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Electrokinetic Enhanced Amendment Delivery – Current Successes and Future Research Directions

Silvia Mancini (Ph.D., P.Geo.), Mark Watling, Michelle Cho, James Wang, Evan Cox, David Reynolds

NAVFAC

U.S. ARMY ENGINEER RESEARCH AND DEVELOPMENT CENTER ERDC

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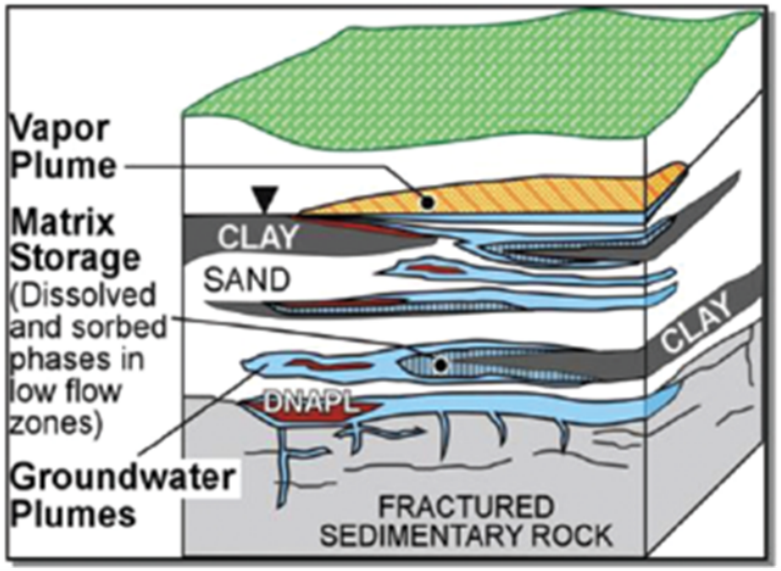
Challenge of Low Permeability Materials

- Contaminants diffused into low permeability (low-K) materials serve as secondary sources lasting for decades
- In situ technologies (e.g. EISB, ISCO & ISCR) are effective, but amendment distribution is challenging in low-K and heterogeneous materials
- Better amendment delivery techniques are required for low-K sites



From ESTCP, ER-200530

Delivery & **Contact**

Presentation Outline

- Principles of Electrokinetics (EK)
- EK Applications
- Case Study Highlights
- State of the Technology
- Future Research Directions

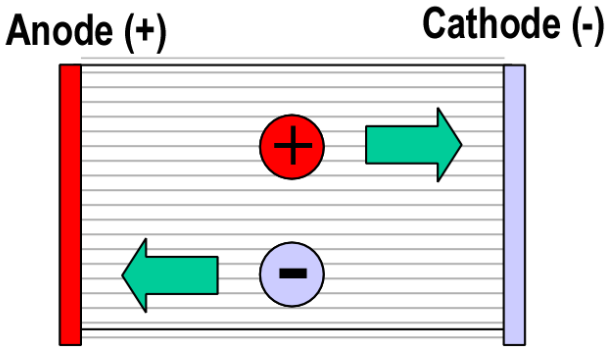
EK Principles and Processes

Electromigration (EM) - the movement of ions under electric field.

Electroosmosis (EO) - the bulk movement of water under electric field.

Electro-migration

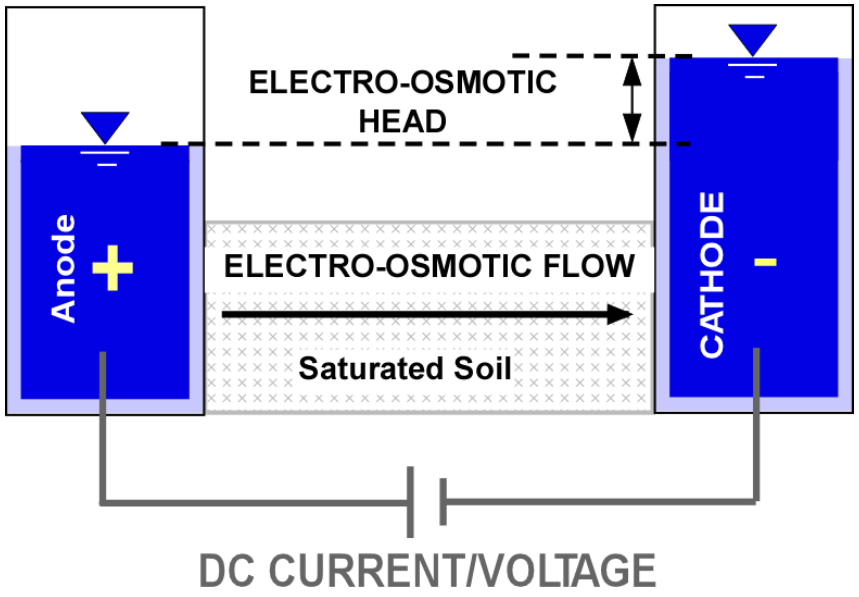
Ions transport in soil pore fluid to electrode opposite in polarity



Anions: negatively charged ions
Cations: positively charged ions

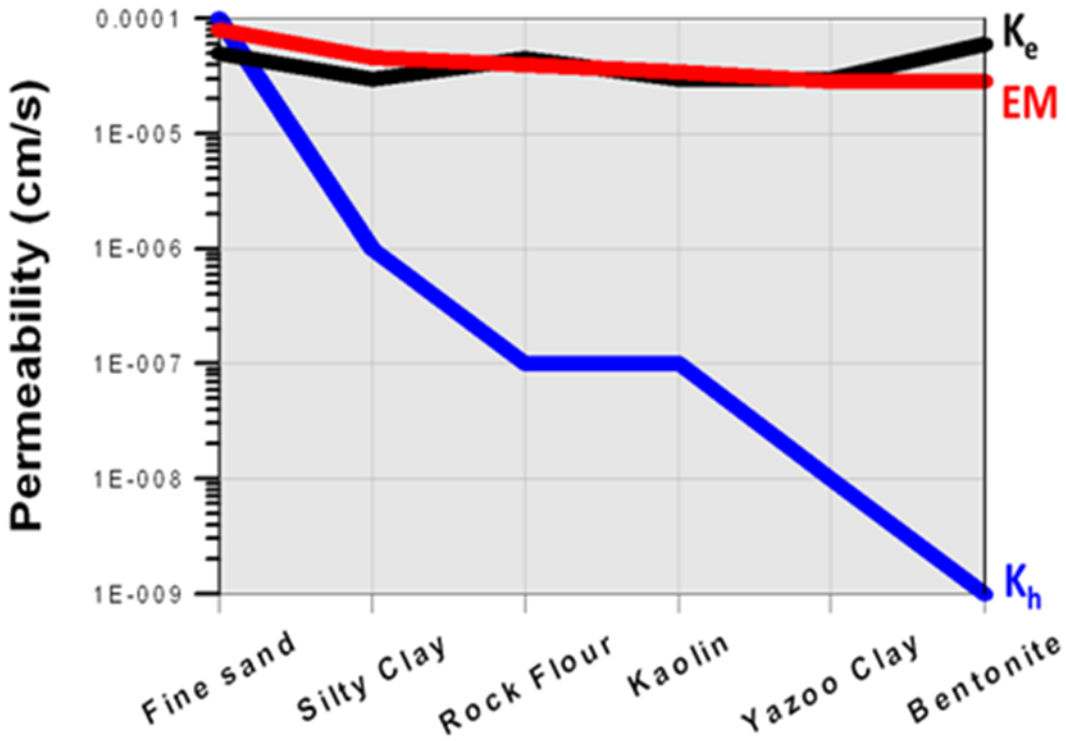
Anode: Positively charged electrode
Cathode: Negatively charged electrode

Electro-osmosis

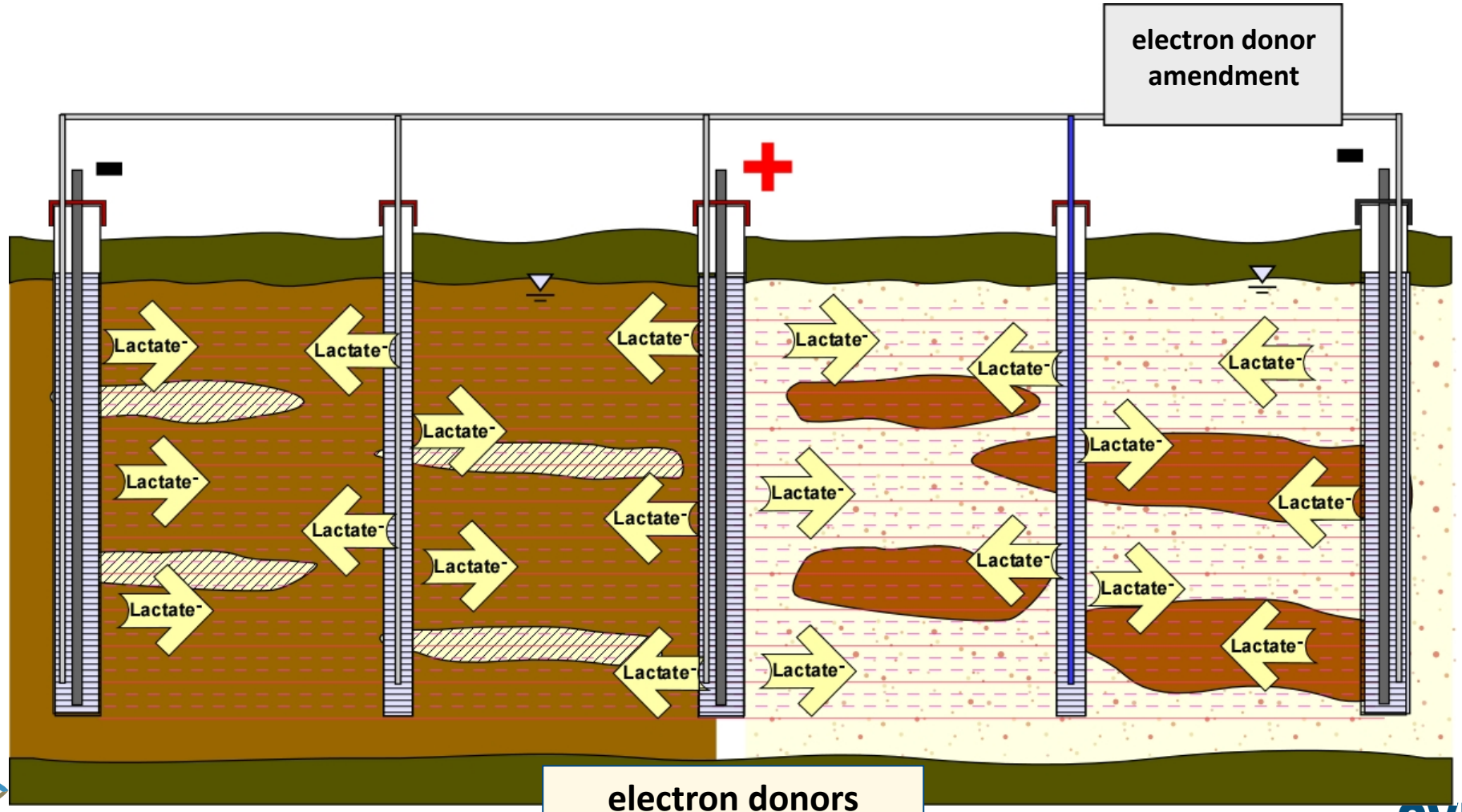


Why EK Works in Low-K Formations

- EK transport relies on electrical properties of soil (not hydraulic)
- Soil electrical properties ≈ between sand and clay
- As K_h decreases, EK becomes a much more efficient delivery method



EK Application in the Field



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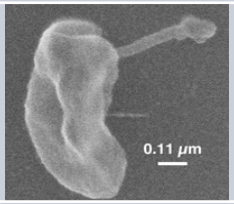
EK Remediation Applications

EK-BIO™

Bioremediation

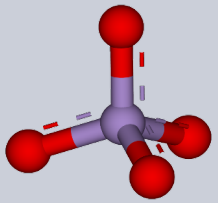
Electron donors, acceptors and/or microbes



EK-ISCO™

Chemical Oxidation

Permanganate (MnO_4^-)



EK-ISCR™

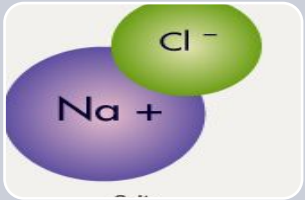
Chemical Reduction

Nano Zero Valent Iron (ZVI)

EK-SALT™

Electrical Migration

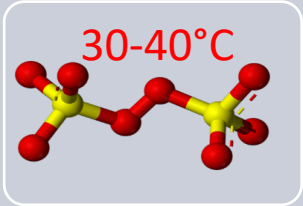
pH Buffers



EK-TAP™

Chemical Oxidation & Thermal Activation

Persulfate ($S_2O_8^{2-}$)



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Case Study Highlights

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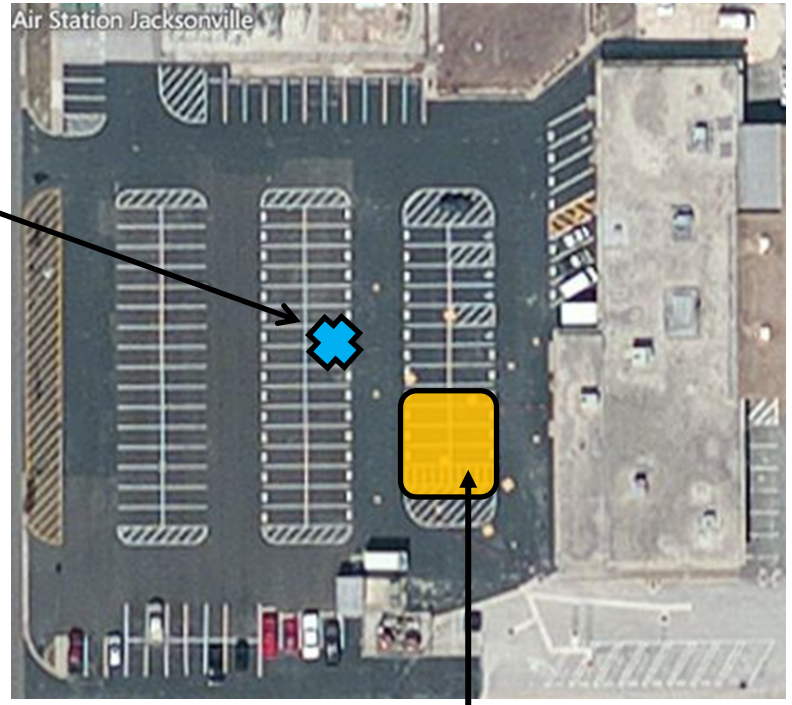
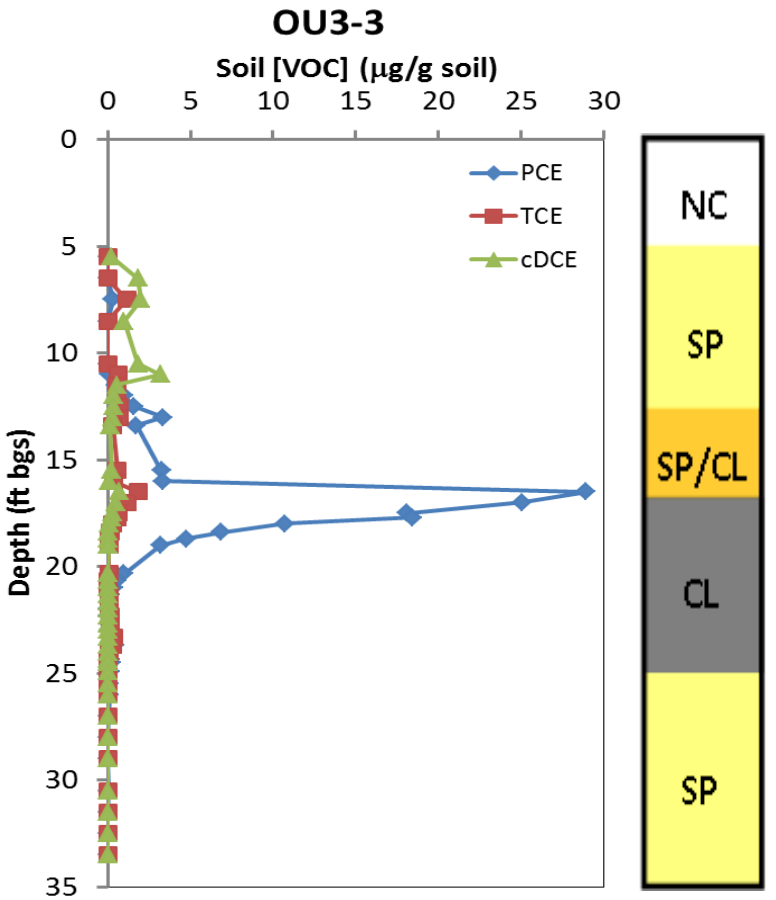
PCE Source Treatment by EK-BIO™
Naval Air Station Jacksonville, Florida (ER201325)

- Former dry cleaner
- Source for a large dissolved plume in shallow sandy aquifer
- Source area now under an active parking lot
- Many existing subsurface utilities



Demonstration Area



NC – not characterized; SP – sand; CL – clay

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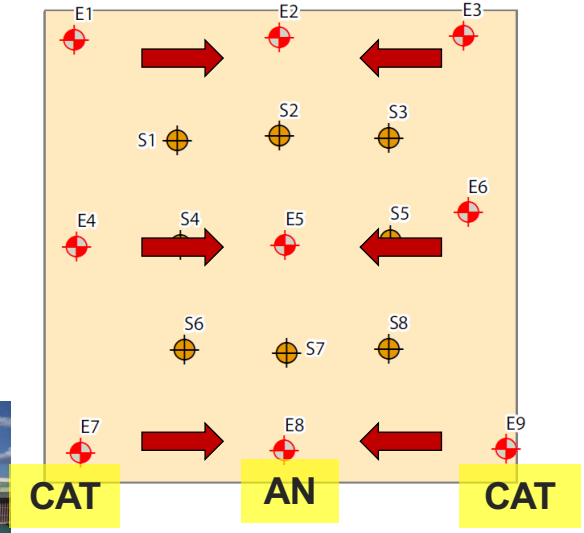
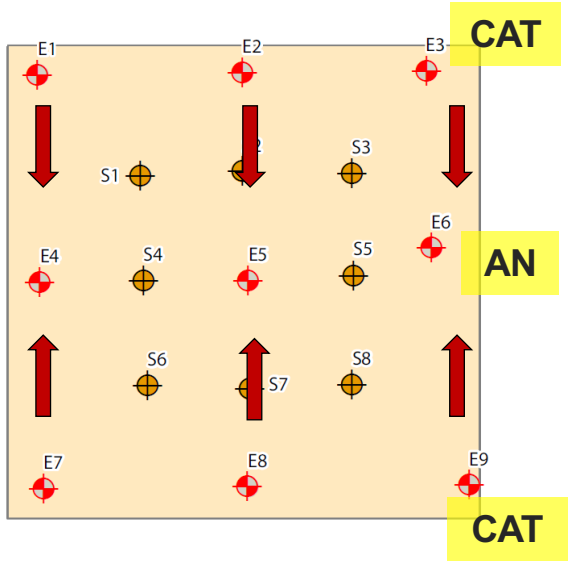
EK-BIO™ Installation & Operation

- 35 ft x 35 ft TTA
- 9 Electrode Wells (~ 17.5 ft spacing), 8 Supply Wells (no electrode)
- Two stages of 5 months active operation
- Total power ~ **1,500 kW-hr**
- Lactate & Buffer Amendment Supply
- Bioaugmentation with KB-1

Stage 1 Operation



Stage 2 Operation



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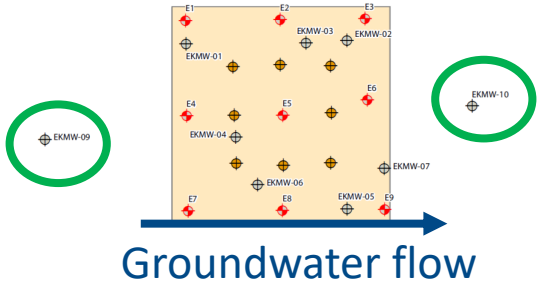
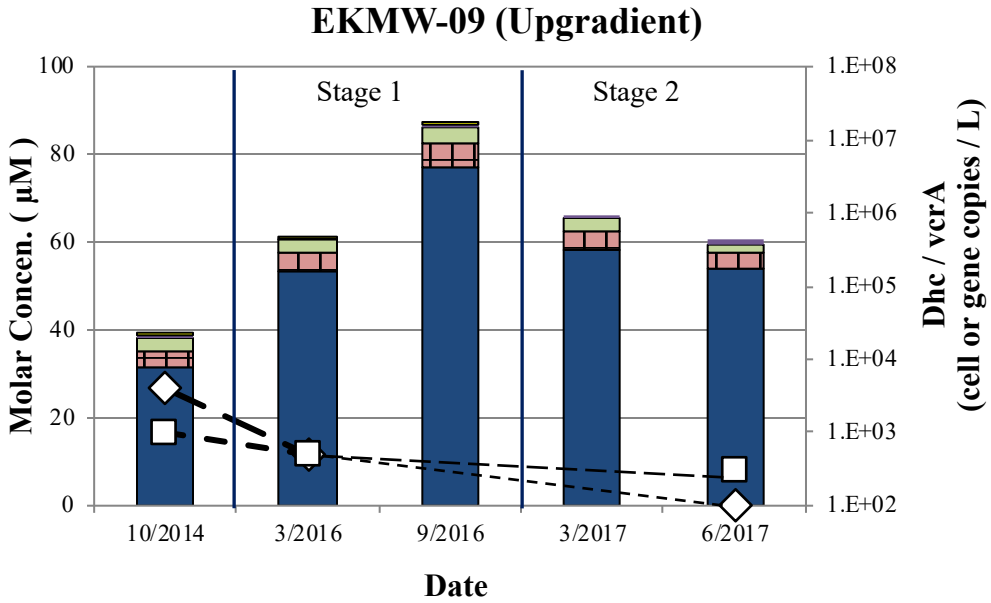
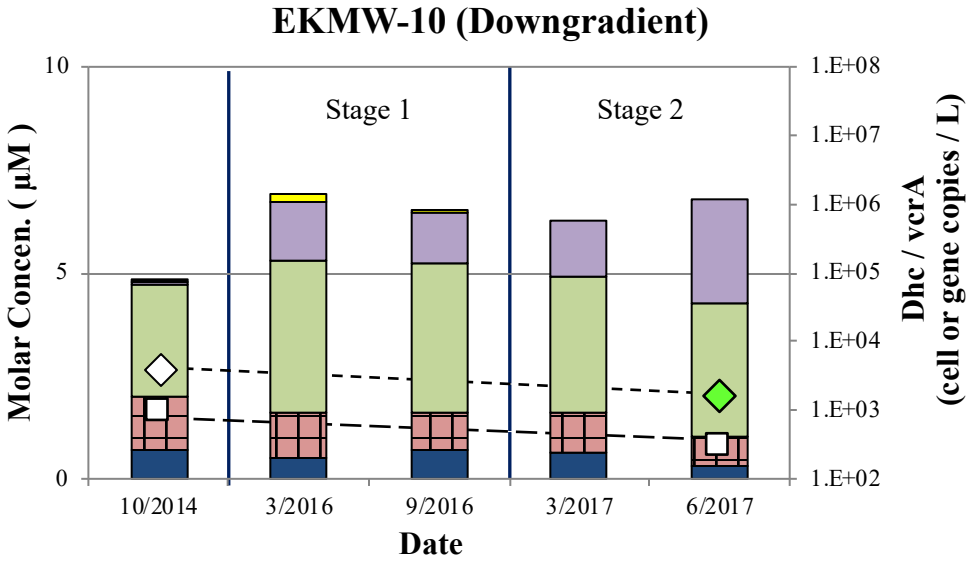
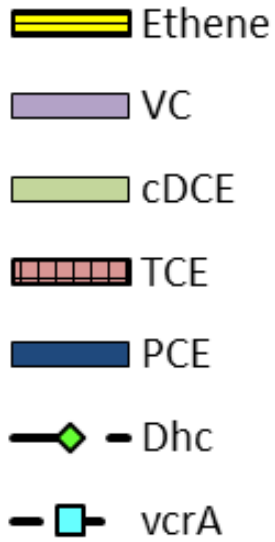
Background Wells – VOCs and Biomarkers

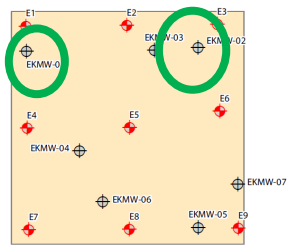


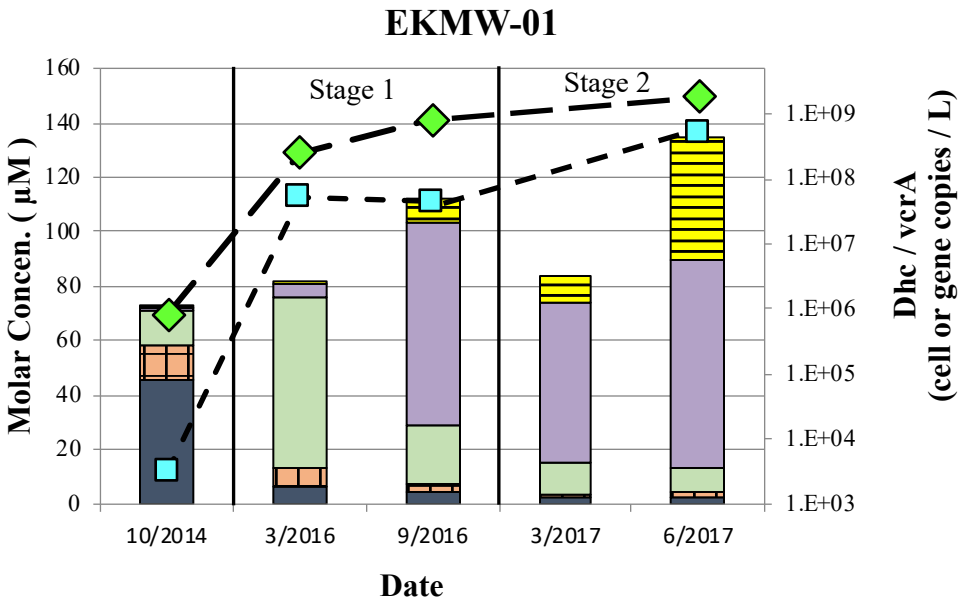


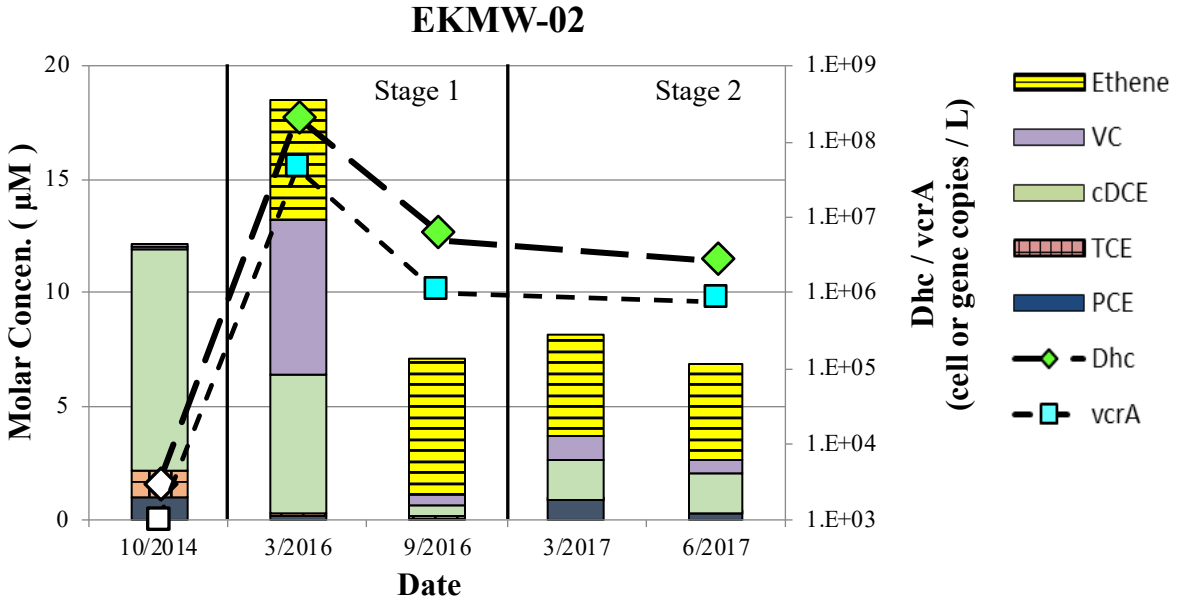


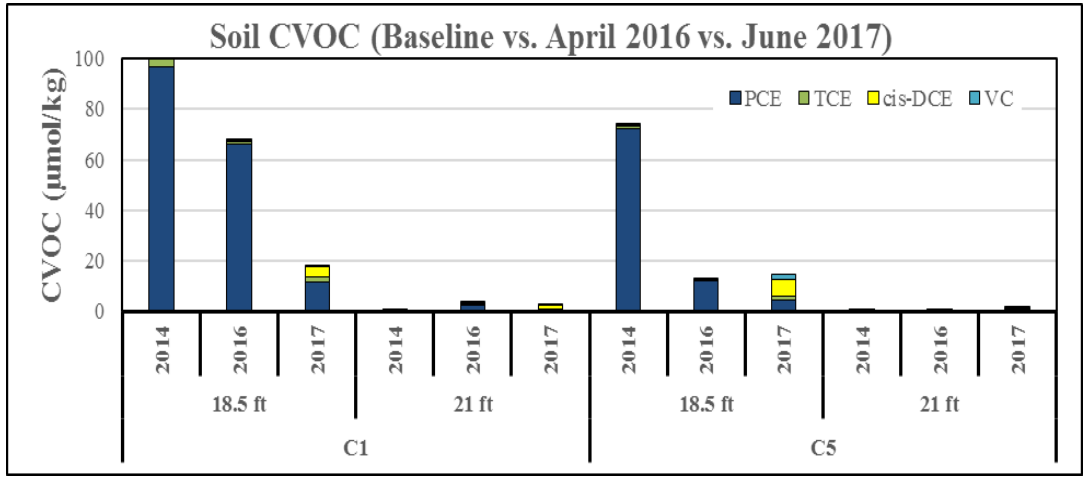


Groundwater and Soil Within Test Area – VOCs and Biomarkers









Soil PCE concentrations reduced by 78% to 99% within Treatment Area

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EK-Bio State of the Technology

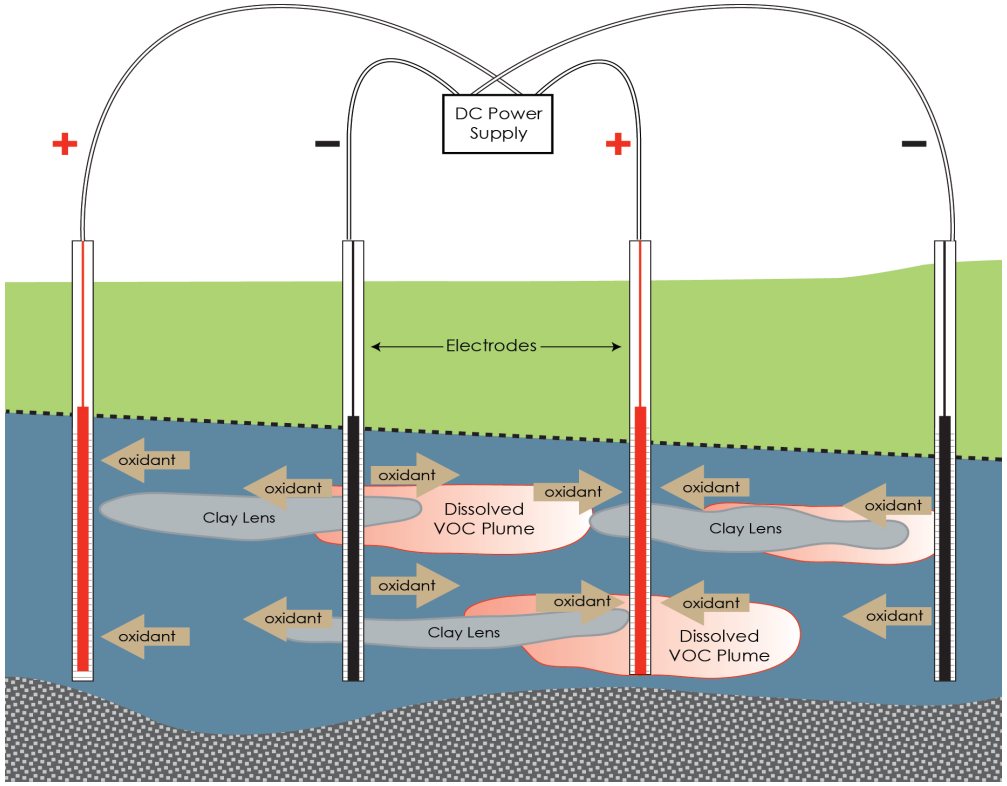
State of the technology development:

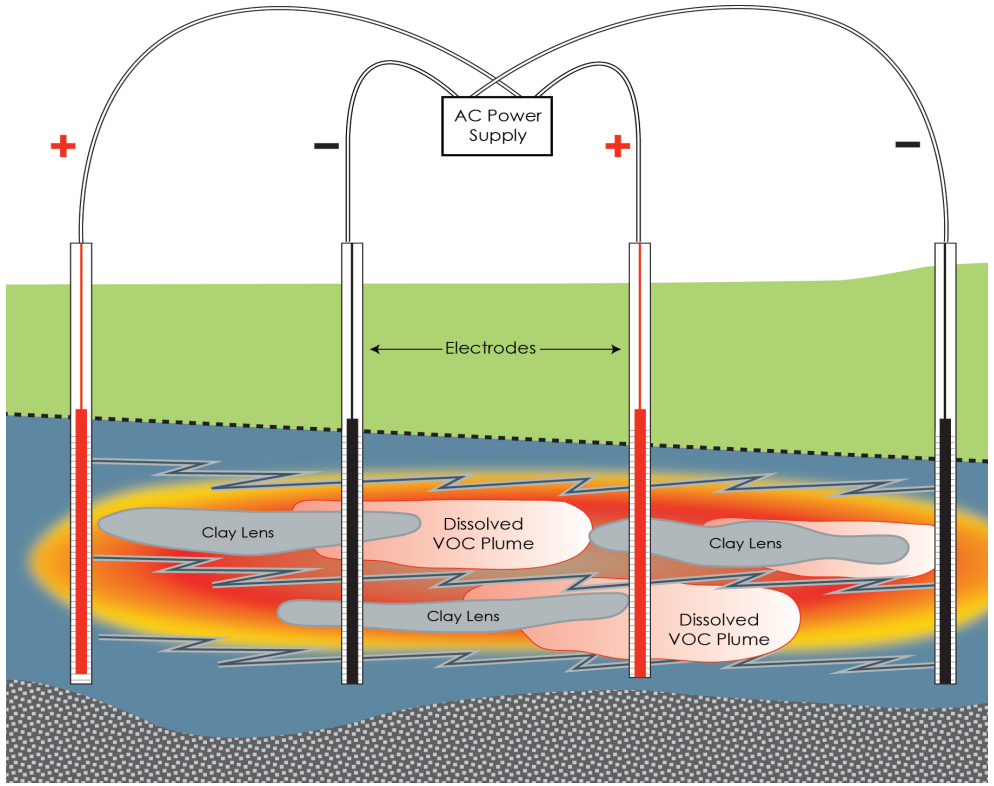
- ✓Successful laboratory and pilot scale tests
- ✓Full-scale application (Denmark)
- ✓Developed an understanding of configuration and operations optimization

Remaining questions/design considerations:

- Typical biotreatment considerations (e.g. biofouling)
- Can we achieve remediation to MCLs?

EK-TAP – How does it work?





1. Application of direct current (*DC*) to distribute persulfate <u>*uniformly*</u> through clays and silts

2. Application of alternating current (*AC*) to heat soils and activate distributed persulfate

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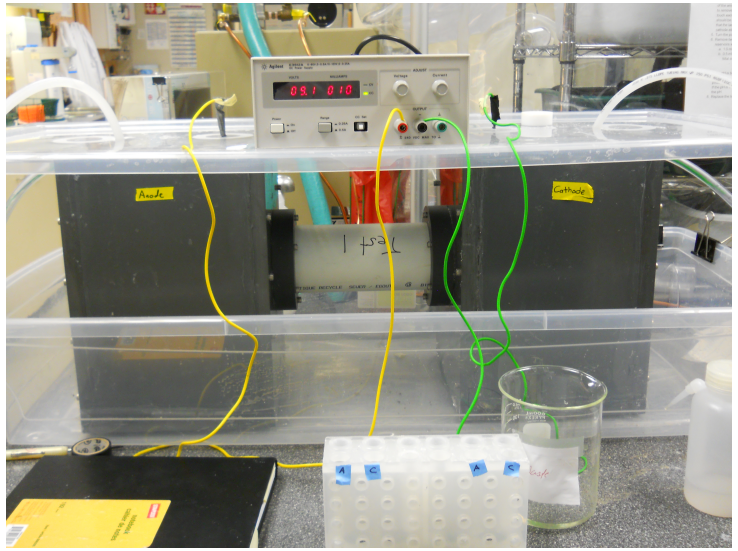
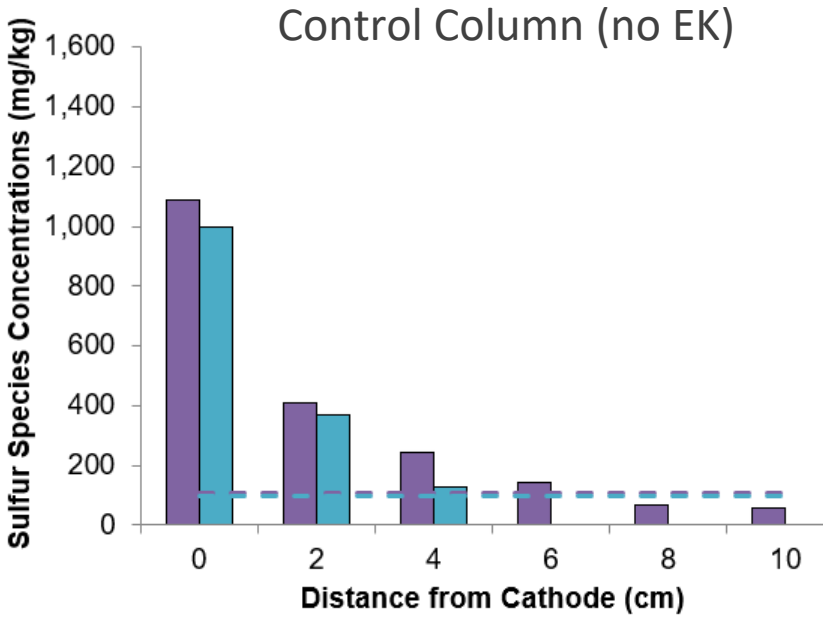
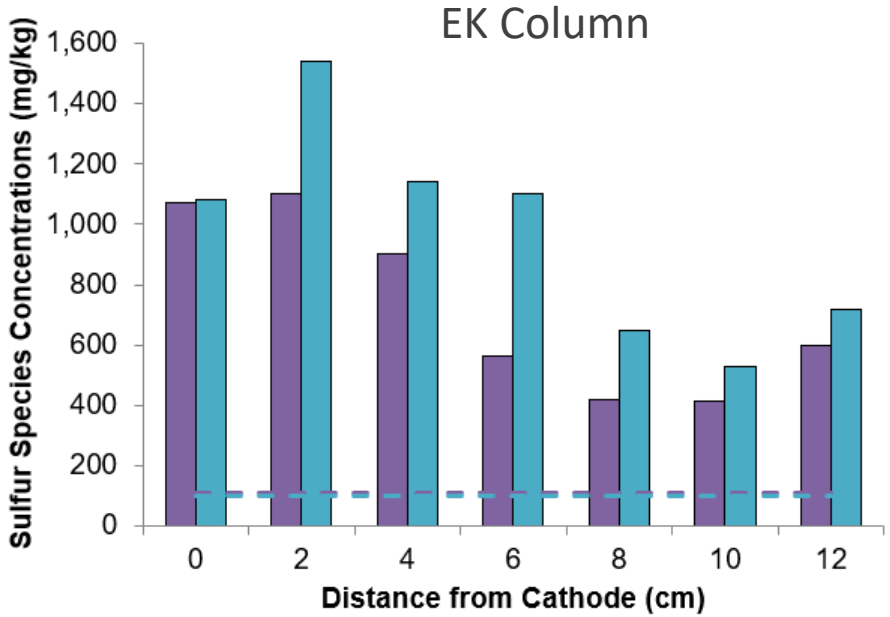
EK-TAP Bench-scale Testing

- Bench-scale tests of EK-TAP successful in demonstrating:
  - EK-enhanced migration of persulfate across entire soil column from cathode to anode





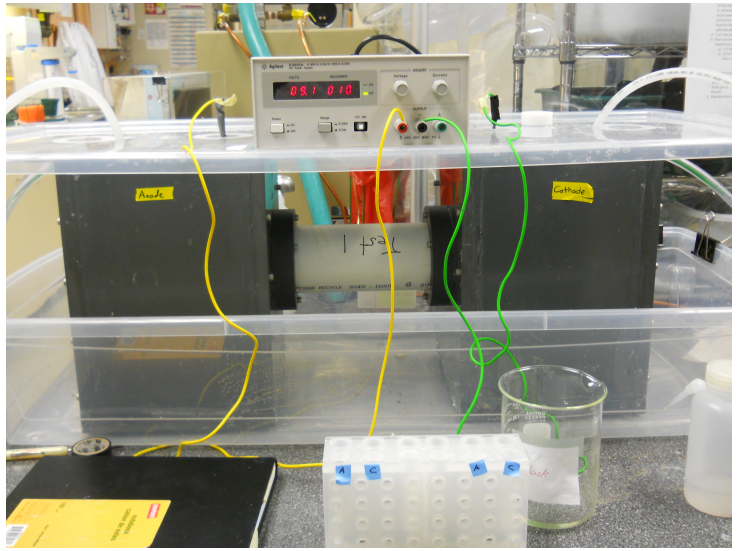


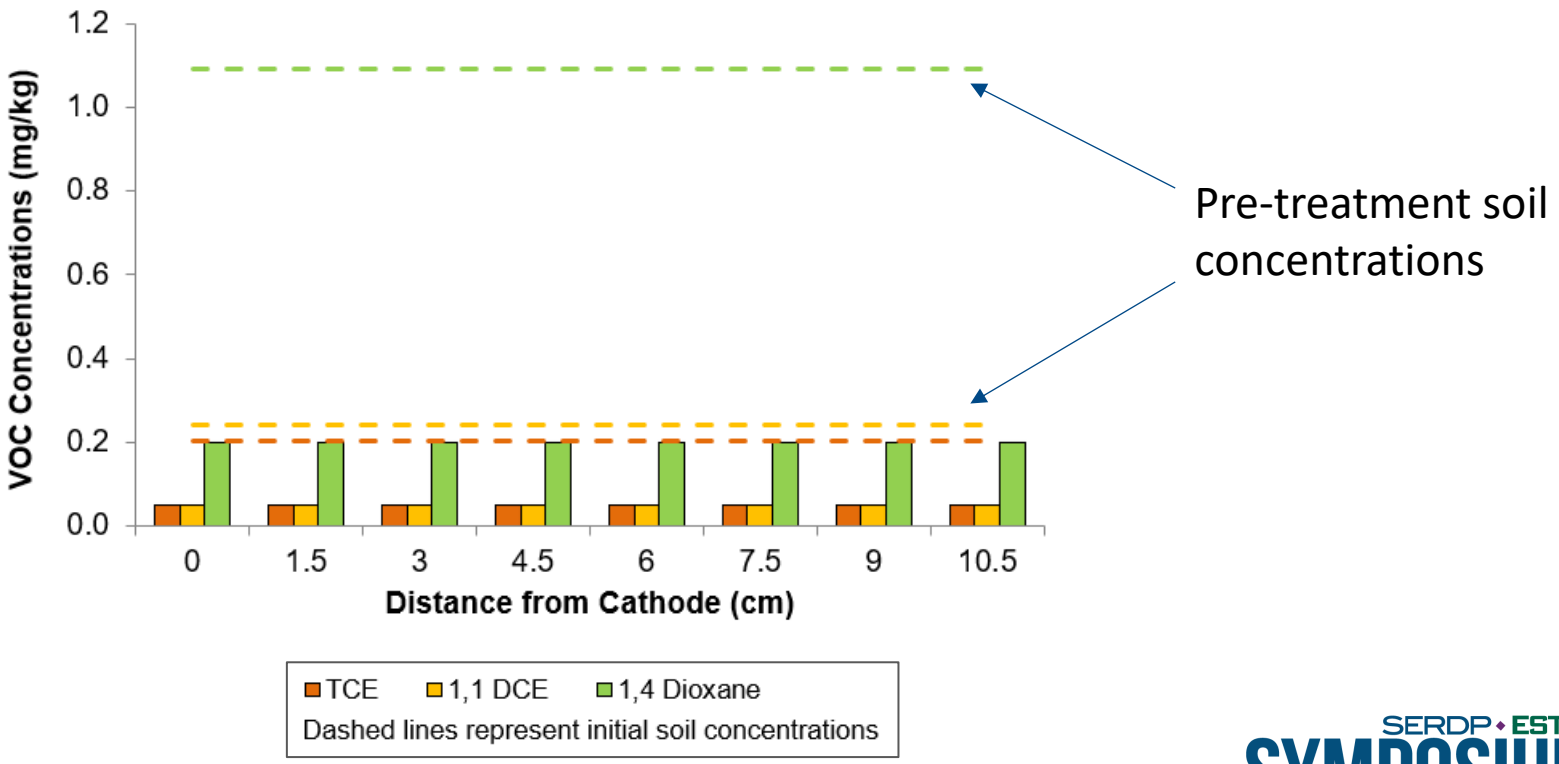
Sulfate Total Sulfur

Dashed lines represent initial soil concentrations

EK-TAP Bench-scale Testing

- Bench-scale tests of EK-TAP successful in demonstrating:
  - Treatment of VOCs and 1,4-dioxane to non-detect in soil column following thermal activation of persulfate





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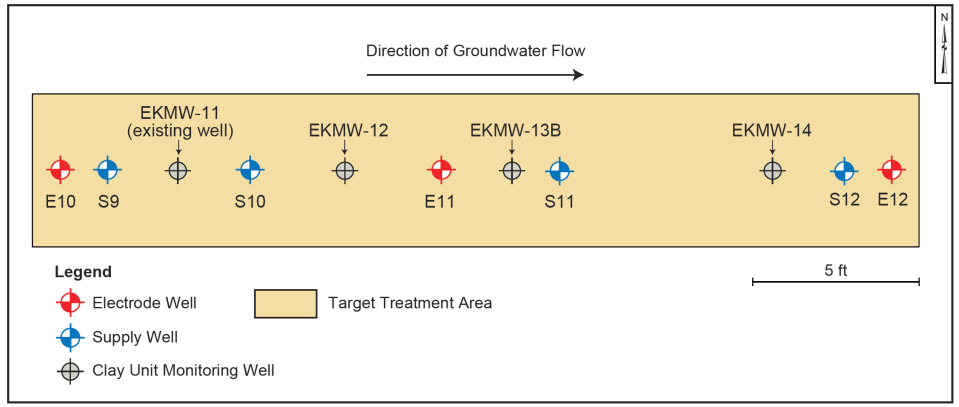
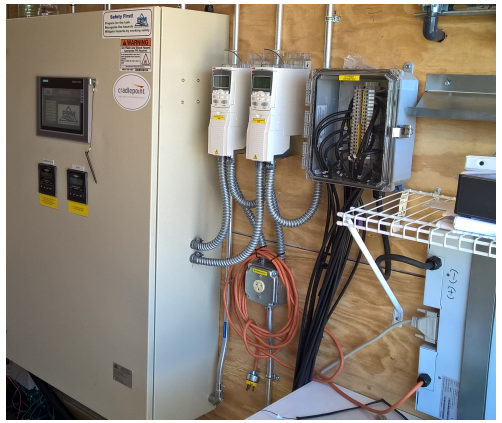
EK-TAP State of the Technology (Field Dem/Val NAS Jacksonville, FL; ESTCP ER-201626)

- ✓Laboratory and field pilots (6) completed to date
- ✓Design considerations:
  - Site conditions (treatment depth, geochemistry)
  - Well spacing
  - Electrode well configuration (cathodes vs anodes)
  - Premature activation of persulfate (ex-situ or in-situ)





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Future Research Directions

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ecohydrology research group

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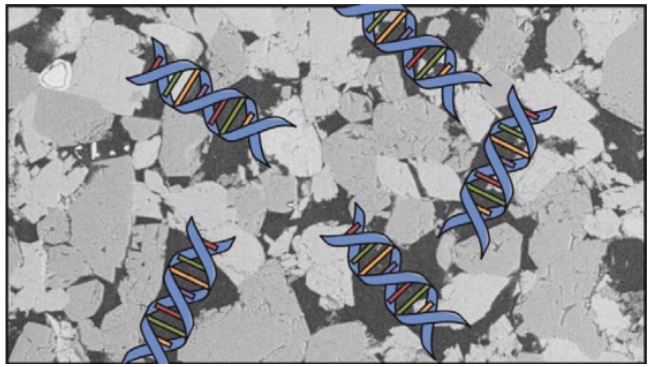
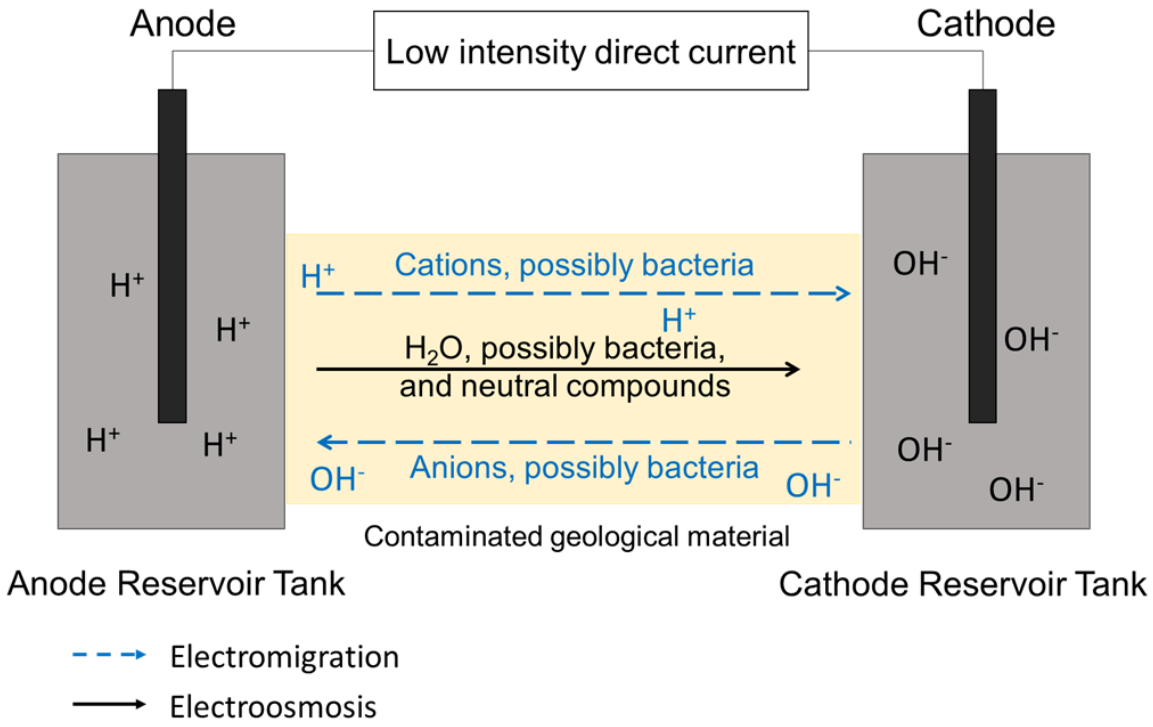
EK in Rock Matrices (M.A.Sc. Thesis – Elaine Secord)

- In fractured sedimentary rock contaminant mass resides in porous, low-K matrix
- Microbial biomass attached to fractures in matrix pores and can be important for biodegradation (Schaefer, 2010; Lima, 2012)
- Paired EK-Bioaugmentation to overcome slow diffusion rates and limited delivery and contact of amendments and bacteria



From Lima, 2012



(modified from Ng et al., 2014)

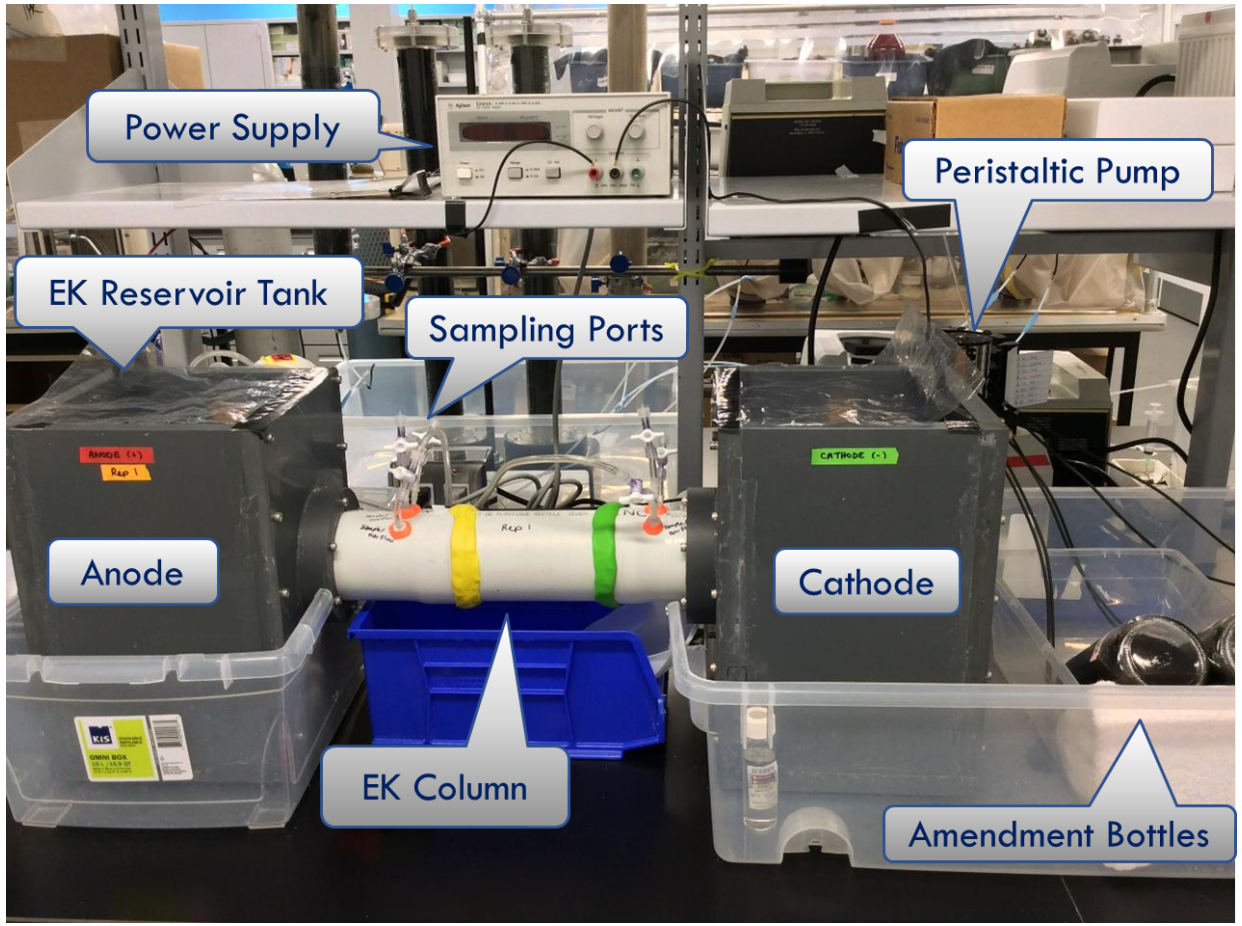
Microbial Viability and Dechlorination Experimental Set-Up

Research goals:

- Determine bacteria viability (KB-1) in the primary porosity of sandstone bedrock
- If bacteria are assessed to be viable, determine if they are capable of dechlorination

Research method:

- EK transport of bacteria into primary porosity via EO and EM
- 5-9 week incubation columns



Microbial Viability and Dechlorination Baseline

EM (+)						EM (-)
	n.a.	n.a.	*vcrA* - <4.2×10^7 U *bvcA* - <4.2×10^7 U **TCE - 0.33, cDCE - 0.99** VC - <0.09 U DHGs - <0.01 U	n.a.	n.a.	
Inner clay: TCE - 4.8 cDCE - 14 VC - 0.1 DHGs - n.a.	n.a.	***vcrA* - 1.2×10^8** *bvcA* - <4.2×10^7 U **TCE - 0.18** **cDCE - 0.42** VC - <0.08 U DHGs - <0.01 U	*vcrA* - <3×10^7 U *bvcA* - <3×10^7 U **TCE - 0.25** **cDCE - 0.55** VC - <0.08 U DHGs - <0.01 U	***vcrA* - 1.2×10^7 J** *bvcA* - <4.2×10^7 U **TCE - 0.48** **cDCE - 0.92** VC - <0.08 U DHGs - <0.01 U	n.a.	Inner clay: TCE - 4.1 cDCE - 17 VC - 0.1 DHGs - n.a.
	n.a.	n.a.	*vcrA* - <4.2×10^7 U *bvcA* - <4.2×10^7 U **TCE - 0.40, cDCE - 0.70** VC - <0.08 U DHGs - <0.01 U	n.a.	n.a.	

Vinyl chloride reductases – in gene copies/L

Volatile organic compounds and dissolved hydrocarbon gases – in mg/L

Microbial Viability and Dechlorination Results (9 week cores)

EM (+)

Inner clay:
TCE - <0.03 U
cDCE - <0.13 U
VC - <0.05 U
DHGs - n.a.

EO

n.a.	n.a.	***vcrA* - 6×10^9** ***bvcA* - 6×10^7** TCE - <0.04 UJ cDCE - <0.04 UJ VC - <0.20 UJ DHGs - <0.01 U	n.a.	n.a.
n.a.	***vcrA* - 4.8×10^9** ***bvcA* - 6×10^7** TCE - <0.04 U cDCE - <0.04 U VC - <0.20 U DHGs - <0.01 U	***vcrA* - 6×10^9** ***bvcA* - 1.8×10^8** TCE - <0.04 U cDCE - <0.04 U VC - <0.20 U DHGs - <0.01 U	***vcrA* - 3.6×10^9** ***bvcA* - 6×10^7** TCE - <0.04 U cDCE - <0.04 U VC - <0.20 U DHGs - <0.01 U	n.a.
n.a.	n. a.	***vcrA* - 6×10^9** ***bvcA* - 1.8×10^8** TCE - <0.04 U cDCE - <0.04 U VC - <0.20 U DHGs - <0.01 U	n.a.	n.a.

EM (-)

Inner clay:
TCE - <0.03 U
cDCE - <0.13 U
VC - <0.05 U
DHGs - n.a.

Vinyl chloride reductases – in gene copies/L

Volatile organic compounds and dissolved hydrocarbon gases – in mg/L

Microbial Viability and Dechlorination Conclusions

- Determine bacteria viability in the primary porosity of sandstone bedrock
  - ✓KB-1 bacteria were confirmed to be transported into the primary porosity of sandstone
  - ✓KB-1 bacteria were confirmed viable

- If bacteria are assessed to be viable, determine if they are capable of dechlorination
  - ✓Complete dechlorination was observed in the 9-week incubated cores
  - ✓Near-complete dechlorination was observed in the 5-week incubated core

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State of the Technology

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Overall State of the Technology

Tried and Validated

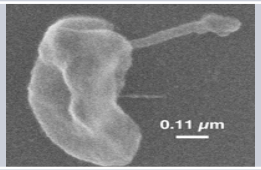
In Testing & Development

Research

EK-BIO™

Bioremediation

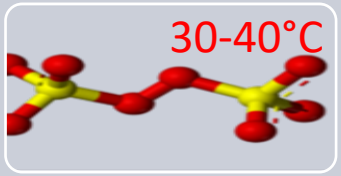
Electron donors, acceptors and/or microbes



EK-TAP™

Chemical Oxidation & Thermal Activation

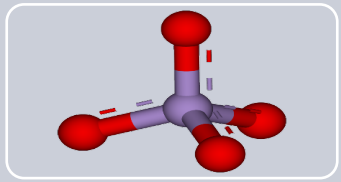
Persulfate ($S_2O_8^{2-}$)



EK-ISCO™

Chemical Oxidation

Permanganate (MnO_4^-)



EK-ISCR™

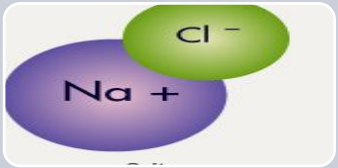
Chemical Reduction

Nano Zero Valent Iron (ZVI)

EK-SALT™

Electrical Migration

pH Buffers



EK Applicability to Sites & COC Treatment

Contaminant	EK-BIO™	EK-ISCO™	EK-TAP™	EK-ISCR™	EK (Other)
Chlorinated Ethenes (PCE, TCE)	Yes	Yes	Yes	Yes	
Chlorinated Ethanes & Methanes (TCA, CT)	Yes	Selected	Yes	Selected	
1,4-Dioxane	TBD		Yes		
Perchlorate	Yes				Yes (SALT)
RDX	Yes	Yes	Yes		Yes (Alkaline Hydrolysis)
Redox-Sensitive Metals	Some			Some	

- ✓ Demonstrated uniform delivery of reagents in low permeability materials
- ✓ Wide applicability to amendments and COCs
- ✓ Demonstrated at multiple sites across North America and Europe

Thank You!

For additional information, please visit

https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Persistent-Contamination/ER-201325

OR

Poster Session (ER-201626)

Speaker Contact Information

smancini@geosyntec.com

416-637-8745

Geosyntec Consultants

- Evan Cox
- James Wang
- David Reynolds
- Rachel Klinger
- Elaine Secord
- Suzanne O'Hara

USACE ERDC

- David Gent

NAVFAC SE

- Michael Singletary
- Adrienne Wilson

Geosyntec consultants

engineers | scientists | innovators

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