

Field-Scale Pilot Study Using In-Situ Electrobiochemical Reactors

Soil and Groundwater Benzene Impacts

Doug Gray

What do you do when...

- 186 days of operation
- 2 separate pilot study areas
- Almost 10MM data points
- 18 minutes to present



Agenda

- 01 Introduction / Background
- 02 Technology Overview
- 03 Project Summary
- 04 Results / Evaluation
- 05 Conclusions / Lessons Learned

Acknowledgements

- Aaron Martin and Ethan Earnest – AECOM
- Troy Lizer – Provectus
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- John Wright – Field Environmental Services
- Betsy Witt and Scott Lang - Client

01

Introduction / Background

Site History

Pipeline Release

- Along ~ 1 mile stretch
- Late 1970s

Investigation / Characterization

- Delineate
- Early 1980s
- 2013-2016 finalized

Groundwater Interceptor Trench

- Multi-year operations
- Diminishing returns

Feasibility Evaluation

- Evaluate alternative remedies
- MPE potentially applicable
- With or without enhanced fracturing



Pilot-scale MPE Study

- With and without enhanced fracturing
- 2010 through 2011
- Successful/Diminishing returns

Full-scale MPE

- Six stages (~800 ft / stage)
- Stage 1 implemented
- Enhanced fractures
- 2013–2018/Stage 1 diminishing returns

Feasibility Evaluation

- Evaluate potential alternative remedies
- Innovative technologies identified

Next Steps

- EBR technology looked promising
- Design / implement pilot demonstration

Site Background

- Historic benzene release site
- Tight natural clay lithology (weathered zone overlying unweathered zone)
- Shallow impacts ranging from ~9 to 15 ft-bgs
- Groundwater present ranging from ~ 5-10 ft-bgs; very low hydraulic gradient and resulting very low groundwater flow
- Two (2) Pilot Areas: 1) Unfractured (native conditions); 2) Fractured (hydraulically enhanced fractures)
- Background benzene concentrations
 - Groundwater - 300 - 800 mg/L (300,000 - 800,000 ug/L)
 - Soils – 400 - 1000 mg/kg (400,000 – 1,000,000 ug/kg)

02

Technology Overview

EBR™ Technology Overview

What is Provect-“EBR®”



Electro Bioremediation (EBR)
well(s) contain an air sparge plus 3
electrodes:

- 💧 O₂ production
- 💧 H₂O₂ production
- 💧 Fe²⁺ release



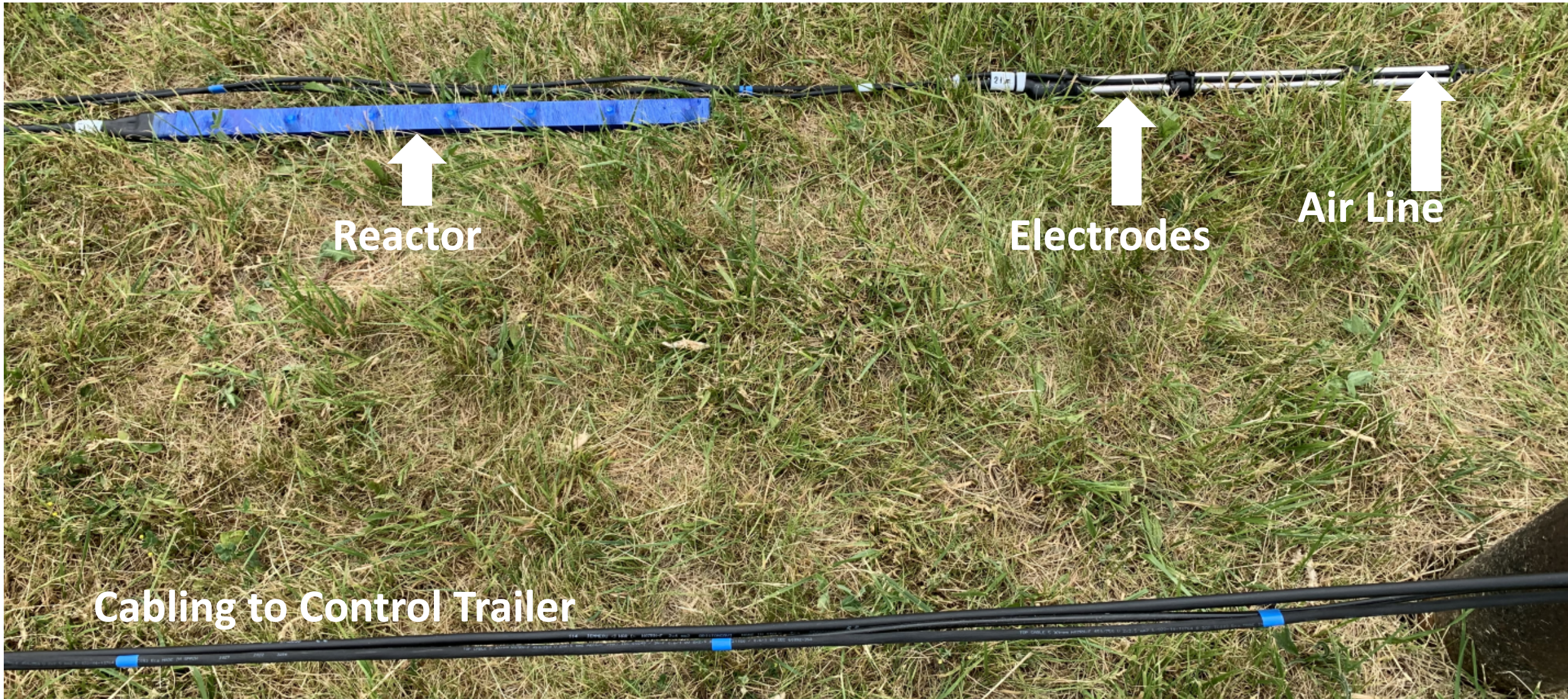
US Patent No. 9,975,156 B2

Computerized control panels for
remote system / adjustment and real -
time performance monitoring



Copyright Provectus

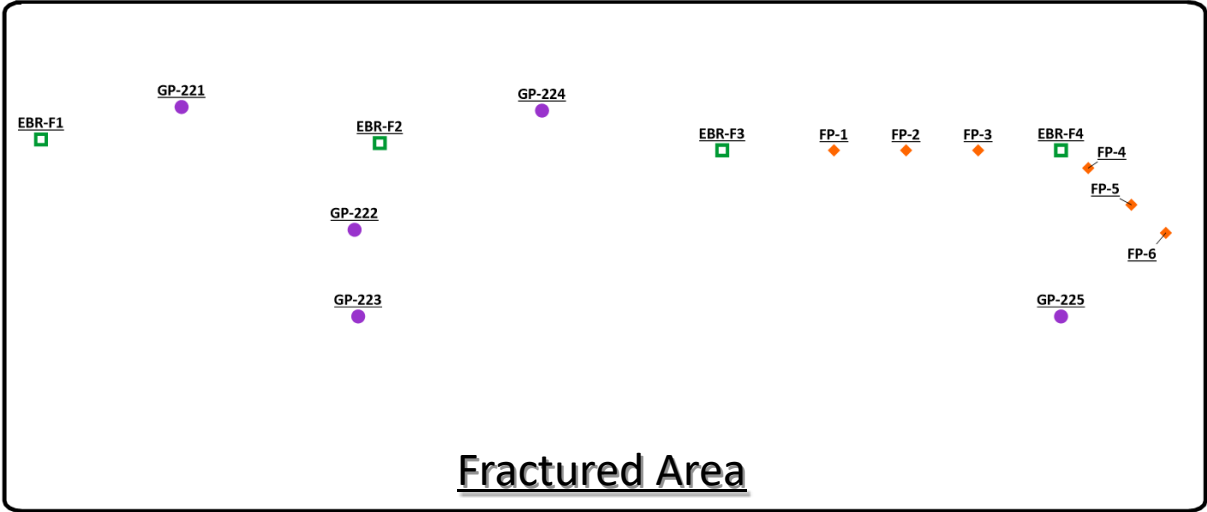
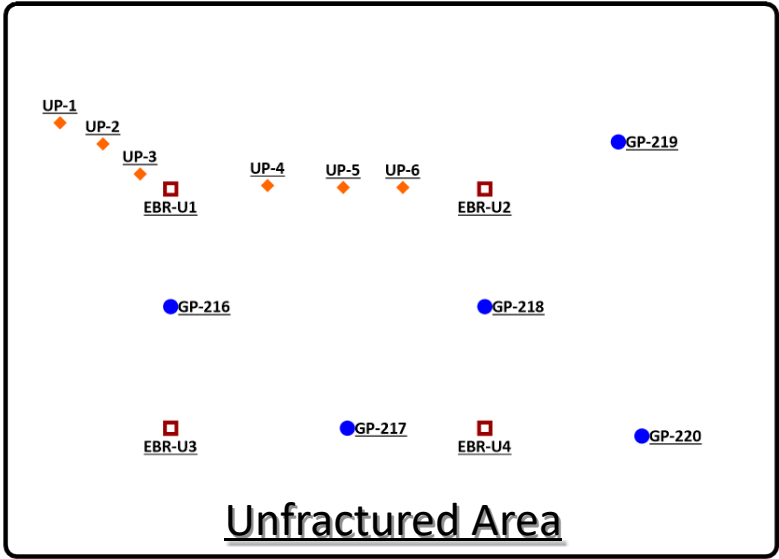
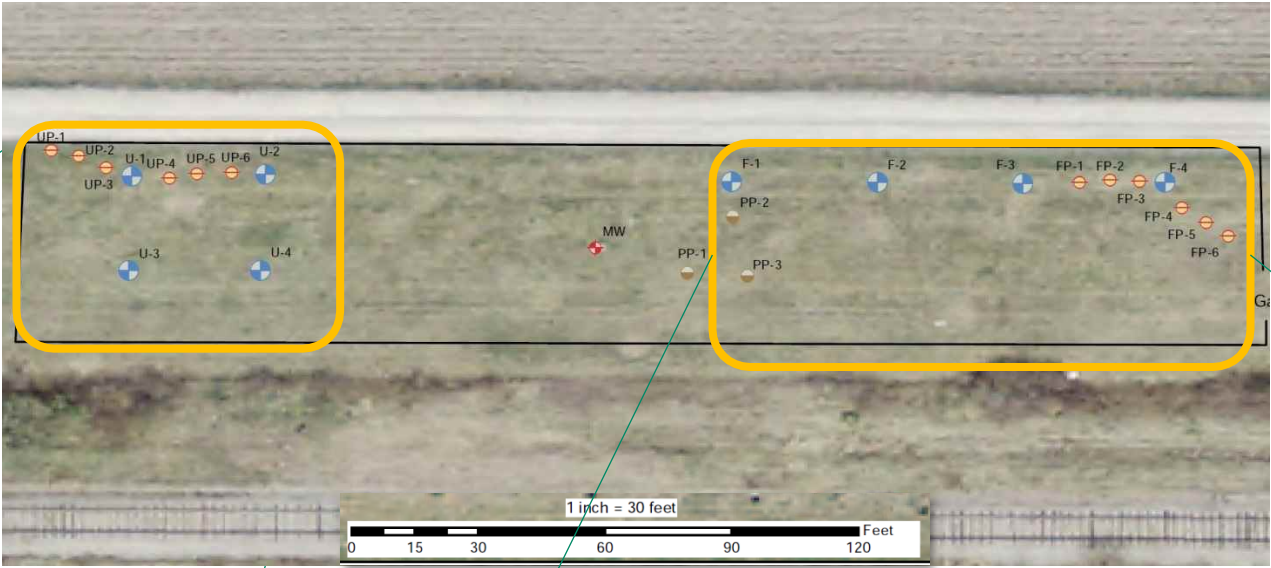
EBR™ Technology Overview



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Project Summary

Pilot Study Areas



Installed Reactor



Control Panel



Unfractured Area

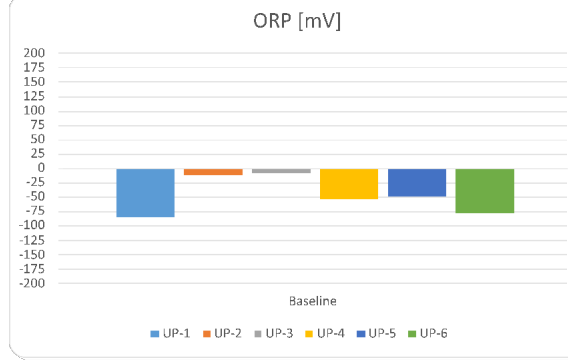
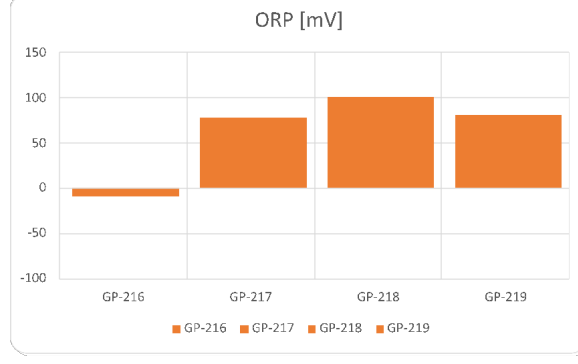
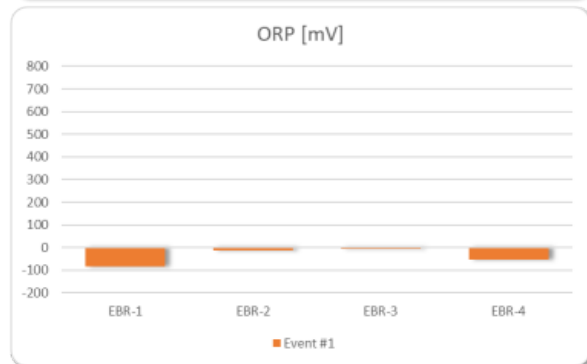
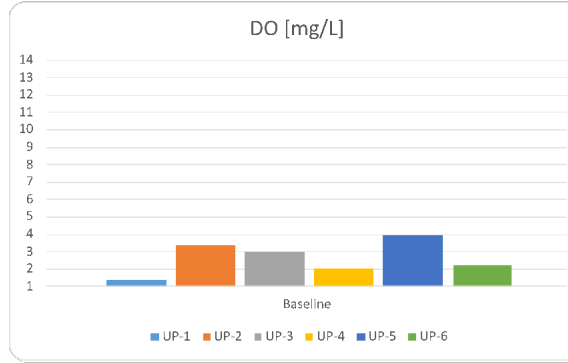
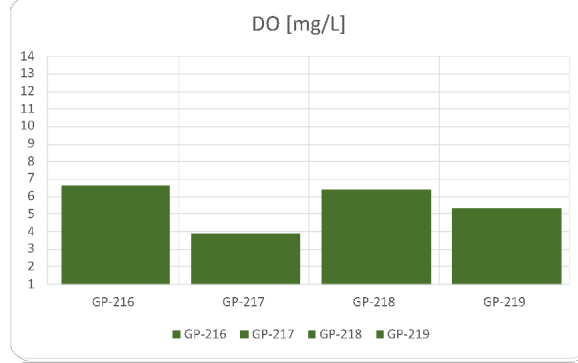
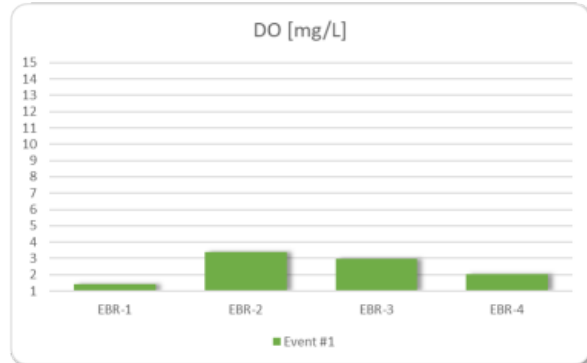
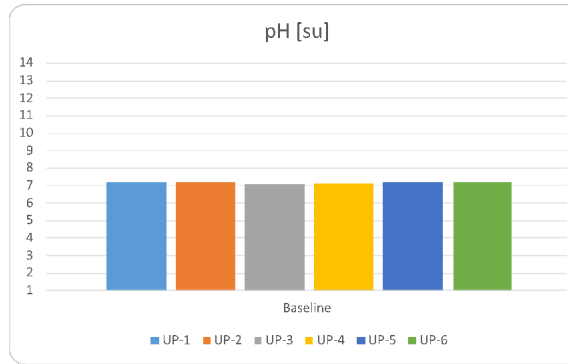
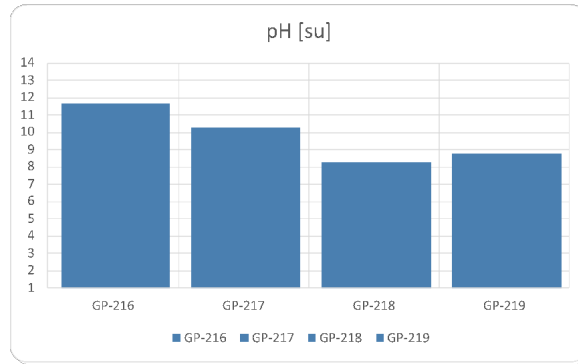
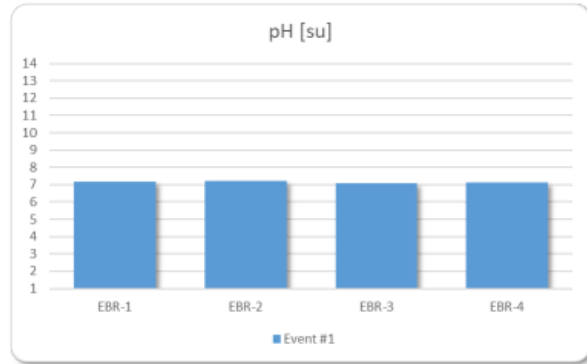


Fractured Area

04

Results / Evaluation

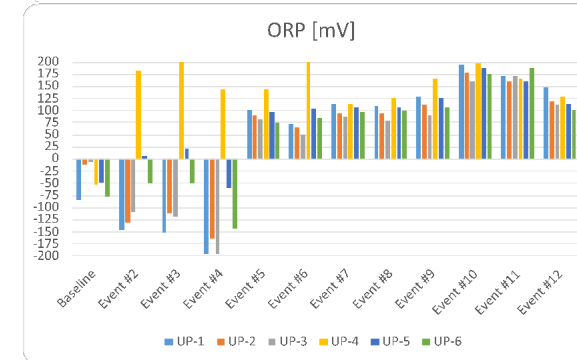
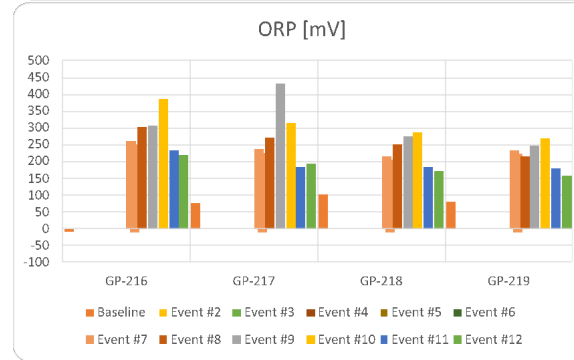
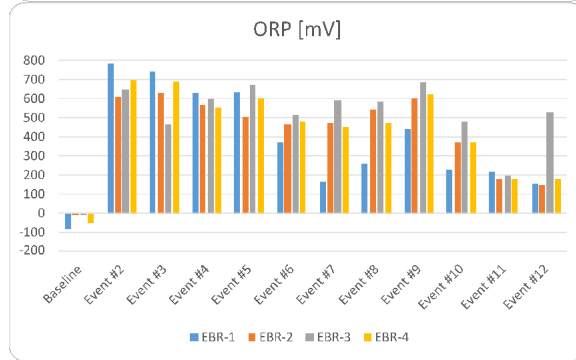
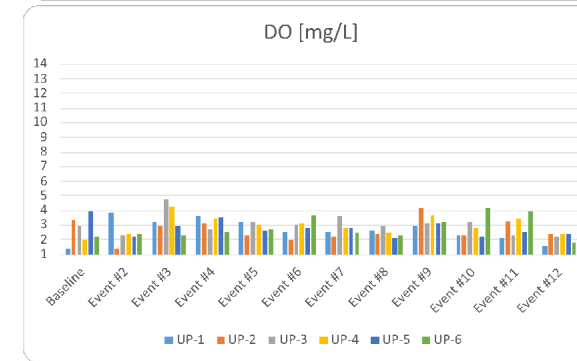
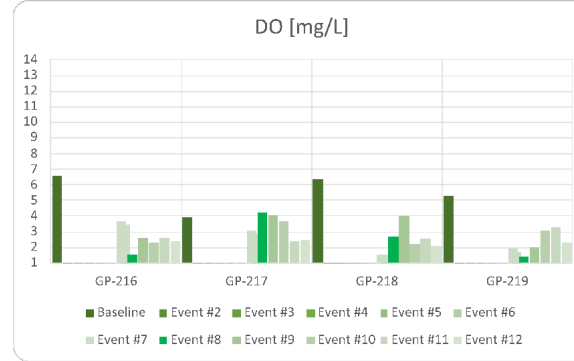
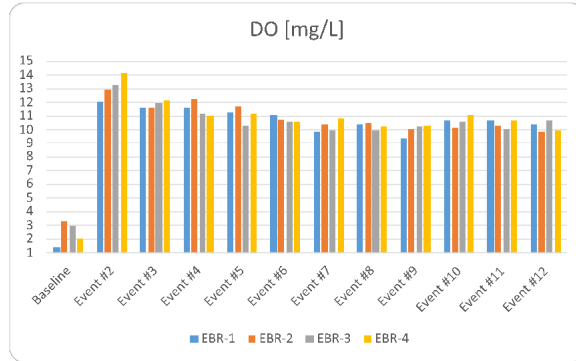
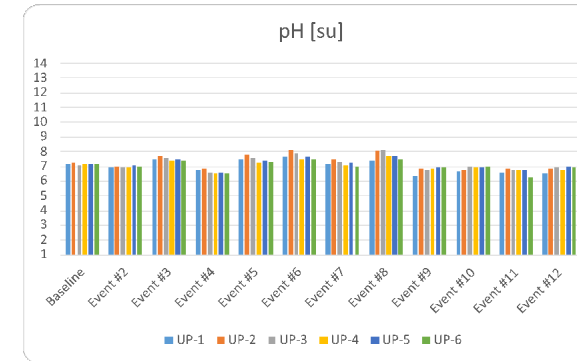
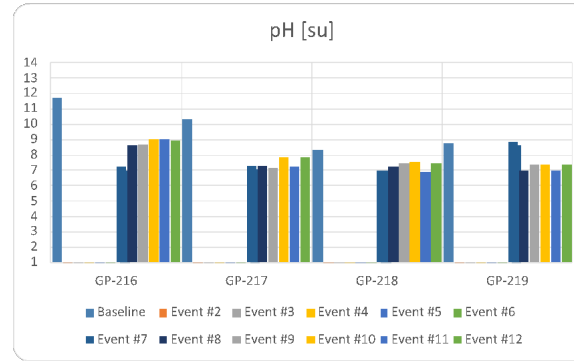
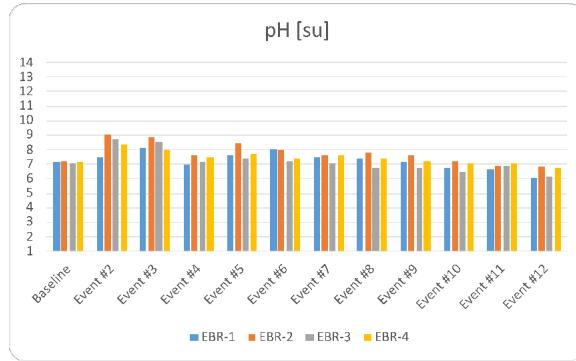
Baseline Conditions – Unfractured Area



Unfractured Area

- pH values generally neutral
- DO values generally > 1 mg/L
- ORP values
 - Reactor wells and piezometers slightly reducing
 - Monitoring wells slightly oxidizing

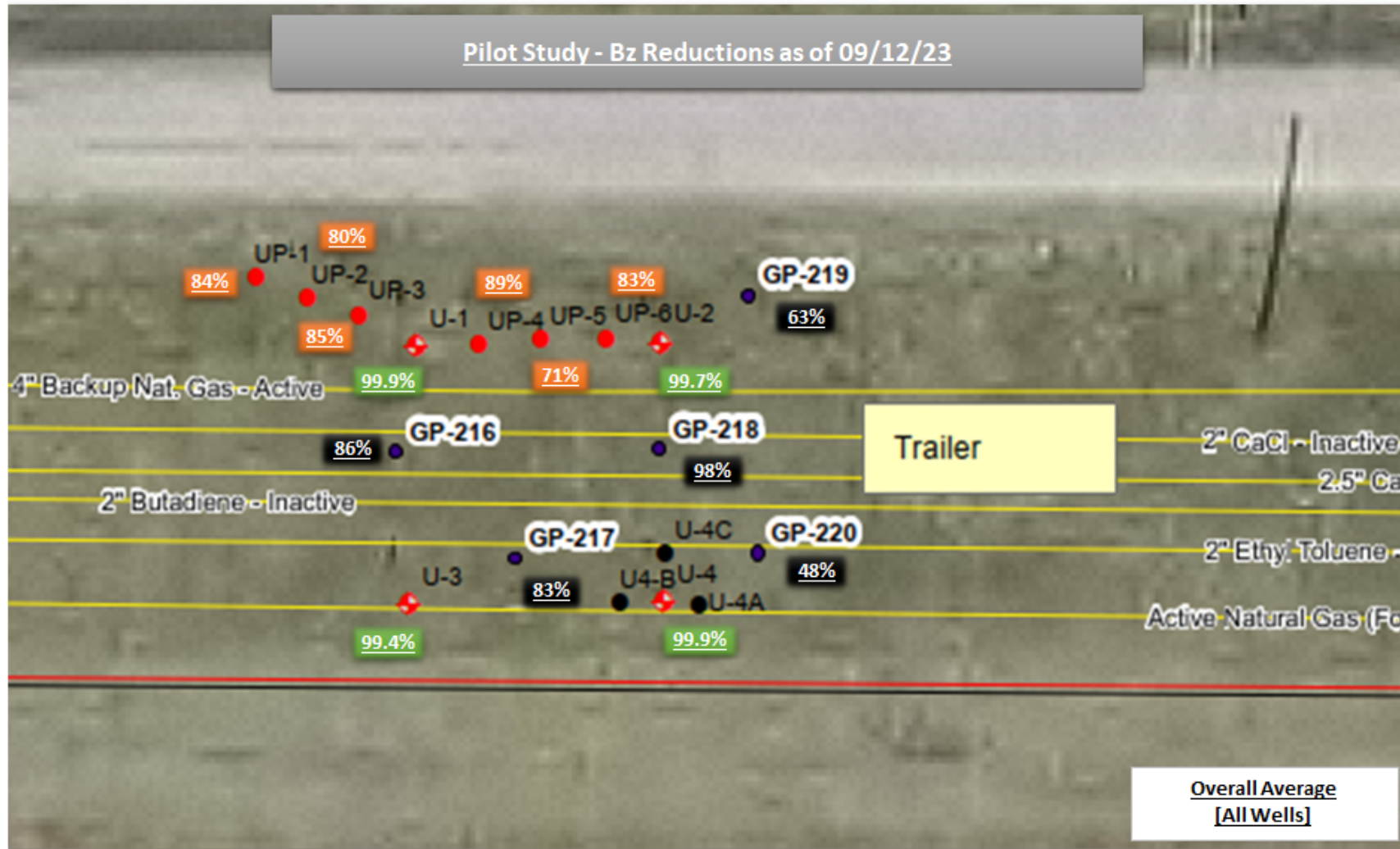
Pilot Study Summary – Unfractured Area



Unfractured Area

- Pilot duration – 94 days
- pH values
 - Relatively constant throughout testing (7-8 s.u.)
- DO values
 - Quickly increased in EBR™ wells to >10 mg/L
 - Increased over time in MWs up to 4 mg/L
 - Increased over time in PZs up to 3-4 mg/L
- ORP values
 - EBR™ wells increased to 700-800 mV then decreased as ROI expanded
 - Increased in MWs from baseline up to ~300 mV
 - Increased in PZs ~40 days (150-200 mV)
 - Area transitioned from reducing to oxidizing

Pilot Study – Overall GW Benzene Changes (Unfractured Area)



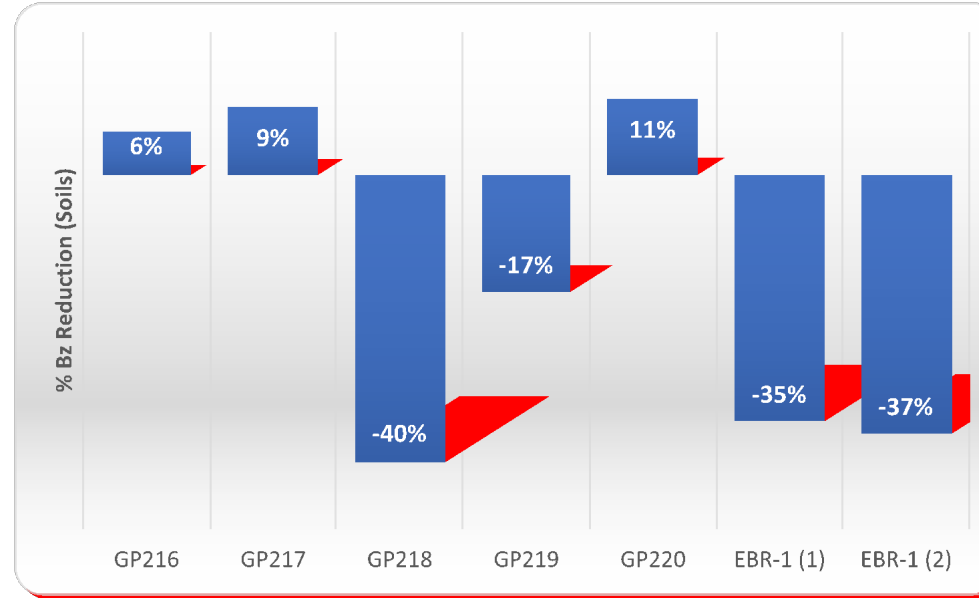
- Piezometers
- Monitoring Wells
- EBR Wells

Unfractured Area

- EBR™ wells > PZs > MWs
- ROIs estimated at 15-20-ft
- Changes in % reduction decrease with distance away from EBR reactor
- Longer operation time would continue to enhance observed concentration reductions

Pilot Study – Overall Soil Benzene Changes (Unfractured Area)

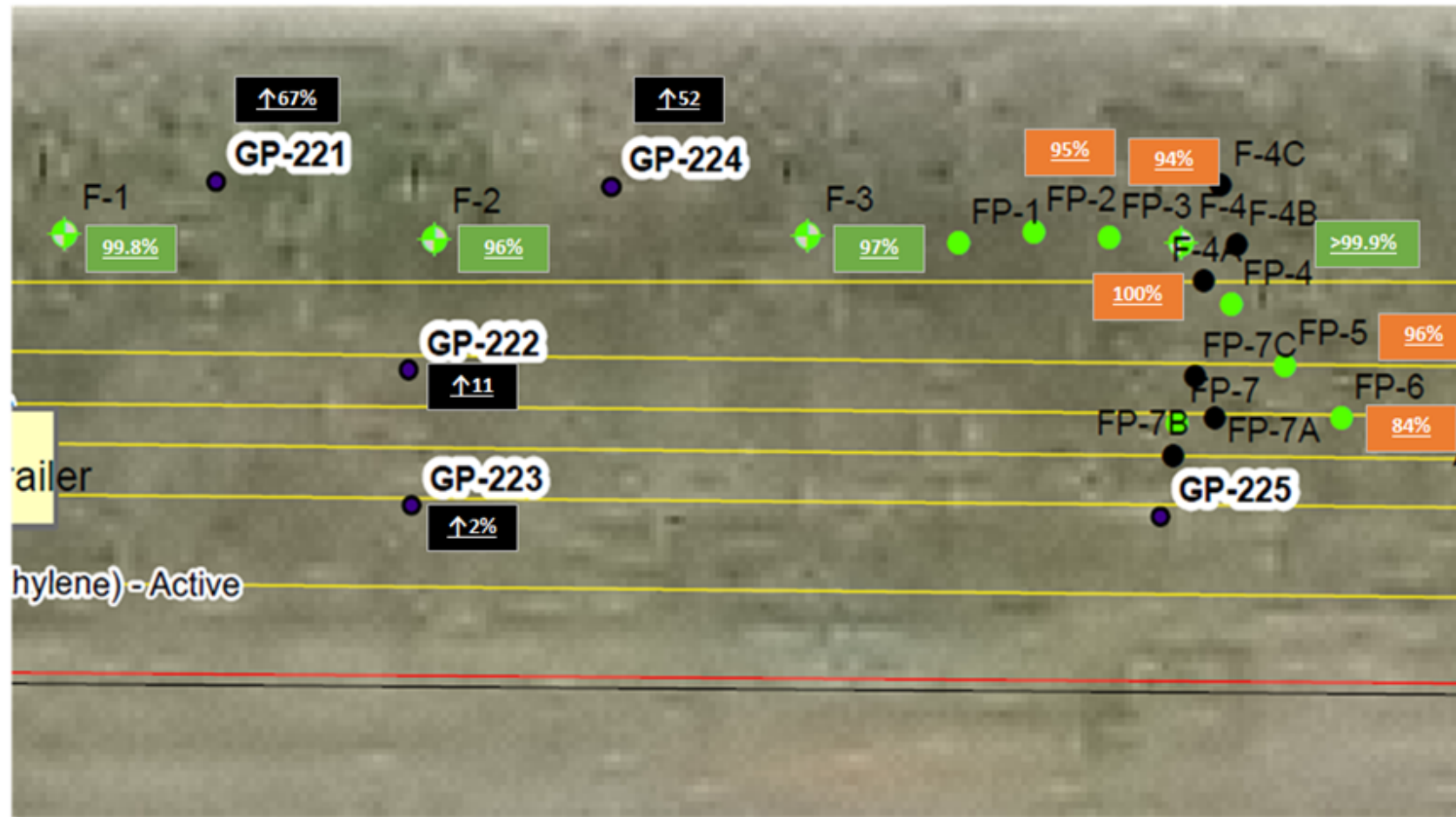
Sample ID	Depth	Constituent	Base Benzene µg/kg	Post Benzene µg/kg	Overall % Change
GP 216	9	Benzene	680,000	800,000	6%
GP 216	11	Benzene	2,600,000	730,000	
GP 216	13	Benzene	2,100,000	4,000,000	
GP 216	15	Benzene	640,000	1,100,000	
GP 216	17	Benzene	470,000	460,000	
GP 217	9	Benzene	430,000	570,000	9%
GP 217	11	Benzene	2,100,000	2,200,000	
GP 217	13	Benzene	2,600,000	2,500,000	
GP 217	15	Benzene	690,000	720,000	
GP 217	17	Benzene	440,000	540,000	
GP 218	9	Benzene	420,000	210,000	-40%
GP 218	11	Benzene	2,600,000	1,600,000	
GP 218	13	Benzene	1,900,000	560,000	
GP 218	15	Benzene	690,000	670,000	
GP 218	17	Benzene	490,000	570,000	
GP 219	9	Benzene	2,300	-	-17%
GP 219	11	Benzene	94,000	-	
GP 219	13	Benzene	1,100,000	820,000	
GP 219	15	Benzene	910,000	1,000,000	
GP 219	17	Benzene	650,000	450,000	
GP 220	9	Benzene	64,000	53,000	11%
GP 220	11	Benzene	460,000	460,000	
GP 220	13	Benzene	1,000,000	1,600,000	
GP 220	15	Benzene	610,000	700,000	
GP 220	17	Benzene	450,000	430,000	
EBR-1 ⁽¹⁾	9	Benzene	680,000	-	-35%
EBR-1	11	Benzene	2,600,000	-	
EBR-1	13	Benzene	2,100,000	830,000	
EBR-1	15	Benzene	640,000	910,000	
EBR-1	17	Benzene	470,000	680,000	
EBR-1 ⁽²⁾	9	Benzene	383,075	-	-37%
EBR-1	11	Benzene	1,848,500	-	
EBR-1	13	Benzene	1,925,000	830,000	
EBR-1	15	Benzene	732,500	910,000	
EBR-1	17	Benzene	512,500	680,000	



Unfractured Area

- Post pilot samples collected ~60 days after system shutdown
- Rebound observed between shutdown and sampling
- Benzene results:
 - Only select locations were sampled
 - Decreases observed in three locations (GP-218/GP-219/EBR-U1)
- High initial Bz soil conc. in this area

Pilot Study – Overall GW Benzene Changes (Fractured Area)

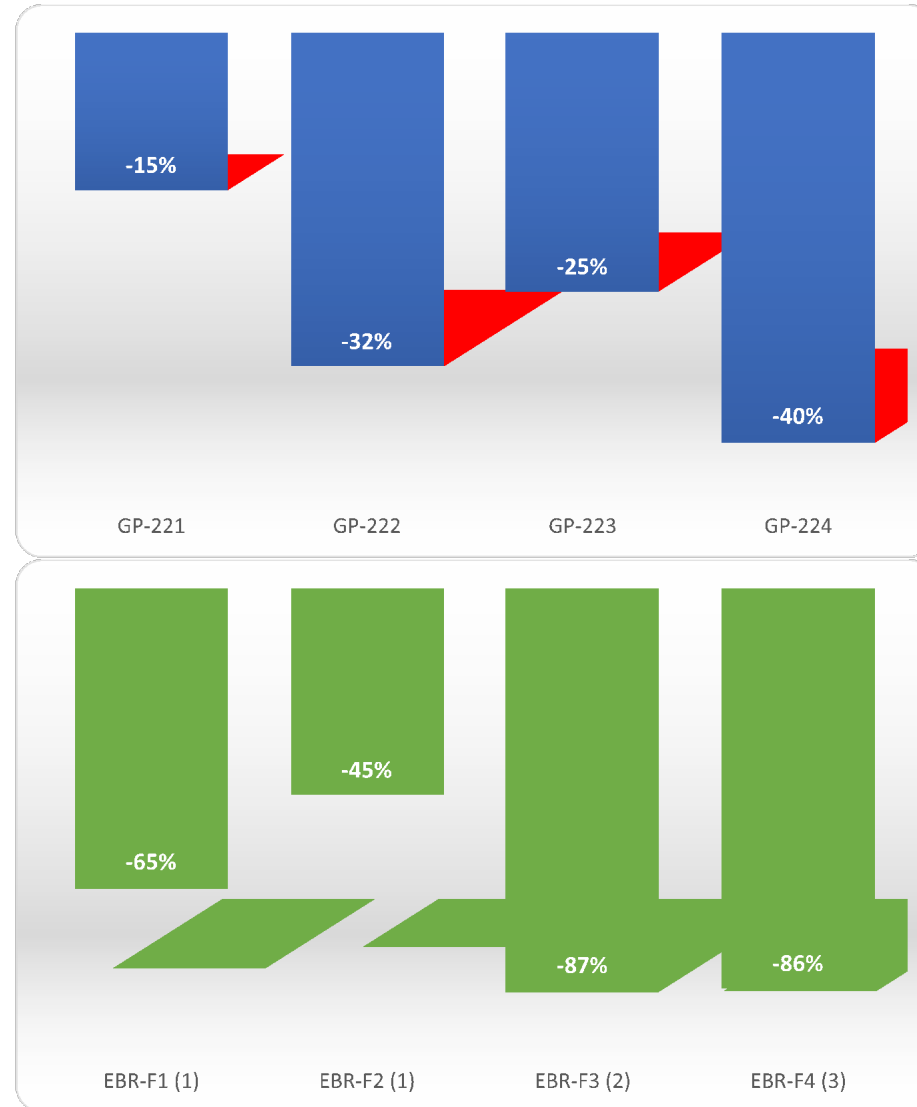


Fractured Area

- EBR™ wells > PZs >> MWs
- ROIs estimated at 15-20-ft
- Changes in % reduction decrease with distance away from EBR reactor
- Longer operation time would continue to enhance observed concentration reductions
- Fractures appear to have improved ROI and concentration

Pilot Study – Overall Soil Benzene Changes (Fractured Area)

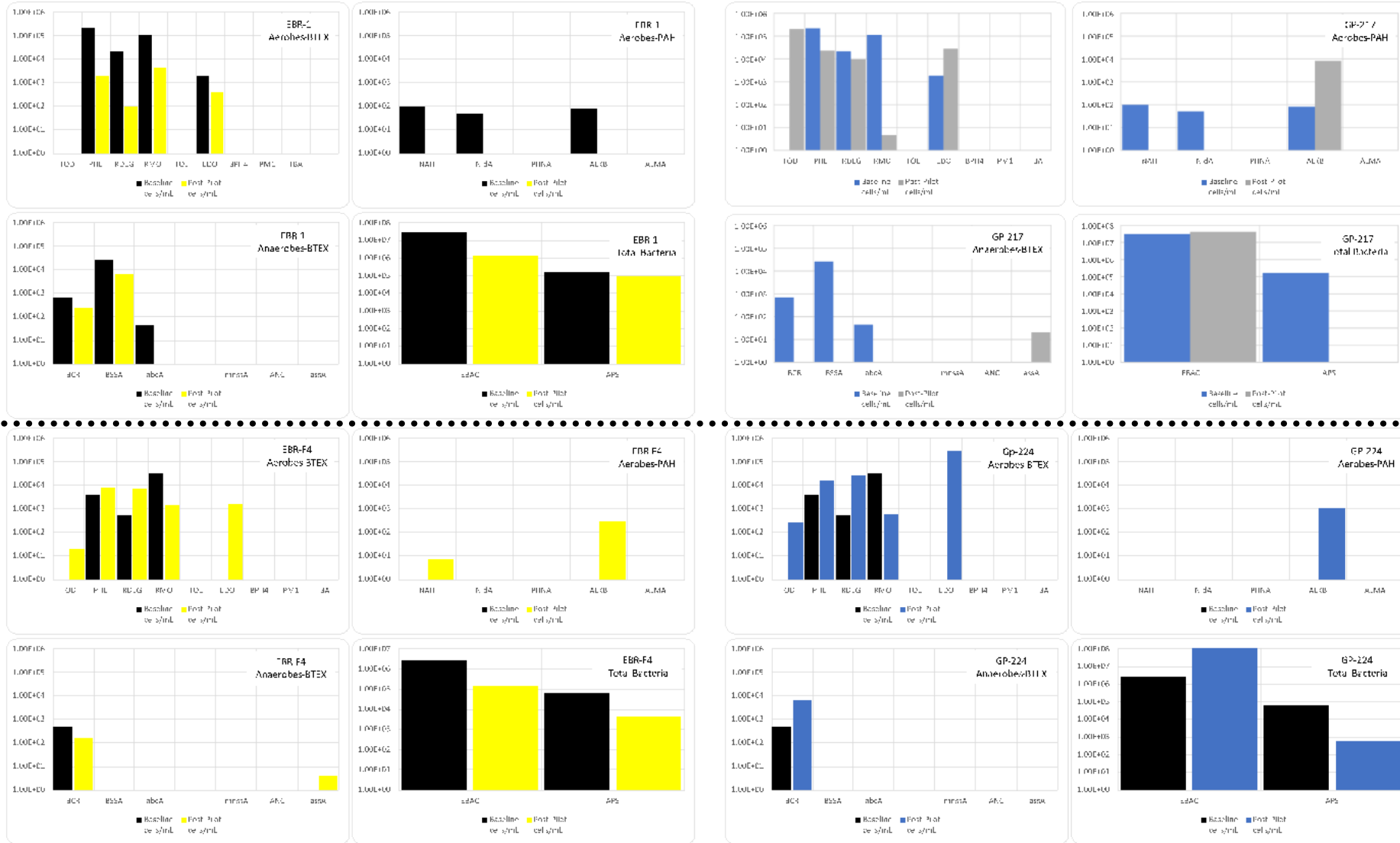
Sample ID	Depth	Constituent	Base Benzene µg/kg	Post Benzene µg/kg	%Change Conc.	Overall % Change
GP-221	9	Benzene	79,000	1,700	-98%	-15%
GP-221	11	Benzene	160,000	400,000	150%	
GP-221	13	Benzene	660,000	75,000	-89%	
GP-221	15	Benzene	440,000	320,000	-27%	
GP-221	17	Benzene	230,000	200,000	-13%	
GP-222	9	Benzene	110,000	79,000	-28%	-32%
GP-222	11	Benzene	370,000	240,000	-35%	
GP-222	13	Benzene	770,000	330,000	-57%	
GP-222	15	Benzene	400,000	350,000	-13%	
GP-222	17	Benzene	410,000	290,000	-29%	
GP-223	9	Benzene	150,000	120,000	-20%	-25%
GP-223	11	Benzene	200,000	87,000	-57%	
GP-223	13	Benzene	220,000	130,000	-41%	
GP-223	15	Benzene	530,000	320,000	-40%	
GP-223	17	Benzene	320,000	420,000	31%	
GP-224	9	Benzene	100,000	120	-100%	-40%
GP-224	11	Benzene	390,000	150,000	-62%	
GP-224	13	Benzene	990,000	780,000	-21%	
GP-224	15	Benzene	590,000	470,000	-20%	
GP-224	17	Benzene	240,000	250,000	4%	
GP-225	9	Benzene	65,000	19,000	-71%	338%
GP-225	11	Benzene	330,000	210,000	-36%	
GP-225	13	Benzene	460,000	520,000	13%	
GP-225	15	Benzene	140,000	320,000	129%	
GP-225	17	Benzene	740	13,000	1657%	
EBR-F1 ⁽¹⁾	9	Benzene	79,000	340	-100%	-65%
EBR-F1	11	Benzene	160,000	120,000	-25%	
EBR-F1	13	Benzene	660,000	200,000	-70%	
EBR-F1	15	Benzene	440,000	1,000,000	127%	
EBR-F1	17	Benzene	230,000	440,000	91%	
EBR-F2 ⁽²⁾	9	Benzene	79,000	1,300	-98%	-45%
EBR-F2	11	Benzene	160,000	110,000	-31%	
EBR-F2	13	Benzene	660,000	630,000	-5%	
EBR-F2	15	Benzene	440,000	690,000	57%	
EBR-F2	17	Benzene	230,000	240,000	4%	
EBR-F3 ⁽²⁾	9	Benzene	100,000	830	-99%	-87%
EBR-F3	11	Benzene	390,000	120,000	-69%	
EBR-F3	13	Benzene	990,000		-100%	
EBR-F3	15	Benzene	590,000	95,000	-84%	
EBR-F3	17	Benzene	240,000	40,000	-83%	
EBR-F4 ⁽³⁾	9	Benzene	100,800	74	-100%	-86%
EBR-F4	11	Benzene	290,000	920	-100%	
EBR-F4	13	Benzene	620,000	130,000	-79%	
EBR-F4	15	Benzene	420,000	160,000	-62%	
EBR-F4	17	Benzene	240,148	21,000	-91%	



Fractured Area

- Samples collected ~20 days after shutdown
- Significantly less rebound observed
- Benzene results:
 - Decreases observed at EBR™ and MW locations
 - Decrease more pronounced @ EBR™ wells; decreases @ MWs lower and likely due to rebound
- Lower initial Bz concentrations in this area
- Longer operation time would further reduce soil concentrations

Microbial Populations



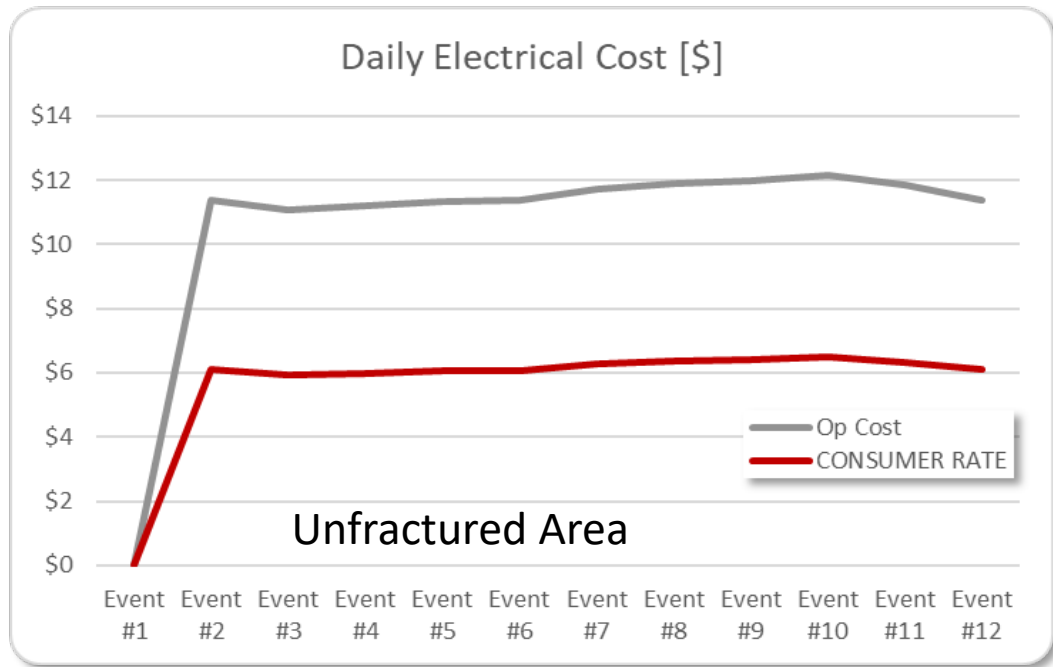
Unfractured Area

- Decrease between Baseline and Post-Pilot samples
- Decrease in aerobes (not expected); Decrease in anaerobes (expected)
- Follow-on enhanced biological processes may be inhibited by elevated soil and groundwater concentrations

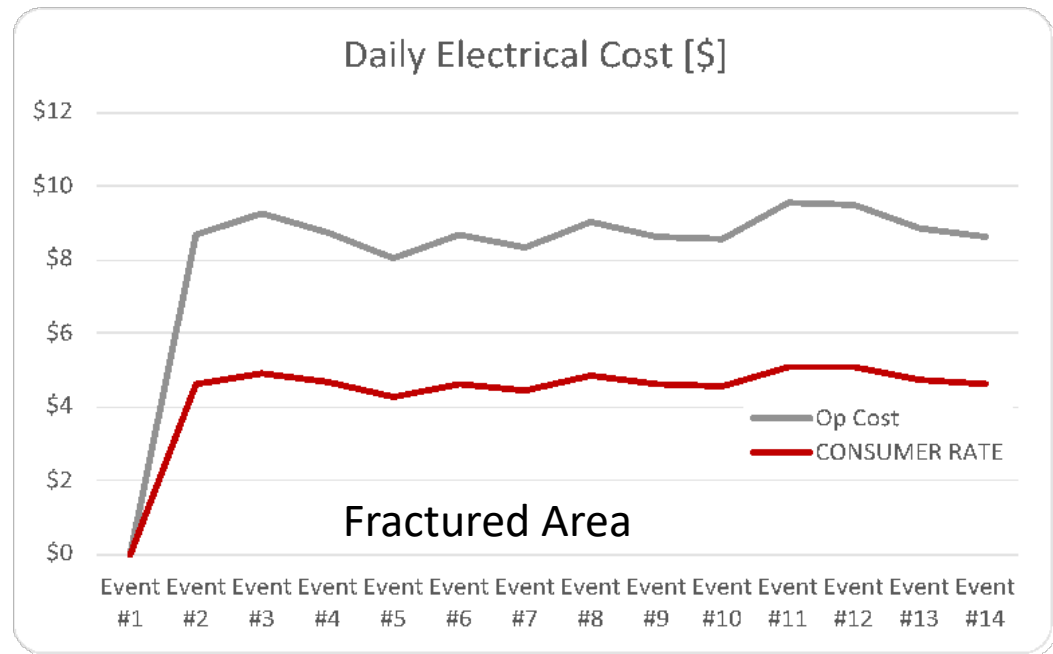
Fractured Area

- Slightly higher aerobic populations following shutdown; little to no anaerobes detected as expected
- Follow-on enhanced biological processes expected, but may still be inhibited

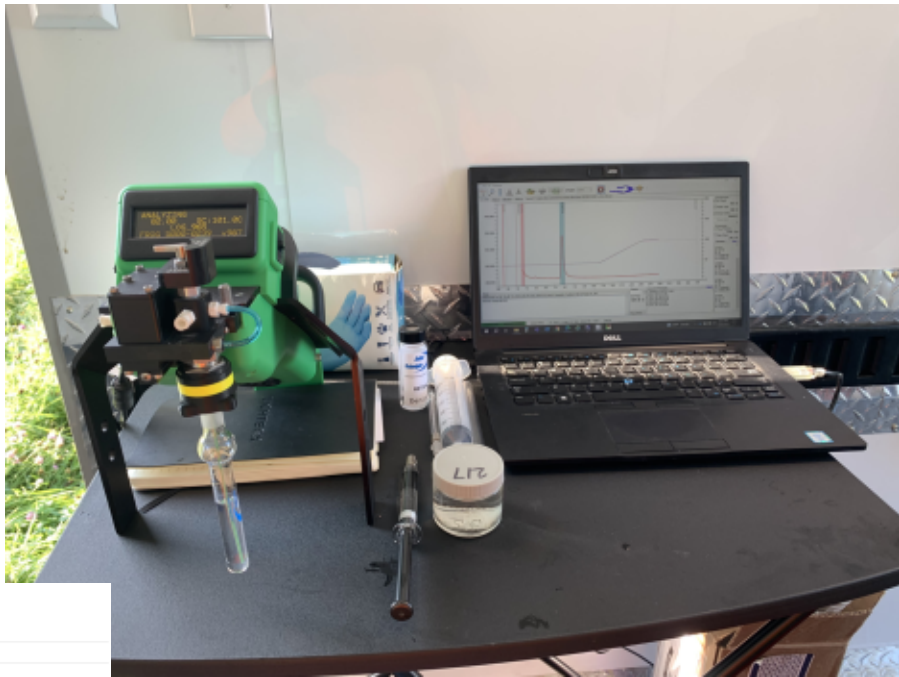
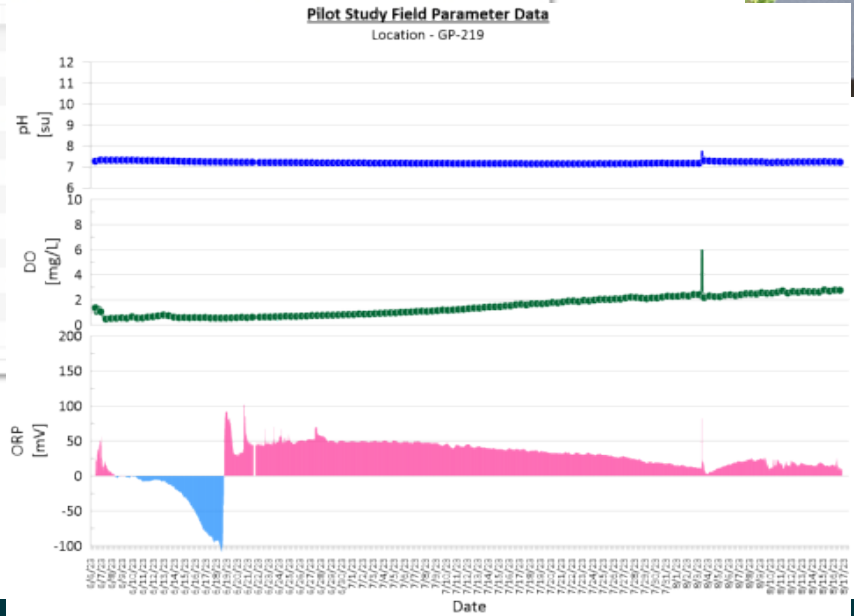
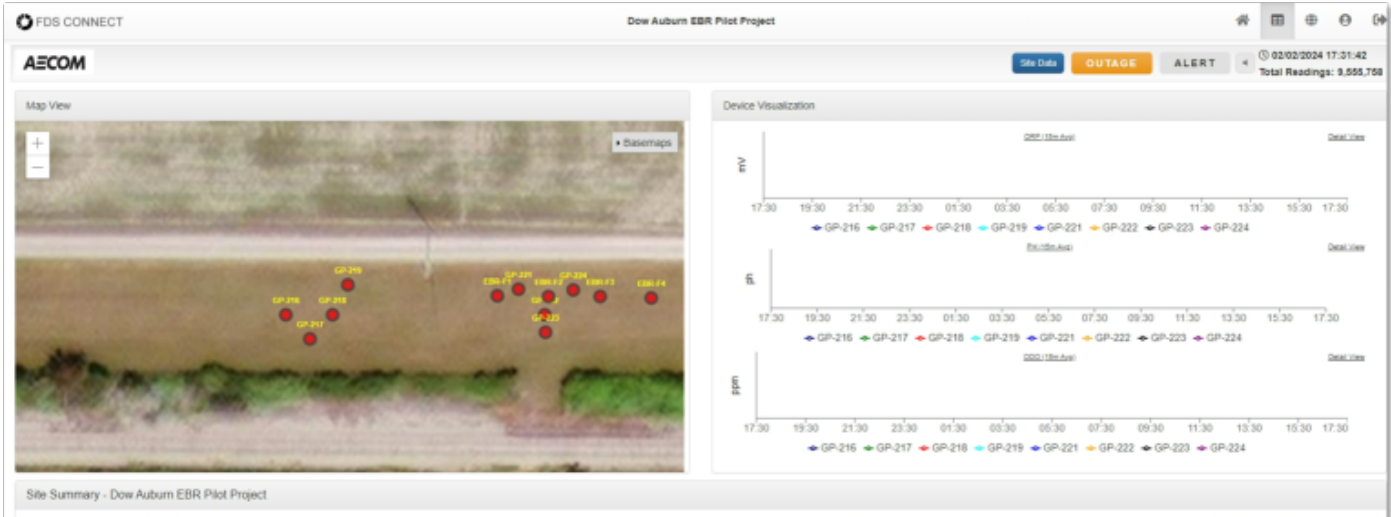
Power Consumption



- Unfractured Area - Operating costs included Control panel, 4-EBR™ wells, downhole sondes, Field GC, laptop, and misc. power tools during operations
- Fractured Area - Operating costs included Control panel, 4-EBR™ wells, downhole sondes, and misc. power tools during operations
- Electrical costs minimal - \$4 to \$12/day



Real-time Monitoring Interface and Field GC



05

Conclusions Lessons Learned

Conclusions – Unfractured Area

- Nearly 100% run-time over 94 days
- Real-time monitoring interface also 100% uptime
- O&M consisted only of monthly EBR reactor cleaning

RESULTS

- pH remained stable (7-8 s.u.)
- DO increases - EBR™ wells (immediate); MWs/PZs (~40 days)
- Observed propagating ROI
- Bz (GW) decreased immediately in the EBR™ wells → PZs (slight delay) → MWs (delay)
- Percentage decreases EBR™ > PZs > MWs (>99.9% [EBR-U1/4] to 63% [GP-219])

RESULTS (cont.)

- Bz (Soil) decreased moderately in the EBR™ wells (~25%); variable in MWs (30% to +20%)
- Rebound due to sampling delays
- No remarkable microbial changes
- Operational costs - \$6 to \$12 per day

OPERATIONAL DETAILS

- Inferred ROI - ~15 feet (~90 days)
- Indicated reactor spacing at no more than 25 feet
- Single reactors in each well will be sufficient
- Operational time frame - Full-scale at least to 12 months

Conclusions – Fractured Area

- Nearly a 100% run-time over 94 days
- Real-time monitoring performed well, with nearly 100% uptime, however:
 - Real-time sonde issues (multiple electrical field interferences); hand measurements implemented
- O&M consisted only of monthly EBR reactor cleaning

RESULTS

- pH remained stable (7-8 s.u.)
- DO increases – EBR™ wells (immediate); MWs/PZs (~30 days)
- Positive effect from fracturing (PZs close to EBR-F4)
- Bz (GW) decreased immediately in EBR™ wells; delays in PZs/MWs (<Unfractured Area)
- Percentage decreases EBR > PZs > MWs (>99.9% [EBR-F4] to ↑60% **[GP-221/224])

RESULTS (cont.)

- Bz (Soil) decreased notably in EBR™ wells (85%); MWs (up to 40%)
- Some rebound due to sampling delays
- Microbial conditions appear more diverse
- Operational costs - \$4 to \$9 per day

OPERATIONAL DETAILS

- Inferred ROI - slightly larger >15 feet (~90 days)
- Indicated reactor spacing could expand (25-30 ft.)
- Single reactors in each well will be sufficient
- Operational time frame - Full-scale at least 9-12 months (enhanced from Unfractured Area)

Lessons Learned

- EBR™ System was demonstrated robust and successful at reducing both dissolved phase groundwater and soil benzene impacts
- Real-time monitoring would be valuable; interference issues should be revisited versus hand measurements
- Estimated power (i.e., operational costs) significantly less than the current MPE remedy
- Fracturing may have advantages related to decreased operational time, ROI, and soil/groundwater benzene mass reductions
 - More detailed economic evaluation and larger scale testing needed before recommending hydraulic fracturing
- Consideration, planning, and initial design of a full-scale EBR™ System is ongoing
- Evaluating potential alternative use of EBR reactors to concurrently treatment of water within existing GW Collection trench to enhance operational efficiency of EBR™ System

THANK YOU!



Doug Gray
Innovative Remediation Technologies
Group Leader



AECOM