



E-Redox[®]

**A Novel Bioelectrochemical Tool for Effective Treatment of
Petroleum Contaminants with Zero Energy Input**

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Fort Collins, Colorado

26th National Tank Conference & Exposition

Louisville, Kentucky

September 2018

Acknowledgement

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Challenges in treating subsurface contaminants?

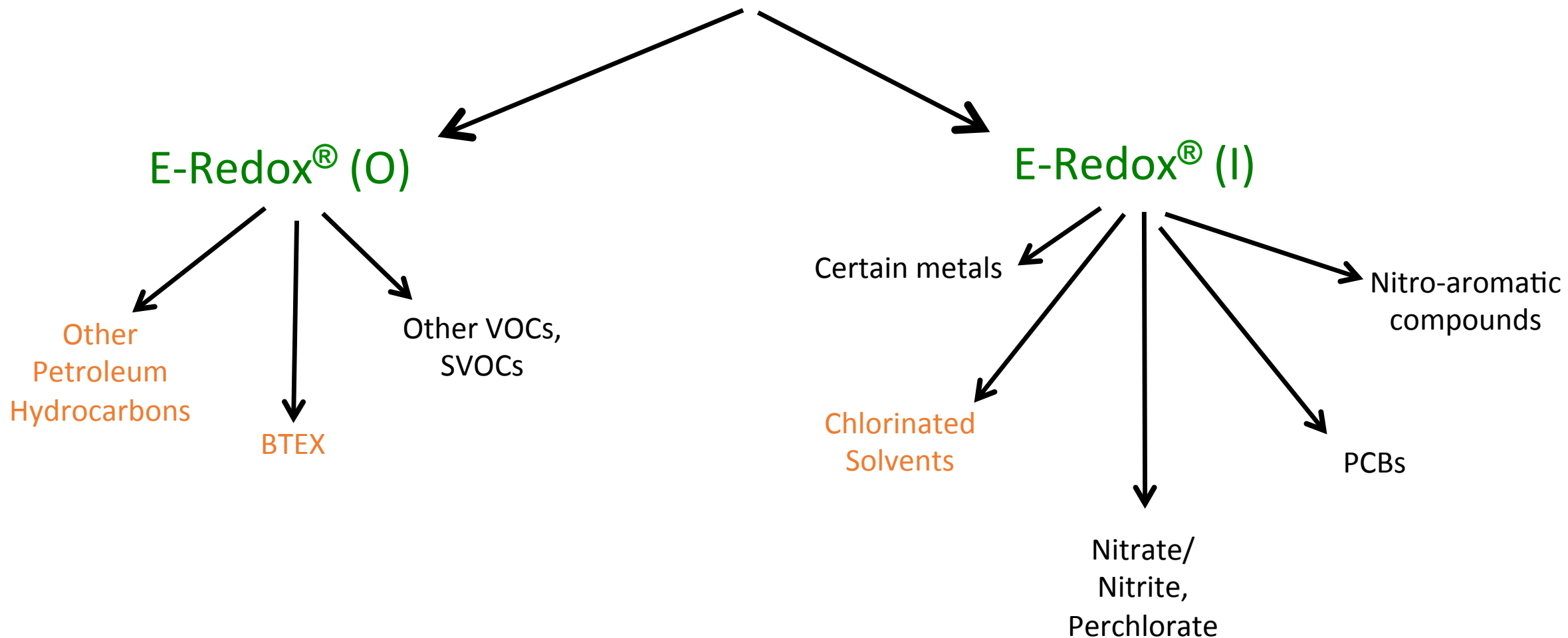
★ Matrix permeability - delivery – ROI

★ rate – time

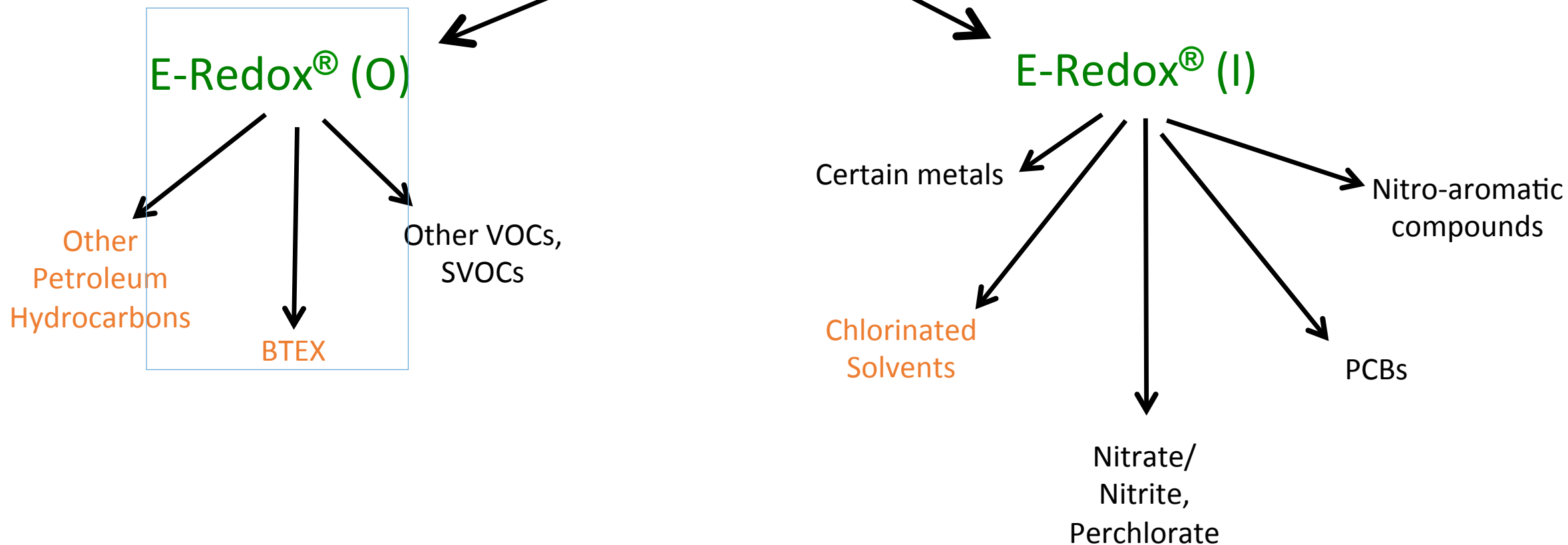
★ \$ - \$ - \$

★ Sustainability

E-Redox[®]



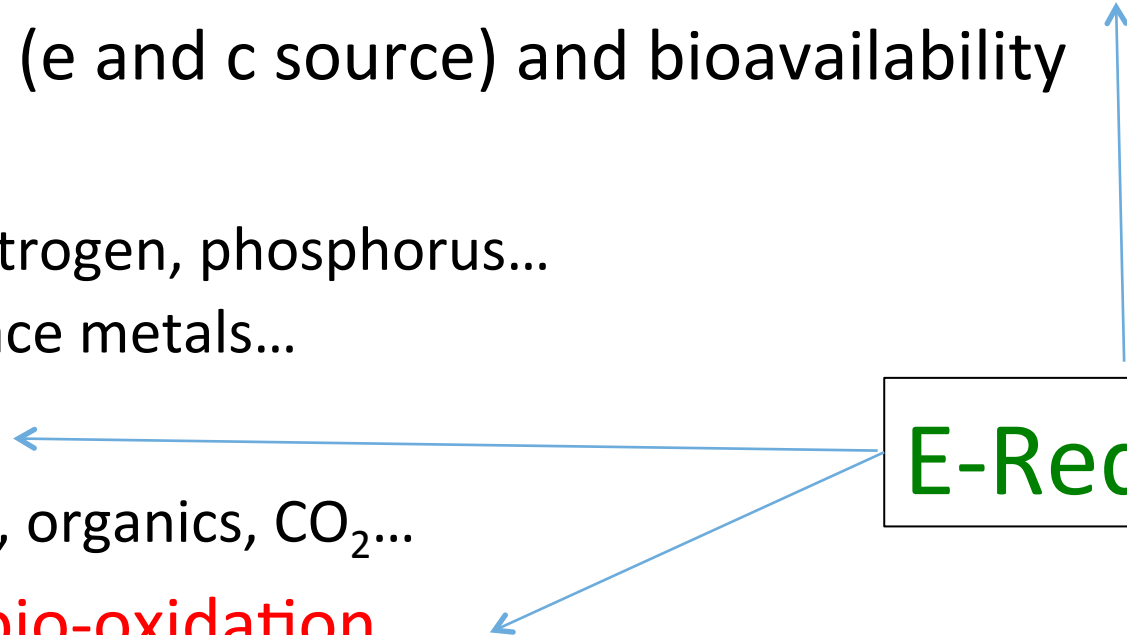
E-Redox[®]

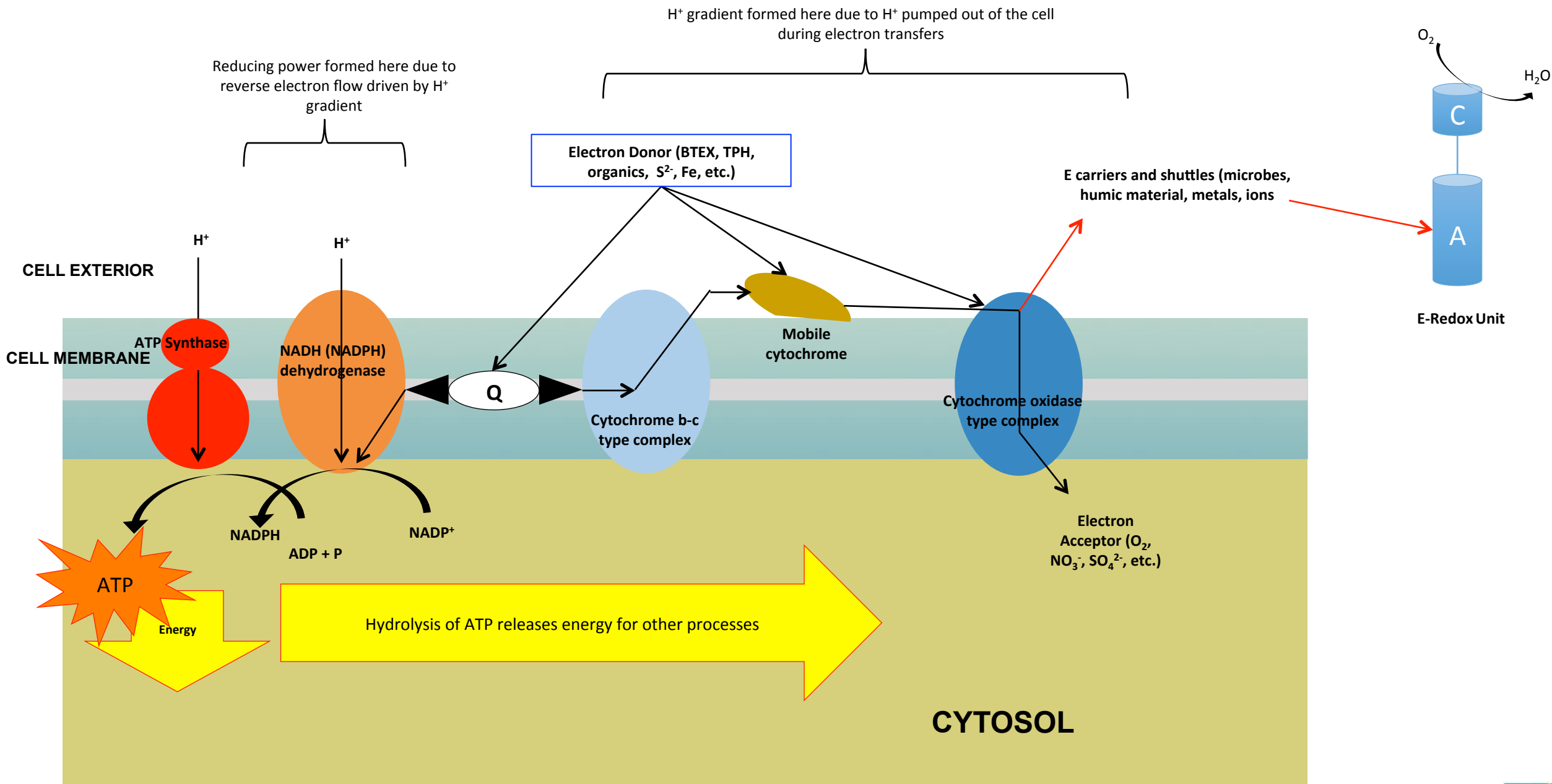


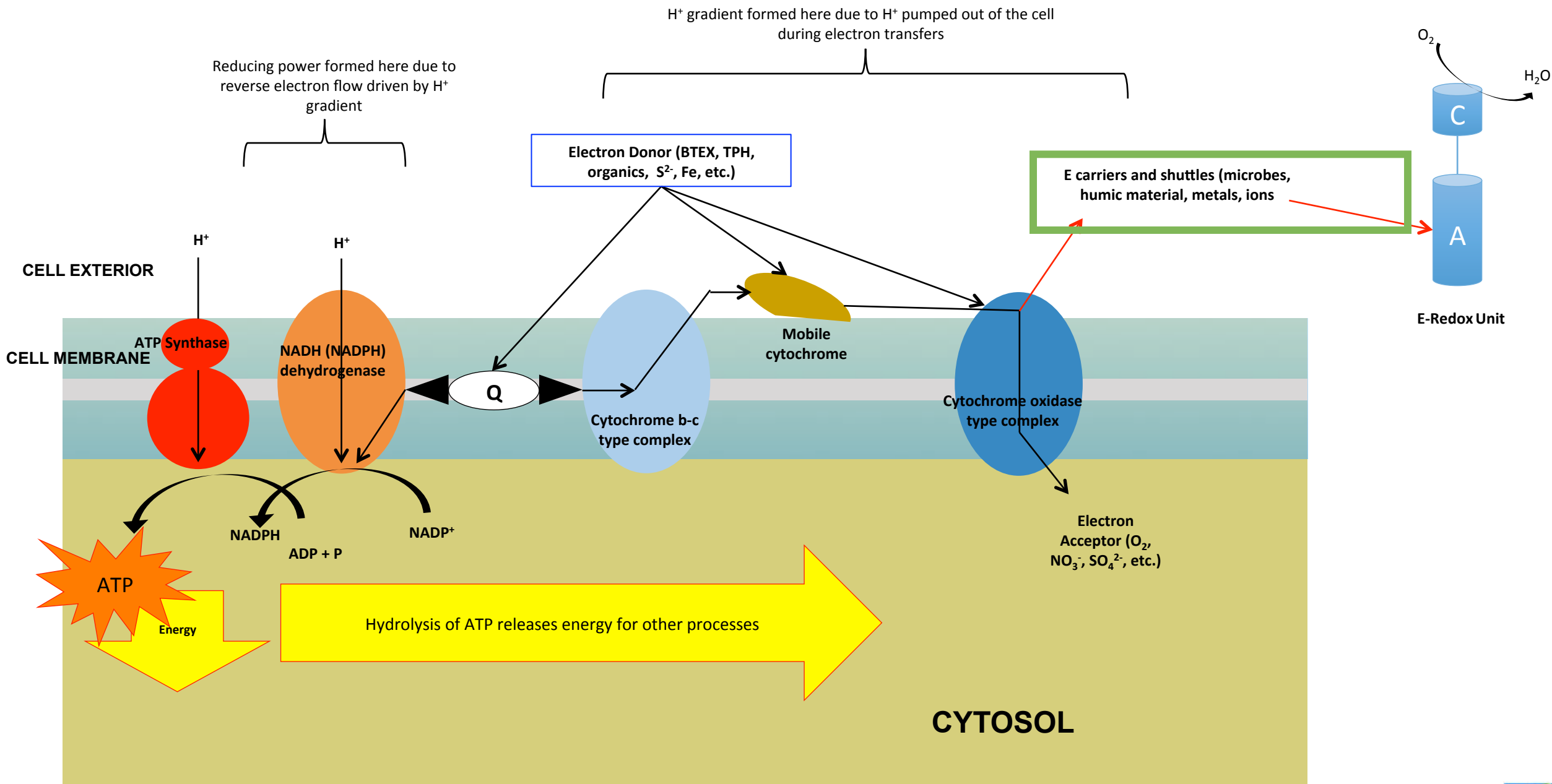
Oxidative Biodegradation

- Capable microorganisms (e.g., bacteria, species and **populations**)
- Organic compounds (e and c source) and bioavailability
- Nutrients
 - Macro-nutrients: nitrogen, phosphorus...
 - Micro-nutrients: trace metals...
- **Electron Acceptors**
 - O_2 , NO_3^- , SO_4^{2-} , Fe^{3+} , organics, CO_2 ...
- **Electron transfer – bio-oxidation**

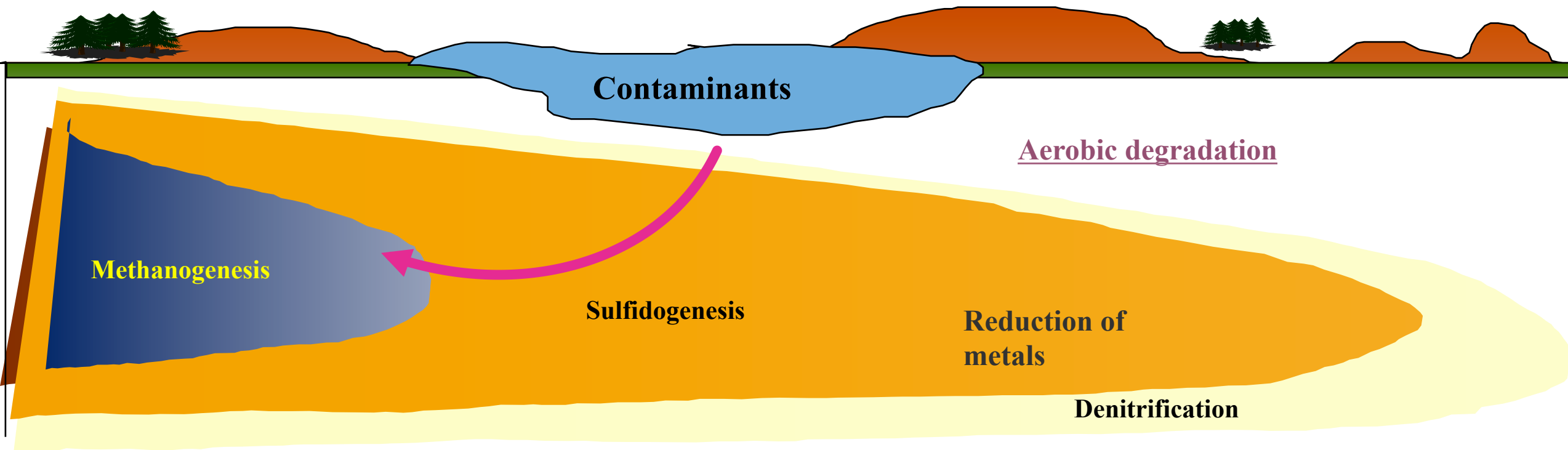
E-Redox[®] (O)



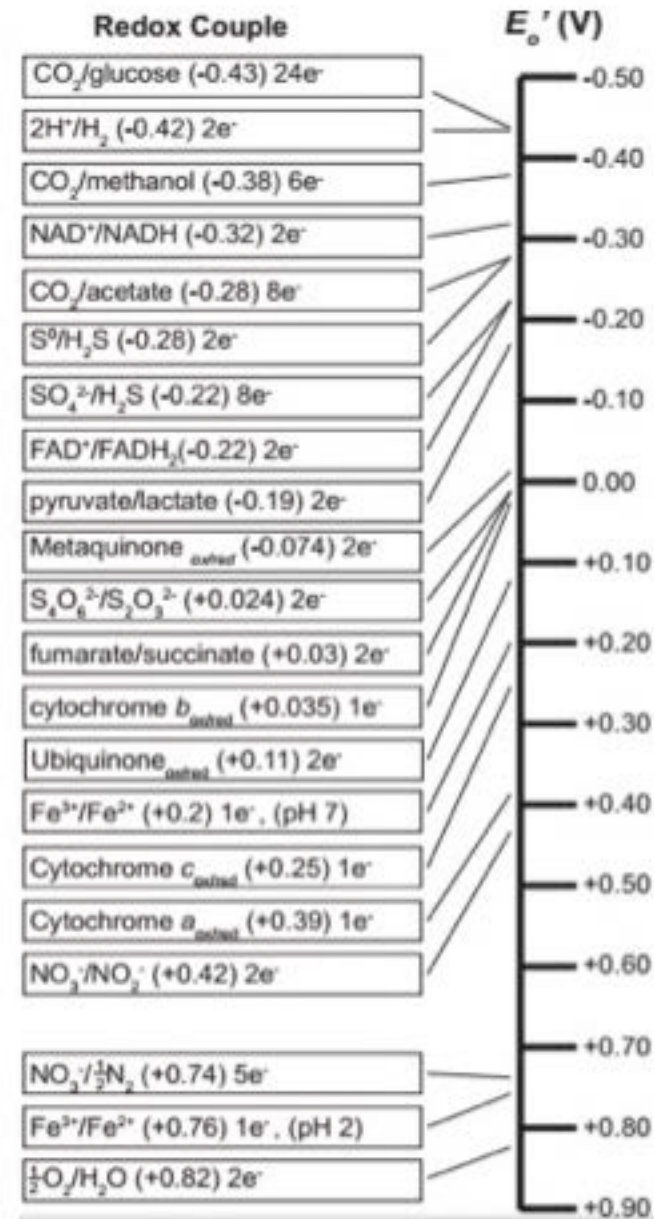
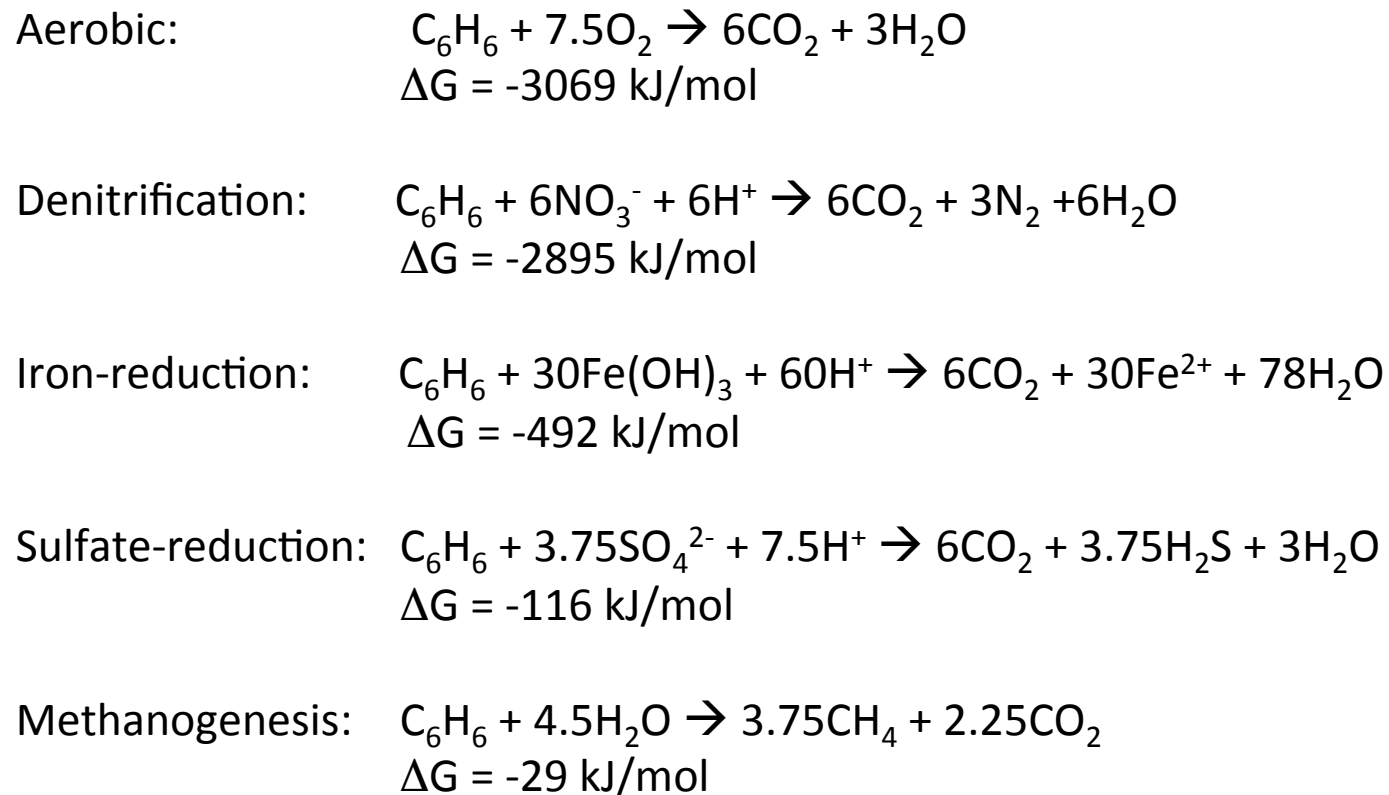




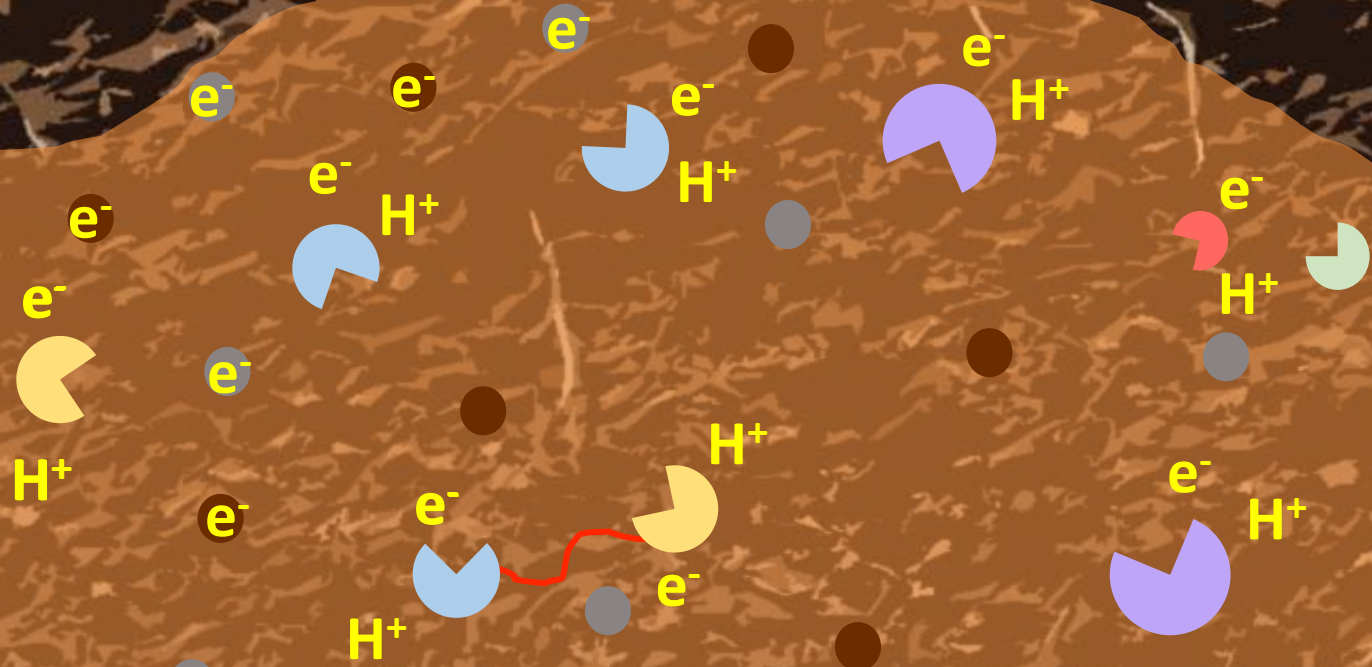
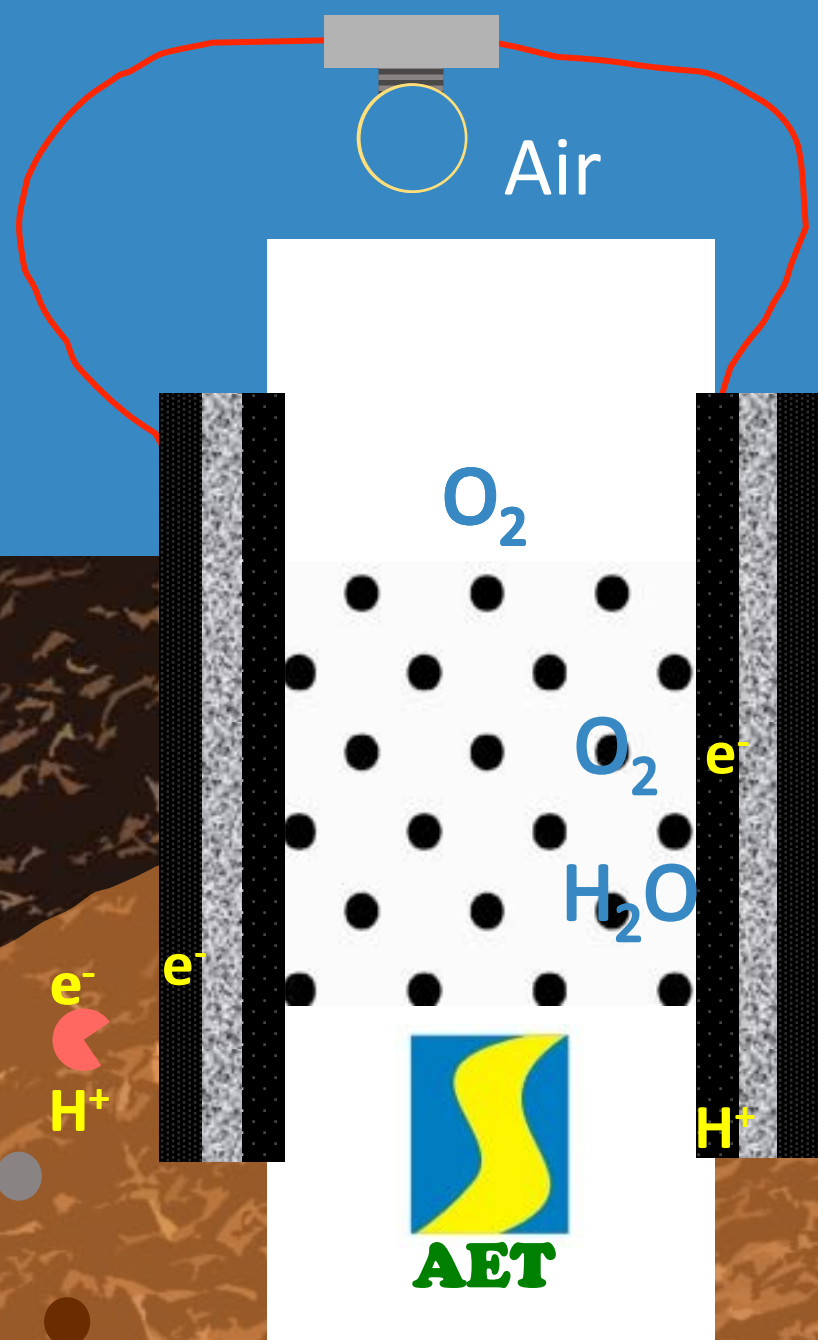
Electron Acceptor Gradient and Biodegradation



Benzene Biodegradation Vs. Different TEAs



E-Redox[®]



Benzene Biodegradation Rates (with nutrient amendments)

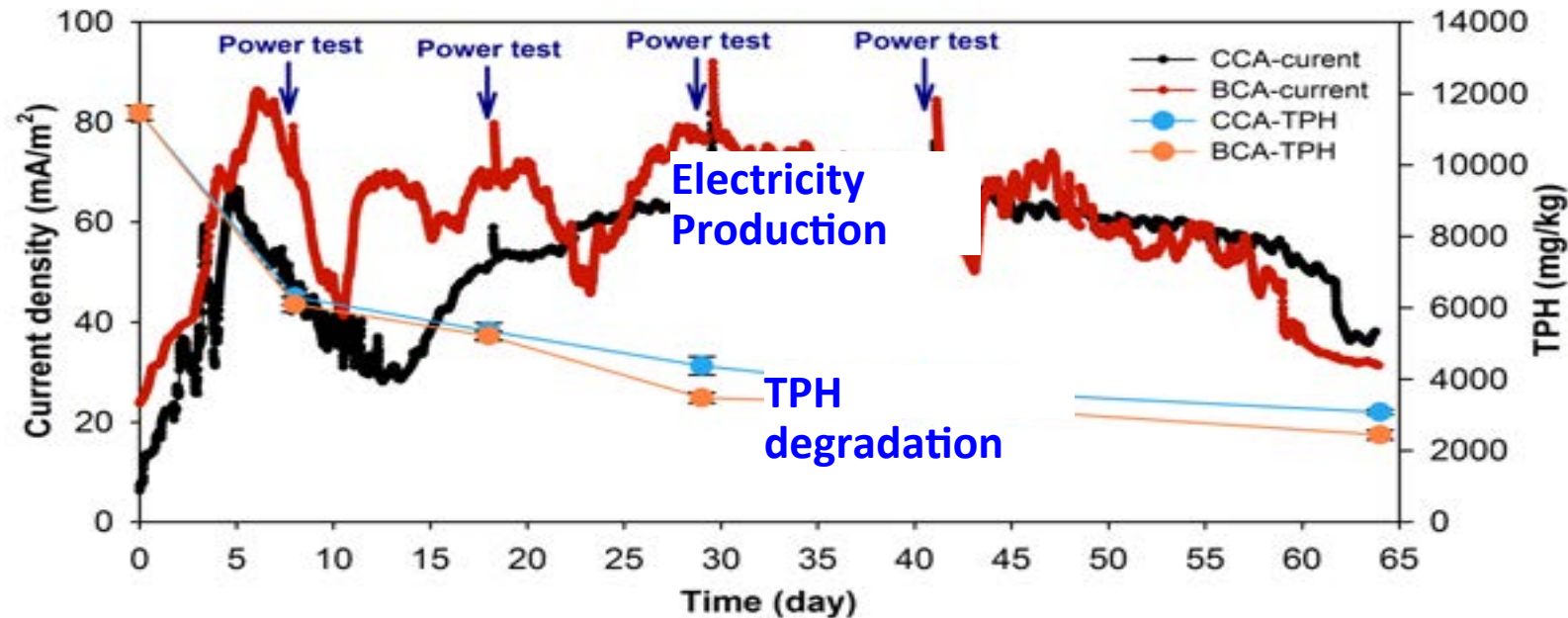
E-Redox: 585 ug/L/day

Aerobic: 400 ug/L/day

Denitrifying: 251 ug/L/day

Sulfidogenic: 189 ug/L/day

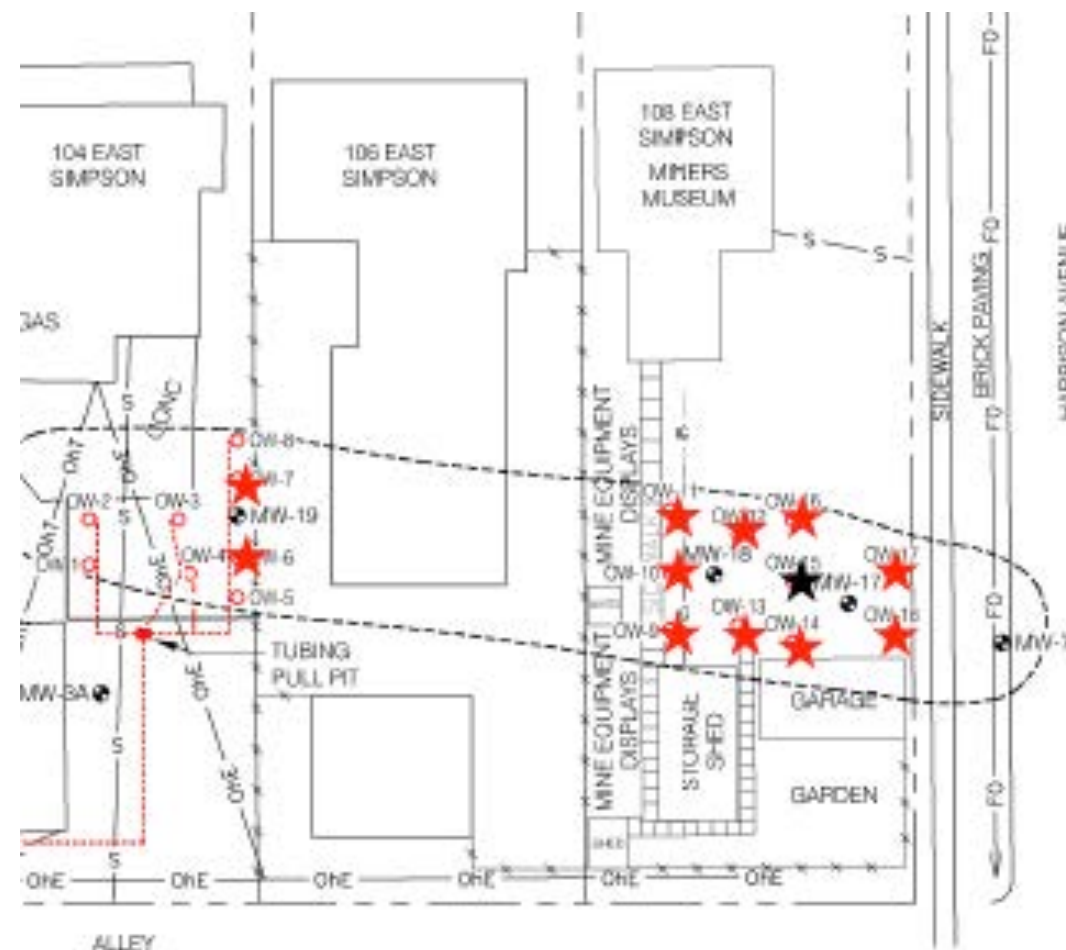
Methanogenic: lowest to negligible



Bioremeter™

Electricity generated in the E-Redox® system serves as an indicator for biodegradation and provides a weak power source ($\sim$ mA/m²)

E-Redox[®] Field Implementations



E-Redox[®] Field Implementations In Colorado

Locations: a number of fuel stations, ~2 street blocks area, Denver area, Colorado

Main COC: BTEX and other petroleum hydrocarbons in groundwater and saturated zones, sporadic sources in smear and vadose zones

Lithology: silty to clayey sand in the vadose zone, clay in the saturated zone starting 10-15 ft bgs

Other Site Notes:

- Groundwater flow velocity estimated at 0.04 ft/day

- Past remediation efforts involved nutrient amendments, air sparging, injection of carbon-based materials, and chemical oxidants

Bench Tests (2-3-wk)



Field samples



Microbial assays



Bench-scale E-Redox[®]



E-Redox® System Field Installation (2-3 days for a typical UST site)



Site



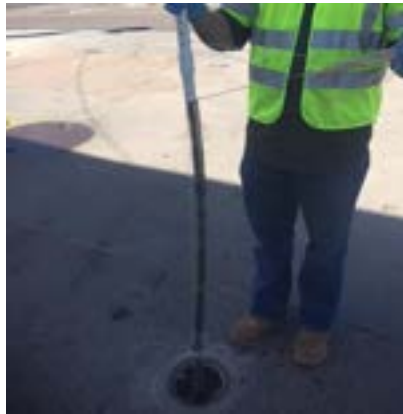
Health & Safety Meeting



Pre-installation monitoring



E-Redox® unit prep



E-Redox® unit installation



Closing well cover



Voltage monitoring



Securing E-Redox® unit



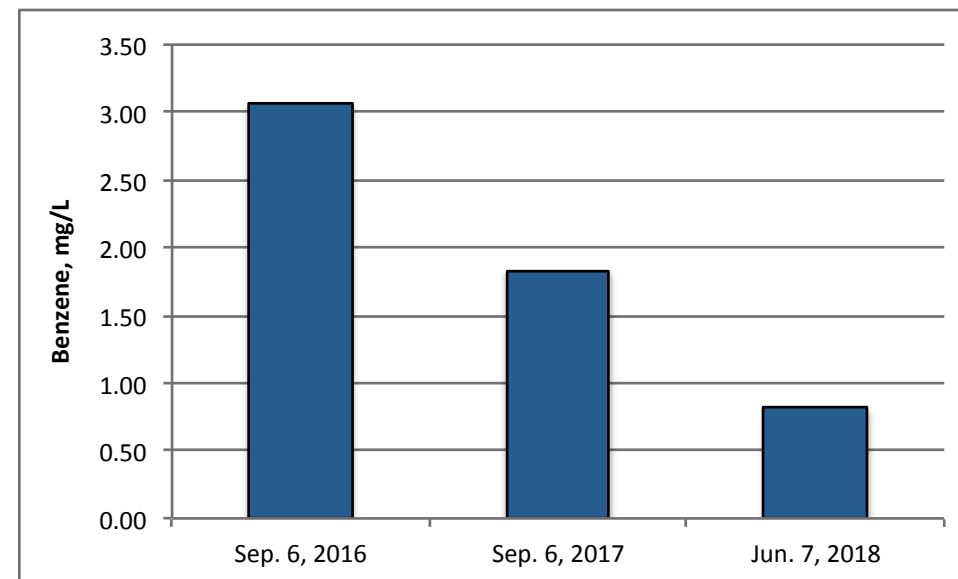




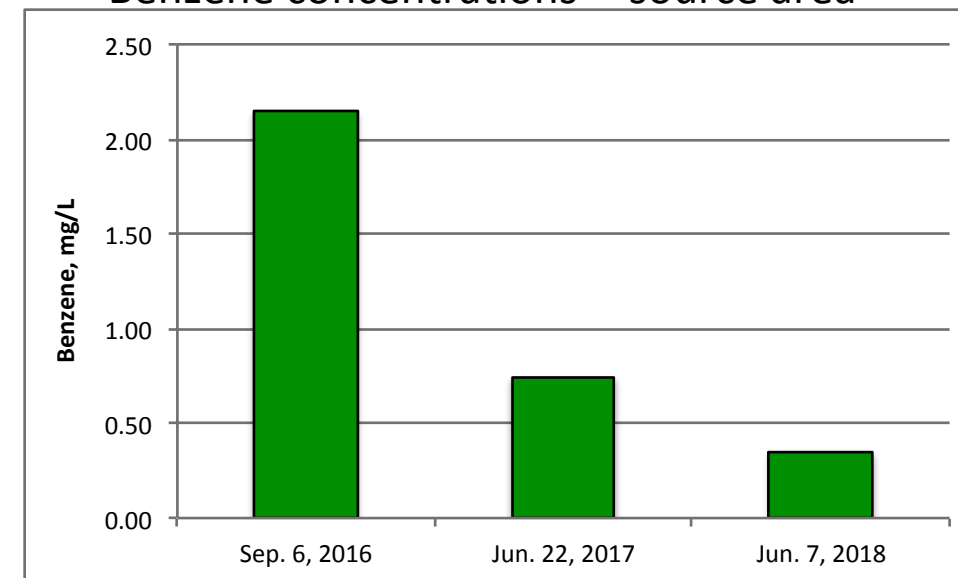


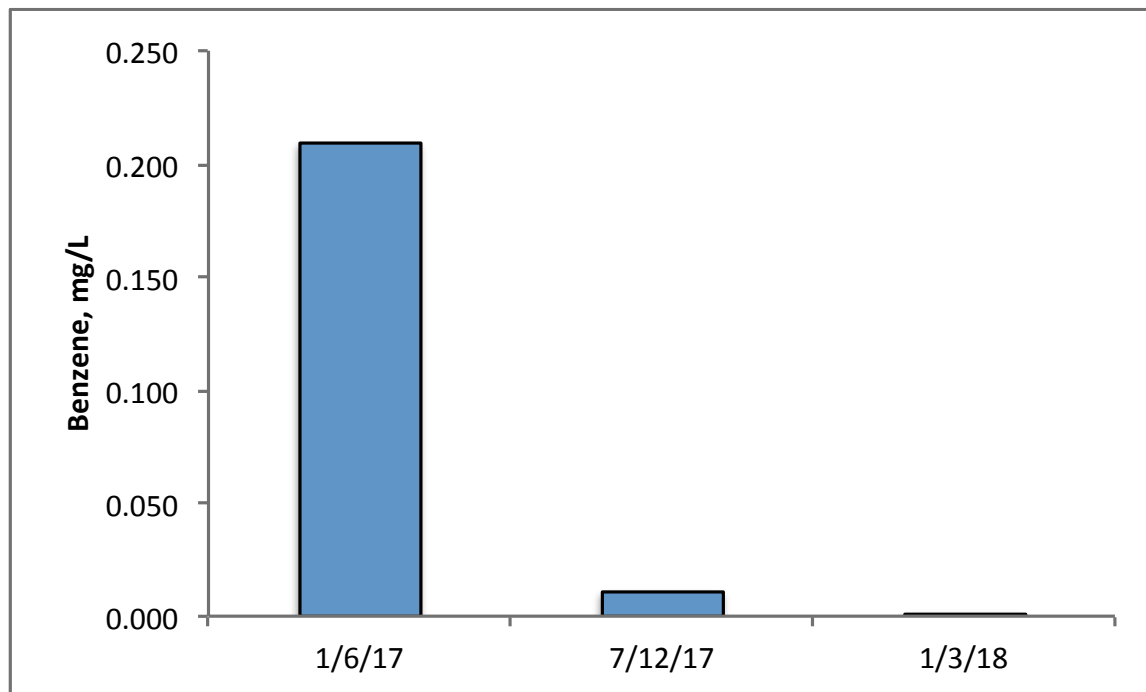
Operating fueling station in Denver, CO

Benzene concentrations -- whole site

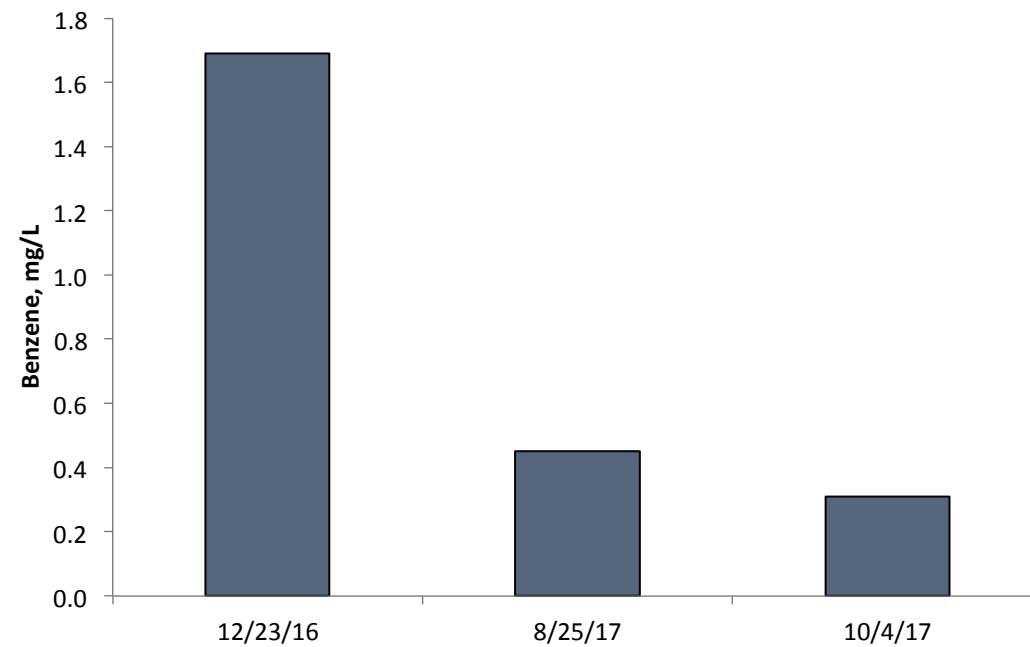


Benzene concentrations -- source area





Active fueling station in Lakewood, CO



Former bulk plant facility in Lafayette, CO

Field Applications of E-Redox[®] (O)

Site	Location	Contaminant	Matrix
Former gas station	Pine Ridge, South Dakota	BTEX, TPH-DRO	Groundwater
Former and operating gas stations, 2x	Lakewood, Colorado	BTEX	Groundwater
Operating gas stations, 2x	Denver, Colorado	BTEX	Groundwater
Operating gas station	Wheat Ridge, Colorado	BTEX	Groundwater
Former bulk station	Lafayette, Colorado	BTEX	Groundwater
Former gas station	Montrose, Colorado	BTEX	Groundwater
Operating gas station	Pueblo, Colorado	BTEX	Groundwater
Former products terminal	Northern California	BTEX, TPH-DRO	Groundwater, saturated and vadose zone soils
Operating MWTP x2	Beijing, China	COD, N, P	Municipal wastewater

BioRemeter™

- “Miniature” modifications from E-Redox® configuration
- For real-time measurement of microbial activities
 - “Collects” and measures electrons from microbial reactions in the matrix
- Survey by using existing groundwater wells
- A new tool for site assessment and real-time evaluation of enhanced bioremediation, NSZD, and MNA

BioRemeter™ Field Survey for Biodegradation Activities



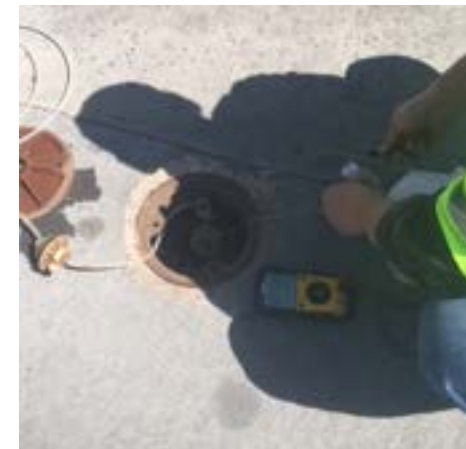
Conditioning BioRemeter



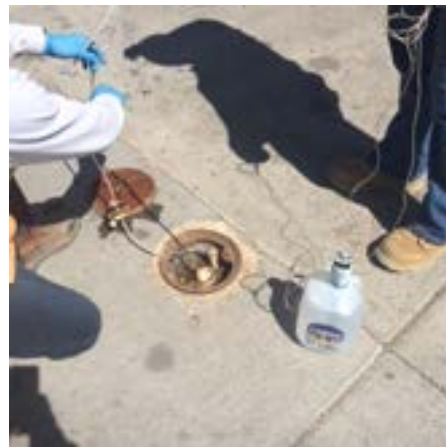
Calibration



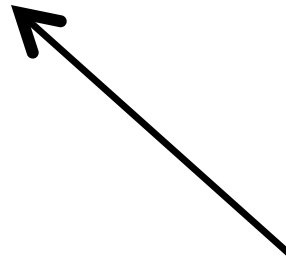
BioRemeter in well



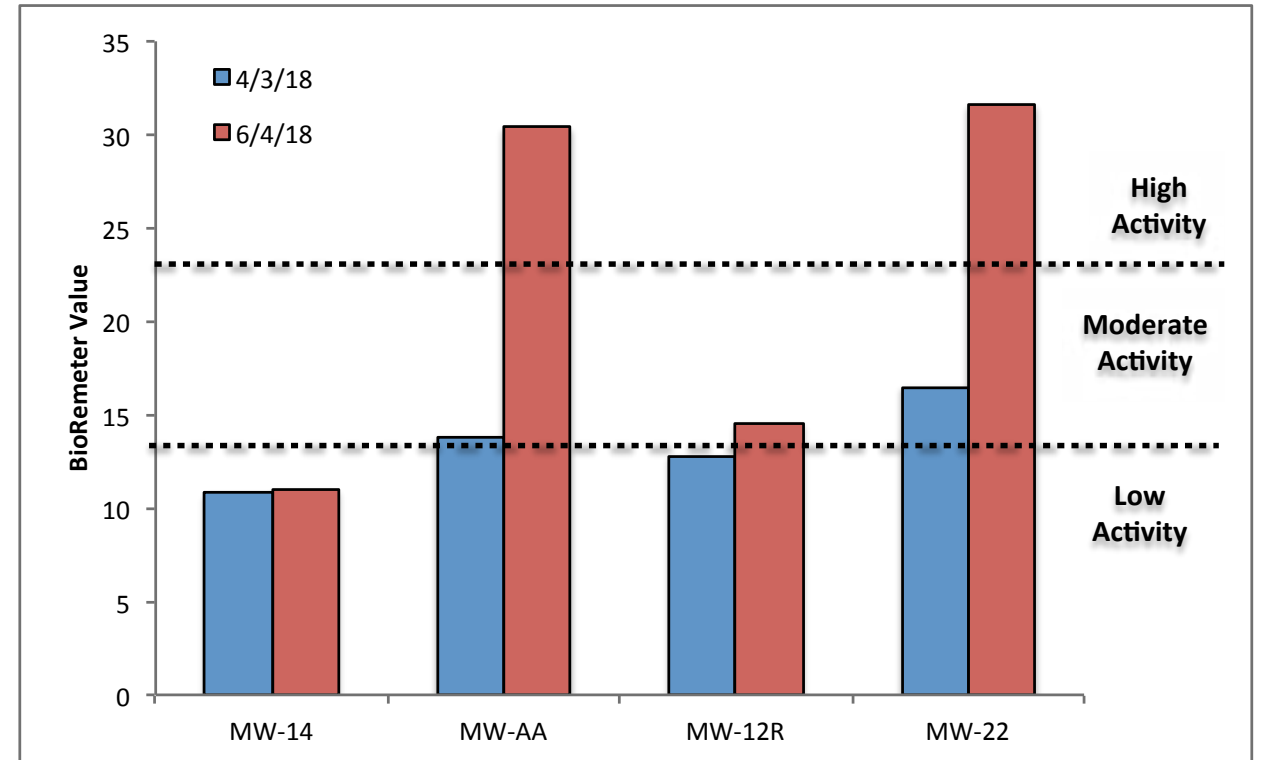
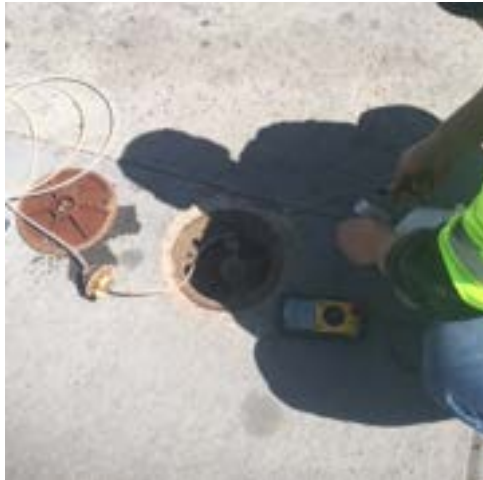
Measurement of voltage



Close well and rinse probe



Case Study of BioRemeter™: Active Fuel Station in Denver, CO



E-Redox[®] (O) Summary

- ✓ **E-Redox[®]**-O technology is a “passive” but active treatment for BTEX, TPH-GRO, TPH-DRO and other petroleum hydrocarbons, e.g., >5x rate for benzene in GW, >10x for TPH-DRO in sediments
- ✓ Voltage profiles in the E-Redox[®] device correlate with active biodegradation activities, resulting in an *in situ* tool for real-time monitoring of biodegradation – **BioRemeter[™]**
- ✓ Modular, sustainable, no energy input, minimum maintenance
- ✓ E-Redox[®] works best when matrix conductivity is high and electron acceptor is deficient (most sites)
- ✓ E-Redox[®] can be a stand-alone remedy or synergistically used with other remedial technologies (e.g., bioaugmentation, nutrients addition, carbon, chemOx, SVE, etc.)

Mechanism Studies

- The anode (in contact with the contaminated matrix) and the established biofilm at the anode-matrix interface serve as a solid and highly conductive electron collector for electrons released from biodegradation. The circuit and specific resistance load serve as the conduit to transfer electrons to the cathode (exposed to oxygen in ambient air), and electricity is generated during the electron transfer. Meanwhile, protons migrate through the matrix towards the cathode. The cathode (at its interface with air) serves as a perpetual electron acceptor that consumes the electrons and protons and completes the electron transport (*Morris and Jin, 2009, 2012*).
- The extracellular transfer of electrons to the remote O₂ at the E-Redox-O system can revive, stimulate, and sustain aerobic respiration/degradation in an otherwise anaerobic matrix. The matrix-wide electron transfer via a number of biological (certain cells and cell organelles) and abiotic (ions, metals, humic materials, other small organic constituents) shuttles has been well documented (e.g., *Müller, et. al., 2016; Lovley, 2017*). Such electron movements can trigger two processes: competition with petroleum-degrading microbes for electrons, stimulating microbial enzyme production and higher degradation rate to "make up" the loss; certain opportunistic microbes in the matrix can harvest "free electrons", helping microbial growth and subsequent degradation.
- E-Redox-O system creates a higher redox at its immediate proximity and beyond (with time), which further enhances electron flow towards the system and consumption at the cathode by O₂. This weak redox gradient helps shift microbial population composition (*Lu et al., 2017; Lu et al., 2018, under review*). This shift towards thermodynamically more favorable species further benefits biodegradation at distant location but within the ROI of the E-Redox-O system (*Lu et al., 2018, under review*).
- The E-Redox-O system stimulates biological oxidation by expediting electron transfer from the biodegradation process, "pulling" electrons to ambient O₂, the favorable electron acceptor, competing with microorganisms for extracellular electrons, thus accelerating metabolic rates, and maintaining low electron density and H₂ levels in the matrix to eliminate potential product feedback and inhibitory influence (*Jin and Ren, 2018, unpublished*).

Thank You

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