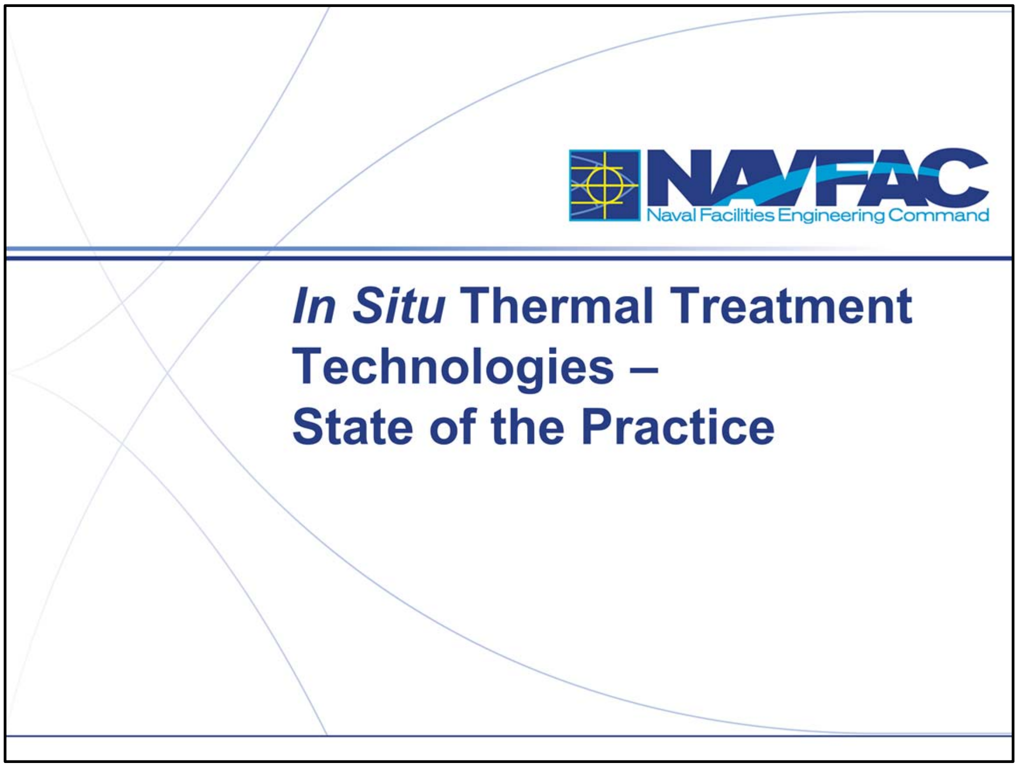
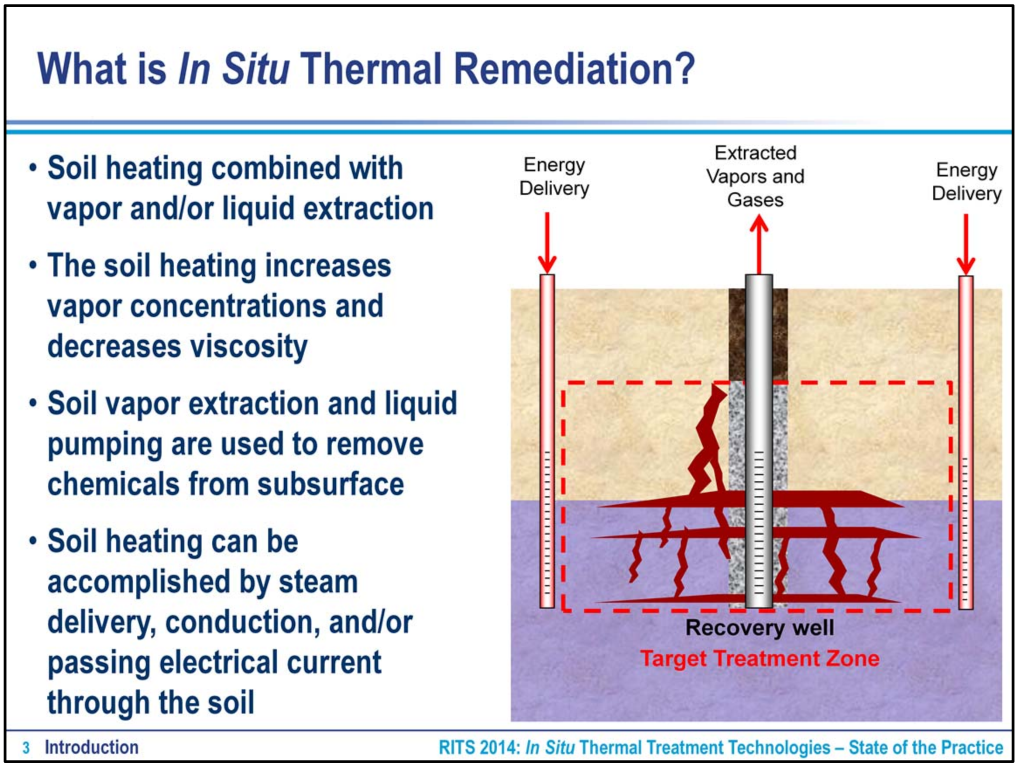


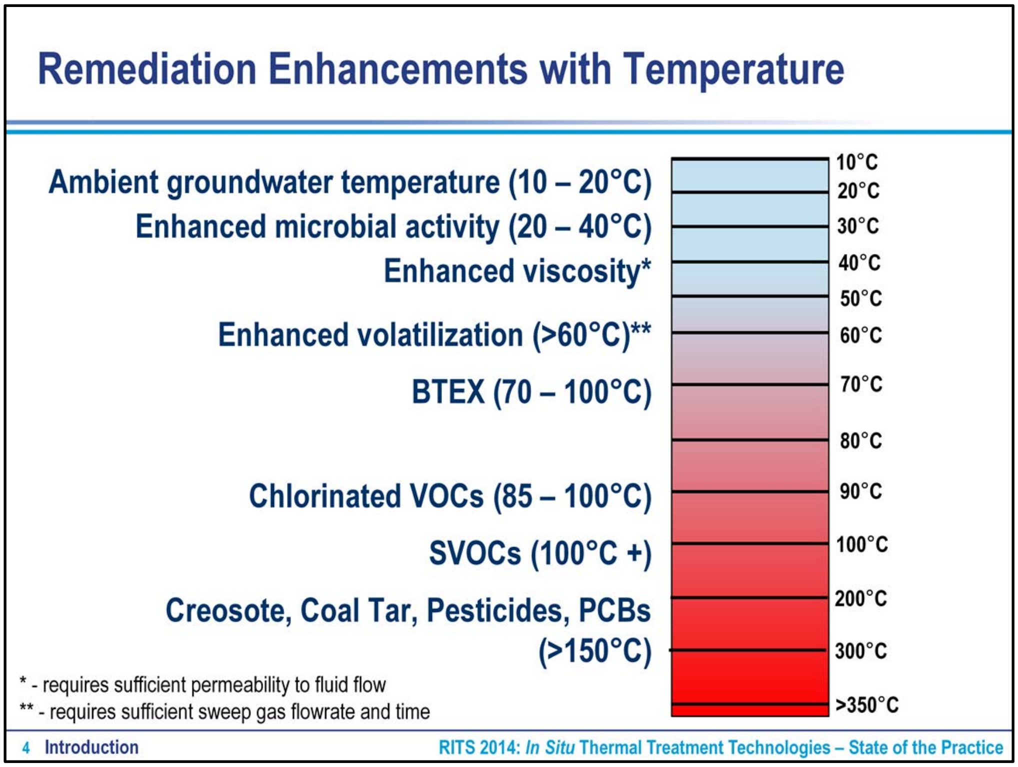
The background material and case studies presented here are based on research which was funded by ESTCP and completed in 2007.

Presentation Overview

- Introduction
- Evolution of Thermal Technologies
- Current Thermal Treatment Technologies
- Lessons-Learned
  - Empirical Assessment of Documented Applications
- Case Studies & Supplemental Data Collection
- Reasonable Performance Expectations for Future Projects
- Key Messages and Wrap Up



In situ thermal is a remediation technology that is used to treat source areas by delivering energy to heat the subsurface, causing contaminants to become less viscous and more volatile, and therefore, more easily recovered via vapor and liquid extraction systems. Thermal can be completed in both the vadose zone and in the groundwater. Thermal treatment is typically applied at small to medium depth sites, but can be applied at larger or deeper sites depending on the type of thermal technology chosen.



This graphic provides a broad overview of potential remediation enhancements with increasing temperatures. It is in no way completely encompassing. For example, complete SVOC removal is seen at temperatures between 200°-300°C, however, it has been shown that we start seeing some removal of SVOCs at lower temperatures (ex. Visalia Pole Yard). Additionally, with all of these chemicals it is typically better to achieve the higher end of the temperature range, so that the potential for "cold spots" is reduced, however, the RPM/vendor needs to also balance other costs/risks.

Past RITS Featuring *In Situ* Thermal

- ***In Situ*** **Thermal Desorption (ISTD)**
  - RITS Fall 1998
- ***In Situ*** **Thermal NAPL Remediation Technologies**
  - RITS Fall 2000
- **Knowledge Exchange – Source Removal Technologies**
  - RITS Fall 2001
- **DNAPL Management Challenges – Source and Associated Dissolved Plume**
  - RITS Spring 2006
- **Electrical Resistance Heating (ERH) – Design and Performance Criteria**
  - RITS May 2007
- **Embracing Mass Flux and Mass Discharge to Enhance GW Plume Mgmt.**
  - RITS Spring 2011
- **Integrated DNAPL Site Strategies**
  - RITS 2012
- **Lessons Learned from DNAPL Site Remediation**
  - RITS 2013

5 Introduction RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

Introduction – *In Situ* Thermal Remediation Technologies

- Use of *in situ* thermal technologies for source zone remediation has matured
- They promise shorter remediation timeframes
- Their performance might not be limited by soil heterogeneity like other treatment options
- They might be able to achieve >99% reductions, if optimized

EPA 542-F-12-013, September 2012

6 Introduction RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

In situ thermal technologies have matured over the last decade. These technologies have key selling points of 1) shorter remediation times and 2) the potential to be less sensitive to soil heterogeneities, but it does depend on the technology. Additionally, the thermal industry has been taking the lessons learned over the years and applying them to present day applications, so the cost for thermal remediation has been decreasing over time.

Illustration is a recent document illustrating maturity of technology(ies).

Presentation Objectives

- Provide an overview of the evolution of *in situ* thermal treatment
- Introduce *in situ* thermal options and how they work
- Review lessons-learned from past applications, including designs, operating conditions, monitoring, and performance
- Recommendations for selecting and managing thermal projects

7 Introduction RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

Presentation Overview

- Introduction
- Evolution of Thermal Technologies
- Current Thermal Treatment Technologies
- Lessons-Learned
  - Empirical Assessment of Documented Applications
- Case Studies & Supplemental Data Collection
- Reasonable Performance Expectations for Future Projects
- Key Messages and Wrap Up

RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice 8

Evolution of Thermal Treatment Technologies

- Adaptation of enhanced oil recovery techniques in the late 1980s for remediation uses
  - *e.g.*, steam injection – Solvent Services Site in San Jose, CA 1987-1988
- Continued innovation and testing in the 1980s and 1990s
- Pilot and full-scale uses increased in the 2000s
- USEPA and ESTCP evaluate documented applications

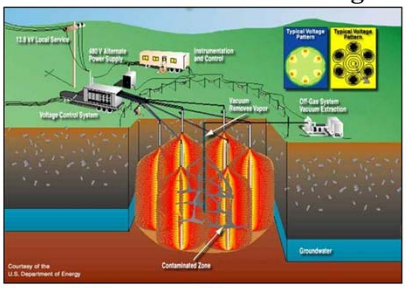
Thermal technologies have been adapted from the oil fields, both steam and electrical resistance heating.

Presentation Overview

- Introduction
- Evolution of Thermal Technologies
- **Current Thermal Treatment Technologies**
- Lessons-Learned
  - Empirical Assessment of Documented Applications
- Case Studies & Supplemental Data Collection
- Reasonable Performance Expectations for Future Projects
- Key Messages and Wrap Up

Most Common *In Situ* Thermal Treatment Technologies

Electrical Resistance Heating



Courtesy U.S. Department of Energy

Conductive Heating

Steam Injection

Steam + ERH

Steam + Hot Air

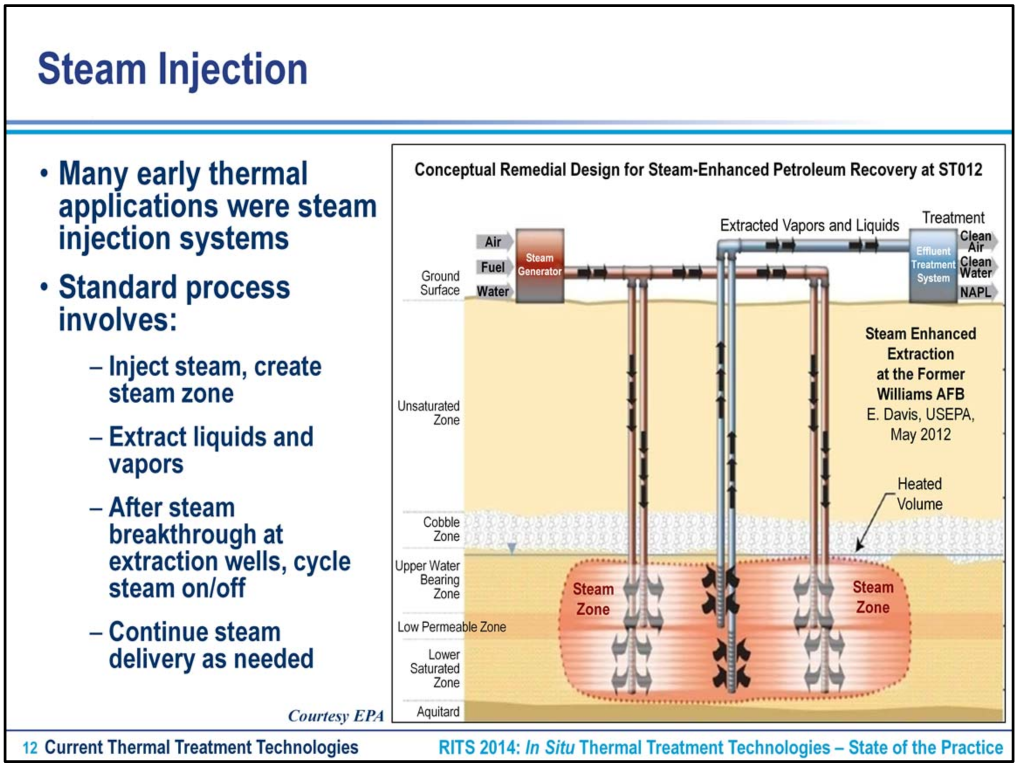
Steam + Auger Mixing

Other less-used or developing variants include radio-frequency heating, microwave heating, gas thermal remediation and *in situ* smoldering

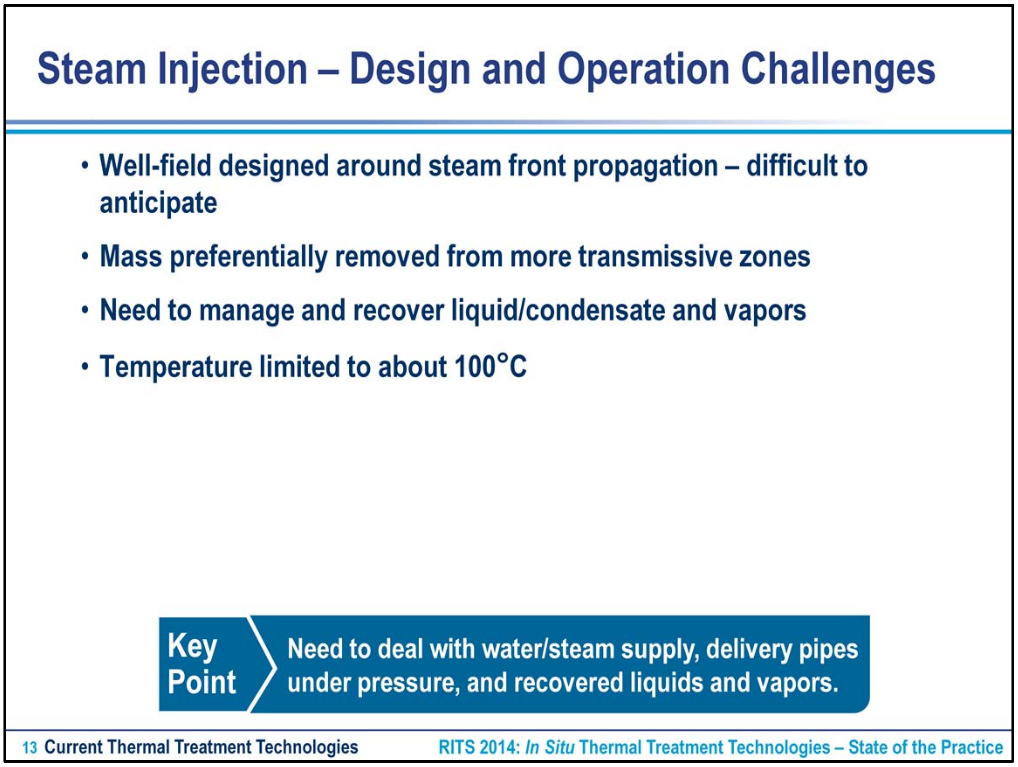
Electrical Resistance Heating (ERH) – A thermal technology that heats the subsurface by passing current through the soil between electrodes. This technology is capable of raising the temperature of the subsurface to the boiling point of water, as long as water is present in the treatment region.

Conductive Heating (TCH and ISTD) – A thermal technology that heats the subsurface via heating rods inserted into the subsurface. This technology is capable of raising the temperature of the subsurface to temperatures greater than 300 degrees Celsius.

Steam Injection – A thermal technology that heats the subsurface via the injection of steam under pressure. This technology is capable of raising the temperature of the subsurface to the boiling point of water.

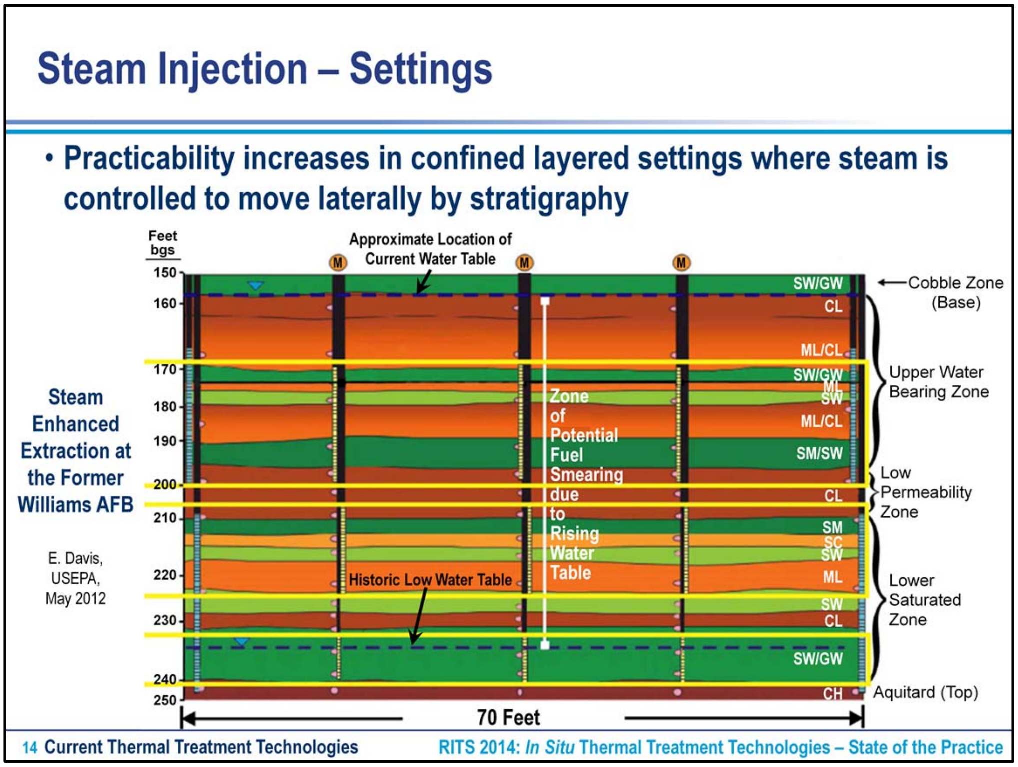


The steam injection process revolves around the concept of creating the steam front. This front is then “pushed” to the recovery well(s). After steam breakthrough is observed, the steam injection process can move to cyclical injection or cycling of steam. Throughout the entire process control of the steam front must be maintained.

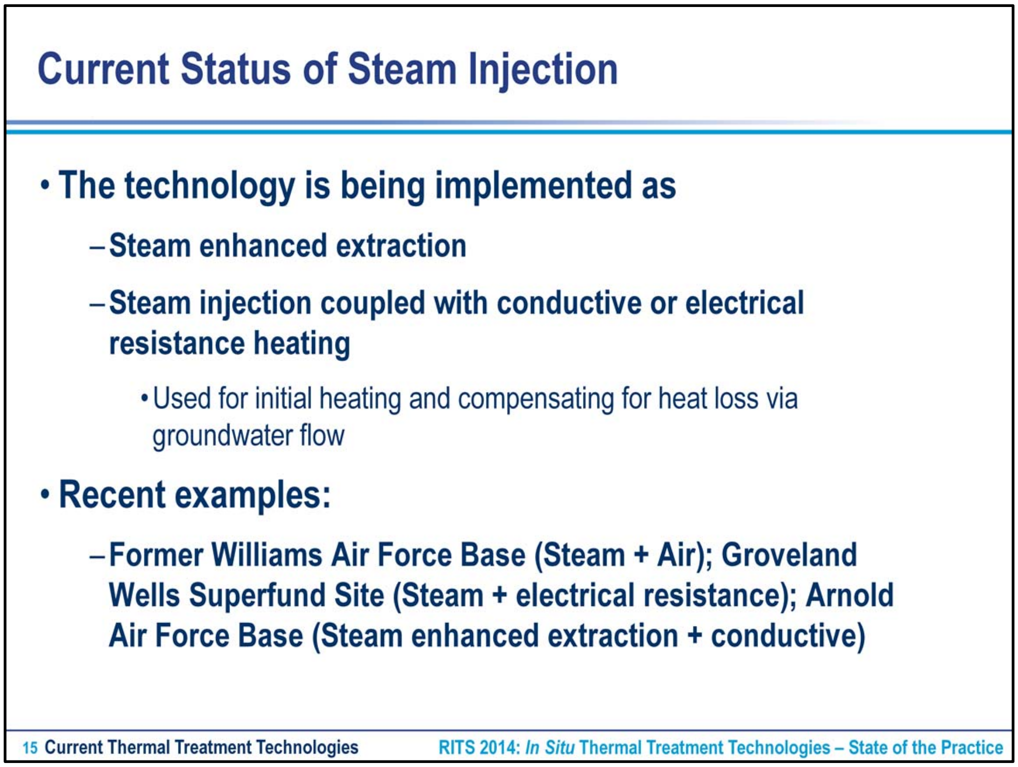


Steam rises in the subsurface which is due to the buoyancy effect of steam. This rise is one of the steam front movements that must be controlled.

Steam injection remediation is different than the other thermal technologies because the process is under pressure due to the injection of steam whereas the other remediation technologies are under vacuum. This increases certain safety issues that must be addressed.



Steam injection is best suited for stratified setting, so that the ability of the steam to rise can be mitigated by the geologic conditions. This illustration from the Former Williams Air Force Base in Mesa, Arizona is an example of stratified geology that is suitable for steam injection.



Recently, low temperature variations have also been implemented, but these types of applications are not considered to be state of the art for source zone remediation.

Conductive Heating

- **Heats soil by conduction away from heater elements** (like the ones in your oven)
  - **Vertical heater wells are most often used:**
    - For VOCs and CVOCs, 15-ft heater spacing is typical
    - For higher-boiling SVOCs, 8- to 10-ft heater spacing is typical
- **Only thermal technology that can achieve soil temperatures >> 100°C**
  - **Needed for PCB's, PAH's, dioxins, *etc.***

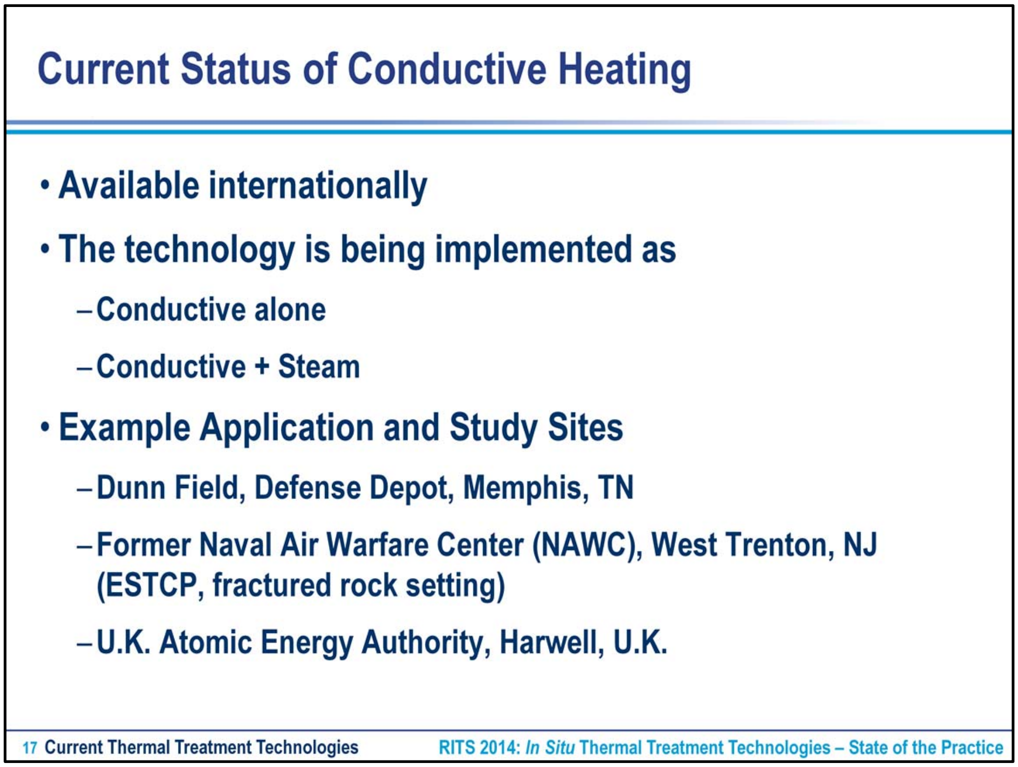
Lower Temp ← **Hot** → Lower Temp

Heat Conduction Away from a Heater

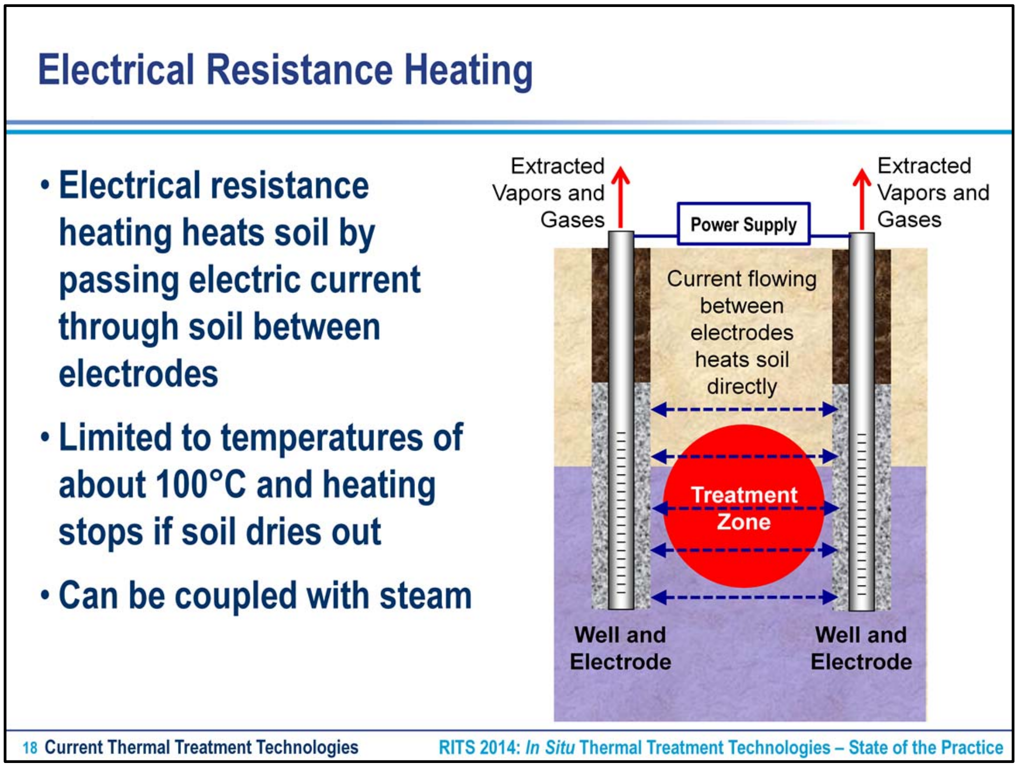
16 Current Thermal Treatment Technologies — RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

For conductive heating, the heater rod can reach temperatures on the order of 800-900C. This heat radiates out from the heater rods and heats the subsurface. However, the heater rods are typically not operated at this temperature, rather they are operated at the temperature appropriate for the chemicals of concern because operating at full temperature throughout the thermal treatment operation can also desiccate the sail around the heater rod which can also be an issue.

Note that when conductive heating first became available, the technology also had a surface heating blanket system for shallow soils (2'-3' depths). The heating blanket technology is typically never used anymore



Conductive heating is also termed *In Situ* Thermal Desorption or ISTD.



Electrical resistance heating uses the soil as the resistor and passes current between the electrodes. This technology is limited to the boiling point of water as it stops working when the water has evaporated completely. Current practice is for electrical resistance vendors to use water addition or other engineered controls at the electrode to confirm that soil drying is not an issue.

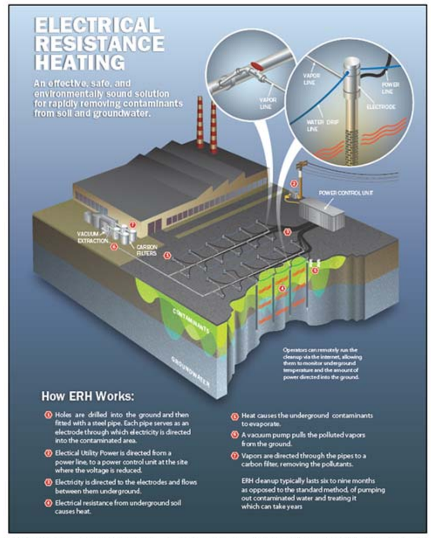
Electrical Resistance Heating (cont.)

- Electrical current flow through soil between electrodes wells; Uses 3-phase (or 6-phase) alternating current
- Co-located electrodes and recovery wells

In the past, electrical resistance was referred to as six-phase heating or three-phase heating depending on the selected resistance heating design. Today, electrical resistance heating applications are typical three-phase applications.

Electrical Resistance Heating (cont.)

- **Commercially available**
  - **ERH**
  - **Other companies with other installation techniques (sheet piles, *etc.*)**
- **Technology is being implemented**
  - **Standalone, and**
  - **With steam-enhanced extraction**
- **Recent Examples:**
  - **Silresim Chemical Corporation Superfund**
  - **Paducah Gaseous Diffusion Plant**



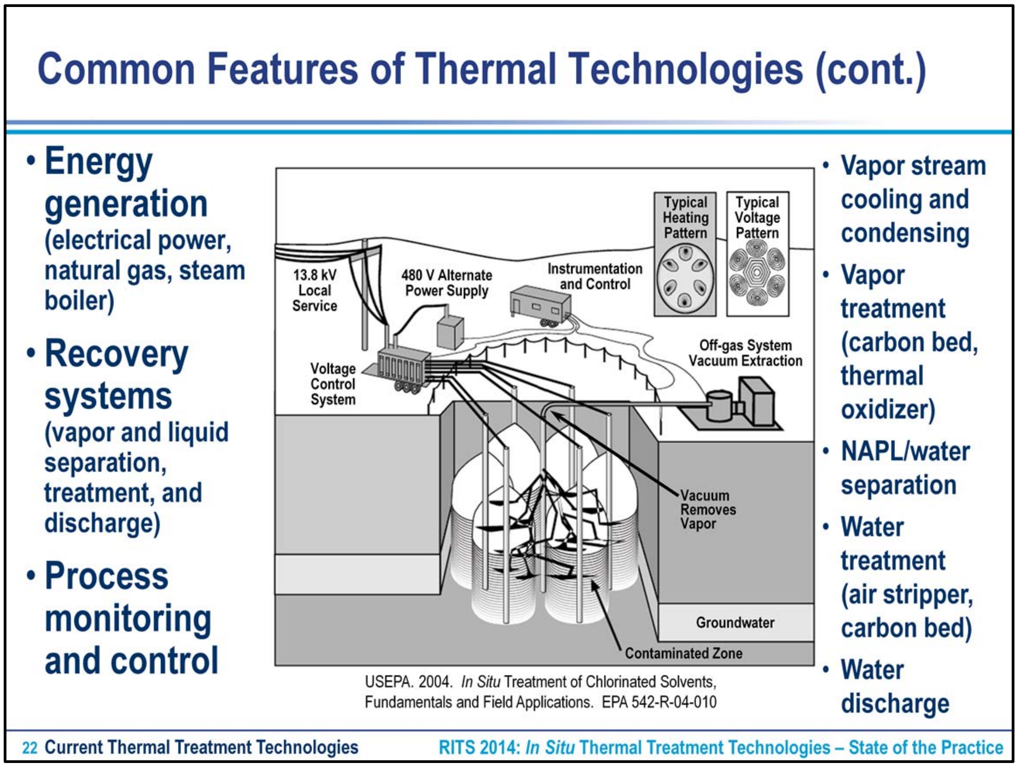
USACE. 2007. *In Situ* Thermal Remediation (Electrical Resistance Heating). East Gate Disposal Yard, Ft. Lewis, Washington (USACE, 2007).

Common Features of Thermal Technologies

- **Energy delivery points** (injection wells, heaters, and/or electrodes)
- **Recovery wells**
- **Surface seals**
- ***In situ* monitoring** (temperature, pressure)

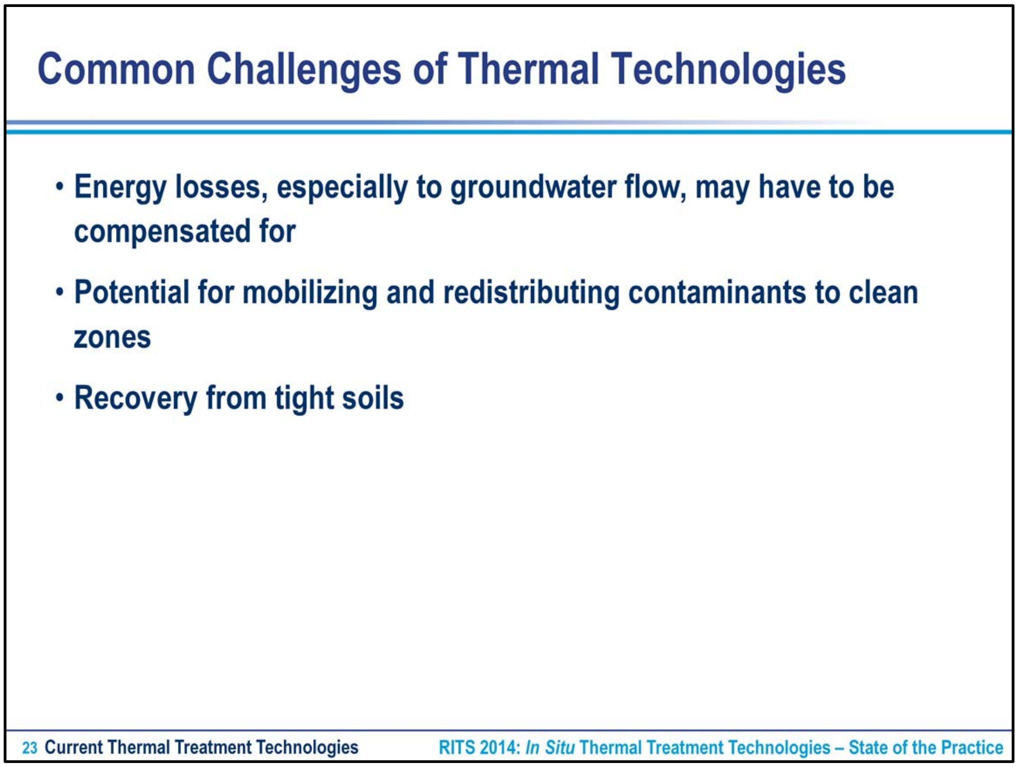
21 Current Thermal Treatment Technologies RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

There are many different acronyms, names, combinations, *etc.* for each step of thermal depending on the technology selected. For the overall system, these are the common features that every RPM should expect to see or have suggested (*i.e.* surface seal) for a thermal remediation.

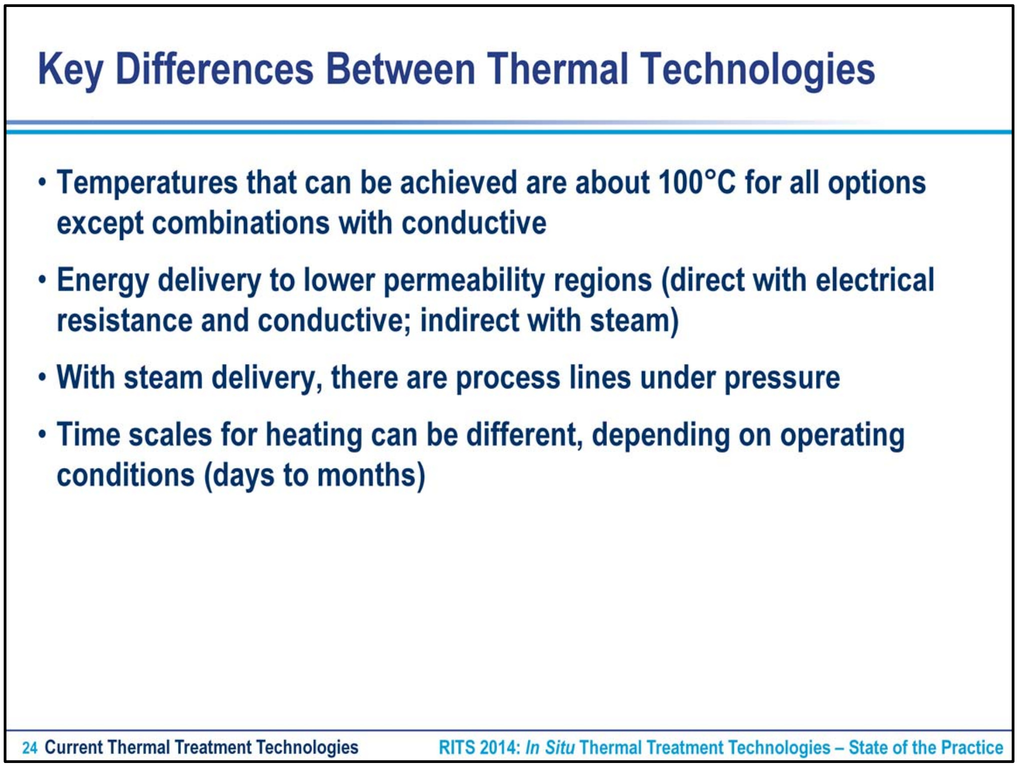


Continued from previous slide. Depending on the type of technology selected, these are the energy, recovery systems, and process monitoring that should be expected for a thermal treatment.

Note that this is a diagram of six-phase heating which is typically not used for full-scale applications, but is sometimes used in pilot scale applications.



Two of the largest challenges to thermal remediation are 1) heat losses through groundwater flow which limit how fast the site can be heated and 2) designing a recovery system that can capture vapors.



Energy delivery is one of the key differences to thermal technologies. Conductive and electrical resistance heating are direct methods. Conductive heating is like sticking a curling iron in the ground and turning it on so that it heats all the area around it whereas electrical resistance uses the soil as the resistor to heat the soil. Conductive heating starts heating at the rod whereas electrical resistance heating can start at any point between the electrodes.

Thermal Treatment Examples

- **Former Williams AFB (jet fuel): steam-enhanced extraction selected because of highly layered geology and treatment zone depth below groundwater table**
- **Memphis Defense Depot (chlorinated solvents): thermal conduction selected because of finer-grained soils**
- **Fort Lewis East Gate Disposal Yard (CHCs): electrical resistance selected because of highly permeable soils**

25 Current Thermal Treatment Technologies RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

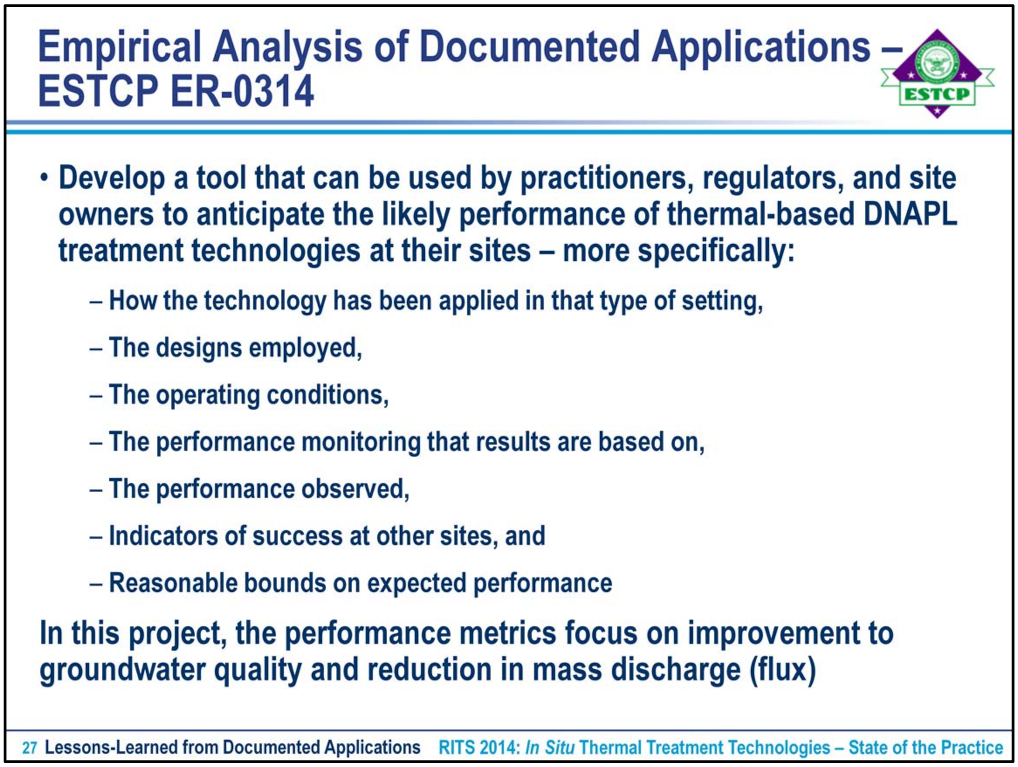
AFB – Steam was selected because of an on-site source and because of the stratified geology, depth to groundwater, and depth of contamination.

Ft. Lewis – Electrical resistance was selected not only because of the high permeable soils, but also to minimize time to implement the remedy in a cost effective manner. Electrical resistance heating had been completed at two other areas in the Ft. Lewis East Gate Disposal Yard.

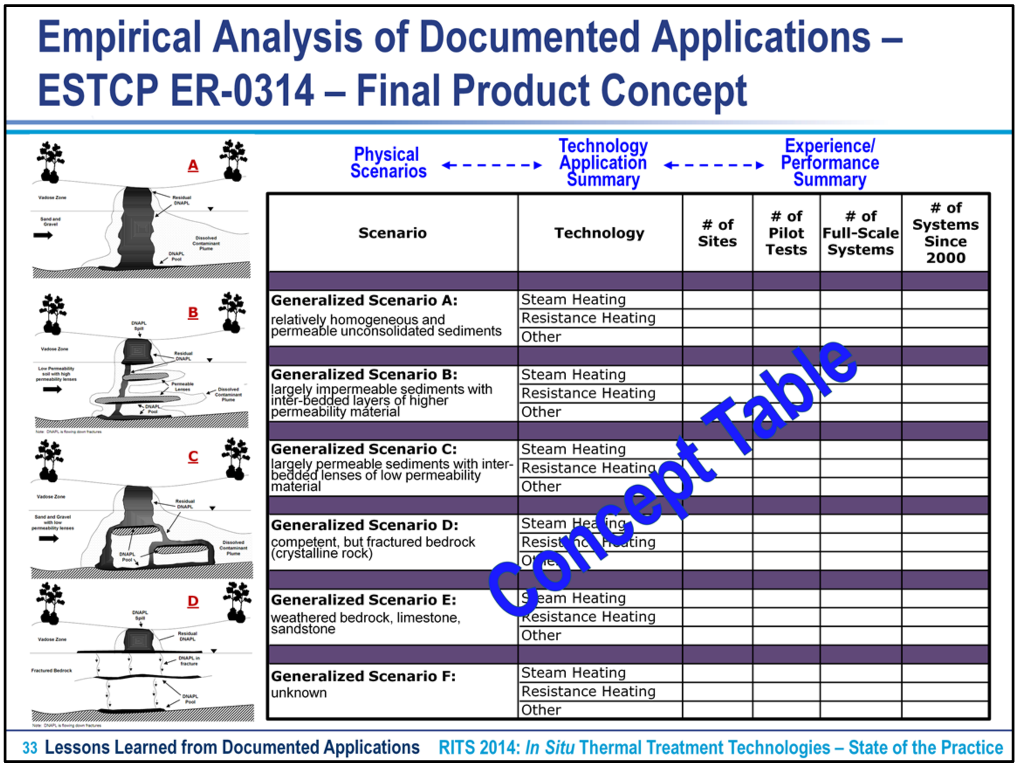
Memphis – Conductive heating was chosen through a competitive bid process but was selected to treat the finer grain soils in both the vadose and groundwater zones.

Presentation Overview

- Introduction
- Evolution of Thermal Technologies
- Current Thermal Treatment Technologies
- Lessons-Learned
  - Empirical Assessment of Documented Applications
- Case Studies & Supplemental Data Collection
- Reasonable Performance Expectations for Future Projects
- Key Messages and Wrap Up

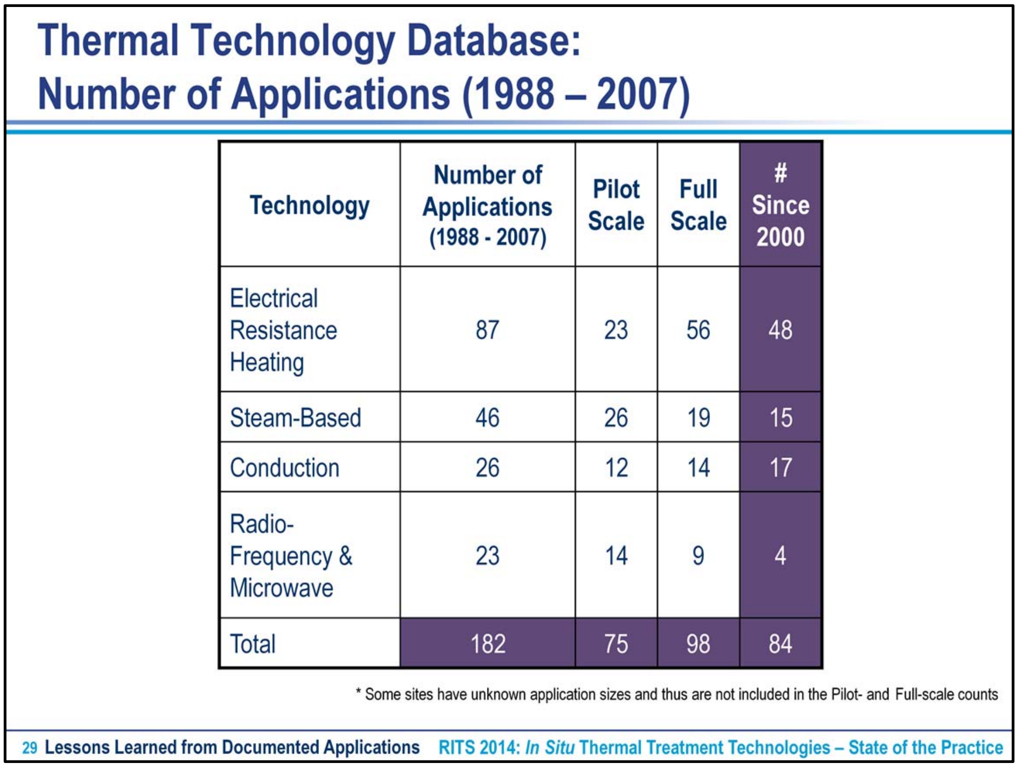


This study was funded by the Environmental Security Technology Certification Program (ESTCP) and was completed in 2007. Thus there are many thermal applications both documented and not documented that have occurred since that time. The following slides are based on this research. If possible, it would be good for an additional study to follow-up on this work to see if additional data is available to better document thermal post-treatment groundwater quality.



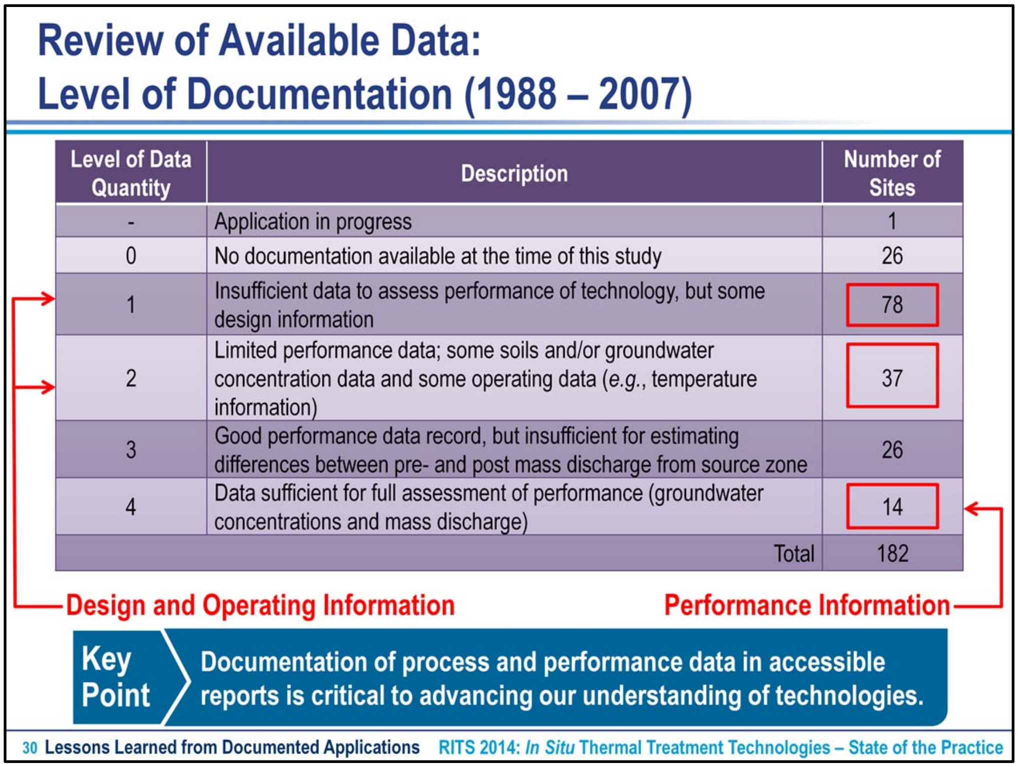
Scenario	Technology	# of Sites	# of Pilot Tests	# of Full-Scale Systems	# of Systems Since 2000
Generalized Scenario A: relatively homogeneous and permeable unconsolidated sediments	Steam Heating				
	Resistance Heating				
	Other				
Generalized Scenario B: largely impermeable sediments with inter-bedded layers of higher permeability material	Steam Heating				
	Resistance Heating				
	Other				
Generalized Scenario C: largely permeable sediments with inter-bedded lenses of low permeability material	Steam Heating				
	Resistance Heating				
	Other				
Generalized Scenario D: competent, but fractured bedrock (crystalline rock)	Steam Heating				
	Resistance Heating				
	Other				
Generalized Scenario E: weathered bedrock, limestone, sandstone	Steam Heating				
	Resistance Heating				
	Other				
Generalized Scenario F: unknown	Steam Heating				
	Resistance Heating				
	Other				

This is a conceptual picture of the final table from the 1988 to 2007 data. Please refer to the ESTCP report for the published tables.



Technology	Number of Applications (1988 - 2007)	Pilot Scale	Full Scale	# Since 2000
Electrical Resistance Heating	87	23	56	48
Steam-Based	46	26	19	15
Conduction	26	12	14	17
Radio-Frequency & Microwave	23	14	9	4
Total	182	75	98	84

Vendors have identified that at least 175 thermal applications have been completed since 2000. This database does not even cover 50% of the most recent thermal applications.



Data from 141 sites had design and operation information, but only 14 sites had enough data for performance assessment.

Thermal Technology Database: Basic Design Information (1988 – 2007)

Technology	Number of Sites with Target Treatment Zones with Sizes in this Range [ft²]				Number of Sites with Density of Energy Delivery Points (electrodes or wells) in this Range [# per 100 ft²]			
	$<10^4$	$10^4 - 4x10^4$	$<4x10^4$	Unknown	<0.25	0.25-0.50	>0.5	Unknown
Steam-Based Heating	16	6	4	20	20	2	4	20
Resistance Heating	36	24	0	27	10	23	27	27
Conductive Heating	19	6	0	1	1	1	23	1
Other (including Mixing/Heating)	8	2	0	13	2	0	8	13

* For the three steam auger sites, the density is one energy point per cell. This does not fit into the number calculation so it is classified as <0.5.

<1/2 acre sites

<20 ft spacings

31 Lessons Learned from Documented Applications RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

Recent discussions with thermal vendors are showing that larger sites are being completed, but a majority of thermal applications are still occurring in the ~1/2 acre size range.

Thermal Technology Database: Basic Design Information (1988 – 2007) (cont.)

Technology	Number of Sites with Target Treatment Zones with Sizes in this Range [ft^2]				Number of Sites with Density of Energy Delivery Points (electrodes or wells) in this Range [# per 100 ft^2]			
	$<10^4$	10^4 - $4x10^4$	$<4x10^4$	Unknown	<0.25	0.25-0.50	>0.5	Unknown
Steam-Based Heating	16	6	4	20	20	2	4	20
Resistance Heating	36	24	0	27	10	23	27	27
Conductive Heating	19	6	0	1	1	1	23	1
Other (including Mixing/Heating)	8	2	0	13	2	0	8	13

* For the three steam auger sites, the density is one energy point per cell. This does not fit into the number calculation so it is classified as <0.5.

Key Point

1. Close spacing of energy delivery points is critical to success.
2. Thermal treatment is typically used for focused source treatment.

32 Lessons Learned from Documented Applications RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

Thermal Technology Database: Basic Operating Conditions (1988 – 2007)

Technology	Number of Sites with Temperatures in Target Treatment Zone in these Ranges [°C]				Number of Sites with Active Heating Durations in these Ranges [y]				Number of Sites with Post-Treatment Monitoring in these Ranges [y]			
	<80	80 - 110	>110	Unknown	<0.5	0.5 - 1.0	>1.0	Unknown	<0.5	0.5 - 2.0	>2.0	Unknown
Steam-Based Heating	7	13	1	25	14	0	3	29	2	0	0	44
Resistance Heating	9	37	0	41	38	2	0	47	1	5	1	80
Conductive Heating	0	11*	12*	4	18	3	0	5	1	1	0	24
Other (including Mixing/Heating)	2	2	1	18	6	0	0	17	3	0	0	20

* One site had two different temperature values. The 80-110° C temperature was for the saturated zone and the >110° C temperature for the vadose zone.

Reflection of technology capabilities ↑

↑ Treatment durations often selected *a priori*

↑ Limited monitoring?

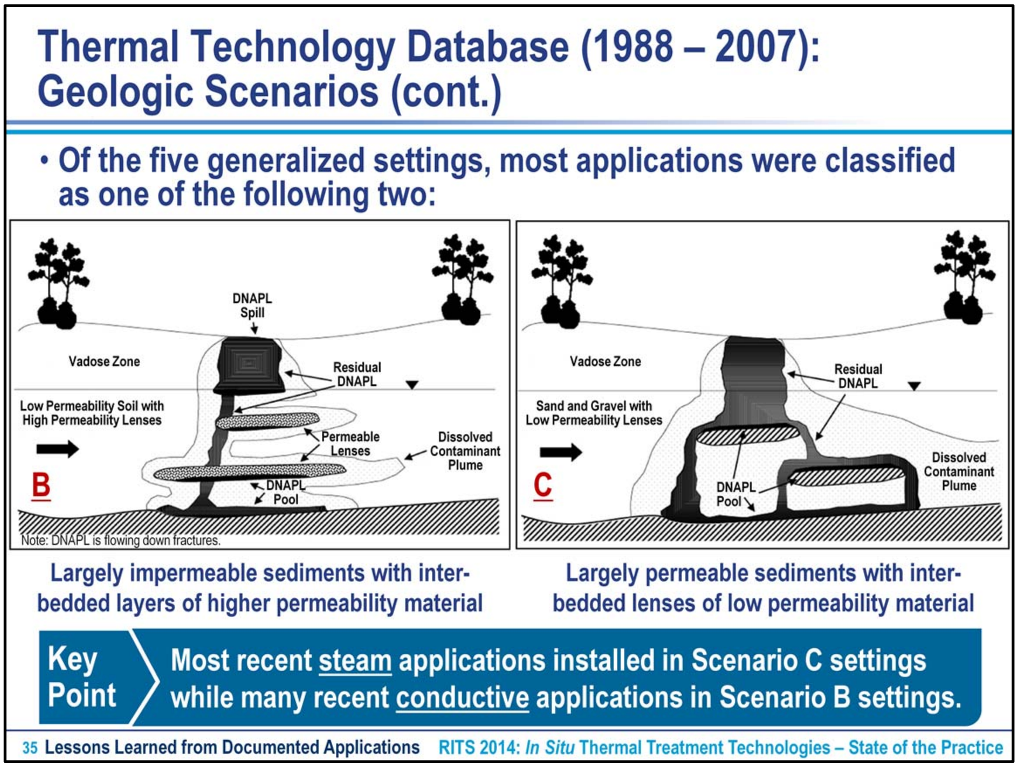
33 Lessons Learned from Documented Applications RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

More recent thermal applications are selecting treatment durations based on theoretical energy balance completed prior to treatment to meet specified standards. It is still not clear how the performance standards are being selected and thus the treatment durations could still be a bit arbitrary, so the RPM should be aware that this heating duration may need to be modified once treatment is initiated if the energy balance is not following the theoretical model.

Thermal Technology Database (1988 – 2007): Geologic Scenarios

- **Scenario A:** relatively homogeneous and permeable unconsolidated sediments (mixtures of sands, gravels and silts, *etc.*)
- **Scenario B:** largely impermeable sediments with inter-bedded layers of higher permeability material
- **Scenario C:** largely permeable sediments with inter-bedded lenses of low permeability material
- **Scenario D:** competent, but fractured bedrock (crystalline rock)
- **Scenario E:** weathered bedrock, limestone, sandstone

34 Lessons Learned from Documented Applications RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice



Based on the ESTCP study, we found that most recent <u>steam</u> applications installed in Scenario C settings while many recent <u>conductive</u> applications in Scenario B settings.

The recent applications by all thermal vendors is moving towards working in all geological scenarios including fractured rock. A lot of this work is still in the “maiden” stages of being optimized as the industry moves into a new geologic setting.

Key Take-Away Points from Review of Applications

Key Point 1
- *Through 2007, not a lot of post-treatment monitoring data available to use to anticipate performance and factors affecting it*

Key Point 2
- *Market preference is trending towards electrical resistance and conductive heating, with occasional use of steam as a pre-heat delivery to highly transmissive regions*

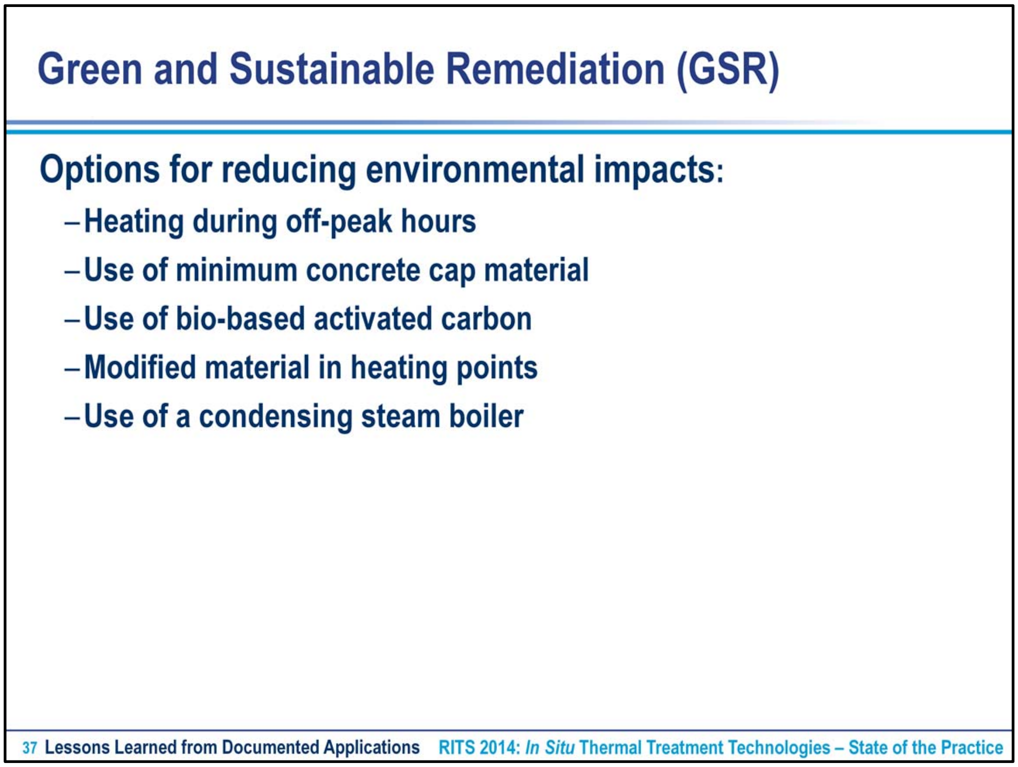
Key Point 3
- *Spacing of energy delivery points for electrical resistance and conductive heating should be less than 25 feet*

Key Point 4
- *Thermal technologies can achieve temperatures greater than 80°C, and conductive heating can achieve temperatures greater than 300°C*

Key Point 5
- *Our knowledge is largely derived from applications in permeable sediments with inter-bedded lenses of low permeability material and impermeable sediments with inter-bedded layers of higher permeability material*

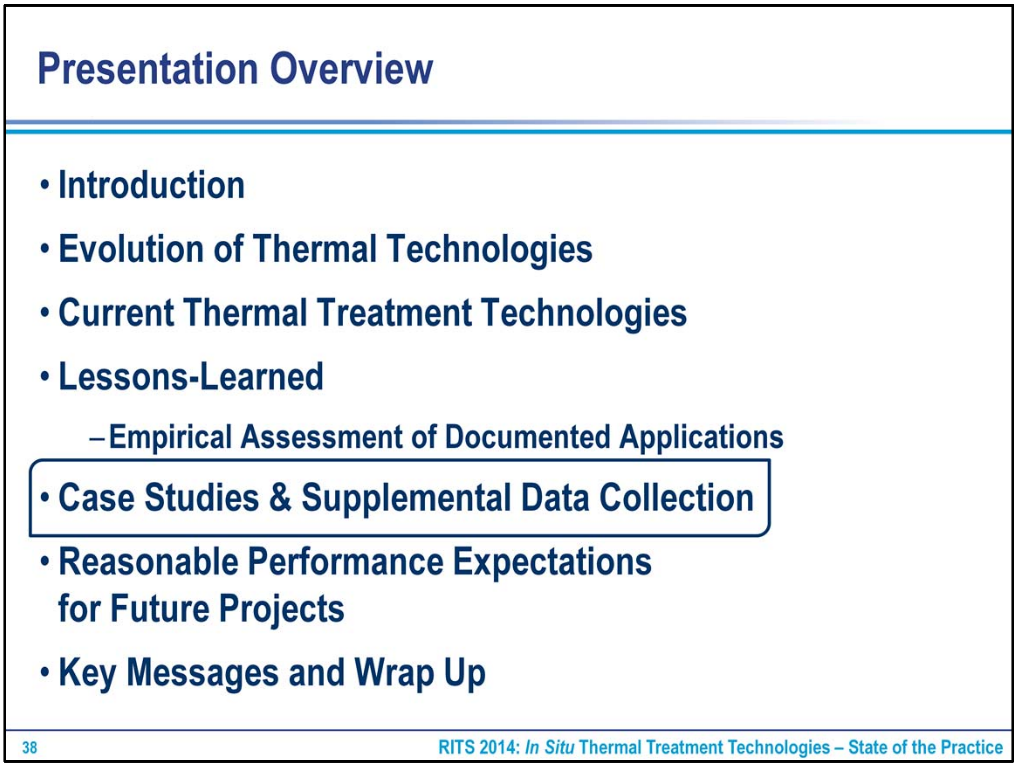
Key Point 6
- *The treatment duration seems to have been selected based on a target temperature and arbitrary duration prior to operation, rather than based on monitoring and optimization of system performance*

36 Lessons Learned from Documented Applications RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice



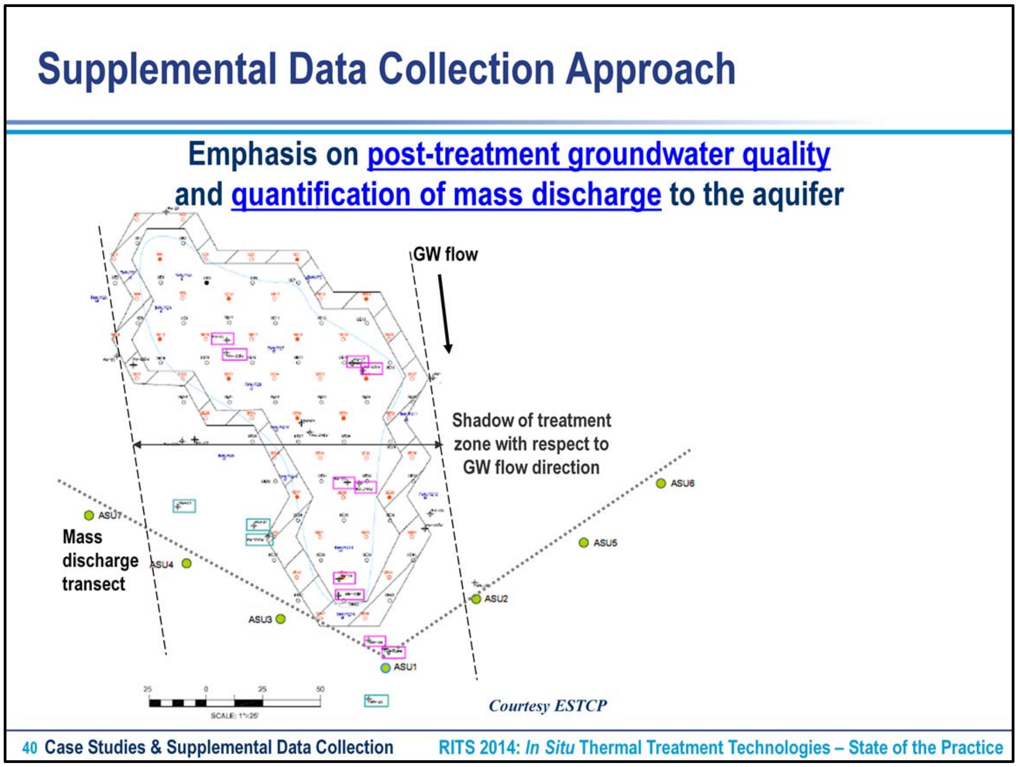
Key points from the study:

1. Heating during off-peak hours does increase the overall energy consumption. The study says 3% in ISTD and 6% in ET-DSP.
2. Use of the modified material in heating points in ISTD have not been field tested.

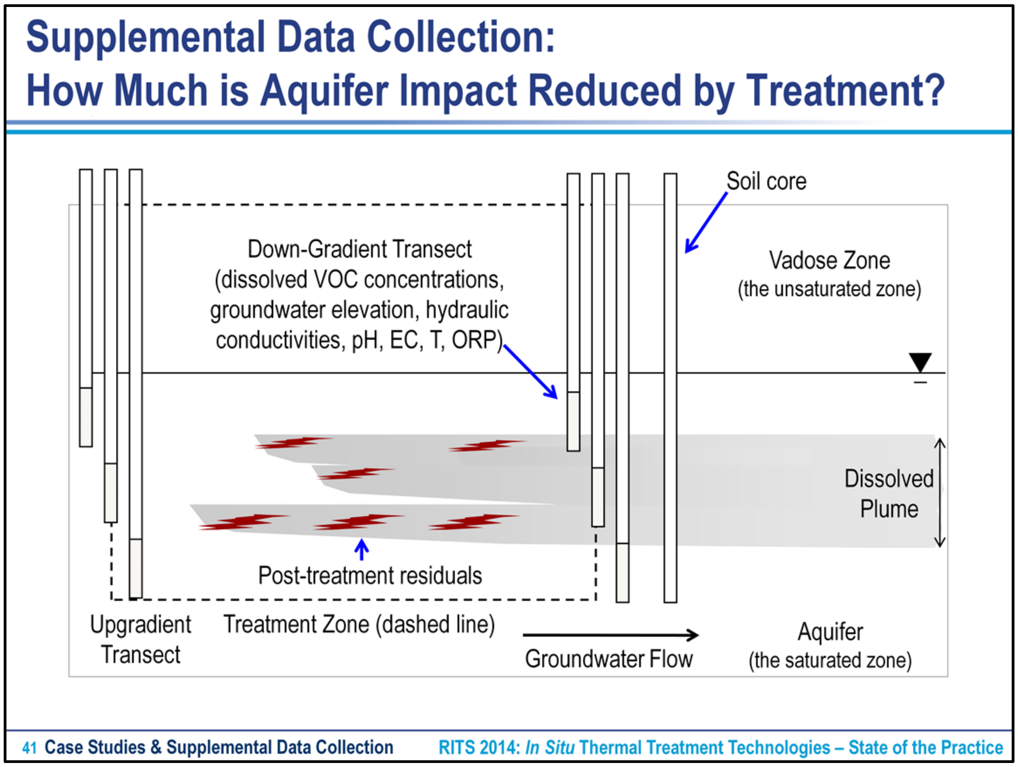

Presentation Overview
• Introduction
• Evolution of Thermal Technologies
• Current Thermal Treatment Technologies
• Lessons-Learned
– Empirical Assessment of Documented Applications
• Case Studies & Supplemental Data Collection
• Reasonable Performance Expectations for Future Projects
• Key Messages and Wrap Up
38
RITS 2014: In Situ Thermal Treatment Technologies – State of the Practice

Case Studies & Supplementation Data Collection

ESTCP
ER-0314



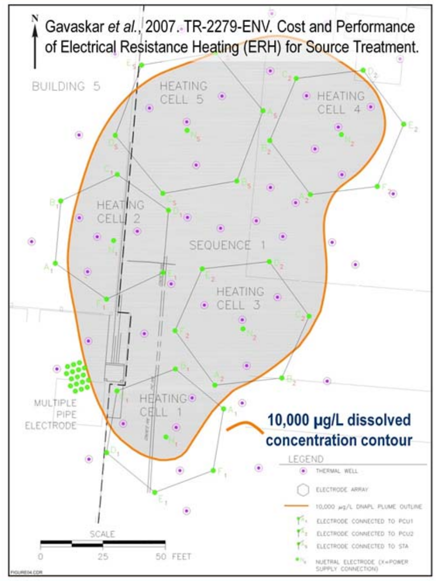
Supplemental Data Collection Approach
Emphasis on post-treatment groundwater quality
and quantification of mass discharge to the aquifer
GW flow
Shadow of treatment zone with respect to GW flow direction
Mass discharge transect
ASU1
ASU2
ASU3
ASU4
ASU5
ASU6
ASU7
Courtesy ESTCP
40 Case Studies & Supplemental Data Collection
RITS 2014: In Situ Thermal Treatment Technologies – State of the Practice



Conceptual diagram showing transect sampling approach for determine groundwater treatment performance. This same method can be used to define the source zone prior to treatment.

Case Study Site 1: NAS Alameda (IR Site 5)

- Electrical Resistance: 7/04-11/04
- DNAPL source (chlorinated solvents)
- Depth to top of treatment zone: 0 ft
- Depth to water: approximately 6 ft
- Largely permeable sediments with low permeability lenses
- Target interval: 21 ft thick
- 35 energy delivery points with 4 sheet piles making-up an electrode
- 25 ft electrode spacing
- Appr. 14,500 ft^2 (130 ft x 185 ft)



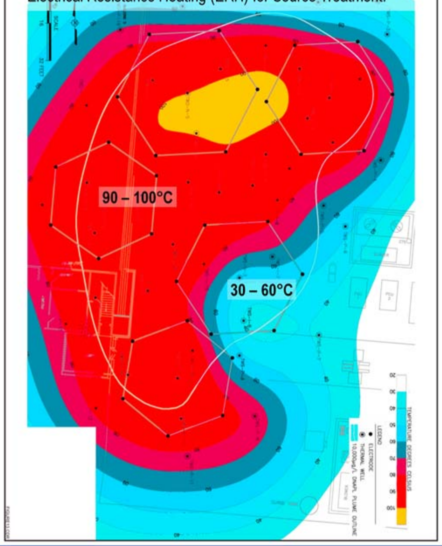
42 Case Studies & Supplemental Data Collection RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

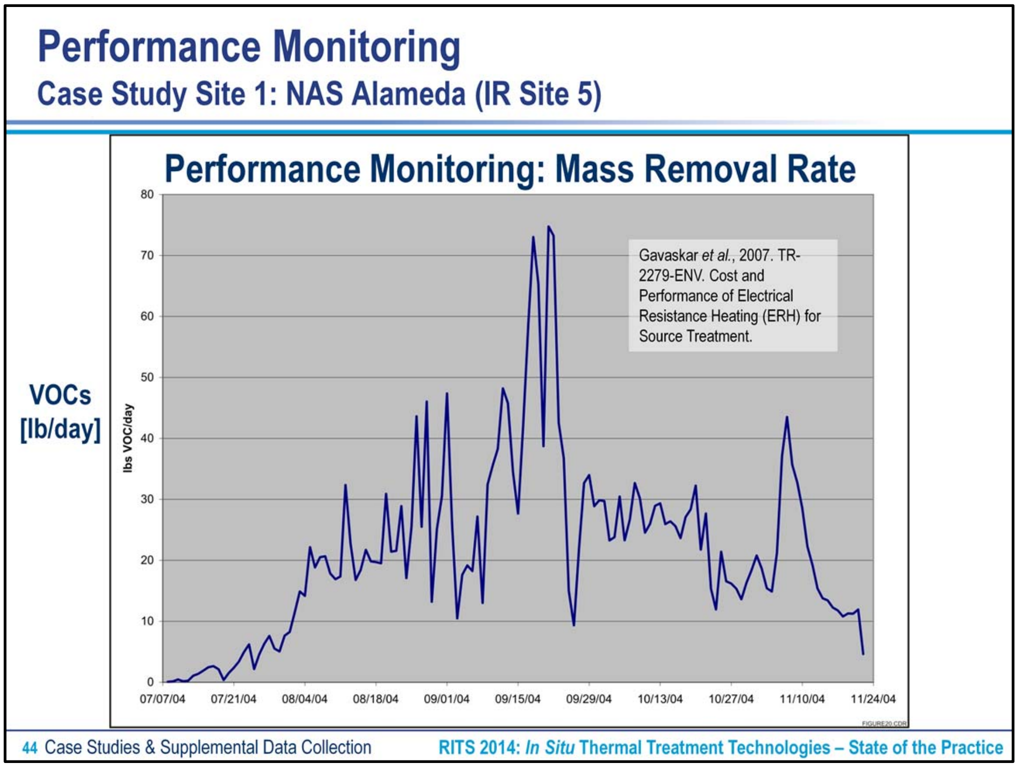
NAS Alameda, IR Site 5 was completed inside and immediately outside of Building 5.

Operating Conditions
Case Study Site 1: NAS Alameda (IR Site 5)

- **Initial formation temperature: 22°C**
- **Maximum representative temperature: 92°C**
- **Time to reach maximum representative temperature: 90 days**
- **Duration at maximum representative temperature: 30 days**

Gavaskar *et al.*, 2007. TR-2279-ENV. Cost and Performance of Electrical Resistance Heating (ERH) for Source Treatment.





This is a typical thermal remediation mass removal graph. Showing time versus pounds per day. We would expected to see this general rise in VOCs over time as temperatures across the site increases then after the boiling points of chemicals have been achieve, the decline in VOCs.

Project Costs

Case Study Site 1: NAS Alameda (IR Site 5)

Item	Basis	Cost ($)
Design, planning	Work Plan, SAP, HASP, QC Plan, Procurement, Meetings, Data Investigation and Design, and Removal Design	$1,262,500
	Vendor Cost	
Mobilization, setup		$410,800[a]
Equipment		$833,333[a]
Operation	07/08/04 to 11/05/04 Costs included here include management of the entire project which in addition to system operation	$1,169,445
Power consumption	1,500,000 kW-Hrs	$277,145
Demobilization	Not available	NA
	Adjusted Vendor Cost	**$2,690,723[b]**
	Site Incurred Cost	
Site preparation	Included in mobilization/setup	$0
Waste disposal	Not available	$0
Monitoring and performance assessment	Groundwater sampling and analysis and final reports	$750,000
	Site Incurred Cost	**$750,000**
	Total Cost	**$4,703,223**

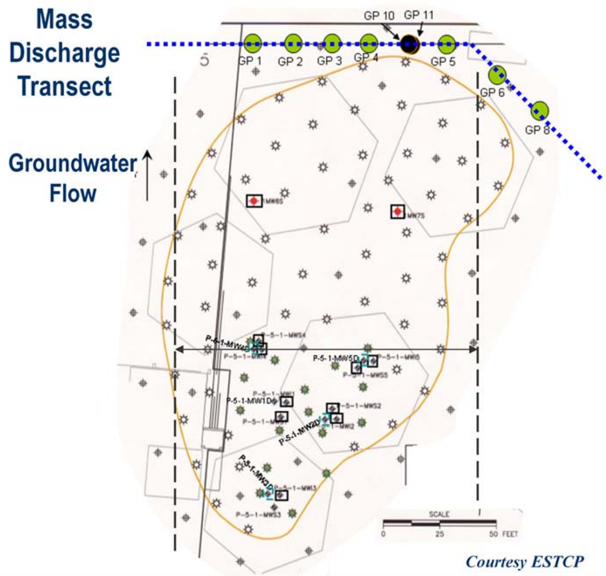
Gavaskar *et al.*, 2007. TR-2279-ENV. Cost and Performance of Electrical Resistance Heating (ERH) for Source Treatment.

45 **Case Studies & Supplemental Data Collection** **RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice**

~$417/yd3

Site Layout and Sampling Locations

Case Study Site 1: NAS Alameda (IR Site 5)



Courtesy ESTCP

Supplemental Data Collection

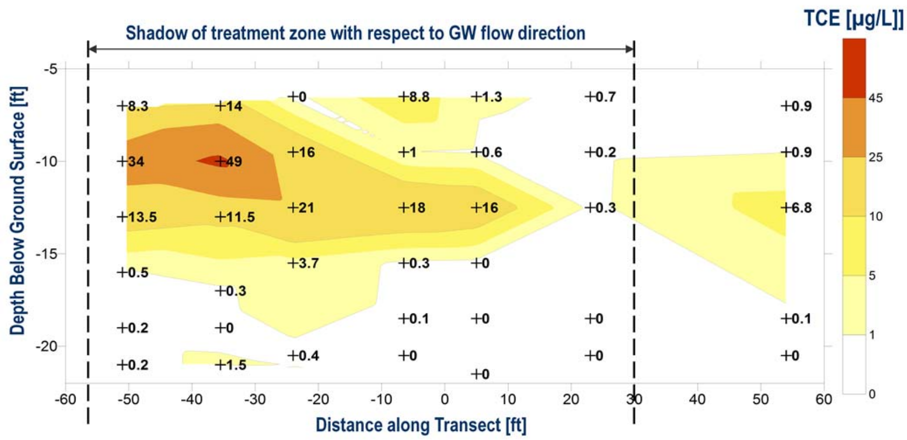
Case Study Site 1: NAS Alameda (IR Site 5)

- 40+ hydraulic conductivity tests performed in 7 locations
- 2 continuous soil core collected at transect location
- 11 groundwater samples collected from 11 wells at 7 locations
- 29 depth-specific groundwater samples collected from 7 direct-push locations; aquifer characterization mini-pump tests performed at each depth
- pH, EC, Temp., DO, ORP, TCA, PCE, TCE, DCA, DCE isomers, VC

Concentration Transect

Case Study Site 1: NAS Alameda (IR Site 5)

TCE concentrations from samples collected along the transect perpendicular to groundwater flow on the down-gradient edge of the source zone

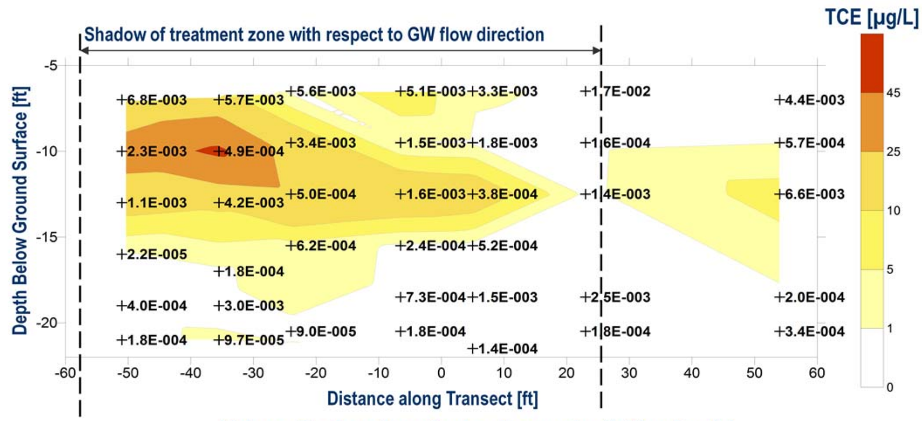


48 **Case Studies & Supplemental Data Collection** RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

Mass Discharge

Case Study Site 1: NAS Alameda (IR Site 5)

Estimated to be about 0.1 kg/year using the ESTCP-sponsored Mass Flux Toolkit Software from GSI (initially about 50 kg/y)



Values displayed are hydraulic conductivities [cm/s] superimposed on the concentration contour plot

Results

Case Study Site 1: NAS Alameda (IR Site 5)

- Electrical resistance treatment resulted in a significant reduction in dissolved contaminant concentrations throughout the 20-ft depth of treatment
  - From 1,000 – 10,000 to ND – 50 µg/L
- Mass discharge reduced by >100X

50 Case Studies & Supplemental Data Collection RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

This Case Study Illustrates…

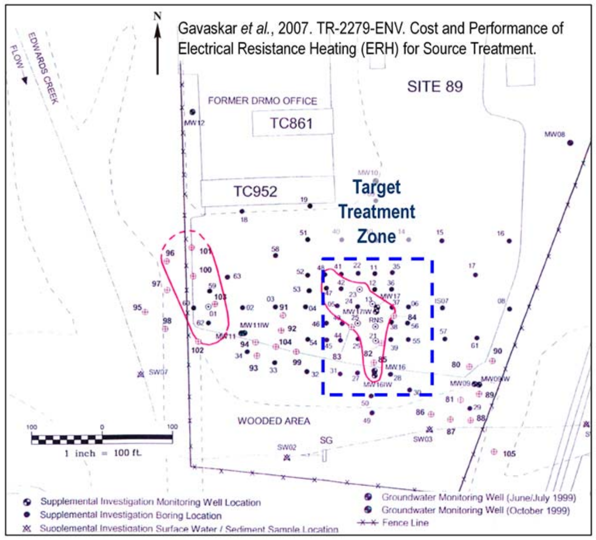
Case Study Site 1: NAS Alameda (IR Site 5)

- That low 10's of µg/L dissolved concentrations can be achieved when the thermal treatment:
  - Covers the areal extent of the source zone
  - Treats the full depth of contamination
  - Is operated for sufficient duration at sufficient temperature
- That temperatures above the boiling point of contaminants can be achieved
- That months were required to achieve temperatures throughout the treatment zone
- State-of-the-practice electrode spacings
- Typical removal rate vs. time and temperature behavior

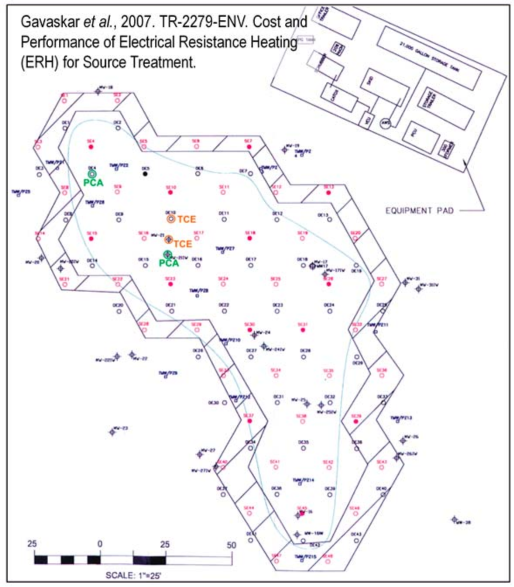
51 Case Studies & Supplemental Data Collection RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

Case Study Site 2: Camp Lejeune

- Electrical Resistance: 9/03 – 5/04
- DNAPL source (chlorinated solvents)
- Top of treatment zone: 5 ft bgs
- Depth to water: 6 ft
- Largely permeable sediments with low permeability lenses
- Target interval: 21 ft thick
- 43 deep/48 shallow electrodes
- 25-ft electrode spacing
- Appr. 16,000 ft^2 (1,850 ft x 255 ft)



Case Study Site 2: Camp Lejeune

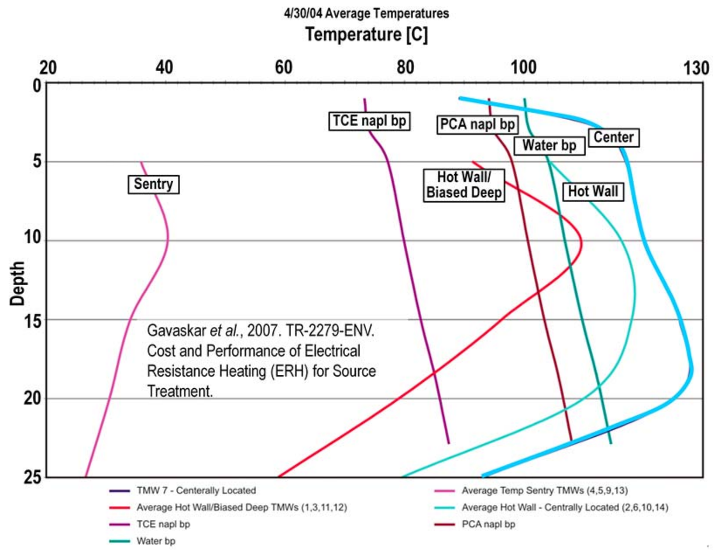


Gavaskar *et al.*, 2007. TR-2279-ENV. Cost and Performance of Electrical Resistance Heating (ERH) for Source Treatment.

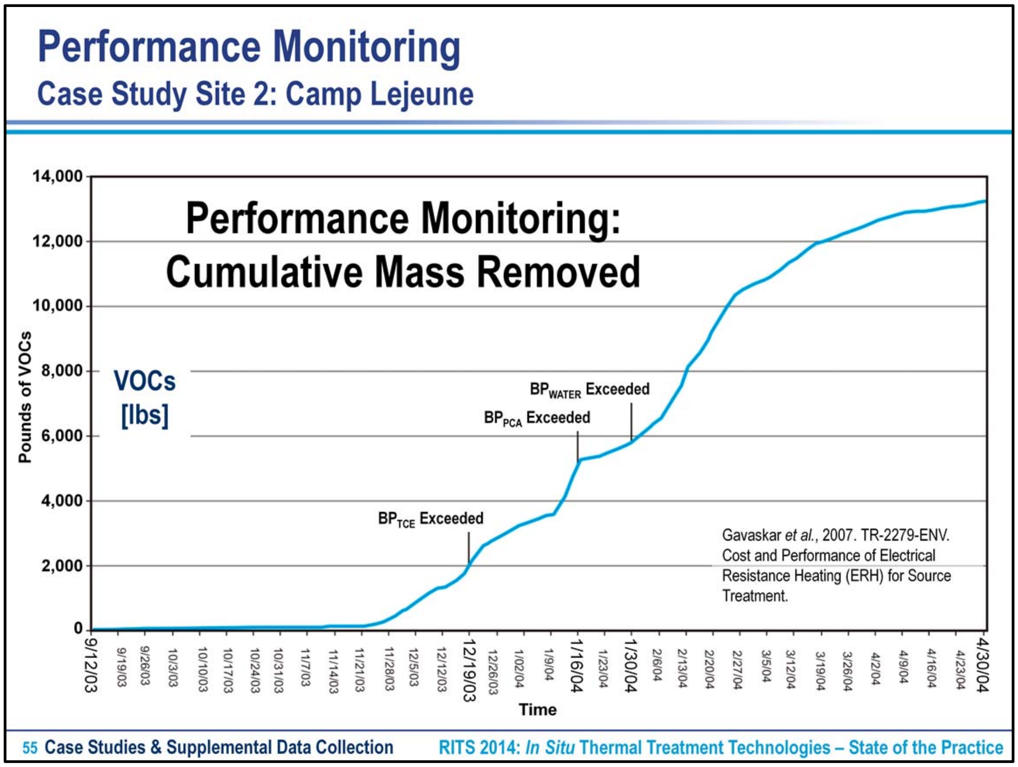
Operating Conditions

Case Study Site 2: Camp Lejeune

- **Initial formation temperature: 20°C**
- **Maximum representative temperature: 100°C**
- **Time to maximum representative temperature: 156 days**
- **Duration at maximum representative temperature: 86 days**



54 **Case Studies & Supplemental Data Collection** RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice



This is another typical type of way to show mass removal. This is cumulative mass removal of VOCs versus time. As the boiling point of chemicals is reached, we see increases in the mass removed over time. This curve then starts to level out over time known as asymptotic conditions meaning that the mass we are removing is not changing with time.

Note: This curve does not show true asymptotic conditions.

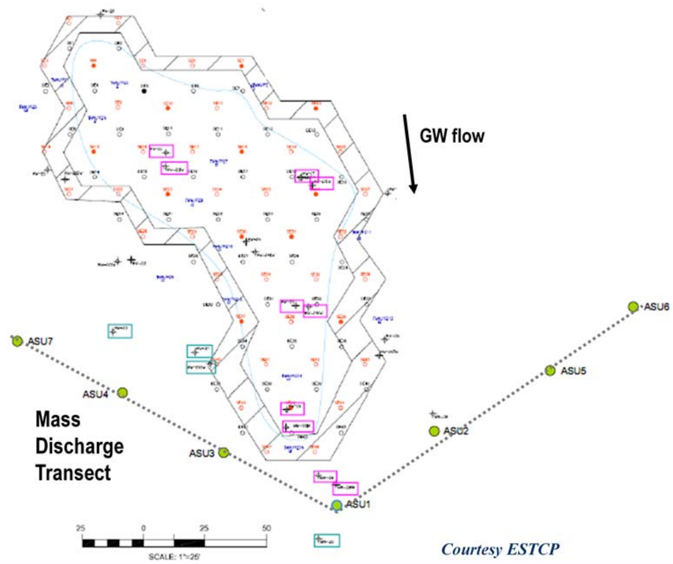
Project Costs
Case Study Site 2: Camp Lejeune

Vendor Costs	
System Installation	\$672,550
System O&M (225 days)	\$907,400
Power Cost	\$142,691[(a)]
Vendor's Total Cost	**\$1,722,641**
Site Incurred Costs	
Monitoring/Analysis	\$324,410
Site Preparation and Costs	\$31,275
Total Site Incurred Cost	**\$355,685**
Administration/Plans/Reports	\$169,580
Total Cost	**\$2,247,906**

Gavaskar *et al.*, 2007. TR-2279-ENV. Cost and Performance of Electrical Resistance Heating (ERH) for Source Treatment.

~\$182/yd3

Site Layout and Sampling Locations
Case Study Site 2: Camp Lejeune



Courtesy ESTCP

Supplemental Data Collection

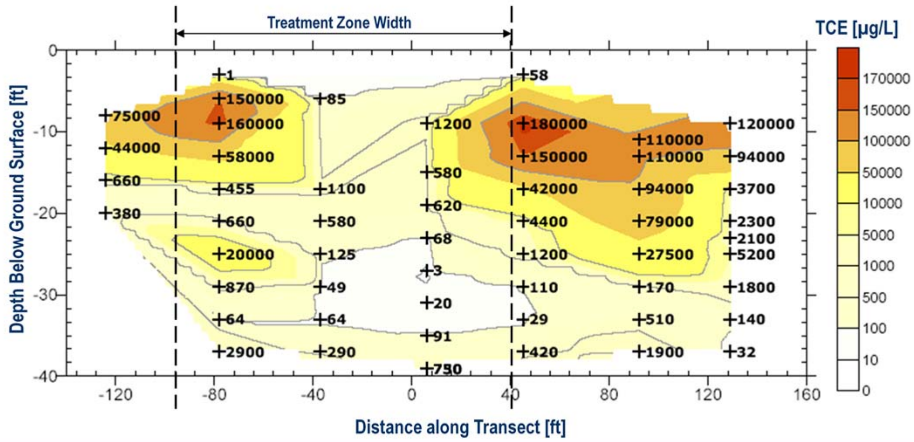
Case Study Site 2: Camp Lejeune

- 60+ hydraulic conductivity tests performed in 7 locations
- 1 continuous soil core collected at transect location
- 26 groundwater samples collected from 26 wells
- 78 depth-specific groundwater samples collected from 7 direct-push locations; aquifer characterization mini-pump tests performed at each depth
- pH, EC, Temp., DO, ORP, TCA, PCE, TCE, DCA, DCE isomers, VC

Concentration Transect

Case Study Site 2: Camp Lejeune

TCE concentrations from samples collected along the transect perpendicular to groundwater flow on the down-gradient edge of the source zone

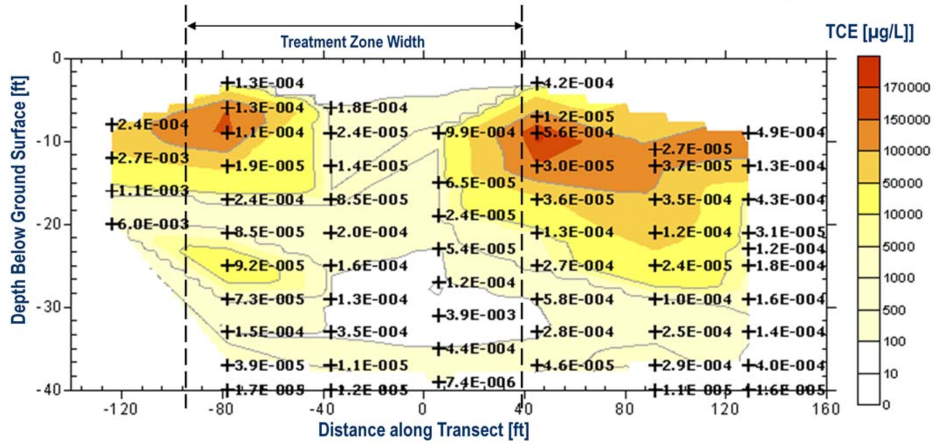


59 Case Studies & Supplemental Data Collection RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

Mass Discharge

Case Study Site 2: Camp Lejeune

Estimated to be about 82 kg/y using the ESTCP-sponsored Mass Flux Toolkit Software from GSI (initially 680 kg/y)

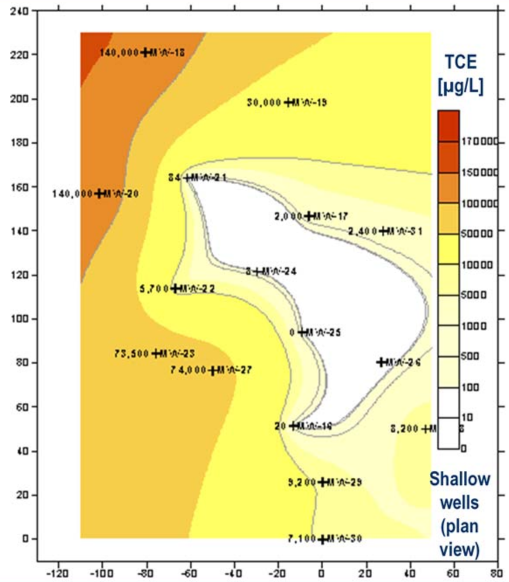


Values displayed are hydraulic conductivities [cm/s] superimposed on the concentration contour plot

Results

Case Study Site 2: Camp Lejeune

- **Treatment effectiveness at this site compromised by DNAPL residuals outside of the treatment zone that were not fully-delineated prior to the electrical resistance heating design and application**



61 Case Studies & Supplemental Data Collection   RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

This Case Study Illustrates…..

Case Study Site 2: Camp Lejeune

- That it is important to confidently delineate the areal extent of the source zone prior to treatment
- That downgradient sampling transects are a good tool for determining the width of the source zone
- That about 5 months was required to achieve desired temperatures above the contaminant boiling points
- State-of-the-practice electrode spacing
- Upward and downward heat losses
- Typical mass removal vs. time and temperature behavior

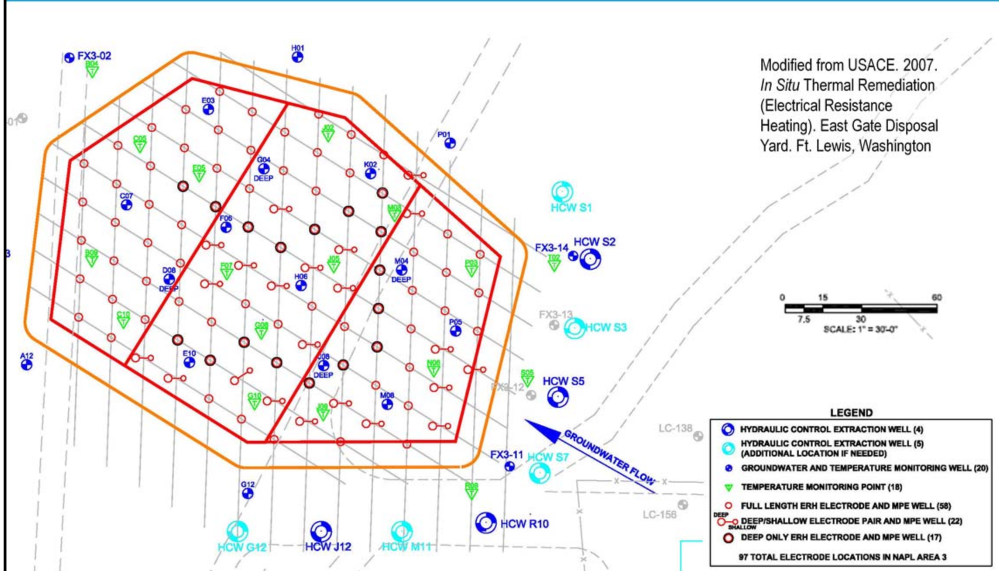
Case Study Site 3: Fort Lewis EGDY Area 3

- Electrical Resistance: 10/10/06 – 1/26/07
- DNAPL source (chlorinated solvents)
- Top of treatment: 0 ft bgs
- Depth to water: 9 ft
- Largely permeable sediments with low permeability lenses
- Target Interval: 30 ft thick
- 93 electrodes
- About 18,200 ft^2

63 Case Studies & Supplemental Data Collection RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

Site Layout

Case Study Site 3: Fort Lewis EGDY Area 3

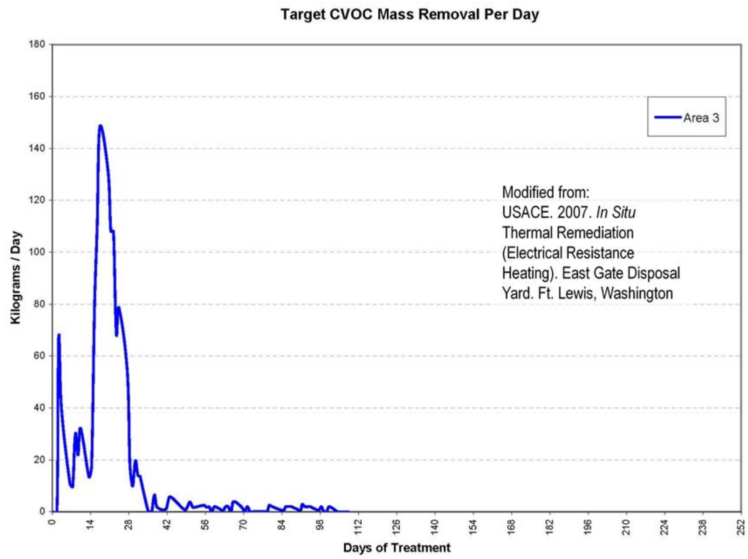


64 **Case Studies & Supplemental Data Collection** **RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice**

Operating Conditions

Case Study Site 3: Fort Lewis EGDY Area 3

- **Initial formation temperature: 13°C**
- **Maximum representative temperature: 89°F**
- **Time to reach max. representative temp: 38 days**
- **Duration at max. representative temp: 13 days**



Completion Data

Case Study Site 3: Fort Lewis EGDY Area 3

Comparison of East Gate Disposal Yard NAPL Area Completion Data

Data Point	NAPL Area 1	NAPL Area 2	NAPL Area 3
Duration of ERH Operations	231 days	172 days	107 days
TCE Mass Removed	2,576 kilograms	1,089 kilograms	847 kilograms
cis-1,2 DCE Mass Removed	405 kilograms	245 kilograms	285 kilograms
TPH Mass Removed	40,171 kilograms	11,337 kilograms	529 kilograms
Groundwater Volume Removed	2.42×10^7 gal	3.39×10^7 gal	2.59×10^7 gal
Groundwater Removal Rate	104,863 gal per day (73 gpm)	200,437 gal per day (139 gpm)	243,161 gal per day (169 gpm)
ERH Energy Applied	7,898 megawatt-hours	9,181 megawatt-hours	5,856 megawatt-hours

USACE. 2007. *In Situ* Thermal Remediation (Electrical Resistance Heating). East Gate Disposal Yard. Ft. Lewis, Washington

Project Costs

Case Study Site 3: Fort Lewis EGDY Area 3

Summary of Actual Costs for Areas 1, 2, and 3

Project Costs	Area 1	Area 2	Area 3	Total
Equipment	$936,817	$558,759	$334,327	$1,829,903
Labor	$781,501	$795,099	$206,239	$1,782,839
Operating costs w/o electricity	$3,248,176	$1,975,414	$2,152,648	$7,376,238
Total	$4,966,494	$3,329,272	$2,693,214	$10,988,980
Total Electricity Used				
Electricity (KWH)	7,998	9,181	5,856	23,035
Electric cost	$359,910	$397,445	$245,308	$1,002,663
Unit Costs				
Cost per cubic yard				
Treatment Process	$160	$91	$129	
Electricity	$12	$11	$12	
Total	$172	$102	$141	
Total cost per pound of mass (VOC) removed	$123	$294	$1,781	

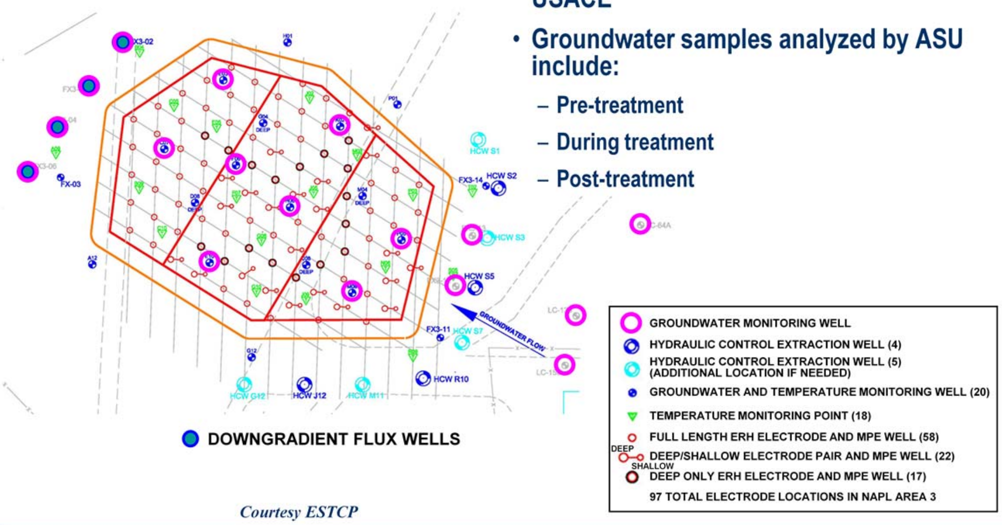
USACE. 2007. *In Situ* Thermal Remediation (Electrical Resistance Heating). East Gate Disposal Yard. Ft. Lewis, Washington

67 **Case Studies & Supplemental Data Collection** RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

Site Layout, Sampling Locations, and Data Collection

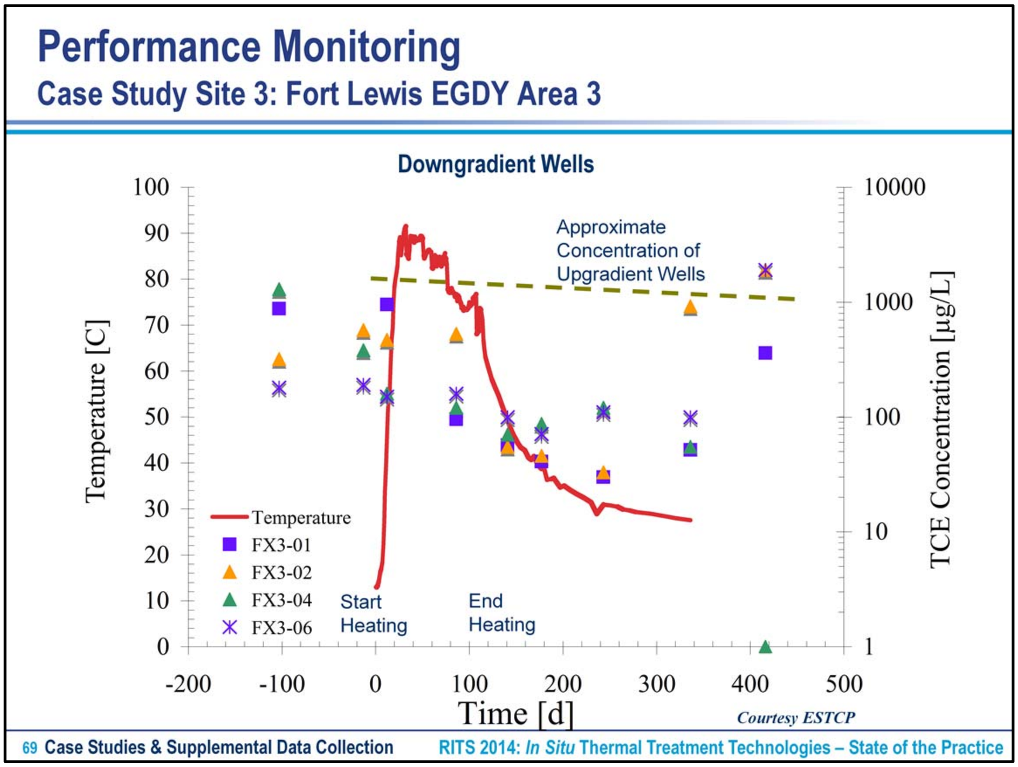
Case Study Site 3: Fort Lewis EGDY Area 3

- Groundwater samples collected by USACE
- Groundwater samples analyzed by ASU include:
  - Pre-treatment
  - During treatment
  - Post-treatment



Courtesy ESTCP

68 Case Studies & Supplemental Data Collection — RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice


Performance Monitoring
Case Study Site 3: Fort Lewis EGDY Area 3
Downgradient Wells
Temperature [C]
TCE Concentration [µg/L]
Time [d]
Approximate Concentration of Upgradient Wells
Temperature
FX3-01
FX3-02
FX3-04
FX3-06
Start Heating
End Heating
Courtesy ESTCP
69 Case Studies & Supplemental Data Collection
RITS 2014: In Situ Thermal Treatment Technologies – State of the Practice

Mass Discharge

Case Study Site 3: Fort Lewis EGDY Area 3

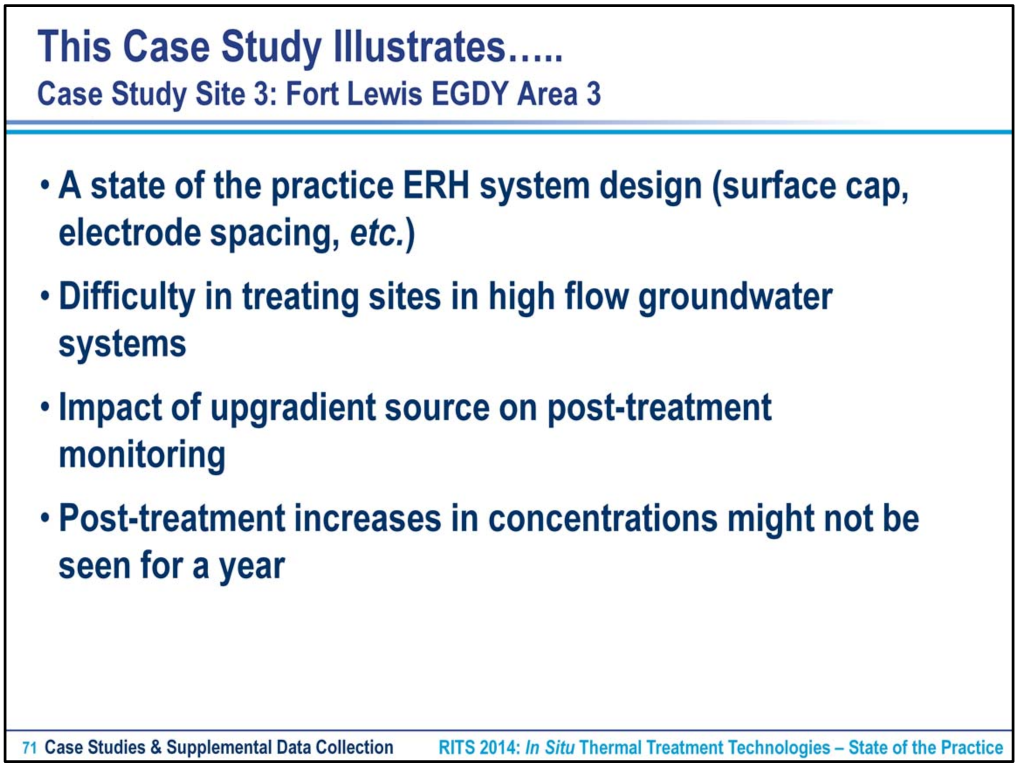
Site	Contaminant	Pre-treatment Discharge (kg/y)[1]	Post-treatment Mass Discharge (kg/y)[2]	Post-treatment Mass Discharge per Linear Foot (kg/y/ft)
Ft. Lewis EGDY Area 3*	Total Contaminant Flux	3.2×10^{1}	2.1	1.9×10^{-2}

Notes:
1 Mass discharge calculations were based on monitoring well data from the documentation.
2 Mass discharge calculations were based on discrete-depth sampling data, or a combination of discrete-depth sampling data and monitoring well data.
*Mass discharge calculations were based on monitoring well data analyzed by ASU personnel.

- **Electrical resistance treatment resulted in a reduction in contaminant concentrations by about 10X during treatment, but then they returned to pre-treatment concentrations during the cool-down period**
- **This could be due to an upgradient source**

70 Case Studies & Supplemental Data Collection RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

At Ft. Lewis, the return of concentration to pre-treatment concentrations has been shown with pretty high certainty by others that source zones upgradient to Area 3 were impacting the post-treatment groundwater quality results. Subsequent to thermal remediation, these zones were treated by bioremediation and reductions in Area 3 groundwater concentrations have been seen.



Note that at other site, it might not be considered concentration increases, but rather rebound. This definition depends on the site and the circumstances surrounding the concentration increases.

Case Study Site 4:

Air Force Plant 4 Bldg 181 (inside operating building)

- ERH Treatment:
  5/02-12/02; about half as "targeted treatment"
- 73 electrodes
- Approximately 22,000 ft^2 (125 x 150 ft)
- Target interval thickness: 40 ft
- Depth to top of treatment zone: 0 ft
- Largely impermeable sediments with high permeability lenses
- Depth to water: approximately 30 ft
- About $2.5M project

72 Case Studies & Supplemental Data Collection RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

Supplemental Data Collection

Case Study Site 4: Air Force Plant 4 Bldg 181 (inside operating building)

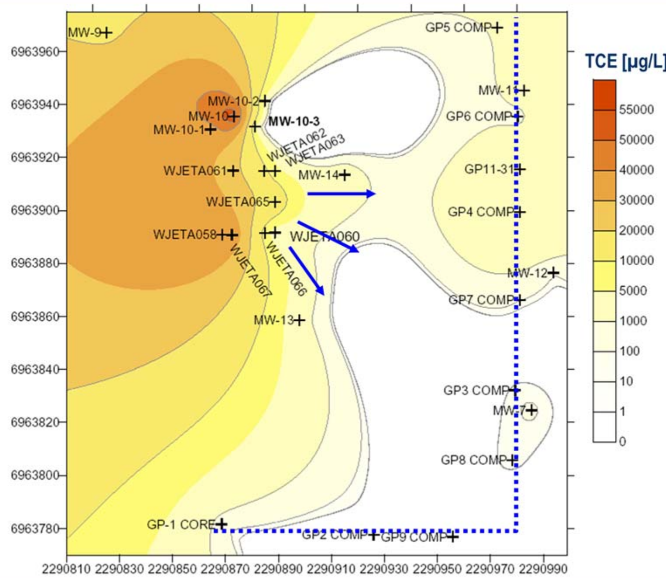
- 9 hydraulic conductivity tests using a Geoprobe pneumatic slug test kit
- 3 continuous soil core collected at transect location
- 18 groundwater samples collected from 18 wells at 18 locations
- 13 depth-specific groundwater samples collected from 5 direct-push locations
- 10 composite samples collected from 10 direct-push locations
- pH, EC, Temp., DO, ORP, TCA, PCE, TCE, DCA, DCE isomers, VC

73 Case Studies & Supplemental Data Collection RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

Supplemental Data Collection (cont.)

Case Study Site 4: Air Force Plant 4 Bldg 181 (inside operating building)

- **ERH treatment resulted in a reduction in dissolved concentrations throughout the 32 ft treatment zone, with the exception of the very low permeability area near MW-10**
- **Pre-treatment concentrations ranged from 10,000 – 100,000 µg/L**

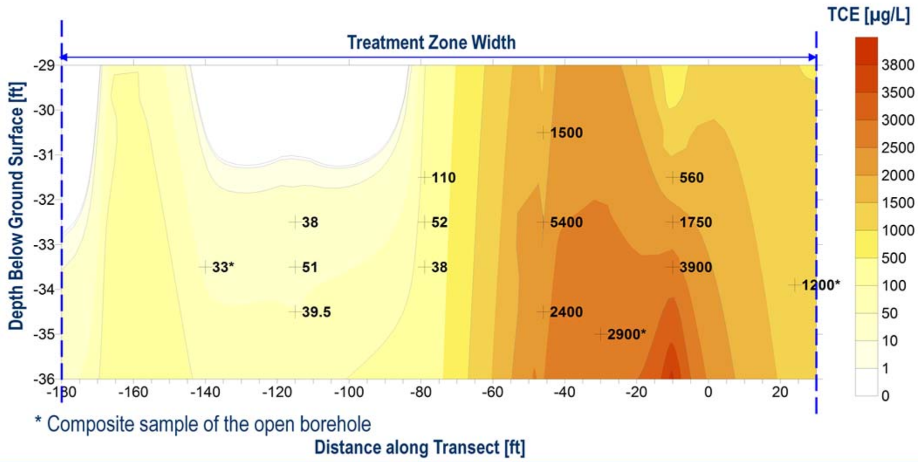


74 Case Studies & Supplemental Data Collection RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

Concentration Transect

Case Study Site 4: Air Force Plant 4 Bldg 181 (inside operating building)

- **TCE concentrations measured along the transect perpendicular to groundwater flow on the down-gradient edge of the source zone**
- **Mass discharge estimated to be reduced from about 60 kg/y to about 5 to 21 kg/y**



This Case Study Illustrates…..

Case Study Site 4: Air Force Plant 4 Bldg 181 (inside operating building)

- How *in situ* thermal treatment can be conducted in an operating building
  - Electrodes installed through slab
  - Angled boring used
- How operators tracked the temperature distribution and optimized the energy delivery to focus on the tight soils where known mass resided
- How treatment can be spatially variable

Presentation Overview

- Introduction
- Evolution of Thermal Technologies
- Current Thermal Treatment Technologies
- Lessons-Learned
  - Empirical Assessment of Documented Applications
- Case Studies & Supplemental Data Collection
- Reasonable Performance Expectations for Future Projects
- Key Messages and Wrap Up

All Sites: Mass Discharge Reduction Summary Table

Part 1 of 2

Site No.	Heating Technology	Generalized Scenario/Site	Dissolved GW Conc Reduction	Mass Discharge Reduction				
				<10x	10x	100x	1000x	>1000x
1	Electrical Resistance	Relatively homogeneous and permeable unconsolidated sediments (SDC)	10x			x		
2	Electrical Resistance	Largely impermeable sediments with inter-bedded layers of higher permeability material + (SDC)	<10x	x	x			
3	Electrical Resistance	Largely permeable sediments with inter-bedded lenses of low permeability material	10x		x			
4	Electrical Resistance	Largely permeable sediments with inter-bedded lenses of low permeability material * (SDC)	>10x to <100x		x			
5	Electrical Resistance	Largely permeable sediments with inter-bedded lenses of low permeability material ^	<10x	x				
6	Electrical Resistance	Largely permeable sediments with inter-bedded lenses of low permeability material ^	<10x	x		x		
7	Electrical Resistance	Largely permeable sediments with inter-bedded lenses of low permeability material	<10x				x	

* Pilot application appeared to encompass the entire source zone based on documentation reviewed.
+ Mass discharge assessment involved two calculations using first only the post-treatment field investigation data and then the post-treatment field investigation data supplemented with data from a set of monitoring wells that were directly in line with the field investigation transect.
^ Site used two different vertical intervals to calculate mass discharge: 1) Only shallow geology and 2) shallow and deep geology.
SDC – supplemental data collection site for this project

78 **Reasonable Performance Expectations** RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

These are the mass discharges calculated using the Mass Flux Toolkit Software from GSI. The data was taken from published reports or from data collected by ASU.

All Sites: Mass Discharge Reduction Summary Table

Part 2 of 2

Site No.	Heating Technology	Generalized Scenario/Site	Dissolved GW Conc Reduction	Mass Discharge Reduction				
				<10x	10x	100x	1000x	>1000x
8	Electrical Resistance	Largely permeable sediments with inter-bedded lenses of low permeability material (SDC)	10x		x			
9	Electrical Resistance	Largely permeable sediments with inter-bedded lenses of low permeability material (SDC)	100x			x		
10	Electrical Resistance	Largely permeable sediments with inter-bedded lenses of low permeability material	1000x		x			
11	Steam	Largely permeable sediments with inter-bedded lenses of low permeability material	100x			x		
12	Steam	Largely permeable sediments with inter-bedded lenses of low permeability material	10x	x				
13	Steam	Largely permeable sediments with inter-bedded lenses of low permeability material ^	10000x				x	x
14	Steam	Competent, but fractured bedrock *	<10x	x				

* Pilot application appeared to encompass the entire source zone based on documentation reviewed.
^ Site used two different vertical intervals to calculate mass discharge: 1) Only shallow geology and 2) shallow and deep geology.
SDC – supplemental data collection site for this project

79 Reasonable Performance Expectations   RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

These are the mass discharges calculated using the Mass Flux Toolkit Software from GSI. The data was taken from published reports or from data collected by ASU.

Presentation Overview

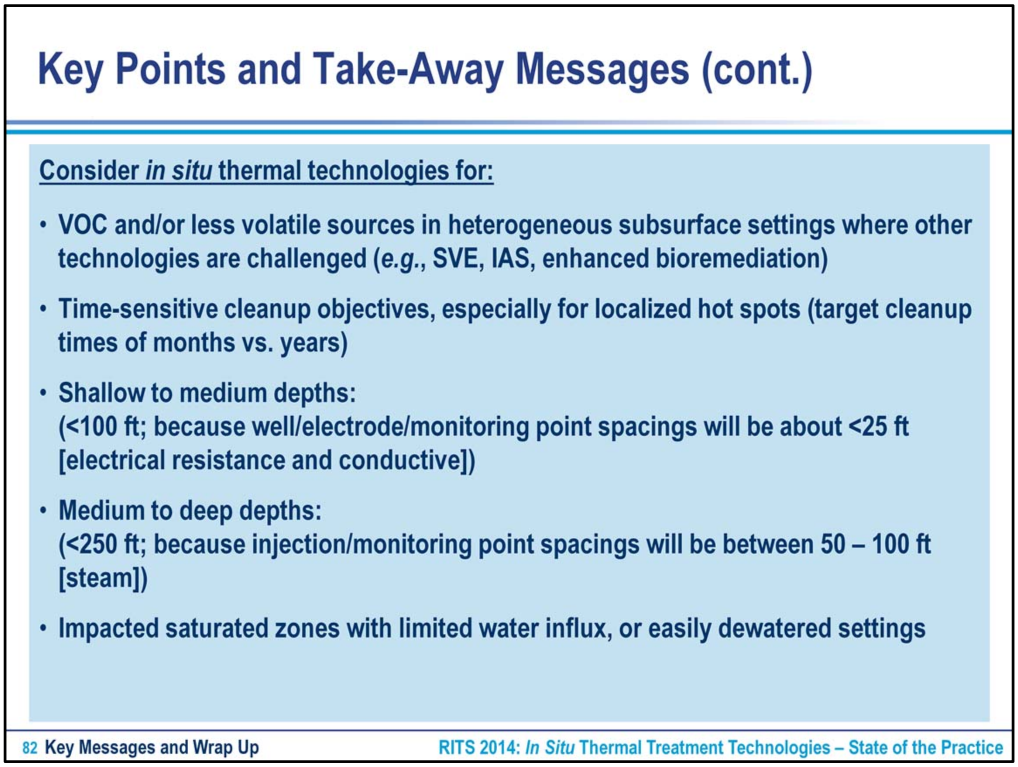
- Introduction
- Evolution of Thermal Technologies
- Current Thermal Treatment Technologies
- Lessons-Learned
  - Empirical Assessment of Documented Applications
- Case Studies & Supplemental Data Collection
- Reasonable Performance Expectations for Future Projects
- Key Messages and Wrap Up

Key Points and Take-Away Messages

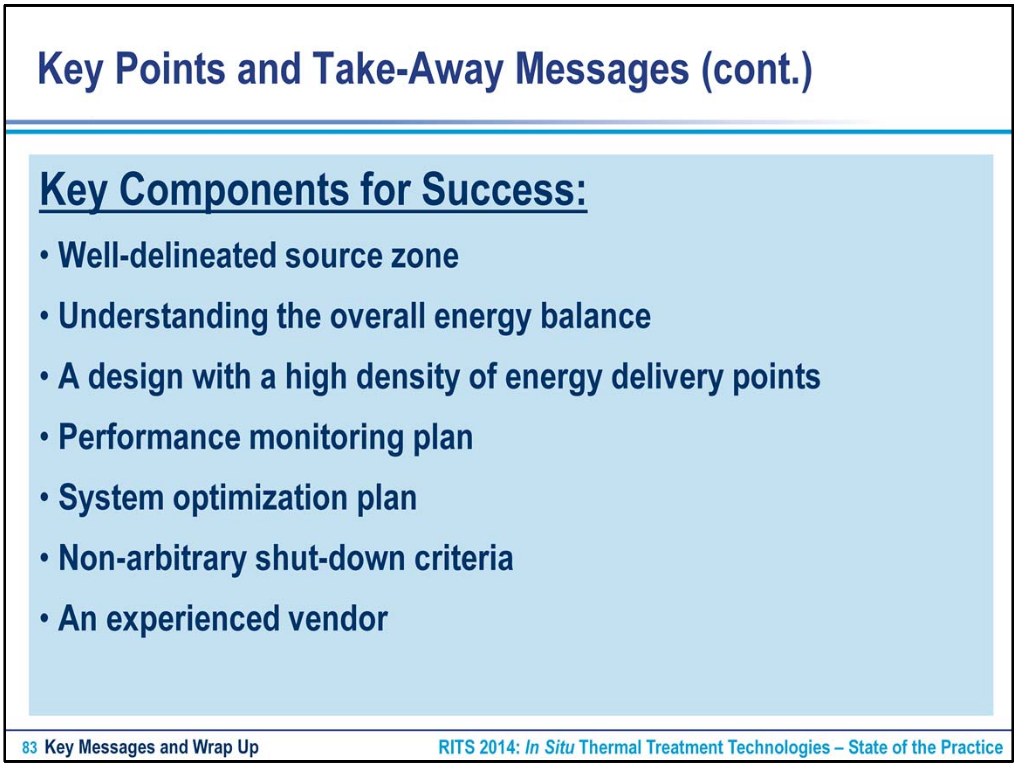
- *In situ* thermal technologies are available commercially and internationally
- Few specialty vendors, but their experience and knowledge base has grown significantly
- Recent applications emphasize electrical resistance and conductive, and combinations of these two with steam
- Well-designed and operated systems in unconsolidated settings can accomplish >90% reduction in concentrations and mass discharge to groundwater
- Optimized systems might be able to achieve >99% reductions
- Best achievable performance in fractured settings is still being evaluated

81 Key Messages and Wrap Up — RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

When steam injection is coupled with conductive or electrical resistance, this is usually for sites with substantial water flow in specific zones as a method to minimize pumping or at sites were they have a layered stratigraphy and would like to quickly heat specific layers.



The shallow to medium depths are for sites that may implement conductive or electrical resistance heating. Steam injection can be implemented at deeper depths and with larger spacings.



RPMs should understand or have a consultant that understands and values these key components prior to implementing thermal. Thermal remediation is a dynamic remediation where the RPM and the vendor must be ready to implement optimization strategies throughout the project to get the most out of the technology.

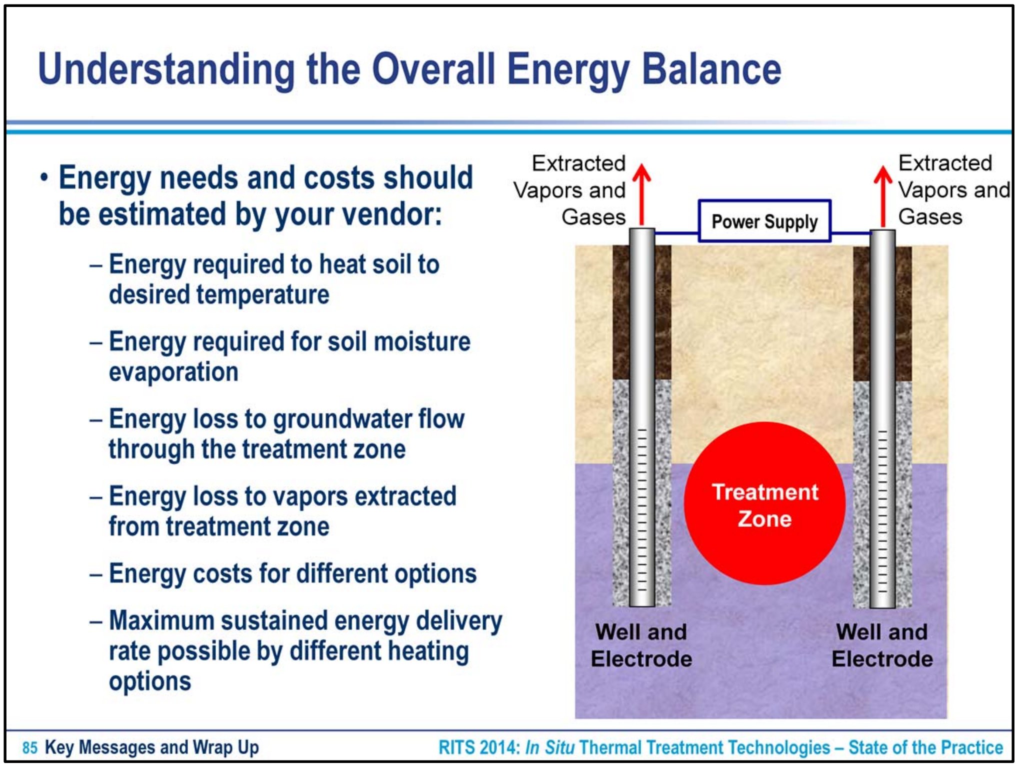
Well-Delineated Source Zone

Verify rough geometry of the source zone prior to feasibility assessment and design (length, width, depth)

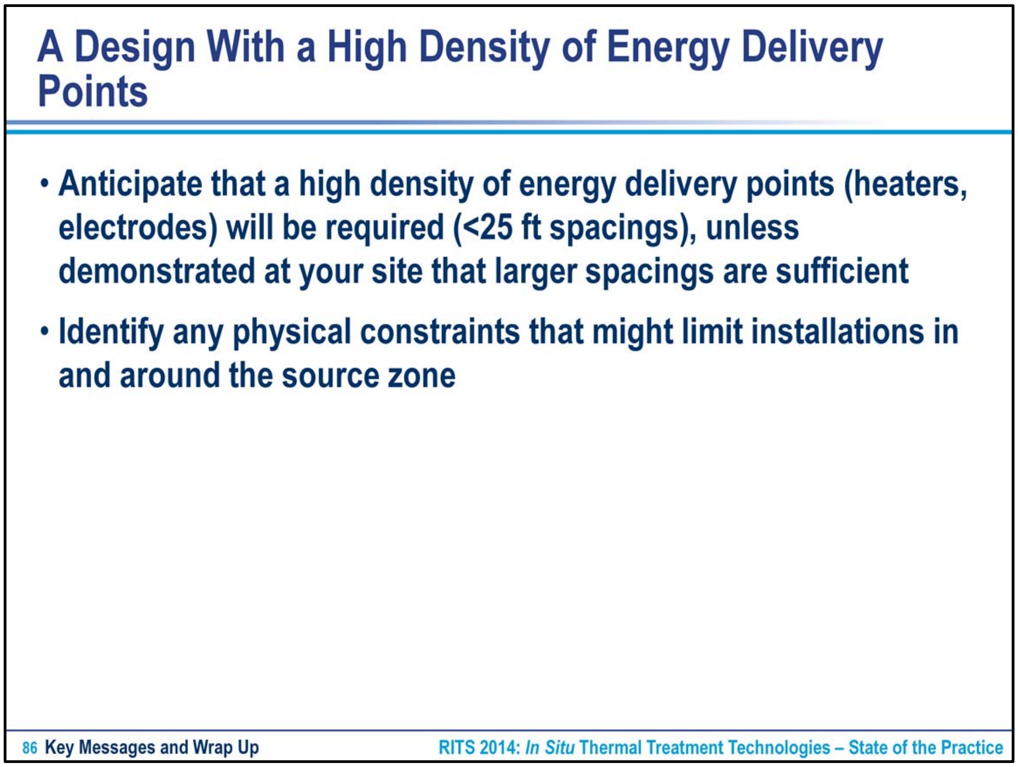
- Groundwater transect approach is one strategy to determine and/or verify this prior to design
- Can also use this information to validate and refine the site conceptual model
- Treatment system footprint should be at least as large as source zone footprint and energy needs to be delivered at least as deep as source depth

84 Key Messages and Wrap Up RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

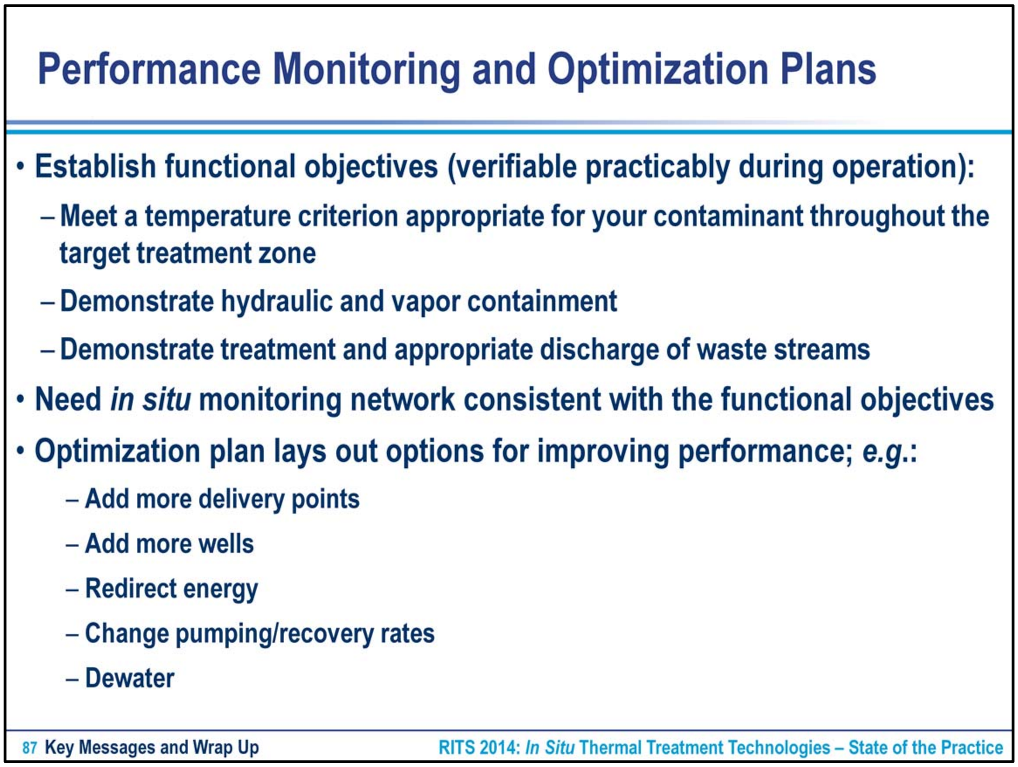
A delineated source zone is the main key to the success of a thermal project. If a thermal project is completed then it is determined that a large portion of the source or an upgradient source is present, then entire treatment zone could be re-contaminated and the thermal work completed could be negated.



Every thermal vendor should be able to supply a theoretical energy balance prior to thermal treatment as the basis of cost. In this model, they need to under site total organic carbon and maximum concentrations, but they do not need to understand where the mass is located.



Note that steam injection spacing will be much larger on the order of 50 to 100 feet.

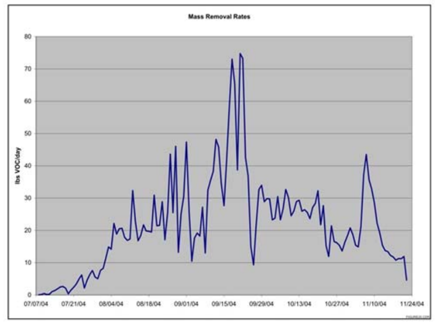


Prior to treatment, the RPM should verify the temperature criterion that must be meet to remove the chemicals of concern at the site. The achievement of this temperature criterion then the hydraulic and vapor containment is necessary prior to being able to optimize the system. Optimization may include the items described above or items that include green and sustainable remediation measures.

Non-Arbitrary Shutdown Criteria

- **Avoid the use of arbitrary shutdown criteria based only on achieving some average target temperature for a pre-specified number of days.**
- **Note that operating costs are often insignificant compared to sunk one-time costs (design, equipment, mobilization, and demobilization) – get the most out of your system.**
- **RPMs should evaluate operating costs versus mass removal rate, costs of managing stakeholder issues, and potential costs of long-term management and associated risks**

Performance Monitoring: Mass Removal Rate



88 Key Messages and Wrap Up RITS 2014: *In Situ* Thermal Treatment Technologies – State of the Practice

Shutdown criteria selection is critical to success of a thermal project. Criteria that are not achievable should not be selected nor should criteria that are two low and will not provide benefit to the overall treatment plan.

Evaluating Vendor Quotes

- **Check for:**
  - **High density spacing of energy delivery points**
  - **Energy balance – good vendor should readily supply this**
  - **Operational strategy for:**
    - Liquid extraction, treatment, and disposal*
    - Vapor extraction, treatment, and disposal
  - **Performance monitoring and optimization plans**
  - **Shutdown criteria**

*** Check the assumptions for total organic carbon (TOC) and groundwater pumping as these may affect your above ground treatment costs.**