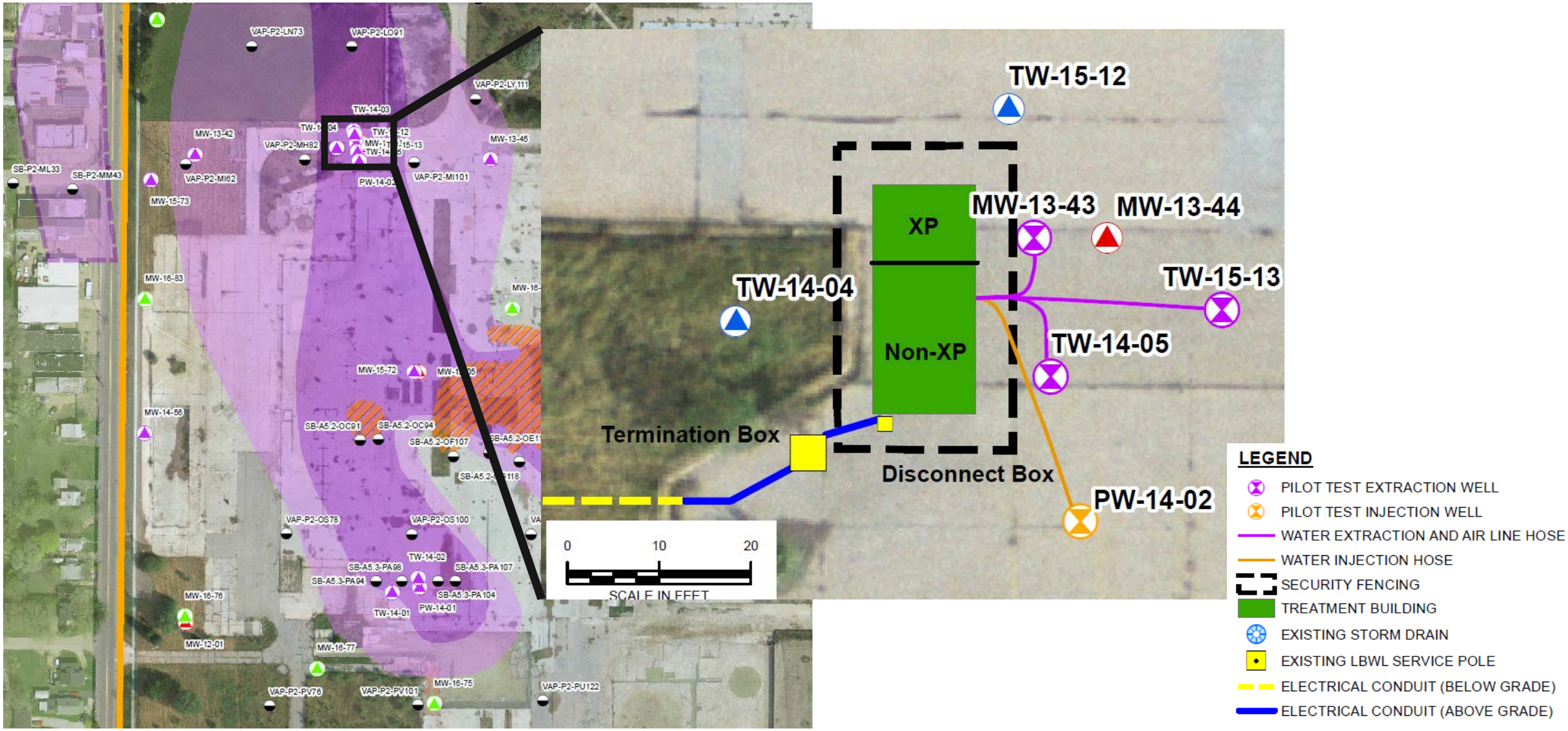
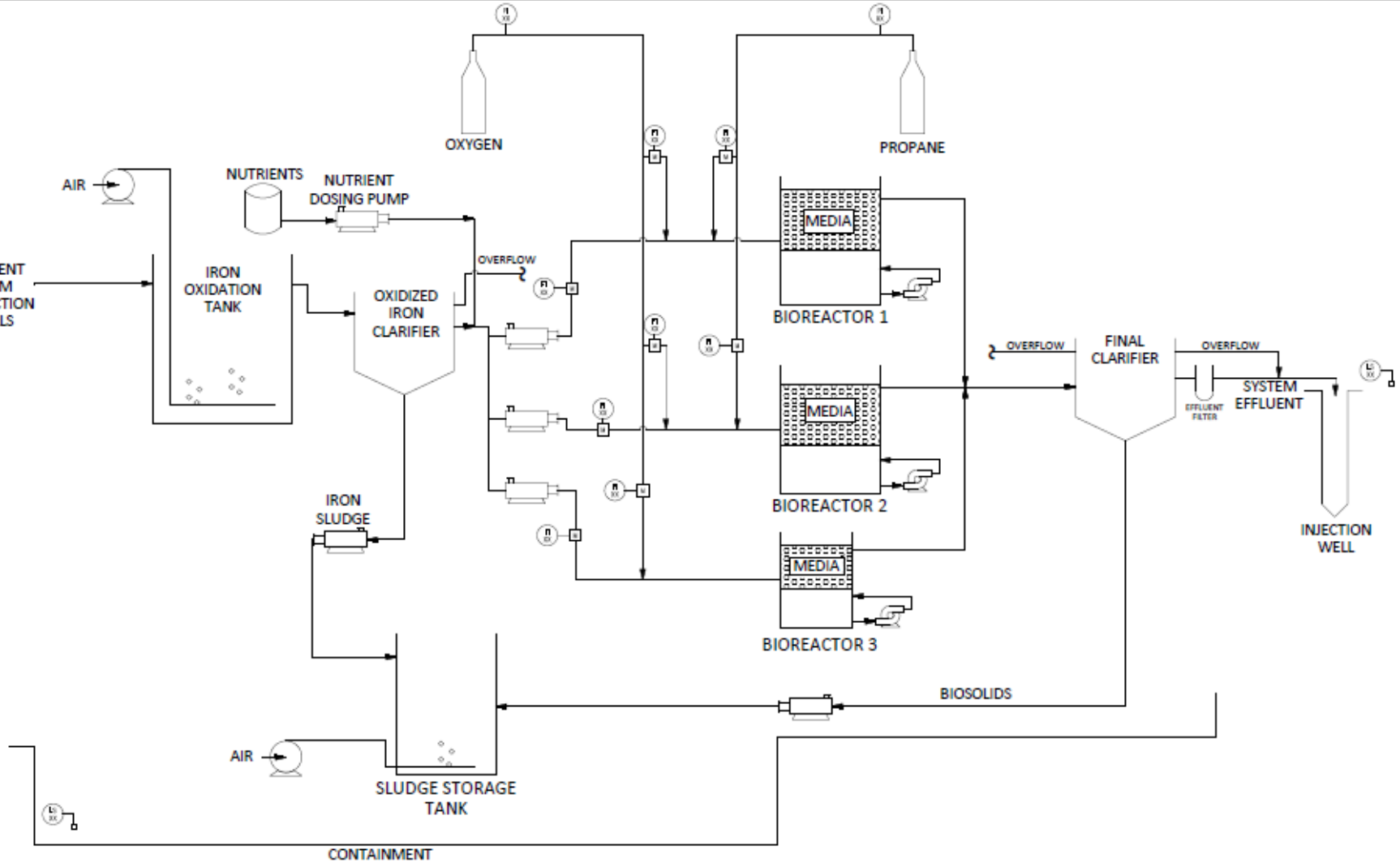
Bioreactor

Bioreactor Pilot Test Objectives

- Evaluate effectiveness and cost savings of bioreactors compared to AOP
- Test different two bacterial cultures (metabolic and co-metabolic) for 1,4-dioxane degrading ability
- Test different hydraulic residence times to determine full-scale system sizing
- Determine system resiliency to upset conditions

Bioreactor Pilot Test Layout





Bioreactor Process Flow Diagram

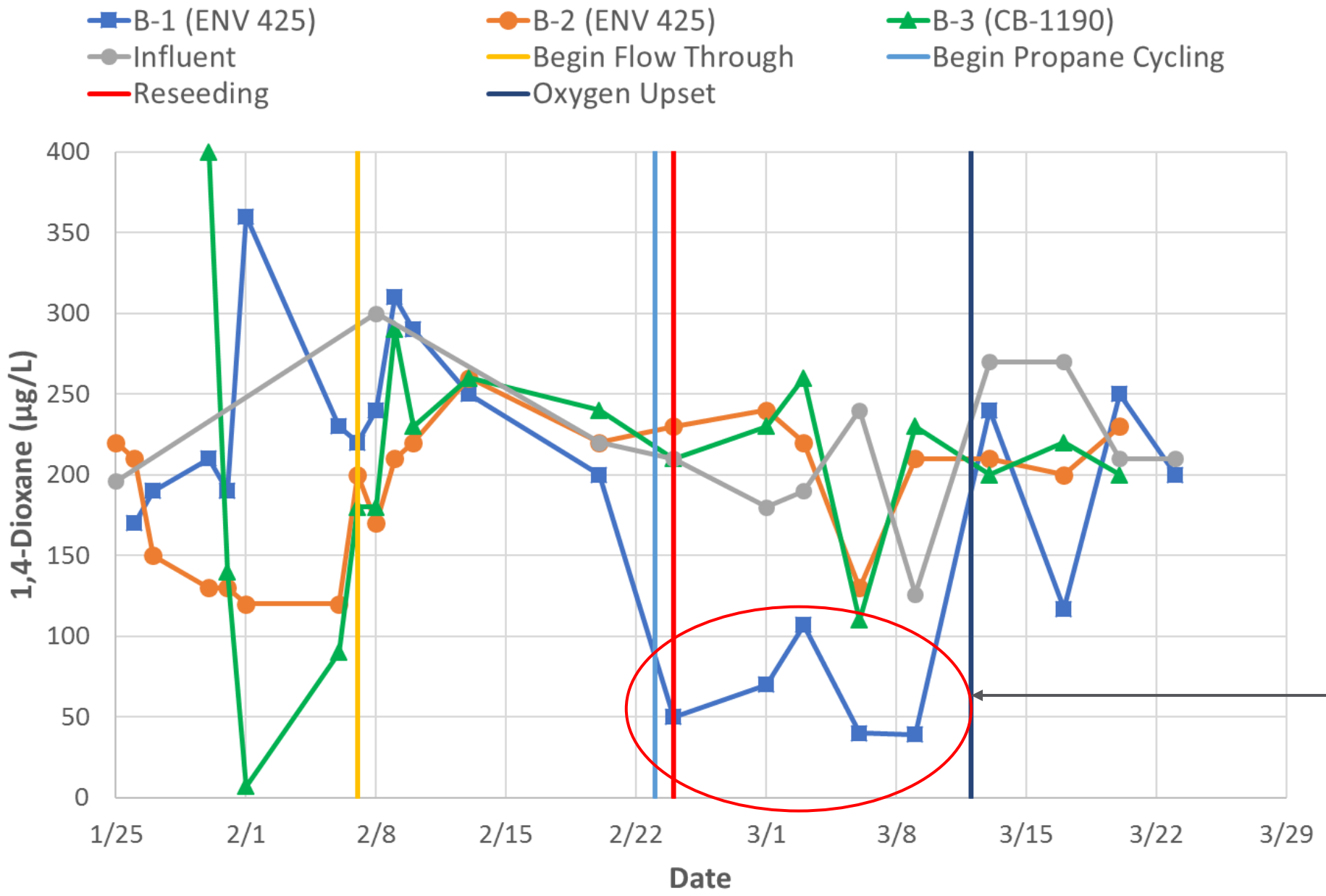
Bioreactor Pilot Test

- Extracted groundwater out of MW-13-43, TW-15-13, and TW-14-05 (0.6 – 1.2 gpm)
- Injection into PW-14-02
- Bioreactors
  - B-1 and B-2 seeded with ENV 425 co-metabolic biodegradation requiring propane and oxygen
  - B-1 changed to propane cycling during test (30 min on – 30 min off)
  - B-3 seeded with CB 1190 metabolic biodegradation requiring oxygen only
  - Plastic media with high surface area to promote bio-growth
  - Height is based on head required to keep gases in solution
  - Each bioreactor 0.2 – 0.4 gpm under flow through conditions

Timeline

Event	Date
System delivered to site	December 21, 2016
System modifications and injection well troubleshooting	December 21, 2016 – January 23, 2017
Seeded bioreactors and started-up in batch mode	January 25
Began flow-through mode	February 7
Converted bioreactor #1 to propane cycling	February 22
Reseeded bioreactors #1 and #2 and increased residence time	February 23
Oxygen upset	March 12
Replaced oxygen	March 13
Ended pilot study	March 27

Results



Treatment to 40-100 ug/L with propane cycling in B-1

Result Summary

- Bioreactors 1 and 2 (ENV 425)
  - No decrease in 1,4-dioxane with constant propane feed
  - 50% reduction in 1,4- dioxane with propane feed cycling on and off to between 40 and 100 ppb
  - Consistent reduction in 1,4-dioxane was not resumed after the oxygen upset
  - Multiple lines of evidence that iron oxidizing bacteria were outcompeting the propanotrophs
    - Orange color in bioreactor
    - Post pilot samples showed DNA and mRNA iron oxidizers multiple orders of magnitude higher than propane oxidizers
- Bioreactor #3 (CB1190)
  - Initial decrease from 3,200 to 5 ug/L (1,4-dioxane spiked culture)
  - No decrease in 1,4-dioxane from influent concentration (~200 ppb) once flow through conditions with Site groundwater began
- Biofouling of the injection well reduced injection capacity over time

B-1 Significant biogrowth on media

B-3 Minimal biogrowth on media

Bioreactor vs. AOP

	Bioreactor	AOP
Treatment	Pilot achieved 70 ppb, potential for the technology to reach ~7 ppb, likely not feasible to get lower	Can treat to below 1 ppb consistently and reliably
Reliability	Days to weeks to recover from an upset condition	Tried and true technology, full treatment immediately upon addressing upset condition (mechanical failure, power outage, etc.)
Energy Requirements	Relatively high energy requirements for bioreactor due to vessel, pump, and blower size requirements due to low 1,4-dioxane concentrations and retention time requirements (approx. equal to AOP energy requirements)	Relatively low energy requirements for AOP due to low 1,4-dioxane loading and minimal scavengers present in groundwater (approx. equal to bioreactor energy requirements)

Bioreactor will not be carried forward. Remedies evaluated requiring abovegrade treatment will include AOP