Addressing ISTR's Core Inquiry through a Pilot Test: Optimal Temperature and Operating Conditions

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Case Study Confronting ISTR's Ultimate Challenge: Pre-ZVI Altered Permeabilities and Floating LNAPLs/Sinking DNAPLs on Bedrock

Outline: Pilot test case study exploring temperature fundamentals in ISTR with three key Takeaways

Pilot Test Case Study

- Site Challenges
- Pilot Test Design
- Temperature Evolution
- Vapor Mass Balance
- Results

Core Inquiry for ISTR: Optimal Temperature and Operating Conditions

Three Key Takeaways

1) MPE is a game changer for the thermal design in saturated

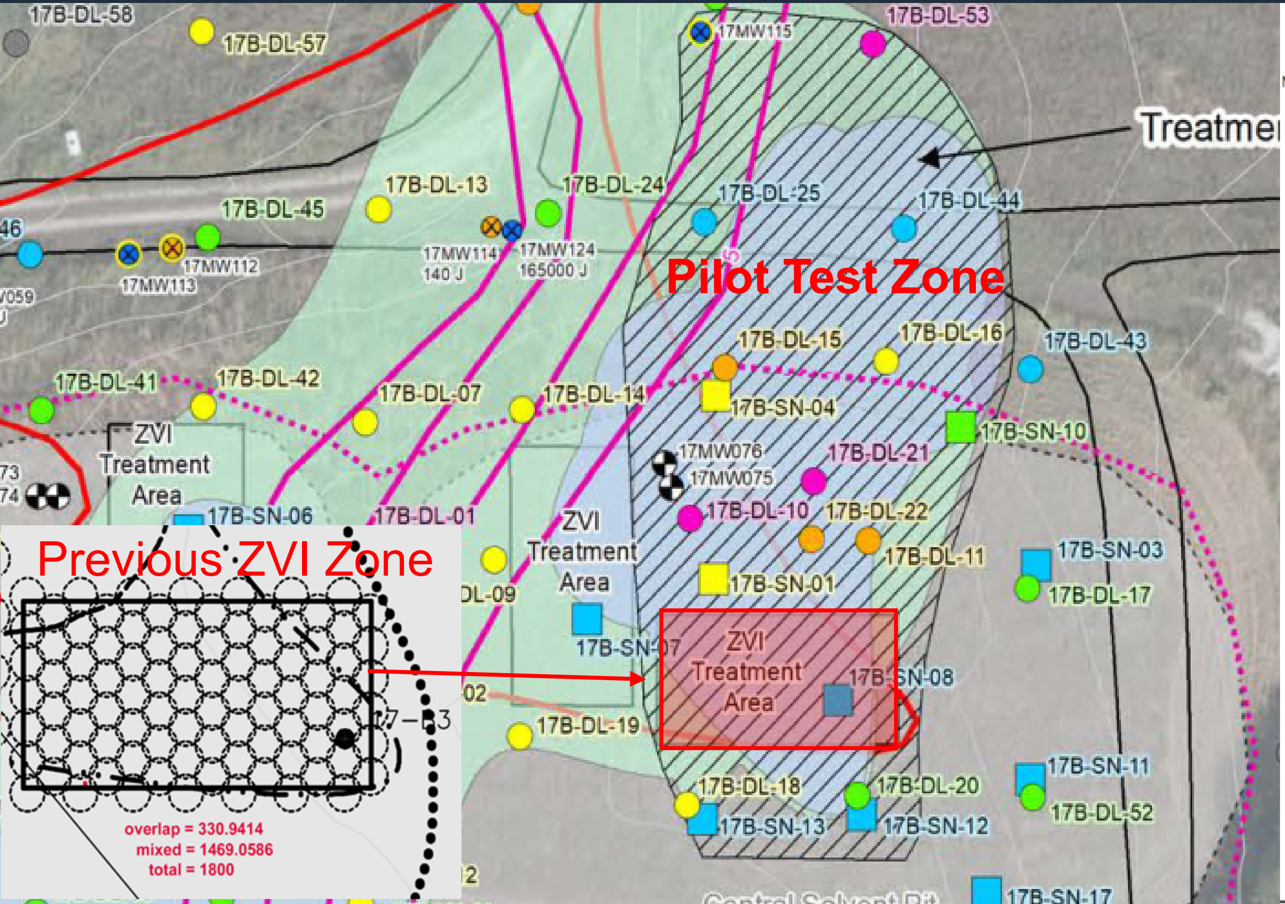
2) Vapor extraction is crucial for heating energy and mass

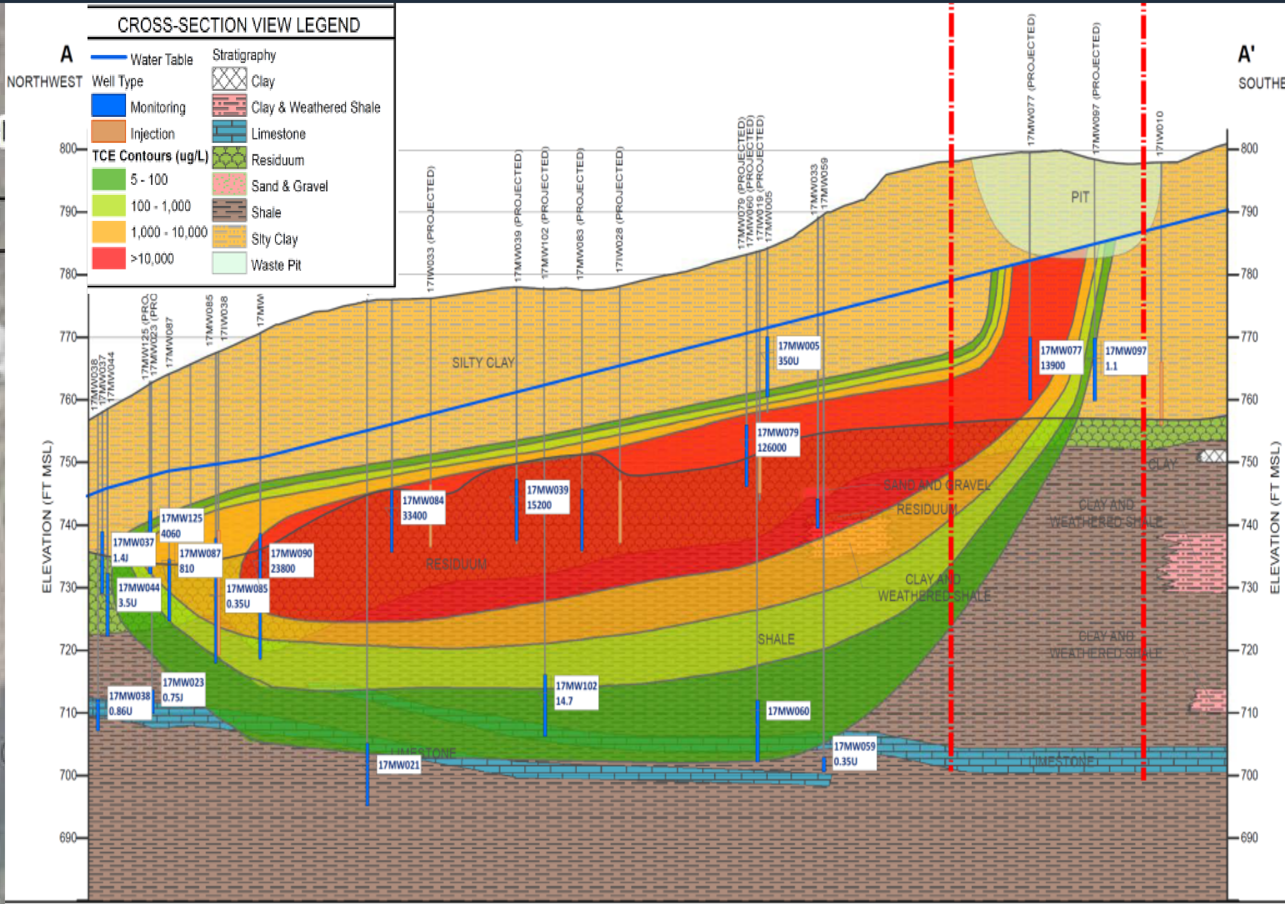
3) Vapor treatment needs to be comprehensive during heating

Challenge 1: Complicate Lithology and Altered permeabilities by ZVI.

15,072 ft², targeting depths from 44.5 to 57 ft due to varied competent bedrock

- Complicate lithology including waste pits, low permeability silty clay, and weathered bedrock;
- Pre-conducted ZVI zone altered permeability;



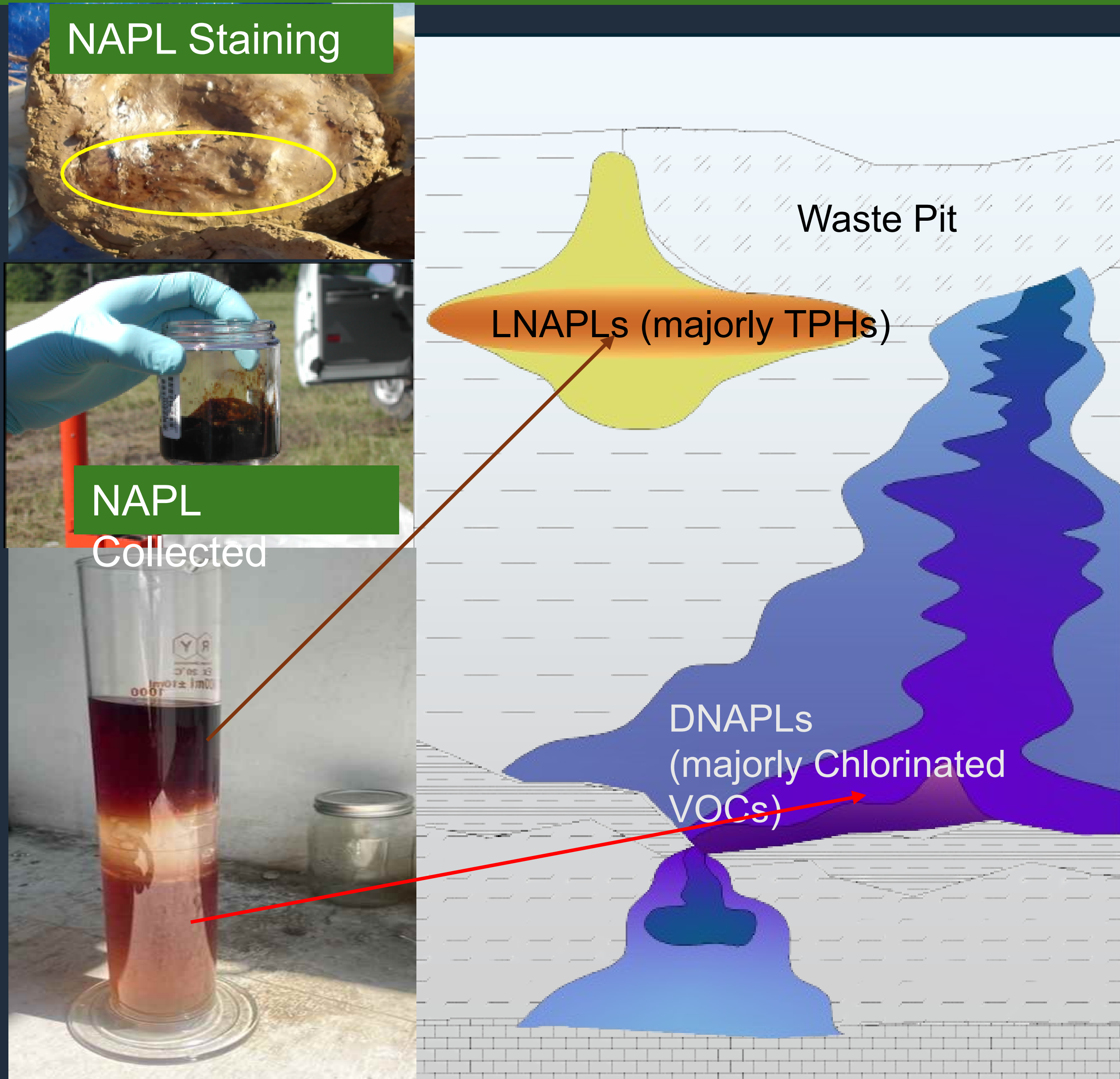


Challenge 2: Complex chemicals including VOCs and SVOCs, with both DNAPLs and LNAPLs exist

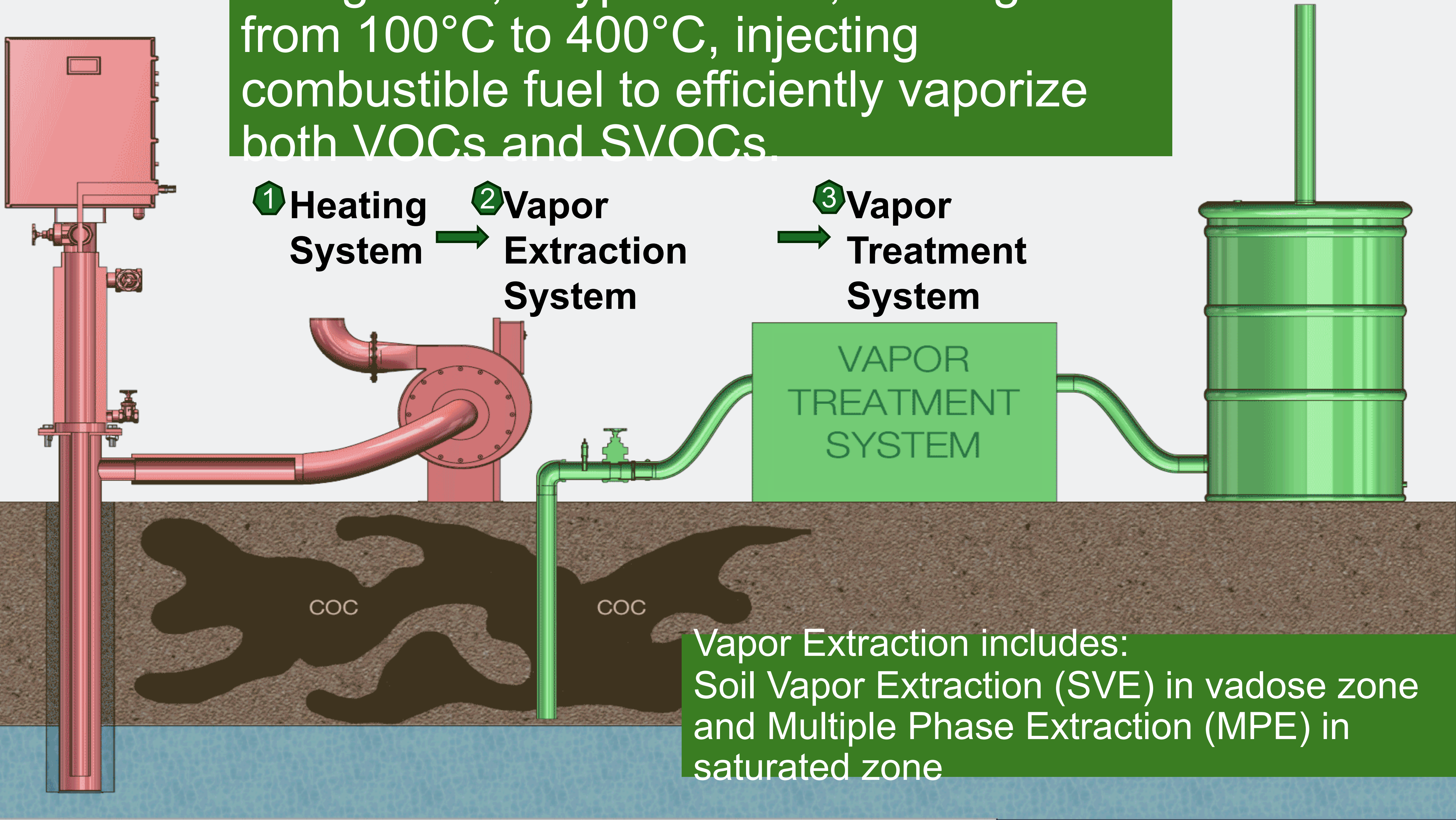
- Both DNAPLs and LNAPLs with concentration is >12%
- Both VOCs and SVOCs

VOCs	Max Conc. (ug/kg)	Boiling Point (°C)
Phthalene	98,700	218
Trimethylbenzene	230,700	170
Xylene	1,332,000	140
Ethylbenzene	289,000	136
PCE	7,850,000	121.1
4-Methyl-2-Pentanone	1,610,000	116
Toluene	19,900,000	110.6
TCE	32,300,000	87.2
cis-1,2-DCE	7,990,000	60.3

SVOCs	Max Conc. (ug/kg)	Boiling Point (°C)
Benz(a)anthracene	361,000	438
Pyrene	741,000	404
Benzo(b)fluoranthene	386,000	400
Fluoranthene	972,000	375
Phenanthrene	913,000	340



Using GTR, a type of TCH, we target T
from 100°C to 400°C, injecting combustible fuel to efficiently vaporize both VOCs and SVOCs.



Vapor Extraction includes:
Soil Vapor Extraction (SVE) in vadose zone and Multiple Phase Extraction (MPE) in saturated zone

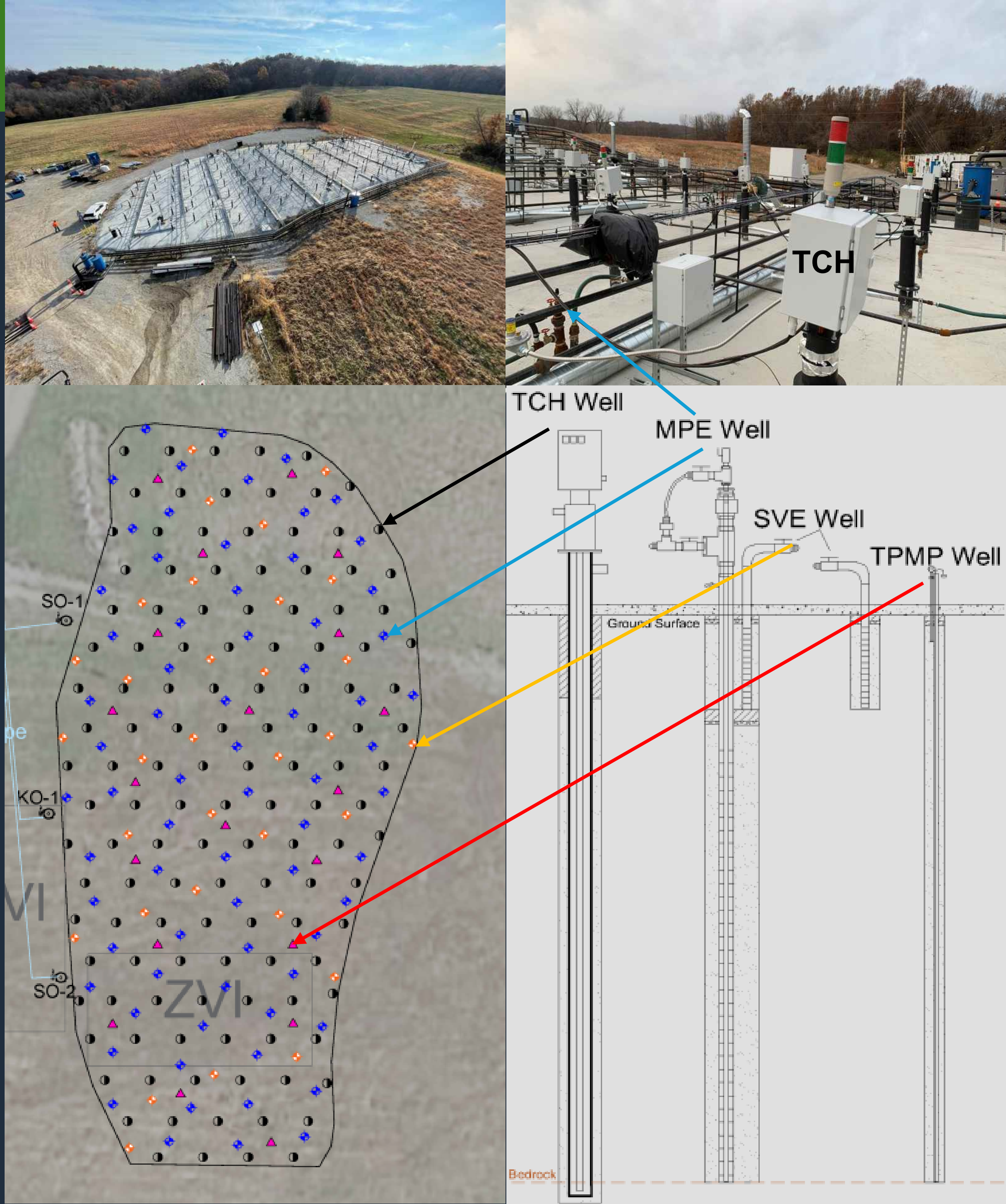
Well-layout Strategy for Our Pilot:

127 TCH Wells Adjusted well density based on initial concentration; 1-ft penetrate competent bedrock creating an effective "hot floor."

20 TPMP Provides precise temperature and pressure monitoring for operation control and adjustments.

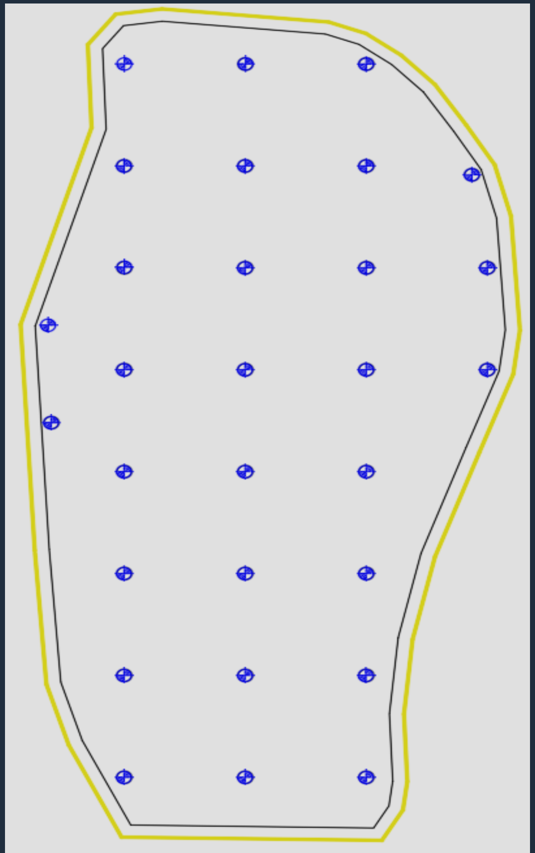
158 SVE Wells shallow and horizontal distribution targeting fugitive COC vapors near the surface.

71 MPE Wells Focused on enhancing contaminant recovery; intensifies for efficient steam management in low-permeability ZVI zones.

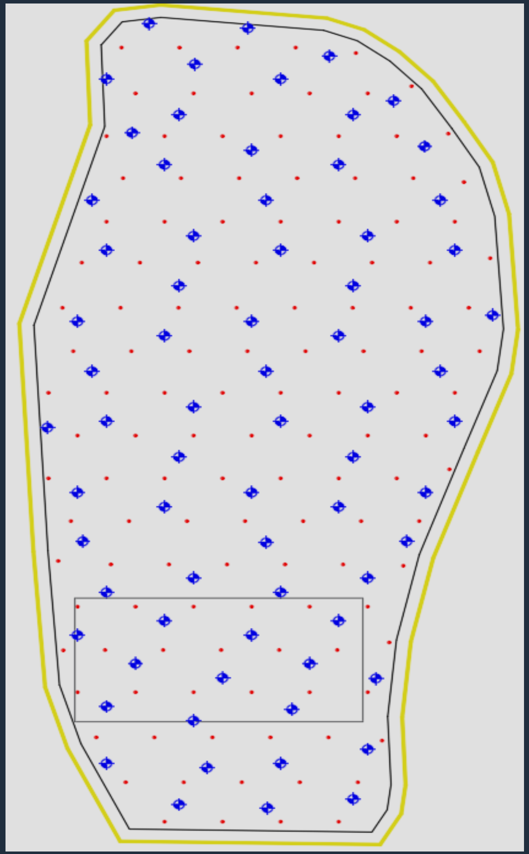


We used more MPE than non-heated sites.

Traditional MPE site
without heating:
29 MPE (ROI=15ft)



Heat enhanced MPE site:
71 MPE (ROI=8~10ft)
+127 TCH



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Core Inquiry for ISTR:
How high the temperature needs to be and how long to keep in this

Three Key Takeaways

1) MPE is a game changer for the thermal design in saturated

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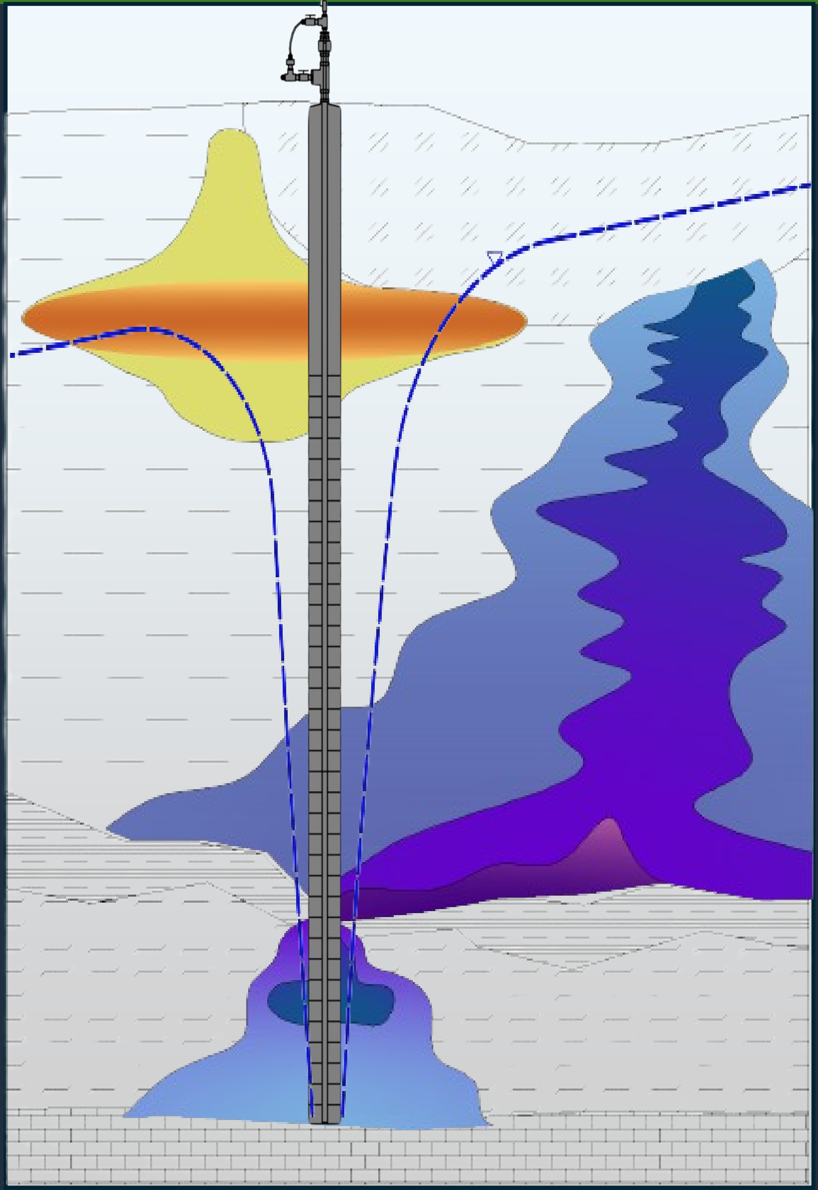
Takeaway 1: MPE is a game changer for the thermal design due to three key functions.

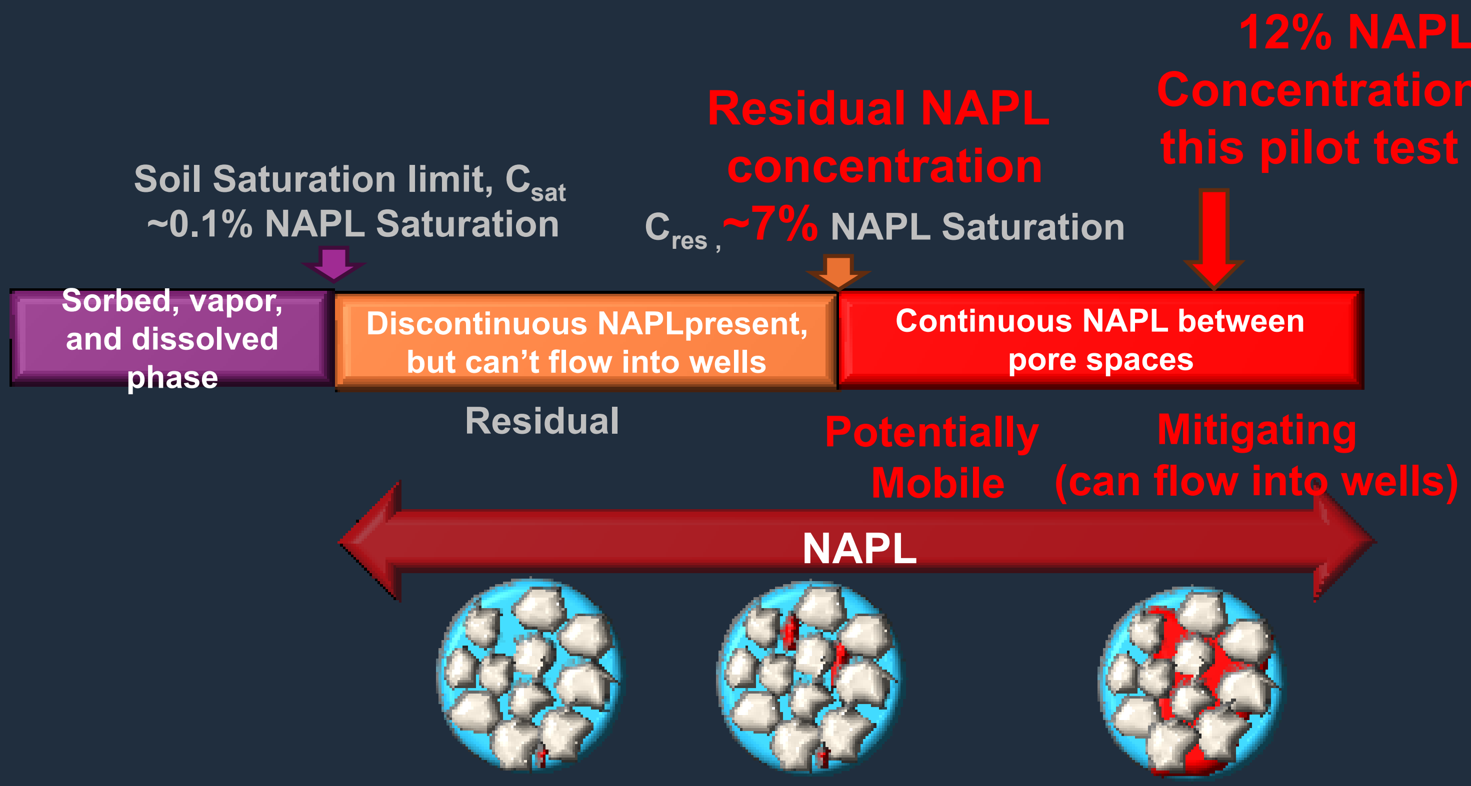
The use of a higher density of MPE wells, which are the game changers in our in-situ thermal project , is justified by three functions:

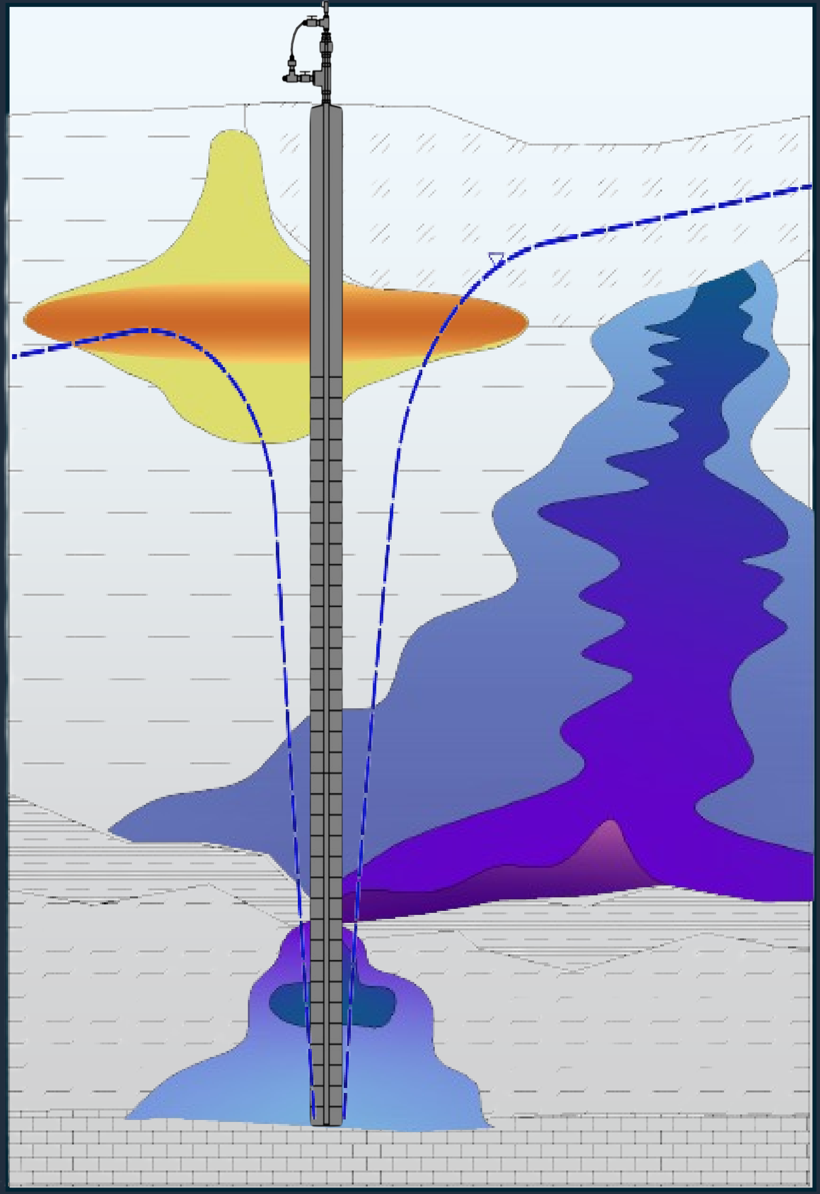
1) Skimming before and during the early heating stage (below 80°C) to prepare the site;
2) Creating vacuum pathways in deep zones, which eliminates the need to exceed 100°C for effective remediation;
3) Initiating steam stripping as temperatures approach 100°C, effectively using steam to remove chemicals and achieve lower



(1) Utilizing skimming: Effective removal of NAPL to residual NAPL concentration (~7%) mixed with steam, groundwater and gas.

MPE is a type of Skimming technique to extract the mobile NAPLs into slotted wells with stingers, which use a high vacuum to suck both NAPLs, water, and soil gas simultaneously, and reduce the NAPL concentration to Residual NAPL concentration.

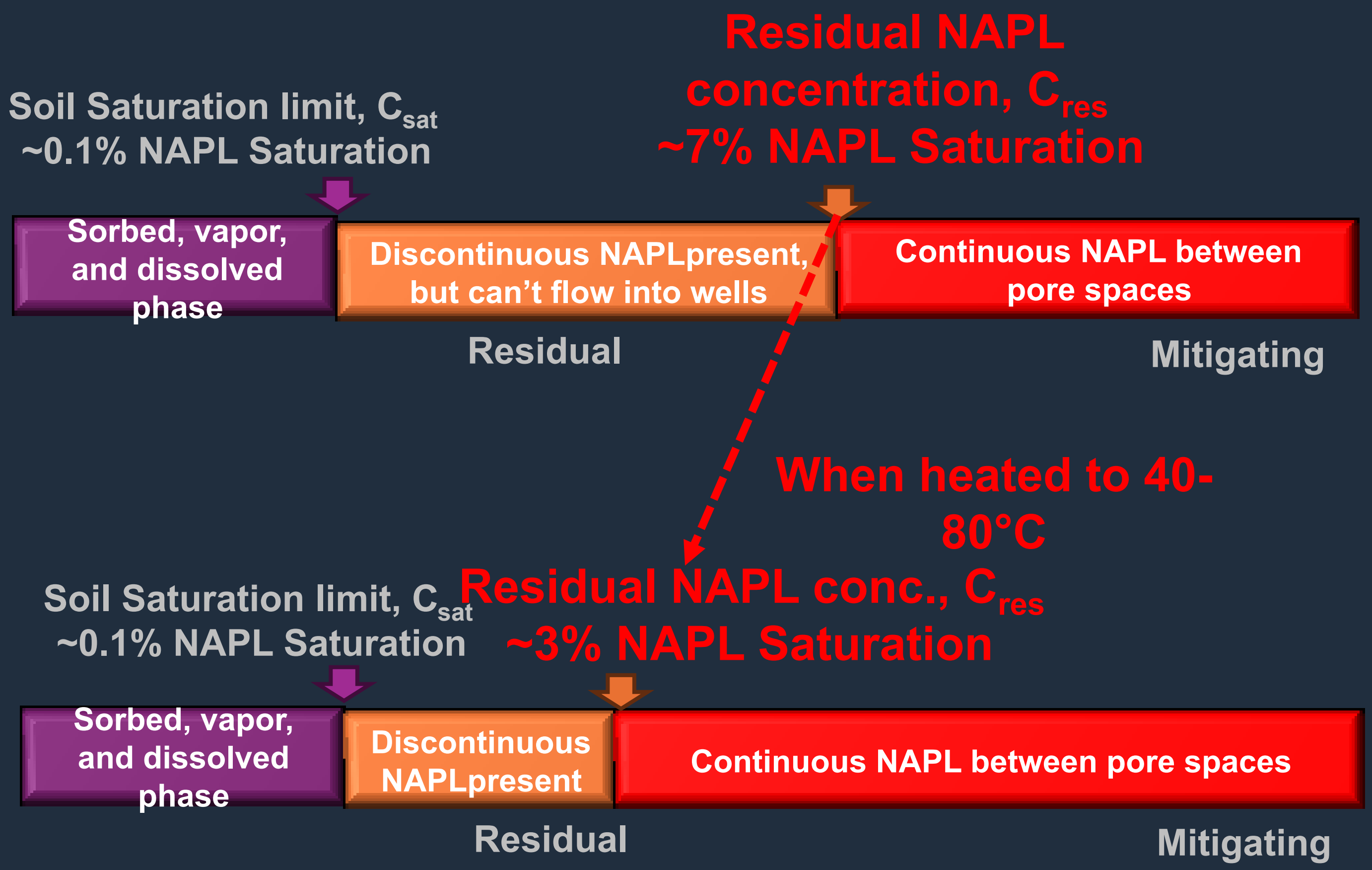




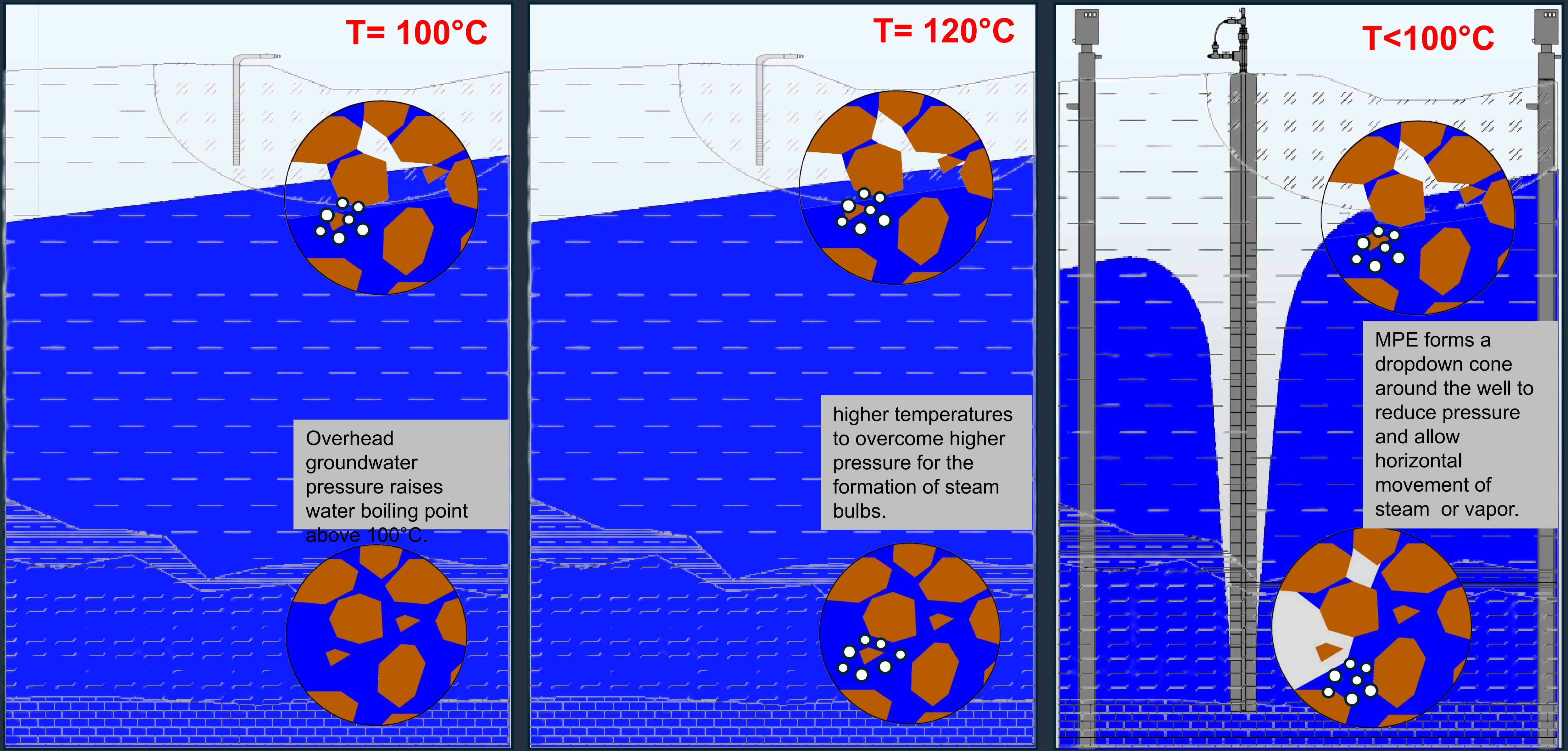
Adapted from Interstate Technology & Regulatory Council (ITRC). 2018. *Light Non-Aqueous Phase Liquid (LNAPL) Site Management: LCSM Evolution, Decision Process, and Remedial Technologies.* LNAPL-3. Washington, D.C. https://lnapl-3.itrcweb.org.

(1) MPE skimming enhanced when T→40-80°C, improving NAPLs mobility and achieving a lower residual concentration (about 2 - 4%).

As temperature increases, such as reaching 80°C, residual NAPL concentration decreases from 7% to around 3% due to heat reducing NAPL viscosity and enhancing mobility.



(2) MPE creates vacuum pathways for steam flow in deep saturated zones, eliminating the need to exceed 100°C for effective remediation.



(3) MPE initiates steam stripping when approaching 100°C, effectively removing chemicals with steam to achieve lower concentrations.

What is steam stripping?
The azeotropic point (or co-boiling point), where water and contaminants boil together at a lower temperature than water's boiling point (<100°C). When temperature approaches 100°C, MPE removes these vaporized contaminants mixed with steam from different depths, allowing effective remediation.

VOCs	Max Conc. (ug/kg)	Boiling Point (°C)
Phthalene	98,700	218
Trimethylbenzene	230,700	170
Xylene	1,332,000	140
Ethylbenzene	289,000	136
PCE	7,850,000	121.1
4-Methyl-2-Pentanone	1,610,000	116
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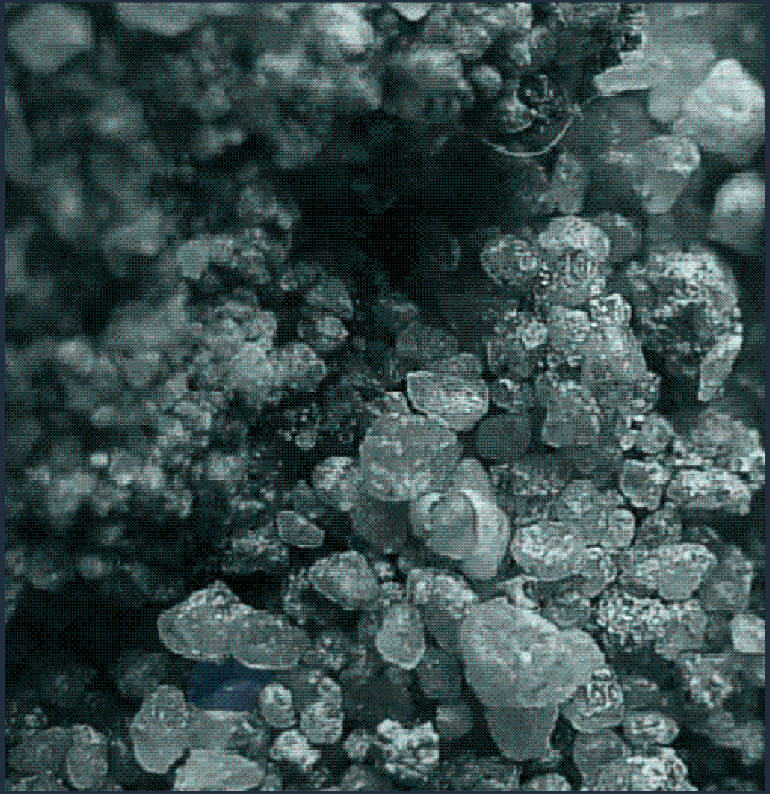
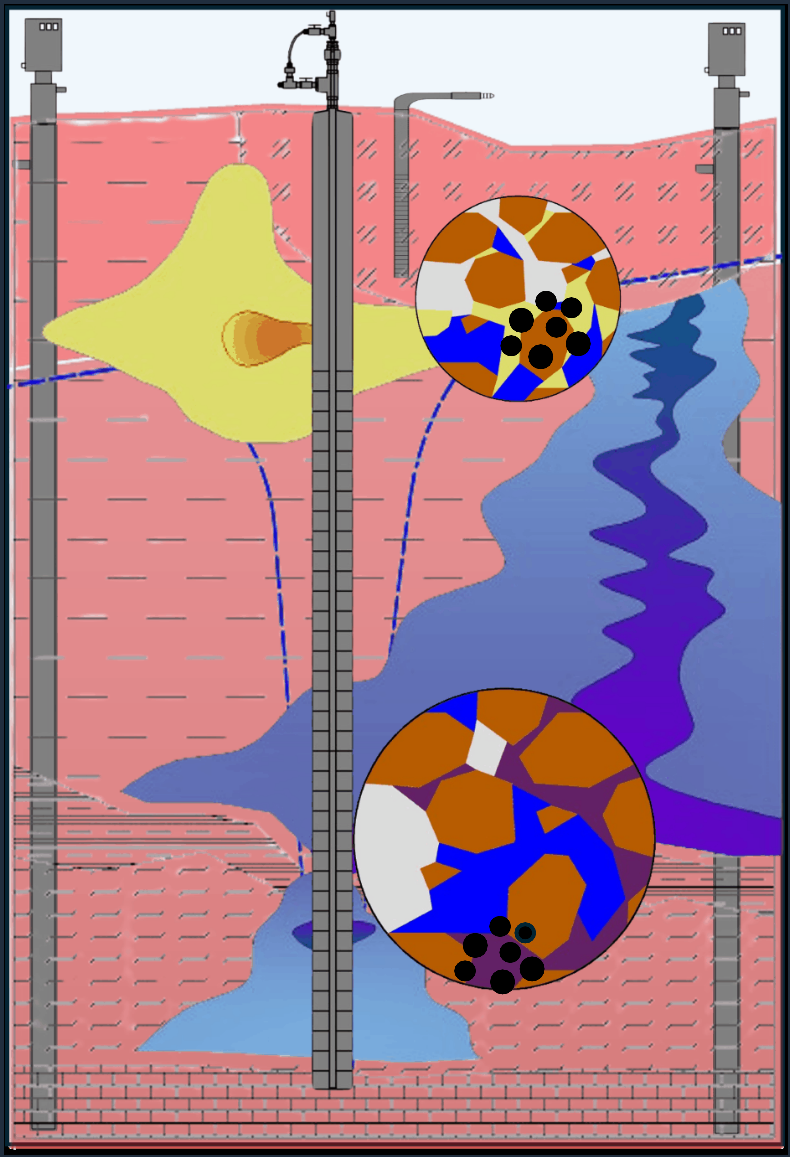
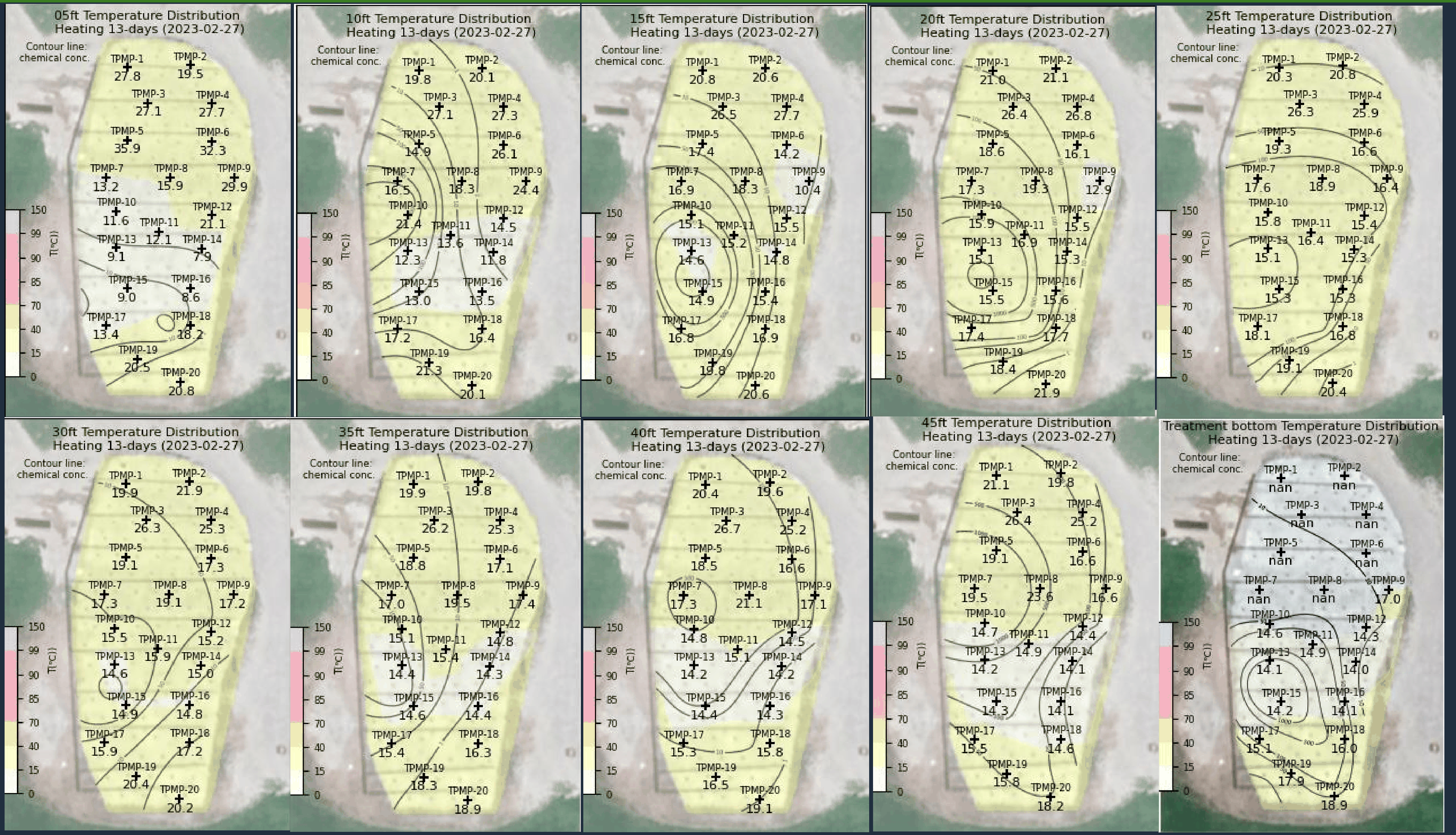




Temperature Evolution of this pilot test. (This site detailed report including the animation is available in www.georemco.com/demo-site1)

- Temperature reached between 90˚C and 105˚C in 62 days and maintained for at least 42 days.
- Temperature evolution in ZVI zone is similar to other zones.
- Temperature (color filled contour) and chemical concentration data (dashed contour lines) comparison offers insights into the efficacy of the ISTR system.



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Takeaway 2: Vapor extraction is crucial for energy and mass balance.

Theory about Energy and Mass Balance during Thermal Treatment

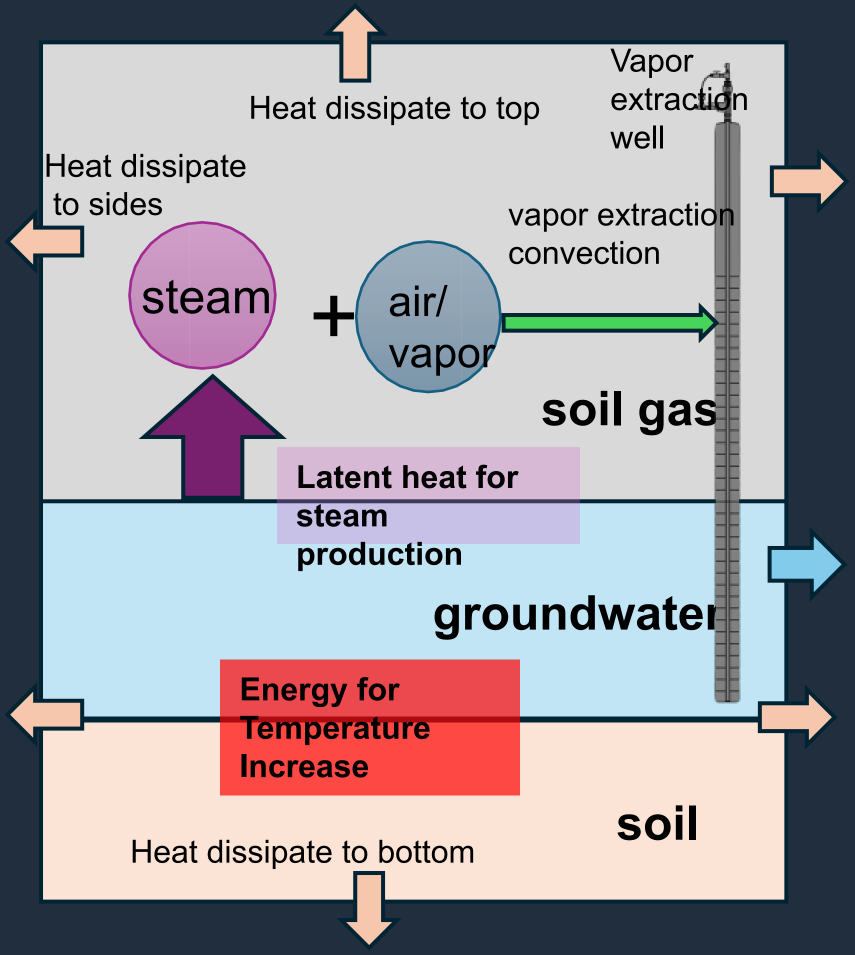
Injected Energy =

(1) Energy for soil and groundwater temperature increase
(2) Latent heat for steam production
(3) Heat dissipate to site boundaries (side, bottom and top)
(4) Heat loss from groundwater convection outside
(5) Vapor extraction convection (air and vapor mixed)

- Specific Heat Capacity of Water Temperature increase from 20°C to 100 °C = 335 J/g.
- Latent Heat of Vaporization of Water=2260 J/g.

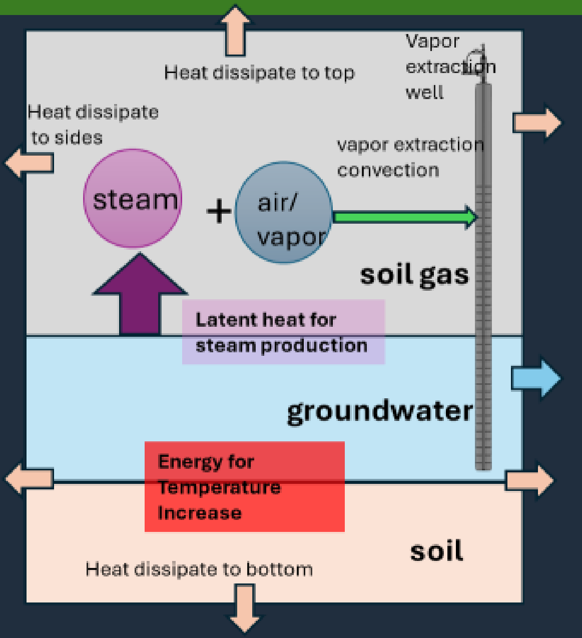
Understanding Phase Mass and Energy Dynamics:

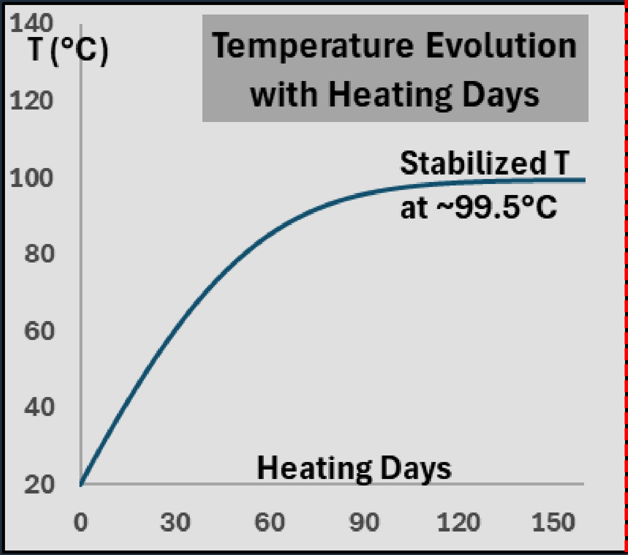
Vapor extraction rate and energy balance are important in maintaining the mass balance of steam and water phases. As steam is extracted, the equilibrium requires additional latent heat to vaporize new groundwater and restore balance.



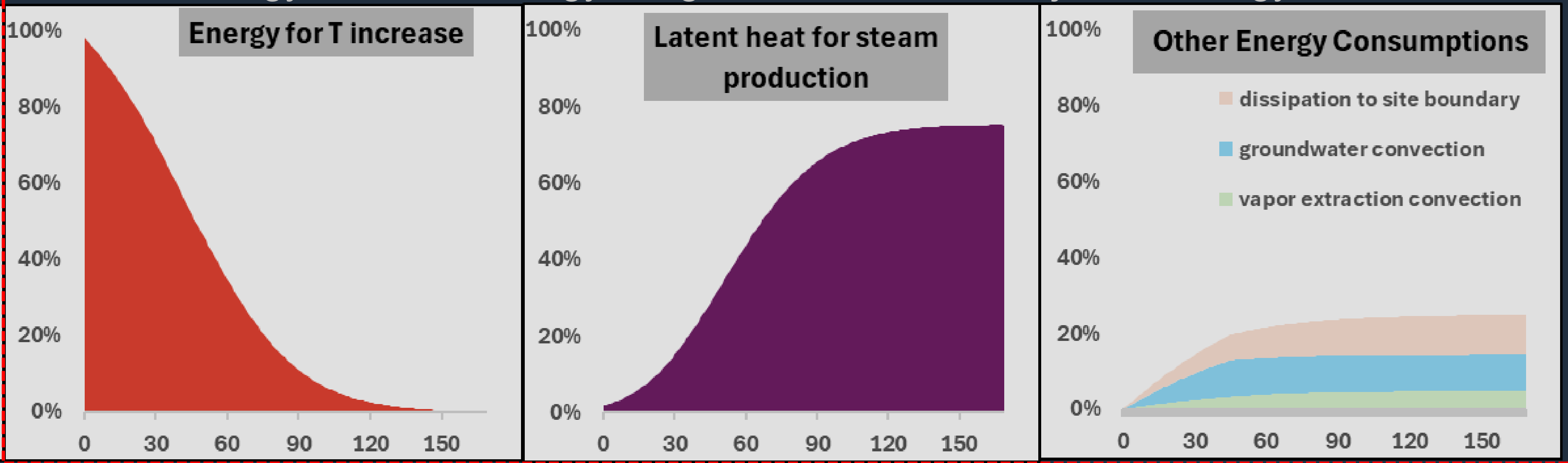
Pilot Test Insights: Achieving Thermal Equilibrium Through Energy and Mass Balance under 1500 SCFM vapor flow rate.

Energy initially raises soil and groundwater temperatures.
As temperatures surpass 80°C, a greater proportion of energy shifts towards producing latent heat for steam, effectively extracted via vapor extraction. This process stabilizes the temperature at approximately 99.5°C.



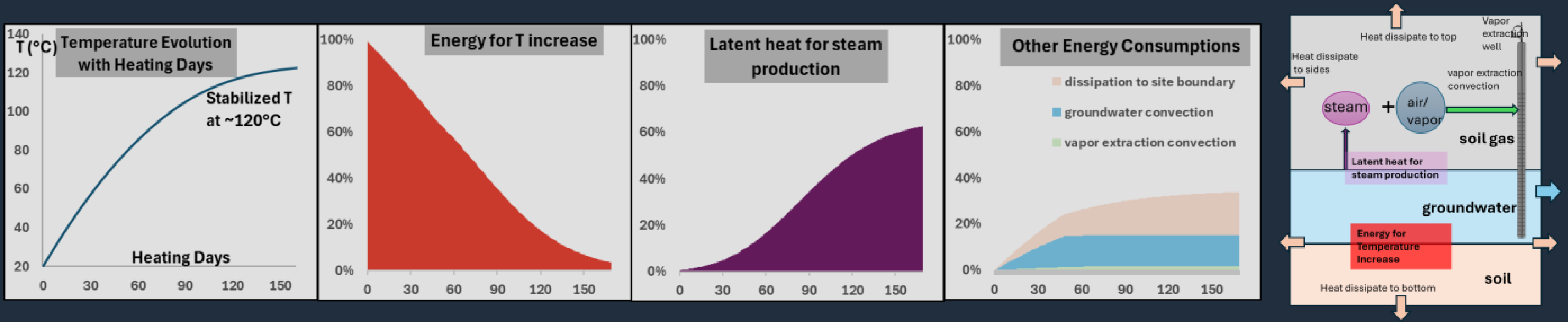


Energy Balance: energy usage rate out of total injected energy

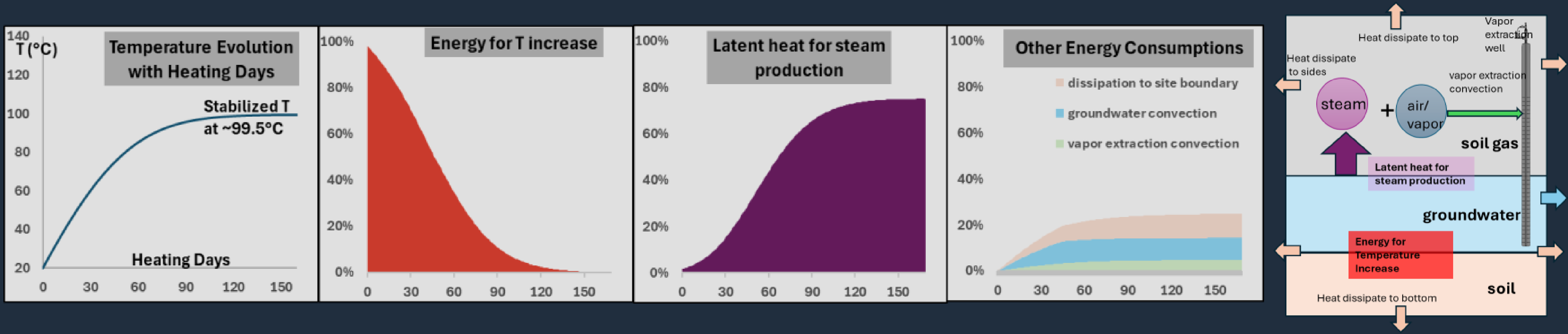


Other Design: Delay extraction until T→120°C and vapor rises to the vadose zone to optimize energy use and increase vapor pressure.

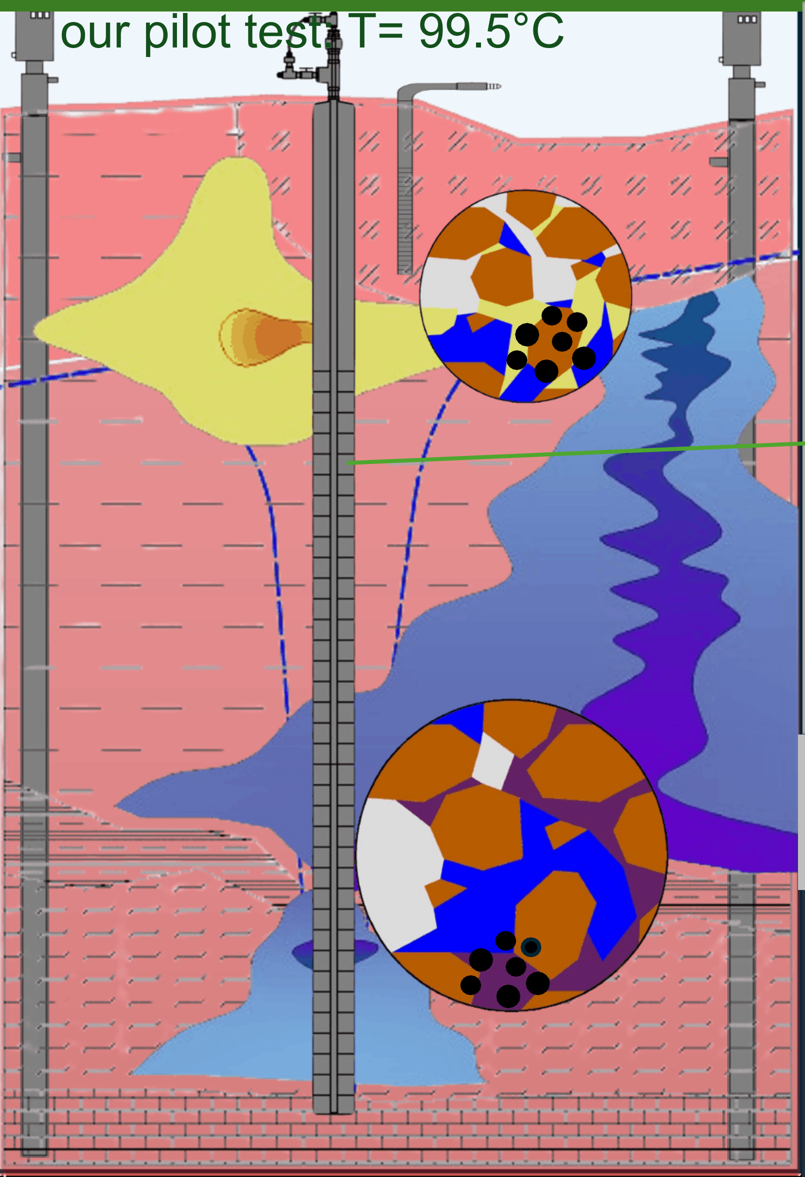
Other design: 500-SCFM with minimal MPE, and rely on SVE for catching rising vapor and steam from saturated zone to vadose zone.

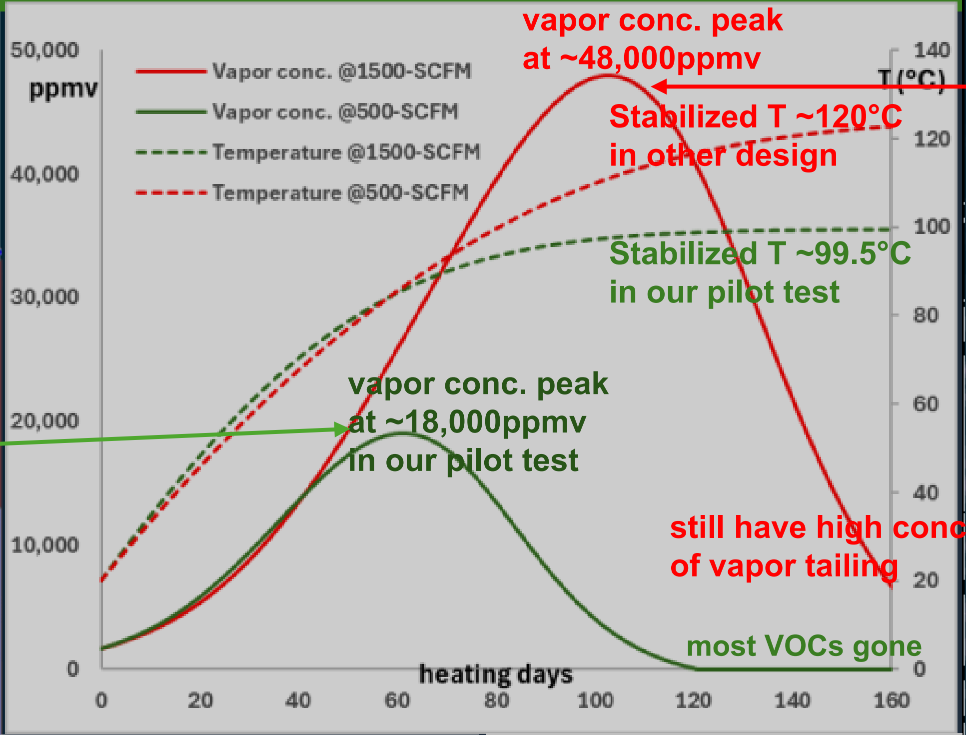


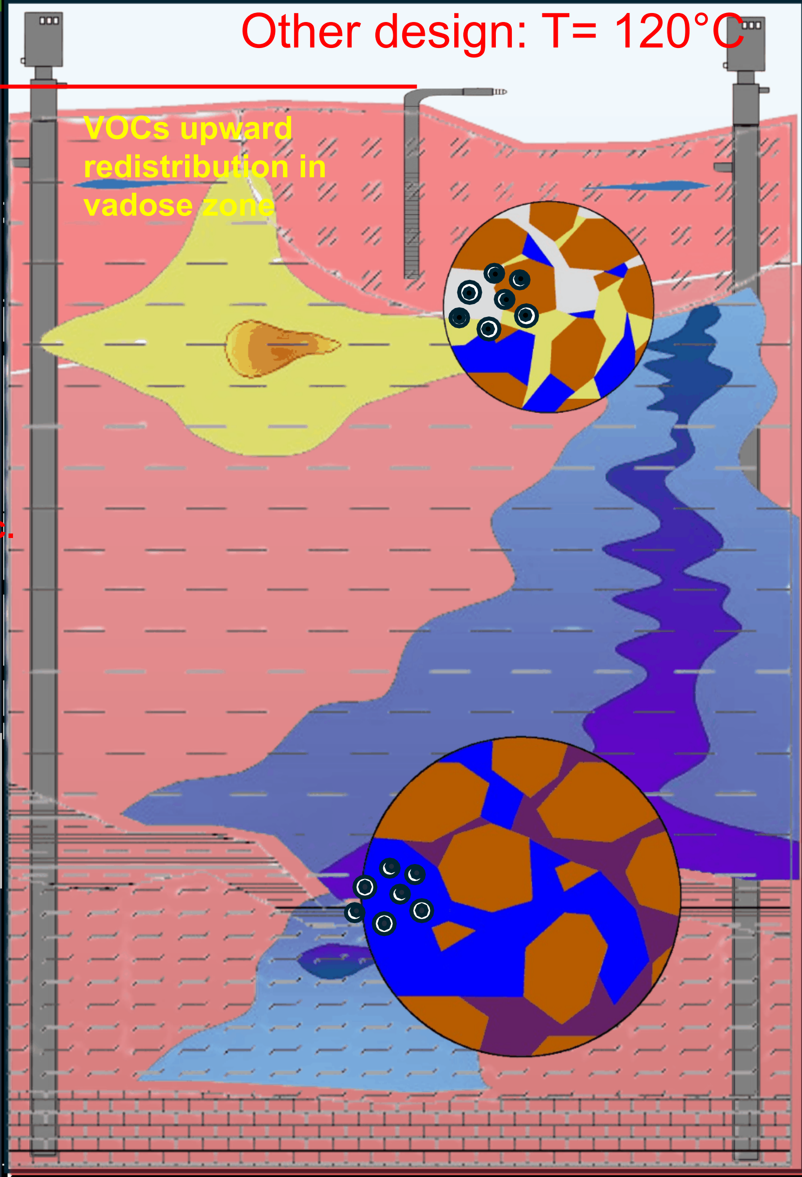
Our design: 1500-SCFM with sufficient MPE.



1) Superheating drives VOCs upward, causing pollution redistribution; 2) Concentrated vapor peaks can overwhelm the treatment system; 3) Longer tailing effects require extended treatment duration







Our pilot test: sufficient vapor flow (1500-SCFM) with both MPE and SVE

stabilized temperature slightly below 100C, but the chemicals are still completely removed with steam and vapor

Other design: insufficient vapor flow (500-SCFM) with majorly SVE

higher T but the vapor concentration will be more than double, and the tailing vapor concentration is higher and need long treatment

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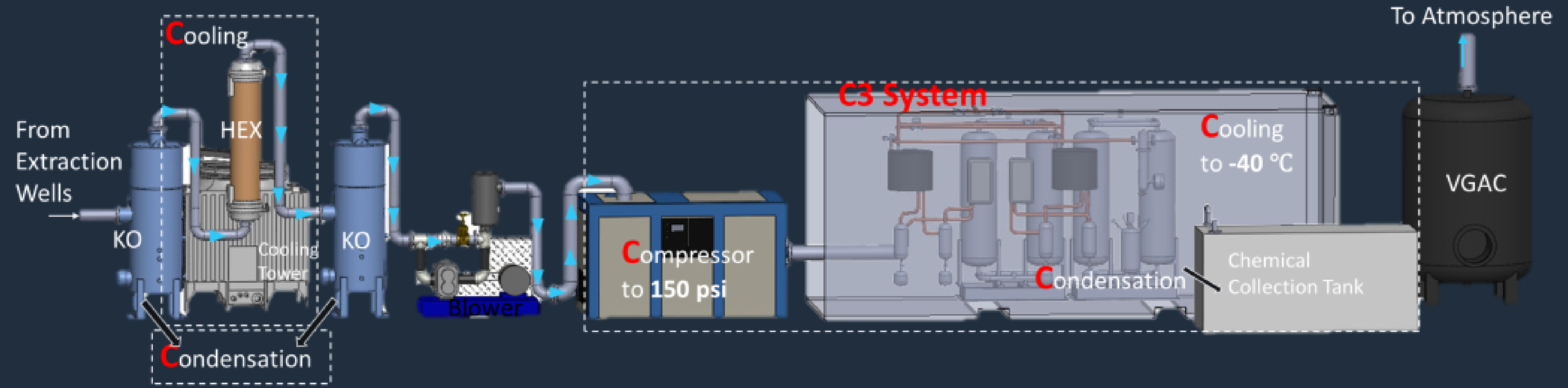
Takeaway 3: comprehensive vapor treatment system is needed. Three stages: Cooling-condensation, C3, and VGAC absorption.



In this pilot test, we implemented a vapor treatment system with a capacity of 1500 scfm.

For the highly contaminated saturated zone to MPE wells, we connected a three-stage system:

1) Cooling and condensation to ambient temperature,

2) Compressed Cryogenic Condensation (C3) system,

3) VGAC polishing.

For the lower concentration vadose zone linked to an SVE well, we used a two-stage system without secondary C3

C3 (compressed cryogenic condensation) converts vapor to liquid, allowing unlimited inlet conc. and requiring minimal maintenance.

Industrial-level concentrated vapor

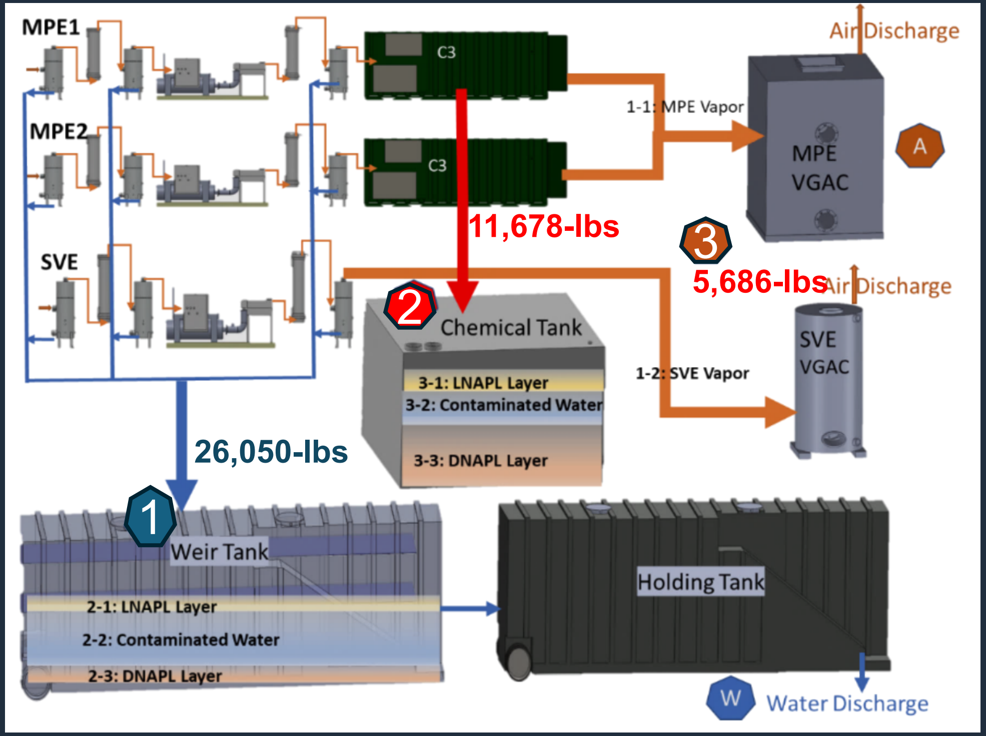
Highly Compressed Cryogenic Cooling Complete Condensation

Vapor emissions meet regulations

Vapor convert to liquid for collection and analysis

Advantages:
- **No inlet concentration limit**
- **No secondary by-products**
- **Low maintenance**
- **Recycling and reuse**

Mass production: direct extraction, concentrated condensation in C3, and VGAC absorption, offering insights for future ISTR vapor treatment.

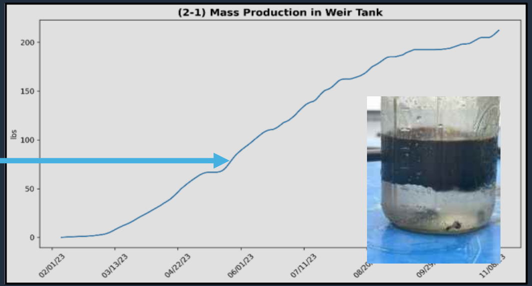


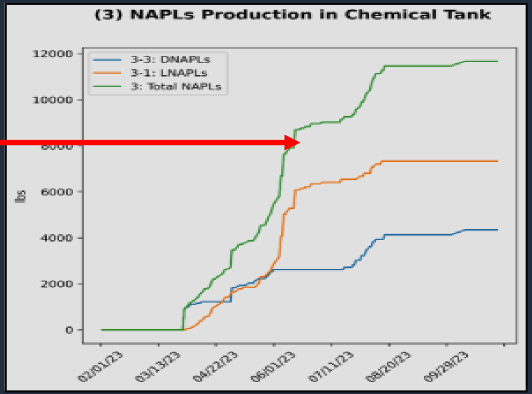
Total mass 43,414-lbs collected during pilot test:

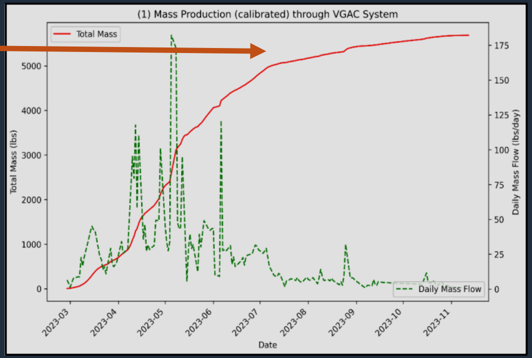
1 **from direct extraction and cooling and condensation at ambient temperature:** Recovered approximately **26,050-lbs** of NAPLs from MPE extraction and cooling and condensation under ambient temperature.

2 **from C3 System:**
Recovered **11,678-lbs** of LNAPLs and DNAPLs from compressed cryogenic condensation.

3 **from VGAC System:**
Processed approximately **5,686-lbs** of VOCs post-cooling stages, majorly from SVE stream without C3







Confirmation sampling results: ISTR and vapor extraction strategy successfully removed >95% mass in complex, heterogeneous lithology.

VOCs	Max Conc. (ug/kg)	Boiling Point (°C)
Phthalene	98,700	218
Trimethylbenzene	230,700	170
Xylene	1,332,000	140
Ethylbenzene	289,000	136
PCE	7,850,000	121.1
4-Methyl-2-Pentanone	1,610,000	116
Toluene	19,900,000	110.6
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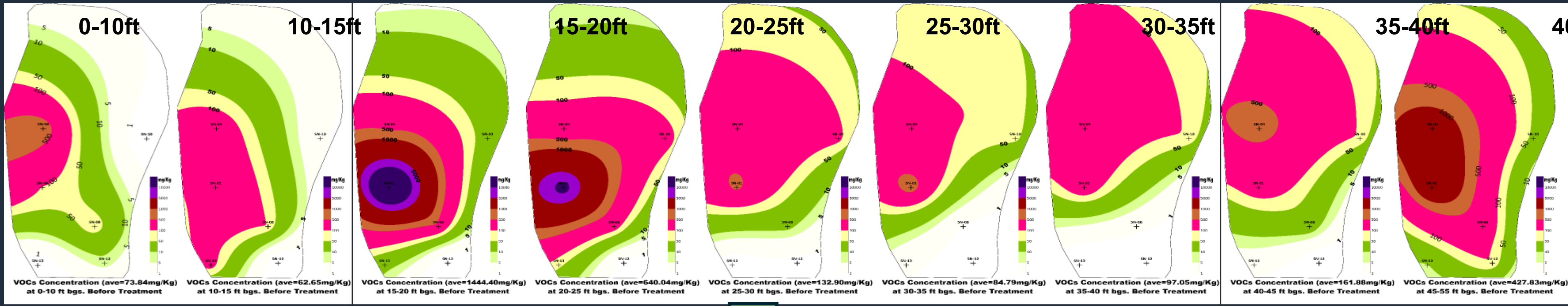
Depth Range (ft bgs.)		0-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-55	Ave. Conc. (mg/kg)
ave. VOC conc. (mg/kg)	before Treatment	73.84	62.65	1,444.40	640.04	132.90	84.79	97.05	161.88	427.83	329.63
	after Treatment	7.37	0.28	0.78	0.86	0.58	5.06	7.21	16.39	67.68	16.48
	Reduction Rate	90.0%	99.6%	99.9%	99.9%	99.6%	94.0%	92.6%	89.9%	84.2%	95%

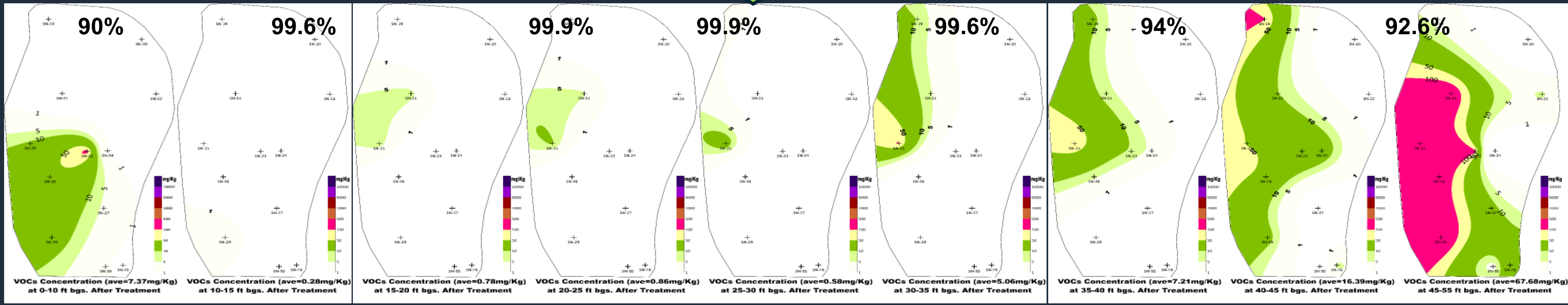
- VOCs average removal rate >95%.
- VOCs in previous ZVI zones were reduced to >99%.
- Need to have additional heating tube in the full scale to reach the goal at bottom.

case study are in our website: www.georemco.com/demo-

Before Treatment



After Treatment



Even the SVOCs showed a removal efficiency >76% at ~100°C, due to effective vapor extraction and steam stripping.

SVOCs	Max Conc. (ug/kg)	Boiling Point (°C)
Benz(a)anthracene	361,000	438
Pyrene	741,000	404
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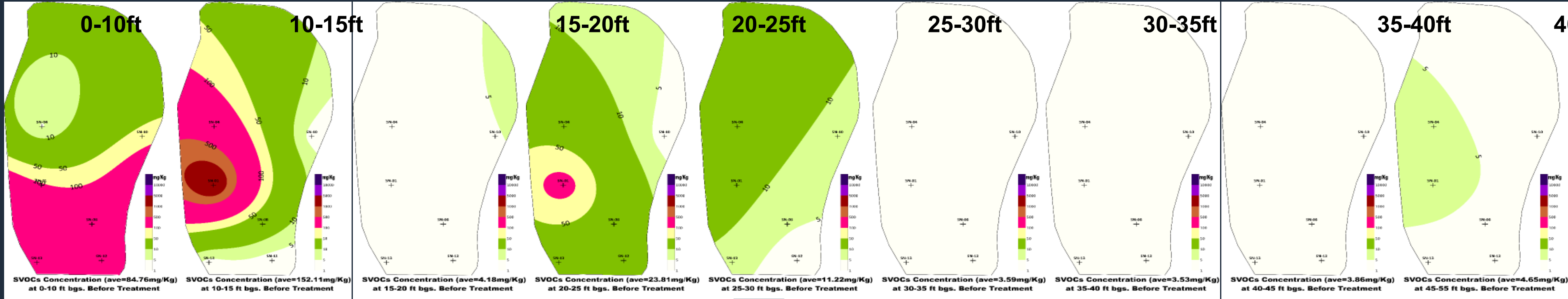
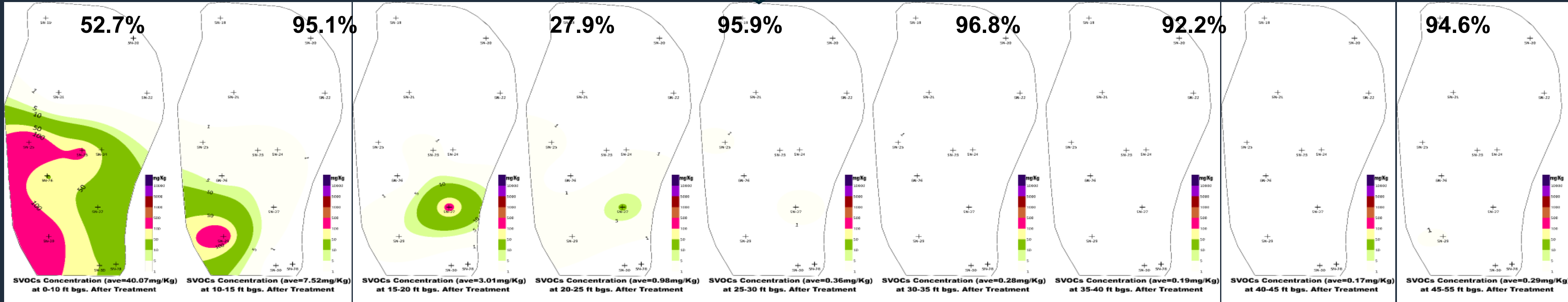
Depth Range (ft bgs.)		0-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-55	Ave. Conc. (mg/kg)
ave. SVOC conc. (mg/kg)	before Treatment	84.76	152.11	4.18	23.81	11.22	3.59	3.53	3.86	4.65	34.64
	after Treatment	40.07	7.52	3.01	0.98	0.36	0.28	0.19	0.17	0.29	8.47
	Reduction Rate	52.7%	95.1%	27.9%	95.9%	96.8%	92.2%	94.6%	95.6%	93.8%	76%

SVOCs reduced from 2,854-lbs to 697-lbs in the target treatment zone.

Before Treatment



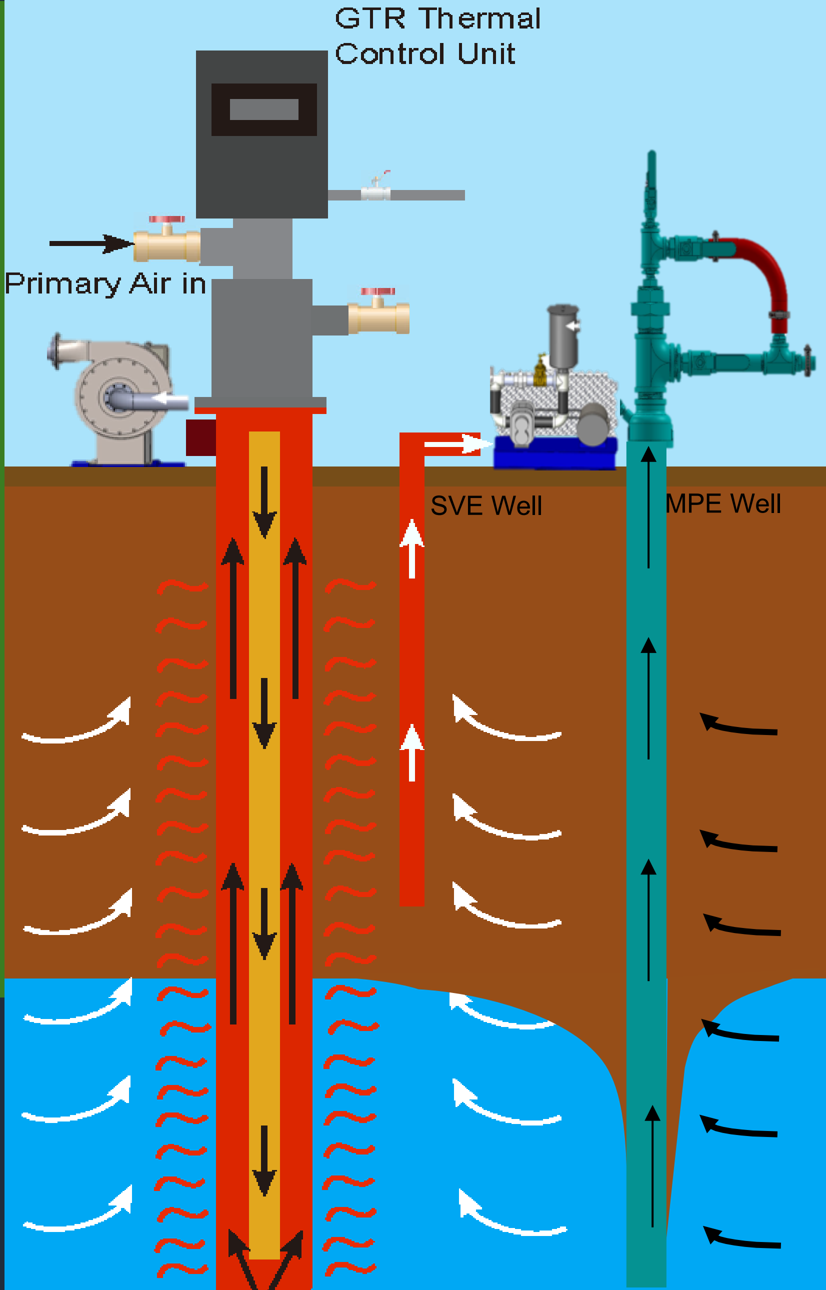
After Treatment



More information about this case study are in our website: **www.georemco.com/demo-site1**

Answers to the core inquiry and three takeaways:

1) **MPE is a game changer for thermal design in saturated zone.** Thermal treatment was developed to boost vapor extraction efficiency. MPE extraction provides NAPLs skimming, vacuum pathway, and steam stripping for chemical removal.
2) **Vapor extraction is crucial for energy and mass balance.** Thermal treatment needs to leverage energy and mass balance for comprehensive effectiveness. It needs to combine with appropriate vapor extraction to achieve environmental clean-up goal, instead of just using taxpayer money to cook soil.
3) **Vapor treatment needs to be comprehensive during heating.** Avoid superheating and overloading the vapor treatment system and emissions—don't bite off more than you can chew.



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