

# Chapter 18

## Advances in Low-Temperature Thermal Remediation



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**Abstract** Remediation through traditional high-temperature thermal techniques (over 100 °C) are designed to remove contaminants like petroleum hydrocarbons via enhanced mobilization and volatilization. However, remedies of this nature can require significant infrastructure, capital, operational and maintenance costs, along with high energy demands and carbon footprints. Conversely, low-temperature thermal approaches (in the mesophilic range of ~15–40 °C) are an inexpensive and more sustainable method that can enhance the physical, biological, and chemical processes to remove contaminants. Heat transfer properties of subsurface sediments and other geological materials do not vary considerably and are relatively independent of grain size, unlike hydraulic properties that can vary several orders of magnitude within a site and often limit the pace of remediation of many in-situ technologies. Therefore, low-temperature thermal remediation is a promising alternative that can remediate contaminant mass present in both high- and low-permeability settings, including fractured rock. Emergence of risk-based non-aqueous phase liquid management approaches and sustainable best management practices further offer a platform for low-temperature thermal remedies to advance petroleum hydrocarbon remediation with lower capital and operational costs. Case studies demonstrating

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this approach along with preliminary sustainability comparisons of the associated reduced energy use and carbon footprint are described in this chapter.

**Keyword** Enhanced biodegradation · Heat transfer · Petroleum hydrocarbons · Solar energy · Sustainable site management

## 18.1 Emergence of Low-Temperature Thermal Remediation

In-situ thermal remediation (ISTR) technologies include various methods for applying energy to the subsurface to raise in-situ temperatures within a targeted treatment area. Traditional ISTR is generally considered an enhanced physical recovery technology for volatile organic compounds (VOCs) and select semi-volatile organic compounds because it is typically employed in combination with physical extraction methods (e.g., multiphase extraction, soil vapor extraction [SVE]) with ex-situ treatment of recovered vapors/fluids. The primary effect of introducing heat to the subsurface is enhanced VOC mass transfer to the vapor phase by increasing vapor pressures and volatilization rates, increasing the air permeability of the soil, and enhancing the gas-phase diffusion process, thereby significantly improving overall contaminant mass removal rates. Therefore, conventional “higher temperature” ISTR technologies (i.e., thermal conduction heating [TCH], electrical resistive heating [ERH], and steam-enhanced extraction) are designed to achieve subsurface temperatures (> 100 degrees Celsius [ $^{\circ}\text{C}$ ]) with the objective of rapid removal of high mass contamination including non-aqueous phase liquids (NAPLs) from source zones. However, it has been observed that elevated subsurface temperatures may persist up to two years after ISTR operations are terminated (Krauter et al. 1995) and this residual heat can enhance microbial activity, resulting in further degradation of contaminants and/or increased release of electron donors via hydrolysis (Suthersan et al. 2012; Macbeth 2019).

Over the past two decades, numerous field- and bench-scale studies have demonstrated accelerated rates of biotic and abiotic degradation mechanisms based on increased temperature (e.g., Dablow et al. 1995; Powell et al. 2007; Truex et al. 2007). Truex et al. (2007) referred to this as “fortuitous” remediation where enhanced contaminant degradation was seen as temperatures cooled but remained more than typical background temperatures, conditions that prevailed for months following the end of subsurface heating. Recently, low-temperature thermal remediation (LTTR) approaches have been developed that integrate all the above and (for situations appropriate) target subsurface temperatures far lower than temperatures achieved with conventional higher temperature thermal remedies. The infrastructure requirements to achieve lower temperature goals can be far simpler than a conventional thermal application, but the approach still relies on the fundamentals of heat transfer.

Until relatively recently, the focus of LTTR has mainly been on abiotic chemical reactions (such as hydrolysis and dehydrohalogenation) that can be greatly enhanced for some contaminants under comparatively low subsurface temperatures (generally less than 70 °C). However, the ability to stimulate biotic mechanisms for contaminant degradation has received less attention despite the available supporting fundamental research.

Studies have also indicated that for microbial consortia existing in the soil, a corresponding threefold increase in biodegradation rates of benzene, toluene, ethylbenzene, and total xylenes (BTEX) can occur by raising the temperature from 20 to 30 °C (Margesin and Schinner 2001; Dettmer 2002). Kulkarni et al. (2022) reported that increasing the temperature by 10 °C could double natural source zone depletion (NSZD) rates in NAPL-impacted sites. Another study on petroleum hydrocarbon biodegradation rates due to increase in temperature has shown peak degradation rates between 30 and 40 °C (Xu 1997). Temperatures above the operating range for a type of microorganism may result in a switch in the microbial consortia, and changes in microbial biochemistry may be observed. From a field remediation perspective, 15–40 °C seems to be the operational range for enhancing most biological treatment mechanisms that can be enhanced by increasing temperature.

Physical extraction systems (e.g., ex-situ groundwater treatment, air sparge [AS]/SVE) remain important conventional solutions to address contaminant mass, particularly in zones of high concentration and fine lithological formations. Combining low-temperature thermal remediation with physical extraction systems has the potential to enhance mass recovery via liquid extraction, volatilization or gradually increasing NAPL dissolution. These enhanced mechanisms can provide a low-cost way to improve the effectiveness of an existing physical extraction systems while lowering cleanup timeframes.

In this chapter, we explore the basis for the approaches mentioned above through a discussion of the following:

- Effects of temperature on certain chemical properties and degradation potential of constituents of concern (COCs);
- The fundamentals of in-situ heat transfer important to LTTR, including thermal modeling;
- Types of contemporary and advanced LTTR approaches;
- Case studies that represent state-of-the-practice applications and performance of LTTR technologies to treat petroleum hydrocarbons; and
- Potential advantages and benefits of the approaches in treating sites with low-permeability geologic materials and in developing sustainable remedial strategies.

The last item includes opportunities in utilizing sustainable sources of heat, such as solar energy and waste heat, significantly enhancing the sustainable aspects of the approach. We explore both with a detailed review of how to implement such an approach and multiple example field applications to demonstrate the potential of the technique.

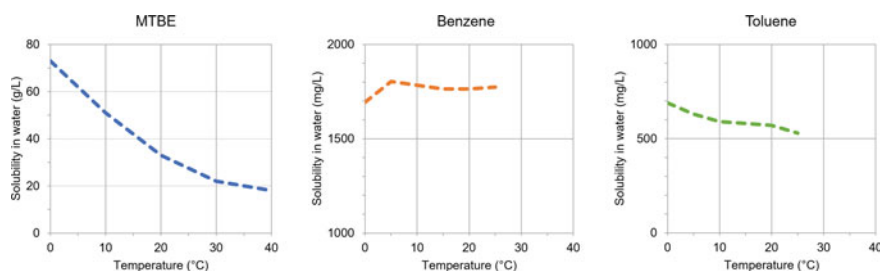
## 18.2 Temperature-Dependent Contaminant Properties

As the temperatures in the subsurface change, important aspects of the behavior of the COCs will also change. For the purposes of this discussion, we will focus on the enhancing effect on contaminant partitioning followed by contaminant degradation.

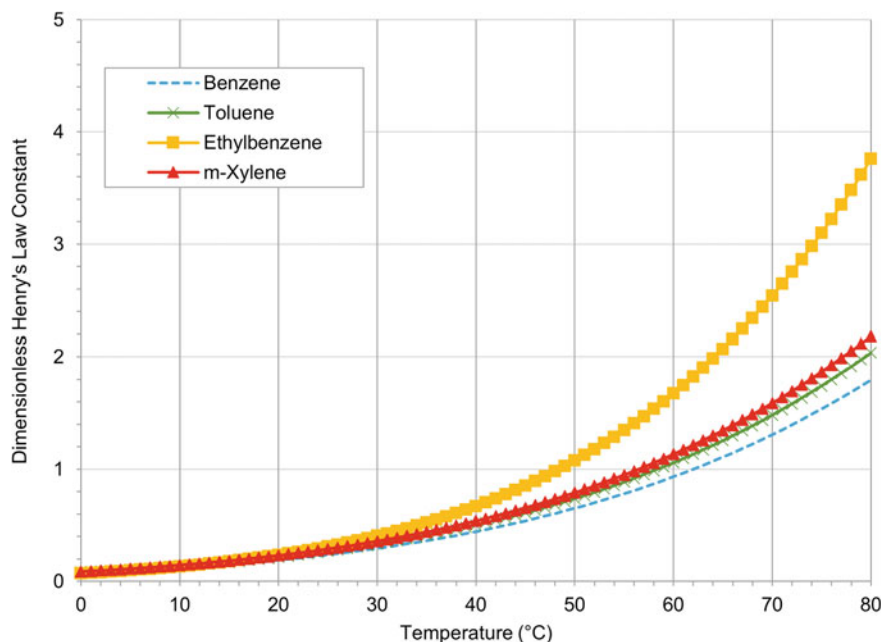
### 18.2.1 Contaminant Partitioning

In general, an increase in temperature can increase the solubility of organic contaminants in water, enhancing NAPL dissolution and contaminant recovery rates of groundwater-focused remedies. However, solubility dependence on temperature can be complex, particularly in the context of petroleum mixtures, where COCs for remediation are a small portion of the large number of compounds present. This needs to be carefully considered because the solubility enhancement of different contaminants may behave differently as temperatures change. Published solubility data for petroleum hydrocarbon compounds span a range of values, with authors reporting different results and noting that contradictory or conflicting values in literature are common. This variability may be due to differences in accounting for effects of phase change, biodegradation, and co-occurring compounds present in petroleum mixtures. However, published data can generally be helpful in assessing the potential effects of heating on dissolution. Figure 18.1 compares the approximate solubility of methyl tert-butyl ether (MTBE), benzene, and toluene. These concepts are discussed in detail by the US Environmental Protection Agency (USEPA) in the supporting documentation for their On-Site Assessment Tool (USEPA 2021).

The increase in temperature can also enhance dissolved phase/vapor phase partitioning for those same higher molecular weight chemicals as measured by changes in Henry's Law constants, as shown in Fig. 18.2. Henry's Law constants represent the proportionality between the gas phase and the dissolved phase for VOCs; therefore, as the Henry's Law constant increases so does the susceptibility of those contaminants to partitioning from the dissolved phase to the vapor phase.



**Fig. 18.1** Solubility of MTBE, benzene, and toluene relative to temperature (data from USEPA 2021, adapted from Shaw 1989 and Peters et al. 2002)



**Fig. 18.2** Henry's Law constant relative to temperature (adapted from Sander 2015 and Staudinger and Roberts 2001)

When considering physical extraction systems (e.g., ex-situ groundwater treatment, AS/SVE) together with LTTR, the potential to increase volatilization can make the recovery of organic contaminants easier. The relationship between Henry's Law constants and temperature for COCs can be used to evaluate the potential for increased risk of vapor intrusion exposures during heating. This is a common concern raised during remedy evaluation and planning stages for LTTR approaches. It should be noted that temperature-dependent increases in volatilization or dissolution of constituents will likely be occurring simultaneously with temperature-dependent increases in biotic and abiotic degradation of volatilized or dissolved mass. Increases in mass transfer rates and increases in degradation rates can act to balance each other to some degree, making the net effect on exposure potentially lower than would be predicted through the evaluation of changes in mass transfer alone. As such, empirical evaluation of constituent concentrations in the medium or media of concern (e.g., monitoring of concentrations in soil gas or groundwater) is likely the most appropriate way to assess potential exposure concerns.

### 18.3 Temperature-Enhanced Biological Degradation

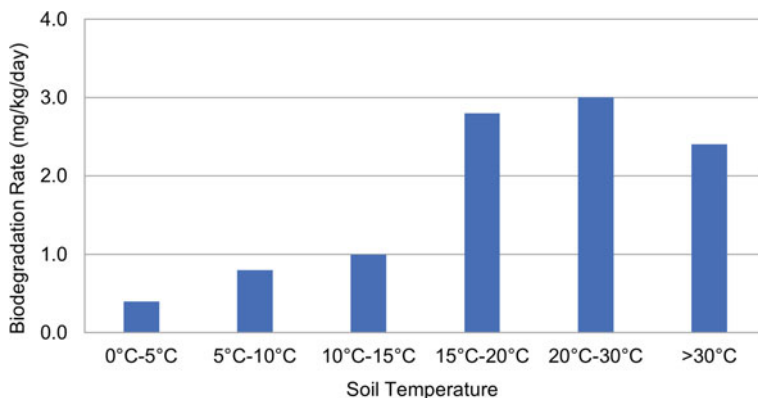
As remediation practitioners' understanding of biodegradation has grown, these natural processes are increasingly recognized as major contributors to positive remedial outcomes and observed successes at petroleum sites, even at sites where engineered mass transfer and mass removal (e.g., AS, SVE, and light non-aqueous phase liquid [LNAPL] pumping) were previously thought to provide the bulk of remedial benefit. Relatively modest increases in temperature can substantially accelerate biological reactions and offer important possibilities for engineering of in-situ bioremediation approaches.

Overall, the process of anaerobic, methanogenic biodegradation of organic material is well-understood through past work in engineered systems (e.g., study of landfills and anaerobic digesters in wastewater treatment) and the study of sites such as the U.S. Geological Survey's National Crude Oil Spill Fate and Natural Attenuation Research site located near Bemidji, Minnesota (Essaid et al. 2011; Garg et al. 2017). Microorganisms relevant to in-situ contaminant degradation are often classified based on the temperature range at which they are most active or prolific. Table 18.1 provides an example classification following this approach (Dettmer 2002). Mesophilic and thermophilic bacteria are promising for biodegradation of hydrocarbons with low water solubility, as solubility and subsequent bioavailability are enhanced at elevated temperatures (Margesin and Schinner 2001).

In general, a temperature range of 15–40 °C is conducive to favorable rates for typical biodegradation processes, with kinetics increasing toward the upper end of that range (Daniel et al. 2000). This is especially true for BTEX compounds as shown in Fig. 18.3. Maximum biodegradation rates in engineered anaerobic systems are often observed in the vicinity of 35–40 °C (Gerardi 2003; Xu 1997). Additionally, laboratory-observed biodegradation rates of LNAPL were found to be 0.002 mg L/h, 0.008 mg L/h, 0.012 mg L/h, and 0.015 mg L/h at increasing soil–water temperatures of 4 °C, 20 °C, 28 °C, and 36 °C, respectively (Yadav and Gupta 2022). Beyond 40 °C, biological degradation mechanisms may be limited by the decomposition or denaturing of enzymes involved in degradation pathways. Additionally, for in-situ systems where direct manipulation of the microbial population is difficult, the maximum attainable increase in biodegradation rates may come from modest increases in subsurface temperature (e.g., raising temperature to levels at the high end of historical natural ranges for a site, allowing the native microbial population

**Table 18.1** Microorganisms classified based on temperature range (adapted from Dettmer 2002)

Classification	Low (°C)	High (°C)
Psychrophilic	0	20
Mesophilic	20	40
Thermophilic	40	80
Hyperthermophylic	80	> 100



**Fig. 18.3** BTEX biodegradation increase with soil temperature (adapted from Dettmer 2002)

to thrive rather than creating higher-temperature conditions suitable for microbes which may not be abundant) (Zeman 2013).

The natural degradation processes typically in place at petroleum hydrocarbon release sites are complex, and research into specific components and limiting factors is ongoing as part of work on natural source zone depletion. In general, however, a typical petroleum hydrocarbon site undergoing natural degradation will exhibit a strongly reducing zone of acetogenesis, fermentation, and methanogenesis in an anaerobic setting. Methane is often subsequently oxidized by subsurface bacteria as soil vapor reaches more aerobic conditions distant from the petroleum source, yielding carbon dioxide as the primary degradation product. The conversion of heavier petroleum compounds to methane and carbon dioxide as part of these processes can be tracked using established soil gas flux measurement methods (as described in American Petroleum Institute Publication 4784, API 2017) to evaluate approximate contaminant degradation rates.

Aerobic degradation processes can also be accelerated through temperature increases, leading to potential benefits from addition of low-temperature heating to traditional biosparging and bioventing systems designed to maintain oxygen-rich subsurface environments for petroleum degradation. The basic relationship between kinetics of aerobic hydrocarbon degradation and temperature, with increased oxygen utilization at temperatures of 20–30 °C, is well-documented in a variety of settings (e.g., Thamdrup et al. 1998). Furthermore, the exothermic nature of aerobic oxidation of hydrocarbons can create substantial heat, leading to a positive feedback loop and reducing the need for external energy inputs as biodegradation rates accelerate. A variety of performance indicators can be used to track progress of thermally enhanced aerobic biodegradation systems, including subsurface heat flux, oxygen utilization, and carbon dioxide generation.

## 18.4 In-Situ Heat Transfer Considerations

The application of LTTR generally involves the direct transfer of heat from an energy source to a delivery point (e.g., borehole heat exchanger [BHE]) installed within the subsurface. The fundamentals of heat transfer in porous media involve the following three primary mechanisms:

**Conduction:** This mechanism requires physical contact and is driven by temperature differences. The rate of heat flux is proportional to the magnitude of the temperature gradient, the surface area involved in the transfer, the properties of the matrices through which the heat must be transferred, and the length of the travel path.

**Convection:** This mechanism involves the transfer of heat associated with the macroscopic movement of fluids, which expand and become less dense when heated. This density change causes the hot fluid to rise, displacing cooler fluid that will sink. This can set up a circular current until the fluid temperature approaches the temperature of the heat source, which is generally a solid surface. Like conduction, convection is driven by the magnitude of the temperature gradient, the surface area of the heat source, and the properties of the fluid (including its bulk motion and permeability of the medium).

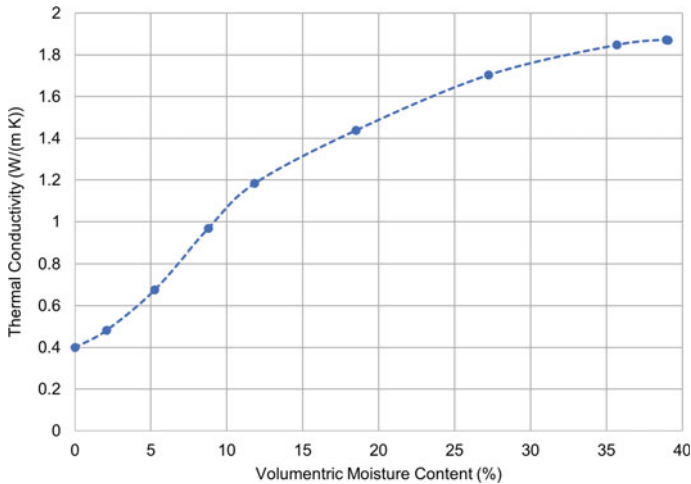
**Radiation:** This is the only transfer mechanism that does not require direct contact. All objects radiate thermal energy based on their temperature, the hotter the object the more it radiates.

Conduction and convection are the main heat transfer mechanisms that govern the resulting temperature distributions during LTTR applications. More often, advection (the flow of fluids) can inhibit heating by continuously exchanging the fluid volume with fresh unheated fluid, a factor that must be identified and considered during the design stage. To help explain, we can consider a unit volume within the subsurface that contains solid material and void space (i.e., pores). The solid material can consist of different types of rocks, minerals, and organic materials of various shapes and sizes. The pore space can contain varying amounts of gases and liquids. The composition of the unit volume leads to variations in the thermal properties. Heat transfer by thermal conduction is related to its effective thermal conductivity, which is a measure of its ability to transmit heat by way of random molecular motion. This is represented in the energy conservation equation (Eq. 18.1) that governs subsurface temperature distribution (Hegele and McGee 2017):

$$\nabla \cdot [\lambda \nabla T] - \rho C_f q_f \cdot \nabla T + U = \frac{\partial}{\partial t} (\rho C T) \quad (18.1)$$

where  $\lambda$  is the bulk thermal conductivity (watts per meter-kelvin [W/mK]),  $T$  is temperature (K),  $\rho C_f$  is the volumetric heat capacity of the fluid,  $q_f$  is the Darcy velocity,  $U$  represents the heat source/sink term (watts per cubic meter [W/m<sup>3</sup>]), and  $\rho C$  is the bulk volumetric heat capacity of the unit volume. It should be noted that soil thermal conductivity is affected by water saturation. Figure 18.4 presents





**Fig. 18.4** Laboratory-measured relationship between thermal conductivity and saturation for a silty sand

a laboratory-measured relationship between thermal conductivity and the saturation of a silty sand. In this case, the relationship is nonlinear and the thermal conductivity of the soil under fully saturated conditions is more than six times higher than when it is completely dry. In some cases, it may be important to measure or use tools to predict this relationship (e.g., Likos 2014; Zhang and Wang 2017) and use this understanding to further parameterize predictive models.

Heat capacity is another important physical characteristic of any material relative to the ability to conduct heat and represents the ratio of heat added to (or removed from) an object to the resulting temperature change. This can be used to determine the thermal diffusivity, which is a measure of a material's ability to conduct heat relative to its ability to store heat (i.e., thermal conductivity divided by heat capacity). When heat is applied to a unit volume of soil, the heat flux through the unit volume will depend on the effective thermal conductivity and the corresponding rise in temperature will depend on the thermal diffusivity (in turn controlled by specific heat capacity) and amount of time involved in the heat transfer.

From a practical perspective, the heat transfer properties of a subsurface soil matrix do not vary considerably, unlike hydraulic properties that can vary many orders of magnitude. Consequently, where relevant, LTTR can reach contaminant mass that other technologies reliant on subsurface permeability characteristics cannot readily access. Compared to fluid injection processes, the conductive heating process is very uniform in its vertical and horizontal sweep (i.e., the entire treatment zone can be heated). This is governed by the thermal conductivity of a wide range of soil types only varying by a factor of about four over the complete range of soil types (sand, silt, clay, gravel, and even bedrock) and moisture contents. Thus, even in highly heterogeneous settings, heat transfer in both high- and low-permeability aquifer settings, including fractured rock, can be robust and highly predictable if designed,

**Table 18.2** Comparison of thermal and hydraulic conductivity of varying lithologies (adapted from Marquez et al. 2016; Freeze and Cherry 1979; and Wong et al. 2009)

Media	Thermal conductivity range (W/mK)	Hydraulic conductivity range (m/s)
Basalt	1.3–2.3	$5^{-7}$ – $5^{-2}$
Clay	0.9–2.3	$9^{-12}$ – $9^{-9}$
Gabbro	1.7–2.5	$2^{-9}$ – $6^{-4}$
Gneiss	1.9–4	$2^{-9}$ – $6^{-4}$
Granite	2.1–4.1	$2^{-9}$ – $6^{-4}$
Gravel	1.8–1.8	$1^{-3}$ –1
Greenstone	2–2.9	$2^{-9}$ – $6^{-4}$
Limestone	2.5–4	$5^{-10}$ – $2^{-6}$
Loam	1.5–3.5	$1^{-7}$ – $1^{-3}$
Marble	1.3–3.1	$2^{-9}$ – $6^{-4}$
Mica schist	1.5–3.1	$2^{-9}$ – $6^{-4}$
Peat	0.2–0.7	$10^{-5}$ – $10^{-8}$
Peridotite	3.8–5.3	$2^{-9}$ – $6^{-4}$
Quartzite	3.6–6.6	$2^{-9}$ – $6^{-4}$
Salt	5.3–6.4	
Sand	1.7–5	$6^{-6}$ – $1^{-2}$
Sandstone	1.3–5.1	$1^{-10}$ – $6^{-6}$
Shale	1.5–2.1	$1^{-13}$ – $9^{-10}$
Silt	0.9–2.3	$2^{-10}$ – $5^{-5}$
Siltstone	1.1–3.5	

constructed, and implemented properly. Table 18.2 compares corresponding ranges to both thermal and hydraulic conductivities associated various subsurface lithologies.

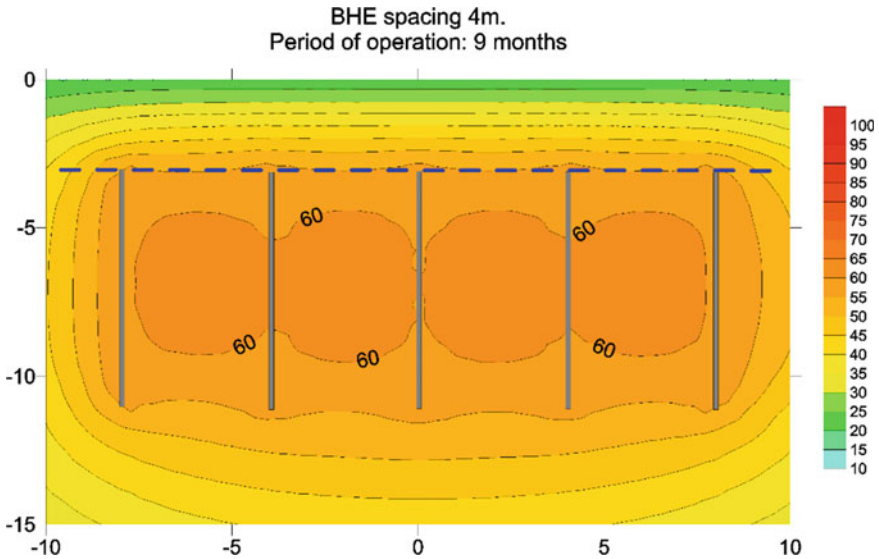
In low-permeability formations, an entire targeted treatment zone can be heated to a desired treatment temperature regardless of the challenges in moving fluids through the same formation. While the above is true, careful consideration of the subsurface properties is important to ensure that a LTTR system design will ultimately raise the temperature of the subsurface to the desired target in the desired timeframe. Effective thermal conductivity does still vary (Brigaud and Vasseur 1989; Abu-Hamdeh 2003), which requires an understanding of subsurface composition and thermal modeling to simulate the subsurface temperatures expected to be achieved. The modeling can predict the magnitude of heating that can be achieved relative to remediation goals, by factoring in the heat source, the properties of the subsurface matrix, and the impact of, for example, heat loss due to radiation (although minimal) and advection. This is discussed in more detail below.

## 18.5 In-Situ Heat Transfer Modeling

Thermal modeling software is commonly used to simulate the subsurface temperatures expected to be achieved and support the overall design of a thermal remediation system. The model is used to determine the magnitude of impact that certain parameters have on heating, such as various sources of heat loss, which can lead to a more optimized design. To improve the accuracy of such predictions, there has been significant work to better predict thermal conductivity for such applications (Berdal et al. 2006; Rubin and Carlton 2017). Many different analytical and numerical models are available in the marketplace that can be utilized. For example, the Department of Energy TMVOC multiphase flow code (Pruess and Battistelli 2002) is comprehensive and robust, and considers the three-dimensional compositional flow of a gas, aqueous, and NAPL phases with full partitioning of contaminants between the phases. Each phase flows in response to gravitational and pressure forces with relative permeability and capillary pressure effects. Additionally, the heat transfer occurs by conduction, and by convection of both latent and sensible heat in each phase. The thermodynamic effects of evaporation and condensation are included in the energy balance, and the chemical properties (vapor pressure, Henry's Law constant, solubility) are temperature-dependent. Alternately, the simpler modeling software FlexPDE<sup>®</sup>, a two-dimensional simulation solving heat balance equations on a finite element grid has been used for Thermal In-situ Sustainable Remediation (TISR<sup>®</sup>) applications, with empirical temperature data used to refine the model and improve predictions. Figure 18.5 depicts the modeling output for an TISR<sup>®</sup> installation showing the ability to achieve temperatures between 40 and 60 °C (enhancing hydrolysis reactions) after nine months of operation at a site in Mexico where five BHE were placed 4 m apart (Horst et al. 2018).

Recently, previously published analytical solutions (e.g., Molina-Giraldo et al. 2011) were utilized to develop a full three-dimensional BHE model that is incorporated into the widely used Microsoft Excel program (Ornelles 2021). The Excel-based tool uses a Visual Basic code to utilize super positioning of an analytical model to predict changes in space and time associated with customizable BHE arrays (Ornelles 2021). In this tool, the propagation of heat applied to the subsurface through discrete BHEs can be simulated over time. The model can account for groundwater flow and considers vertical heat flow, both up to the ground surface and down below the heater. This program was used to perform a preliminary analysis of the degree of heating expected from a BHE array at a specific site located in California.

The Darcy velocity at the test location considered by Ornelles (2021) and Ornelles et al. (2023) is expected to be low, on the order of 0.03 m per day (0.1 foot per day), and the flow is in the westerly direction. For the purpose of this preliminary model, the porosity was assumed to be 0.3, the grain density was set to 2650 kg per cubic meter, the grain heat capacity was 1000 J per kilogram per °C, and the thermal conductivity was 2.5 W/m °C. Based on the experience from similar solar heating thermal projects, the average power to each borehole was assumed to be ranging from 53 to 66 watts per meter. The BHE array consists of eight heat exchangers that extend



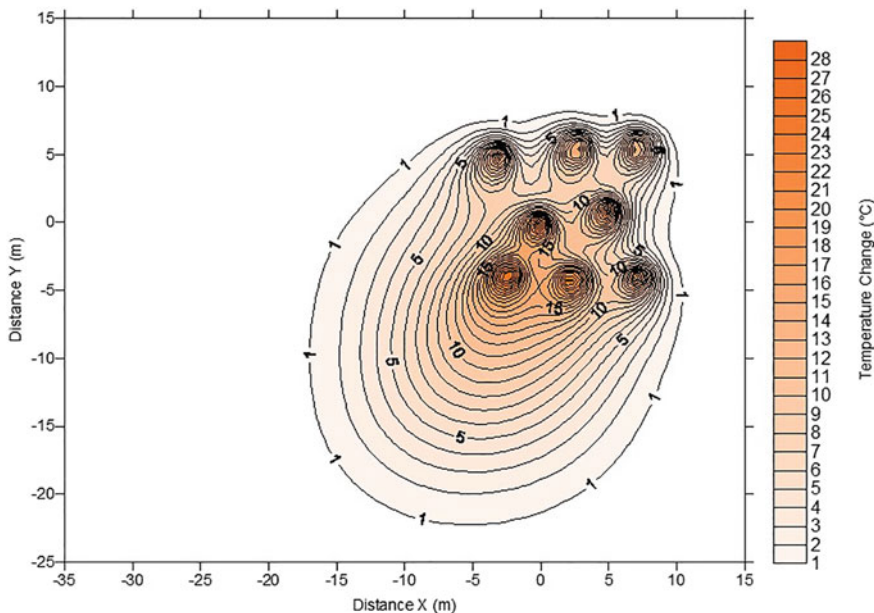
**Fig. 18.5** FlexPDE<sup>®</sup> model output for a TISR<sup>®</sup> installation showing the ability to achieve temperatures between 40 and 60 °C in the treatment zone after nine months of operation at a site in Mexico (Horst et al. 2018)

from a depth of about 6 m to a depth of about 12 m (~20–40 feet). The boreholes are arranged in a triangular arrangement, and the spacing distance was optimized through iterative modeling. The final design was based on a spacing distance of 4.9 m (16 feet) between boreholes. The simulation was run for a total time of 1.5 years.

Figure 18.6 shows a plan view (elevation is 9 m below ground surface) of the predicted temperature increase (in °C) after 400 days of heating. Each contour line represents 1 °C of temperature increase over background. The effect of groundwater flow is evident, and the predicted average temperature increase inside the BHE array is about 10 °C (for 400 W average thermal power to each BHE), except immediately near the BHEs, where the temperature increase may be as high as 15–20 °C.

## 18.6 Low-Temperature Heating Methods

Currently, there are several conventional ISTR heating technologies that can be utilized for low-temperature thermal remediation and include ERH and TCH. Other traditional heating equipment that can be used include inline/instantaneous water heaters or geothermal heat pumps combined with open-loop (hot water flushing) and/or closed-loop (heat exchange) systems. Recently, sustainable sources of heat such as solar or capturing waste heat have come into the marketplace and are being utilized for reduced carbon footprint remediation. Selection of the appropriate heating



**Fig. 18.6** Map view of simulated temperature increase ( $^{\circ}\text{C}$ ) after 400 days of heating with a thermal power of 400 watts per heater (figure courtesy of Justin Trainor and Ron Falta using the model tool described in Ornelles 2021)

technology is dependent on chemical and physical properties of the targeted COCs; concentration and mass distribution; the geologic/hydrogeologic setting in which heating will be employed; remedial objectives; source and magnitude of sustainable energy available; and the overall site location/infrastructure (i.e., space constraints, public perception/acceptance, power availability). Common heating methods used for low-temperature thermal remediation are discussed below.

### 18.6.1 Thermal Conduction Heating

TCH are soil remediation technologies in which a network of steel heater wells consisting of continuous, sealed steel casings are installed using conventional drilling techniques through the entire treatment interval. Heat is applied by installing electric- or gas-powered heaters inside the steel casings that heat the treatment area via thermal conduction. Traditionally, this approach heats to the boiling point of water ( $100^{\circ}\text{C}$ ) or higher, a large amount of steam and vaporized contaminants are formed and need to be controlled, extracted, and treated. However, these traditional heaters as well as their associated power supply, distribution, control, and monitoring equipment are over-designed and over-engineered for low-temperature applications.

Recently, more cost-effective electrically powered heaters have been developed to be specifically used for LTTR. These heaters have a narrower profile compared to their higher temperature counterparts that can be installed in a smaller diameter pipe and borehole. This allows for the heaters to be installed to desired depths with less expensive and faster direct-push drilling technologies. While the low-voltage, low-power heaters require substantially less energy to operate, a power source is still required, usually supplied from the electrical grid. On smaller or remote systems, the power may be provided by solar photovoltaic panels. The low-voltage, low-power heaters can be easily customized in the field to the required heating lengths, eliminating costly fabrication and shipping charges. The heaters are also constructed of simple, easy to find, and inexpensive materials that can be re-used on future projects. This can significantly reduce the consumption of natural resources (steel, copper, concrete, equipment, fuel, chemicals, energy, etc.) and the carbon footprint associated with remediation activities.

### ***18.6.2 Electrical Resistance Heating***

Like TCH, traditional ERH will heat to 100 °C for the production of steam and volatilization of contaminants. However, it can be used to heat the subsurface to temperatures below 100 °C and utilized for LTTR applications. ERH directs low-frequency (60 Hz) three-phase electrical power to a network of subsurface electrodes installed in a repeating triangular pattern. Adjacent electrodes are out of phase such that gradients in electric potential are induced, which causes current conduction and resistive heat dissipation (i.e., Joule heating) throughout the treatment volume. ERH is typically best applicable in soil having electrical resistivity ranges from 5 to 500  $\Omega$ -meters ( $\Omega$ -m) using standard power delivery equipment, which covers a wide range of naturally occurring fine- or coarse-grained media, and can be designed to account for heterogeneities in soil electrical properties. Both the saturated and vadose zones can be heated with ERH providing that sufficient soil moisture and electrical conductivity exist for efficient and safe current flow. In addition, ERH typically requires the addition of water and sometimes a conductive solute (e.g., potassium chloride) at the electrodes to maintain electrical continuity.

### ***18.6.3 Geothermal Heat Pumps and Hot Water Flushing***

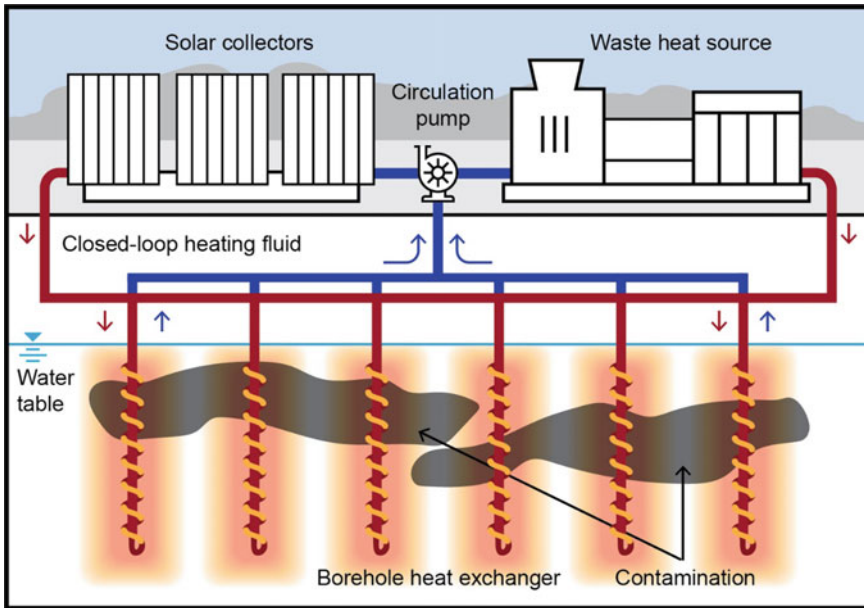
Geothermal heat pump applications have been used for decades in the supplemental heating and cooling of commercial and residential buildings. This is done by embedding large heat exchangers into the subsurface and either circulating or injecting (closed loop or open loop) a transfer fluid from which heat is extracted (for heating) or to which waste heat is discharged (for cooling). Within a closed-loop system, the transfer fluid is re-circulated and heated/cooled via conduction through the

heat exchanger and the subsurface. Conversely, open-loop systems typically extract groundwater that is then re-injected to the subsurface after above grade heating/cooling occurs. The advantages and potential challenges between closed-loop and open-loop systems should be considered when designing for remedial applications. Heat transfer via closed-loop systems will primarily be governed by thermal conductivity of the soil matrices, whereas open-loop systems will be heavily reliant on the hydraulic properties of the aquifer. However, when discharging heat, geothermal heat pumps have shown to increase the natural temperature of soils from 8 to 12 °C and as high as 40 °C in some regions of the world. Environmental engineers and policy makers have recognized the “positive side effects” of such extraction and injection-based heating–cooling systems for contaminant attenuation and enhanced biodegradation in urban groundwater legacy plumes (Slenders et al. 2010; Slenders and Verburg 2010).

One example is a former industrial facility in Europe that started its activities in 1915 and at its peak, employed more than 10,000 people. As a result of decades of industrial activity, soil and groundwater at the site were contaminated with chlorinated solvents to a depth of 60–70 m below ground surface. In 2009, an approach was implemented combining groundwater remediation with a geothermal energy system to support the facility, called “Sanergy”. This was a first of its kind harnessing of a site mechanical system to benefit remediation. Since implementation, regulatory closure has been achieved for the remediation and the site continues to be part of an active technology headquarters for the owner.

#### ***18.6.4 Thermal In-Situ Sustainable Remediation (TISR®)***

LTTR has a lower energy demand for heating compared to high temperature. Therefore, energy can be generated by capturing heat from a sustainable source (i.e., solar radiation or waste heat from commercial/industrial facilities) rather than more traditional electric or gas-fired energy sources. However, some electrically powered heating systems may use electricity generated by renewable sources. The conversion of solar radiation to electricity and/or heat continues to grow in popularity as the efficiency of the conversion equipment increases and costs decrease. Capitalizing on the improvement of solar collection and photovoltaic devices allows for LTTR to be implemented at a lower cost and solely dependent on renewable energy sources (i.e., self-sustainable). TISR® is a patented LTTR technology (US Pat. No. 10384246 and US Pat. No. 10,688,545) that transfers energy from solar radiation and/or waste heat to the subsurface by means of solar collectors (solar application), modified above grade heat exchangers (waste heat application), a closed-loop heat transfer fluid system, and BHEs designed to maximize the conductive heat transfer. The solar collectors or above grade heat exchangers heat a fluid generally consisting of propylene glycol and distilled water. The heated fluid is pumped by a small transfer pump through insulated manifolds and subsurface piping to BHEs as shown in Fig. 18.7. Because the system uses solar or waste heat energy, there are no utility costs incurred for the



**Fig. 18.7** TISR<sup>®</sup> process flow diagram using a solar energy and/or waste heat application

heating unit, and only minor power consumption to operate controls and the recirculation pump. In some instances, the minor electrical requirements for system controls and the recirculation pump can be powered by photovoltaic panels and invertors. This enables the system to be completely off the electrical grid and can be used for remote applications that are isolated from traditional power sources.

Solar-based TISR<sup>®</sup> systems use either evacuated tube or flat-plate collectors, which collect solar energy and focus it on a heat transfer fluid passing through the collector (Fig. 18.8). The use of solar energy is a sustainable application but is of course dependent on adequate solar radiation. The magnitude and duration of radiation varies based on such site characteristics as cloud cover, elevation, and latitude and changes seasonally due to sun angle and daylight length. Most of these factors can be overcome during the design phase but limitations of area to place collectors may hinder the ability to collect adequate solar energy to reach target heating temperatures. In some cases, supplemental heating via a traditional energy source may be necessary, particularly in the winter season in which day length is shorter and sun angle is decreased or at more extreme latitudes, but in all cases, utilization of a renewable energy source for at least part of the heating energy would provide a more sustainable approach and is likely to reduce overall energy and operational costs. Air temperature is less of a factor if the system is properly insulated to avoid heat loss. Table 18.3 shows the results from a case study in northern New York, United States, demonstrating the ability to capture significant heat energy away from the equator and when the sun is available, regardless of outside air temperature.





**Fig. 18.8** TISR infrastructure for solar energy (solar collectors) and waste heating (blower heat exchanger) applications

**Table 18.3** Field data demonstration of the ability to capture solar energy regardless of the ambient air temperature

Outside air temp (°F)	Weather conditions/ cloud over	Collector temp (°F)
38	Rain/overcast	39
37	Rain/overcast	43
36	Partly cloudy	115
57	Partly cloudy	114
15	Sunny	275

The availability of space for the installation of solar collectors, potential obstacles blocking the solar radiation for all or part of the day, and the possibility for the solar collectors to be periodically covered (leaves, snow, dust, etc.) all must be considered during the design phase. The direct use of solar energy for subsurface heating is a diurnal process which provides a heating period followed by a period of no heating during each 24-h period. This creates a pulsed approach to heating the subsurface. Extended periods of cloud cover and no or limited heating may have detrimental effects on sustaining temperatures, but the diurnal pulsing allows for temperature equilibration during the period of no heating. This increases temperature gradients at the borehole heat exchangers for the next day, which appears to allow for greater heat transfer compared to using a heat storage unit to support continuous heating.

The second sustainable energy source utilized for heating is the use of waste heat, where available. Waste heat sources can range from a large adjacent industrial or manufacturing facility to an existing remediation system which utilizes a heat exchanger for cooling (Fig. 18.8). The amount of waste heat and the impact on the process in which the waste heat is generated must be thoroughly understood and compared to the amount of heat needed for the remedial application. Integration of a waste heat system with an existing production operation could have effects on the production operation which can impact business and cause detrimental losses if not properly designed with adequate failsafe and alternate heat dissipating capabilities, should they be needed. Design and implementation are often straightforward depending on the location and characteristics of the process stream or equipment creating the waste heat.

Such systems generally require minimal operation and maintenance, typically involving inspections, failsafe testing, and performance monitoring. A system that uses waste heat provides a beneficial reuse for heating and will be dependent on the operation of the equipment or process that is generating the waste heat. Therefore, the potential for operation interruptions should be considered. Waste heat applications are generally operating as a continuous heating operation, unlike the solar application. A continuous steady source of heat is transferred to the subsurface. Waste heat offers relatively steady heat transfer to the subsurface compared to the diurnally or seasonally variable heat transfer provided by a solar collector based system.

An evaluation of available sustainable energy, energy requirements to reach target temperatures, as well as other factors previously outlined must be considered when determining the optimal sustainable energy source to use for low-temperature

heating. Consideration of a hybrid approach utilizing both sustainable energy sources and supplementing a sustainable energy source with a traditional energy source can also provide benefit to achieve remedial goals within a shorter timeframe.

Custom BHEs are fabricated for each system based on the depth to water, extent of impacts, water and soil chemistry, and constructability. Typically, BHEs are installed in a vertical orientation within the saturated zone. Multiple BHEs are oriented in parallel to optimize the heat transfer by maintaining a maximum change in temperature between the subsurface and the BHE at all locations. During operation, the TISR<sup>®</sup> system is optimized through data collection from a combination of monitoring wells and thermocouples. Typically, thermocouple points will be installed at varying distances and depth intervals to gain a three-dimensional view of the temperature profile of the subsurface. In addition, groundwater samples for COCs, geochemical parameters, and microbial assessment tools can be used to evaluate contaminant degradation and treatment progress.

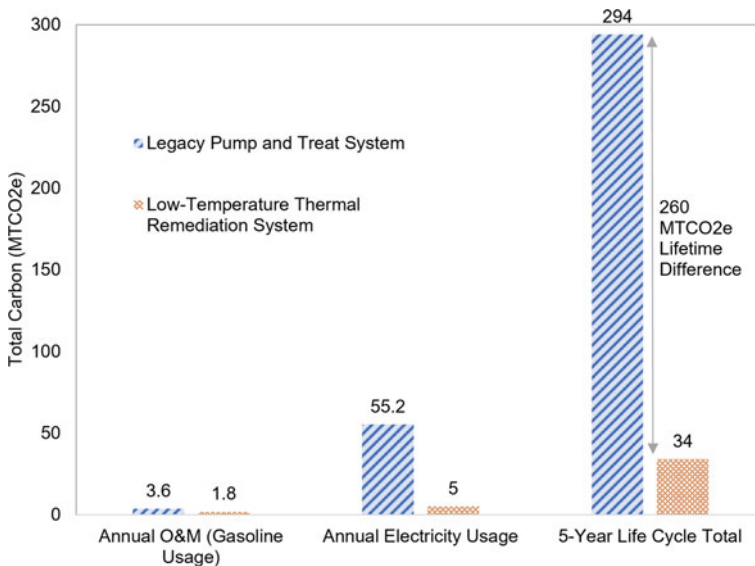
TISR can be applied in a complimentary function to existing remediation systems and is particularly well suited for accelerating treatment rates in systems designed to promote bioremediation. BHE heating coils can be installed inside or around the riser or screen of traditional remediation well including air sparge, biosparge, and injection wells. The combination of these technologies can greatly accelerate remediation due to the chemical property changes caused by increased temperatures as well as the increased desorption and dissolution which partitions the target compounds to a more accessible state for remediation. In addition, an increase in temperature can also increase the volatility of some compounds to allow them to be remediated via air sparging which may not be feasible at ambient conditions.

## 18.7 Sustainability and Resilience

As remediation practitioners continue to look for opportunities to reduce cleanup timeframes, reduce associated costs, and complete remediation in a sustainable and resilient manner, LTTR will continue to gain traction as a standalone option or as an option to enhance, replace, or augment other traditional remedial techniques. Offering innovative and resilient solutions to stakeholders will result in more beneficial ecosystem reuse and greater social impact. As we have reviewed, the value is derived from the fact that increases to subsurface temperatures can result in order-of-magnitude improvements in active biodegradation rates. The corresponding change in chemical properties can also be harnessed to enhance physical extraction (e.g., multiphase recovery of contaminant mass) by driving contaminant mass from immobile phases (sorbed to soils, trapped in silts and clays) to mobile phases (dissolved and vapor). This can allow extraction systems to work more efficiently and effectively, which reduces the time required for treatment and lifecycle costs. Similarly, traditional physical recovery methods that often reach asymptotic mass recovery may be either replaced or augmented to reach/accelerate the transition from active to passive remediation (e.g., natural source zone depletion, monitored natural attenuation).

Traditional ISTR as a standalone application is often not viewed as a sustainable remediation treatment technology due to material consumption for construction and the large energy demand required for operation (Horst et al. 2021). However, comparing the full lifecycle of the project entirety, combining or supplementing ISTR with sustainable technologies may minimize material input and significantly reduce energy consumption (Fig. 18.9).

Driven by a lower energy or sustainable heat source, incorporating LTTR into existing infrastructure reduces ecosystem restoration time, project lifecycle cost, and overall carbon footprint. Ecosystem restoration using sustainable technologies, such as TISR<sup>®</sup>, offers an innovative tool for environmental practitioners, facility owners, and our society. Utilizing solar and waste heat collection, TISR<sup>®</sup> has now been implemented at over a two-dozen sites worldwide including in the United States, Canada, Mexico, Brazil, and the Netherlands. The scale and magnitude of these systems has expanded, while best practices and guidance continue to be refined for greater efficiencies and optimization of heat transfer and energy use. Installation of a TISR<sup>®</sup> system utilizing an active manufacturing facility’s waste steam is underway (at the time of publication) to integrate production and remediation in a symbiotic manner. Based on the preliminary results, the carbon footprint of TISR<sup>®</sup>, compared with other comparable in-situ remediation technologies, is significantly lower due to the low energy consumption. This is the most important parameter to indicate the difference between technologies. To date, there has been preliminary data indicating that TISR<sup>®</sup> has a carbon dioxide footprint that is 15–25 times lower compared with biosparging (comparable case). This has been roughly estimated comparing the



**Fig. 18.9** Carbon footprint comparison of a legacy pump and treat system and a LTTR system (TISR)

amount of traditional energy consumption saved by using a renewable energy source during system operations. Another system has shown after five years of operation, the reduced carbon dioxide emissions have been tenfold lower when compared to a physical extraction system.

## 18.8 Case Studies

### **United States Army Corps of Engineers (USACE) Upstate, New York (Area 3805)**

A site that has historical impacts from petroleum compounds located in upstate New York, United States. Main COCs were 1,3,5-trimethylbenzene, 1,2,4-trimethylbenzene, and BTEX. Lithology consists of medium to fine sand with depth and groundwater present at approximately 4.6 m below ground surface. A solar collector heating pilot test was implemented on a downgradient side of the plume with initial total petroleum concentrations more than 17 parts per million (ppm). The two-year pilot test was concluded in 2017 following two years of operation. The infrastructure layout is presented in Fig. 18.10 and consisted of three BHEs, six temperature monitoring points (TCs) and two 30-tube evacuated tube solar collectors circulating heated propylene glycol/water solution to the BHEs in a closed-loop system (Horst et al. 2018).

After approximately 18 months of heating, the temperature of the treatment area was increased from an average of approximately 12 °C to an average of approximately 20 °C as measured by the TCs. Baseline total BTEX groundwater concentrations near the BHEs ranged from 3 to 17 ppm (average 12 ppm). Concentrations during the last two sampling events of system operation (October 2017 and January 2018) were below detection limits—after approximately 18 months of heat application. The system was deactivated to evaluate post-treatment rebound, during which an average VOC concentration of 0.001 ppm was reported in the test area. As depicted in Fig. 18.11, the TISR solar application was able to reduce the VOC concentration by 99.9% in the two-year period (Horst et al. 2018).

The heating infrastructure (solar collectors, sensors, pump station, pump controller, and expansion tank) has since been trailer mounted and moved to address a different impacted area at the same site, which will continue to improve the cost effectiveness of the technology.

### **USACE Upstate, New York (Area 1795)**

Located in another area at the site mentioned above, a full-scale application of waste heat coupled with AS/SVE was implemented in 2020. The main COCs were also 1,3,5-trimethylbenzene, 1,2,4-trimethylbenzene, and BTEX. Lithology also consisted of medium to fine sand with depth but groundwater was present at approximately 6 m below ground surface. This full-scale system was implemented following LNAPL recovery within the target zone and a comprehensive soil boring

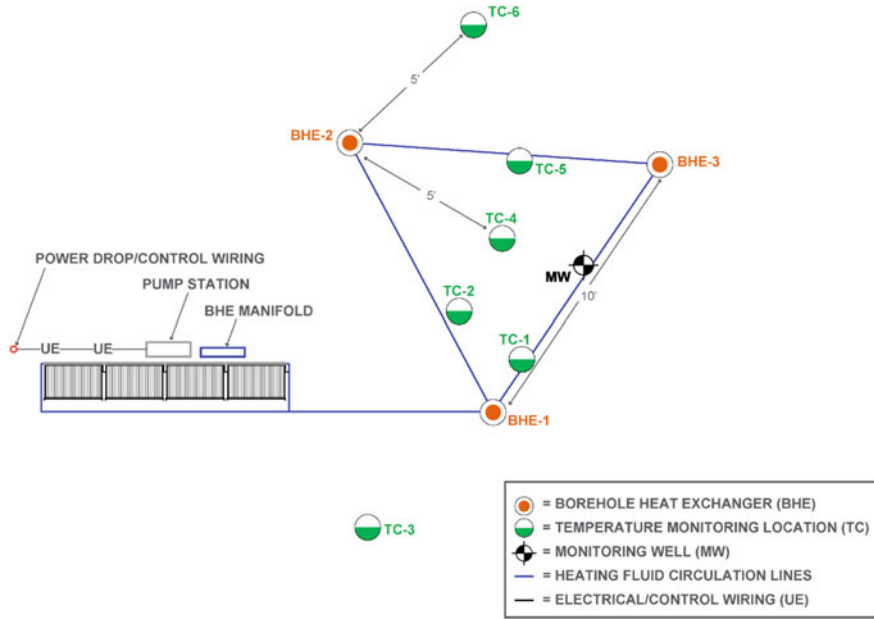


Fig. 18.10 USACE 3805 TISR<sup>®</sup> pilot test layout (adapted from Horst et al. 2018)

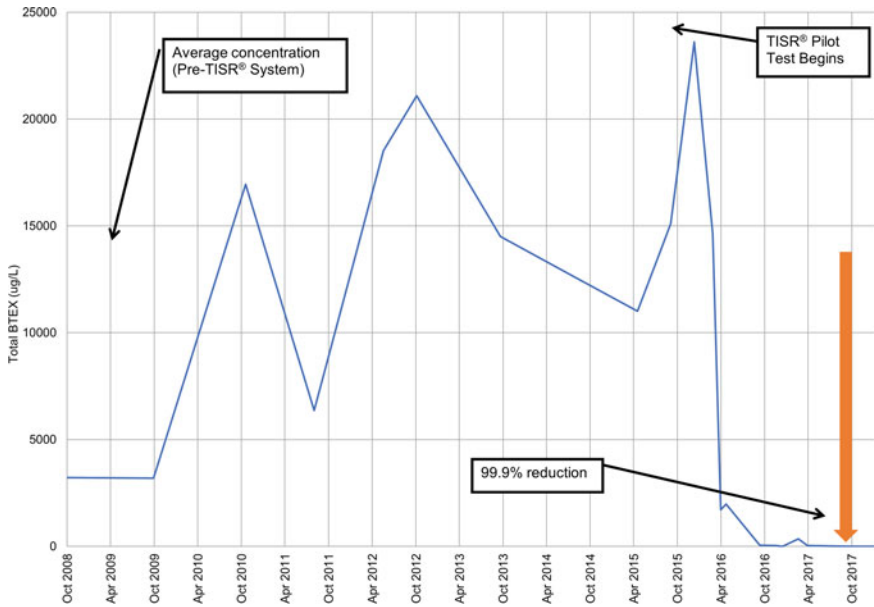


Fig. 18.11 USACE 3805 total BTEX concentrations over remedial timeline (Horst et al. 2018)



investigation. A pre-design soil boring investigation indicated that at least 60% of the target zone contained headspace readings from soil samples with greater than 1000 parts per million by volume (ppmv) based on field photoionization detector readings and LNAPL historically detected in wells. The system targeted impacts across an area approximately 5016 m<sup>2</sup> for AS operation of which approximately 2601 m<sup>2</sup> were heated utilizing the hybrid waste heat and inline heater application.

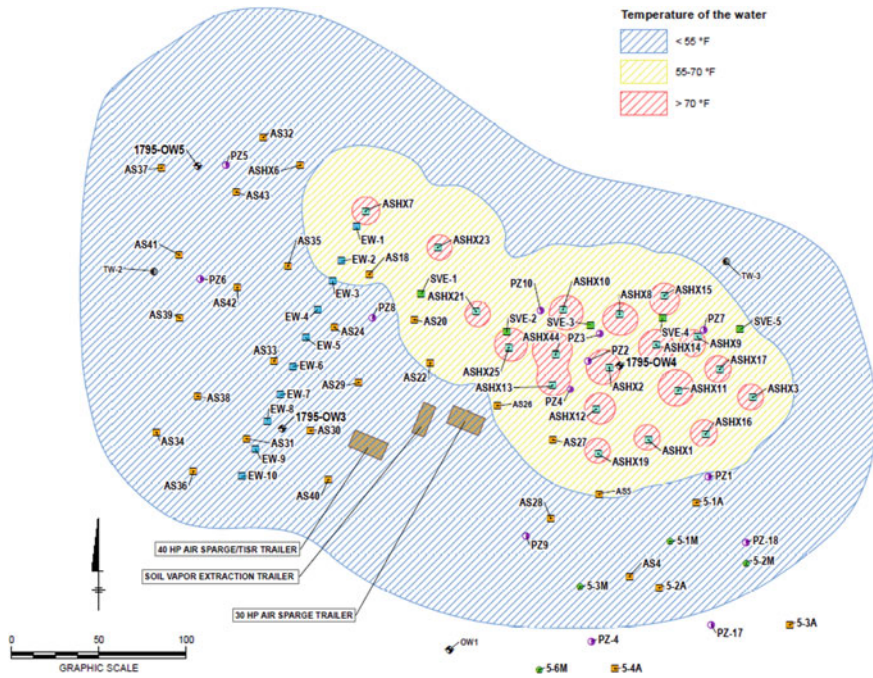
The AS system was designed and installed for the capture of waste heat from the AS blower, and heat was utilized to increase subsurface temperatures and increase contaminant desorption, dissolution, and volatility in an effort to reduce remedial system operation duration. The waste heat infrastructure included an alternate heat exchanger from the traditional air-to-air heat exchanger (which generally transfers heat to the atmosphere), to an air-to-liquid heat exchanger, a pump and control station, heating fluid conveyance tubing, and BHEs. Based on the volume within the heating target zone, a supplemental traditional electric inline heater was also utilized. When evaluating the costs of the waste heat operation, the AS/SVE system costs were not considered because that was the primary remedial approach; therefore, the additional costs associated with the addition of the heating were minimal relative to the costs associated with the full system installation because the same boreholes were utilized for the BHEs and AS wells and the air-to-air heat exchanger was simply replaced with an air-to-liquid heat exchanger.

Remedial operation of the AS and heating system began in September 2020. Operational data indicated that the waste heat alone was able to increase the heating fluid temperatures from 30 to 50 °C and with the supplemental inline heater increasing the temperature to 60 °C. The interpolated subsurface temperatures following 12 months of operation are presented in Fig. 18.12.

SVE operation recovered vapors at an average flow of 1000 normal meter cubed per hour (nm<sup>3</sup>/hr) and a concentration of 2000 ppmv during the first weeks of SVE operation which occurred following approximately one month of heating operation. Following 3 months of SVE operation, influent concentrations declined to less than 100 ppmv and continued to drop until system deactivation. Several monitoring well headspace photoionization detector readings were initially greater than 10,000 ppmv and had dropped to less than 500 ppmv within 6 months of operation and continued to decline until system deactivation. Following one year of system operation, dissolved phase concentrations in performance monitoring wells declined well below target concentrations and close to drinking water standards following a temporary system deactivation to evaluate potential for concentration rebound. Two quarters of post-remediation groundwater sampling have been conducted and concentrations remain below target concentrations and near drinking water standards with no rebound observed.

### **Aerobic Hydrocarbon Treatment-Schenectady, New York (Information provided by TerraTherm Inc., 2022)**

A site with historical impacts associated with an extensive LNAPL footprint was in New York. The primary COC was total xylenes. Lithology of the targeted impacted



**Fig. 18.12** USACE 1795C TISR<sup>®</sup> waste heat application wellfield temperature contours

zone consisted of low-permeability silts and clays with the water table located approximately 4.6 m below ground surface (bgs). A full-scale thermally enhanced bioremediation project was implemented using electrically powered TCH to address the xylenes.

Laboratory studies indicated that the native microbial population was capable of readily degrading the xylenes under aerobic conditions at 35 °C. However, the impacted interval had limited oxygen due to the relatively tight soils and over decades since the releases occurred, soil concentrations of total petroleum hydrocarbons and xylenes remained high, indicating little natural degradation under ambient conditions. The primary remedial objective for the site was to reduce soil concentrations of total xylenes to below 1000 ppm.

LTTR with electrically powered heaters was used to heat the subsurface to between 35 and 40 °C. A total of 143 heaters were installed at a 5-m spacing, to treat the 17,611 cubic yards of target volume (Fig. 18.13). To stimulate aerobic biological degradation, air/oxygen was delivered to the vadose zone via 143 passive air inlet wells and below the water table under pressure using 143 air injection wells. A network of SVE and dual-phase extraction (DPE) wells were used to keep pneumatic and hydraulic control of the vadose zone while recovering vapors and pushing air into the passive air inlet wells. A vapor treatment system was utilized to control vapor emissions while air was pulled into and from the targeted treatment zone. Waterloo





**Fig. 18.13** Low-temperature heating via thermal conduction heating for thermally enhanced bioremediation of hydrocarbons-Schenectady, New York

profiling was used prior to construction to identify layers of high and low permeability within the treatment interval as the basis for selecting the screen intervals of the vapor recovery wells.

Heating progress was monitored through a network of temperature-monitoring points located both at the heaters and at the centroid locations between heaters (heaters were installed in a triangular pattern). Temperatures at centroid locations represent the furthest from any surrounding heaters and thus the slowest portions of the heated zone to increase in temperature. Additionally, vapor concentrations of COCs and biodegradation indicators (e.g., oxygen, carbon dioxide) were monitored within the well field at the SVE and DPE wells, along the section of the vapor collection manifold, and at the inlet to the treatment system. Interim soil sampling was used to track the progress.

Figure 18.14 shows the total average temperature at the centroid locations during operation. Heating was initiated in January 2017 with the heaters set initially at low power output (65–98 W/m) and then slowly ramped up over the next month to operational levels of between 262 and 328 W/m. Increases in temperature were observed at the centroid monitoring locations approximately one month after heating was initiated.

Over the course of 14 months of heating, the following observations were made with respect to concentrations of xylenes and biodegradation parameters sampled in the vapor stream: 1) maximum xylene concentrations were reported near the end of June 2017 which corresponded peak soil temperatures, 2) xylene concentrations decreased sharply one month later (July 2017) and then gradually over the next 4 months of heating, 3) oxygen concentrations in extracted vapors averaged 20.5% at the start of heating and then steadily decreased to < 19% (low of 17%) following 10 months of heating, 4) carbon dioxide concentrations started off low (<1%) and reached a peak after 7 months of heating (ranging between 2 and 24%). These data



**Fig. 18.14** Thermally enhanced bioremediation TCH low-temperature heating progression

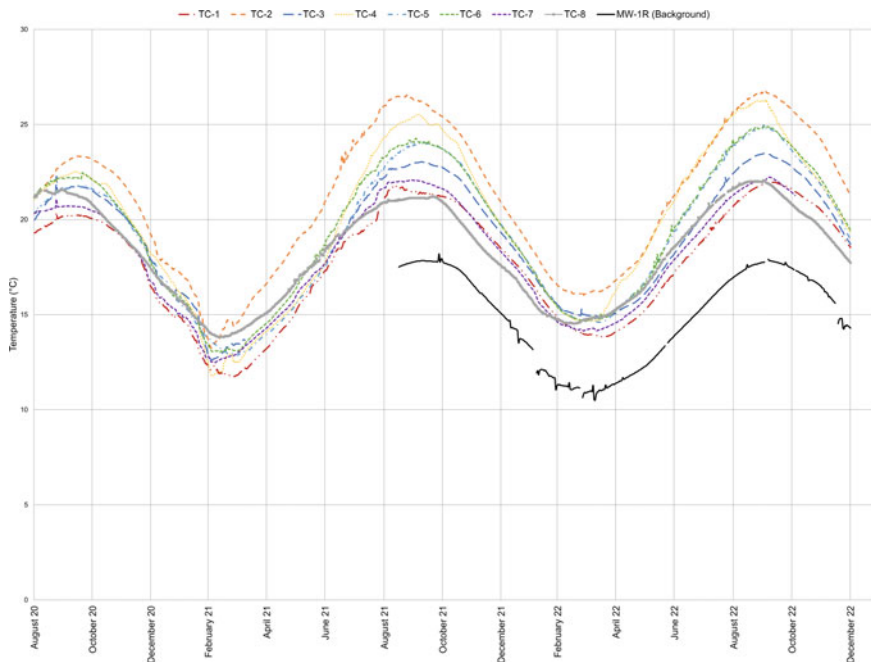
are consistent with the thermally enhanced aerobic biodegradation of the xylene. Of the initial estimated starting COC mass of 21,000 pounds, only 3,800 pounds were removed by the vapor recovery system. The remaining COC mass was aerobically degraded in-situ using thermally enhanced biodegradation.

After 7 months of heating, the first interim soil sampling event revealed that the goals had been met in more than 75% of the treatment volume, with two hotspots remaining, where xylene concentrations remained above the treatment goals. The system was operated for an additional 6 months to improve the distribution of heat and degradation. Subsequent soil sampling events demonstrated that the goals were met, and New York State Department of Environmental Conservation granted site closure. It is estimated that over the 14 months of LTTR treatment, over 17,000 pounds of xylene were removed by thermally enhanced bioremediation alone. Importantly, the maximum temperature of the targeted treatment zone never exceeded 40 °C.

### **Former Gasoline Station-New Jersey, United States**

The site located in New Jersey was a former gasoline station that operated between 1960 and 2007 before closing and subsequently being demolished. The station contained five gasoline underground storage tanks that were the source of soil and groundwater impacts. Concentrations of benzene were detected in soil more than 200 ppm, and LNAPL was measured in four monitoring wells during groundwater monitoring events. The site is currently vacant and maintained as a grassy field.

Lithology consisted of a low-permeability silt and sand mixture, and groundwater was present at approximately 2.5 m below ground surface. A TISR<sup>®</sup> system using solar collector heating was implemented on the downgradient side of the plume and



**Fig. 18.15** Temperature monitoring data located 4.3 m below ground surface (approximately 2 m below the water table) during TISR<sup>®</sup> solar heating operations. Temperature monitoring points, TC-4, TC-5 and TC-6 were located approximately 0.8 m, 1.5 m and 4.6 m away from the closest BHE

within a portion of the LNAPL body. TISR was selected due to logistical challenges associated with other remedial options. Excavation was not feasible and was cost prohibitive, and the ineffectiveness of conventional mass removal technologies (e.g., AS/SVE and multiphase extraction) in low-permeability soils (silt and sand mixture) was demonstrated through pilot testing.

The TISR system comprised 12 solar collectors connected to seventeen BHEs (BHE-1 through BHE-17) installed downgradient of the former source area. Heating began in August 2020 and at the time of publication, operation was sustained through December 2022. Figure 18.15 displays temperature data from sensors located at 4.3 m below ground surface (approximately 2 m below the water table) in monitoring wells placed 0.8 m (TC-4), 1.5 m (TC-5), and 4.6 m (TC-6) away from the closest BHE. Groundwater temperature data were collected over two seasonal cycles where roughly a 10–13 °C fluctuation was observed between midwinter to midsummer (6–8 °C above ambient). Consequently, maximum heating of the subsurface and associated temperature increases occurred during the summer months but were not sustained throughout the winter months. This can be contributed to both the magnitude and the duration of solar radiation available to the solar collectors based on the geographical location of the site. Furthermore, heat energy is transferred to the

subsurface during daylight hours and stopped overnight when there is no solar radiation available for the solar collectors to harvest and transfer. The seasonal variability in daily operating hours, which are generally higher in the summer, also matches the seasonal trend of solar radiation availability. These fluctuations associated with solar heating need to be assessed and integrated into the heating source design to ensure target temperatures can be obtained and maintained to increase contaminant degradation rates. Otherwise, a more sustainable heating source such as the sources introduced in the case studies above should be considered.

At the time of publication, soil re-sampling was not completed; however, operation of the TISR<sup>®</sup> system was able to achieve one of the primary project milestones, to reduce or eliminate measurable LNAPL at the site. Carbon dioxide and methane concentrations in soil gas have increased indicating enhanced microbial activity. Additionally, the results for dissolved-phase impacts have shown a decreasing trend in the core of the treatment area.

## 18.9 Conclusion

While LTTR continues to grow and evolve, certain key benefits have been identified and are as follows:

- **Enhanced biodegradation:** Biological degradation rates may double (some cases triple) for every 10 °C rise in temperature under mesophilic conditions.
- **Application in tandem:** Application in conjunction with source zone AS/SVE or multiphase extraction systems could significantly reduce treatment timeframes and complement natural attenuation.
- **Effective in complex and heterogeneous geology:** Heat transfer and corresponding treatment benefits not as limited by challenging hydrogeology (heterogeneous strata, tight clays, etc.) as other processes involved in the application of conventional remediation technologies.
- **Cost savings:** The potential to significantly supplement/enhance many existing remedial strategies can lead to reduced cleanup time and operational cost reductions.
- **Reduced energy use/carbon footprint:** As shown in one of the examples, five years of operation may reduce carbon dioxide emissions tenfold compared to a physical extraction system.
- **Remote areas application:** Remote areas present a challenge for traditional remedial approaches due to lack of availability of conventional energy sources. By utilizing solar energy to power subsurface heating, LTTR can help overcome that challenge.

Further research is encouraged to better characterize subsurface processes to optimize the implementation of LTTR systems and their integration with other site management strategies. With the combination of potential treatment enhancement and offering of a more sustainable solution, LTTR represents yet another area of

significant opportunity for remediation practitioners to show their creativity—and one that is here right now.

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