When In Situ Thermal Challenges You

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In situ thermal remediation (ISTR) is a robust suite of technologies used to treat volatile and semi-volatile organic compound (VOC and SVOC) source zones (Davis, 1997). The three most widely used technologies are:

- Electrical Resistance Heating (ERH) – the subsurface is heated by passing electricity through it using electrodes.
- Thermal Conduction Heating (TCH) – hot steel borings are used to transfer heat to the formation by simple conduction.
- Steam Enhanced Extraction (SEE) - steam is injected into wells, travels in the formation, and fluids are extracted using multi-phase extraction wells.

For treatment of VOCs, most projects involve heating the target zone to around 100°C, a temperature at which water boils, and below which the liquid and sorbed phase VOCs efficiently transfer to the gas phase. The steam generated acts as a carrier gas, bringing the contaminant vapors to extraction wells. All three thermal technologies can be used to achieve the target temperature, but the hydrogeology of each site determines which method is more cost-effective.

This paper presents some of the major challenges ISTR practitioners face when selecting technology, installing the system, and operating to meet project objectives. We use case studies to illustrate the physical situations and the solution to the challenges but will refrain from sharing site locations or names. Any resemblance to actual sites is purely coincidental.

We are really good at one ISTR Method, but the RFP calls for a different one.

Most of the thermal providers started as specialists in one technology and later realized the advantages of mastering more than one. Now we have ERH specialists learning TCH, and TCH specialists adopting ERH. Several companies offer SEE, but have not received the training in applying it from the gurus in the field such as Kent Udell. When a demanding RFP is released, with firm objectives and contract terms, it is therefore tempting to fall back on the technology we know best and feel most comfortable with. This results in proposals where the best suited technology for a site is not selected. Examples are:

- SEE proposed in tight formations where heating will be marginal.
- ERH proposed for sites with too dry of a vadose zone to conduct the electricity, or too saline conditions.
- TCH proposed for sites with more groundwater flow than can be heated.

At TRS we try to be objective, and to let the site conditions drive the selection. As an example of that, we have proposed and been selected for four TCH projects in 2019, despite being known as an ERH provider. It starts with a careful review of the site conditions. If more than one ISTR method works, we model both and select the one which is more cost-effective.

The groundwater flows a bit too fast

Water can carry heat away and cool the zones surrounding where it flows (Hegele and McGee, 2017). Pumping and water treatment is expensive and requires significant equipment and labor. It is therefore tempting to adopt optimistic assumptions for the site and select TCH or ERH combined with vapor extraction. The argument is that that steam is produced from boiling groundwater and extracted as a vapor, which is equivalent to pumping. The problem is that the rate of extraction often is modest – the equivalent of a few gallons per minute for a medium sized site.

Many sites have more flow across the target zone than that. Unless liquids are extracted up-gradient, or a barrier installed, unwanted things may occur:

1. Heating at the up-gradient end will lag behind and locally not be sufficient to reach target temperatures. Treatment will be incomplete.
2. Water flowing through the TTZ may carry heat and mobilized contaminants down-gradient into the plume, increasing mass discharge temporarily.
3. When water flows in a permeable zone next to a tight zone (silt, clay, rock matrix), the cooler water removes heat and results in less-than-optimal temperatures reached in the tight material.

A typical challenging situation is shown in Figure 1. On the right the resulting temperature profiles are illustrated. Higher flow below the clay/silt may cause the bottom to remain too cold.

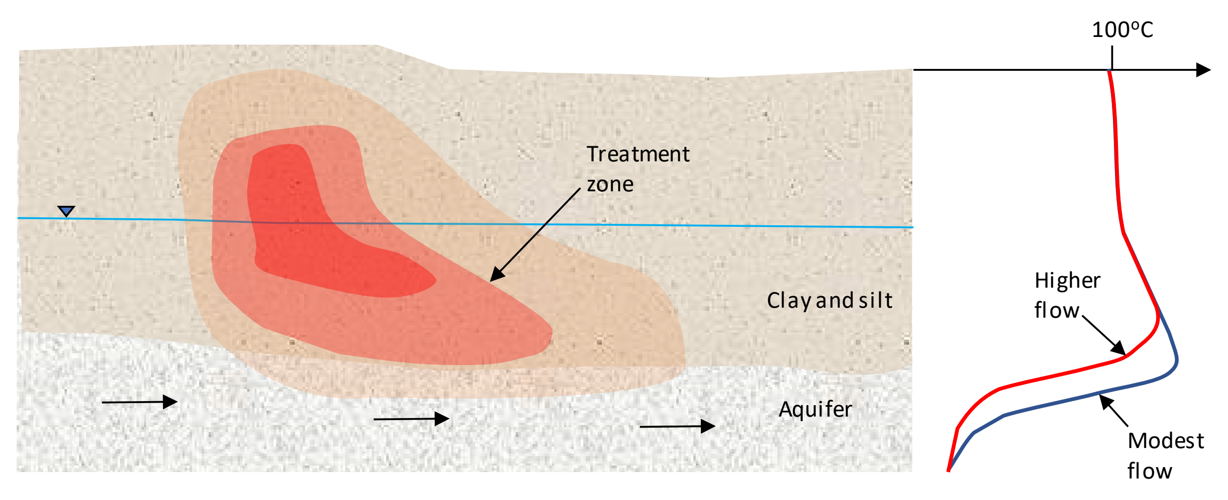

***Figure 1:** Illustration of groundwater flowing in an aquifer below a clay layer, hindering heating to boiling at the base of the clay. Steam can be injected at the top of the aquifer, or up-gradient*

This challenge is made difficult by the nature of hydrological data typically available. While gradient data is reliable, hydraulic conductivity data is not always. Slug tests are notorious for underestimating K values. Pump tests may do the same, unless strict protocols are followed to avoid fines smeared onto the screened zone, well development is complete, and the test is run long enough to provide data from the formation (and not the sand pack). The resulting uncertainty, and the interpretation of how fast water will flow, may be the difference between needing to pump water or not.

Low bid almost always wins – the vendor who does not pump and treat groundwater gets the job. The result is some sites where this groundwater flow challenge is discovered later, often during the heating process, and a scramble to remedy the situation starts.

One option is to combine ERH or TCH with SEE, using steam to heat the more permeable layers (Newmark et al. 1994; Heron et al. 2005; Nielsen et al. 2008).

High organic carbon sediments – more water, more sorption, subsidence

Sedimentary layers with organic matter content of more than 1% by weight can create challenges. A good ISTR design must account for the stronger sorption and slower release of COCs when heated, the potential for shrinkage and subsidence as organic matter is oxidized, and in some instances the large amount of water held in the porosity of peat (up to 80% porosity compared to 30-40% for most sands, silts and clays). Such layers require more energy to heat because the heat capacity of water is higher than that of solids.

The subsidence which occurs as organic material is oxidized and the sediment shrinks may cause the vapor cover to slump, crack or break (Nielsen et al. 2010). This allows precipitation to infiltrate, potentially vapors to escape, and loss of vacuum in the vadose zone. Covers must be designed to withstand the subsidence, or frequent repairs are needed. At one site underlain by Meadow mat, more than a foot of subsidence was observed. At a site in Louisiana, heating of an organic-rich clay resulted in a cracked parking lot which had to be resurfaced after thermal treatment.

Underestimated heat losses – slow heating

Not all ISTR providers have reliable tools for predicting heat losses to the surface, sides and bottom of a target volume. The geometry and surface area must be used in site-specific modeling of the energy balance for a site. When this is not done properly, proposals with insufficient power and energy delivery are seen. It can be very difficult for the consultants to tell the difference and decide whether a proposal is unrealistic.

We recommend that the following should be required:

- Clear documentation of target treatment zone dimensions, volume, surface area.
- Clear assumptions for the flow of water in the subsurface.
- The result of a reliable energy balance calculation.
- Power density – the proposed power input per unit volume, measured in W/cy. This is a key parameter for how quick the heating will occur.
- Energy density – the proposed energy delivery per unit volume, measured in kWh/cy. This parameter reveals the anticipated total energy usage and can be compared to laboratory treatability study results.

- Steaming energy density – this parameter reveals how much energy is estimated to lead to boiling of water (not heat losses) and thereby formation of steam – the driving force for the remediation.

If these parameters are known, one can compare ISTR options more fairly.

The power is on, the energy is going in, but it heats up slower than predicted

We track heating progress by reading dedicated temperature sensors located in between borings, electrodes and heaters, often in the coolest spots (centroids). With proper power density delivered (between 50 and 200 W/cy, typically), the energy balance provides an estimate for the heat-up, initially as the average increase in temperature expressed as degrees per day. For instance, heating a site from 10 to 100°C in a target period of 100 days, the predicted average increase is 0.9 C/day. Figure 2 shows an energy balance model output.

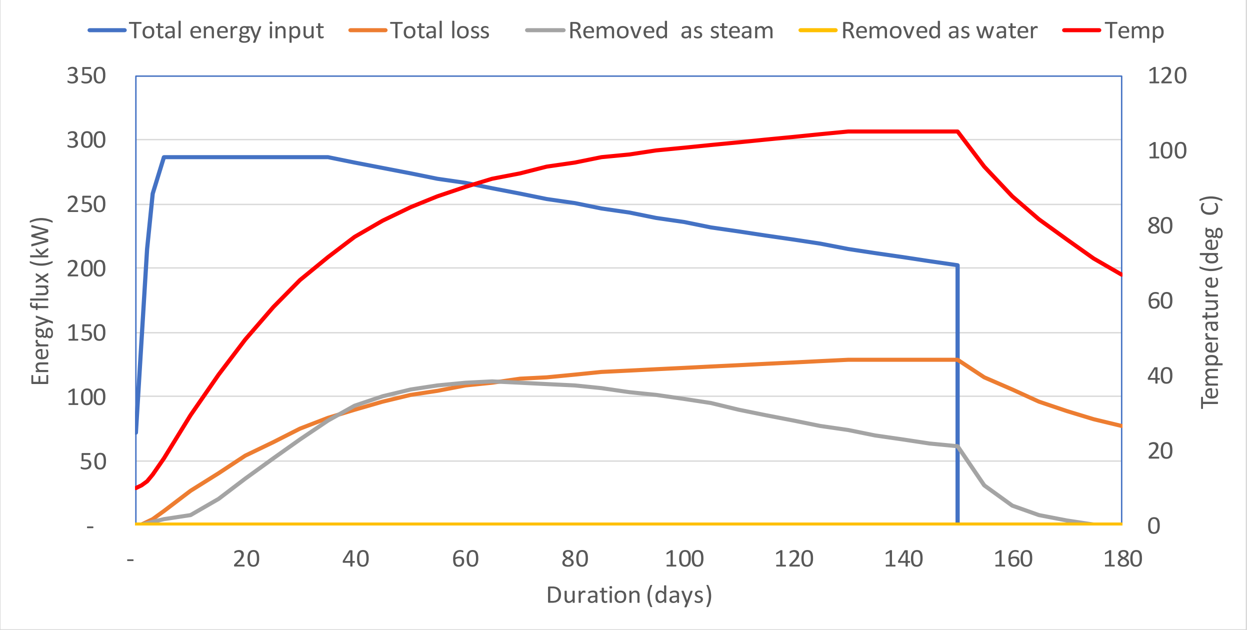

Figure 2: *Example* ***HeatWave™*** *energy balance for a site- heat losses are predicted and varies over time. For most sites the heat losses account for more than 25% of the injected energy.*

It can happen that the system delivers the energy, but the temperature increases less than predicted. Some explanations include:

- The equipment monitoring is over-predicting the actual energy delivery (faulty meters or instruments).
- Errors in the energy balance model leading to underestimated heat losses.
- Groundwater flow may be carrying heat away from the treatment zone.
- The heat escapes out of the treatment volume (could be by current straying below the target interval at an ERH site with lower electrical resistance at depth).
- The formation has a higher heat capacity than modeled (higher water content and/or porosity).

- For TCH sites, the formation may not be able to conduct the heat fast enough, and the zone around each heater over-heats and stores energy.

It is critical to track the heating early in the operations phase, identify any discrepancies, and remedy the issue.

Recommendations

We all want to avoid problems and failed remedies. We recommend that extra care be taken when specifying ISTR technology for a site, and that the data is collected early in a project to ensure that the treatment zone and surrounding hydrogeology are well understood. It is better and less costly to realize the tricky situations early.

Sometimes the lowest bid is exactly that because the proposal ignores a site-specific challenge, underestimates a critical parameter, or fails to account for critical heat losses.

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