In-Situ Thermal Remediation

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Module 1: Introduction

Learning Objectives

By the end of this section, you will be able to:

- **Identify** the three primary in situ thermal remediation (ISTR) technologies and their fundamental delivery mechanisms.
- **Evaluate** the advantages and limitations of ISTR compared to conventional remediation methods like pump-and-treat or SVE.
- **Determine** the appropriate data needs and regulatory considerations for screening and selecting thermal technologies at HTRW sites.

Executive Summary: In Situ Thermal Remediation (ISTR) represents the most aggressive class of technologies for treating high-concentration organic contaminants and Non-Aqueous Phase Liquids (NAPL). By leveraging thermal conductivity—which varies significantly less than hydraulic permeability in subsurface media—ISTR achieves more uniform treatment in heterogeneous or low-permeability soils where traditional reagent-based methods often fail.

Design Purpose and Guidance

This Engineer Manual (EM) serves as the primary guidance for the screening, selection, and oversight of **In Situ Thermal Remediation (ISTR)** technologies. It specifically addresses:

- **Steam Enhanced Extraction (SEE)**
- **Electrical Resistivity Heating (ERH)**
- **Thermal Conductive Heating (TCH)**

The document is designed for technical professionals—including engineers, geologists, and project managers—who require a deep understanding of design, operational, and monitoring issues relevant to Government oversight.

⚠️ **Safety Constraint:** You must consult with the appropriate Office of Counsel regarding the application of laws, regulatory requirements, and patent law. ISTR technologies are often protected by specific patents which may influence procurement and implementation.

Applicability

This EM is mandatory for all **USACE commands** with responsibilities for Civil Works and/or Military Programs involving hazardous, toxic, or radioactive waste (HTRW) projects.

Background: The Challenge of NAPL

Conventional technologies like groundwater extraction, bioremediation, and soil vapor extraction (SVE) frequently struggle with **Non-Aqueous Phase Liquids (NAPL)**, especially below the water table. These contaminants act as long-term sources of dissolved-phase plumes, persisting for decades or centuries.

ISTR is deployed as a "source-removal" technology to aggressively address these mass-transfer limitations.

ISTR Methods and Mechanisms

Heat is transferred into the subsurface through three distinct physical mechanisms:

1. **Thermal Conductive Heating (TCH):** Direct conduction of heat from high-temperature heaters placed in wells or trenches.
2. **Electrical Resistivity Heating (ERH):** Passing electrical currents through the soil moisture to generate heat via resistance.
3. **Steam Enhanced Extraction (SEE):** Injection of steam to heat the formation and displace contaminants.

These methods are typically paired with **vapor extraction** and/or **liquid recovery** systems to capture the mobilized and volatilized contaminants.

Exclusions from Scope

The following technologies are **not** addressed in this EM:

- **In Situ Vitrification (ISV):** Total soil melting for radioactive isotope isolation.
- **Auger-based Steam Injection:** Mechanical mixing during steam delivery.
- **Radio Frequency (RF) Heating:** Use of electromagnetic energy for soil heating.

Engineering Advantages of ISTR

The primary advantage of thermal remediation is its relative independence from **hydraulic permeability**. In natural geological materials, permeability can vary by several orders of magnitude, leading to preferential flow and "dead zones."

Thermal Conductivity vs. Hydraulic Permeability

- **Hydraulic Permeability:** Varies by up to 10^6 or more, causing non-uniform delivery of liquid reagents.
- **Thermal Conductivity:** Varies by less than one order of magnitude across most earth materials.

Thermal Effects on Contaminants

- **Increased Vapor Pressure:** Facilitates volatilization of organic compounds.
- **Decreased Viscosity:** Enhances the mobility of separate-phase liquids (NAPL).
- **Increased Diffusion and Solubility:** Speeds up the rate of mass transfer into the mobile phase.
- **Accelerated Abiotic Degradation:** Increases rates of hydrolysis and oxidation.

💡 **Design Tip:** While heat moves uniformly via conduction, earth materials are effective insulators. Successful design depends on the economical delivery of heat and ensuring the extraction system is sized to handle the resulting vapor and liquid loads.

Limitations and Constraints

ISTR is not a universal solution. Engineers must evaluate the following limitations:

- **Contaminant Type:** Generally ineffective for inorganic contaminants (except volatile metals like mercury).
- **Volatility:** Some methods may struggle with extremely low-volatility organics (e.g., certain dioxins or PCBs).
- **Site Conditions:** High groundwater flux (which can "quench" the heat), buried ordnance, or sensitive underground utilities can preclude the use of ISTR.
- **Cost:** The high energy requirements make ISTR a significant capital and operational expenditure, often reserved for high-mass source zones.

Scope and Organization

This manual moves from fundamental principles to practical application. It does not provide a "cookbook" design but establishes the engineering thought process required for oversight.

Key Chapters for Implementation

- **Module 2:** Physics and Technology Descriptions.
- **Module 3-4:** Site Characterization and Screening.
- **Module 6:** Design Considerations and Modeling.
- **Module 8-9:** O&M and Assessing Remedial Objectives.

Checkpoint Quiz

1. **Why is thermal conductivity considered a superior mechanism for treating heterogeneous soils compared to hydraulic delivery?**
   a) Thermal conductivity varies by several orders of magnitude, allowing heat to find contaminants.
   b) Thermal conductivity is much higher in clay than in sand.
   c) Thermal conductivity in most earth materials varies by less than one order of magnitude, ensuring more uniform heat distribution.
   d) Thermal conductivity eliminates the need for any vapor extraction.

Answer: (c). The narrow range of thermal conductivity across different soil types allows for predictable and uniform heating regardless of lithology.

2. **Which of the following is specifically excluded from the scope of EM 200-1-21?**
   a) Electrical Resistivity Heating (ERH)
   b) In Situ Vitrification (ISV)
   c) Thermal Conductive Heating (TCH)
   d) Steam Enhanced Extraction (SEE)

Answer: (b). ISV (soil melting) is a separate technology focused on vitrification and is not covered in this manual

3. **What is a primary site condition that could act as a technical limitation for ISTR?**
   a) Low-permeability clay layers.
   b) High groundwater flux.
   c) Presence of chlorinated solvents.
   d) Depths greater than 10 feet.

Answer: (b). High groundwater flux can introduce a constant "cooling" effect that removes heat faster than it can be applied, potentially making target temperatures unachievable.

Module 2: Underlying Physical Principles and Technology Descriptions

Learning Objectives

By the end of this section, you will be able to:

- **Identify** the physical, chemical, and hydrogeological principles that govern contaminant mobilization and removal during ISTR.
- **Select** the appropriate ISTR technology (TCH, ERH, or SEE) based on nominal upper-bound temperature requirements and site conditions.
- **Evaluate** the potential ecological and physical impacts of thermal treatment on the subsurface and surrounding infrastructure.

Executive Summary: Chapter 2 details the fundamental science behind in situ thermal remediation (ISTR), explaining how heat alters the four-phase distribution of organic chemicals to enhance removal. While the three primary technologies—Thermal Conductive Heating (TCH), Electrical Resistivity Heating (ERH), and Steam Enhanced Extraction (SEE)—differ in their delivery mechanisms and temperature limits, they all leverage the relative uniformity of thermal conductivity in soil to achieve superior mass removal compared to conventional fluid-based methods.

Fundamental Principles

Organic contaminants exist in the subsurface in four phases: **solid soil matrix**, **gas phase**, **aqueous phase**, and **Non-Aqueous Phase Liquid (NAPL)**. ISTR shifts this equilibrium to mobilize mass into fluid phases for extraction.

Chemical Principles

- **Aqueous Solubility:** For most hydrocarbons, solubility increases exponentially at high temperatures. Large molecules like **naphthalene** see dramatic increases (up to 45 times from 25 to 100°C), facilitating aqueous-phase removal.
- **Sorption:** Soil-water sorption coefficients generally decrease with heat, increasing the ability of fluids to strip contaminants from the soil.
- **Vapor Phase:** Volatilization is governed by **vapor pressure**, which increases with temperature. Boiling occurs when vapor pressure exceeds atmospheric pressure.

Purchase this course to see the remainder of the technical materials.