediation efforts not effective due to low-permeability of aquifer material (clay and shale)
- No municipal power access; solar cells were used for establishing low-intensity electric field



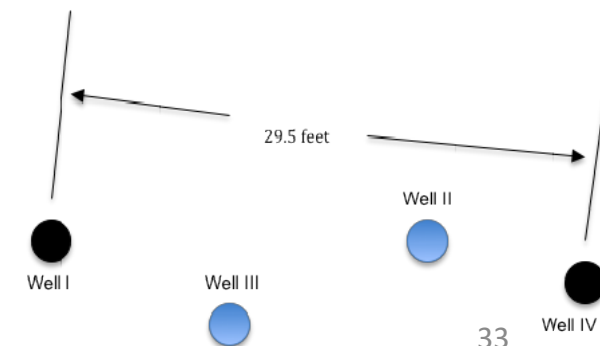
E-Redox® field test site layout



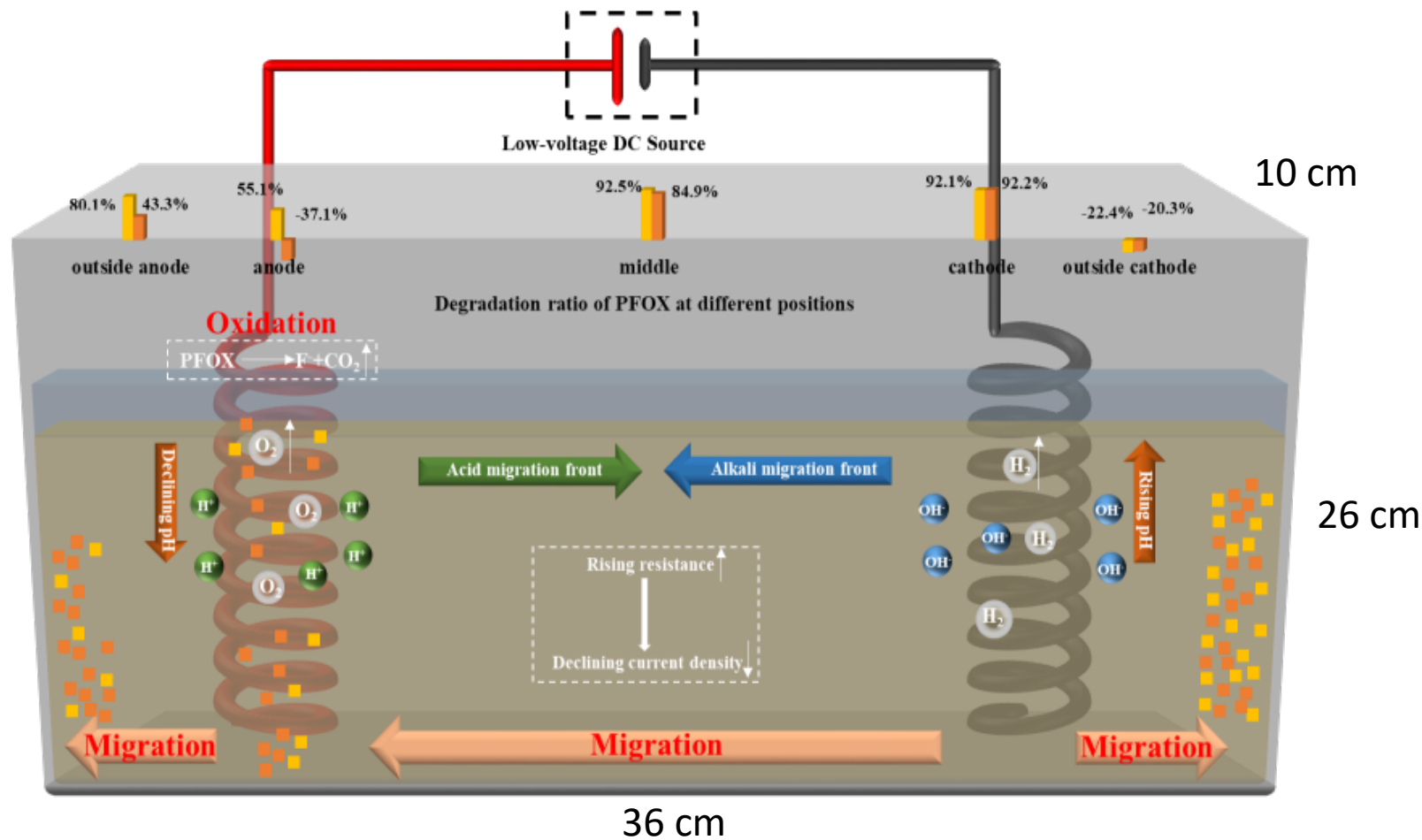




Perchlorate concentrations after 98 days of field test



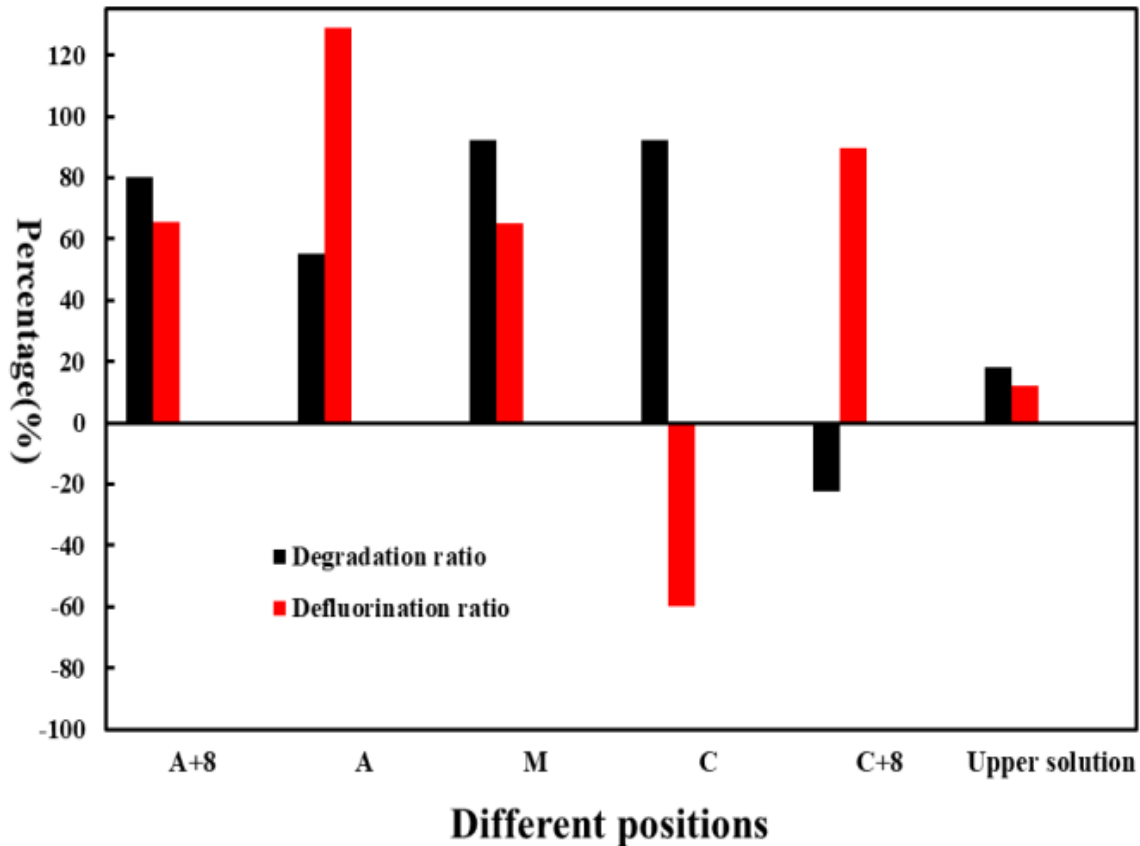
E-Redox I for PFAS Treatment in Water



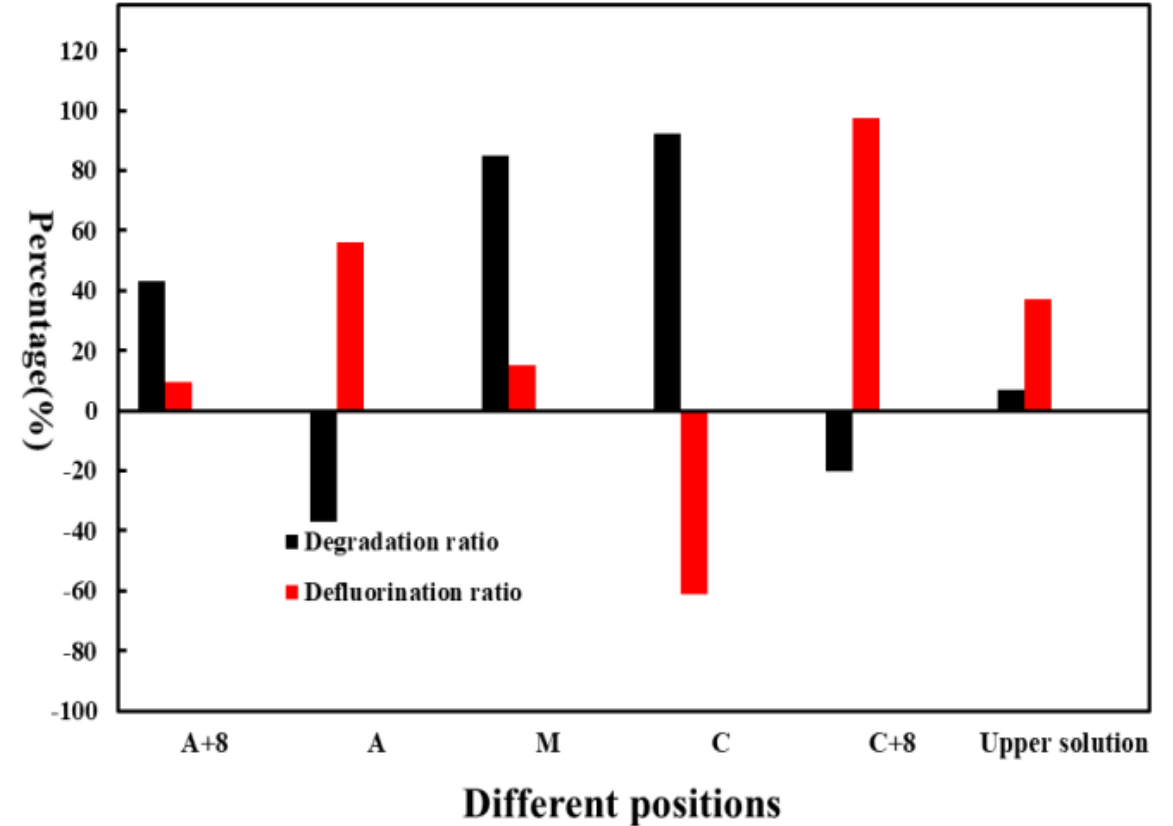
E-Redox-initiated destruction and migration of Perfluorooctanoic acid POFA (■) and perfluorooctane sulfonate PFOS (■) compounds in lab reactors

(Hou et al., 2022, *Chemosphere* 287) (perfluorinated butyric acid [PFBA], perfluoropentanoic acid [PFPeA], perfluorohexanoic acid [PFGxA], perfluoroheptanoic acid [PFHpA], perfluorooctanoic acid [PFOA, 98%]), perfluorohexane sulfonate [PFHxS] and internal standards (perfluorooctanoic acid internal standard [13C-PFOA, 98%] and perfluorooctane sulfonate internal standard [13C-PFOS, 98%])

PFOA



PFOS



A = Anode
C = Cathode
M = Middle
+8 = distance (i.e., 8 cm)

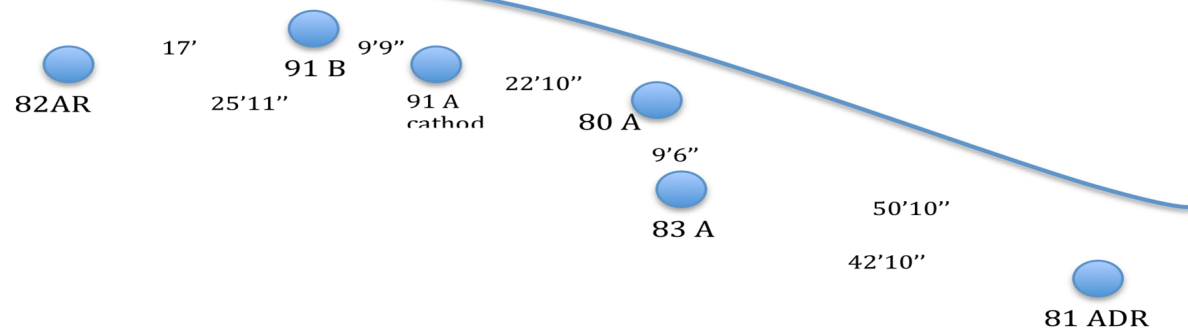
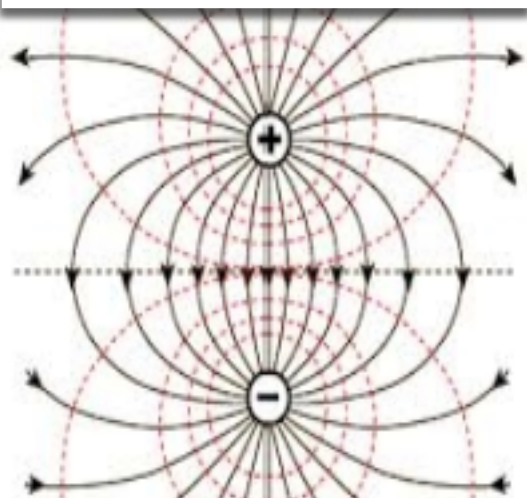
Degradation ratio: positive bar indicates PFAS degradation or migration away; negative bar indicates PFAS migration in. **51.7%** of PFOA and **33%** of PFOS degraded within 10d

Defluorination ratio: positive bar indicates defluorination or fluoride migration in; negative bar indicates fluoride decrease (migration away). **44.7%** and **23%** defluorination mass balance for PFOA and PFOS, respectively

(Hou et al., 2022, *Chemosphere* 287)







ORP decreased >115 mV after 30 min and continued to decrease in the area with continued E-Redox-I operating

During the testing period of 4 hr, E-Redox-I system has a measured ROI of >26 feet from either electrode outward

*Fallgren, P.H., Eisenbeis, J.J., Jin, S. 2018. *J. Environ. Sci. Health Part A* 53:517-523.

