IN-SITU DELIVERY OF HEAT BY THERMAL CONDUCTION AND STEAM INJECTION FOR IMPROVED DNAPL REMEDIATION

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ABSTRACT: Thermal Conduction Heating (TCH) is a major component of In Situ Thermal Desorption (ISTD), a soil remediation technology in which heat and vacuum are applied simultaneously. Heat flows into the soil primarily by conduction from heaters typically operated between 1000 and 1500ºF (540 and 815ºC). The heaters are installed in wells at regular intervals within the soil. As the soil is heated, water is boiled and dense non-aqueous phase liquid (DNAPL) constituents in the soil are vaporized. The resulting steam and vapors are drawn toward extraction wells for in-situ and aboveground treatment. Compared to fluid injection processes, the conductive heating process is very uniform in its vertical and horizontal sweep. Field project experience at numerous TCH/ISTD sites has confirmed that maintaining target temperatures for several days results in extremely high destruction and removal efficiency of chlorinated volatile organic compounds (CVOCs), polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs) and other DNAPLs. Provided that water influx is managed, the effectiveness of the TCH/ISTD process is not limited by the presence of heterogeneous soil conditions or clay, and can be applied effectively below the water table. Despite high pre-treatment soil contaminant concentrations, post-treatment soil concentrations have typically been non-detect, with most of the contaminants (95-99% or more) being destroyed in the soil by hydrolysis, oxidation, and pyrolysis.

The TCH process progressively heats soil and soil fluids in a highly predictable way even under heterogeneous and saturated soil conditions, resulting in 100% sweep of the targeted DNAPL zone, and making it possible to offer guarantees of cleanup performance. Due to the invariability of thermal conductivity across a wide range of soil types and conditions, TCH does not demand as detailed knowledge of subsurface conditions as do technologies that depend on delivery of fluids. Nevertheless, TCH alone is not well suited to treatment of high-permeability zones below the water table without adoption of methods to manage groundwater influx. One of the most preferable of such methods is Steam Injection (SI), which can be combined with TCH in a variety of ways that offer synergies due to their complementary thermodynamics and logistics.

Analytical and numerical models are of particular value in TCH practice, in part because of the highly predictable nature of conductive heating. A simple example is provided showing how to estimate the heating budget and duration for a given site.

INTRODUCTION

TCH is an in-situ thermal remediation technique that relies on the use of heating elements, typically electrically powered, suspended inside steel pipes in contact with the soil. The operating temperature of the heating elements is typically between 1000-1500ºF (540-815ºC). Vertically oriented heaters are installed in the soil typically in triangular patterns, which at the scale of a well field appear as repeating series of hexagons (Figure 1). In a typical ISTD well field, a ring of "Heater-Only" (H-O) wells surrounds each "Heater-Vacuum" (H-V) well. An H-O well is comprised of a heating element inside of a heater can, the purpose of which is to inject heat into the ground. Wattages can vary depending on the application, but are generally ≤350 W/ft (1,150 W/m) of thermal well to avoid overheating the well materials. Silicon Control Rectifiers on each circuit permit the automatic regulation of the heaters based on the temperature of representative thermocouples. Other thermocouples are installed within the target treatment zone (TTZ) to enable monitoring of heating progress.

When the heaters are energized, heat is transferred from the heating elements to the walls of the heating pipes by radiation. Heat transfer from the hot pipes ("heater cans") through the surrounding soil is primarily by thermal conduction, with convection of fluids, primarily steam, playing a supporting role.

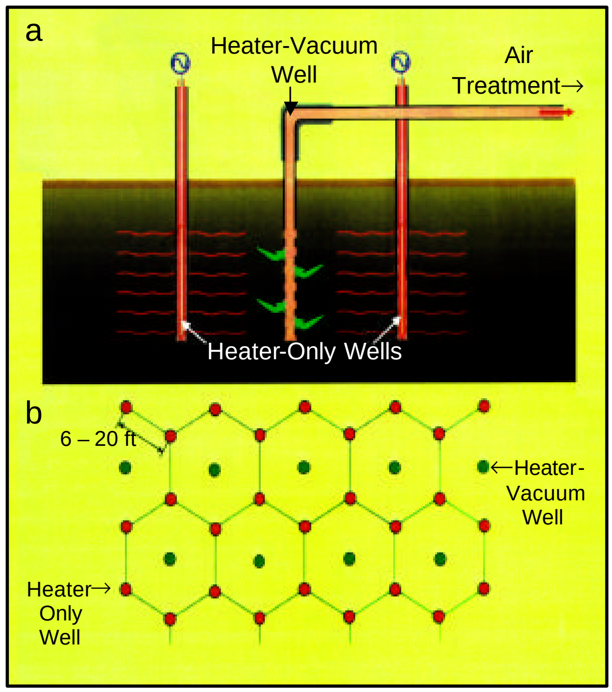

FIGURE 1. Schematic of Typical TCH/ ISTD Well Field. (a) Cross-section showing one Heater-Vacuum (H-V) well and two Heater-Only wells within a larger pattern. (b) Plan view showing thermal well field layout. H-V wells are located in the center of each hexagon, and well spacing typically ranges from 6 to 20 feet (1.8 to 6.1 m).

Figure 2 provides a qualitative snapshot of the transient distribution of temperature and water saturation around a TCH well. There are three distinct zones, the relative proportions of which will vary depending on soil properties:

- The dry conduction zone where pore water has been vaporized, while steep temperature gradients drive conductive heating with an energy flux oriented radially outward from the heater well.
- The convective zone characterized by varying water saturations, but a relatively constant temperature equal to the local boiling point of the pore water (212°F [100°C] above the water table, gradually increasing with depth below the water table). It is also referred to as a "heat-pipe" zone (Udell and Fitch 1985; Hiester et al. 2003), where steam generated by boiling transfers heat outward, while water wicks back towards the well by unsaturated flow, driven by a gradient in capillary pressure. This zone will vary in relative proportions over time and depending on soil properties.
- The saturated zone, where steam recondenses, and both hot water movement and thermal conduction lead to more distal heat propagation.

As heat propagates radially outward from each heater, the cylindrically shaped heated zones expand until they overlap and superimpose. While the heaters are energized, the highest temperatures are always closest to the heaters, and the relatively coolest temperatures within the TTZ are in the region midway between the heaters.

As the soil/waste is heated, contaminants are vaporized or destroyed by several mechanisms, including evaporation, steam distillation, boiling, oxidation, and pyrolysis. Vaporized constituents and steam are drawn toward heated extraction wells ("Heater-Vacuum" [H-V] wells), each of which consists of a heater can inside a screened well. The super-heated soil (e.g., at 1,100ºF [590ºC]) adjacent to the H-V wells comprises a hot packed-bed reactor, such that oxidation and pyrolysis reaction rates are very high relative to residence times. Typically ≥95-99% of the organic contaminant mass that moves through it undergo in-situ destruction (Baker and Kuhlman, 2002). The extracted vapors that remain after passage into the collection piping are treated in an aboveground Air Quality Control system.

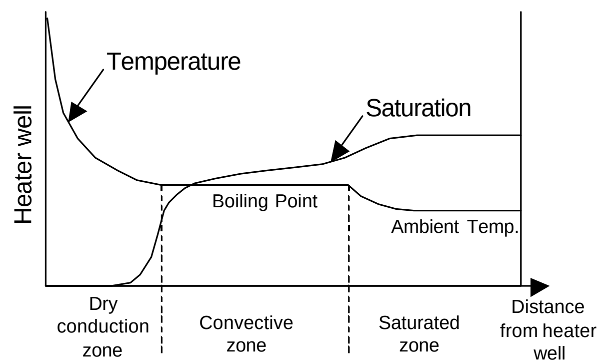

FIGURE 2. Conceptualized snapshot of transient temperature and water saturation with distance from a heater well.

Selection of the target temperature to be achieved between thermal wells depends on the physical properties of the highest-boiling contaminant of concern (COC). For CVOCs and non-CVOCs such as benzene, toluene, ethylbenzene and xylenes (BTEX), a target temperature of 212ºF (100ºC) has been demonstrated to be sufficient to achieve >99.9% removal from clay soil, mainly through in-situ steam distillation (LaChance et al. 2004a,b). For the treatment of higher-boiling semi-volatile organic compounds (SVOCs) such as PCBs, PAHs and dioxins, 617°F (325°C) has been demonstrated to be a suitable target temperature to accomplish >99.9% removal from sandy, silty and clayey sites (Stegemeier and Vinegar 2002; Bierschenk et al. 2004). Important distinctions between these two approaches are summarized in Table 1.

TABLE 1. Contrasting applications of TCH/ISTD.[1]

Contaminant Type	Target Treatment Temperature (°F [°C])	Thermal Well Spacing (ft [m])	Hexagonal Pattern Diameter (ft [m])	Desiccate Target Treatment Zone?	Typical Heating Duration (months)
SVOCs (PCBs, PAHs, dioxins)	>212 [>100]	6-7.5 [1.8-2.3]	12-15[3.7-4.6]	Yes	2 to 4
VOCs (CVOCs, BTEX)	212 [100]	12-20 [3.6-6.1]	24-40 [7.3-12.2]	No	4 to 12

[1]Values given reflect those required to achieve stringent remedial goals.

The closer the well spacing, the sooner target temperatures are achieved, so the choice of spacing tends to be dictated by balancing capital expenditures and operational costs. Note that the range of thermal well spacing for VOCs is consistent with those in common use by practitioners of Steam Injection (SI)/Steam Enhanced Extraction (SEE) and Electrical Resistance Heating (ERH) in heterogeneous formations. The ease of installation of TCH wells, especially of H-O wells, which can be installed rapidly and inexpensively (e.g., 200-400 linear ft/d [60-120 linear m/d] by direct-push methods), facilitates the construction of large thermal well fields, if needed. These attributes also open the way for TCH to be used in combination with other in-situ thermal technologies to treat a wider variety of sites than previously thought, as will be discussed below.

To ensure that all portions of the TTZ achieve the target temperature, heat losses to the surroundings must be factored into TCH/ISTD design. Typical measures include the following: (a) placing an additional row of H-O wells just outside the perimeter of the TTZ; (b) extending all the thermal wells at least 2-3 ft (0.6-0.9 m) below the bottom of the TTZ; and (c) installing an insulated surface cover over the TTZ, extending horizontally at least 10 ft (3 m) beyond its lateral extent. Having each hexagonal pattern include a screened H-V well (Figure 1b) ensures capture/treatment of mobilized vapors.

CHARACTERISTICS OF TCH

Thermal energy provided by THC wells heats the soil, water, and contaminants in a highly uniform manner, because thermal conductivity is one of the most invariant of all soil physical properties. In comparison with permeability values, which for the most widely contrasting soil materials, clay and gravel, can vary by a factor of at least one million, their thermal conductivity values vary by a factor of less than four in dry soil (Farouki, 1986), making THC a very precise and predictable process, regardless of the degree of heterogeneity. The reason for focusing on the dry soil thermal conductivity values is that with heaters operating typically between 1000 and 1500ºF (540 and 815ºC), the soil adjacent to the thermal wells quickly dries out, meaning that thermal conduction heat transfer occurs through an enveloping cylindrical zone of dry soil with a thermal conductivity typically ranging from 0.25 to 1.04 BTU/hr ft ºF (0.001 to 0.004 cal/s cm ºC). Steam is uniformly generated within the adjacent convective zone. In higher permeability zones beneath the water table, groundwater influx can prevent the soil from exceeding the boiling point of water adjacent to the THC wells, in which case either installation of a hydraulic barrier (e.g., slurry wall, steel sheeting, jet grout, freeze wall) may be required to control groundwater influx and achieve target temperatures, or a combination of TCH and SI can be used to heat such zones.

COMBINING TCH WITH SI

For sites with complex geology and layers with highly permeable materials (e.g., sandy or gravelly aquifers), a combination of TCH and SI can be used to address the entire TTZ (Figure 3). At each well location, TCH is used along the entire depth interval, and steam is injected into the permeable zones. The roles of the two heating techniques are as follows: **TCH** heats at all depths, including the bottom of the TTZ, where it can form a "hot floor" that prevents downward migration of condensate and/or DNAPL; heats the near-surface soils such that shallow NAPL condensation is prevented; and heats thick clay layers. **SI** is used to heat the permeable zones; and build a high-pressure steam-filled zone that reduces the water flow into the TTZ by reducing or negating the inward hydraulic gradient and by reducing the relative permeability of water within the steam-saturated porous media. The combined approach can be used to optimize overall heating and treatment efficiency, and reduce the operational period and cost.

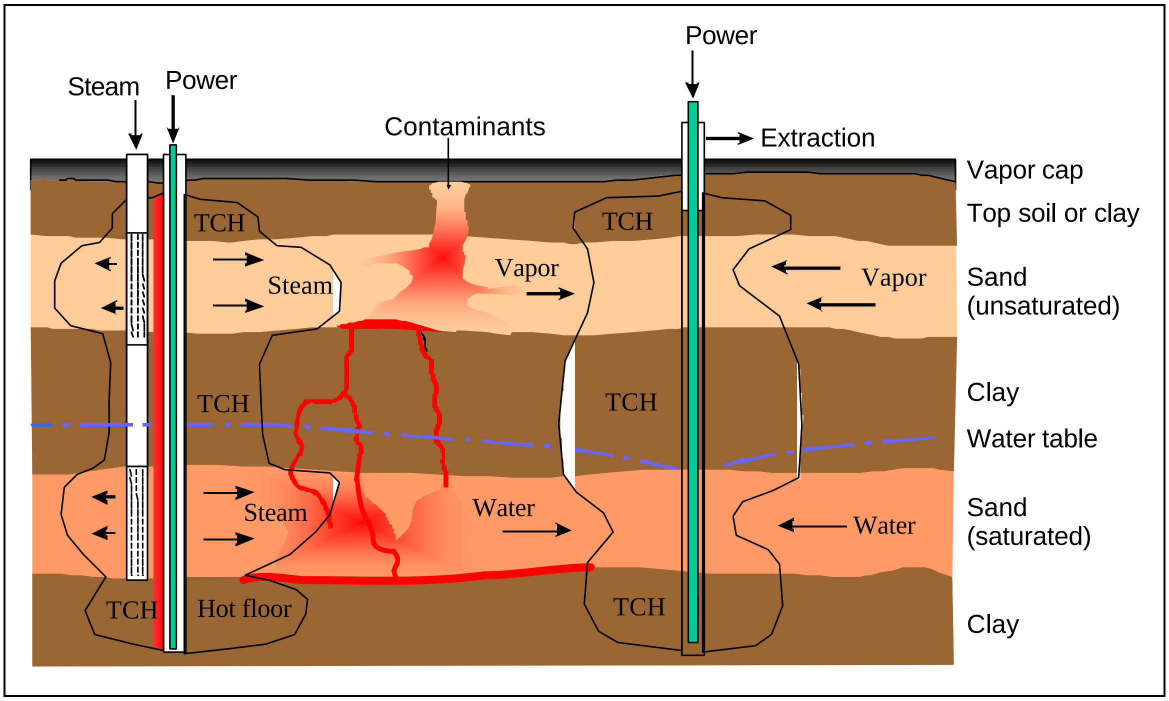

FIGURE 3. Combination approach for complex sites, using TCH and steam injection (SI) to heat and treat both high- and low-permeability zones.

Managing high permeability zones below the water table. For sites with zones of high permeability located below the water table, water management is required to minimize the amount of energy expended to heat groundwater that enters from the outside. Figure 4

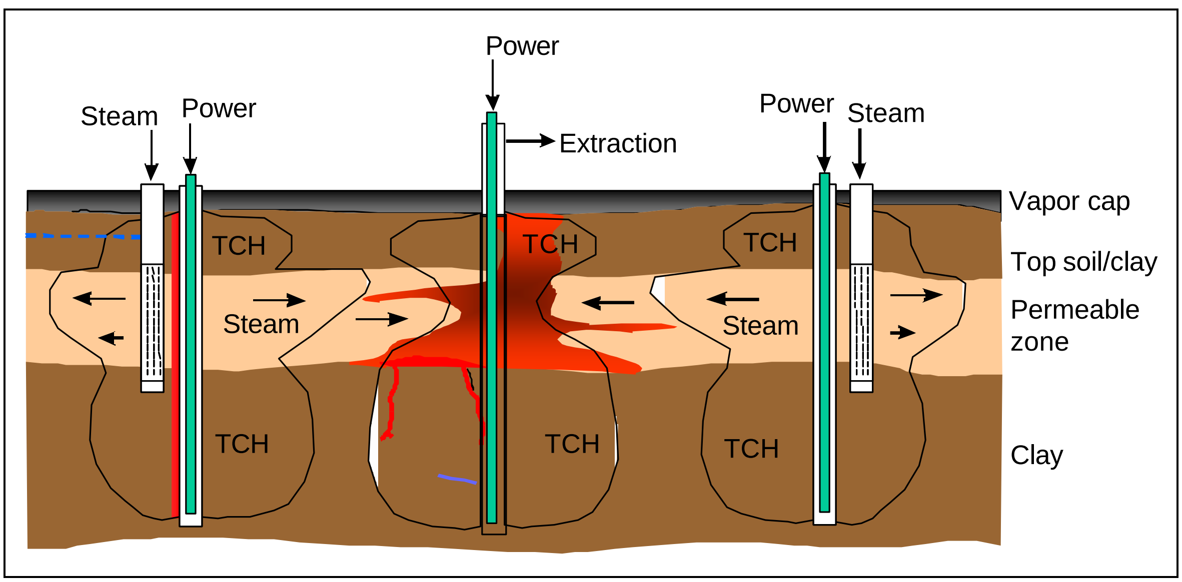

FIGURE 4. Schematic of combined TCH and SI to overcome water influx challenges in a high-permeability zone below the water table. The steam zone reduces water inflow by creating a perimeter steam barrier.

shows a conceptual approach for heating such a site, while minimizing water influx. The water is partially blocked by the formation of a perimeter steam zone, with the following advantages:

- The steam is injected over various depth intervals under pressures higher than that of the surrounding water, leading to a pressure barrier to water inflow.
- The steam zone reduces the relative permeability of water, thereby diminishing the water flow.
- Highly contaminated zones within the permeable layers can be flushed with several pore volumes of steam before they are heated to temperatures above the boiling point. This leads to NAPL displacement and removal and reduces corrosivity associated with destruction of large quantities of organics.

The combination of TCH and SI employs advantages of the combined approach, which is analogous to, but materially different than the Dynamic Underground Stripping technology (Daily et al. 1995).

ESTIMATING THE IN SITU HEATING BUDGET

Analytical and numerical models are essential tools in predicting the heat required to achieve target temperatures at a given site, regardless of the method of heating. A simple box model can be used to readily estimate the duration of heating, as functions of energy input and well spacing, necessary to heat solid and liquid phases within the TTZ. A multiplier can then be applied to factor in heat losses to the site's surroundings. The following example illustrates, for a hypothetical saturated silty-clay site, how one can employ Equation 1 to estimate the heating budget to: (a) raise the subsurface temperature within the TTZ to the boiling point of water (i.e., to accomplish steam-distillation and hydrolysis of CVOCs); (b) boil off a portion of the pore water initially present (e.g., by superheating the soil within 2 to 3 ft [0.6 to 0.9 m] of TCH wells; and (c) boil off a fraction of the water outside those zones. Note that the given parameters can be easily varied to provide estimates for specific site conditions of interest.

$$[r_R\, C_R\, (1-f)+r_w\, C_w\, f\, S_w](T_b-T_i)]+[r_R\, C_R\, (1-f)f_b](T_f-T_b)+r_w\, h_w\, f\, S_w\, f_b = b\, t_h /A \qquad (1)$$

r_R = density of solids (quartz: 2.650 x 10^6 g/m^3)
C_R = heat capacity of the solids (silica: 1.211 x 10^{-5} W·d/g °C)
f = mean porosity of silty-clay soil (typical range 0.25 to 0.50)
r_w = density of water (1.00 x 10^6 g/m^3)
C_w = heat capacity of water (4.846 x 10^{-5} W·d/g °C)
S_w = initial water saturation (fraction of the pore space occupied by liquid water)
f_b = fraction of the soil volume within the TTZ in which water will boil off by the end of the treatment period (typical value of 0.25 derived from past ISTD simulations and field measurements)
T_b = boiling point of water at atmospheric pressure (100°C)
T_i = initial temperature of subsurface
T_f = final temperature value for superheated soil in close proximity to TCH wells
h_w = latent heat of vaporization of water (0.0261 W·d/g = 2,240 kJ/kg)
b = average power input per unit length of TCH well (~1000 W/m)

t_h = time required to heat to target temperature, and boil off the expected fraction of the initial water (days)

A = area heated by each well embedded within an equilateral triangular pattern of wells (example: 18.3 m^2 per well for 4.6 m [15 ft] spacing)

The 1st term on the left of Equation 1 is the energy required to heat the mineral grains to the boiling point of water; the 2nd term is the "sensible" energy required to heat the pore water to its boiling point; the 3rd term is the energy required to superheat a fraction, f_b of the mineral grains past the boiling point of water; and the 4th term is the energy required to vaporize the fraction, f_b of the initial water content that is expected to boil. The right-hand side of the equation is the energy input by a TCH well within a well field into the soil volume surrounding that well. Note that f, S_w, T_i, b and A are typically user-specified input values, while the remaining terms are constants, except for t_h (to be solved for). Equation 1 does not account for conductive heat losses to the adjacent formation and overlying surface (typically 20% of the energy input), nor for convective heat losses through: (a) collected gas (typically ~1/3rd of the energy input to the H-V well only, which for a 2:1 ratio of H-O:H-V wells (Figure 1) is equivalent to ~10% of the energy input to the TTZ), and (b) water that originates from outside the treated volume (given the low permeability, expected to be no more than 10% of the energy input). These user-specified factors (20+10+10=40%), plus a 10% contingency call for multiplying the heating budget by a factor of 1.5. Rearranging Equation 1 to solve for t_h:

$$t_h=(1.5A/b)\{[r_R C_R(1-f)+r_w C_w f S_w](T_b-T_i)]+[r_R C_R(1-f)f_b](T_f-T_b)+r_w h_w f S_w f_b\} \qquad (2)$$

For typical sites, the time t_h required to heat the soil and boil off the expected fraction of the water initially present under the stated conditions and thermal well spacing is between 60 and 150 days. This prediction corresponds well with field experience under similar treatment conditions (e.g., CVOCs in saturated silty-clay soil at a recently completed TCH/ISTD site [LaChance et al. 2004a]). Using Equation 2, the total energy consumed per unit soil volume (m^3) can be estimated as P = 24 kW *[$t_h b/A$]. Typical energy requirements are in the 100-250 kWhr/m^3 range for CVOCs, equal to a power cost of \$6-20/m^3(\$4.60-15/cy), and in the 300-500 kWhr/m^3 range for SVOCs (\$20-40/m^3 [\$15-30/cy]).

Results of 3-D numerical simulations of TCH/ISTD underscore the importance of proper placement of TCH wells relative to the geometry and boundary conditions of the TTZ in minimizing energy input and preventing unwanted condensation of vapors in cool adjacent zones. Although it is beyond the scope of this paper to include examples of such simulations, they play an essential role in TCH/ISTD design and process optimization (e.g., Baker and Kuhlman 2002; Baker et al. 2004), and will continue to do so as we combine TCH/ISTD with SI/SEE technologies and apply them to treat DNAPL in challenging subsurface settings including heterogeneous aquifers and fractured rock.

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