CHAPTER 3

Site Characterization for ISTR Technology Screening and Design

3.1. Introduction. This chapter describes the site characterization data necessary for screening and designing remediation systems using the three ISTR technologies that are the subject of this EM. ISTR techniques can be used for a variety of applications where providing heat accelerates physical, chemical, and biological reactions to affect remediation. The most common applications of ISTR technologies to date are for source treatment, where non-aqueous phase liquids are encountered. As a result, this will be the perspective used in this EM.* This EM does not focus on describing, or prescribing, the most appropriate investigative techniques, but instead presents the data requirements for designing and implementing the three ISTR methods. The project engineer/manager must then determine the most appropriate means to obtain the required information based on project objectives, site constraints, and budget.

3.2. Data Collection Requirements to Support Remedy Selection and Design.

3.2.1. To adequately characterize a site for remediation, a conceptual site model should be developed that explains the distribution of the contaminants in the subsurface (defining treatment area and depth). The basic elements of the conceptual model are the nature and extent of the plume, the extent of the source zone, and locations of known or suspected NAPL.

3.2.2. In developing a conceptual site model, an understanding of the geological history is also important to help explain the distribution of the contaminants in the subsurface. For example, in glaciated terrains, multiple advances and retreats of glaciers leave behind separate till units (that may or may not be readily differentiable). At many locations in the Chicago area, till units may be separated by an inter-till layer, typically containing sand and gravel in the order of a few inches to 2 ft (0.015 to 0.61 m) thick. Because these inter-till layers may be thin, they may be missed or ignored in the logging of the boreholes. However, inter-till layers have been observed to be zones of accumulation and migration of NAPL.

3.2.3. The development of the site conceptual model also involves groundwater flow, subsurface stratigraphy (boundaries between till units, inter-till deposits), joints and fractures in tills, mineralogy, and manmade influences (groundwater pumping, artificial conduits or barriers such as building footings, subsurface fill, abandoned foundations, fill material, proof-rolled soil surfaces, caissons, sheet piling, and subsurface utilities).

3.3. Site Physical Properties and Site Conditions. As with other in situ technologies, when evaluating the application of ISTR technologies, one should acquire and evaluate information

* ISTR methods (ERH) have also been used to enhance biodegradation in Alaska, and to reduce aqueous phase concentrations to facilitate the sale of a commercial property in Washington State. It is also believed that in situ thermally enhanced hydrolysis represented a significant destruction mechanism for a methylene chloride cleanup in Waukegan, IL. As well, ISTR methods are also used for in situ destruction through oxidation and hydrolysis pyrolysis oxidation.

regarding the physical properties and conditions of the site. Physical site information needs include:

a. Description of the site and setting, including a scaled site plan.

b. Stratigraphic features.

c. Hydrogeological and hydraulic parameters.

d. Accessibility of the area to be treated.

e. NAPL volume estimates.

f. Evaluation of contaminant mobility to determine cost-effectiveness of ISTR.

3.3.1. *Description of Site Including Site Plan*. To adequately design a remediation system, one of the most basic needs is for scalable maps of the site. The maps should have surveyed locations of site features, including utilities (above and below ground), surface features (e.g., paved surfaces, creeks, rivers, overhead lines), natural subsurface features such as bedrock faulting and joint orientation, neighboring facilities, and locations of buried features (underground storage tanks, subsurface vaults, abandoned foundations, pipelines, etc.). These maps are used to present and interpret data from the site characterization, and to lay out the remedial design. Further, the survey information needs to be field checked for accuracy prior to or during the design phase.

3.3.2. *Stratigraphic Features*. Stratigraphic features are typically depicted in boring logs and or geological cross-sections. Information from these sources should include soil type, rock type, observations on fractures and joints, mineral infilling of fractures and joints, depth to groundwater, location of perched zones, piezometric information, contaminant distribution, and stratigraphic boundaries. Some information may be collected or confirmed as part of the installation process. Information on stratigraphic boundaries should also carry with it an understanding of geological history. For settings were there have been multiple glacial advances and retreats, the stratigraphic boundaries between the till zones may have associated with it thin layers of ablation material from the glaciers or glacio-fluvial or glacio-lacustrine deposits. These may provide zones for NAPL accumulation, and may also provide zones to focus treatment, providing zones of elevated permeability for steam injection in an otherwise clayey sediments.

3.3.3. *Hydrogeologic and Hydraulic Parameters*. In heating the subsurface, it must be recognized that the specific heat capacity of water (4.21 $kJ \bullet kg^{-1} \bullet {}^{o}C^{-1}$) is more than four times greater than the rock or soil matrix (1.0 $kJ \bullet kg^{-1} \bullet {}^{o}C^{-1}$). Therefore, to control the cost of the remediation, it is important to minimize the flux of groundwater into the treatment zone to minimize heating water. Groundwater velocity is a key design factor in the design of ISTR systems. A good understanding of groundwater velocity and flow, and potentially more detailed hydrogeological information on well yield and distance–drawdown relationships from pump tests are parameters for input into selecting the appropriate ISTR technique and designing a successful ISTR application.

3.3.3.1. Hydraulic conductivity is an important input parameter for steam injection to estimate the steam injection and fluid recovery rates. Soil permeability is less critical in thermal conduction and ERH applications, but is important to design vapor recovery systems. When soil is completely dried by the thermal conduction process, even tight soils develop sufficient permeability for removal of contaminants.

3.3.4. *Site Accessibility.* Site accessibility can determine the ease or difficulty of implementing an in situ remediation technique, which affects cost and feasibility. These accessibility issues include obstacles to drilling, such as low overhead clearance because of ceilings, obstructions, and power lines, or steep slopes that do not allow conventional drilling rigs that would be used as part of the installation of ISTR systems to safely operate.

3.3.4.1. Constraints on construction activity also need to be determined. Access, noise, dust (during construction), length of working hours, and odors all may be restricted, and personal protective equipment may be required. Operation of ISTR systems during winter may melt snow that has the potential to run-off from the site on to traveled ways. Care must be taken to prevent hazards resulting from the implementation of the remediation effort.

3.3.5. *NAPL Location and Volume Estimates*. Each of the ISTR technologies may be implemented in a modular fashion, and as a result, it may be only necessary to know the extent of the zone to be treated relative to the dimensions of the module of the particular technology to be used. For instance, if using ERH, the distance between electrodes is typically, 2.6 to 6.1 m (8.5 to 20 ft).[*] Therefore, the lateral extent of the area containing NAPL need only be defined to this level of accuracy (i.e., ± 8.5 to 20 ft; ± 2.6 to 6.1 m). In many cases where the extent of the NAPL is uncertain, it may be less expensive to simply expand the array of heater wells/electrodes/wells to account for the uncertainty, rather than to further characterize the spill. It is good practice to sample the soils from the perimeter heater wells/electrodes/wells as confirmation of adequate coverage of the treatment area.

3.3.5.1. Estimating NAPL volume is typically an exercise involving broad simplifying assumptions with uncertain results. The mass of NAPL removed or recovered or destroyed typically exceeds NAPL estimates. However, NAPL volume should be estimated to at least approximate the volumes that can be expected to be recovered. The reason for this is fourfold: 1) for permitting purposes to estimate organic discharges from the remediation system; 2) to determine the most appropriate and cost effective air quality control technique; 3) to budget for the air quality control treatment; and 4) to indicate for the project engineer and manager the mass to be produced to compare against the conceptual site model. If the recovered NAPL volume greatly exceeds the calculated volume, the engineer may need to re-evaluate his or her site conceptual model and assess impacts on schedule and budget. Alternate sources of NAPL may

* At several ERH sites because of site conditions and the compounds being treated, the spacing has been considerably closer (e.g., 2.74 m at Lowry AFB North Pit, Denver, CO (Beyke, TRS); 4 to 6 meters at ‘Inhabited Residential Apartment Building’ (McGee 2002); and ~1.5 to 3 m at ICN Pharmaceutical Portland, Oregon (Sutter 2002).

be present that were not identified in the site characterization. This may influence the length of remediation time and, hence, the budget.

3.3.5.2. If the quantity is significantly less than calculated, the remediation engineer should evaluate the effectiveness of the recovery technique or techniques. There may be blockages in the piping and treatment equipment (e.g., condensate buildup in the carbon canisters) that are affecting the determination of the recovered mass. If poor recovery is taking place, this also affects the length of remediation time and, hence, the budget.

3.3.6. *Evaluation of Contaminant Mobility*. ISTR techniques have the potential to mobilize NAPL. If heating can significantly change the physical characteristics of the NAPL, the remediation engineer must ensure that it can be captured. Therefore, NAPL characteristics such as specific gravity and changes in viscosity with temperature should be measured to appropriately design the recovery system.

3.4. Chemical Analyses and Contaminant Properties. Chemical analyses required for ISTR techniques include conventional analyses for VOCs and SVOCs (in both soil and groundwater) to define the extent of the compounds of concern and to estimate the organic loading to the vapor treatment equipment. Additional analyses should also be done to address issues that may affect the operation or effectiveness of the remediation system.

3.4.1. *Organic Parameters*. Concentrations of target and non-target compounds need to be evaluated to determine the loading and to properly design the treatment system. Non-target compounds may impact the effectiveness of the remediation. For example, VOC evaporation rates will be slowed if the target contaminant is dissolved into oil or grease, as described by Raoult's Law.

3.4.1.1. A parameter that is typically overlooked for active in situ remediation applications is total organic carbon (TOC). The TOC content of the soil influences lower-temperature methods of in situ remediation (i.e., ERH and shallow SEE applications) because TOC preferentially adsorbs VOCs that may be present in the subsurface.

3.4.2. *Inorganic Parameters*. Concentrations of major anions and cations in groundwater are important in evaluating treatment options. Calcium and iron compounds may precipitate on well screens and treatment equipment during heating, affecting maintenance and, potentially, feasibility. At the high temperatures that can be achieved using thermal conduction, anions such as carbonates can provide in situ buffering capacity for the acidic products of in situ destruction of chlorinated hydrocarbons (HCl).

3.4.3. *NAPL Characteristics*. The characteristics of the NAPL need to be known prior to selecting and designing an ISTR application. Characteristics include specific gravity, interfacial tension, viscosity, vapor pressure, and aqueous solubility, including variability with temperature. Many of these characteristics may be obtained from literature sources.

3.4.4. *Trends in Dissolved Phase Compounds*. If the site to be remediated has historical groundwater monitoring data associated with it, the remediation engineer should evaluate concentration trends. These concentrations trends can be used to evaluate whether natural attenuation is taking place, whether investigations have mobilized NAPL, and the effectiveness of a pre-existing remediation system (which may provide insight into the probability of success for the ISTR method to be implemented). Further, historical concentration trends may provide insight into the presence of NAPL (especially at sites where it may not have been physically observed) to appropriately place the ISTR system.

3.4.4.1. Upon initial heating, concentrations of most VOCs in groundwater will increase in the zone being heated until the temperature of the water reaches the eutectic point of the azeotropic mixture. As temperatures increase beyond this point, concentrations will decline. Therefore, groundwater concentrations can be expected to vary over the period of the ISTR application and it will be necessary to determine if there will be potential adverse effects and engineer the remediation system accordingly.

3.5. Data Needs Specific to each Technology.

3.5.1. *Thermal Conductive Heating*. TCH is the least sensitive of any in situ remediation technology to variations in soil type[*] and total dissolved solids in groundwater. This is because thermal conductivity varies by only a factor of ±2 for a wide range of common earth materials. This lack of variability in soil heat conductivity is one of the key factors in the versatility of ISTD.

3.5.1.1. There is no practical limitation to the geometry of the TCH treatment zone, i.e., it can be thin, irregular, or deeper than 30 m. Nor does the presence of subsurface debris, such as concrete walls, tanks, or landfill debris (including metallic objects), impede thermal conductive heating. Site characteristics do, however, influence TCH design. For example, treatment of shallow contamination requires that an insulating surface cover be installed to manage heat losses. Shallow contamination may be addressed more cost-effectively by using fewer long horizontal heaters placed in trenches than by employing numerous short vertical heater wells. Lithology does affect the choice of drilling methods, with direct-push commonly used for heater-only wells, and auger methods for heater-vacuum wells. Subsurface debris may also affect drilling methods for the installation of heater wells. High permeability zones can affect the ability to achieve superheated temperatures, if needed, and may dictate the need to employ measures to control recharge into the treatment zone. Treatment of VOCs with ISTD TCH, by contrast, is much less affected by recharge zones, and can be readily performed below the water table except in highly permeable aquifers. Generally, the upper limit for hydraulic conductivity is approximately 10^{-3} cm/s.

3.5.1.2. The electrical load of a thermal conductive heating system is comparable to what is typically available at industrial or commercial sites.

* Vapor recovery may be influenced by soil type and variations in lithology

3.5.1.3. The overall size of the treatment zone is an important site characteristic. As with other on-site treatment technologies, economies of scale affect treatment costs, such that large sites exhibit much lower unit costs, whereas very small sites may be more cost-effectively addressed by other means such as excavation.

3.5.1.4. As with other ISTR technologies, site information needs for ISTD include:

a. Concentrations and characteristics of COCs.

b. Extent of contamination (lateral and vertical).

c. Approximate location, nature, and extent of free product or “neat” contaminant.

d. Concentrations of non-target contaminants that may contribute to the loading on off-gas treatment equipment, e.g., granular activated carbon.

3.5.1.5. As a result of the high temperatures achieved using ISTD TCH, inorganic groundwater chemistry can have significant effects. That is, concentrations of anions, such as carbonates, can provide in situ buffering capacity, where the in situ destruction of chlorinated hydrocarbons has the potential to produce hydrochloric acid (HCl). If there is insufficient buffering capacity, the lowered pH must be considered in the selection of piping and treatment equipment materials and possibly in the treatment processes.

3.5.1.6. Because ISTD TCH can be used to treat a wide variety of organic (and some inorganic) contaminants in a range of settings, the data needs vary depending on the remedial context. Four general categories of applications include:

a. Vadose zone VOCs.

b. Vadose zone SVOCs (may include VOCs).

c. Saturated zone VOCs.

d. Saturated zone SVOCs (may include VOCs).

3.5.1.7. Although soils above the water table (i.e., in the vadose zone) and below it can both be treated with TCH, measures will need to be taken to control the rate of water recharge into the thermal treatment zone, particularly below the water table, in the event that the recharge rate is too high. Such measures can include dewatering with wells or trenches, and installation of hydraulic barriers, such as steel sheeting, slurry walls, jet-grout walls and freeze walls, keyed into an underlying aquitard. These actions may have a significant cost impact on the project. A key information requirement for TCH, especially below the water table, is data allowing estimation of recharge rates, including permeability and hydraulic gradient, and spatial variations in the treatment zone. The results of pumping tests are particularly relevant.

3.5.1.8. Although ISTD TCH typically destroys approximately 95 to 99% of the contaminant mass in situ (Stegemeier and Vinegar 2001), the contaminant category and concentration as well as emission standards are of importance as they dictate the selection and design of aboveground Air Quality Control equipment.

3.5.2. *Electrical Resistivity Heating.* The application of ERH is not sensitive to variations in site lithology in achieving even heating.* Some soils or zones of groundwater with total dissolved solids above background concentrations may heat preferentially to others as the treatment volume is heated up. However, as the soils tend to warm toward the limiting threshold of the boiling point of water, soils that may have lagged in the rate of temperature increase also rise in temperature to the boiling point of water. A key role of site lithology in ERH applications is the influence on how NAPL migrates and accumulates, which should be evaluated prior to implementing the remediation. Important information required for site characterization and technology screening includes:

a. The area and depth of the remediation.

b. The contaminant characteristics—especially boiling point, water solubility, and hydrolysis rate.

c. The contaminant percent reduction required.

d. The total organic carbon (TOC) content of the soil.

e. The presence of low volatility co-contaminants such as oil and grease.

f. The location of subsurface utilities.

3.5.2.1. Other common site information can refine technology selection and design, but generally does not affect cost or effectiveness significantly. This information includes:

a. Soil lithology (to identify subsurface features that may retard migration, or accumulate NAPL).

b. Soil saturation or moisture content.

c. Presence or absence of separate phase NAPL.

d. Soil and groundwater electrical (e.g., specific conductance of groundwater) or thermal properties (and delineation as to where these may vary).

3.5.2.2. Because the treatment interval is typically uniformly heated, information regarding the precise distribution of contamination or NAPL is not required. However, it is important to have enough contaminant distribution information to allow designation of a “box” or boundary that includes the contaminant mass to be treated. The remediation boundary can be irregular and the depth interval can vary across the site. If extensive treatment of the upper 2 feet of soil is required, this adds to the cost owing to heat losses to the atmosphere. If extensive (greater than 90%) reduction of such shallow VOCs is required, an insulating surface blanket is often used to achieve higher temperatures. An 8-foot thick interval is the thinnest region that can be

* Vapor recovery may be influenced by soil type and site lithology.

practically treated owing to both vertical fanning of the current as it travels between the electrodes and thermal conduction of heat out of the target zone.

3.5.2.3. The physical and chemical characteristics of the target contaminant affect the remediation energy, time, and cost. The percentage of contaminant reduction (as measured by contaminant mass, before and after soil sampling, or groundwater sampling) is another important remediation parameter. The percentage of reduction desired might be based on a health risk assessment or on the dissolved groundwater concentration at a downgradient receptor. For most VOCs, "adding a nine" to the desired percent contaminant reduction (e.g. changing from 90 to 99% or changing from 99 to 99.9%) will increase the overall project cost by 10 to 20%.

3.5.2.4. If high levels of contamination extend to within 4 feet of the soil surface, subsurface utilities should be evaluated. Most utilities are not affected by ERH if they are constructed of metal, vitrified clay, or other temperature-insensitive material. ERH has been applied in regions that are traversed by metal natural gas pipelines, telephone, fiber optic cables, water, and sewer lines. Temperature-sensitive utilities include plastic water and natural gas lines, and electrical cables that carry significant power.

3.5.2.5. The electrical load of an ERH system is relatively small compared to most industrial and military activities, but significantly larger that most remediation approaches. Utility locations, age, capacity, and rate structures are important issues to be considered. The existing utility infrastructure should be evaluated during the technology screening to determine if it has sufficient capacity to provide power for an ERH system.

3.5.3. *Steam Enhanced Extraction*. The major design data needs for steam injection include:

a. The lateral and vertical extent of the treatment zone. This is used to estimate the volume to be heated, steam need, and overall cost.

b. NAPL presence and contaminants of concern (density, vapor pressure, solubility). This drives the treatment strategy and effluent treatment system component selection.

c. Target cleanup levels for groundwater and soils. This is used to evaluate feasibility and treatment duration, and to determine if polishing steps are desirable.

d. eological stratification (affecting steam injection strategy and number of injection intervals with depth).

e. Horizontal and vertical permeability of target layers (this drives well spacing and screen length selection).

f. Hydrological data (hydraulic gradients, seepage velocity, hydraulic conductivity). This affects the necessary pumping rates for maintaining hydraulic control.

g. Obstructions to well installation (buildings, subsurface installations, etc.). This affects choice of well design and feasibility.

3.5.3.1. Small sites, located at shallow depths, may not be economically treated using steam injection, unless cheaper options such as excavation are ruled out owing to site-specific constraints such as buildings or underground lines that cannot be removed. The pressure of the injected steam is limited by the overburden pressure, which is directly related to the thickness of soil above the injection zone. A general rule-of-thumb is that the injection pressure should not exceed 0.5 psig per foot of overburden. However, recent field demonstrations have shown that this value can be exceeded safely at shallow sites with a surface cover (Alameda Point, Pinellas STAR Center), and at fractured rock size with significant rock strength (Edwards AFB Site 61, Loring Quarry Site) (Heron 2003).

3.5.3.2. In practice, the injection rates for shallow sites are restricted by the limited weight of the overburden, and thereby the minimum practical injection pressures that can be attained in the field. As an example, steam was injected at 10 feet below grade at Alameda Point, and the pressure was limited to about 8 psig. This limited the achievable steam injection rates to below 200 lb/hr per well, which in turn led to a design with the injection wells less than 30 feet away from the central extraction well (Udell and Heron 2003).

3.5.3.3. Injection of steam below paved surfaces and concrete floors may allow for treatment at shallower depths, providing building foundations are not negatively affected. Generally, steam is effective for treating zones deeper than 1–2 m, making this a highly versatile method.

3.5.3.4. Given the infrastructure required for steam injection (steam generators, wells, controls, sources of high quality water, fuel, electricity, etc.), an economy of scale needs to be realized for treatment. Small quantities may not be economically treated.

3.5.3.5. Higher permeability soils are more conducive to steam injection than lower permeability soils. The lower the permeability is, the higher the injection pressures required, resulting in higher steam temperatures. Higher pressures can also result in soil instability. Higher pressure in turn limits mass flux to the vapor phase, because the vapor pressure of the compounds of concern must overcome the induced pressures in the soil resulting from the steam injection. Generally, the lower limit for hydraulic conductivity for steam penetration is approximately 10^{-5} cm/s for sites deeper than 30 feet (9.1 m), with higher permeability needed for shallower sites. For sites less than 20 feet (6.1 m) deep, a practical limit for steam injection is probably around 10^{-3} cm/s. However, if the hydraulic conductivity varies around this value, steam injection can be combined with electrical heating to overcome heat transfer limitations of the tighter zones.

3.5.3.6. Steam can still be effective in treating low permeability soils when the steam is injected into adjacent higher permeability lenses and layers (Adams and Smith 1998). Steam has been injected into gravel-filled inter-till zones to treat clay till with a matrix hydraulic conductivity in the order of 10^{-8} cm/s. In that application, steam was injected into a dewatered thin (0.1 to 0.6 m) sand and gravel zone at the stratigraphic break between two ground moraines. The steam apparently migrated laterally through the inter-till layer and vertically through the joints and fractures in the till, which is believed also represented the vertical migration pathways for the perchloroethene and mineral spirits that were released at the site, rapidly heating approximately 40 feet (12 m) of clay till overlying the inter-till unit.

3.6. Evaluation of Biological Degradation Potential. Source removal, reduction, and recovery achievable using ISTR methods results in a reduction in mass flux to groundwater. At some sites, sufficient mass removal may occur that the assimilative capacity of the aquifer may play an important role in attaining remediation goals. As such, depending upon the remediation goal, it may be appropriate to also evaluate natural attenuation (of which intrinsic biodegradation is typically a significant component) as a component of the overall remediation. It is beyond the scope of this EM to provide background on what natural attenuation parameters to analyze for and how to interpret the data. The reader is referred to the following sources of information:

a. American Society for Testing and Materials (ASTM) (1997a). Standard Guide for Remediation of Ground Water by Natural Attenuation at Petroleum Release Sites.

b. Committee on Intrinsic Remediation (2000). Natural Attenuation for Groundwater Remediation. National Academy Press, Washington, DC.

c. USEPA (1999b). Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action and Underground Storage Tank Sites. Directive Number 9200.4-17P. Washington, DC: EPA Office of Solid Waste and Emergency Response.

d. ITRC (1999). Natural Attenuation of Chlorinated Solvents in Groundwater: Principles and Practices.

e. Rafai, H.R., Borden, J. Wilson, and C.H. Ward (1995). Intrinsic Bioattenuation for Subsurface Restoration. pp 1-30 in Hinchee, R.E., J. Wilson, and D. Downey (eds.) Intrinsic Bioremediation, Battelle Memorial Institute, Columbus, Ohio.

f. Wiedemeier, T.H., J.T. Wilson, D.H. Kampbell, R.N. Miller, and J.E. Hanson (1995). Technical Protocol for Implementing Intrinsic Remediation With Long Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater. Vols. 1 and 2. San Antonio, TX: Air Force Center for Environmental Excellence, Brooks Air Force Base.

g. Wiedemeier, T. H., M. A. Swanson, D. E. Moutoux, E. K. Gordon, J. T. Wilson, B. H. Wilson, D. H. Kampbell, P. E. Haas, R. N. Miller, J. E. Hansen, and F. G. Chapelle (1998). Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Groundwater. EPA/600/R-98/128.

General observations regarding the three ISTR technologies follow.

3.6.1. *Thermal Conductive Heating*. When operated with the aim of having the entire treatment zone attain temperatures above the boiling point of water (as for treatment of SVOCs), the temperatures achieved using ISTD TCH effectively sterilizes the soil in the treatment zone. When operated to accomplish in situ steam distillation of VOCs at temperatures below the boiling point of water, the sterilization effect may be somewhat lessened. In either case, however, microbiota are not permanently eradicated from the treated soil, and may repopulate the soil as it cools. Evidence suggests that a large fraction of the total organic carbon (TOC) remains after ISTD, probably because very high molecular weight compounds such as humic and fulvic acids are not destroyed at such temperatures. This TOC may serve as a carbon source for re-emerging microbiota. At the same time, ISTD tends to mineralize a certain fraction of the organic nutrients into inorganic forms which, being more water-soluble, are likely more bioavailable than prior to thermal treatment. This may help to explain the observation that vegetation has rapidly invaded and flourished on sites where ISTD had been conducted (Vinegar and Stegemeier 1999). Therefore, although research is currently lacking, one may expect that in situ biological degradation can resume after TCH, particularly in fringe zones surrounding the thermal treatment zone, and in the associated dissolved plume, where hydrocarbons may remain following thermal treatment of the source zone. In addition to high temperature applications, TCH may also be used in cold climates to slowly warm soils to accelerate biodegradation of organic contaminants.

3.6.2. *Electrical Resistivity Heating*. Biodegradation can be incorporated into ERH remediation applications. While ERH has the potential to heat the subsurface to the boiling point of water, this does not necessarily sterilize the subsurface. At one of the earliest full-scale applications of ERH in Skokie, Illinois, cis-1,2-dichloroethene (a daughter compound from the biodegradation of trichloroethene) was observed in the off-gas from the treatment area throughout the entire process (Beyke et al. 2000). During this period, concentrations of methane were also observed to increase in the off-gas. Methane (based on oxidation-reduction potential measurements in the groundwater) is believed to have been the result of the anaerobic biodegradation of organic material in the groundwater.

3.6.2.1. Biodegradation was also tracked isotopically at the Skokie Illinois location. Groundwater impacted by chlorinated aliphatic hydrocarbon becomes depleted in ^{13}C and enriched in ^{37}Cl during evaporation (ISTR operations), while during microbial degradation, isotopic concentrations in groundwater become enriched in both ^{13}C and ^{37}Cl (Sturchio et al. 2000). This relationship allowed researchers and the remediation engineer or project manager track the fate of the chlorinated aliphatic hydrocarbon and determine the nature of the remediation taking place. The isotopic data from the Skokie site showed biodegradation to be taking place during and after treatment.

3.6.3. *Steam Enhanced Extraction.* Biological degradation potential under steam injection can be assessed as part of a natural attenuation evaluation. The injection of steam, as described in Paragraph 2.3.3.1.4, creates a steam zone, a variable temperature zone, and an ambient temperature zone. The variable temperature zone, which may be relatively extensive in lower permeability settings, provides an environment to enhance biological activity. Biological activity may increase two- to three-fold for each 10ºC rise in temperature. Nutrients may be added (if necessary) to enhance bioactivity (Basile et al. 1994). At the first application of this approach in Skokie, Illinois, it is estimated that approximately 10,400 kg (23,000 lb) of trichloroethene and 1,1,1-trichloroethane were reductively dehalogenated (biodegraded) as part of the remediation, representing 36% of the mass removed or destroyed during the application period (Smith et al. 2000).