



## ***In Situ* Thermal Treatment Technologies – State of the Practice**

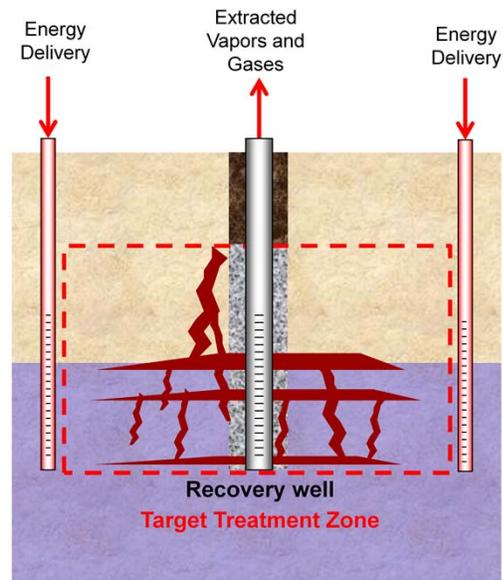
The background material and case studies presented here are based on research which was funded by ESTCP and completed in 2007.

## 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

## What is *In Situ* Thermal Remediation?

- Soil heating combined with vapor and/or liquid extraction
- The soil heating increases vapor concentrations and decreases viscosity
- Soil vapor extraction and liquid pumping are used to remove chemicals from subsurface
- Soil heating can be accomplished by steam delivery, conduction, and/or passing electrical current through the soil

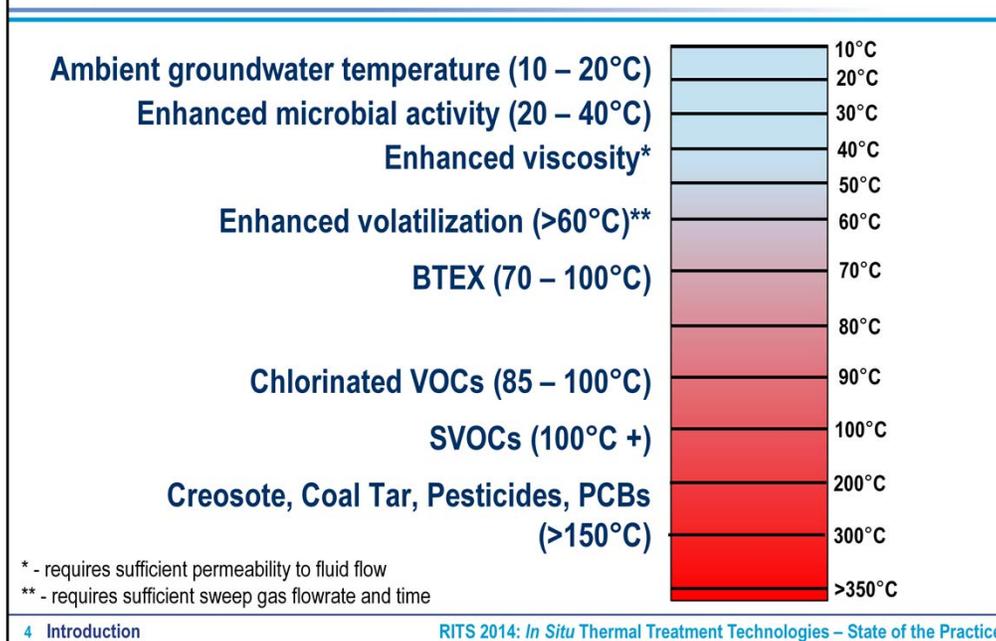


3 Introduction

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

*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.

## Remediation Enhancements with Temperature



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

## 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

**A Citizen's Guide to In Situ Thermal Treatment** 

**What is In Situ Thermal Treatment?**

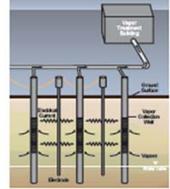
In situ thermal treatment methods move or "mobilize" harmful chemicals in soil and groundwater using heat. The chemicals move through soil and groundwater toward wells where they are collected and placed to the ground surface to be treated using other cleanup methods. Some chemicals are destroyed underground during the heating process. Thermal treatment is described as "in situ" because the heat is applied underground directly to the contaminated area. It can be particularly useful for chemicals called "non-aqueous phase liquids" or "NAPLs," which do not dissolve readily in groundwater and can be a source of groundwater contamination for a long time if not treated. Examples of NAPLs include solvents, petroleum, and creosote (a wood preservative).

**How Does It Work?**

In situ thermal treatment methods heat contaminated soil, and sometimes nearby groundwater, to very high temperatures. The heat vaporizes (evaporates) the chemicals and water changing them into gases. These gases, also referred to as "vapors," can move more easily through soil. The heating process can make it easier to remove NAPLs from both soil and groundwater. High temperatures also can destroy some chemicals in the area being heated.

In situ thermal methods generate heat in different ways:

- **Electrical resistance heating (ERH)** delivers an electrical current between metal rods called "electrodes" installed underground. The heat generated as movement of the current meets resistance from soil converts groundwater and water in soil into steam, vaporizing contaminants.
- **Steam enhanced extraction (SEE)** injects steam underground by pumping it through wells orled in the contaminated area. The steam heats the area and mobilizes and evaporates contaminants.
- **Thermal conduction heating (TCH)** uses heaters placed in underground steel pipes. TCH can heat the contaminated area not enough to destroy some chemicals.



The chemical and water vapors are pulled to collection wells and brought to the ground surface by applying a vacuum. (See A Citizen's Guide to Soil Vapor Extraction and Air Sparging (EPA 542-D-018) for information on how this is done.) The vapors are then treated above ground using one of several cleanup methods available. If concentrations are high, the vapors can be condensed back to liquid chemicals and reused.

**How Long Will It Take?**

In situ thermal treatment might take a few months to a few years to clean up a site. The actual cleanup time will depend on several factors. For example, it might take longer where:

- Contaminant concentrations are high.
- The contaminated area is large or deep.
- A variety of soil types are present, causing the ground to heat unevenly.
- The soil has a lot of organic matter, which causes chemicals to stick to the soil and not evaporate easily.

These factors vary from site to site.

EPA 542-F-12-013, September 2012

*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

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## 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.

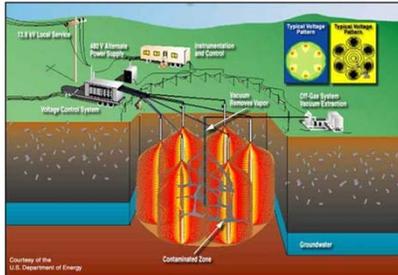
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## Most Common *In Situ* Thermal Treatment Technologies

### Electrical Resistance Heating



Courtesy U.S. Department of Energy

### Steam Injection

Steam + ERH

Steam + Hot Air

Steam + Auger Mixing

### Conductive Heating

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.

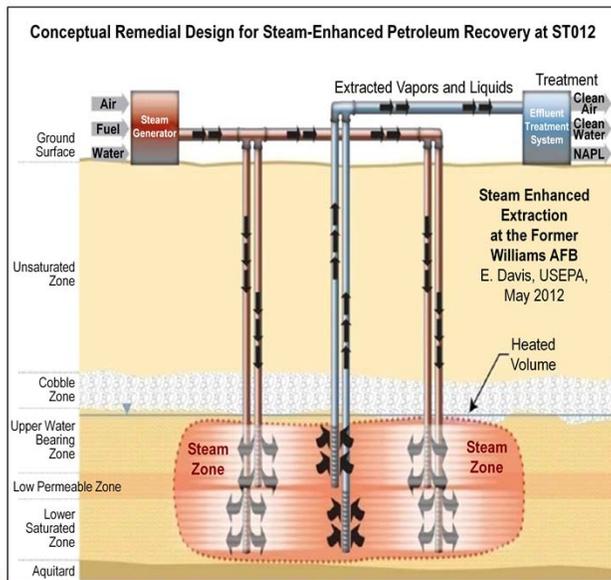
Conductive Heating (TCH and ISTD) – A thermal technology that heats the subsurface via heating rods inserted into the subsurface. This technology is capable of raising the temperature of the subsurface to temperatures greater than 300 degrees Celsius.

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.

## Steam Injection

- Many early thermal applications were steam injection systems
- Standard process involves:
  - Inject steam, create steam zone
  - Extract liquids and vapors
  - After steam breakthrough at extraction wells, cycle steam on/off
  - Continue steam delivery as needed

Courtesy EPA



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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 Injection – Design and Operation Challenges

- Well-field designed around steam front propagation – difficult to anticipate
- Mass preferentially removed from more transmissive zones
- Need to manage and recover liquid/condensate and vapors
- Temperature limited to about 100°C

### Key Point

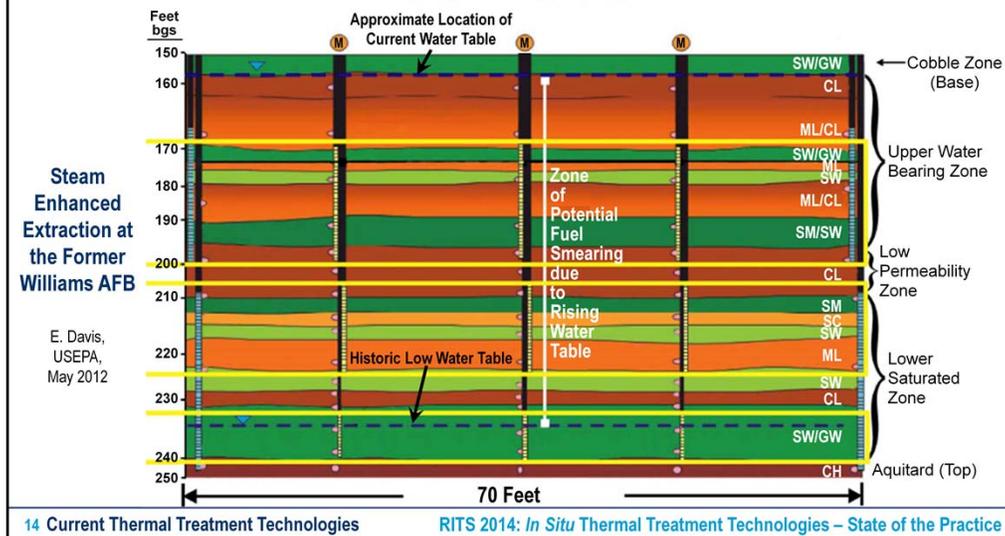
Need to deal with water/steam supply, delivery pipes under pressure, and recovered liquids and vapors.

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 – Settings

- Practicability increases in confined layered settings where steam is controlled to move laterally by stratigraphy



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.

## Current Status of Steam Injection

- **The technology is being implemented as**
  - **Steam enhanced extraction**
  - **Steam injection coupled with conductive or electrical resistance heating**
    - Used for initial heating and compensating for heat loss via groundwater flow
- **Recent examples:**
  - **Former Williams Air Force Base (Steam + Air); Groveland Wells Superfund Site (Steam + electrical resistance); Arnold Air Force Base (Steam enhanced extraction + conductive)**

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  $\gg 100^{\circ}\text{C}$**

- Needed for PCB's, PAH's, dioxins, etc.

Lower Temp ← Hot → Lower Temp

Heat Conduction Away from a Heater

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 soil 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

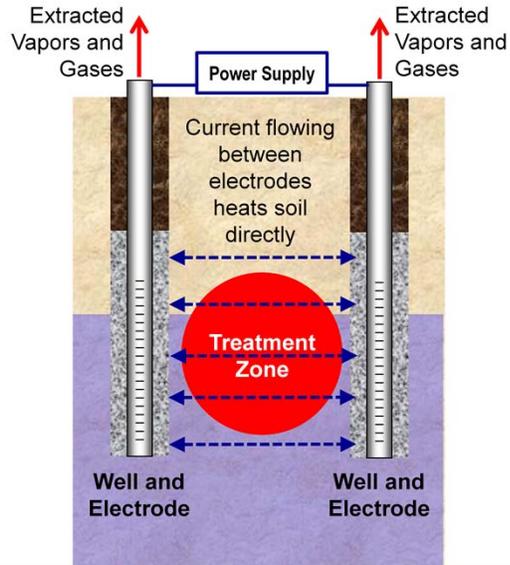
## Current Status of Conductive Heating

- Available internationally
- The technology is being implemented as
  - Conductive alone
  - Conductive + Steam
- Example Application and Study Sites
  - Dunn Field, Defense Depot, Memphis, TN
  - Former Naval Air Warfare Center (NAWC), West Trenton, NJ (ESTCP, fractured rock setting)
  - U.K. Atomic Energy Authority, Harwell, U.K.

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

## Electrical Resistance Heating

- **Electrical resistance heating heats soil by passing electric current through soil between electrodes**
- **Limited to temperatures of about 100°C and heating stops if soil dries out**
- **Can be coupled with steam**



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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.

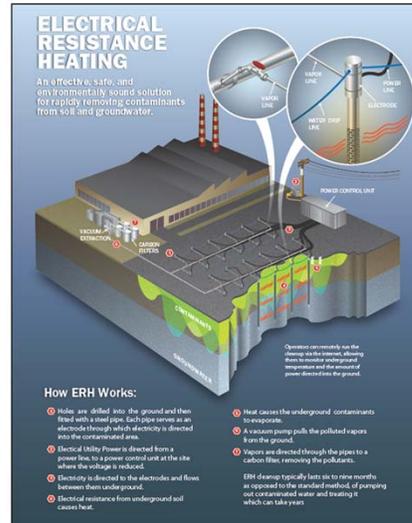
## Electrical Resistance Heating (cont.)

- **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).

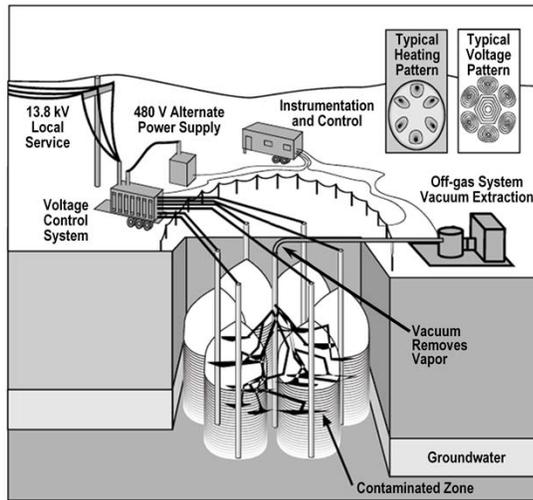
## Common Features of Thermal Technologies

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

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.

## Common Features of Thermal Technologies (cont.)

- **Energy generation**  
(electrical power, natural gas, steam boiler)
- **Recovery systems**  
(vapor and liquid separation, treatment, and discharge)
- **Process monitoring and control**



- Vapor stream cooling and condensing
- Vapor treatment  
(carbon bed, thermal oxidizer)
- NAPL/water separation
- Water treatment  
(air stripper, carbon bed)
- Water discharge

USEPA. 2004. *In Situ Treatment of Chlorinated Solvents, Fundamentals and Field Applications*. EPA 542-R-04-010

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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.

## Common Challenges of Thermal Technologies

- Energy losses, especially to groundwater flow, may have to be compensated for
- Potential for mobilizing and redistributing contaminants to clean zones
- Recovery from tight soils

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.

## Key Differences Between Thermal Technologies

- Temperatures that can be achieved are about 100°C for all options except combinations with conductive
- Energy delivery to lower permeability regions (direct with electrical resistance and conductive; indirect with steam)
- With steam delivery, there are process lines under pressure
- Time scales for heating can be different, depending on operating conditions (days to months)

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**

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.

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## Empirical Analysis of Documented Applications – ESTCP ER-0314



- **Develop a tool that can be used by practitioners, regulators, and site owners to anticipate the likely performance of thermal-based DNAPL treatment technologies at their sites – more specifically:**

- How the technology has been applied in that type of setting,
- The designs employed,
- The operating conditions,
- The performance monitoring that results are based on,
- The performance observed,
- Indicators of success at other sites, and
- Reasonable bounds on expected performance

**In this project, the performance metrics focus on improvement to groundwater quality and reduction in mass discharge (flux)**

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

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.

# Empirical Analysis of Documented Applications – ESTCP ER-0314 – Final Product Concept

Physical Scenarios
Technology Application Summary
Experience/Performance Summary

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

Concept Table

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

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.

## Thermal Technology Database: Number of Applications (1988 – 2007)

| 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            |
| <b>Total</b>                  | <b>182</b>                           | <b>75</b>   | <b>98</b>  | <b>84</b>    |

\* Some sites have unknown application sizes and thus are not included in the Pilot- and Full-scale counts

29 Lessons Learned from Documented Applications [RITS 2014: In Situ Thermal Treatment Technologies – State of the Practice](#)

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.

## Review of Available Data: Level of Documentation (1988 – 2007)

| Level of Data Quantity | Description  | Number of Sites |
|------------------------|--|-----------------|
| -                      | Application in progress  | 1               |
| 0                      | No documentation available at the time of this study   | 26              |
| 1                      | Insufficient data to assess performance of technology, but some design information   | 78              |
| 2                      | Limited performance data; some soils and/or groundwater concentration data and some operating data (e.g., temperature information) | 37              |
| 3                      | Good performance data record, but insufficient for estimating differences between pre- and post mass discharge from source zone    | 26              |
| 4                      | Data sufficient for full assessment of performance (groundwater concentrations and mass discharge)                                 | 14              |
| Total                  |  | 182             |

**Design and Operating Information**

**Performance Information**

**Key Point**

Documentation of process and performance data in accessible reports is critical to advancing our understanding of technologies.

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

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 [ft <sup>2</sup> ] |                                     |                    |         | Number of Sites with Density of Energy Delivery Points (electrodes or wells) in this Range [# per 100 ft <sup>2</sup> ] |           |      |         |
|----------------------------------|---|-------------------------------------|--------------------|---------|---|-----------|------|---------|
|                                  | <10 <sup>4</sup>  | 10 <sup>4</sup> - 4x10 <sup>4</sup> | <4x10 <sup>4</sup> | 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 <sup>2</sup> ] |                                     |                    |         | Number of Sites with Density of Energy Delivery Points (electrodes or wells) in this Range [# per 100 ft <sup>2</sup> ] |           |      |         |
|----------------------------------|---|-------------------------------------|--------------------|---------|---|-----------|------|---------|
|                                  | <10 <sup>4</sup>  | 10 <sup>4</sup> - 4x10 <sup>4</sup> | <4x10 <sup>4</sup> | 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.

## 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

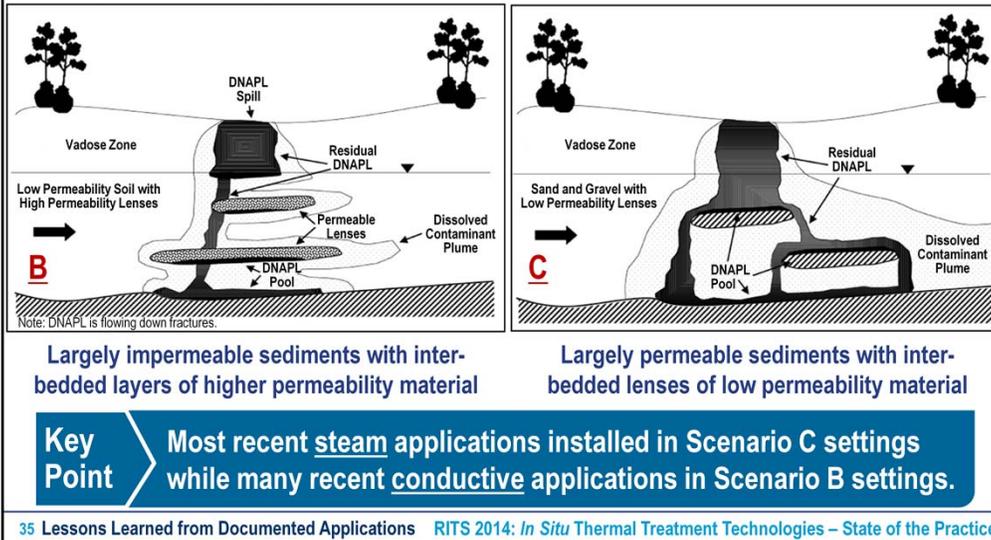
More recent thermal applications are selecting treatment durations based on theoretical energy balance completed prior to treatment to meet specified standards. It is still not clear how the performance standards are being selected and thus the treatment durations could still be a bit arbitrary, so the 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

## Thermal Technology Database (1988 – 2007): Geologic Scenarios (cont.)

- Of the five generalized settings, most applications were classified as one of the following two:



Based on the ESTCP study, we found that most recent steam applications installed in Scenario C settings while many recent conductive 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*

## Green and Sustainable Remediation (GSR)

### Options for reducing environmental impacts:

- Heating during off-peak hours
- Use of minimum concrete cap material
- Use of bio-based activated carbon
- Modified material in heating points
- Use of a condensing steam boiler

37 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

## Case Studies & Supplementation Data Collection

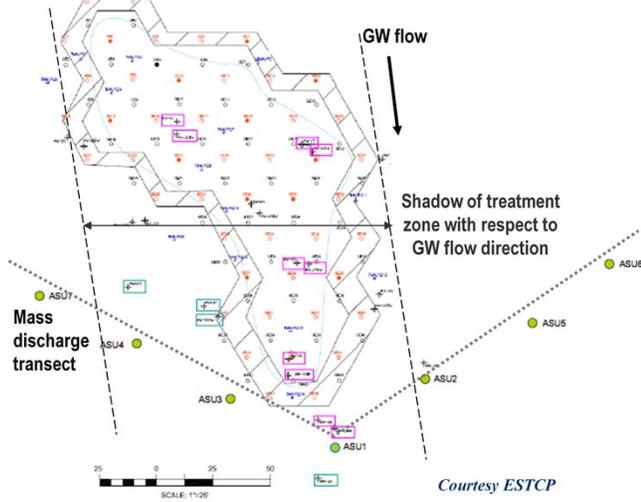


ESTCP  
ER-0314

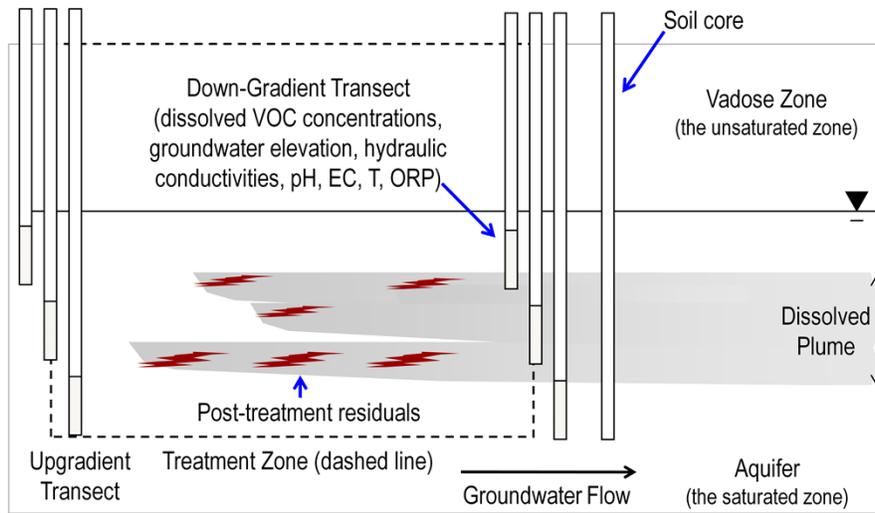


## Supplemental Data Collection Approach

Emphasis on post-treatment groundwater quality  
and quantification of mass discharge to the aquifer



## Supplemental Data Collection: How Much is Aquifer Impact Reduced by Treatment?



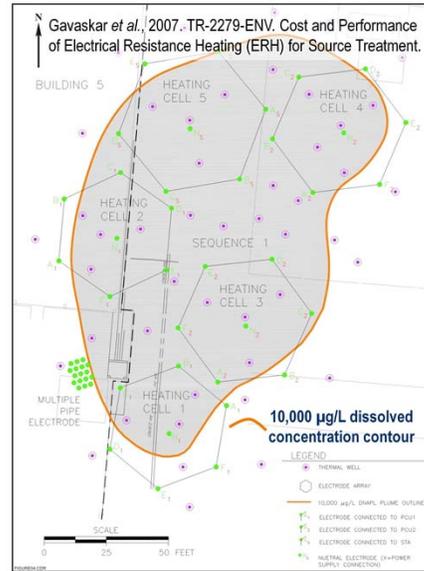
41 Case Studies & Supplemental Data Collection

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<sup>2</sup> (130 ft x 185 ft)**



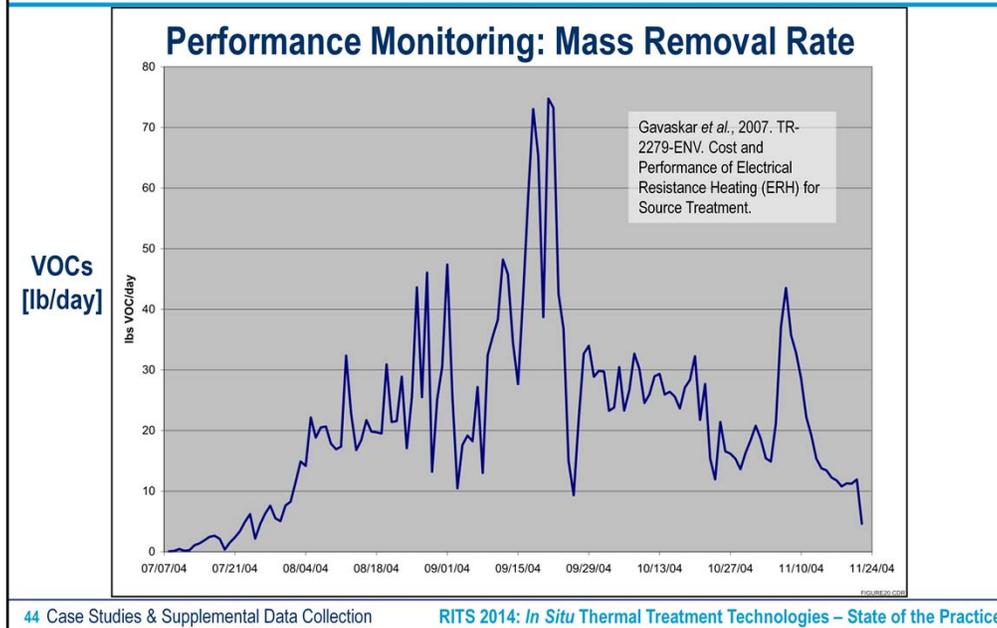
42 Case Studies & Supplemental Data Collection

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.



## Performance Monitoring Case Study Site 1: NAS Alameda (IR Site 5)



This is a typical thermal remediation mass removal graph. Showing time versus pounds per day. We would expect to see this general rise in VOCs over time as temperatures across the site increase then after the boiling points of chemicals have been achieved, 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                      |
| <b>Vendor Cost</b>                    |  |                                  |
| Mobilization, setup                   |  | \$410,800 <sup>(a)</sup>         |
| Equipment                             |  | \$833,333 <sup>(a)</sup>         |
| Operation                             | 07/08/04 to 11/05/04<br>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                               |
| <b>Adjusted Vendor Cost</b>           |  | <b>\$2,690,723<sup>(b)</sup></b> |
| <b>Site Incurred Cost</b>             |  |                                  |
| 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                        |
| <b>Site Incurred Cost</b>             |  | <b>\$750,000</b>                 |
| <b>Total Cost</b>                     |  | <b>\$4,703,223</b>               |

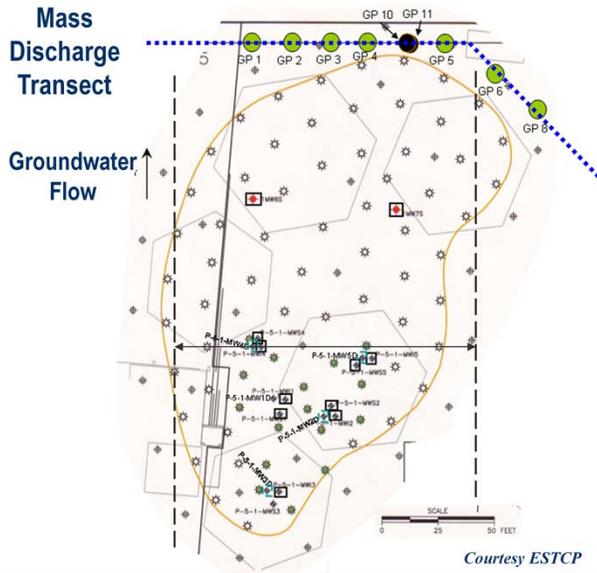
Gavaskar *et al.*, 2007. TR-2279-ENV. Cost and Performance of Electrical Resistance Heating (ERH) for Source Treatment.

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

~\$417/yd<sup>3</sup>

# Site Layout and Sampling Locations

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



## **Supplemental Data Collection**

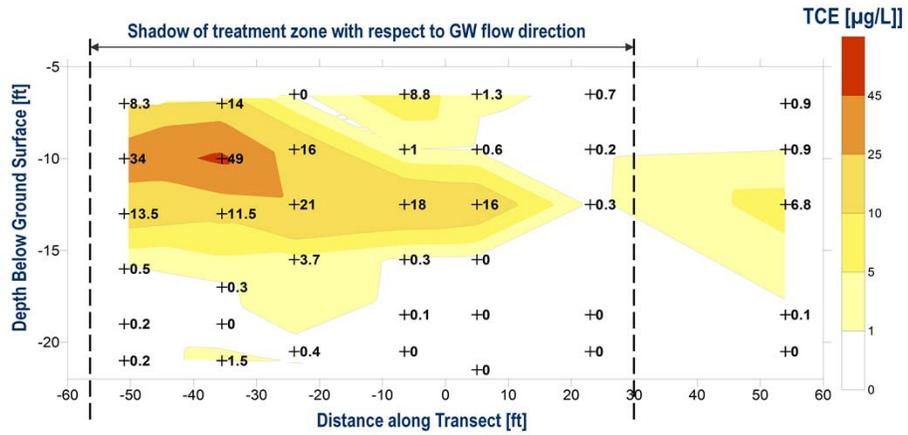
**Case Study Site 1: NAS Alameda (IR Site 5)**

- **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)

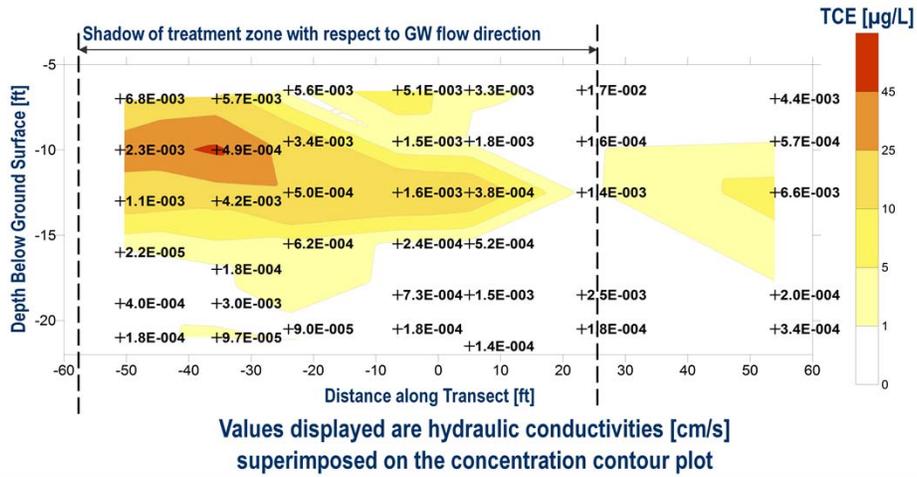
TCE concentrations from samples collected along the transect perpendicular to groundwater flow on the down-gradient edge of the source zone



# 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)



## 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**

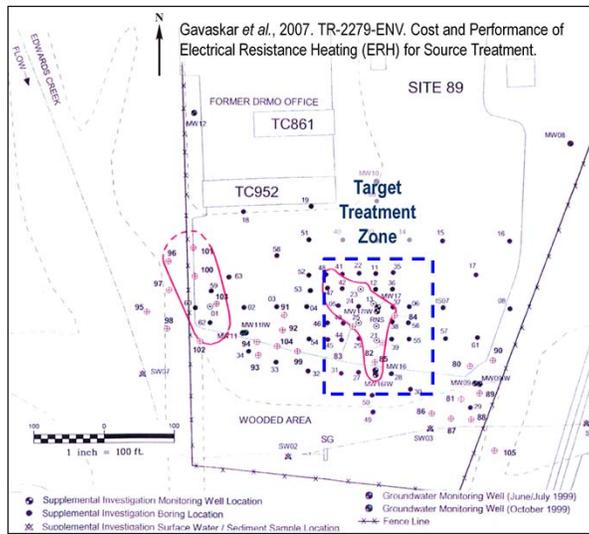
## **This Case Study Illustrates...**

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

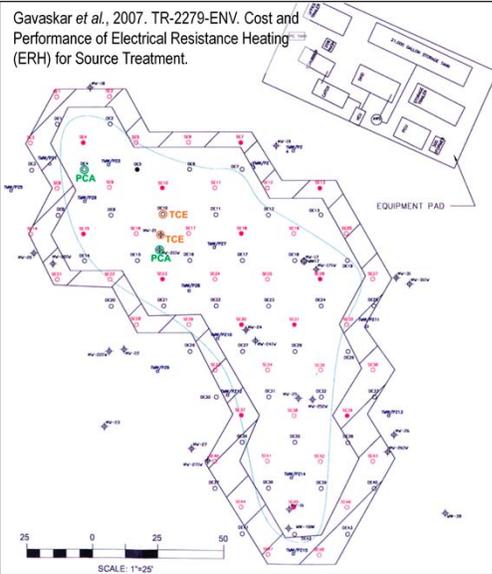
- **That low 10's of  $\mu\text{g/L}$  dissolved concentrations can be achieved when the thermal treatment:**
  - **Covers the areal extent of the source zone**
  - **Treats the full depth of contamination**
  - **Is operated for sufficient duration at sufficient temperature**
- **That temperatures above 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**

## 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<sup>2</sup>  
(1,850 ft x 255 ft)



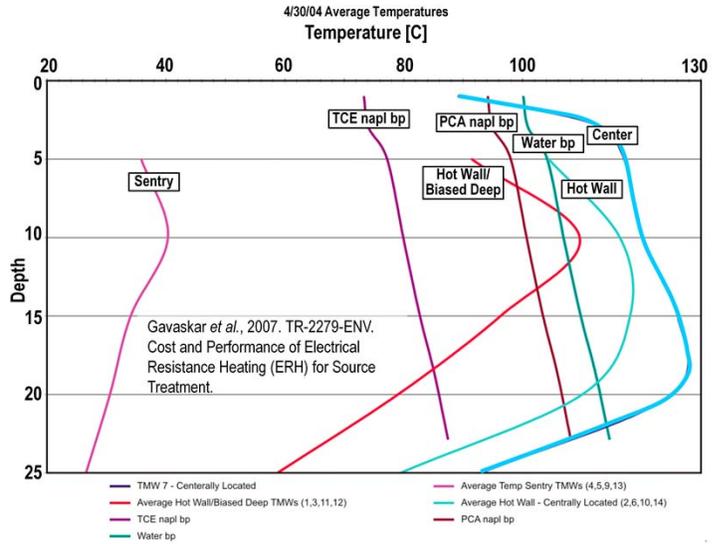
## Case Study Site 2: Camp Lejeune

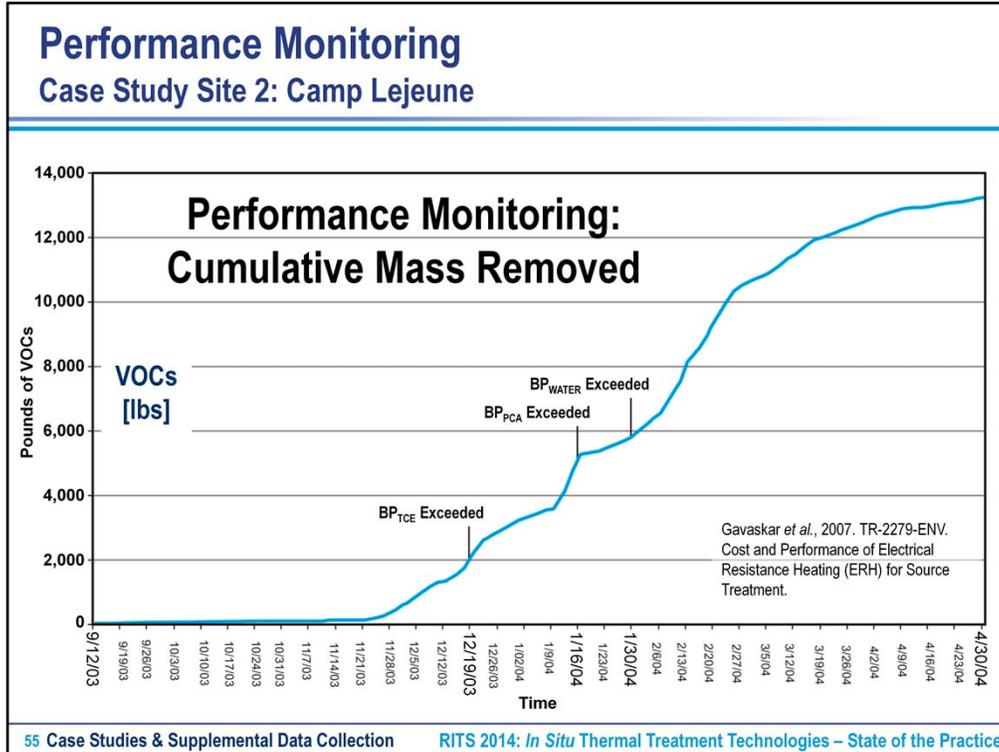


# Operating Conditions

## 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





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

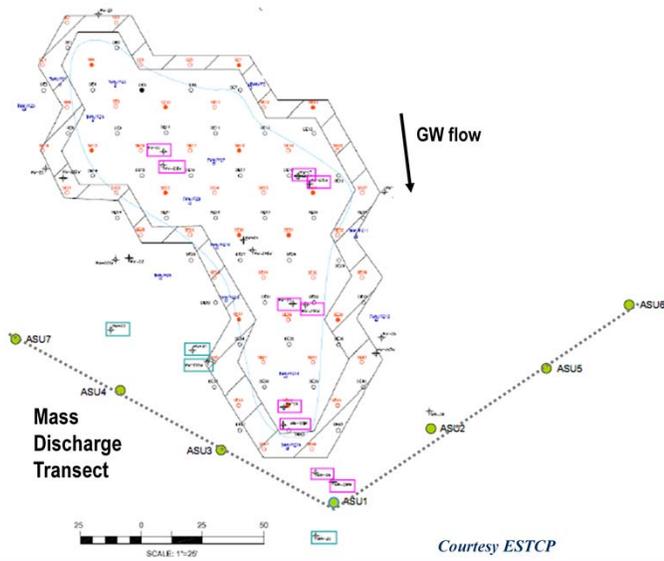
| Vendor Costs                    |                          |
|---------------------------------|--------------------------|
| System Installation             | \$672,550                |
| System O&M (225 days)           | \$907,400                |
| Power Cost                      | \$142,691 <sup>(a)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

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

~\$182/yd<sup>3</sup>

# Site Layout and Sampling Locations

## Case Study Site 2: Camp Lejeune



## **Supplemental Data Collection**

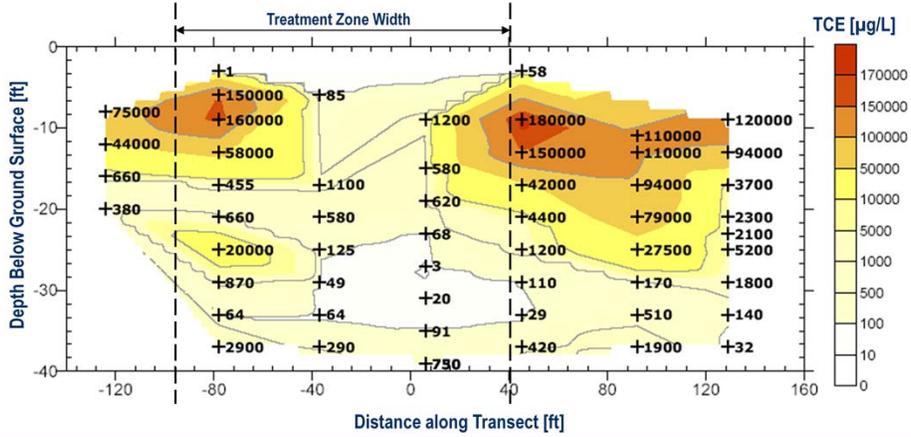
### **Case Study Site 2: Camp Lejeune**

- **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

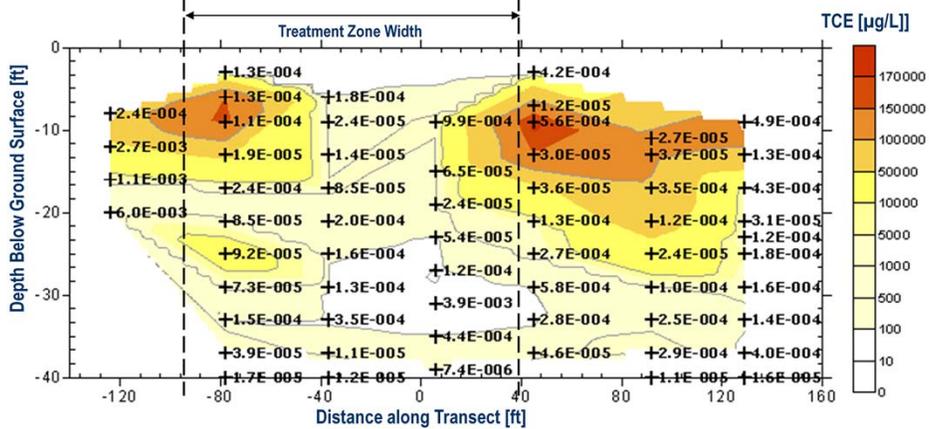
TCE concentrations from samples collected along the transect perpendicular to groundwater flow on the down-gradient edge of the source zone



# 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)

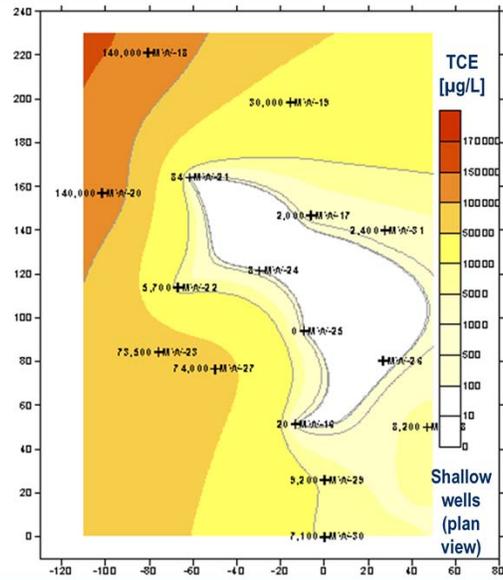


Values displayed are hydraulic conductivities [cm/s]  
superimposed on the concentration contour plot

# 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



## **This Case Study Illustrates.....**

### **Case Study Site 2: Camp Lejeune**

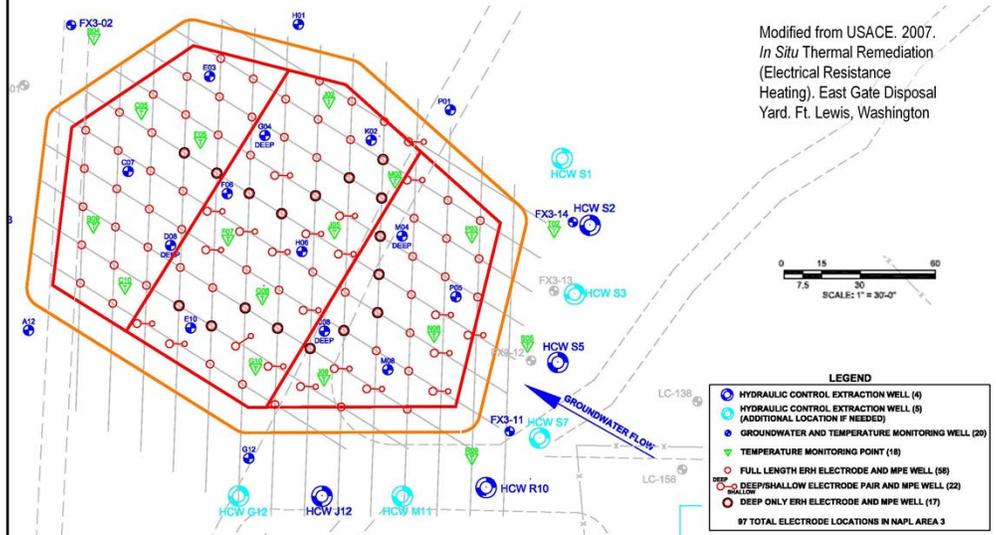
- **That it is important to confidently delineate the areal extent of the source zone prior to treatment**
- **That downgradient sampling transects are a good tool for determining the width of the source zone**
- **That about 5 months was required to achieve desired temperatures above the contaminant 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<sup>2</sup>

# Site Layout

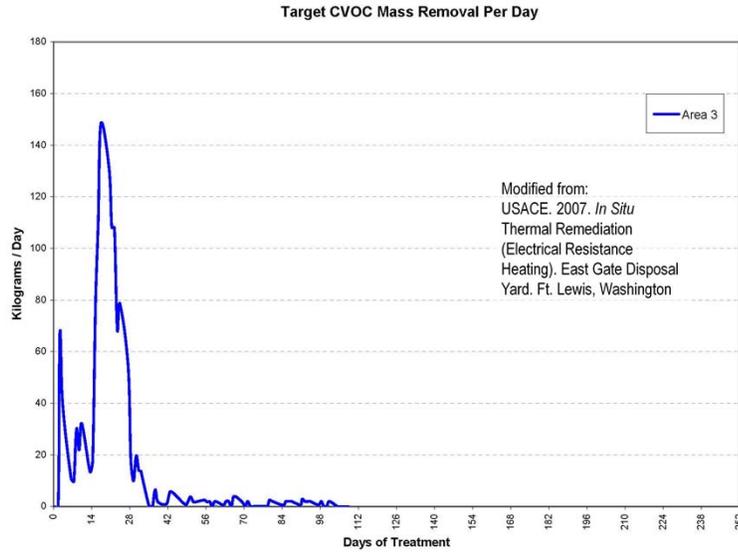
## Case Study Site 3: Fort Lewis EGDY Area 3



# 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

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

| 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                 |
| <i>cis</i> -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 <sup>7</sup> gal   | 3.39 × 10 <sup>7</sup> gal    | 2.59 × 10 <sup>7</sup> 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          |



## Project Costs

### Case Study Site 3: Fort Lewis EGDY Area 3

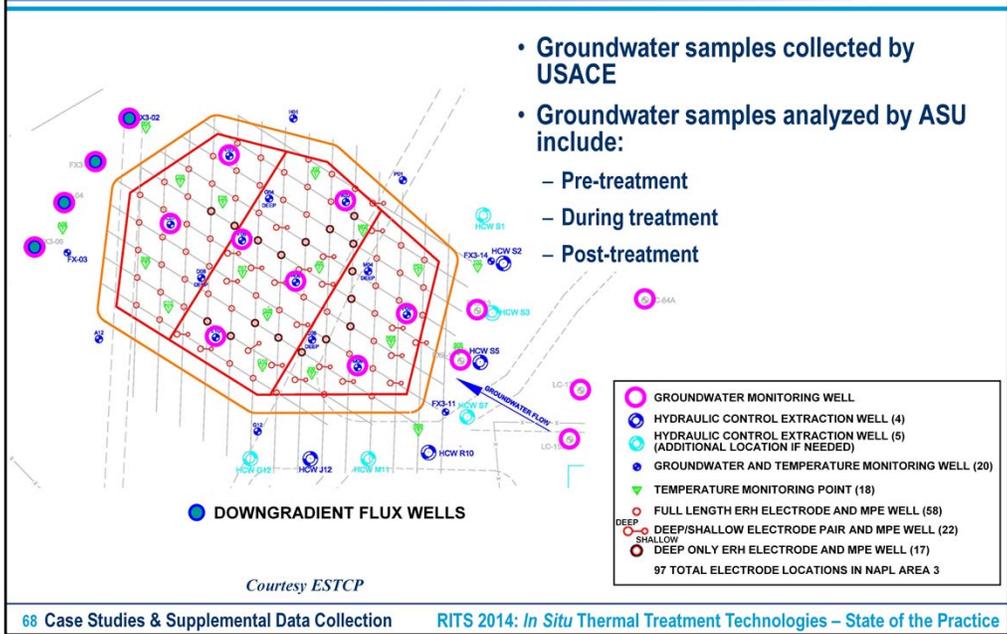
#### Summary of Actual Costs for Areas 1, 2, and 3

| 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 |
| <b>Total Electricity Used</b>              |             |             |             |              |
| Electricity (KWH)                          | 7,998       | 9,181       | 5,856       | 23,035       |
| Electric cost                              | \$359,910   | \$397,445   | \$245,308   | \$1,002,663  |
| <b>Unit Costs</b>                          |             |             |             |              |
| <b>Cost per cubic yard</b>                 |             |             |             |              |
| 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

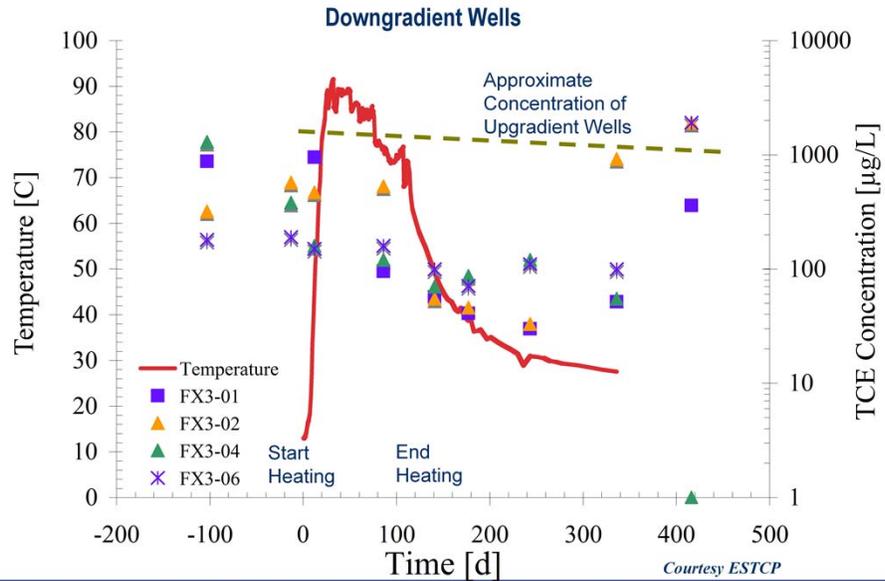
# Site Layout, Sampling Locations, and Data Collection

## Case Study Site 3: Fort Lewis EGDY Area 3



# Performance Monitoring

## Case Study Site 3: Fort Lewis EGDY Area 3



## Mass Discharge

### Case Study Site 3: Fort Lewis EGDY Area 3

| Site                   | Contaminant            | Pre-treatment Discharge (kg/y) <sup>1</sup> | Post-treatment Mass Discharge (kg/y) <sup>2</sup> | Post-treatment Mass Discharge per Linear Foot (kg/y/ft) |
|------------------------|------------------------|---|---|---|
| Ft. Lewis EGDY Area 3* | Total Contaminant Flux | 3.2 x 10 <sup>1</sup>                       | 2.1   | 1.9 x 10 <sup>-2</sup>                                  |

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**

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.

## **This Case Study Illustrates.....**

### **Case Study Site 3: Fort Lewis EGDY Area 3**

- **A state of the practice ERH system design (surface cap, electrode spacing, etc.)**
- **Difficulty in treating sites in high flow groundwater systems**
- **Impact of upgradient source on post-treatment monitoring**
- **Post-treatment increases in concentrations might not be seen for a year**

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<sup>2</sup> (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**

## **Supplemental Data Collection**

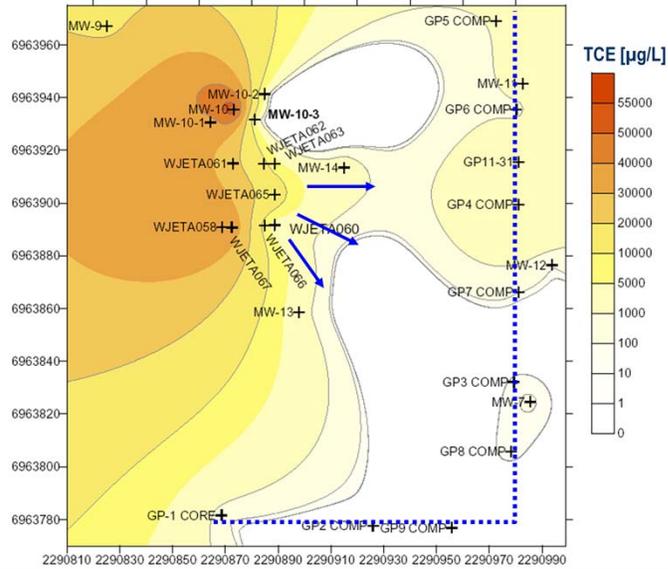
**Case Study Site 4: Air Force Plant 4 Bldg 181 (inside operating building)**

- **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**

## Supplemental Data Collection (cont.)

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

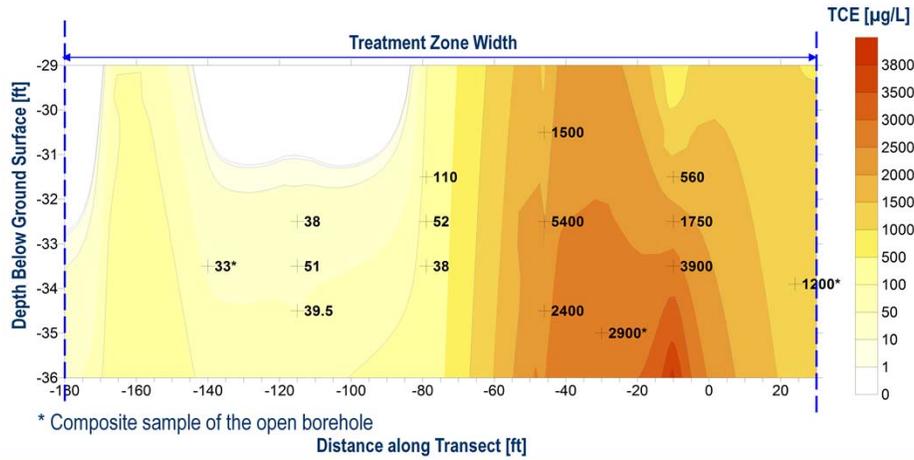
- ERH treatment resulted in a reduction in dissolved concentrations throughout the 32 ft treatment zone, with the exception of the very low permeability area near MW-10
- Pre-treatment concentrations ranged from 10,000 – 100,000 µg/L



## 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**

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## 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 <sup>(SDC)</sup>                            | 10x                         |                          |     | x    |       |        |
| 2        | Electrical Resistance | Largely impermeable sediments with inter-bedded layers of higher permeability material <sup>+</sup> (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 <sup>*</sup> (SDC)      | >10x to <100x               |                          | x   |      |       |        |
| 5        | Electrical Resistance | Largely permeable sediments with inter-bedded lenses of low permeability material <sup>^</sup>            | <10x                        | x                        |     |      |       |        |
| 6        | Electrical Resistance | Largely permeable sediments with inter-bedded lenses of low permeability material <sup>^</sup>            | <10x                        | x                        |     | x    |       |        |
| 7        | Electrical Resistance | Largely permeable sediments with inter-bedded lenses of low permeability material                         | <10x                        |                          |     |      | x     |        |

<sup>\*</sup> Pilot application appeared to encompass the entire source zone based on documentation reviewed.  
<sup>+</sup> 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.  
<sup>^</sup> 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

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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 <sup>(SDC)</sup> | 10x                         |                          | x   |      |       |        |
| 9        | Electrical Resistance | Largely permeable sediments with inter-bedded lenses of low permeability material <sup>(SDC)</sup> | 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 <sup>^</sup>     | 10000x                      |                          |     |      | x     | x      |
| 14       | Steam                 | Competent, but fractured bedrock <sup>*</sup>  | <10x                        | x                        |     |      |       |        |

\* Pilot application appeared to encompass the entire source zone based on documentation reviewed.  
<sup>^</sup> 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

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- 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

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 where they have a layered stratigraphy and would like to quickly heat specific layers.

## Key Points and Take-Away Messages (cont.)

### Consider *in situ* thermal technologies for:

- VOC and/or less volatile sources in heterogeneous subsurface settings where other technologies are challenged (e.g., SVE, IAS, enhanced bioremediation)
- Time-sensitive cleanup objectives, especially for localized hot spots (target cleanup times of months vs. years)
- Shallow to medium depths:  
(<100 ft; because well/electrode/monitoring point spacings will be about <25 ft [electrical resistance and conductive])
- Medium to deep depths:  
(<250 ft; because injection/monitoring point spacings will be between 50 – 100 ft [steam])
- Impacted saturated zones with limited water influx, or easily dewatered settings

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.

## Key Points and Take-Away Messages (cont.)

### Key Components for Success:

- Well-delineated source zone
- Understanding the overall energy balance
- A design with a high density of energy delivery points
- Performance monitoring plan
- System optimization plan
- Non-arbitrary shut-down criteria
- An experienced vendor

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)**

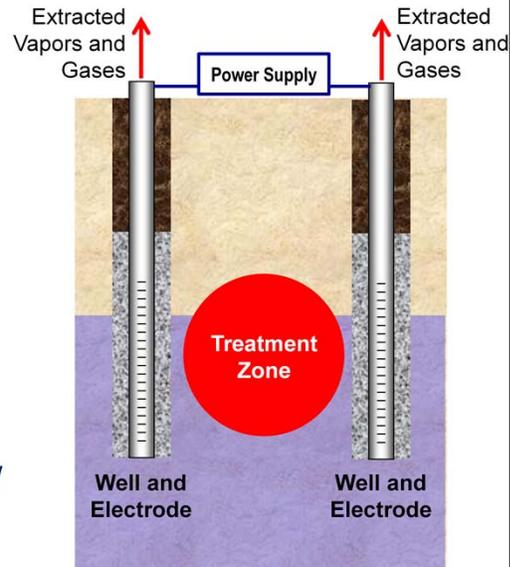
- **Groundwater transect approach is one strategy to determine and/or verify this prior to design**
- **Can also use this information to validate and refine the site conceptual model**
- **Treatment system footprint should be at least as large as source zone footprint and energy needs to be delivered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

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.

## Understanding the Overall Energy Balance

- **Energy needs and costs should be estimated by your vendor:**

- Energy required to heat soil to desired temperature
- Energy required for soil moisture evaporation
- Energy loss to groundwater flow through the treatment zone
- Energy loss to vapors extracted from treatment zone
- Energy costs for different options
- Maximum sustained energy delivery rate possible by different heating options



85 Key Messages and Wrap Up

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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 understand total organic carbon and maximum concentrations, but they do not need to understand where the mass is located.

## **A Design With a High Density of Energy Delivery Points**

- **Anticipate that a high density of energy delivery points (heaters, electrodes) will be required (<25 ft spacings), unless demonstrated at your site that larger spacings are sufficient**
- **Identify any physical constraints that might limit installations in and around the source zone**

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

## Performance Monitoring and Optimization Plans

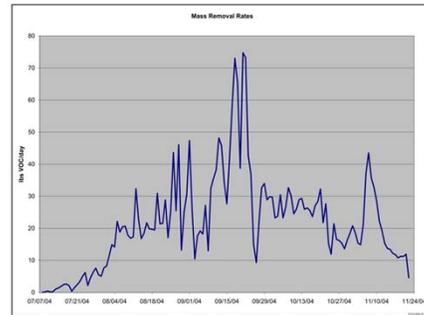
- **Establish functional objectives (verifiable practicably during operation):**
  - Meet a temperature criterion appropriate for your contaminant throughout the target treatment zone
  - Demonstrate hydraulic and vapor containment
  - Demonstrate treatment and appropriate discharge of waste streams
- **Need *in situ* monitoring network consistent with the functional objectives**
- **Optimization plan lays out options for improving performance; e.g.:**
  - Add more delivery points
  - Add more wells
  - Redirect energy
  - Change pumping/recovery rates
  - Dewater

Prior to treatment, the RPM should verify the temperature criterion that must be met 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



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 too 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.