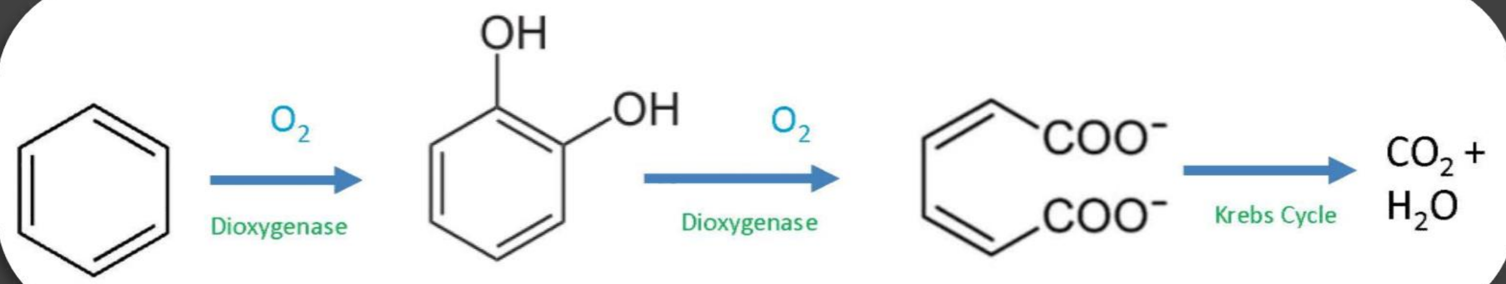
Enhanced In Situ Aerobic Biodegradation
(Busting the Benzene Ring)

Lessons Learned from 5 Case Studies



Why Choose Enhanced In Situ Biodegradation?

When standard approaches don't work!

- ❑ Excavation not feasible
  - o Overlying infrastructure
  - o Source at depths >20 feet (standard excavator reach)
- ❑ AS/SVE not feasible or effective
  - o Low permeability aquifer
  - o Confined/semi-confined aquifer
  - o Interbedded coarse and fine-grain units
- ❑ Heterogeneous, low-permeable sites – mature contamination strongly sorbed and less accessible, slowly back-diffuses over time. Reduces effectiveness of ISCO, etc.

Why Aerobic Degradation?

Electron Acceptor	Type of Reaction	Mass of EA Needed to React Mass of Benzene	Redox Potential/ Reaction Preference
Oxygen	Aerobic	3.1	+820 Most Preferred
Nitrate	Anaerobic	4.8	+740
Ferric Iron	Anaerobic	21.5	-50
Sulfate	Anaerobic	4.6	-220
Carbon Dioxide	Anaerobic	2.1	-240 Least Preferred

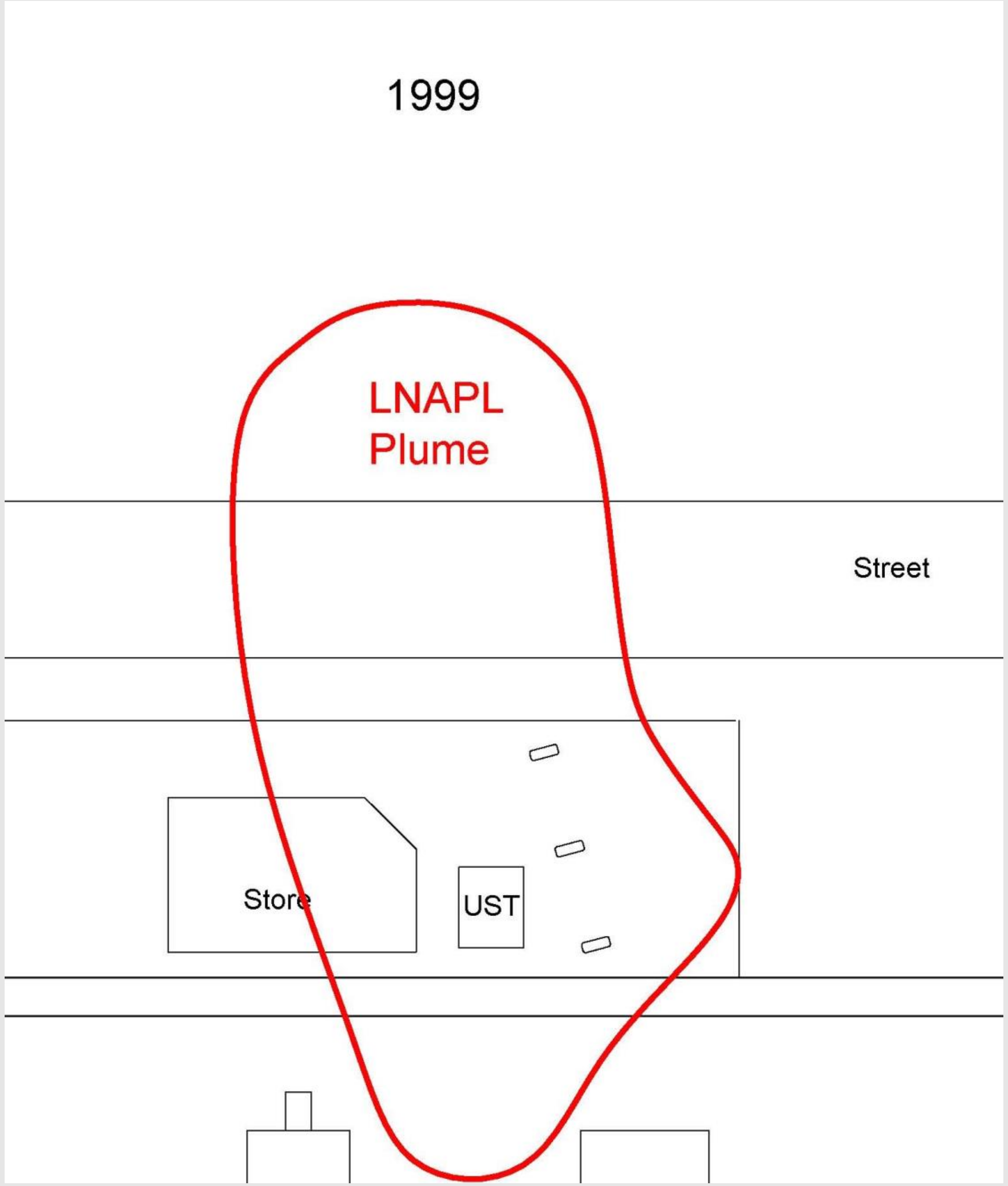
Which Oxygen Source?

- Commercially Available Slow Release Oxygen Compounds
  - Safe to handle
  - Injected through direct-push borings
  - Lasts up to 12 months
  - Multiple injections required
  - $50-60/pound oxygen

- Hydrogen Peroxide
  - Strong oxidizer at high concentrations
    - Compatible w/ SS, Al, PVC, polycarbonate, Teflon
  - Continuous injection into vertical or horizontal wells
  - $4/pound oxygen

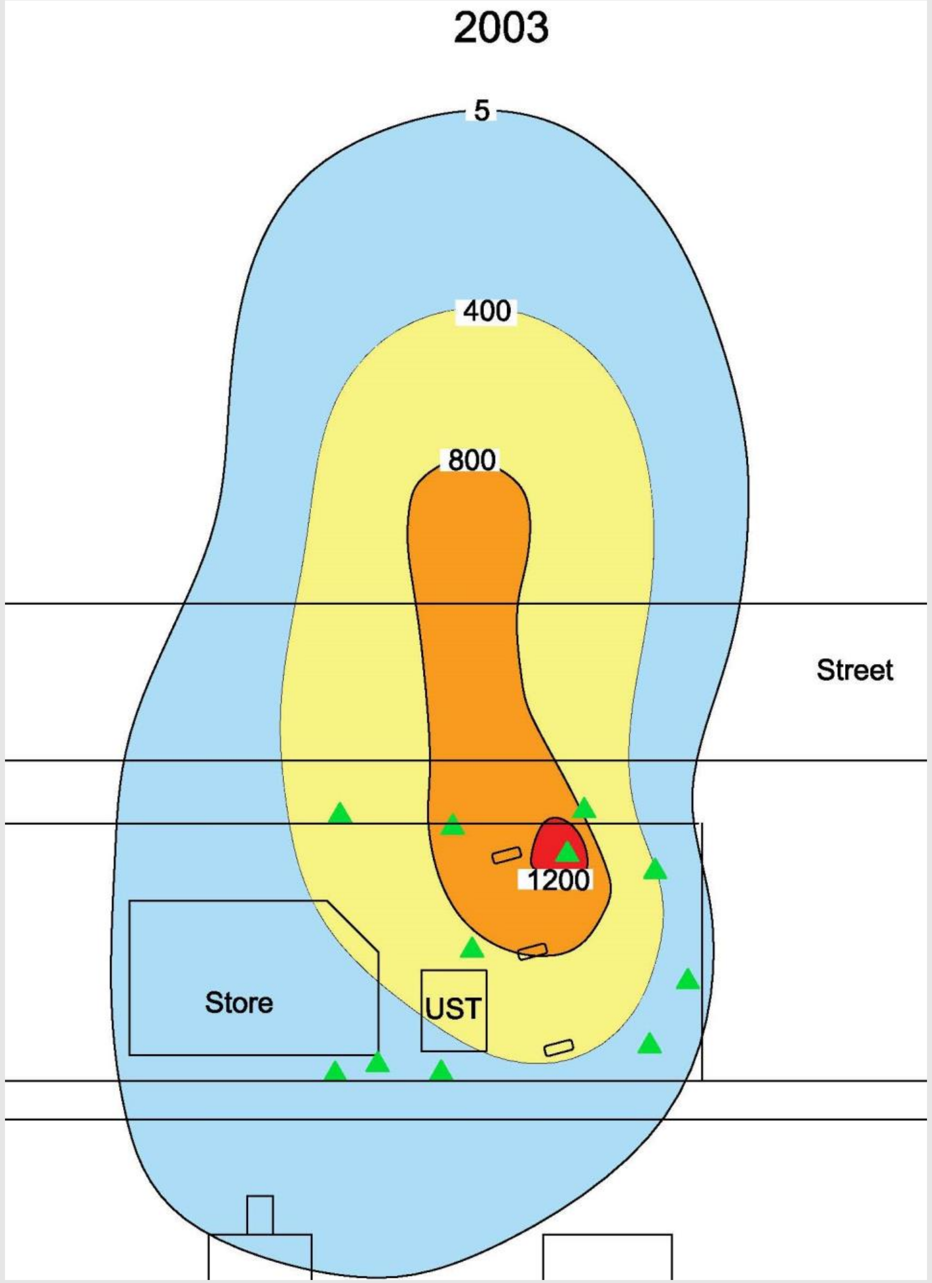
$$C_6H_6 + 7.5O_2 \longrightarrow 7CO_2 + 4H_2O$$

Requires 3 pounds of oxygen to degrade 1 pound of benzene

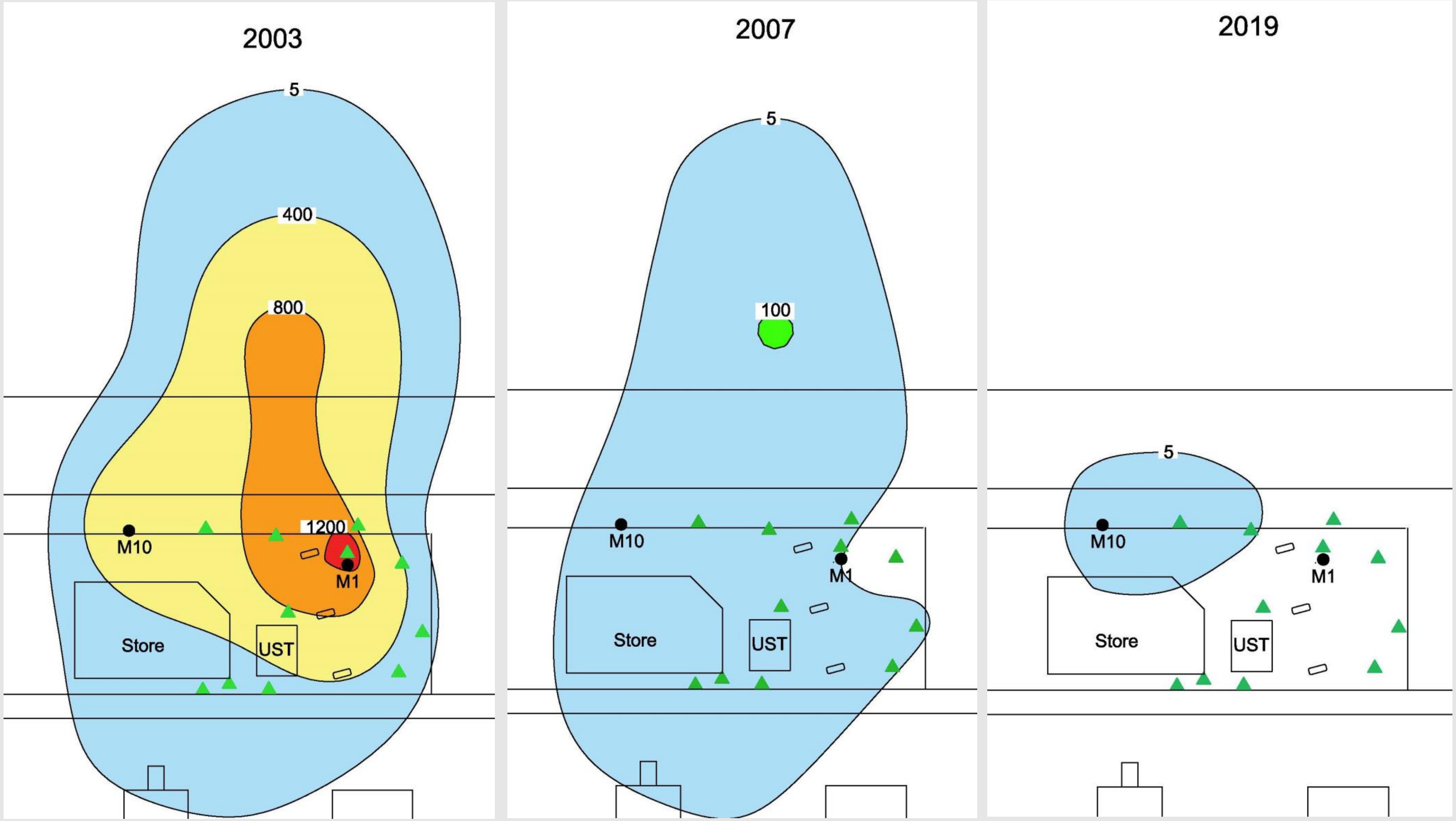


Case 1

- ❑ 11,000 gallons of diesel released from UST between October 1998 and February 1999
- ❑ Aquifer
  - Fractured shale bedrock
  - DTW is 20-30 feet bgs
  - Groundwater flow to N to NNW
- ❑ LNAPL plume with apparent thickness up to 6 feet in several wells. LNAPL was diesel, no gasoline.
- ❑ Recovered ~7,000 gallons of LNAPL from March 1999 to August 2003, after which little LNAPL was observed.



- During NAPL recovery, historical gasoline release discovered. Flat-line dissolved phase BTEX plume covering an area of ~85,000 SF, with benzene concentrations as high as 1,500 µg/L
- Estimated total petroleum hydrocarbon mass of 15,000 pounds, of which ~20% was BTEX
- Aquifer
  - Strongly anaerobic
  - Seepage velocity calculated at 20 feet/year, observed to be ~300 feet/year
- Obstacles to standard approaches
  - Overlying infrastructure, street & UST system
  - Source >20 feet bgs
  - Low-perm bedrock aquifer
  - Mature, sorbed contaminants



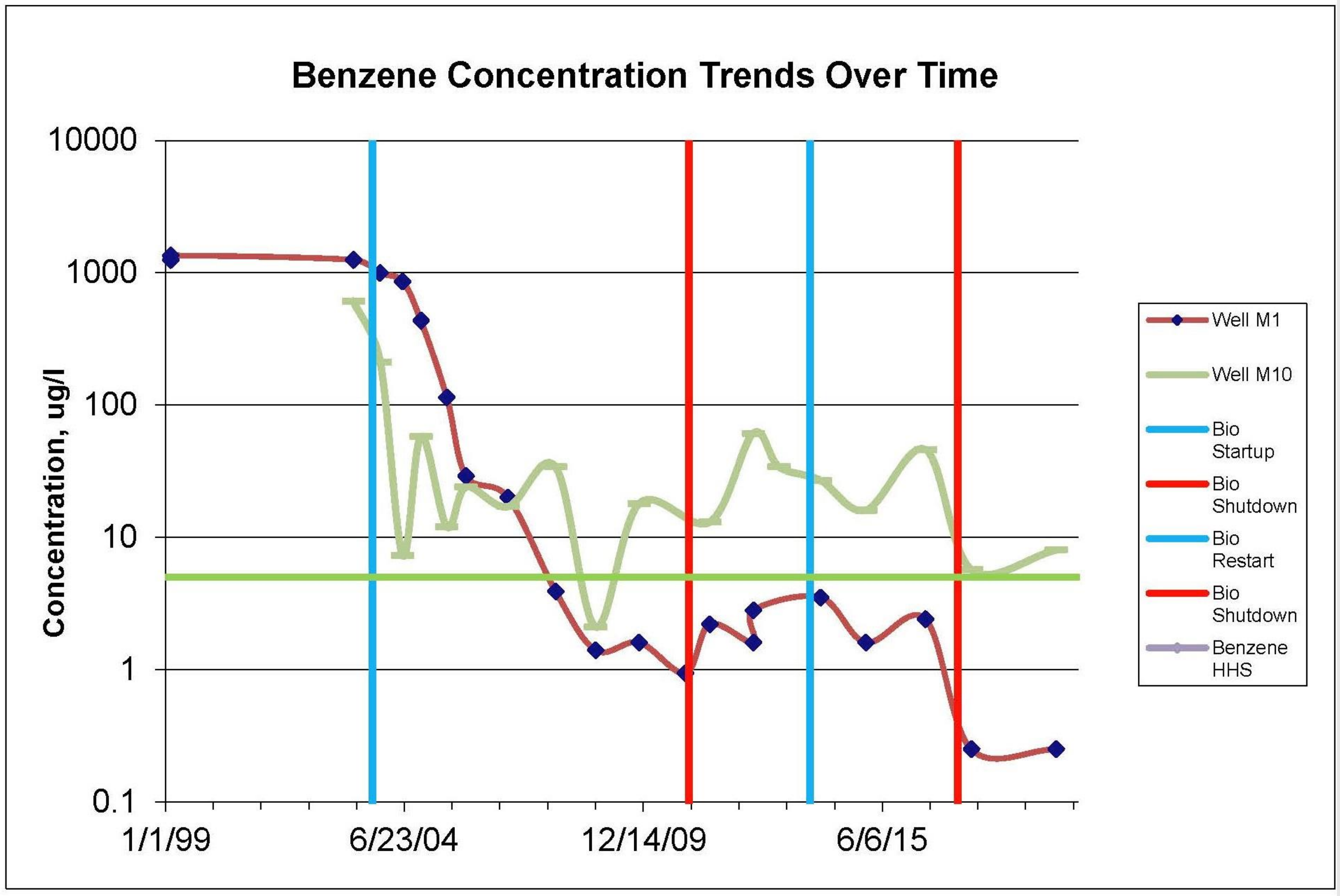
Injection stated in 2003,

Shut down in 2011

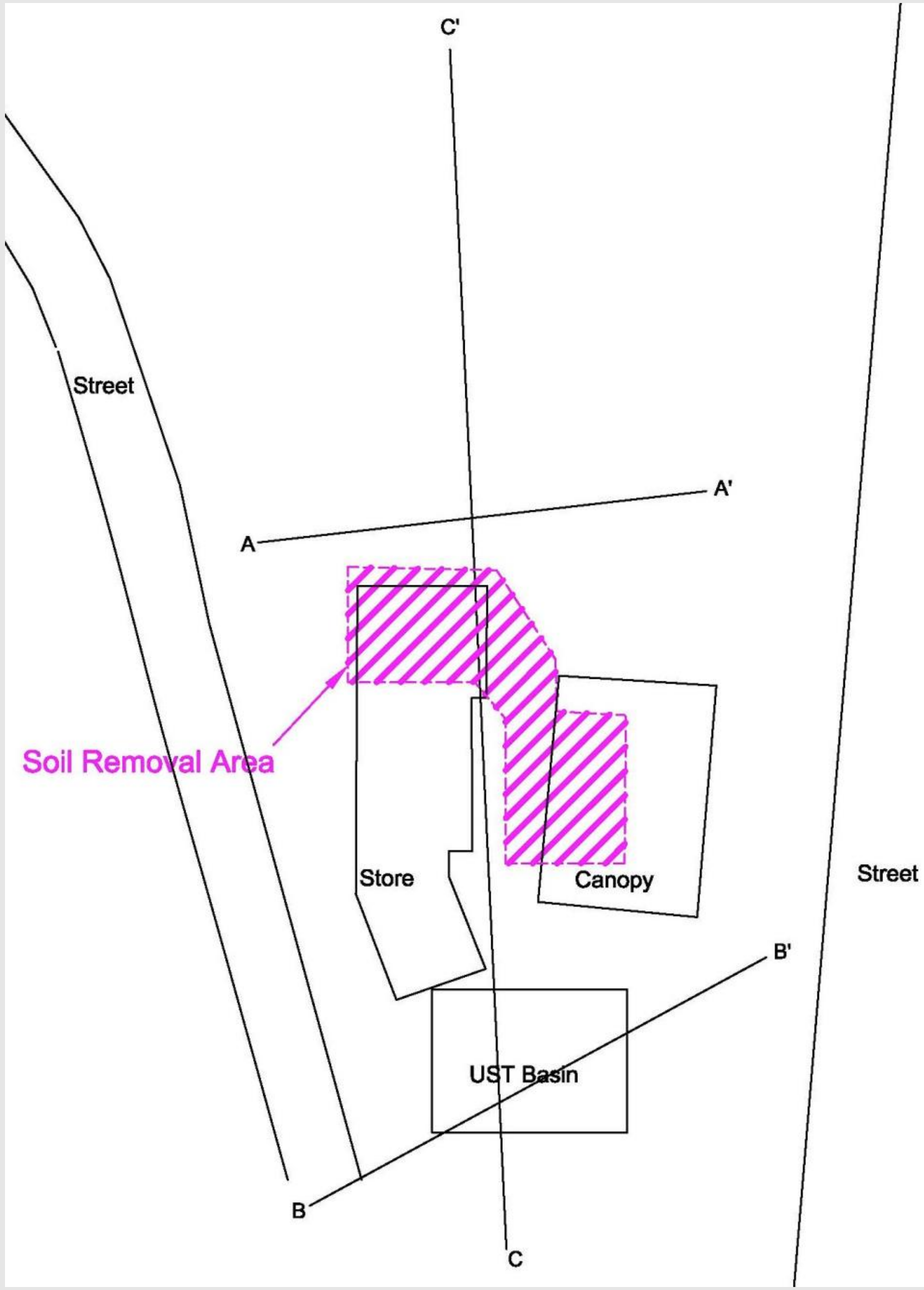
Restarted in 2013

Shut down for good in 2017

Case 1 - Lessons Learned



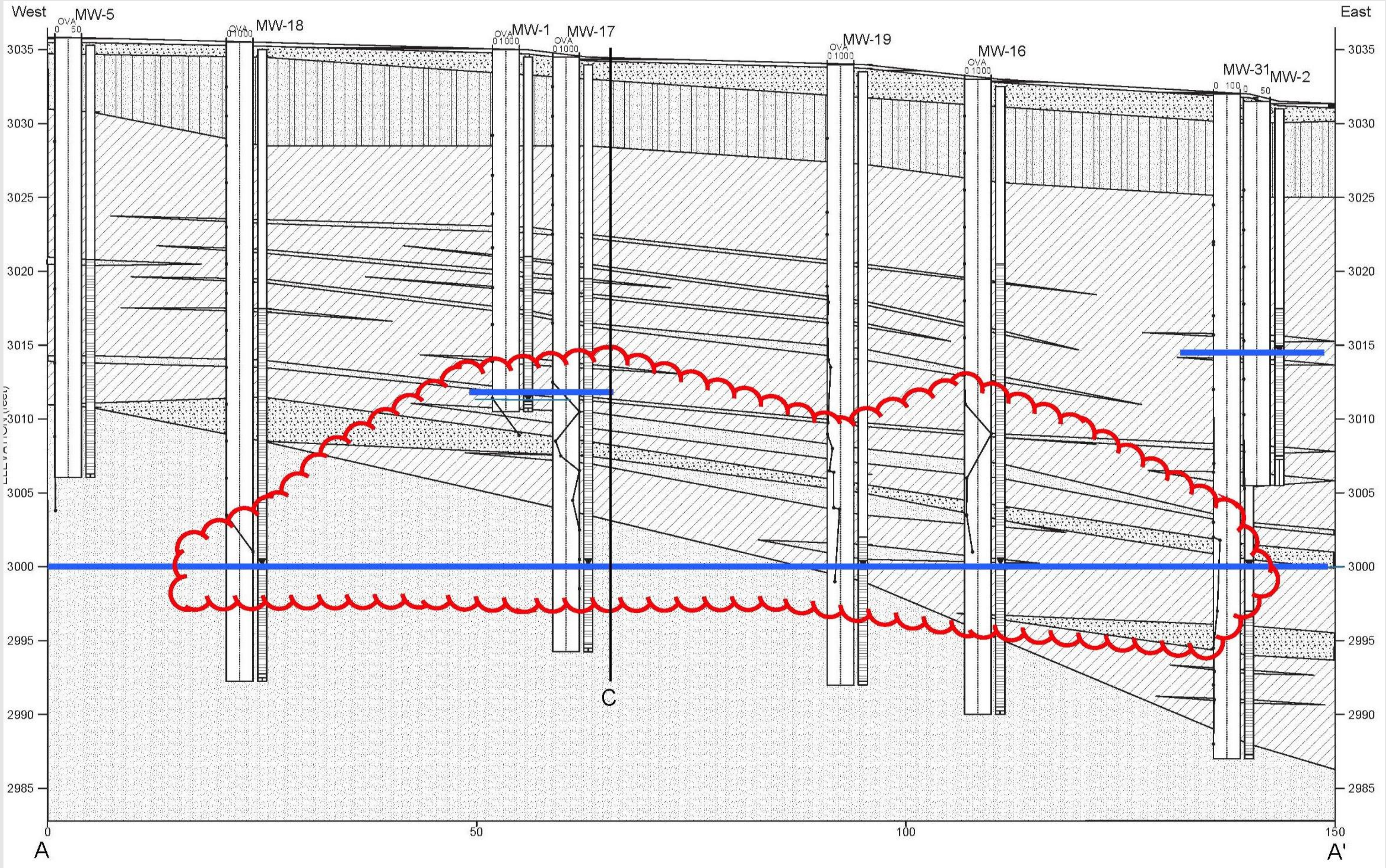
- M10 - Poorest performing location
  - Fringe of targeted injection area
- M1 – One of the better performing locations
  - Targeted injection area
- Demonstrated effectiveness
  - 99% benzene reduction across the site by end of operation
  - Little to no rebound
  - Performance limited solely by how quickly oxygen could be delivered



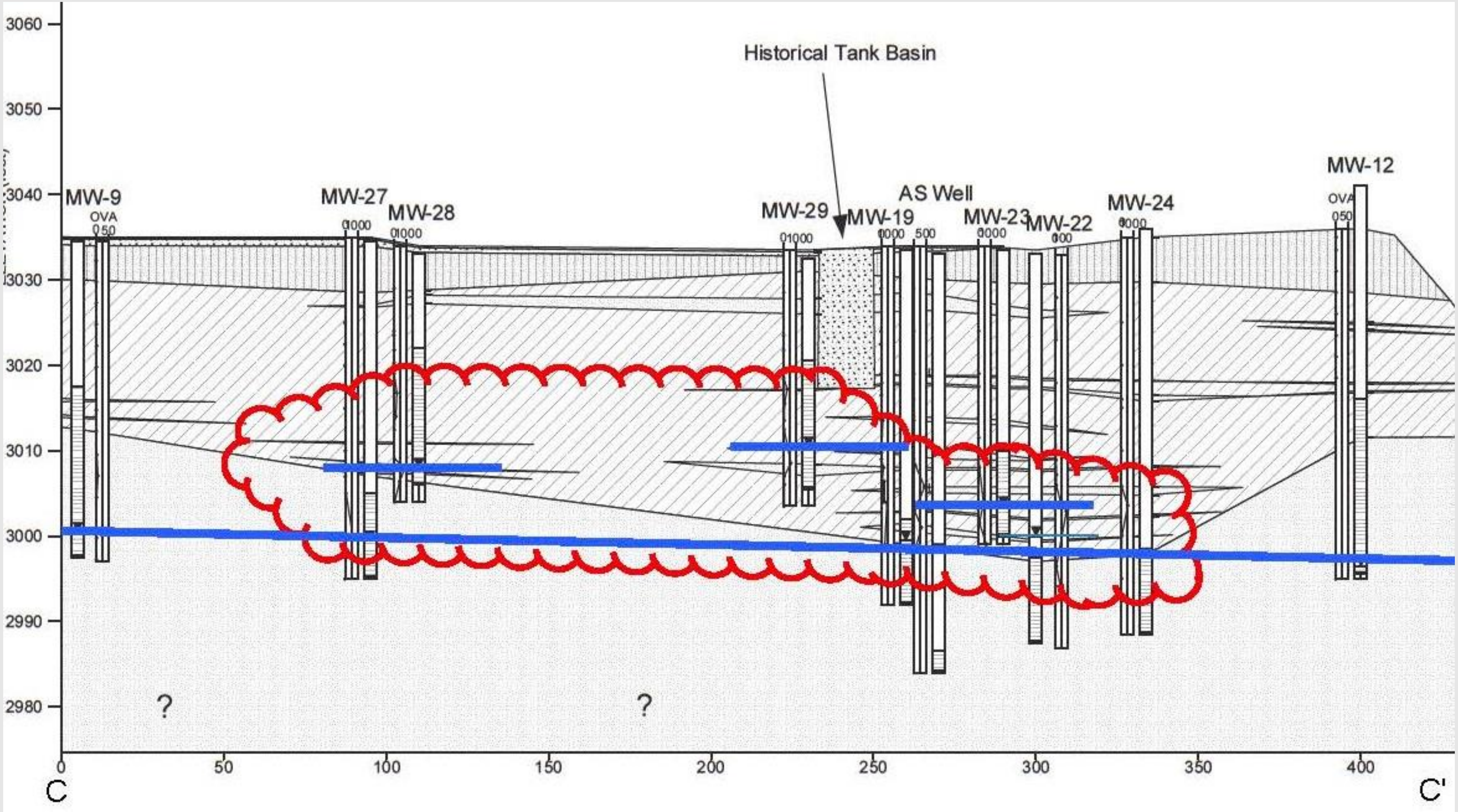
Case 2

- Site was redeveloped in 1989
  - ~2,500 cy of gasoline impacted soil was removed to depths of 15 to 22 feet bgs
  - Store was expanded over the northwestern portion of excavation (historical UST basin)
  - The release was closed, and a new release reported in 2003

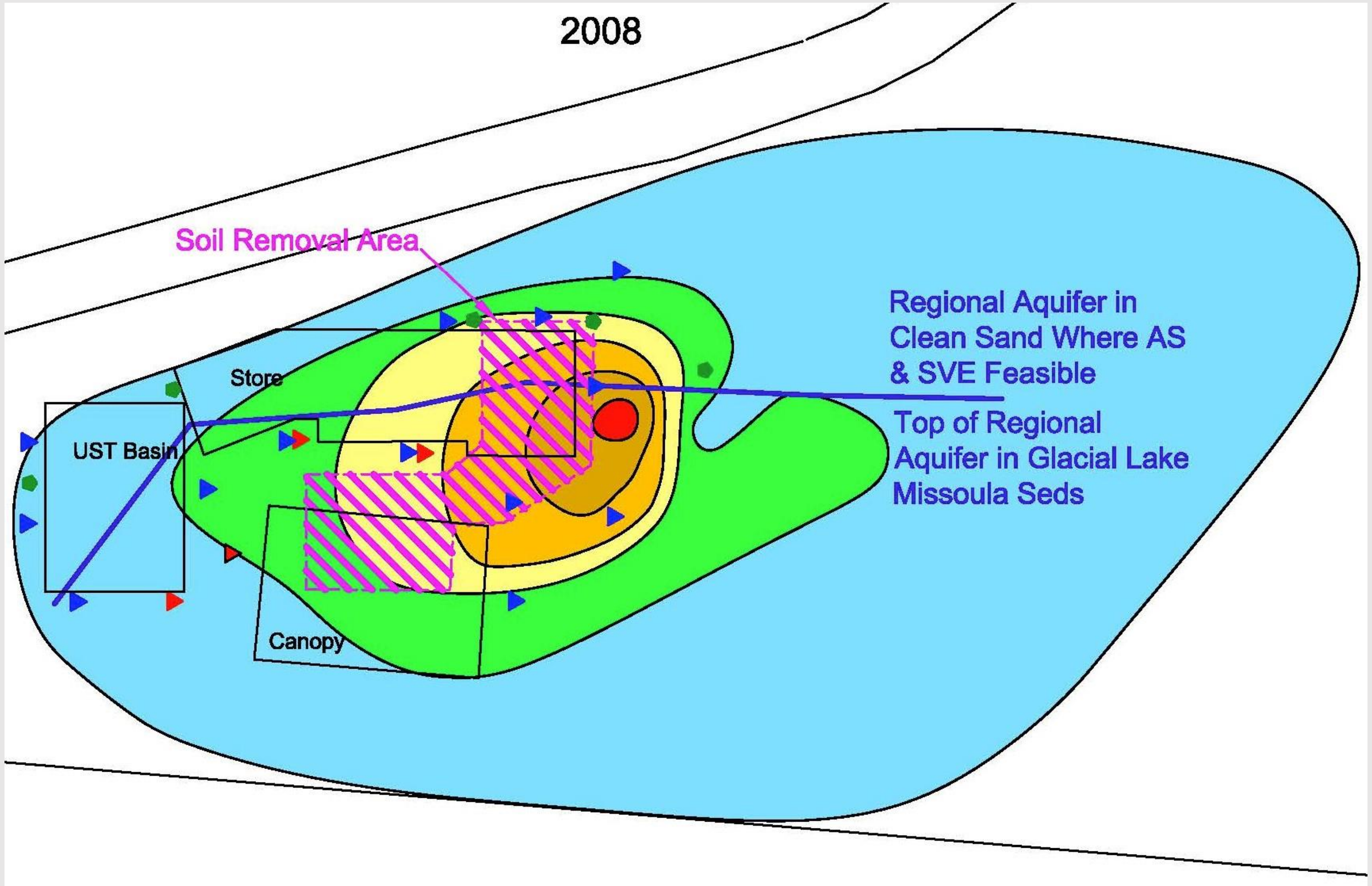
- Complex Aquifer
  - Perched aquifer in glacial lake Missoula sediments -DTW varies from 8 to 30 feet bgs
  - Regional aquifer in clean sand and glacial lake Missoula seds – DTW varies from 30 to 42 feet bgs
  - Groundwater flow to north



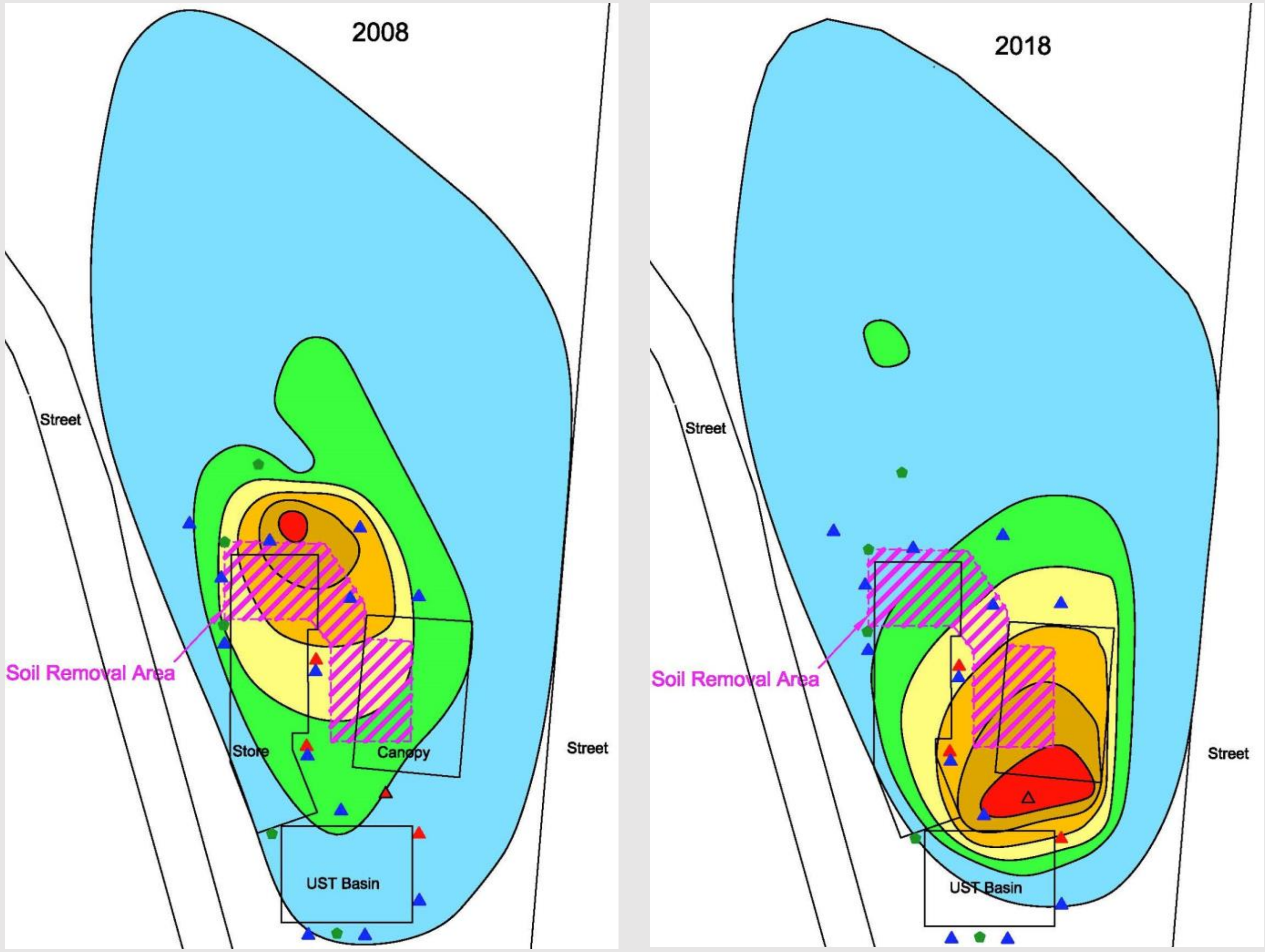
West
East
MW-5
MW-18
MW-1
MW-17
MW-19
MW-16
MW-31
MW-2
OVA
3035
3030
3025
3020
3015
3010
3005
3000
2995
2990
2985
C
0
50
100
150
A
A'



Historical Tank Basin
MW-9
OVA
0 50
MW-27
0 1000
MW-28
0 1000
MW-29
0 1000
MW-19
0 1000
500
AS Well
MW-23
0 1000
MW-22
0 100
MW-24
0 1000
MW-12
OVA
0 50
3060
3050
3040
3030
3020
3010
3000
2990
2980
?
?
0
50
100
150
200
250
300
350
400
C
C'



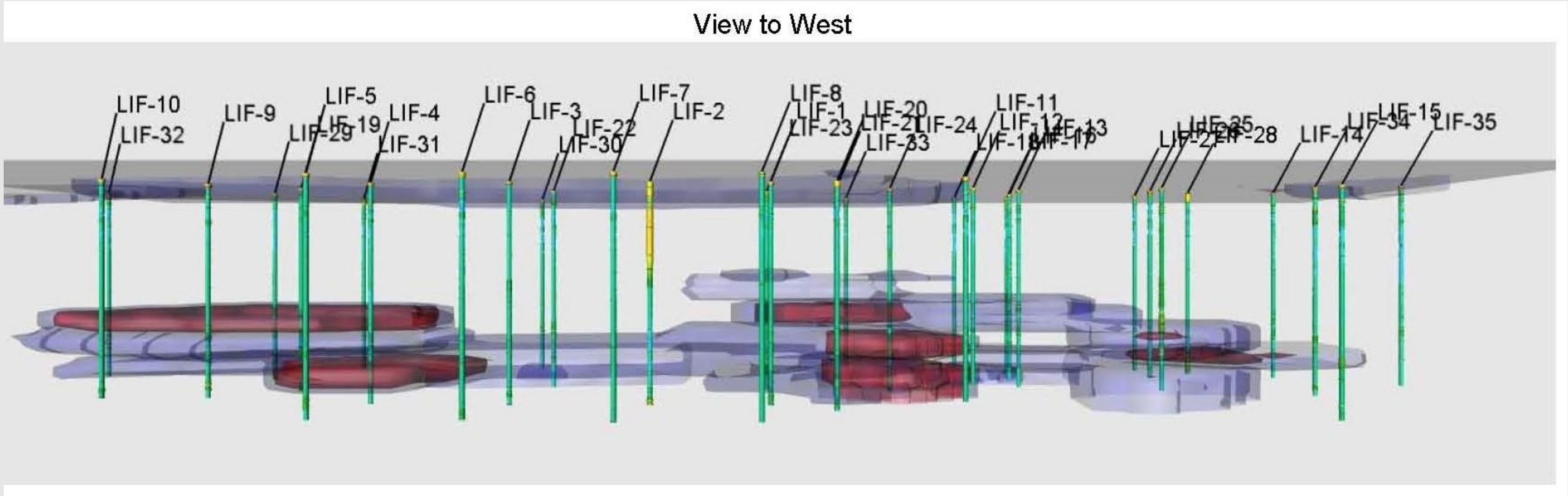
- Benzene plume ~95,000 SF
- Max benzene concentration 5,830 μg/L, 1000 μg/L contours
- Mass of hydrocarbons estimated at 10,000 lbs, 10% of which was BTEX
- Why enhanced bio was selected
  - Impacts >20' bgs
  - Overlying obstacles
    - UST system
    - Store
  - AS/SVE not feasible in worst-case areas

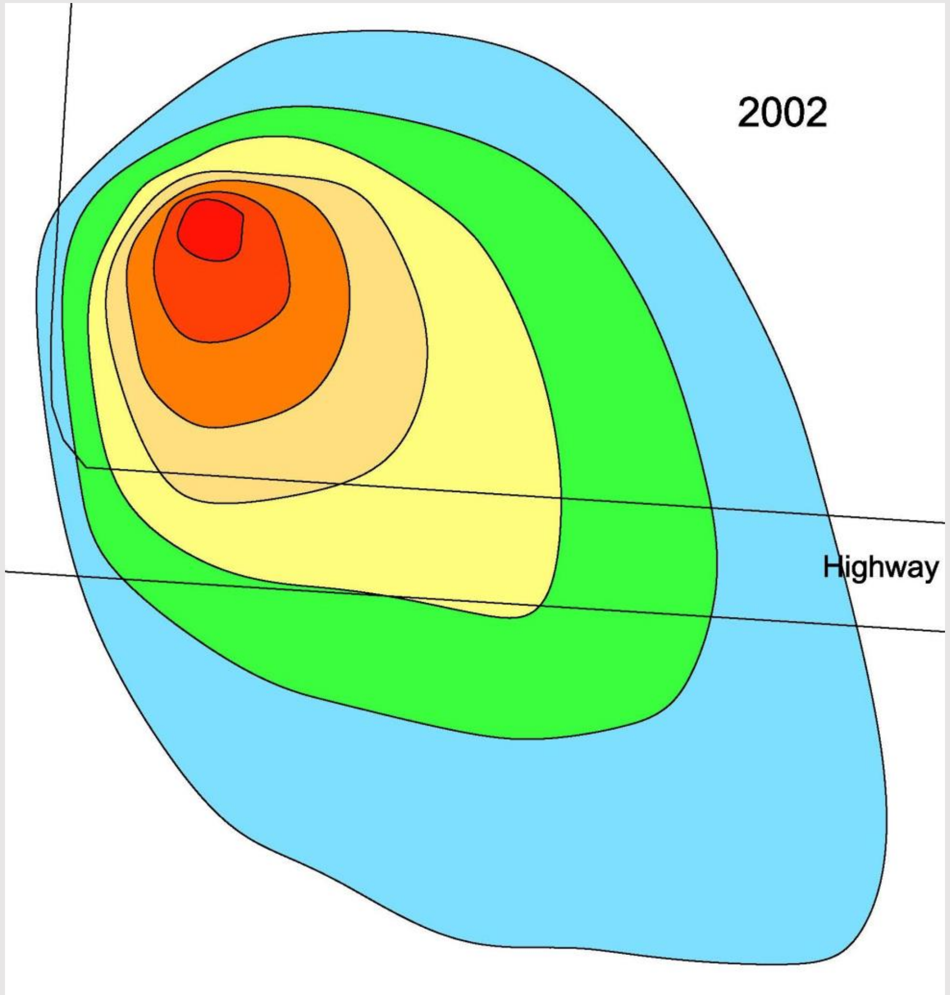


- Enhanced Bio Implemented 2011-2016
- Delivered 7,300 lbs O_2, ~50% more than Case 1 to treat an estimated 30% less mass
- Reduced benzene in former hot spot area, but new one appeared where NAPL had been discovered
- Led to a LIF investigation

Case 2 - Lessons Learned

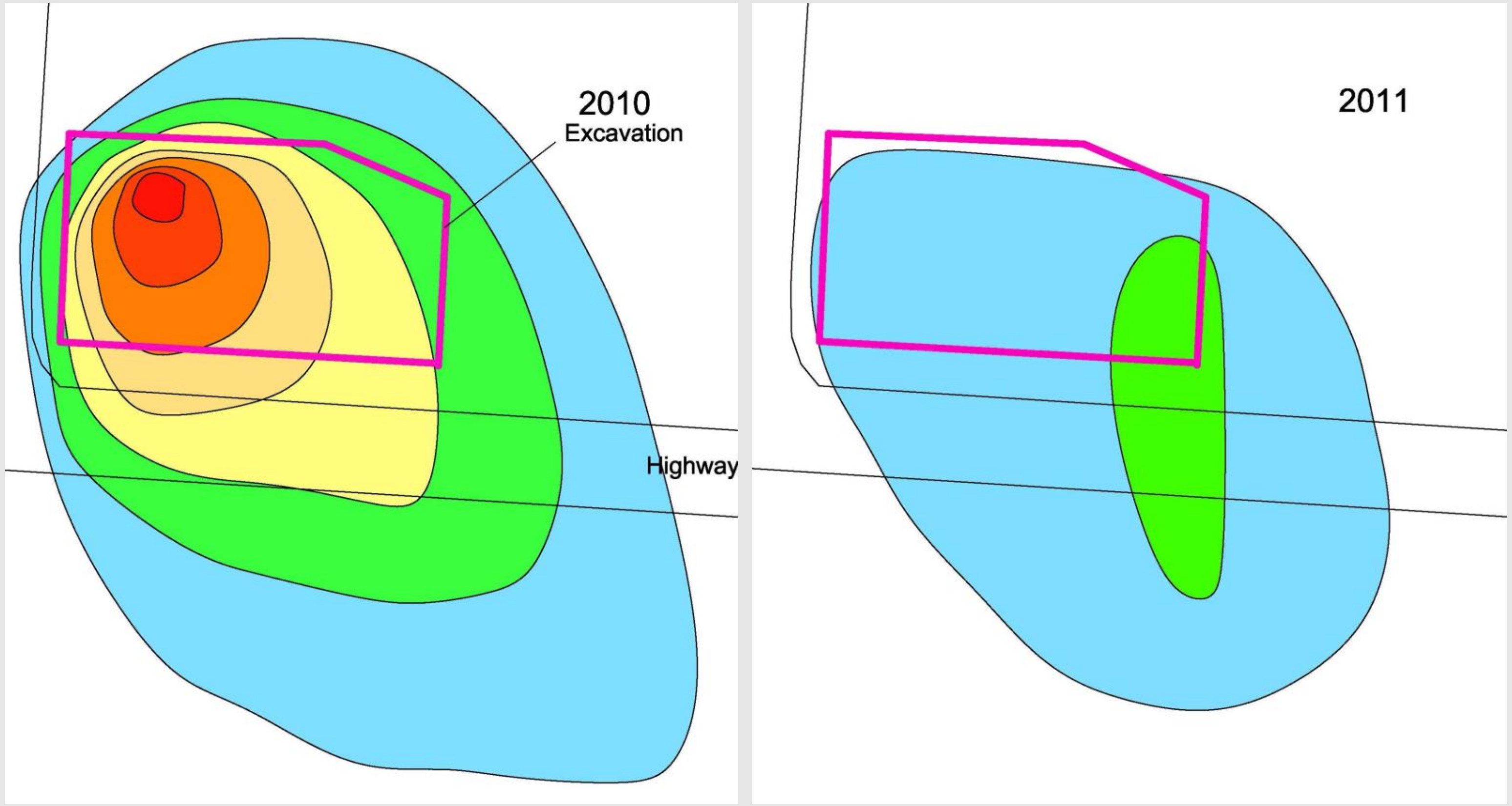
- 3:1 ratio of O_2:Hydrocarbons – Knowing the mass is important
- Don’t rely solely on laboratory data, particularly with thin sand stringers





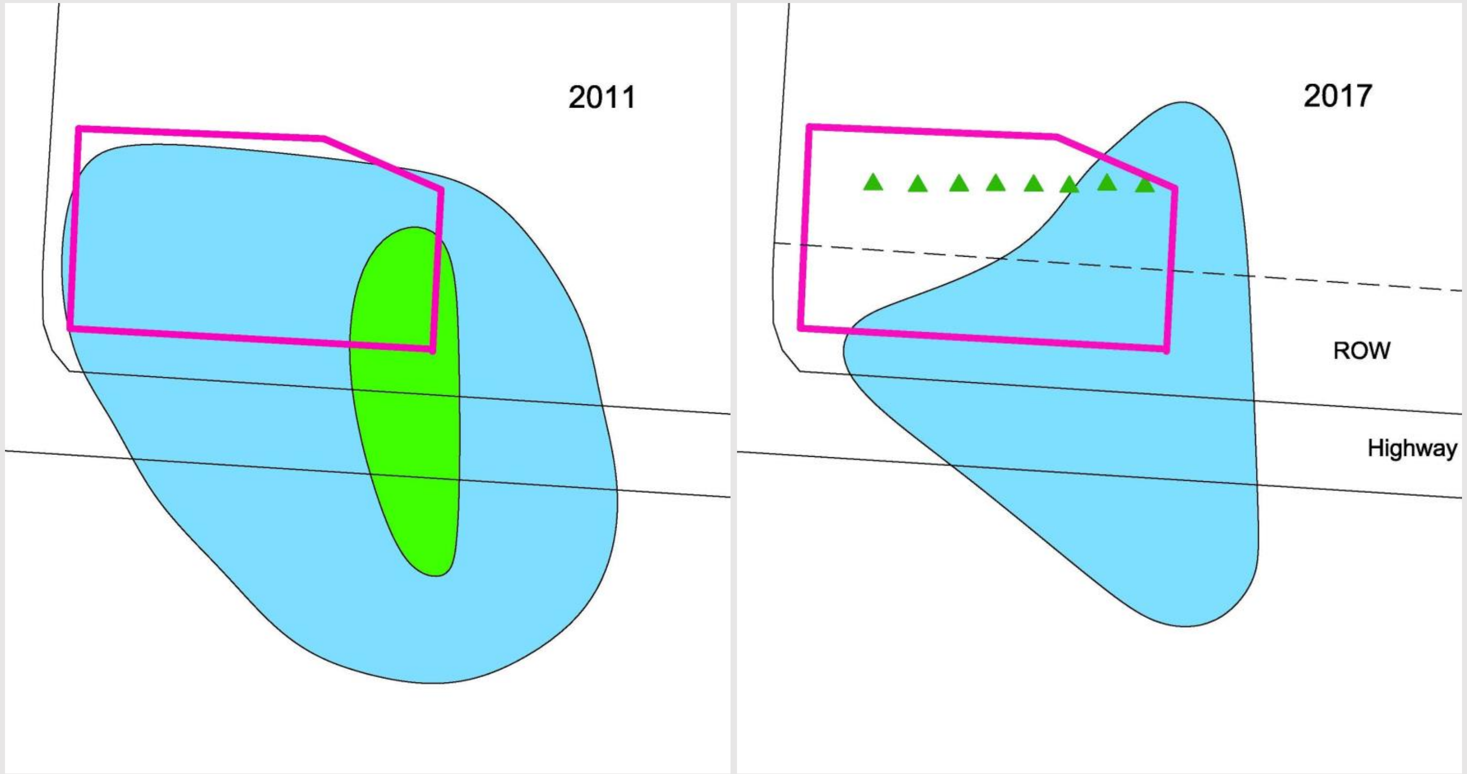
Case 3

- Silty to sandy clay with thinly interbedded sand lens extends to depths of 17-19 feet bgs underlain by gravel with sand and clay.
- Unconfined aquifer, SWL varies seasonally, 10 to 20 feet bgs. Flow to the south.
- Fueling occurred from 1930's to 1993.
- Stagnant, dissolved-phase plume with benzene concentrations as high as 8,720 µg/L.



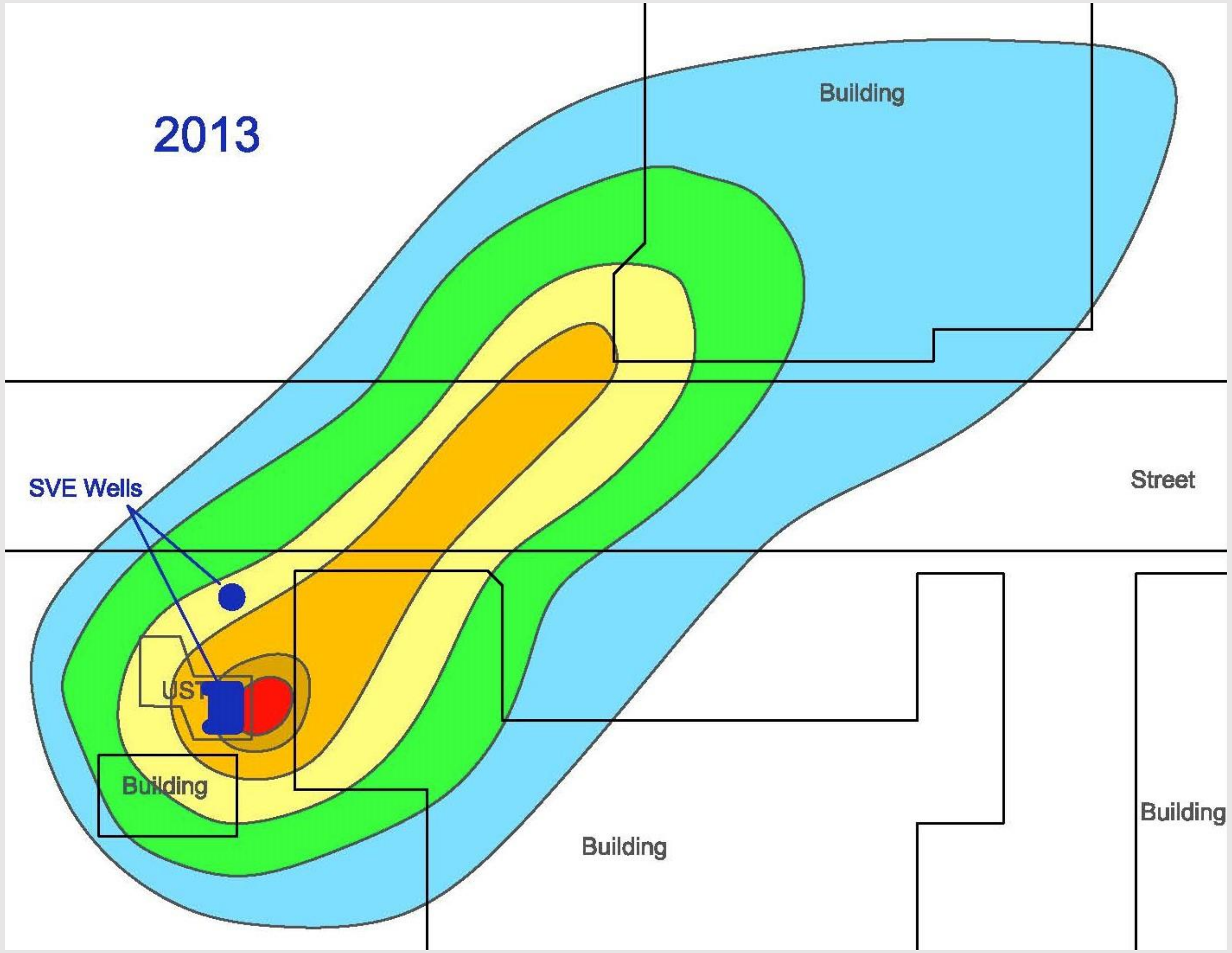
- Excavated 3,200 CY impacted soil in April 2010
- South sidewall contained elevated hydrocarbons in fine grained seds with interbedded sand lenses.
- Dissolved phase plume persist with benzene >1,000 µg/L

- 3,000 lbs O2 delivered from 2014-2017
- Max benzene <10 µg/L north of highway but still as high as 742 µg/L south of highway



Case 3: Lessons Leaned

- Preferential pathway indicated by widely varying concentrations in adjacent wells
- Injection hampered by fine grained sediment-Horizontal wells?
- Not an immediate fix, requires time to deliver the O2

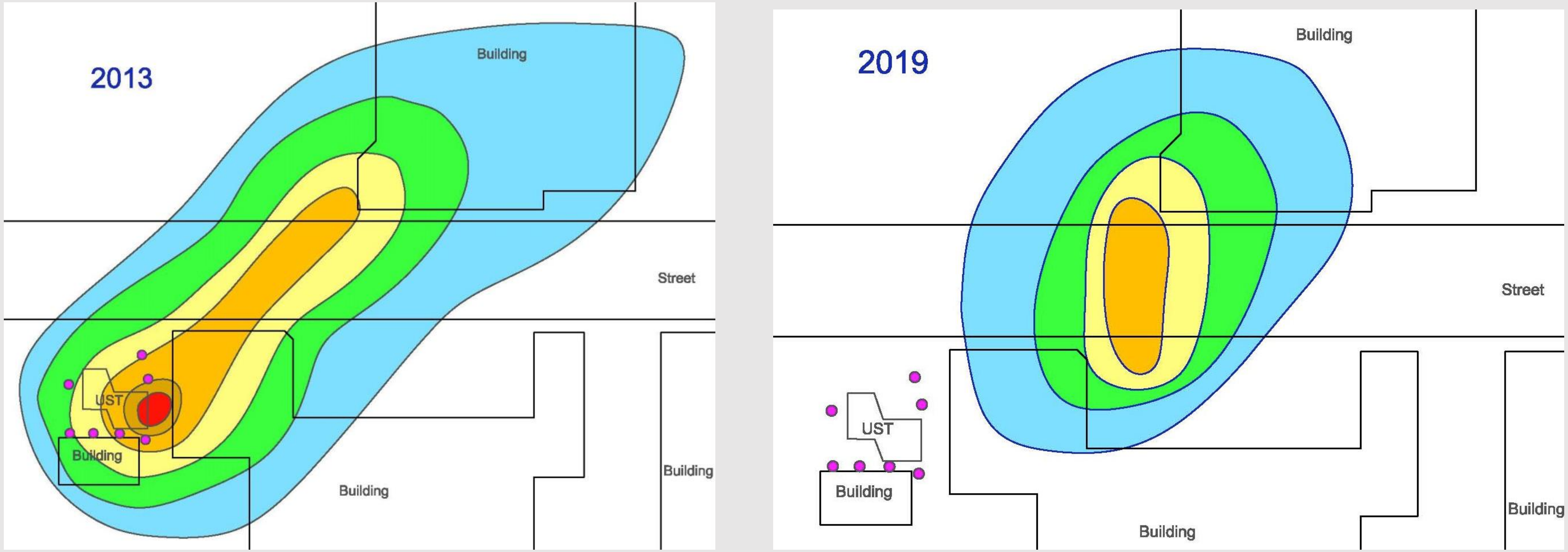


Case 4

- ❑ 450 CY impacted soil removed from UST basin in 1993
- ❑ Aquifer – sand and gravel with clay. DTW 10-16 feet bgs.
- ❑ SVE recovered 9,350 pounds of hydrocarbons between 1994-2015, No measurable vapors after 2010.
- ❑ 123 gallons of NAPL recovered
- ❑ Max benzene concentration in 2013: 5,830 µg/L - Stable
- ❑ Why enhanced bio was selected
  - Overlying obstacles
  - AS/SVE not feasible

Case 4 - Lessons Learned

- ❑ System startup in 2015 and by 2018 BTEX <RBSLs on site, injection ongoing for down-gradient treatment
- ❑ Good delivery resulted in rapid reduction in petroleum hydrocarbons



Lessons Learned

Enhanced Aerobic Biodegradation Can Be Effective

- Mass Matters
  - Most effective after source removal is completed
  - NAPL is not always readily obvious but has a large affect on the amount of O2 needed
- Delivery
  - Geologic conditions can hamper delivery
  - Design with over-delivery in mind
  - Be adaptable, assess and modify as necessary
- Be Patient
  - Typically used at mature, heterogeneous sites where hydrocarbons have diffused deep into pore spaces. It will also take time for the O2 to access those hydrocarbons.