Electrical Resistance Heating (ERH): Design and Performance Criteria

Battelle

Columbus, OH

Presentation Overview

- Introduction to In-Situ Thermal Technologies
  - ERH Technology Description
  - Other In-Situ Thermal Technologies (Steam injection, ISTD)
- ERH Application Site Descriptions
  - High-permeability sites (Alameda, Cape Canaveral)
  - Low-permeability sites (Bedford, Camp Lejeune, Charleston)
- ERH Performance and Costs
- Lessons Learned
- Recommendations for Future Applications

Key Words and Definitions

- **DNAPL**
  - Dense nonaqueous-phase liquid such as chlorinated solvents (CVOCs), typically sink in groundwater until pooling above a low-permeability unit or becoming trapped as residual along the migration pathway
  - DNAPL source zone is the portion of the subsurface that contains this pooled and/or residual DNAPL
  - CVOCs typically found at Navy sites are DCA (dichloroethane), DCE (dichloroethene), TeCA (tetrachloroethane), PCE (perchloroethene), TCA (trichloroethane), TCE (trichloroethene), and VC (vinyl chloride)
- **Azeotropic distillation**
  - The ability of a mixture of certain liquids to boil at temperatures below the boiling points of the individual components

Topic Problem Statement

- The Navy has implemented ERH cleanup technology at several DNAPL sites, including sites representing high-permeability and low-permeability aquifers
  - Success has been mixed
  - Challenges related to site features and ERH capabilities and limitations need to be understood and overcome
  - Suitable performance criteria need to be identified and interpreted during both design and application phases of a project to ensure the success of an ERH application

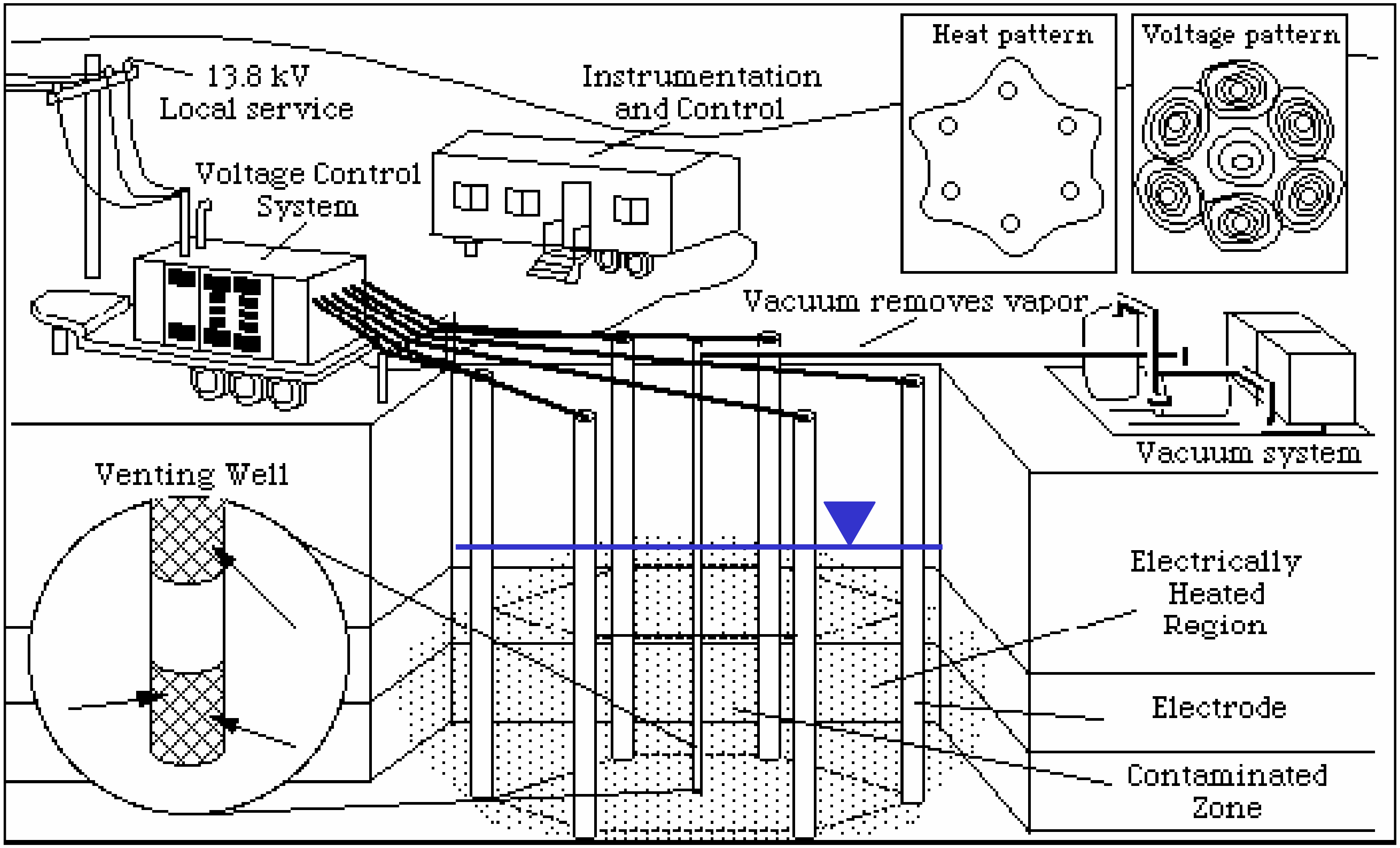
Topic Context

- DNAPL and other types of source zones continue to be a challenge to remediate (RITS Spring 2006)
- ERH has been around for some years as a promising option for source remediation (RITS Fall 2000, Spring 2001)
- A study funded by ARTT Navy work group and conducted by Battelle on the ERH application at various Navy sites is extensively used for the preparation of this presentation.
- What does our experience at various Navy and NASA sites tell us about ERH performance, and what are the implications for applicability and cost of this technology at future sites?

ERH Technology Description

- Passage of electric current between electrodes installed into the subsurface
- Electricity travels through moisture present in the subsurface soil, where the resistance it encounters leads to subsurface heating
- Subsurface temperatures can potentially be raised to the boiling point of water
- Volatile contaminants are removed from groundwater by some combination of volatilization, boiling, and/or enhanced degradation. Vapors generated are captured by soil vapor recovery wells and treated aboveground

ERH Technology Schematic



Source: GWRTAC, 2003

Management Approach Advantages

- Vendors claim that ERH is particularly well suited for low-permeability aquifers, as electricity is conducted primarily through water in porous clays
- High voltage applications have been managed safely by the vendors at all sites so far, without exception
- Can be applied even when DNAPL source lies under a building
- Works with a broad variety of volatile contaminants
  - Not restricted by chemistry
- No potentially hazardous chemicals need to be injected in the aquifer
- Biodegradation and hydrolysis reactions are stimulated at elevated temperatures
- Regulators like the technology conceptually

Management Approach Limitations

- Slower heating and additional design and operational changes needed in low-permeability aquifers, thus resulting in higher time, energy, and cost requirements at such sites
  - Especially when hydraulic gradient also is low
- Could be expensive if source contamination is spread over large volumes of the aquifer
- Requires extensive vapor capture and treatment system

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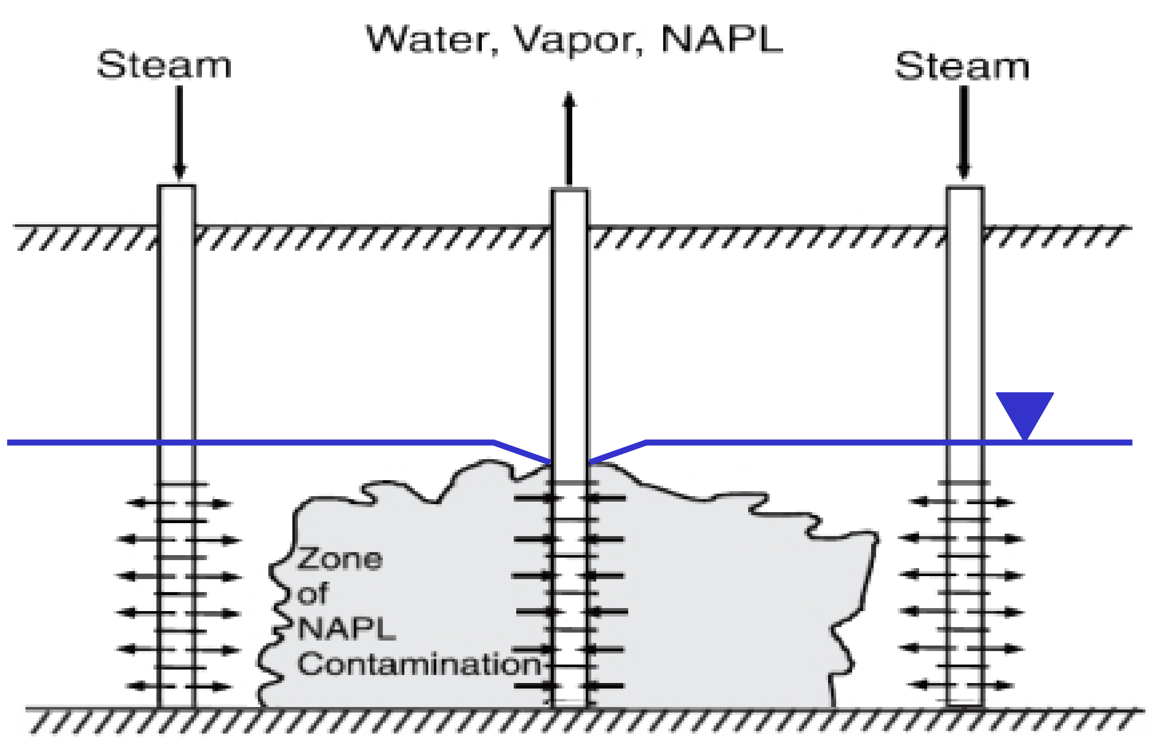
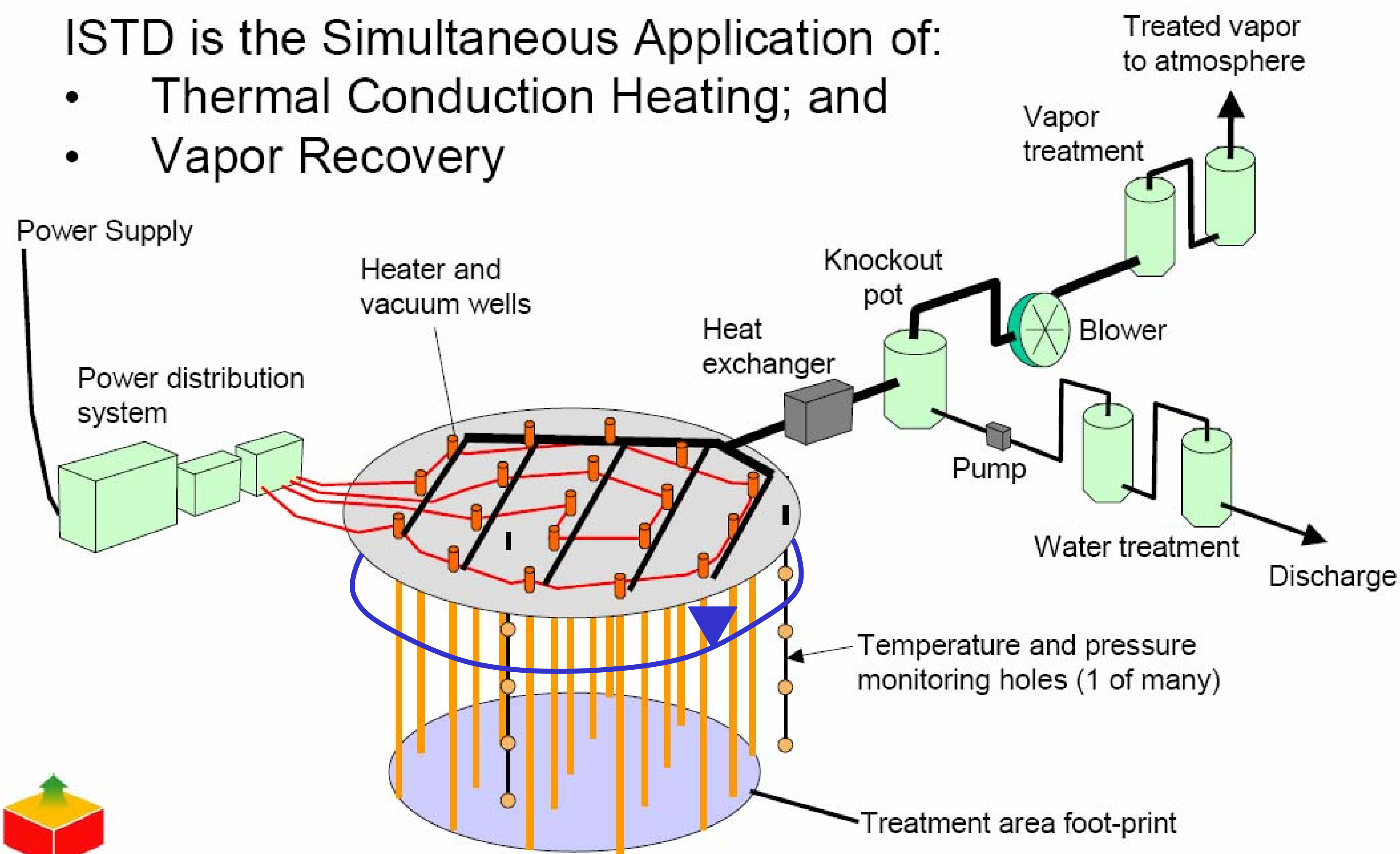
In-Situ Steam Injection Schematic



Source: U.S. EPA, 1998

ISTD Technology Description Illustration



Source: TerraTherm

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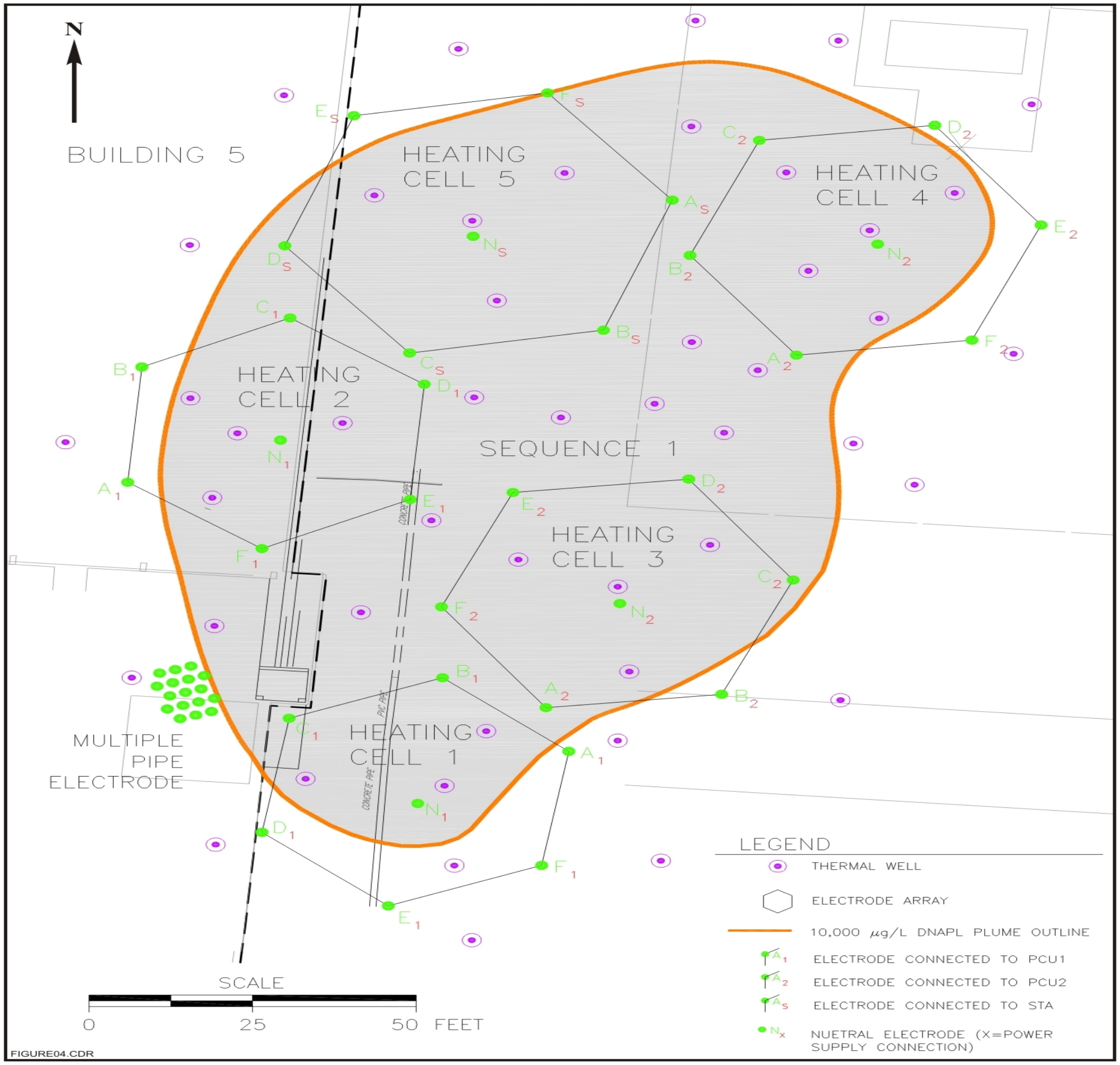
Former Naval Air Station (NAS) Alameda, CA

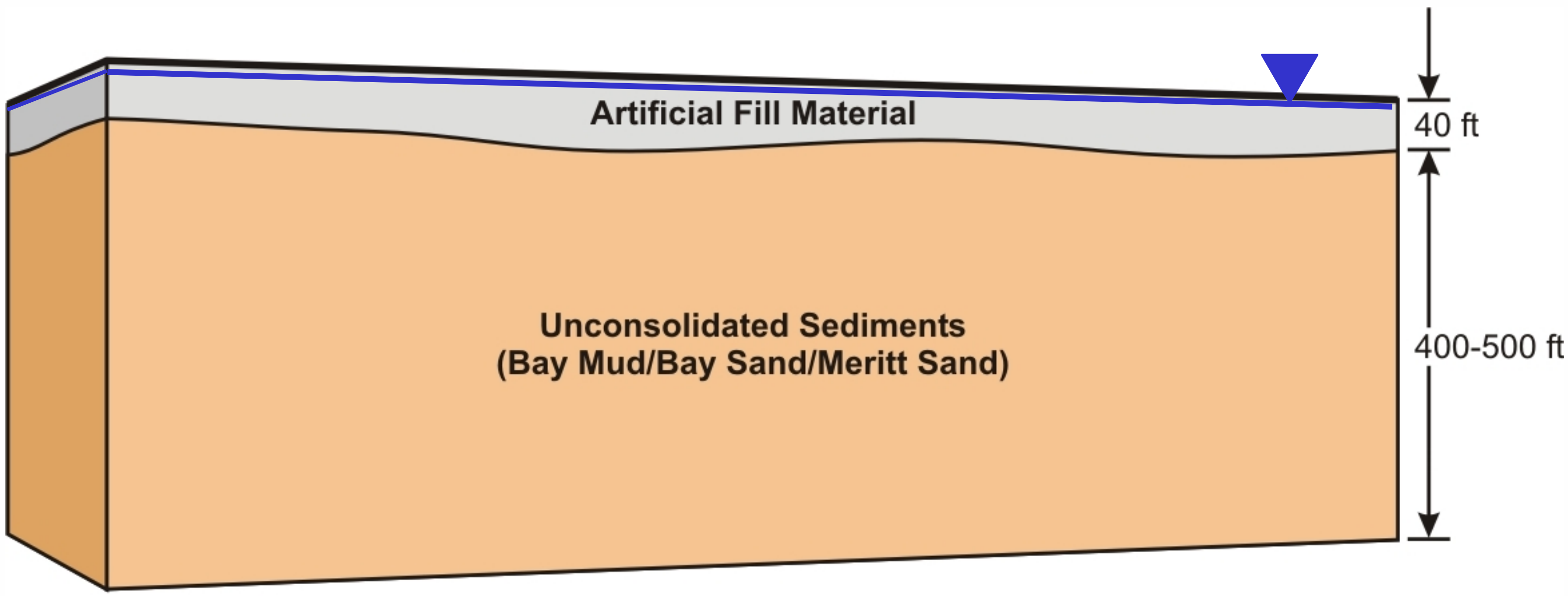
- ERH applied as remedial technology at IR Site 5
  - ERH was applied at plume 5-1, which was 1/3 acre in size
- COCs include 1,1,1-TCA; 1,1-DCA; TCE; *cis*-1,2-DCE; VC; 1,2-DCA; 1,1-DCE; trans-1,2-DCE; 1,1,2-TCA; and PCE
- Highest concentration: 240,000 µg/L total VOCs, 1,1,1- TCA (205,000 µg/L)
- Subsurface consists of two geologic zones
  - High-permeability artificial fill (targeted for treatment)
  - Low-permeability bay sediment unit (BSU)
- Groundwater at Plume 5-1 is between 4 and 7 ft bgs; sediments in the subsurface have moderate to low hydraulic conductivity

Former NAS Alameda, CA – Plan View

NAS Alameda Point, CA – Horizontal Cross-Section



NAS Alameda Point, CA – Vertical Cross-Section

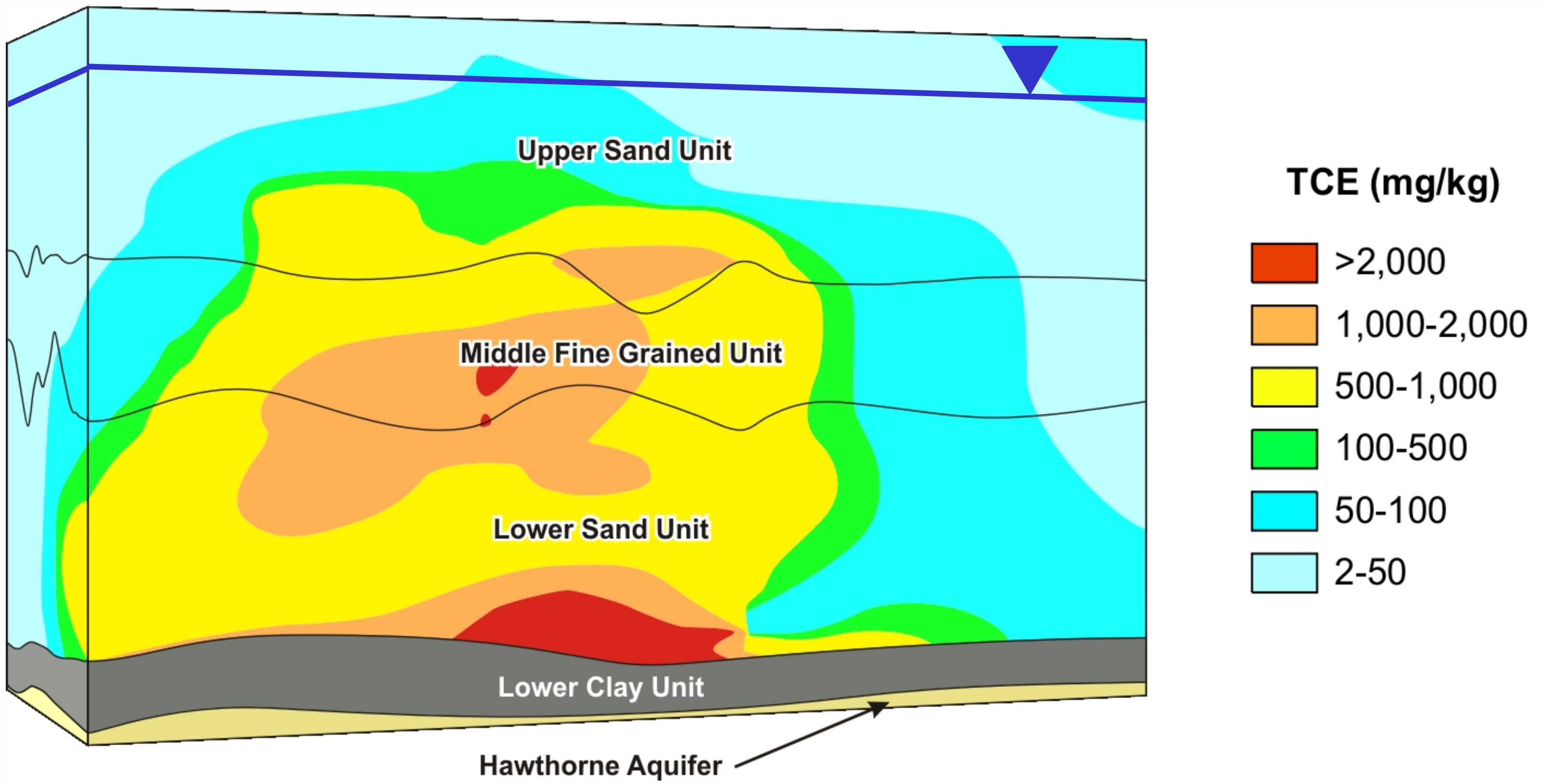


Launch Complex 34, Cape Canaveral, FL

- Surficial aquifer targeted extends from 25 ft bgs (water table) to ~45 ft bgs (clay aquitard)
- The two sand units (Upper Sand Unit, and Lower Sand Unit) demonstrate a relatively flat hydraulic gradient and have high permeability. Middle Fine-Grained Unit has relatively lower permeability.
- Maximum treatment depth was 45 bgs at the site
- DNAPL at the site is comprised mainly of TCE (1,100 ppm)
- Almost 20,600 to 40,000 kg of chlorinated VOCs estimated to be present, with dissolved concentrations approaching the solubility limit of TCE (1,100 mg/L)

Launch Complex 34, Cape Canaveral, FL – ERH Treatment System

Launch Complex 34, Cape Canaveral, FL – Vertical Cross Section



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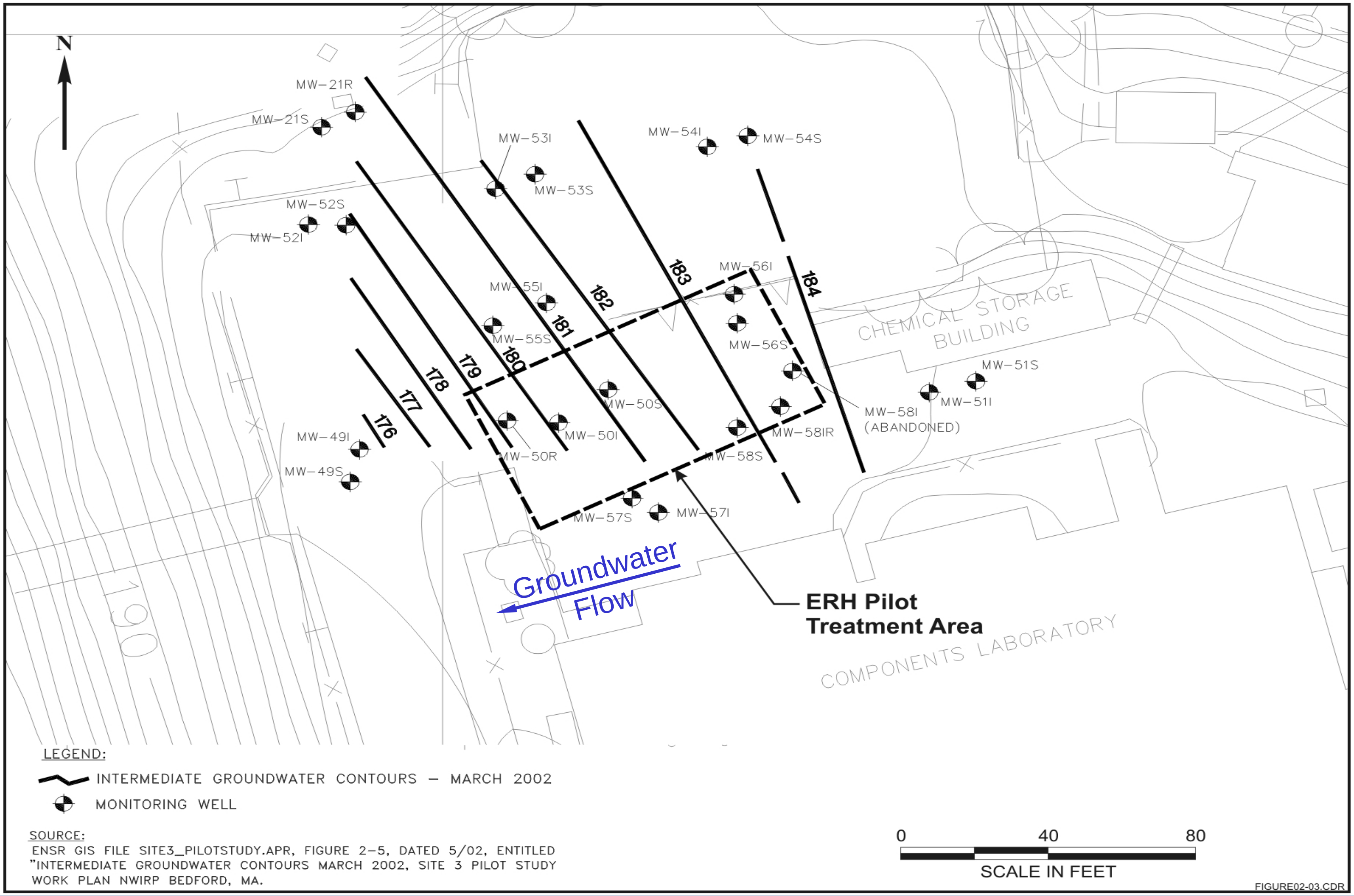
Naval Weapons Industrial Reserve Plant (NWIRP), Bedford, MA

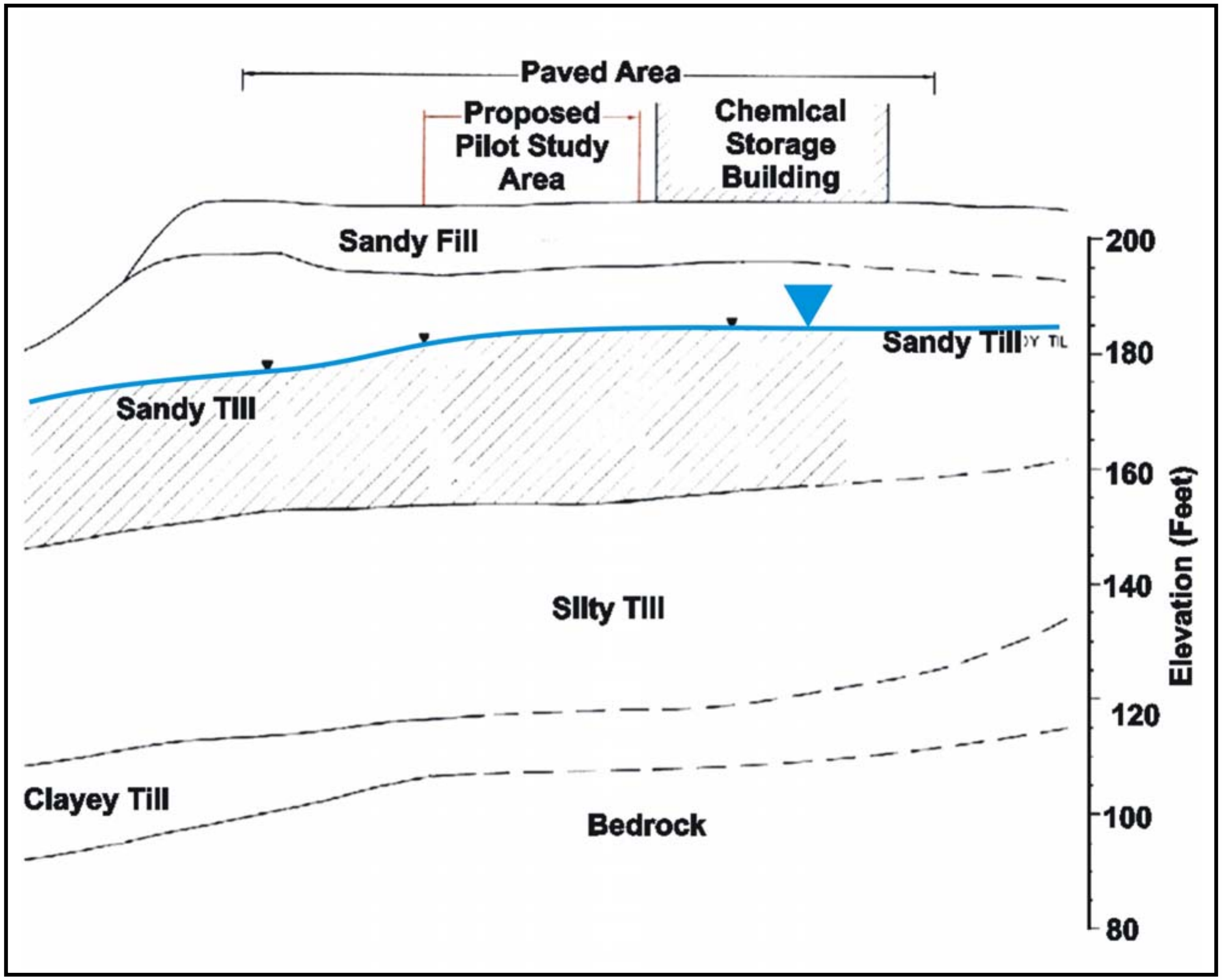
- ERH was applied at Site 3, considered to be the source area
- TCE (42,000 µg/L) is primary contaminant; other contaminants in groundwater are 1,1,1-TCA, 1,2-DCE, 1,1-DCA, and PCE
- Treatment subsurface volume estimated at 112,000 cubic ft, treatment depth was approximately 60 ft bgs
- Subsurface comprised mainly of sandy, silty, and clayey till with groundwater occurring at 25 to 40 ft bgs
- The hydraulic conductivity at the site of 3.5 × 10-5 centimeters per second (cm/s) to 11.20 × 10-7 cm/s indicates low-permeability soils

NWIRP Bedford, MA –
Plan View of ERH Pilot Treatment Area



NWIRP Bedford, MA –
Plan View of ERH Pilot Treatment Area

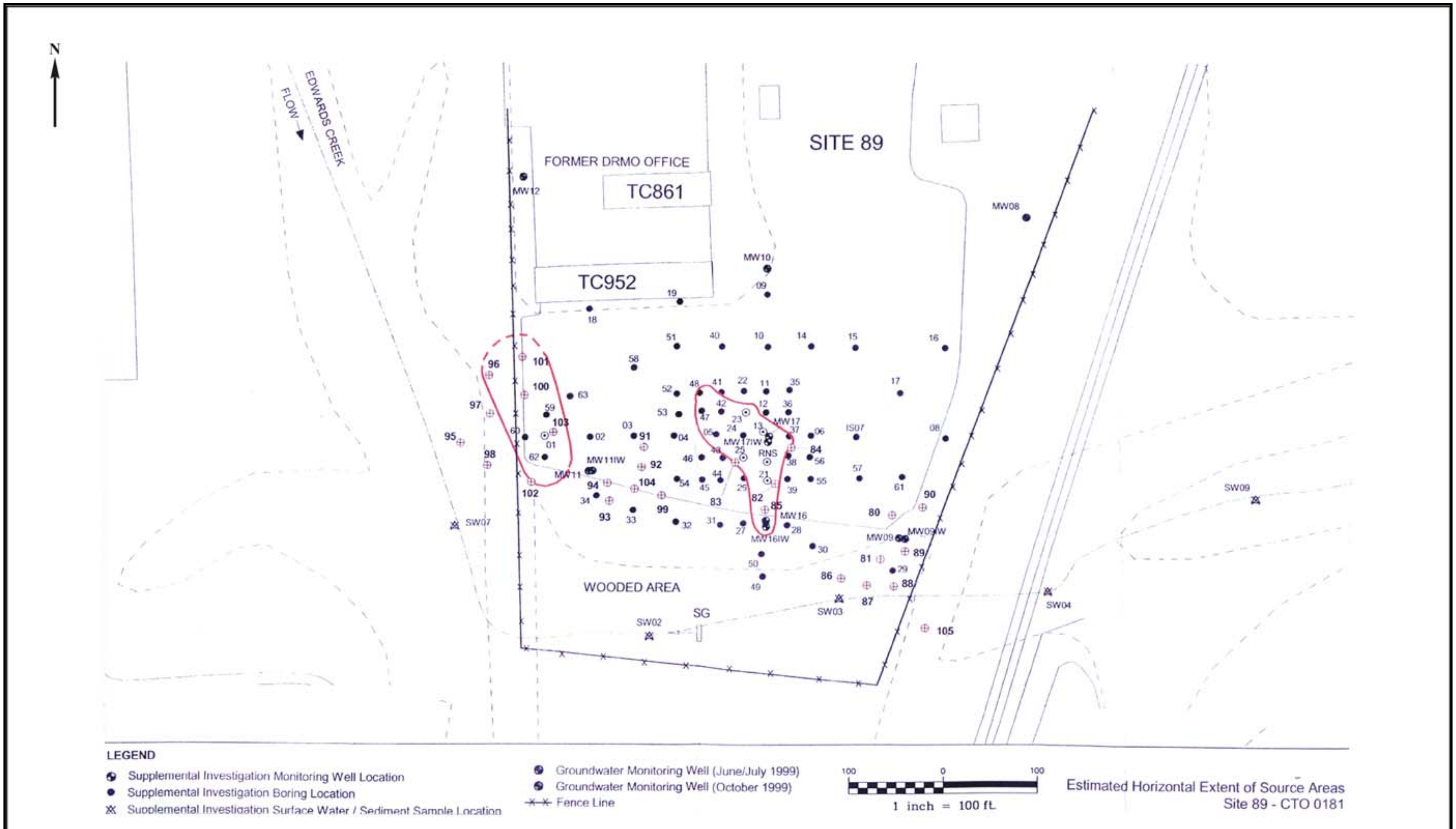
NWIRP Bedford, MA – Vertical Cross-Section of ERH Pilot Treatment Area



Marine Corps Base (MCB) Camp Lejeune, NC

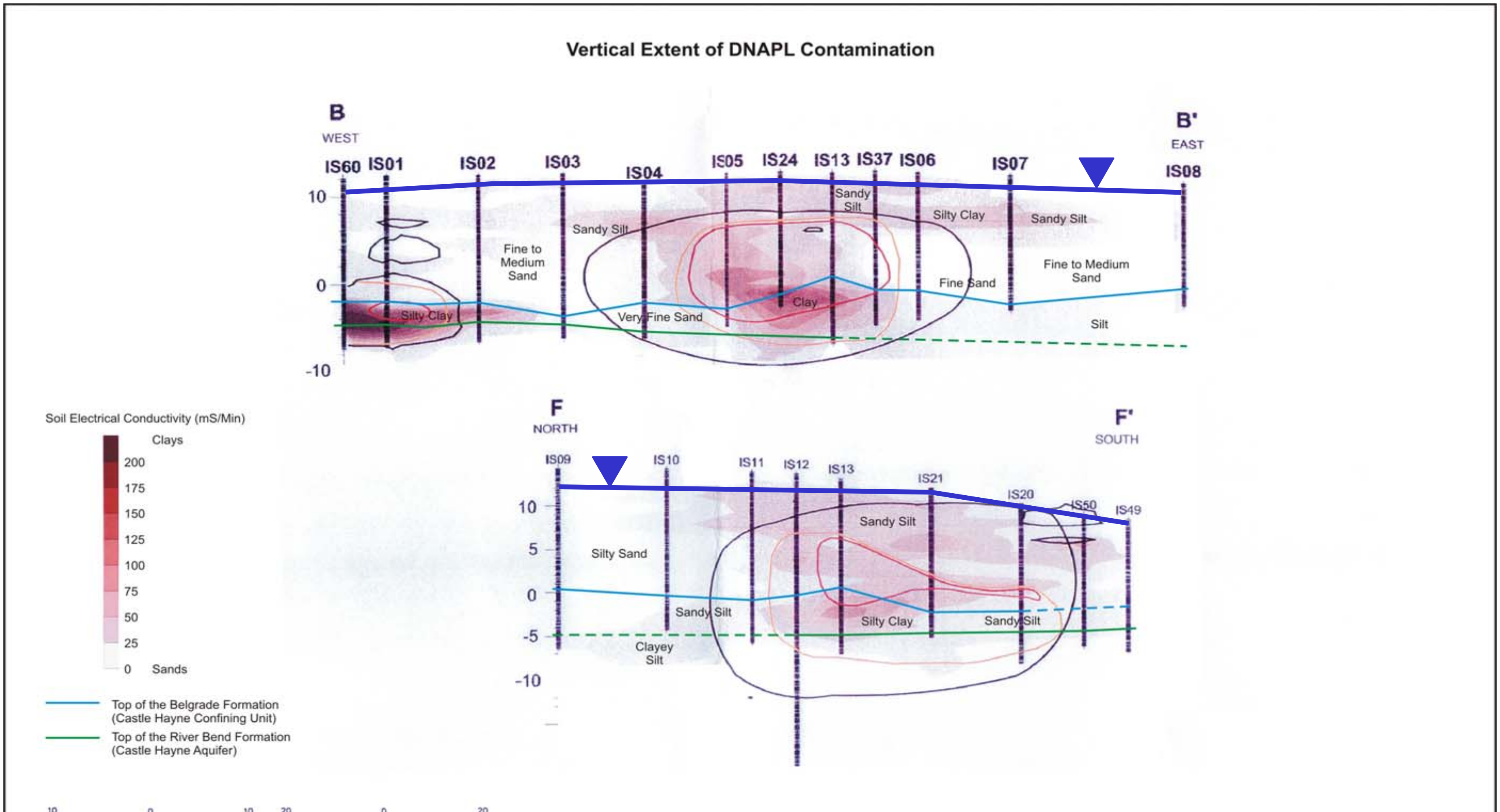
- At former Defense Reutilization Marketing Office (DRMO) Site 89 located at Camp Geiger portion of MCB Camp Lejeune
- Three hydro-stratigraphic units identified at Site 89:
  - Undifferentiated formation (surficial aquifer): sandy interbedded with silt, and clays
  - Belgrade formation (Castle Hayne confining unit): mostly clays
  - River Bend formation (Castle Hayne aquifer): sandy interbedded with silt, and clays
- Water table at 3 to 5 ft bgs; groundwater flow direction south-southwest with hydraulic gradient ~0.01 ft/ft
- Two plumes (eastern and western) exist
  - Concentration of 1,1,2,2-TeCA (nominal boiling point of 147°C) ranged from 650 to 21,250 ppm
  - TCE (nominal boiling point of 87°C) ranged from 33 to 11,100 ppm in soil 3 to 9 ft bgs
- ERH applied at eastern plume (maximum depth of 26 ft bgs)

MCB Camp Lejeune, NC – Site 89 Site Layout



(Adapted from Navy Report, 2005)

MCB Camp Lejeune, NC –
Site 89 Vertical Cross-Section

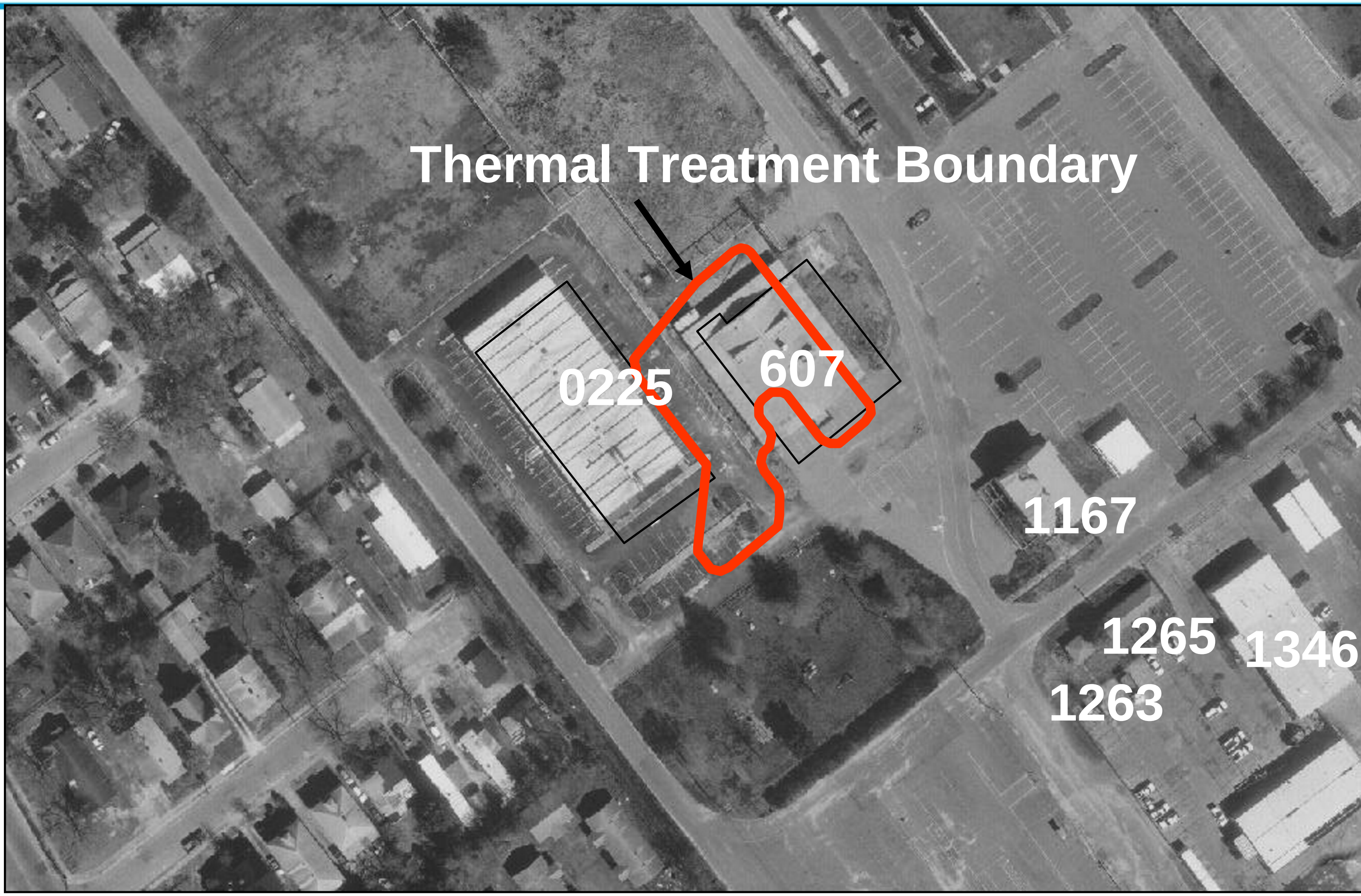


(Adapted from Navy Report, 2005)

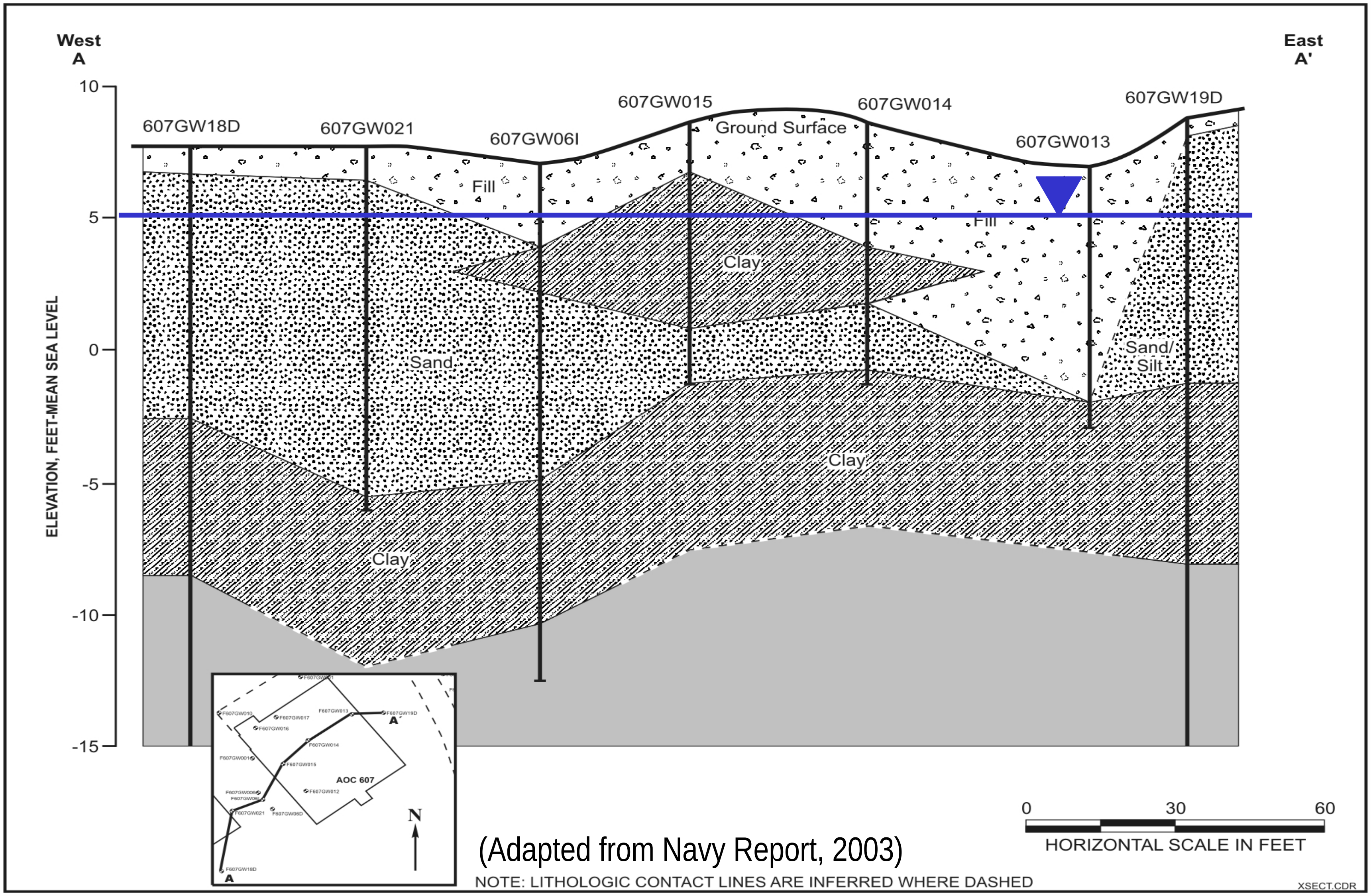
Charleston Naval Complex, Charleston, SC

- ERH applied at Area of Concern (AOC) 67 that housed a dry cleaning facility
- Primary contaminant PCE (6,800 µg/L, 121°C) had migrated until it encountered a clay unit in the subsurface
- Subsurface mainly consists of undifferentiated Quaternary age sands, silts, and clays of the Wando formation to ~20-25 ft bgs
- Quaternary deposits consist of an unconfined aquifer with hydraulic conductivity of 0.44 ft/day or ~10^{-4} cm/s; average groundwater velocity 0.01 ft/day
- Underlying Tertiary Age Ashley formation acts as a lower confining unit

Charleston Naval Complex, Charleston, SC – Plan View



Charleston Naval Complex, Charleston, SC – Vertical Cross-Section



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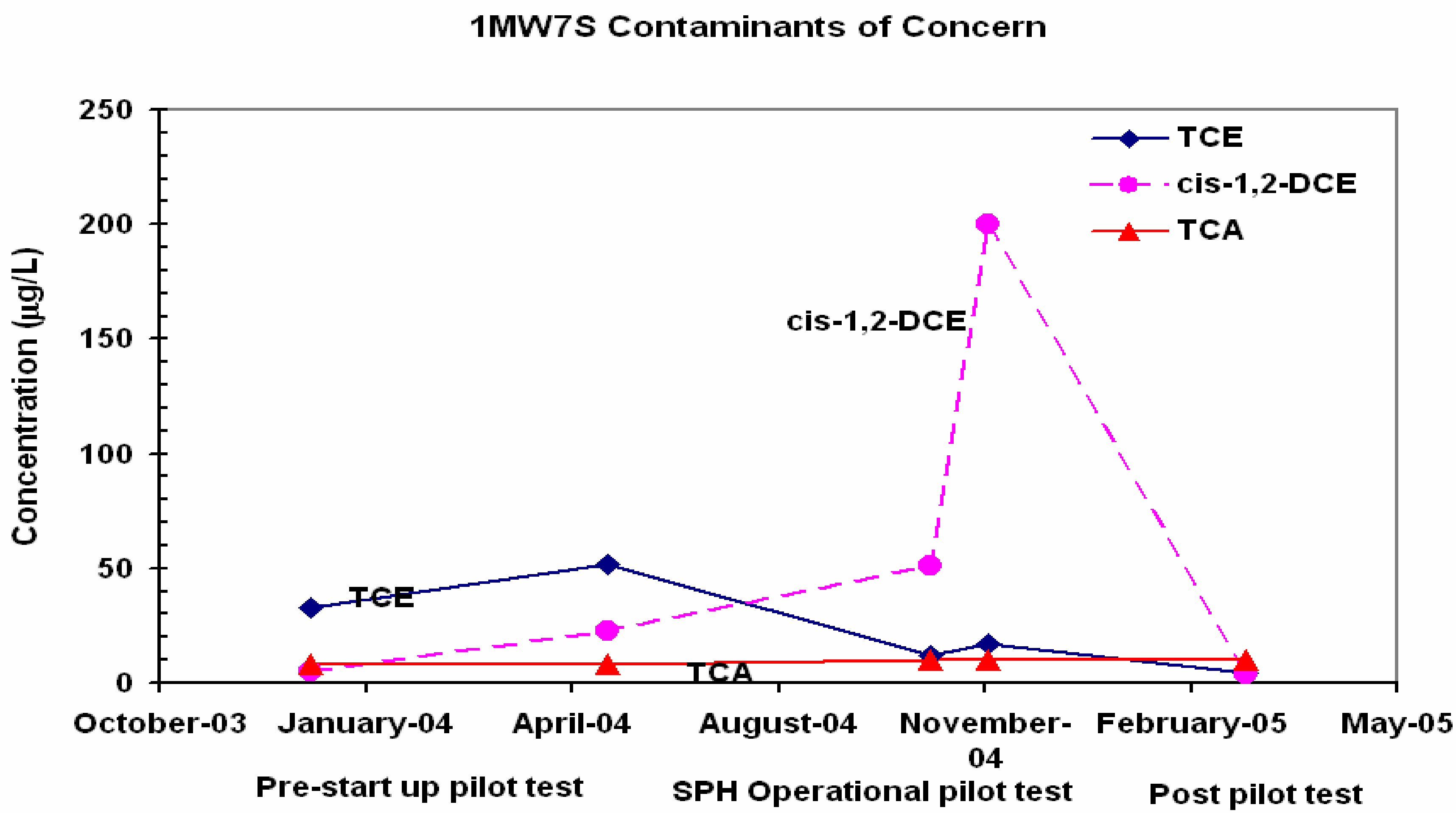
CVOC Mass Removal

- CVOC mass recovered aboveground during ERH treatment:
  - 90 lb of total VOC mass recovered at NWIRP Bedford
  - 4,283 lb of TCE recovered at Cape Canaveral
  - 234 lb of PCE recovered at Charleston
  - 3,000 lb of VOCs recovered from former NAS Alameda
  - 48,000 lb of VOCs recovered from Camp Lejeune
- Additional removal of CVOCs likely to have occurred at these sites due to enhanced biodegradation at elevated temperatures
- Possibly some CVOC removal due to other reactions, such as hydrolysis and abiotic reduction

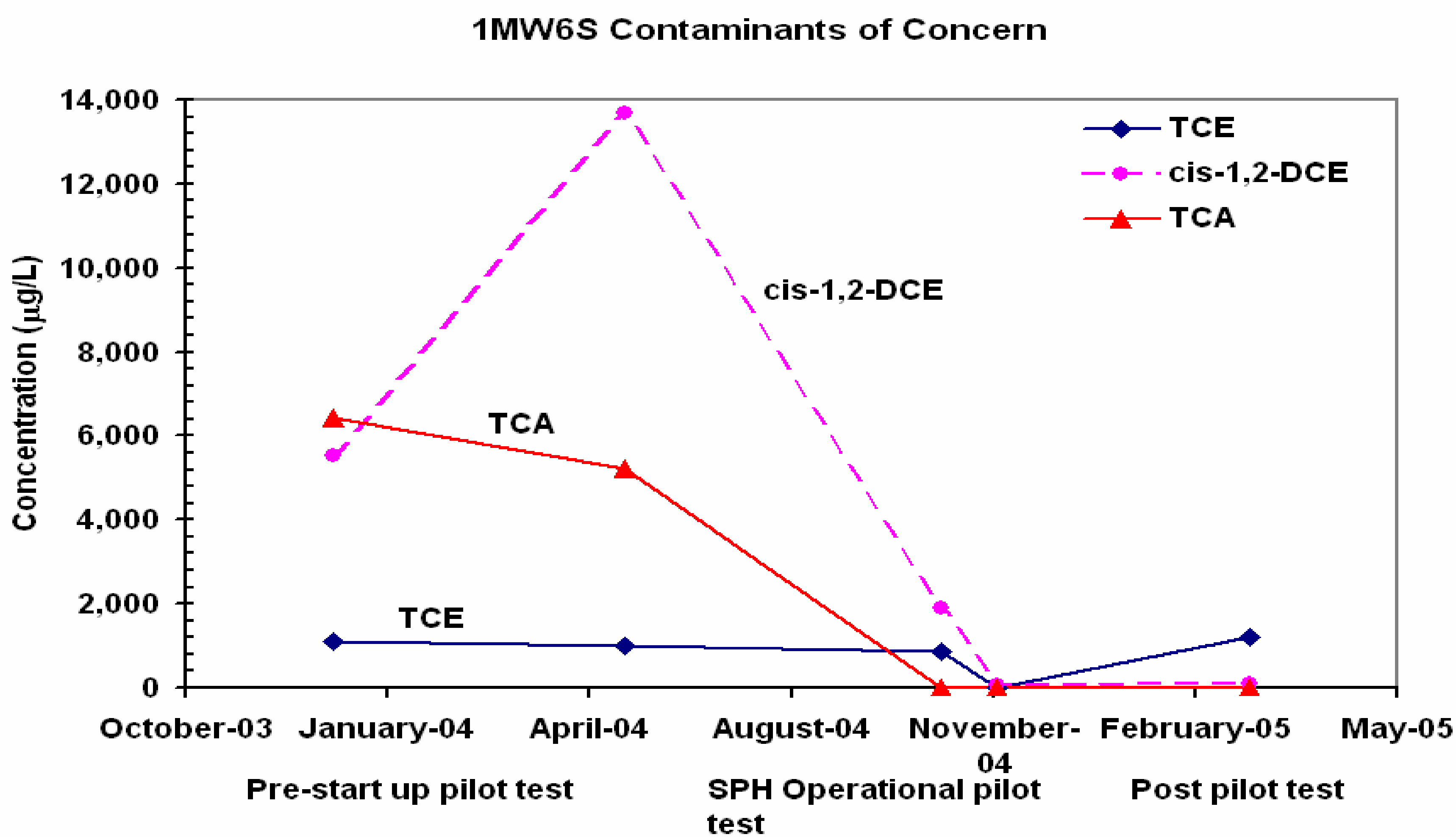
Performance Criteria

- Minimal CVOC concentration rebound in monitoring wells
  - Indicator of residual CVOC mass
- Low byproducts concentration
  - Increase may indicate that aquifer is hot enough to stimulate bioremediation, but not hot enough to effect total VOC mass removal from the soil pores
- Temperatures achieved
- Sufficient operating time

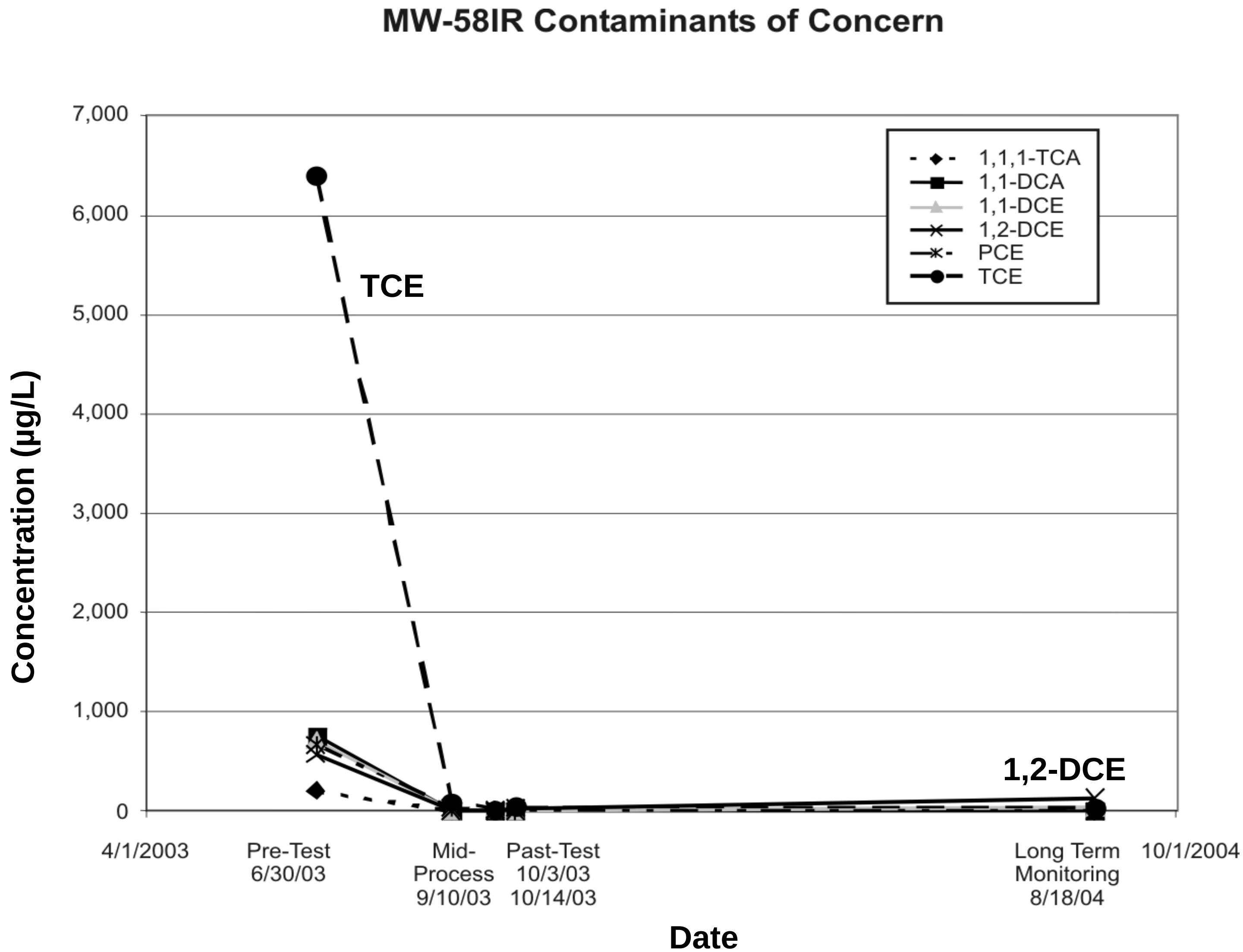
TCE and Byproducts in a High-Permeability Aquifer (Alameda 1MW7S)



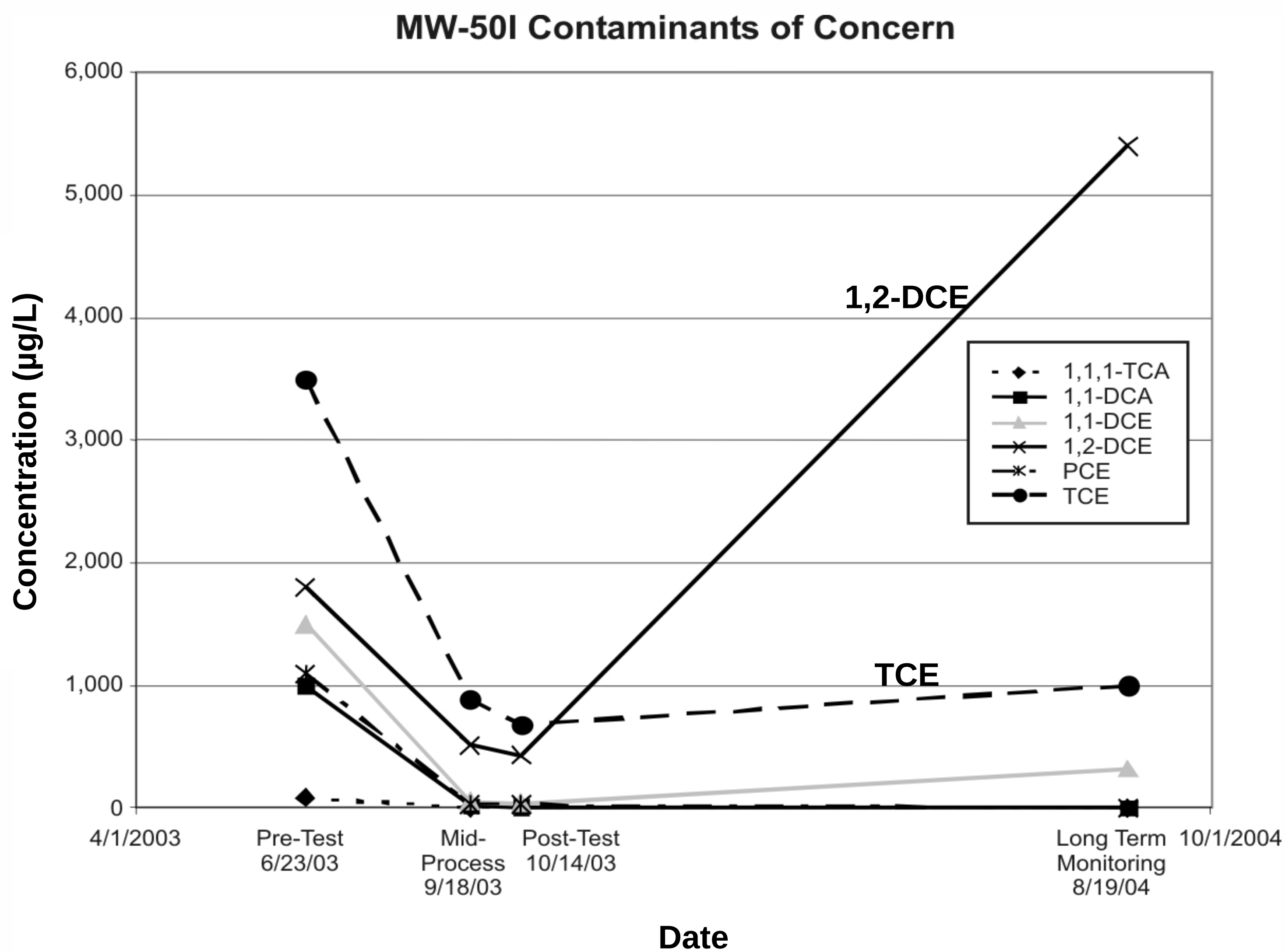
TCE and Byproducts in a High-Permeability Aquifer (Alameda 1MW6S)



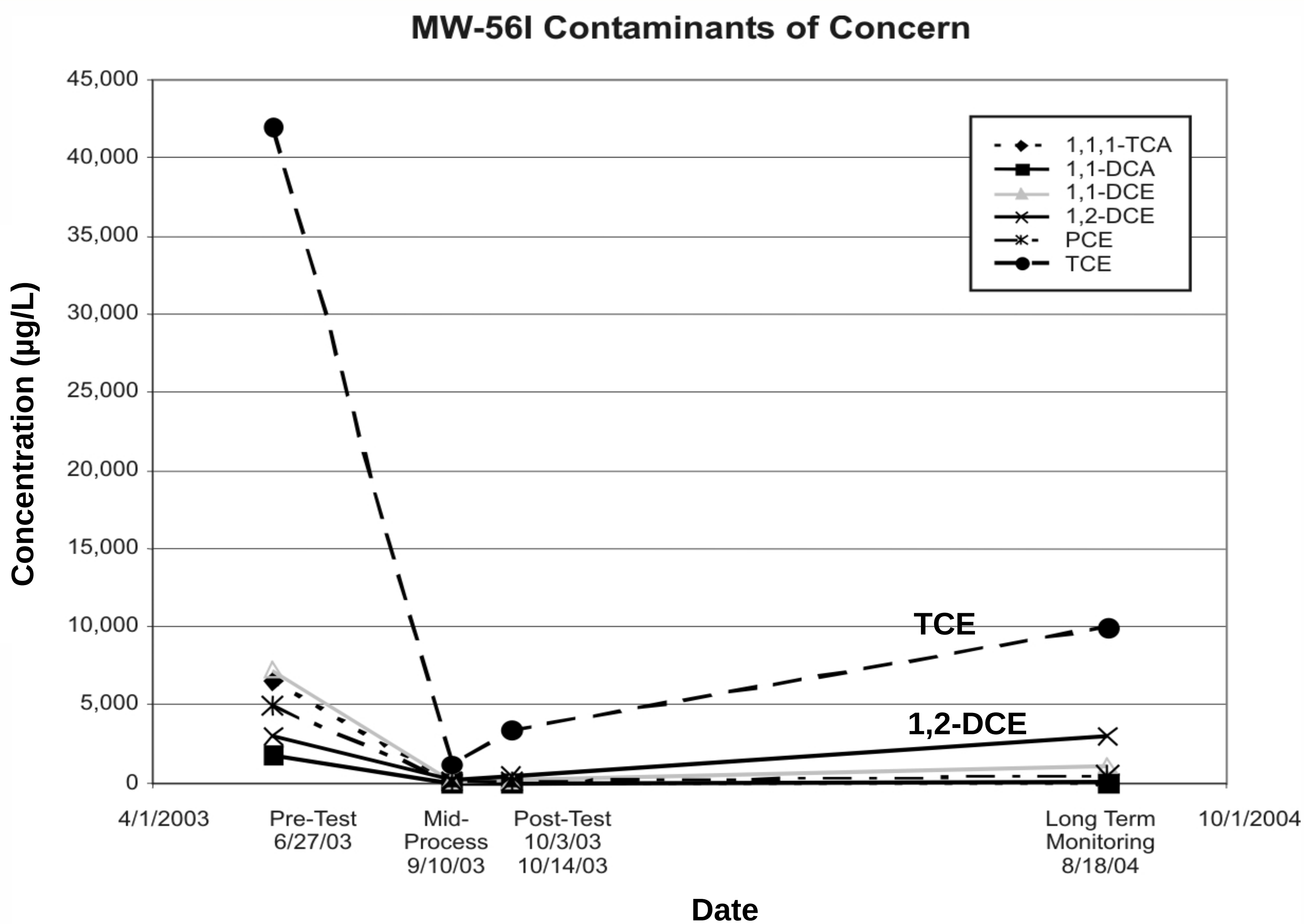
TCE and Byproducts in a Low-Permeability Aquifer (Bedford MW-58IR)



TCE and Byproducts in a Low-Permeability Aquifer (Bedford MW-50I)

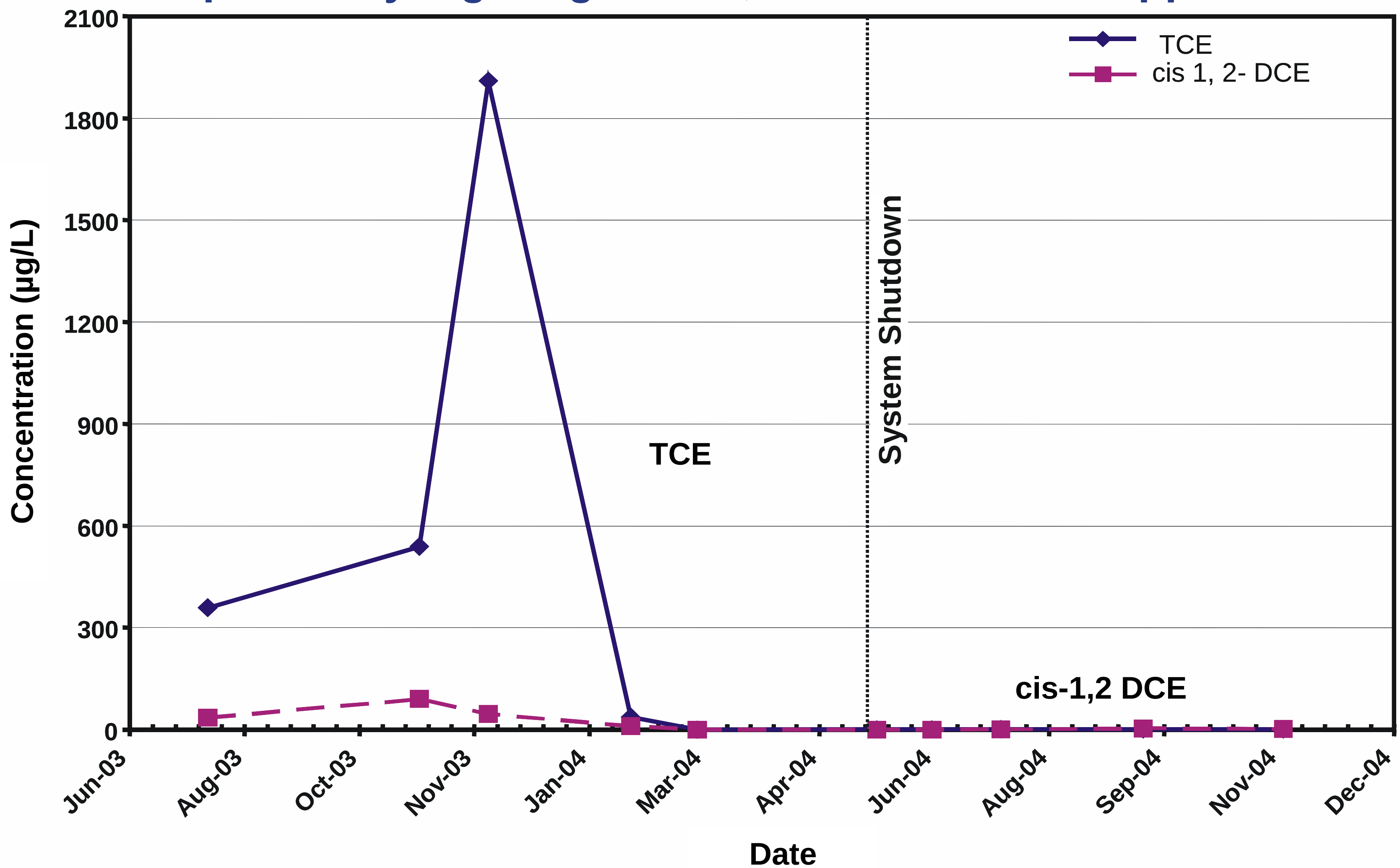


TCE and Byproducts in a Low-Permeability Aquifer (Bedford MW-56I)



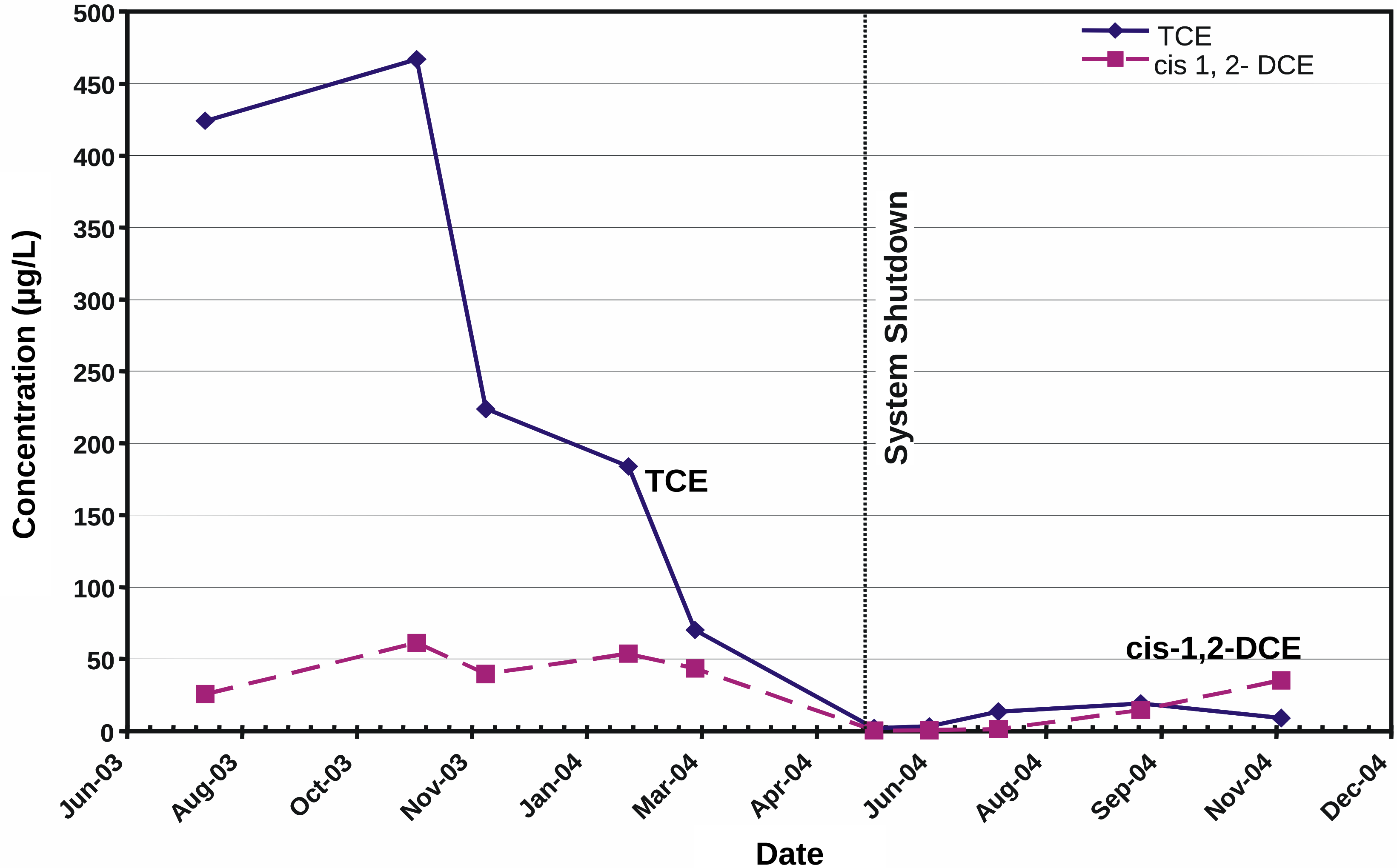
TCE and Byproducts in a Low-Permeability Aquifer (Camp Lejeune MW-24)

Comparatively higher gradient; more controlled application

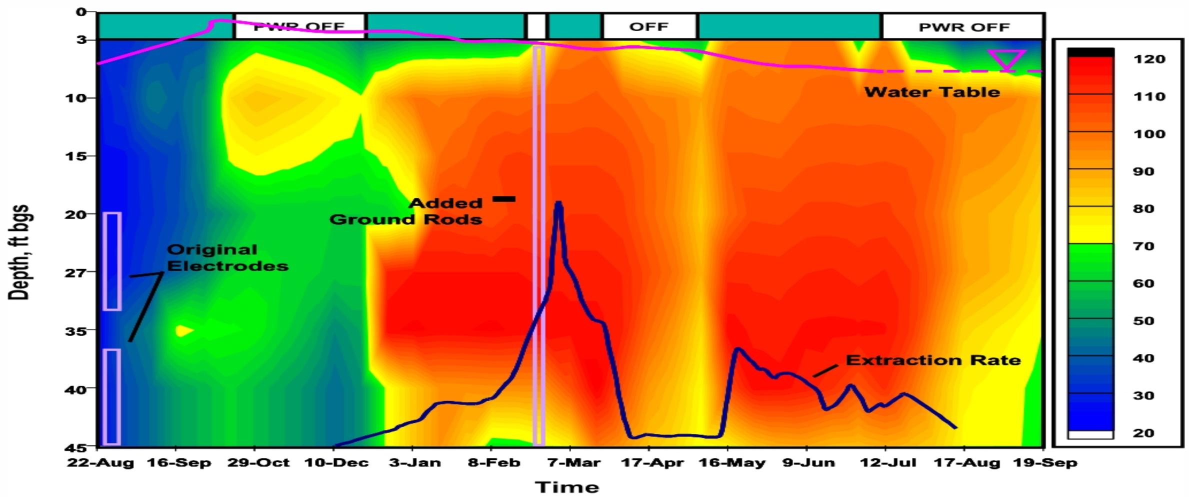


TCE and Byproducts in a Low-Permeability Aquifer (Camp Lejeune MW-16)

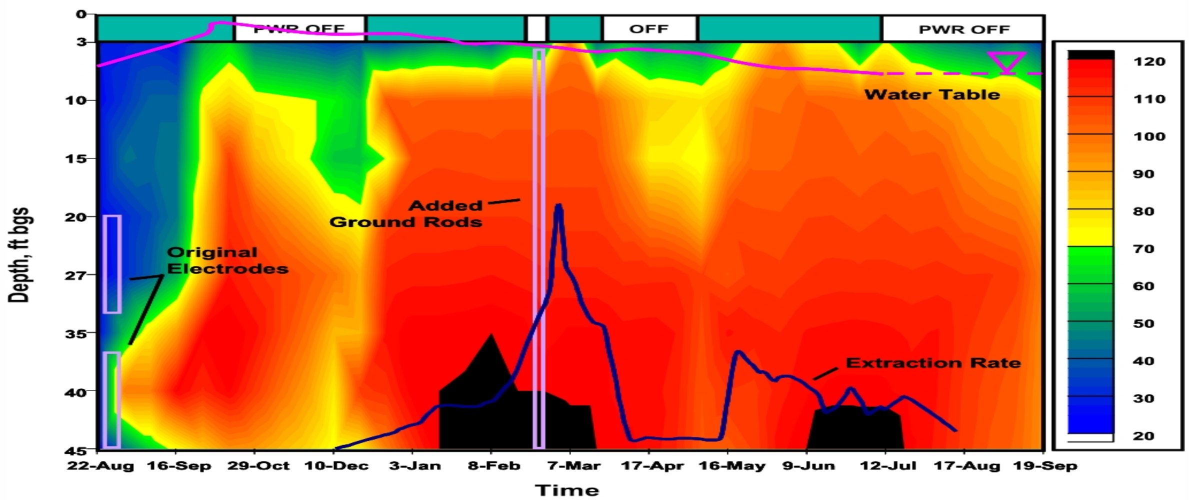
Comparatively higher gradient; more controlled application



Temperature vs. Depth and Time (Cape Canaveral, High-Permeability Site)

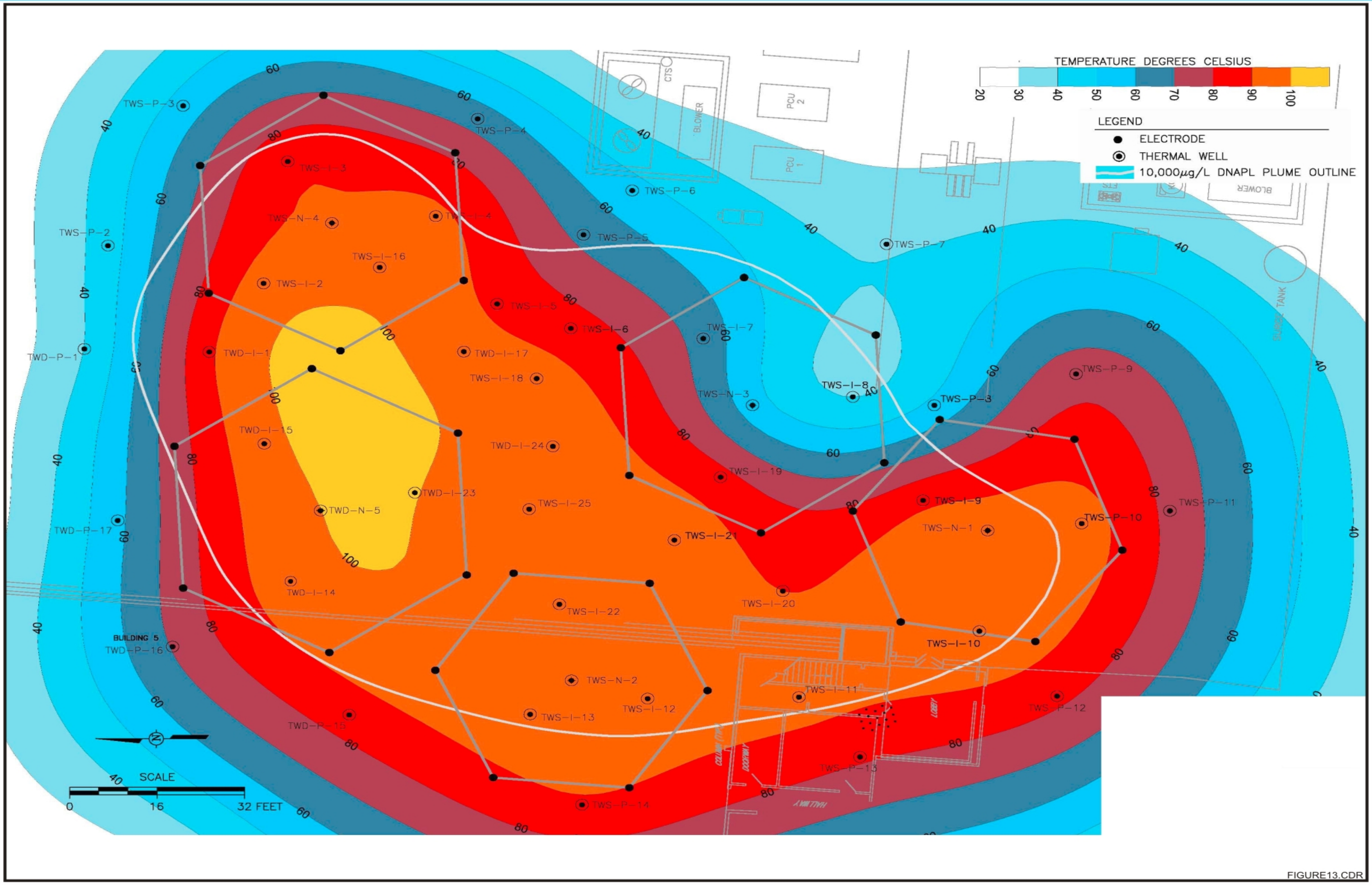


Plot of Subsurface Temperature Profiles at TMP 1

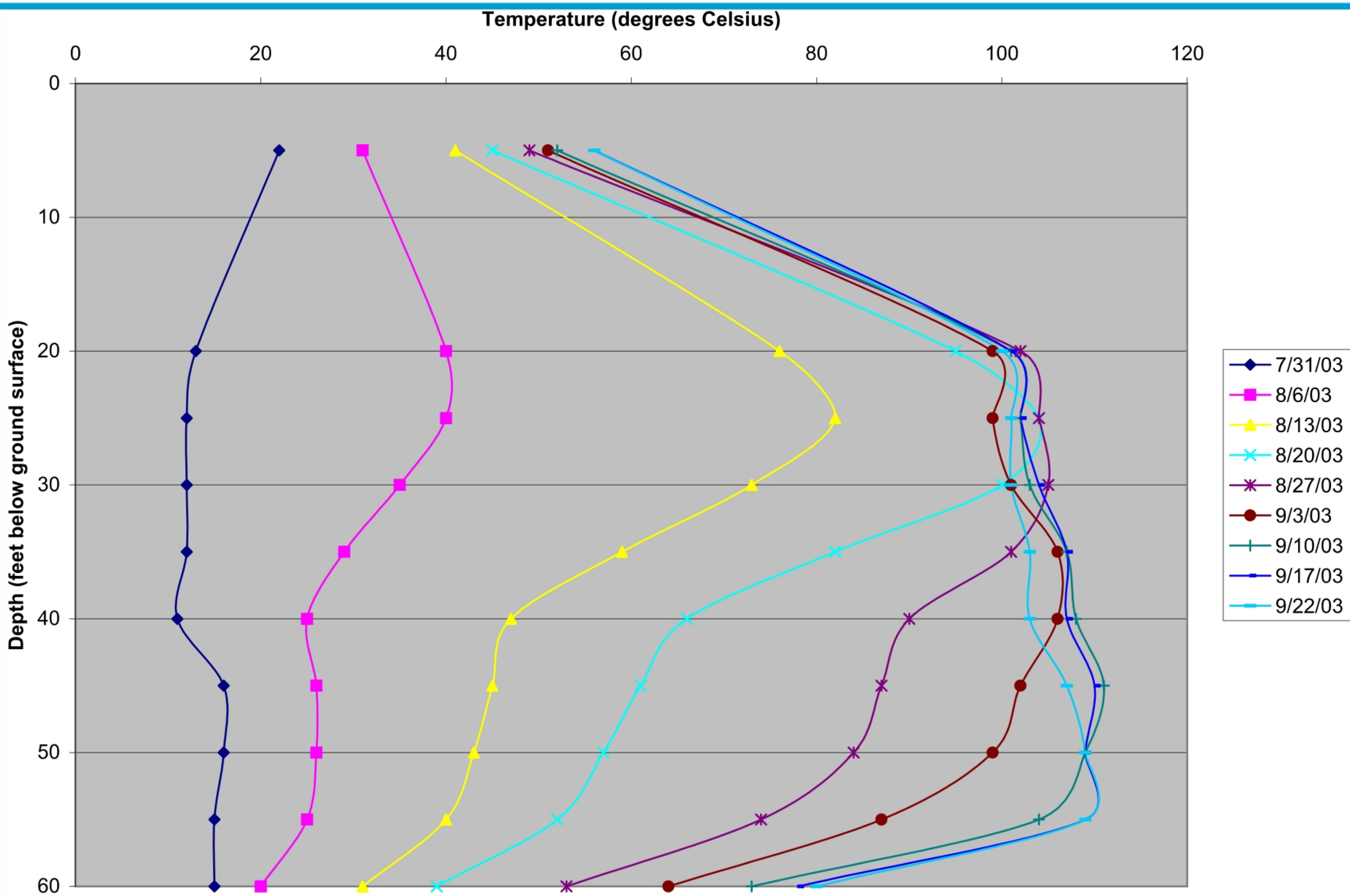


Plot of Subsurface Temperature Profiles at TMP 2

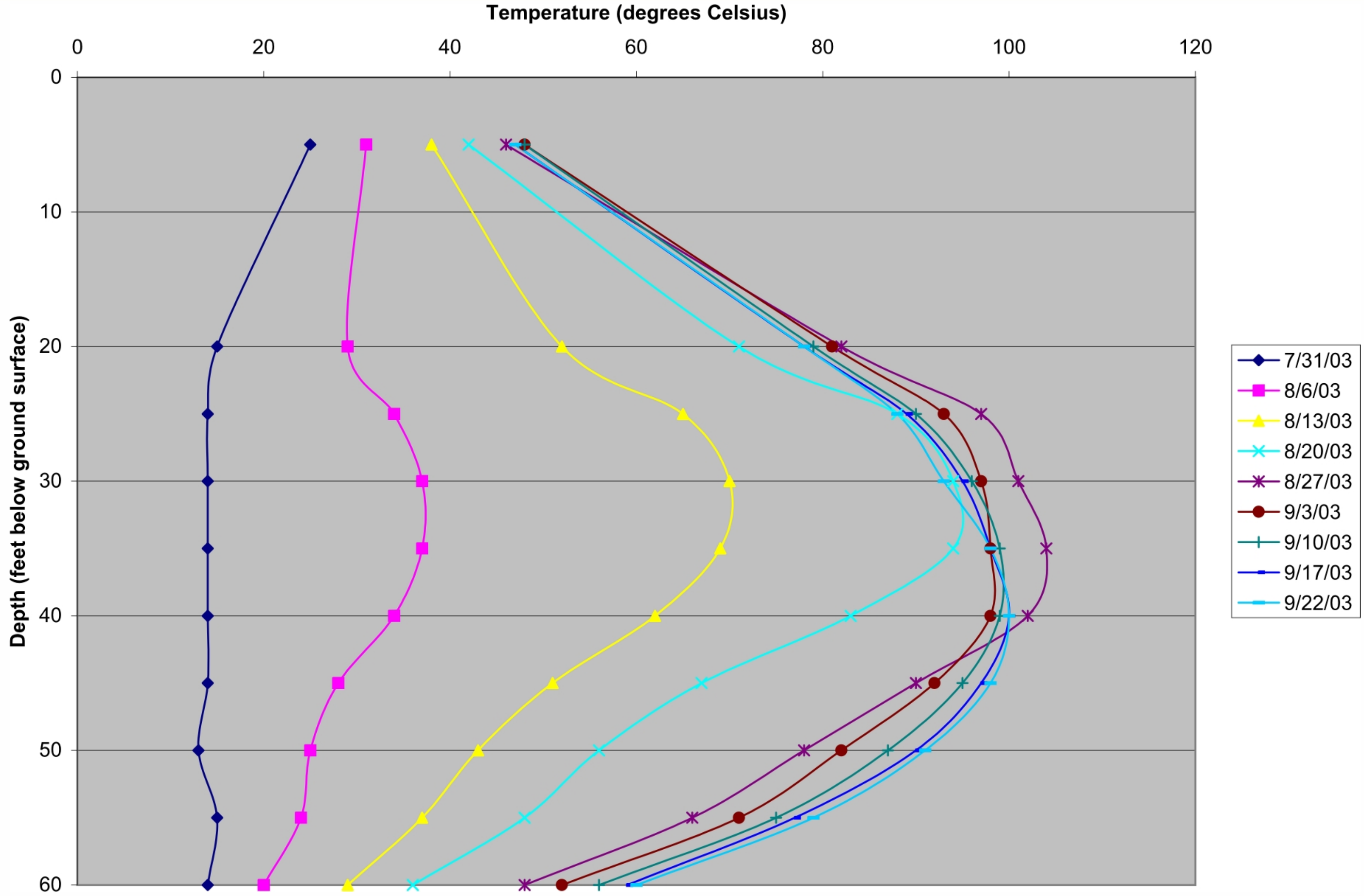
Temperature Distribution
(Alameda, 12 ft bgs – High-Permeability Site)



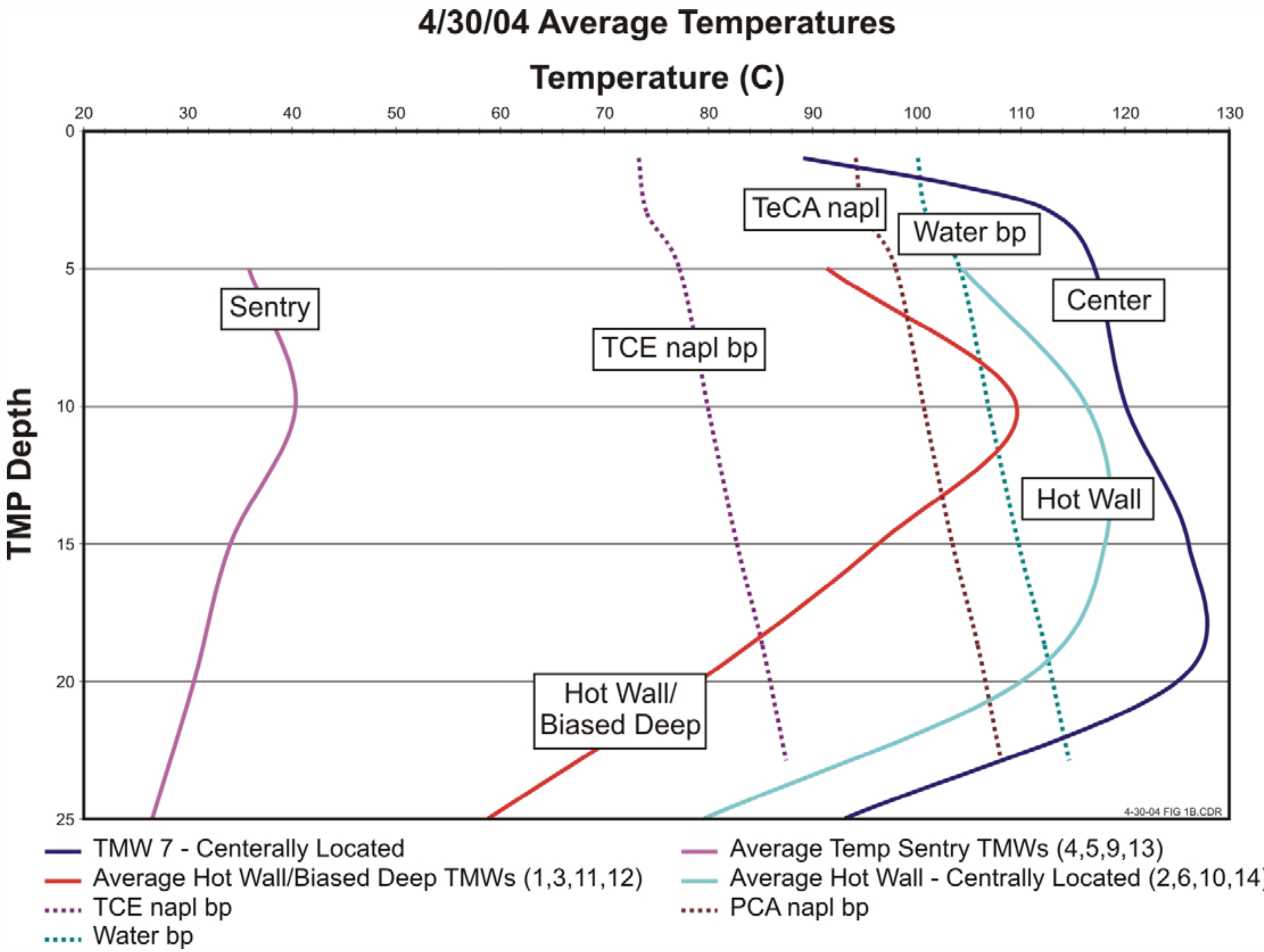
Temperatures vs. Depth Profile at Example Location (Bedford, Low-Permeability Site)



Temperatures vs. Depth Profiles (Bedford, Low-Permeability Site)



Temperatures vs. Depth Profiles (Camp Lejeune, Low-Permeability Site)



Heating Performance at Different Sites

Site	Primary Contaminant	Hydraulic Conductivity	Hydraulic Gradient	Maximum Temp at Lowest Depth
Cape Canaveral	TCE	High	Low	120°C at 45 ft bgs
NAS Alameda	TCA, TCE	High	Moderate	101°C at 12 ft bgs
NWC Charleston	PCE	Low	Low	95°C at 11 ft bgs
NWIRP Bedford	TCE	Low	Low	<90°C at 55 ft bgs
MCB Camp Lejeune	TeCA, TCE	Low	Moderate	128°C at 25 ft bgs

- *Achieving the required temperatures is easier in higher-permeability aquifers than in lower-permeability aquifers, especially at the bottom of the target aquifer zone, where most of the DNAPL often resides*

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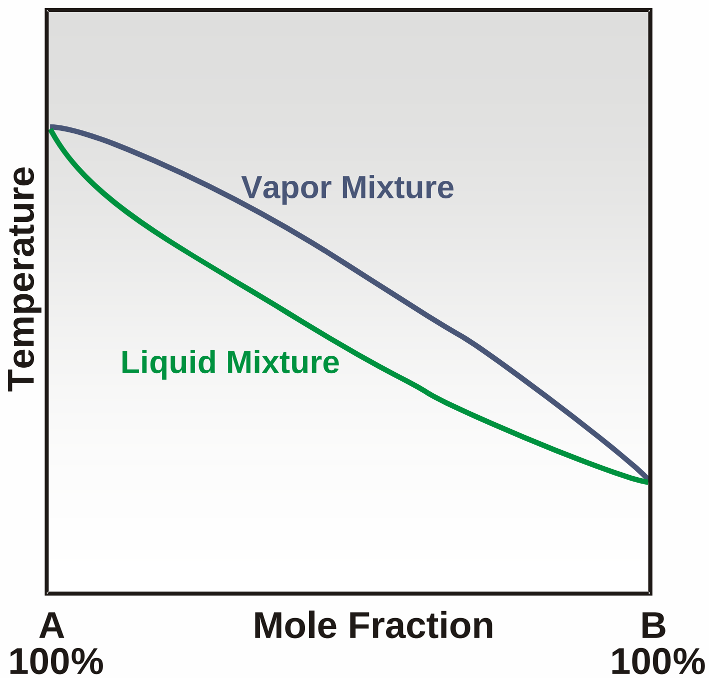
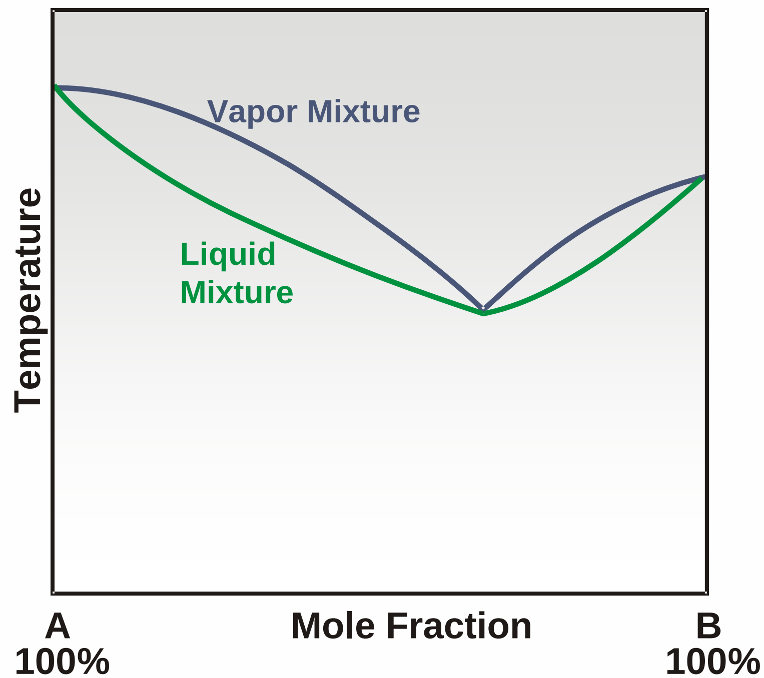
Lessons Learned

- Design and operations perspective
  - What should the design temperature be?
  - What can be done to ensure that you reach it?
- Performance assessment perspective
  - What are the best indicator parameters?
- Regulatory perspective
  - Why regulators like this technology
- Cost perspective
  - Factors driving cost

Boiling Point Range of a Binary Mixture – Some mixtures form azeotropes



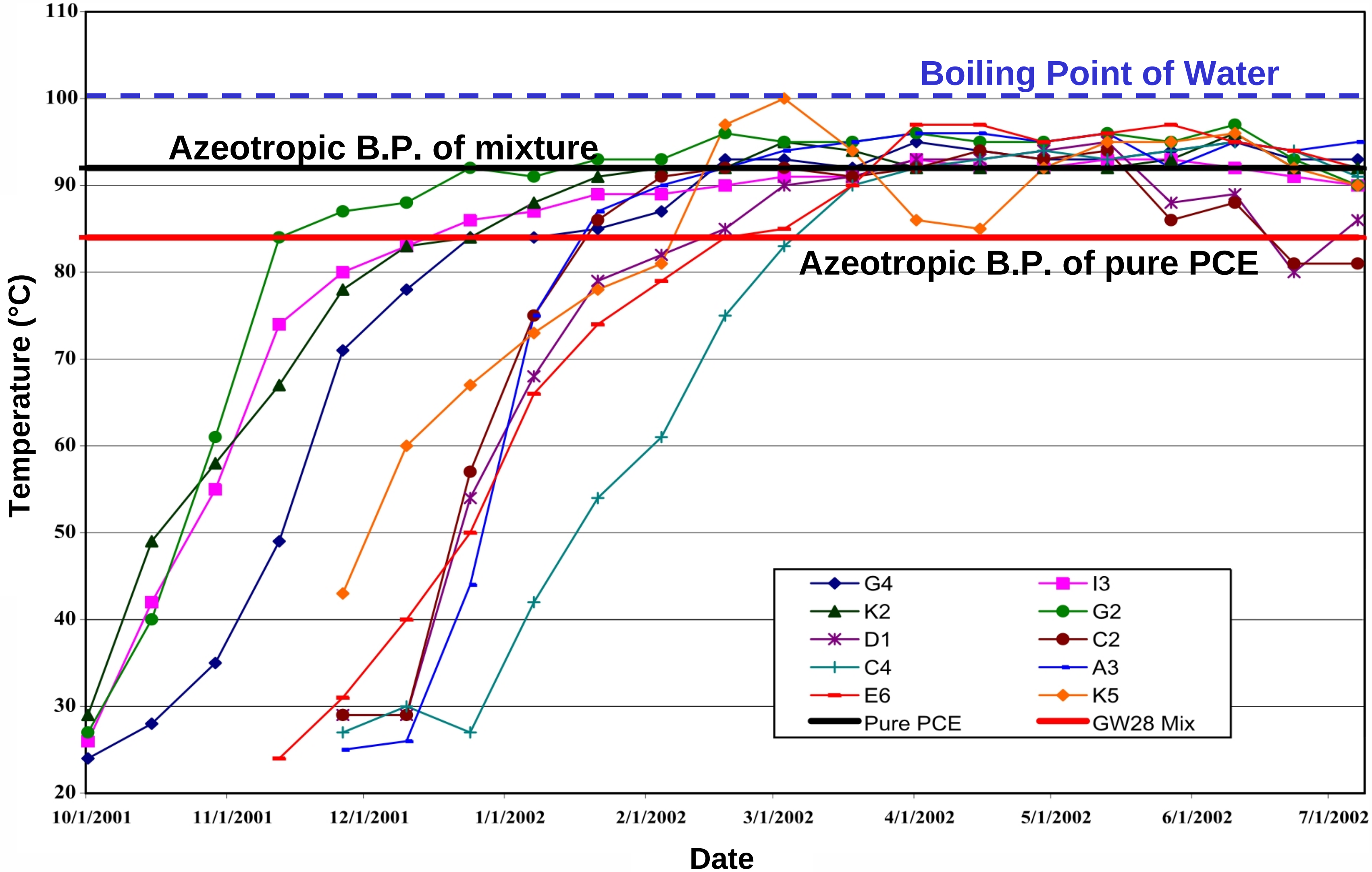


Lessons Learned
– Prospective Design Temperatures

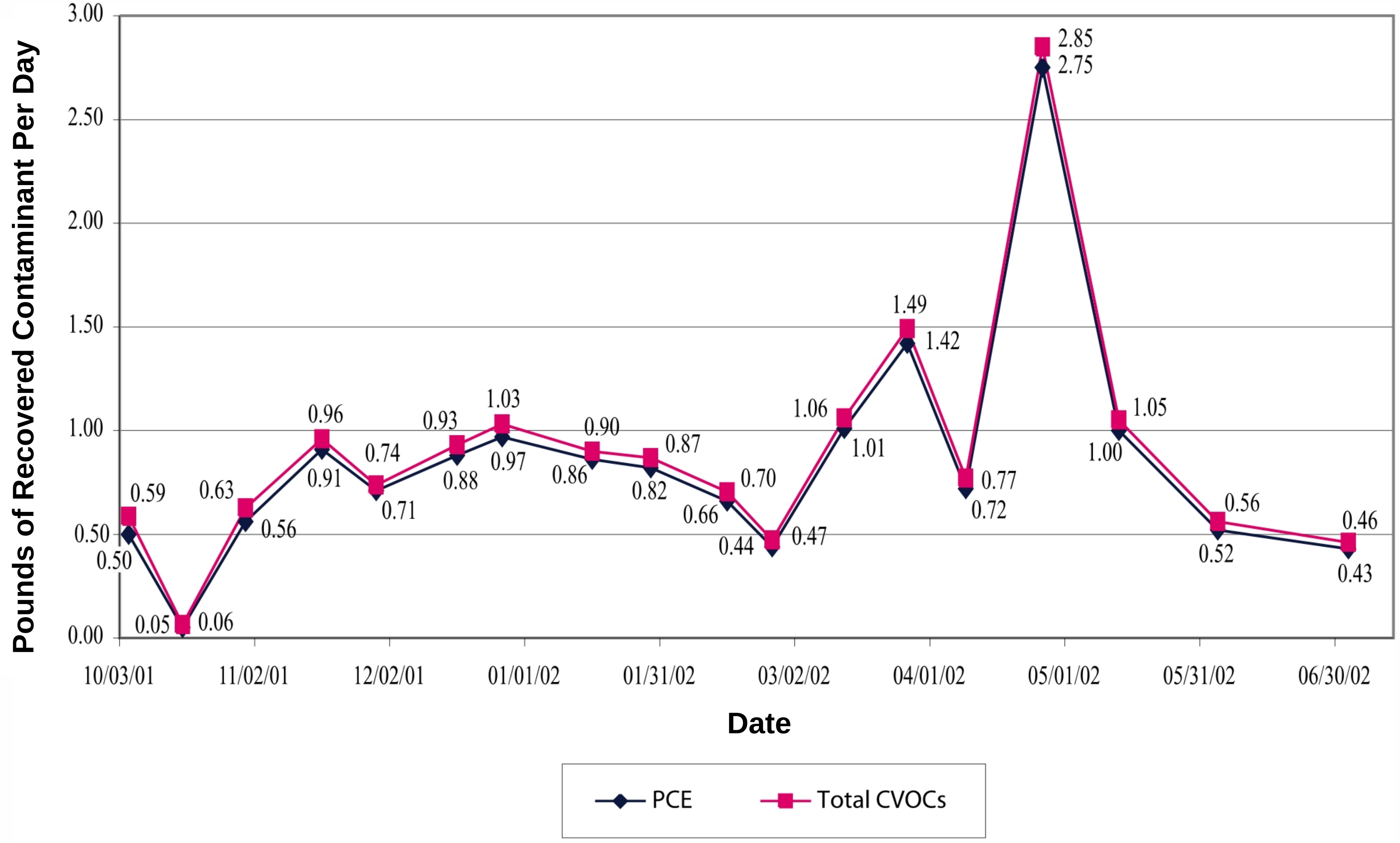
Compound	Boiling Temperature of Compound in Degrees Celsius (°C) In Various Media		
	Air	Water	
		(23 ft bgs)	(55 ft bgs)
Pure water	100	100	120
1,1-Dichloroethane (DCA)	57	53	71
1,1-Dichloroethene (DCE)	32	32	48
***cis*-1,2-Dichloroethene (*cis*-DCE)**	59	54	72
Tetrachloroethene (PCE)	121	88	107
1,1,1-Trichloroethane (TCA)	74	65	84
Trichloroethene (TCE)	87	73	92

Source: TRS, Inc.

Temperatures vs. Depth Profiles (Charleston, Temperature Profile at 11 ft bgs)

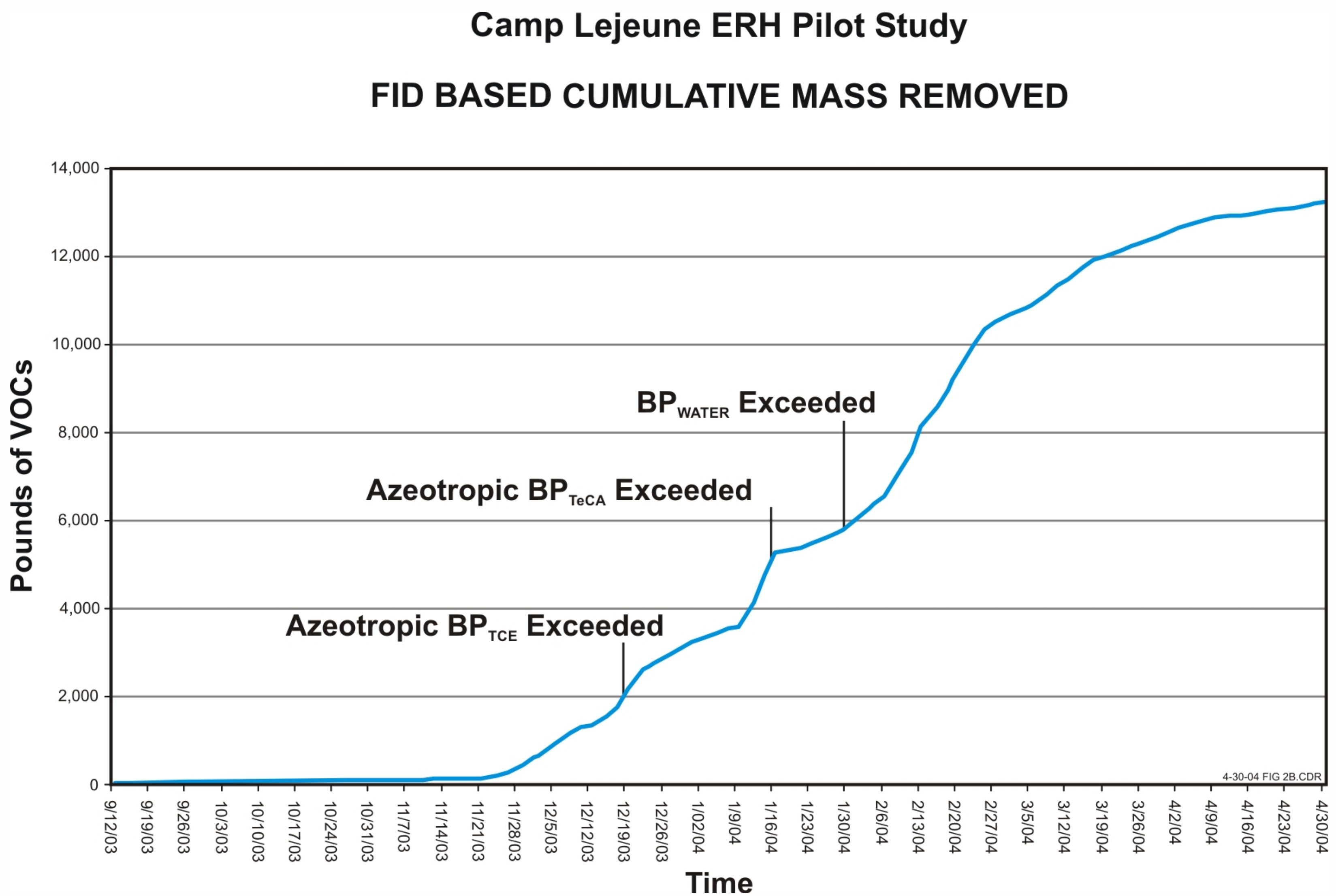


Time vs. CVOC Recovery Profiles (Charleston)



Total CVOCs are a concentration summation of 1,1-DCE, trans-1,2-DCE, cis-1,2-DCE, TCE, PCE, and vinyl chloride

Time vs. CVOC Recovery Profiles (Camp Lejeune)



Lessons Learned
– Design and Operations Perspective

- Initially, reaching boiling point of water at target depth was the design goal at many sites
  - 100°C at water table (atmospheric pressure)
  - 120°C at 55 ft bgs (elevation of boiling point at the higher pressure at greater depth)
- Design temperatures were better achieved at all depths in the sandy aquifers at Cape Canaveral and Alameda than in lower-permeability aquifers at Bedford and Charleston
  - Easier to maintain even heating
  - Steam generation helps strip out DNAPL

Lessons Learned
– Design and Operations Perspective (cont.)

- However, these temperatures were difficult to reach in lower-permeability aquifers at Bedford and Charleston
  - Drying around the electrodes, depression of the water table, and inefficient heating in the newly created unsaturated zone are key factors that make heating difficult in lower-permeability formations
  - Drip lines needed to keep electrodes wet (condensed water vapor can be recycled back to electrodes, but increased energy input required to heat added water)
  - Slower heating to avoid drying
  - At Charleston, design duration of 124 days turned into 279 days of ERH application with 101 conventional electrodes, 12 sheet pile electrodes, 6 Geoprobe™ electrodes, and 310 ground rods (16,500 sq ft area, 11 ft deep). Even then, monitoring showed considerable post-treatment residual DNAPL mass probable.
  - Ground rods added to improve heat distribution (Cape Canaveral, Charleston)

Lessons Learned
– Design and Operations Perspective (cont.)

- At Camp Lejeune, many of these challenges were overcome by:
  - Designing with greater electrode density
  - Installing deeper electrodes
  - Implementing slower, more controlled heating
  - Using ground rods to distribute heat
  - Continuing to heat until water boiling temperatures reached and until VOC levels recovered aboveground tapered off
  - Helped by moderately higher hydraulic gradient, compared to Bedford or Charleston

Lessons Learned
– Design and Operations Perspective (cont.)

- At all five sites, design temperatures were more likely to be achieved in the shallower portions of the aquifer than in the deeper portions near the aquitard
  - Unfortunately, DNAPL often tends to accumulate in the deeper portions
- At the very least, design temperature should meet or exceed the boiling points of the individual constituents (adjusted for depth)
- Preferably, temperatures should reach the boiling point of water

Lessons Learned – Design and Operations Perspective (cont.)

- Factors that Tend to Increase Boiling Temperatures in Groundwater
  - Depth under water table (higher pressure due to water column above)
  - Presence of non-volatile solutes, such as chlorides, sulfate, calcium, carbonate, etc.

Lessons Learned
– ERH Performance Assessment

- Temperature is the key performance parameter that has to be met in all the target regions of the aquifer
- Temperature is an easy and relatively inexpensive measurement that can be made through thermocouple bundles
- Spreading of DNAPL outside the treatment zone has not been encountered, except under relatively unusual circumstances at Cape Canaveral (hurricanes and the consequent sharp rise of the water table)

Lessons Learned – Regulatory Perspective

- Regulatory acceptance is important for this application—regulators have a conceptual liking for this technology
- Regulators seem satisfied by ambient air tests conducted at shoulder level showing no release of VOC vapors to the ambient air
- ERH is a source zone treatment technology. When developing performance objectives for the ERH application, it is not always necessary to reach the final cleanup standards (e.g., drinking water standards) immediately after ERH is completed. Instead, remediation may be completed via enhanced bioremediation and natural attenuation over an extended time period.

Lessons Learned – Cost Perspective

Site	Approximate Volume of Aquifer (ft^3)	Aquifer Type	Approximate number of Days of ERH Application	Estimated Mass of VOCs Recovered from Subsurface (lb)	Adjusted Vendor Cost
Bedford	112,000	Low-permeability, Low gradient	53	90	$658K
Cape Canaveral	169,000	High-permeability, High gradient	270	4,283 (TCE)	$569K
Charleston	135,000	Low-permeability	279	247	$1M
Alameda	133,470	High-permeability	105	3,000	$2.7M
Camp Lejeune	349,000	Low-permeability, Moderate gradient	173	48,000	$1.7M

Lessons Learned – Cost Perspective (cont.)

- ERH is more costly to implement in low-permeability aquifers, especially in ones where the hydraulic gradient too is low, than in higher-permeability aquifers
- ERH can be more costly to implement in very high-permeability aquifers with high gradient too, because of the constant influx of cooler water into the heated zone (e.g., Fort Lewis)
- Treatment train approach of ERH followed by natural attenuation can help to optimize expenditures and be used to determine the extent of ERH treatment required to cost effectively reach cleanup goals over time

Presentation Overview

- Introduction to In-Situ Thermal Technologies
  - ERH Technology Description
  - Other In-Situ Thermal Technologies (Steam injection, ISTD)
- ERH Application Site Descriptions
  - High-permeability sites (Alameda, Cape Canaveral)
  - Low-permeability sites (Bedford, Camp Lejeune, Charleston)
- ERH Performance and Costs
- Lessons Learned
- Recommendations for Future Applications

Recommendations

- Base design on volume of aquifer being treated, not on estimated VOC mass
- At low permeability sites :
  - Design with greater electrode density and depth
  - Add water at the electrodes to prevent drying (but be prepared for increased power consumption)
  - Heat slowly to allow recharge in low permeability aquifers and to prevent drying (longer operating time)
  - Continue heating until nominal water boiling temperature is reached and VOC recovery aboveground tapers off
  - Add ground rods to improve heat distribution
- Do a microbial evaluation to determine fate of VOCs, if water boiling temperatures are not reached
- Pay attention to measured temperatures, DCE, VC levels in aquifer and recovered VOC mass above ground

Summary

- ERH has been applied safely at numerous sites, despite the high voltages involved
- ERH works on a broad variety of volatile contaminants and is not dependent on contaminant and aquifer chemistry
- Low-permeability aquifers pose a challenge for ERH and applications in such aquifers can require considerable time and cost
- However, if enough time and caution is exercised, ERH can reach design temperatures, even in low-permeability aquifers, leading to lower DNAPL residuals
- Design temperature should be the boiling temperature of water
- Enhanced biodegradation and hydrolysis at elevated temperatures aid in contaminant removal and help polish off any VOC residuals

Conclusions

- ERH is a viable option at many sites
- Even at low-permeability sites, the higher cost of ERH needs to be evaluated in the context of the limitations of other remediation technologies that rely on obtaining good reagent distribution

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