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In-Situ Thermal Remediation

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CHAPTER 1

Introduction

1.1. Purpose. This course provides guidance and background for the appropriate screening and selection of in situ thermal remediation (ISTR) technologies, including steam enhanced extraction injection, electrical resistivity heating, and thermal conductive heating. This course is intended to help distinguish proper applications of the technology and identify important design, operational, and monitoring issues relevant to Government oversight personnel. It is intended for use by engineers, geologists, hydrogeologists, soil scientists, chemists, project managers, and others who possess a technical education but only the broadest familiarity with ISTR technologies.

1.2. References**.** This EM does not present a detailed, comprehensive discussion of each and every factor associated with ISTR systems. Such a presentation would require many volumes. This document does reference additional resources that do provide more detail.

1.3. Background. A significant number of sites are contaminated with high levels of organic contaminants, including chlorinated solvents, oils and petroleum products, polychlorinated biphenyls, and wood-preserving compounds above and below the water table. These contaminated sites include hundreds of Federal installations and thousands of private facilities. Many of these sites are known or suspected to contain non-aqueous phase liquids (NAPL), either as mobile or residual immiscible fluids. Some of these compounds have low volatility and solubility. These contaminants, especially NAPL below the water table, have been difficult to treat with conventional technologies such as groundwater extraction, bioremediation, and soil vapor extraction. NAPL often represents a very significant long-term (decades to centuries) source of dissolved phase contaminants. More aggressive technologies have been sought that would address these conditions. These aggressive technologies include in situ chemical oxidation, surfactant/solvent flushing, and ISTR methods. The ISTR methods represent the most aggressive and effective of these techniques.

1.3.1. ISTR Methods. There are several mechanisms by which heat can be transferred into the subsurface, including 1) direct conduction of heat away from heaters placed in trenches or wells (thermal conductive heating or TCH), 2) electrical resistivity heating (ERH) of the subsurface by-passing electrical currents through the soil, and 3) steam injection or steam enhanced extraction (SEE). These methods are addressed in this EM. These techniques are typically applied in conjunction with vapor extraction, and steam injection is typically paired with both vapor and liquid recovery. The three ISTR methods can be used independently or in combination to treat both in the vadose zone and below the water table. Further descriptions of the technologies are provided in Chapter 2. These techniques have been used in full-scale applications and are covered under a variety of patents, some held by Federal agencies, as described in Chapter 10. Vendors of the technologies typically operate under a license from the patent holders.

1.3.1.1. This course does not address the use of electrical heating for soil melting, also referred to as in situ vitrification (ISV), the use of steam injection accompanied by the use of soil augers, or radio frequency (RF) heating. ISV involves the total melting of contaminated soil, with concomitant destruction of the organic contaminants or containment of inorganic contaminant in the vitrified mass. Heating for ISV is accomplished using electrical currents passing between electrodes through the conductive melt. A conductive "starter frit" is placed between the electrodes to initiate the melting. ISV is a patented technology that was originally developed as a means to isolate radioactive isotopes for geologically long periods.

1.3.1.2. At least one vendor injects steam into the subsurface via large rotating augers drilled into the target treatment volume. The soil disruption caused by the augers results in good contact between the steam and the contaminated soil. The augers are moved around the site to ultimately treat the entire volume.

1.3.1.3. RF heating involves propagation of radio frequency energy into the soil from source transmitters and results in the heating of the soil. The use of radio frequency heating of soil was initially tested at the bench-scale level in the mid-1980s (Dev 1986) and a well-documented field application was conducted in 1989 at Volk National Guard Base (USEPA 1997).

1.3.2. Brief History of ISTR. The origins of several of the ISTR technologies can be traced back to the oil industry. Steam injection to enhance recovery of high-gravity oils has been used for several decades (Ramey 1966). The use of steam injection to remediate contaminated soil and groundwater, however, was developed in the 1980s in the Netherlands (Hilberts 1986), and in the United States (Udell and Stewart 1989). ERH, as with other thermal technologies, has its origins in the petroleum industry, where it was developed to heat oil sands and oil shales to enhance oil recovery. ERH was developed in its six-phase configuration by Battelle Memorial Institute for the U.S. Department of Energy at the Pacific Northwest National Laboratory over a period from 1988 to 1992 (Hadim et al., 1993). It was field tested and demonstrated at the Hanford Nuclear Reservation and Savannah River facility in 1993 and the first removal of DNAPL was demonstrated at Dover Air Force Base in 1996. The technology was first commercially applied in Illinois in 1996. The use of radio frequency heating of soil was initially tested at the bench-scale in the mid-1980s (Dev 1986) and a well-documented field application was conducted in 1989 at Volk Air National Guard Base (USEPA 1997). The use of thermal conductive heating for remediation was pioneered by a division of Shell Oil in 1989 (Stegemeier and Vinegar 1995) based on experience gathered in enhanced oil recovery. More recently, well publicized successes with ISTR technologies such as those at the Savannah River Site, SC, and the Visalia Poleyard site in Visalia, CA, have prompted the remediation industry to look closer at ISTR. There are have been a substantial number of both pilot- and full-scale applications of ISTR technologies conducted to date and the number of ISTR sites continues to increase. Appendix C contains information about some of these projects.

1.3.3. Appropriateness of Aggressive Source Removal. The use of the ISTR methods may represent a significant expenditure. The benefits of this scope of investment have been debated in the remediation community over the past several years, with much of the discussion centered on the ability of the ISTR methods to achieve adequate "source" removal to reach strict remediation objectives. Some segments of the remediation community advocate source containment, while others promote the removal of the accessible mass (ITRC 2002). The benefits of the application of ISTR and other aggressive source removal technologies are still being evaluated. This philosophical issue of the appropriateness of source removal will not be debated in this EM; rather, the focus will be on the technical issues surrounding the application of the ISTR technologies.

1.3.4. Advantages of ISTR. Techniques that rely solely on the flow of liquids to deliver reagents or to remove dissolved contaminants are dependent on (amongst other factors) the permeability distribution in or around the contaminated volume. Permeability may vary over many orders of magnitude in natural geological material. As a result, liquid diffusion into and out of zones of low permeability often limits our ability to deliver reagents and remove contaminant mass. The effectiveness of heat in the removal of contaminant mass depends, in part, on the conduction of heat as governed by the thermal conductivity distribution and the thermal gradient. In most earth materials, thermal conductivities range over less than one order of magnitude. The relatively small range of thermal conductivities allows much more uniform heating and treatment within a contaminated zone when compared to delivery of reagents. As heat is transmitted into the contaminated materials, various processes occur to enhance the removal of contaminants. The vapor pressure of organic materials increases, viscosity of separate-phase liquids decreases, diffusion rates and solubility often increase, and rates of abiotic degradation (e.g., oxidation) may increase. Even biological degradation has been observed to increase at higher temperatures, up to a point where microbial dormancy (or, at temperatures well above 100oC, sterilization) occurs. The removal of contaminants using heat can, therefore, be more complete than is possible with other techniques. Unfortunately, the conduction of heat in earth materials is relatively slow as these materials are generally good insulators. Efficient in situ thermal treatment depends on the economical and effective delivery of heat into the subsurface.

1.3.5. Limitations of ISTR. The ISTR methods discussed in this EM will not remediate inorganic contaminants (with the probable exception of volatile metals such as mercury). Some of the ISTR methods may not be appropriate for remediation of very low volatility organics, such as pesticides, some PAHs, dioxins, and PCBs. Site conditions that may not be conducive to ISTR include high groundwater fluxes, buried ordnance or explosive containers, or presence of critical subsurface facilities or utilities. Chapter 2 discusses these limitations further. Where the size of the treatment volume is large, the cost of ISTR may also be considered a "limitation," depending on financial resources.

CHAPTER 2

Underlying Physical Principles and Technology Descriptions

2.1. Fundamental Principles. Organic chemicals released to the subsurface may exist in as many as four phases: the solid soil matrix, the gas phase, the aqueous phase, and a NAPL phase. Application of heat to the subsurface can mobilize NAPL phase contaminants from the soil matrix, allowing them to be removed in the fluid phases via groundwater recovery wells or vapor collection systems. This section presents a general overview of the processes of multiphase flow and multi-component mass transfer in the subsurface, and the manner in which elevated temperatures can enhance those processes for removal of contaminants.

2.1.1. Chemical Principles. Presented in the following sections are chemical, thermal, hydrogeological, and biological concepts to provide a basis of understanding of the changes that take place under ISTR.

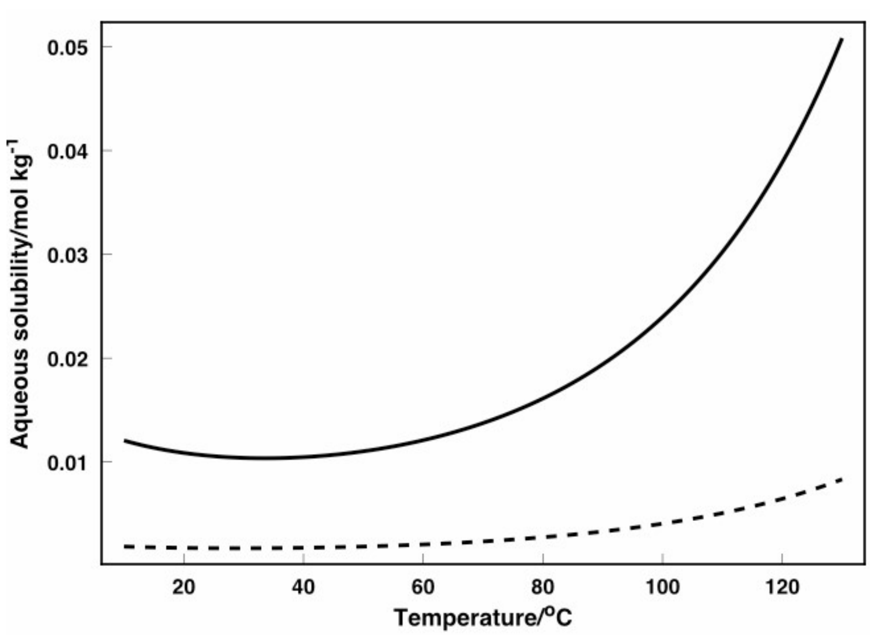

Figure 2-1. Aqueous Solubilities of Trichloroethylene (solid line) and Tetrachloroethylene (dashed line) as a Function of Temperature. (From Knauss et al. 2000, copyright, Elsevier, used with permission.)

2.1.1.1. Aqueous Solubility. For hydrocarbons, data on solubility at the temperatures used during ISTR are scarce. The aqueous solubilities of TCE and PCE as functions of temperature are presented in Figure 2-1. While the solubilities of the two compounds depicted increase exponentially with temperature, they do so only at temperatures above the conventional boiling point of water. A local solubility minimum around 30 to 50ºC has been observed in experimental studies for both TCE and PCE (Imhoff et al. 1997, Knauss et al. 2000, Heron et al. 1998a, b).