A Tale of Two Remediation Systems

MPE source treatment + pulsed oxygen biosparging plume treatment at a well site

RemTech 2026

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worley consulting

Road Map for the Talk



SITE CONDITIONS

01 **Site setting, history & conceptual site model**

Site overview and key elements of the CSM

02 **Excavation**

Initial source removal and what it accomplished

03 **Multiphase extraction (MPE)**

Pilot testing, full-scale design, performance and NSZD end point

04 **Pulsed oxygen biosparging (POBS)**

Rationale, operation, and evidence of effectiveness

05 **Lessons learned**

When to stop, the role of natural depletion, and takeaways

The legacy source began with a 1959 well and petroleum-based drilling mud



COMPANY [redacted]

CONTRACTOR Hi-Tower

DAILY REPORT

Name of Well [redacted] No. [redacted]

DATE Aug 13/59

BOARD COPY (TO BE SENT TO BOARD FIELD OFFICE)

	FIRST TOUR								SECOND TOUR								THIRD TOUR							
DEPTH	Start of Tour		Hole Made This Tour		End of Tour				Start of Tour		Hole Made This Tour		End of Tour				Start of Tour		Hole Made This Tour		End of Tour			
	7038		19		7057				7057		13		7070				7070		18		7088			
TIME	On Bottom		Off Bottom		On Bottom		Off Bottom		On Bottom		Off Bottom		On Bottom		Off Bottom		On Bottom		Off Bottom		On Bottom		Off Bottom	
	6		2														5 3/4		4 1/4					
BIT RECORD	Size	No.	Type	Condition	Pt. Wt.	R.P.M.	Ft. Dld.	Bit-hrs.	Size	No.	Type	Condition	Pt. Wt.	R.P.M.	Ft. Dld.	Bit-hrs.	Size	No.	Type	Condition	Pt. Wt.	R.P.M.	Ft. Dld.	Bit-hrs.
	9	22	W7	Rim	30000	90	19	6	9	22	W7			90	32	11 3/4	9"	23	2W7	R	17	90	18	3 3/4
DRILL PIPE	Size	Stands	Singles	Drill Collar		Kelly		Core Bbl.	Size	Stands	Singles	Drill Collar		Kelly		Core Bbl.	Size	Stands	Singles	Drill Collar		Kelly		Core Bbl.
	4½	73	2	11		22			4½	73	2	324.88		9			4½	74	—	324.88		22		
MUD RECORD	Time	Weight	Vis.	Gel Str.	pH	Am't Added		Kind	Time	Weight	Vis.	Gel Str.	pH	Am't Added		Kind	Time	Weight	Vis.	Gel Str.	pH	Am't Added		Kind
	2	10.9	93		8.5	50 lbs		Crude Oil	10	11.0	150			550# Carbonox			6		Bottom					
	4	10.9	95			15 bags		Carbox	12	11.0	110			50# Quebracho			8							
	6	10.9	95		8.5				2	11.0	120			500# Gel			10	10.9	125		8.0			
	8	10.8	94						4								12	10.8	130					
RING	Time	From	To	Ft. Cut		Ft. Rec'd		Type	Time	From	To	Ft. Cut		Ft. Rec'd		Type	Time	From	To	Ft. Cut		Ft. Rec'd		Type
VEY	Type	Depth		Degrees Off	Direction				Type	Depth		Degrees Off	Direction				Type	Depth		Degrees Off	Direction			
NG	Size	Amount	Set @ K.B.	Wt./Ft.	New/Used	Cement		Additives	Size	Amount	Set @ K.B.	Wt./Ft.	New/Used	Cement		Additives	Size	Amount	Set @ K.B.	Wt./Ft.	New/Used	Cement		Additives
RAT-	From	To	Shot/Ft.	From	To	Shot/Ft.		Type	From	To	Shot/Ft.	From	To	Shot/Ft.		Type	From	To	Shot/Ft.	From	To	Shot/Ft.		Type
NG	From	To	Amount Gals.	Kind	Breakdown Press.	Final Press.		Feed Rate Bbls./Min.	From	To	Amount Gals.	Kind	Breakdown Press.	Final Press.		Feed Rate Bbls./Min.	From	To	Amount Gals.	Kind	Breakdown Press.	Final Press.		Feed Rate Bbls./Min.
S	No.	Interval Tested		to					No.	Interval Tested		to					No.	Interval Tested		to				
	Valve Open		min.	Shut in		mins.			Valve Open		min.	Shut in		mins.			Valve Open		min.	Shut in		mins.		
	Gas to Surface		min. @			Mcf/d Max.			Gas to Surface		min. @			Mcf/d Max.			Gas to Surface		min. @			Mcf/d Max.		
	Oil to Surface		min. @			Bbl/d Max.			Oil to Surface		min. @			Bbl/d Max.			Oil to Surface		min. @			Bbl/d Max.		
	Recovery:	ft.							Recovery:	ft.							Recovery:	ft.						
		ft.								ft.								ft.						

Legacy inputs created a long-lived source in bedrock and groundwater, later interacting with a forested wetland receptor.

HISTORICAL SOURCES AND CONCEPTUAL SITE MODEL

DRILLING MUD

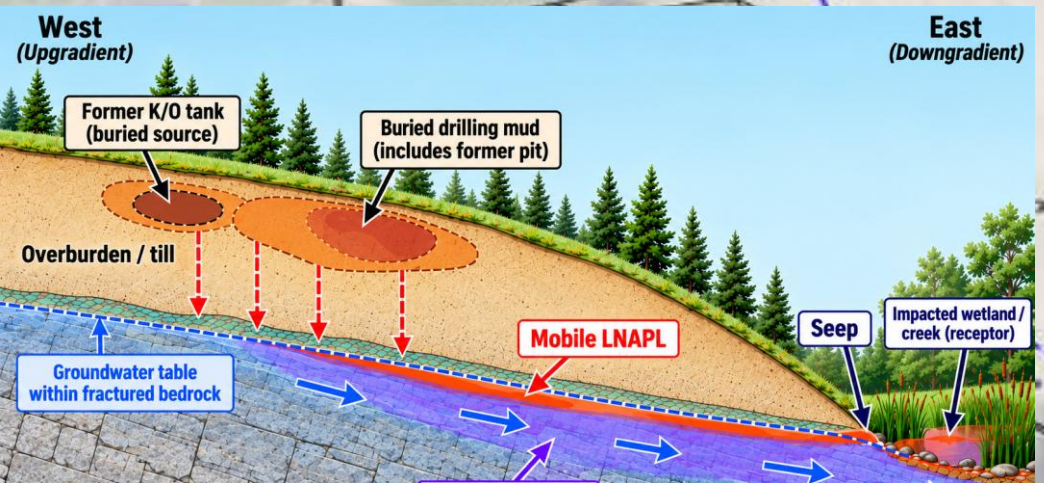
SEEP



1963 FLARE PIT

GROUNDWATER FLOW

K/O UST



Excavation

First major remedial step: bulk source removal



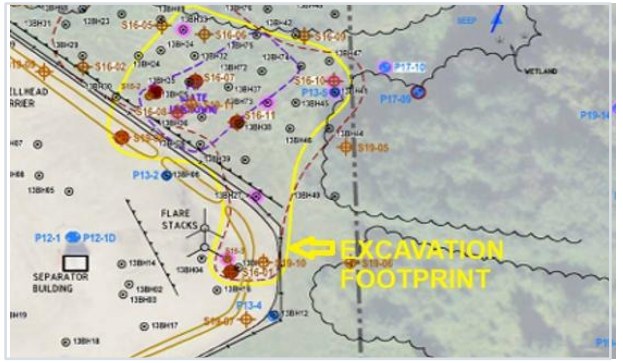
Open source-zone excavation

1 **~9,500 tonnes**
of impacted soil removed during the 2020 source-zone excavation.

2 **Accessible source**
Targeted shallow PHC-impacted soil where it could be physically removed.

3 **To bedrock where practical**
Excavation reduced bulk mass, but did not eliminate all source material.

4 **Residual impacts remained**
Fractured bedrock and downgradient groundwater still required active treatment.



Excavation footprint



Backfilling after source removal

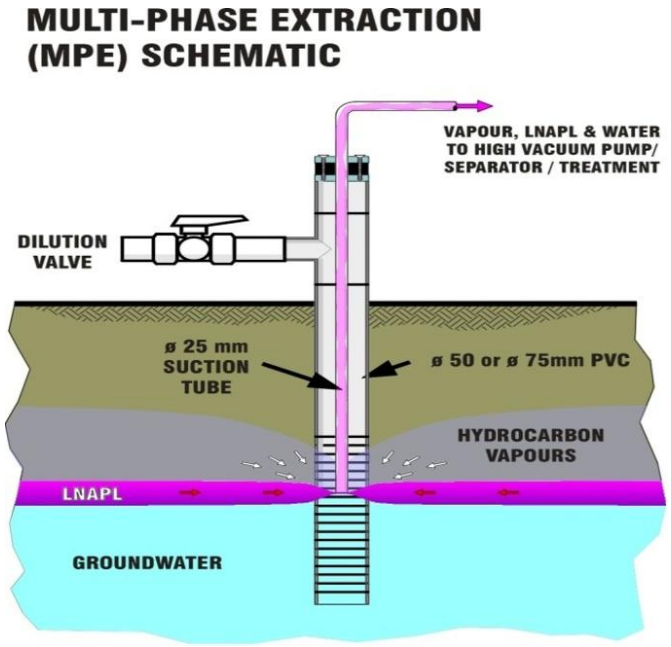
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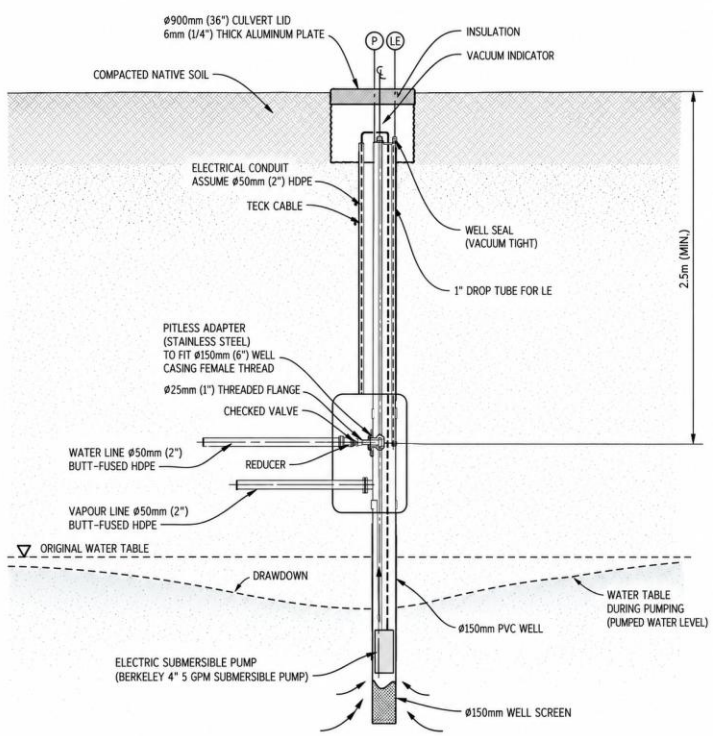
Multi-phase Extraction (MPE)

One technology family, two well configurations

Core idea: apply vacuum and/or pumping to recover vapour, groundwater and LNAPL from the same wellfield. Lower water table to extract residual NAPL with vapour flow

Pilot test configuration: stinger
Single vacuum line focused at the groundwater/LNAPL interface.





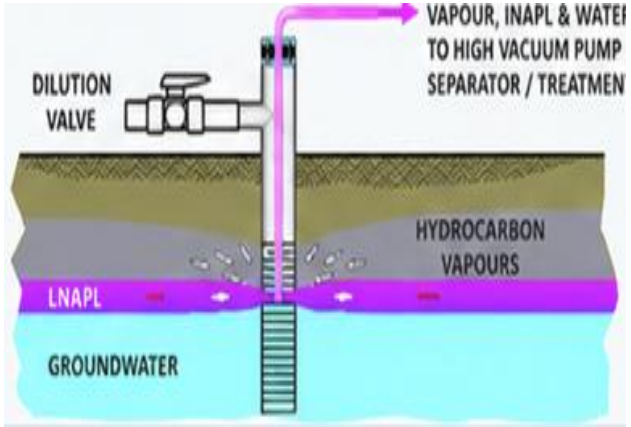
Full-scale configuration: groundwater pump + vapour line
Submersible pump lowers the water table; separate vapour extraction line applies vacuum.

Pilot Testing Confirmed MPE Feasibility

High-vacuum stinger configuration tested in fractured bedrock



Pilot-scale MPE test rig



Stinger configuration (schematic)

Pilot test results

HYDRAULIC RESPONSE

Groundwater drawdown observed at least 24 m from P17-10; seep flow temporarily ceased.

VACUUM INFLUENCE

Measurable response up to 50 m from P13-2.

OPERATING RANGE

Vapour flow 21–31 scfm; typical wellhead vacuum 8.6–10.3 in. Hg at P17-10.

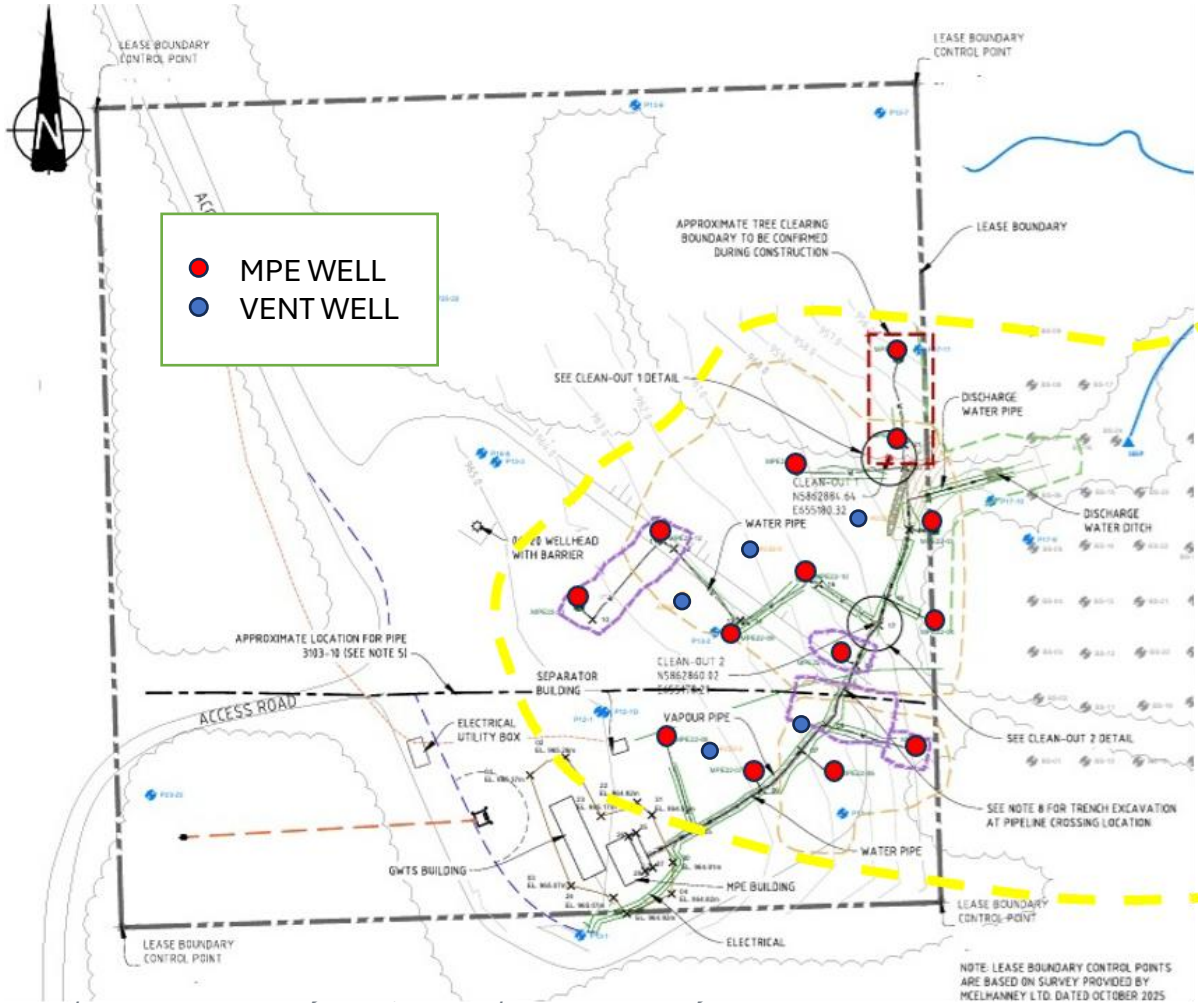
HYDROCARBON REMOVAL

Approximately 19.9 kg in vapour versus 1.9 kg in dissolved phase (excluding methane). Peak vapour recovery was 46 kg/day.

Conclusion **Pilot performance supported full-scale MPE for aggressive source-zone mass removal.**

From Pilot Test to Full-scale Design

Hydraulic response set the extraction-well spacing; airflow modelling refined the layout.



Pilot hydraulic response
Groundwater drawdown and seep response supported a maximum extraction-well spacing of about 20 m.

Airflow modelling
Air3D was used to verify vapour-phase coverage and refine passive vent locations.

Installed full-scale layout
14 MPE wells + 5 passive air vent wells. Design basis included 50 actual m^3/min vapour, 50 L/min groundwater, and -35 kPag vacuum.

Design logic: pilot response → hydraulic spacing → Air3D airflow check → passive vents → final layout

Full-scale MPE installation

The pilot design translated into a substantial year-round extraction and treatment system.



MPE wellfield installation: wells, buried water/vapour lines, and deep service trenches



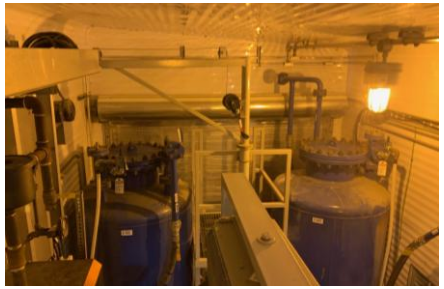
MPE and groundwater treatment buildings



Vapour manifold



V-100 knockout / vapour-liquid separation



Final polishing with bag filters and GAC

Full-scale treatment path

14 MPE wells
submersible pumps + vapour lines

➡

Vapour / liquid separation
knockout + blower

➡

Groundwater treatment
OWS / sparging / GAC

➡

Discharge
treated water release

We defined the MPE endpoint before startup

NSZD gave the active system a site-specific yardstick

1 Control plume and receptors

Treated discharge and downgradient surface water must meet applicable criteria.

2 Remove source mass aggressively

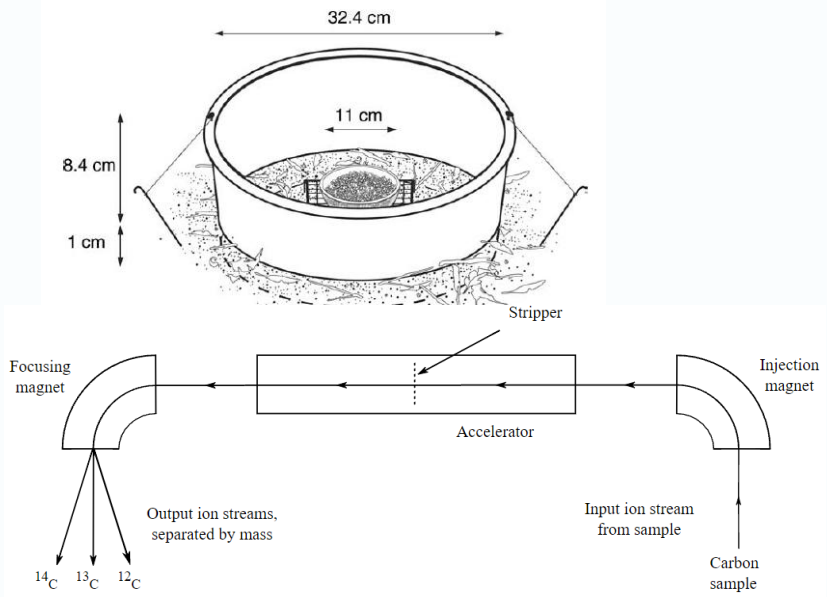
Operate MPE while engineered removal materially exceeds natural depletion.

3 Know when to stop

When sustained recovery approaches NSZD, reassess: optimize or shut down.

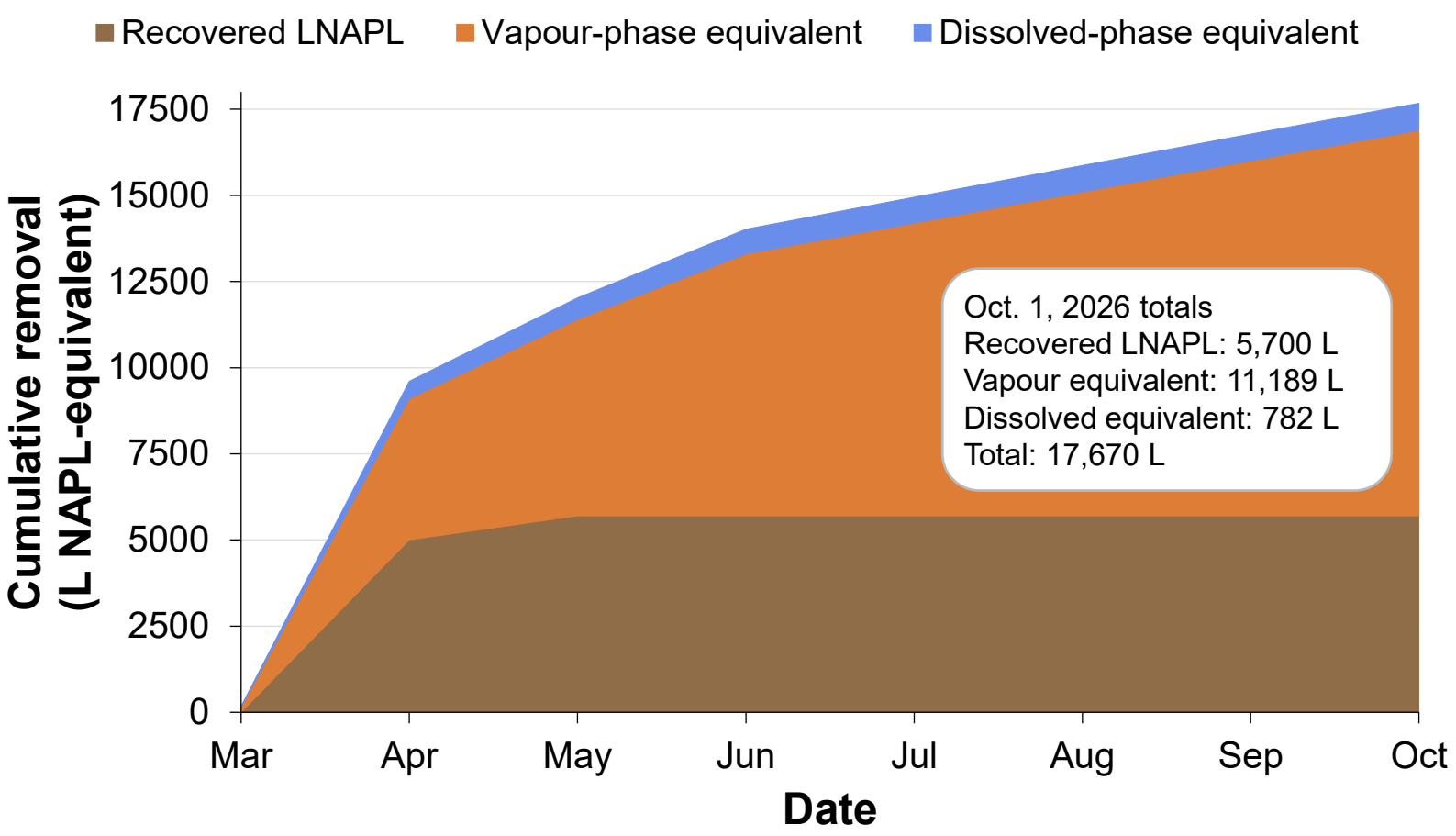
MPE-area NSZD benchmark

~300 L/yr



Endpoint logic: protect receptors → deplete source → compare active removal to NSZD → transition.

MPE Removed ~17.7 m³ NAPL-Equivalent in Seven Months



~17.7 m³

total hydrocarbon-equivalent removal

~5.7 m³

recovered LNAPL

~11.2 m³

vapour-phase equivalent

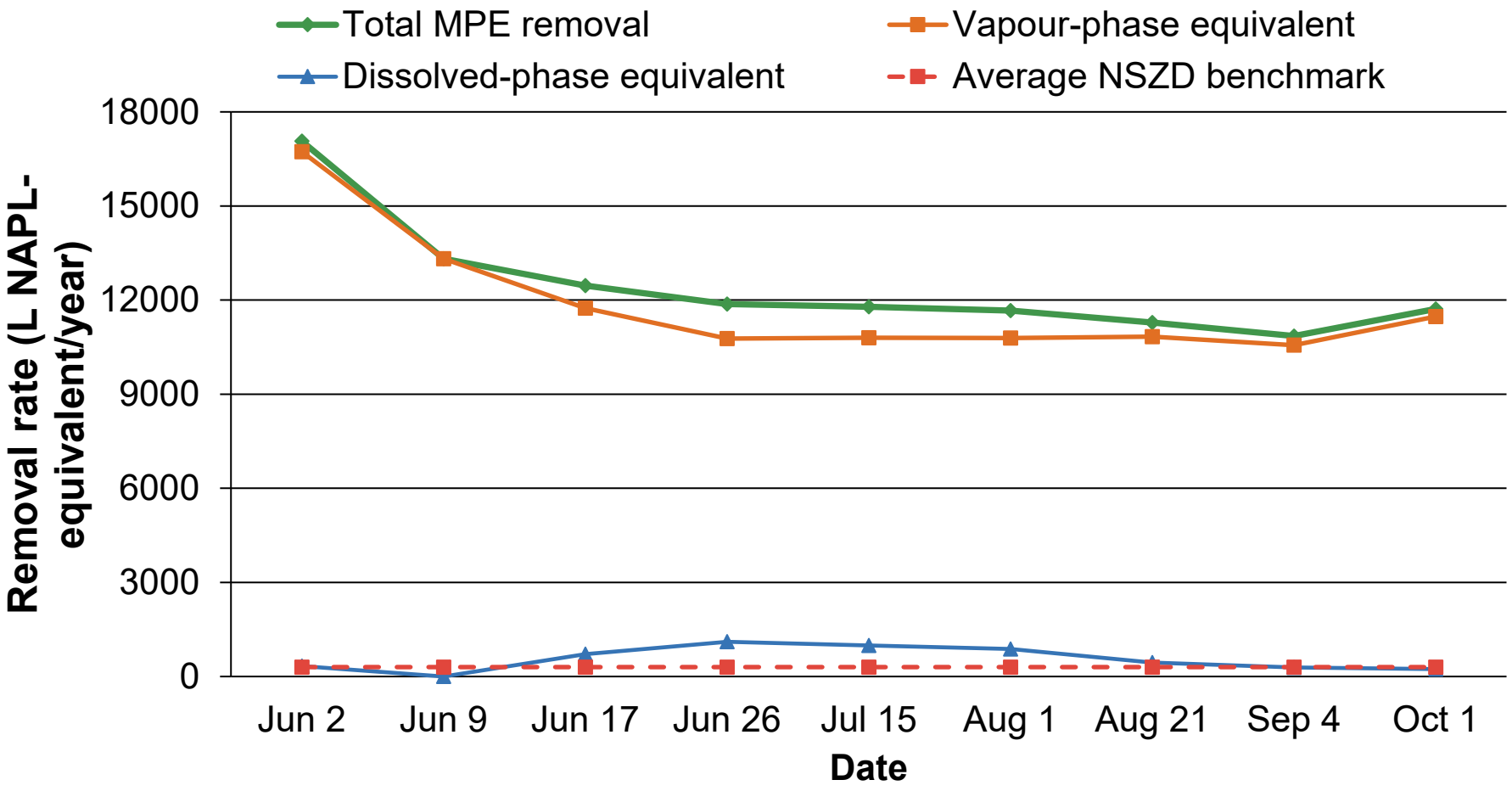
~0.8 m³

dissolved-phase equivalent

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MPE removal rate remains above NSZD

June 2 to October 1, 2026 — annualized removal rates expressed as L NAPL-equivalent/year



~11,700 L/yr
Oct. 1 total MPE removal rate

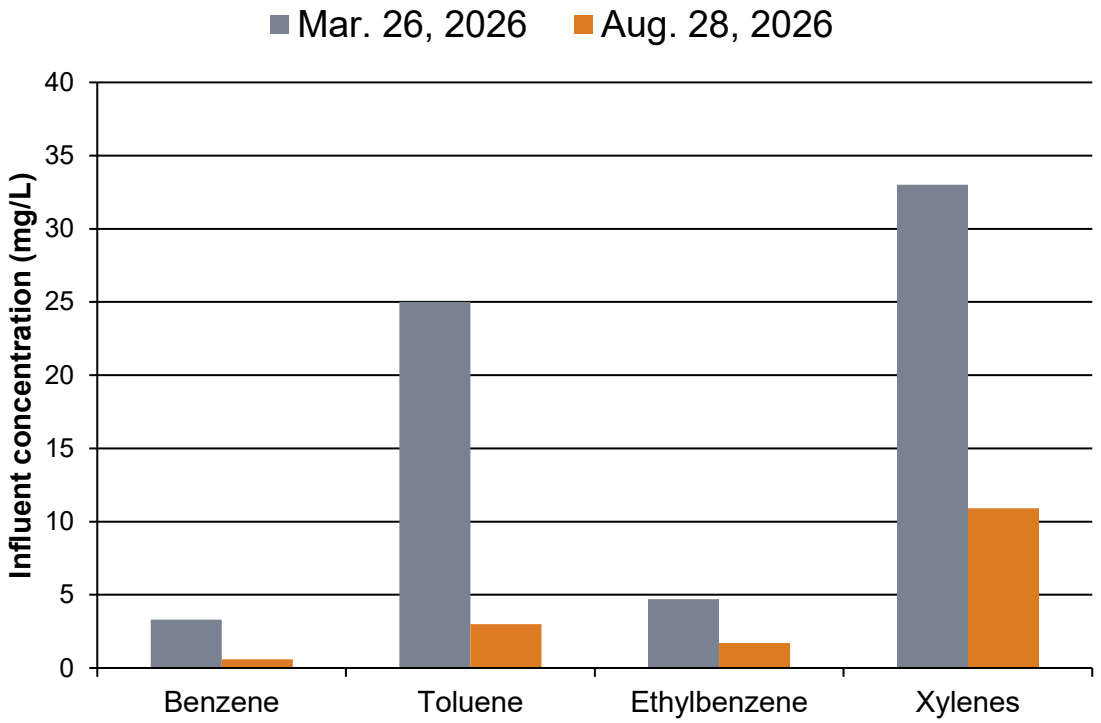
300 L/yr
average NSZD benchmark

Takeaway
Engineered removal was still far above measured NSZD rate.

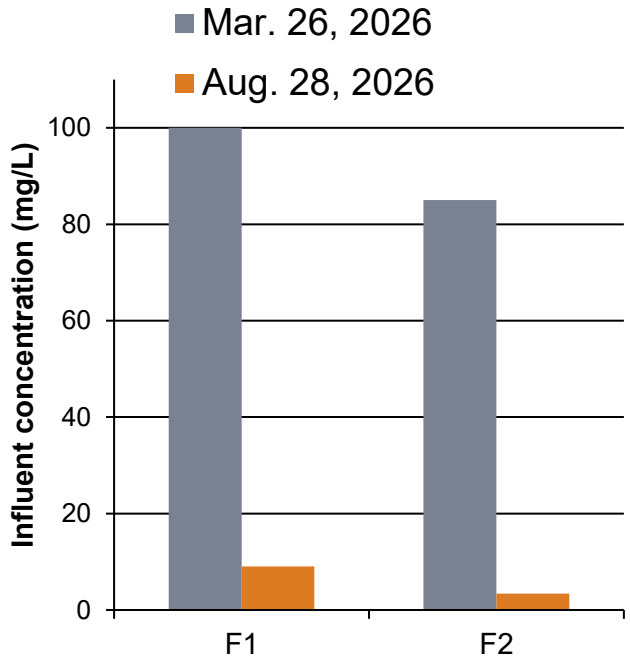
Extracted groundwater concentrations declined quickly after six months

March 26 → August 28, 2026

BTEX influent concentrations



PHC fraction influent concentrations



Percent reductions (BTEX)

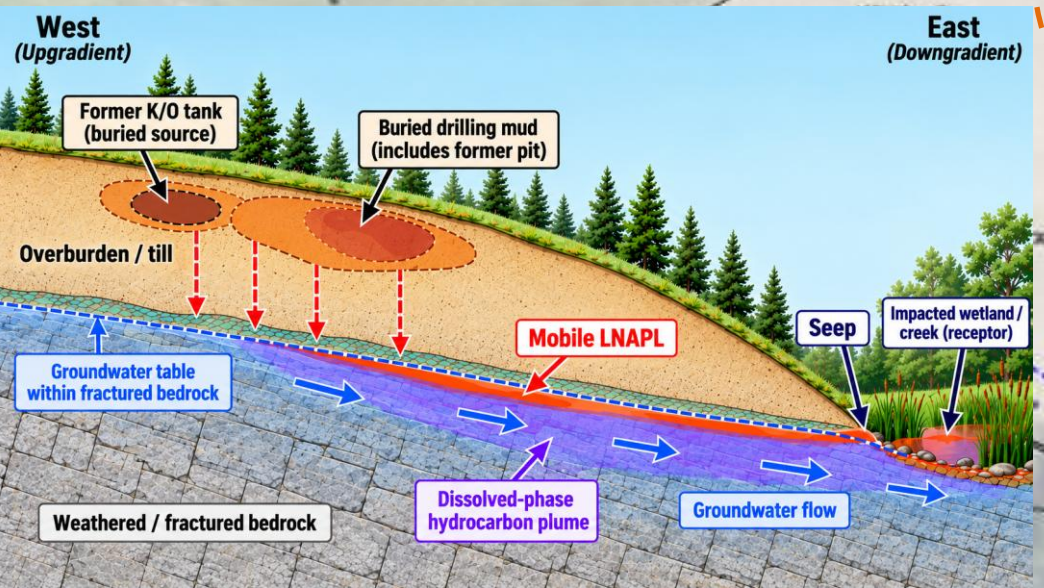
Benzene 81% • Toluene 88% • Ethylbenzene 64% • Xylenes 67%

Percent reductions (PHC fractions)

F1 91% • F2 96%

System began continuous operation March 1, 2026.

Moving Downgradient



SEEP

WETLAND

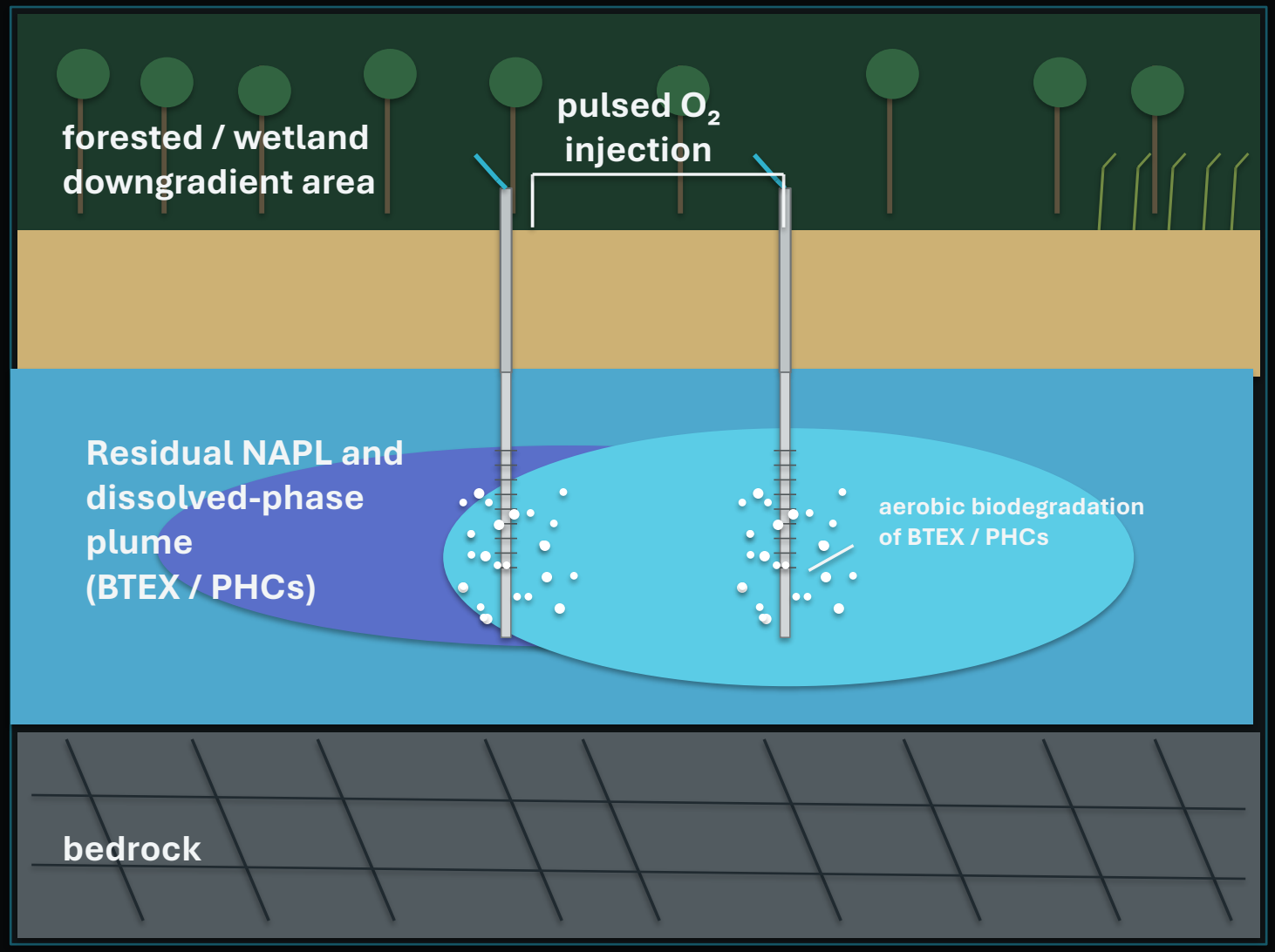
POBS PILOT WELLS

K/O UST

HYDROCARBON PLUME

Pulsed Oxygen Biosparging (POBS)

Low-disturbance treatment of downgradient plume



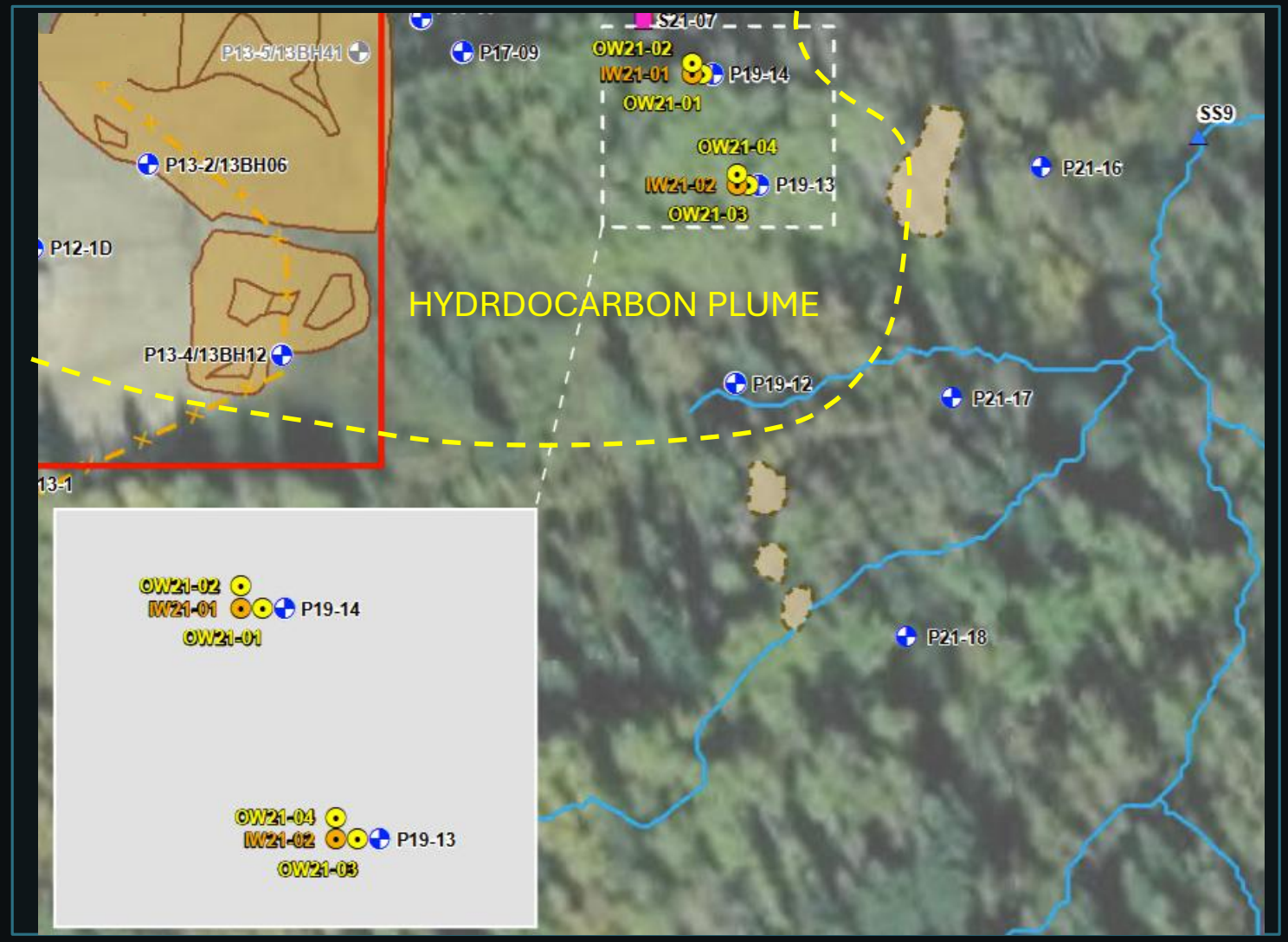




- Pure oxygen injected into the saturated zone in short pulses
- Stimulates aerobic biodegradation of BTEX and PHCs
- Pilot tested oxygen delivery through simple drive-point injection wells

POBS Pilot Test

Field setup and response



Pilot setup

- 2 injection wells (IW21-01, IW21-02)
- Monitoring at P19-13, P19-14 and OW21-01 to OW21-04
- ~94% O_2; 2 pulses per well per day
- Injection pressure: 4–5 psi
- 32 days continuous operation

Key findings

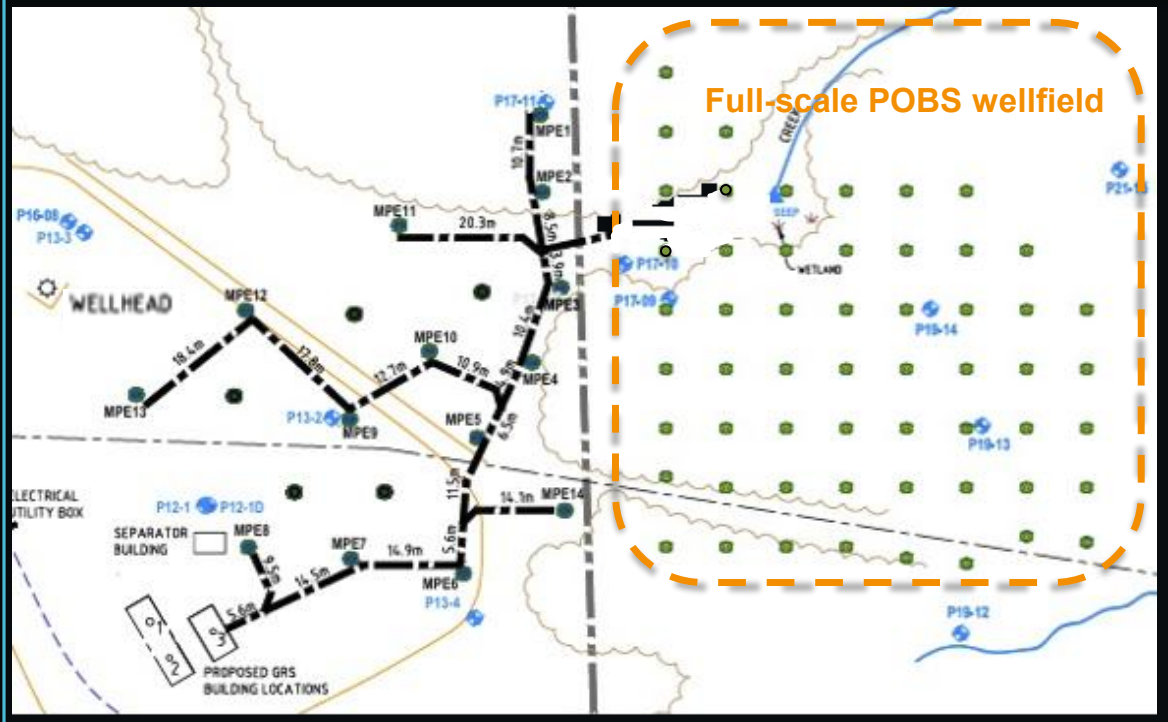
- DO increased to as high as 38.1 mg/L
- PHC F1 decreased in 4 of 5 monitored downgradient / cross-gradient wells
- Largest reduction at P19-13: 1710 → 284 mg/L (-83%)
- 5 min at 5 L/min outperformed 2 min at 2.25 L/min

Example responses	
OW21-01	DO 3.41 → 17.2 mg/L; PHC F1 -50%
OW21-02	DO 2.14 → 8.0 mg/L; PHC F1 -30%
OW21-03	DO 0.3 → 28.1 mg/L; PHC F1 -27%
P19-13	DO to 38.1 mg/L; PHC F1 -83%

Takeaway: pilot results supported full-scale POBS implementation.

From Pilot to Full Scale

Scaling POBS across the downgradient plume









2 pilot injection wells

56 full-scale injection points

Full-scale system

- **14 manifolds**
  ~four injection points per manifold
- **~8 m spacing**
  across the downgradient treatment area
- **Compact drill-rig installation**
  Minimized disturbance in the forested / wetland setting

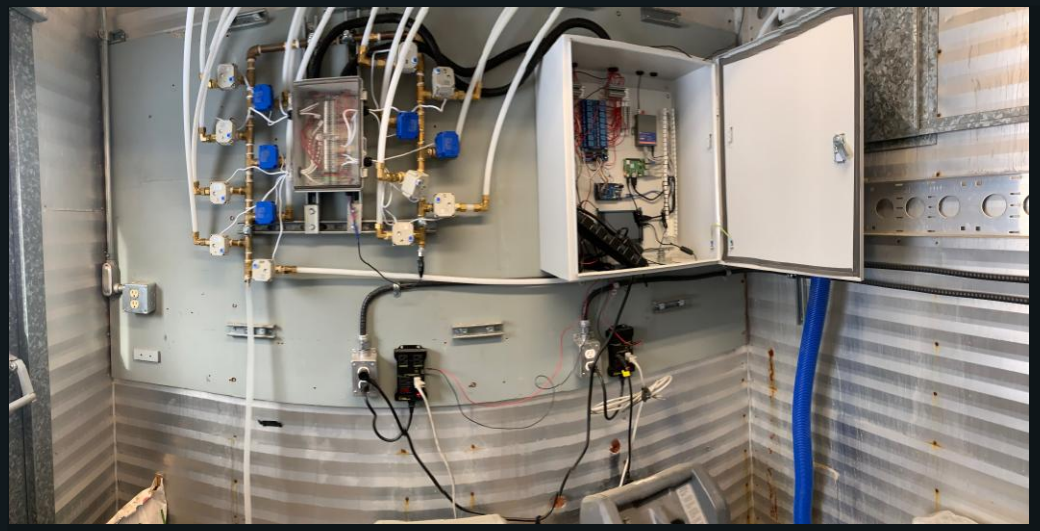
Pilot response provided the basis for scaling POBS across the downgradient plume.

How the Full-Scale POBS System Operates

O_2 generation, distribution and sequential pulsing



POBS generation building



O_2 panel / manifold / generators

O_2 delivery path

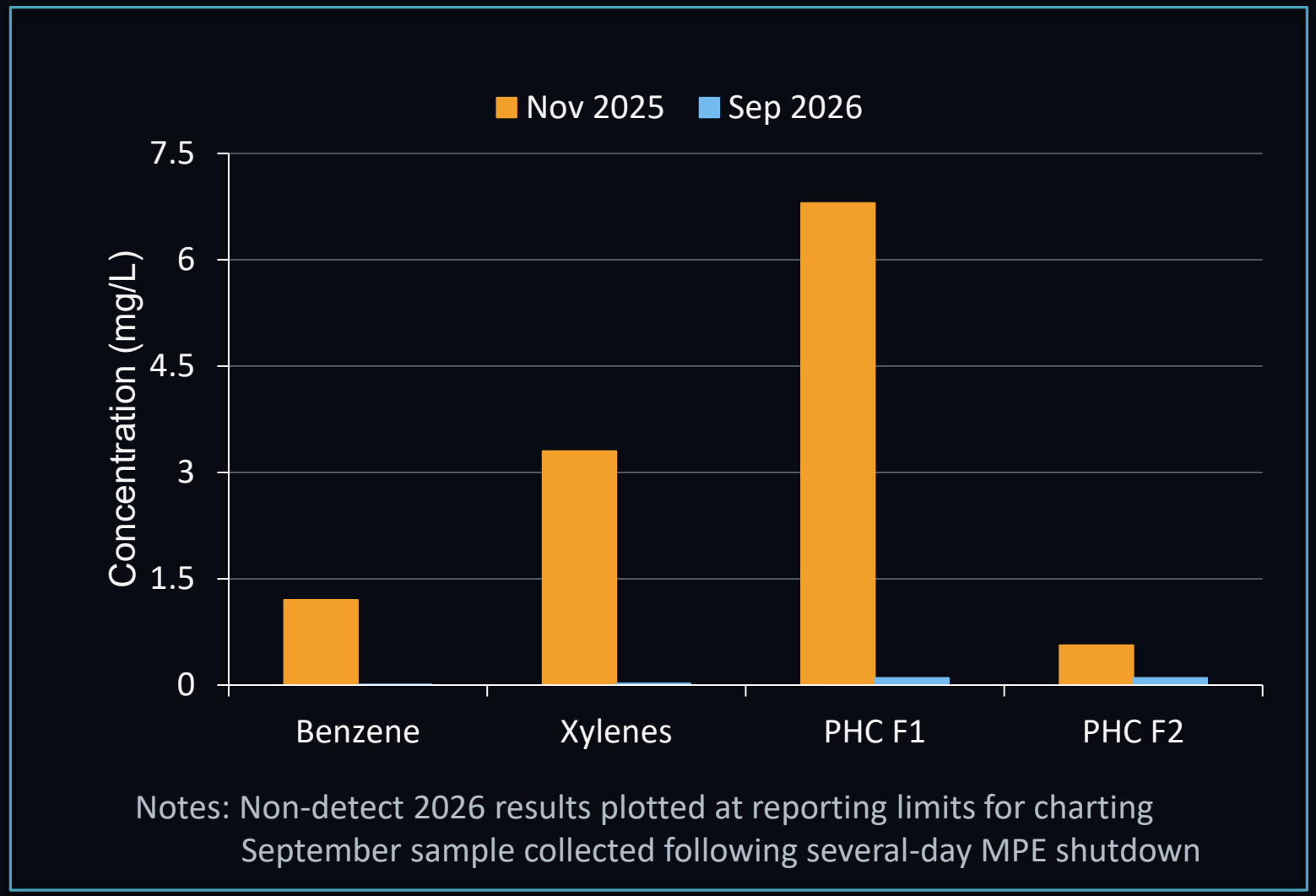
O_2 generators → **Control panel** → **14 manifolds** → **Injection points**

12-hour operating cycle

Warm-up → **Sequential pulsing**
~45 min / manifold
2.5 L/min per well (avg)
→ **Rest**
complete cycle
→ **Repeat**
twice daily

Seep Response After Commissioning

2025 seep results versus post-MPE + POBS commissioning results



Notes: Non-detect 2026 results plotted at reporting limits for charting
September sample collected following several-day MPE shutdown

Marked reduction at the downgradient seep
following commissioning of MPE + POBS

Approximate concentration changes

Benzene: 1.2 → <0.095 mg/L (92.0% lower)
Total xylenes: 3.3 → 0.026 mg/L (~99.2% lower)
PHC F1: 6.8 → <0.10 mg/L (>98.5% lower)
PHC F2: 0.56 → <0.10 mg/L (>82% lower)

Interpretation

This comparison highlights improvement at the seep, but does not isolate the relative contributions of excavation, MPE, POBS and natural attenuation.

Remediation Performance and Diminishing Returns

Removal rate, cost, electricity and GHG intensity shift as active remediation progresses

MPE Measured source-zone recovery

Early productivity

>50,000 L/yr

annualized during first ~100 days

Current productivity

~11,700 L/yr

annualized as of Oct. 1

POBS Estimated biodegradation

Estimated removal

≈700–1,200 L/yr

from O_2 delivery, 50% utilization, and hydrocarbon oxidation stoichiometry

NSZD Measured natural benchmark

Estimated natural depletion

≈300 L/yr

site benchmark (octane-equivalent)

- Supports endpoint decisions
- Useful comparator for active systems

Comparison summary

Metric	MPE	POBS	NSZD
Capital / implementation	>$3 M	~$180k	<$30k
Annual O&M	~$300k/yr	Quarterly visits + power + ~$33k/yr wellfield renewal	Monitoring only
Electricity / GHG	~950 MWh/yr ~416 t CO_2e/yr	≈21–30 MWh/yr ≈9–13 t CO_2e/yr	Negligible
Key message	Highest early removal, but rapidly declining	Lower-rate treatment with lower resource intensity	Benchmark for transition to MNA

The Lowest-Cost Remedy Is Not Always the Best Remedy

MPE

Pay more to remove mass fast

- highest early source-zone removal
- higher capital, O&M, power and GHG
- reduces uncertainty sooner

POBS

Lower-cost, lower-disturbance treatment

- good fit where extraction or excavation is disruptive
- slower source-zone mass reduction
- strong downgradient plume-control tool

NSZD / MNA

Let the site keep working

- lowest active-treatment cost
- longest time to recovery
- important benchmark for stopping active systems

A higher-cost remedy can still be the right decision if it restores a wetland sooner and avoids a visible ecological failure.

“Recalled to life”: the receptor now looks unimpacted





The visual receptor is not a closure criterion. But it illustrates why shortening the recovery timeline can matter.