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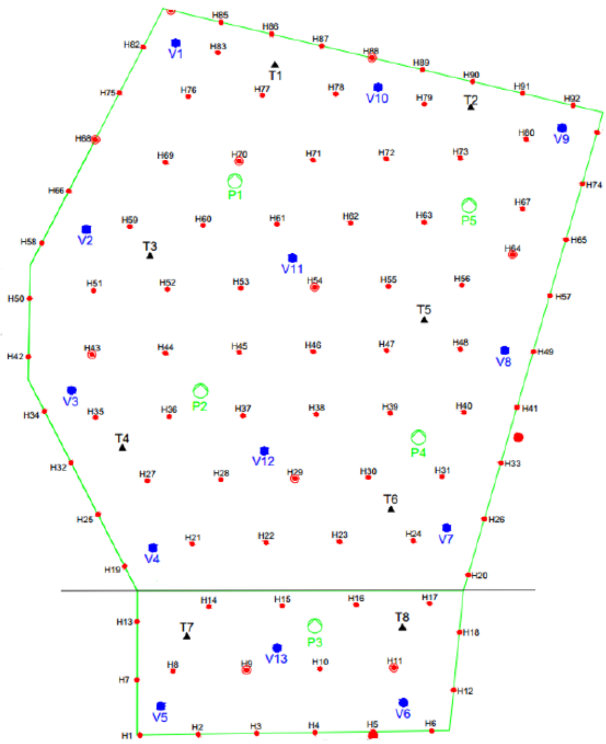

# Experience Feedback from Swedish In-Situ Thermal Treatment Projects

## A retrospective study based on documents and interviews from five sites

Master's thesis in Master Program Industrial Ecology, VT 2020

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Cover: *An illustration of well-installations on a In-Situ Thermal Treatment site.*

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# Abstract

Ever since the late 90's, when Sweden adopted a series of environmental quality objectives, the challenge of remediating contaminated soils has been an on going task. Parallel to the growth of the knowledge base on the national situation, new technologies have emerged with unique features and abilities. This thesis focus on one of the technologies that has gained lots of traction due to it's ability to decontaminate chlorinated solvents in areas difficult to access: In-Situ Thermal Treatment (ISTT). To this date, ISTT has been deployed nationally over a hand-full of times: projects that now are constituents of an increasing knowledge-base on the Swedish application.

The aim of this thesis is to review In-Situ Thermal Treatment-projects conducted in Sweden and compile experiences in order to provide feedback on the application. The study was conducted by three tasks: 1) identification of relevant projects 2) a document study on publications related to the targeted projects, and 3) a set of interviews with actors involved in ISTT-project organisations. The results were processed with main focus on cross-project comparability and international experience.

Findings include the Swedish performance being well in line with, in terms of remediation results, claims in literature and international experience. However, the effort and expenses to attain project goals is subject to considerable variation. A weak trend was identified between financial performance, efforts put in to preparatory work and perceived project success (expressed in interviews). Projects that put more efforts into characterizing the contamination showed better financial results as well as a more unified view of the project performance. An additional feature that was recurrently voiced in the interviews was the need for a large information flow within the projects. The reason is that ISTT-projects require large preparatory efforts of measurements, sampling, and data collection in order to create an accurate site characterization and enable good, information-based decisions. Further, the ISTT technology provides the possibility of extensive progress monitoring. The opinions on the size of the required information flow varies. Technically involved actors generally lifts the process monitoring and control as a security and strength of ISTT and emphasizes an accurate demarcation of the treatment area as crucial factor for a cost efficient remediation. On the other end, actors operating more distant from the technology and on-site action (i.e. stakeholders such as municipality- and environmental protection agency representatives) may experience an information asymmetry. Multiple of these representatives expressed that they struggled to process and evaluate the progress of the treatment and had to completely rely on procured contractor and/or advisor.

Keywords: ISTT, TCH, ERH, In-Situ, soil remediation, decontamination, experience feedback.

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Thank you!

Olle Johnsson, Gothenburg, June 2022

# List of Abbreviations

**ISTT** - In Situ Thermal Treatment

**TCH** - Thermal Conduction Heating

**ERH** - Electrical Resistance Heating

**DNAPL** - Dense Non-Aqueous Phase Liquid

**CAH** - Chlorinated Aliphatic Hydrocarbon

**PCE** - Perchloroethylene

**TCE** - Trichloroethylene

**DCE** - Dichloroethylene

**VOC** - Volatile Organic Compounds

**CVOC** - Chlorinated Volatile Organic Compounds

**PAH** - Poly-aromatic Hydrocarbons

# Contents

# 1
# Introduction

In 1999, Sweden adopted one generational goal and 16 environmental quality objectives to support and guide the transition towards a more sustainable nation. In the generational goal, Sweden's government accepted the task to solve the major environmental issues without compromising the situation outside the Swedish borders before its handed over to the next generation. To highlight what areas pose the largest threats, the 16 environmental quality objectives were developed. One of the environmental quality objectives is "Giftfri miljö" (Toxic-free environment), and it is formulated as follows [1]:

*"The presence of substances in the environment that have been created or extracted by society should not threaten human health or biodiversity. The levels of foreign substances are close to zero, and their impact on human health and ecosystems is negligible. The levels of naturally occurring substances are close to the background levels."*

-Translated from the Swedish Parliament [1]

Part of the work of creating a toxic-free environment constitutes of the remediation of contaminated sites. The Swedish Environmental Protection Agency (Swedish EPA) has investigated this task in a program named "Hållbar sanering" to provide a knowledge-base for concerned actors and authorities. One category of substances that are particularly problematic and expected to be contaminating a large number of locations nationally is chlorinated solvents. These toxic contaminants typically have low solubility in water but also a higher density than water, so called, dense non-aqueous phase liquids (DNAPL). This means that chlorinated solvents often have high mobility in soils leading to difficulties in the characterization and remediation, as well as posing high human health risks in low concentrations. The use of chlorinated solvents is estimated to have peaked nationally in the mid 1970s, although the knowledge on earlier consumption is uncertain. Chlorinated solvents primarily consists of chlorinated aliphatic hydrocarbons (CAH) such as perchloroethylene (PCE), trichloroethylene (TCE), tri-chloroethane (TCA) and dichloroethylene (DCE). These chemicals has mainly been used for degreasing in a variety of productions such as electronics, dry-cleaning, industrial manufacturing leading up to the high expected occurrence in soil. [2, 3, 4].

In addition to providing information on the situation of national contamination of soils, the Swedish EPA further highlighted available treatment methods[3]. Parallel to the development and implementation of the environmental task, a variety of new technologies for soil decontamination has emerged with unique features and applications [5, 6]. One branch of technology that has gained a lot of traction is In-Situ Thermal Treatment (ISTT).

The potential of ISTT as a method for site decontamination has been subject to recurrent recognition over the two last decades. The approach is considered to be both robust and flexible in the context that several contaminants, including chlorinated solvents, can be treated simultaneously. ISTT is also described as a technology relatively unaffected by subsurface heterogeneity[1] enabling the technology at a wide variety of geological conditions [5]. International experience has shown that ISTT can provide desired results under short treatment duration's compared to other technologies. In some cases changing the time-frame from years to months [5, 6].

The literature on ISTT has, over the same time-period, become increasingly extensive. Some areas that have received substantial coverage is the practical application of ISTT [5, 6, 7, 8, 9], consisting of guides and other descriptive publications of how and when to apply the technology. Further, ISTT have been considered in several site-remedy-technology-reviews where strengths and weaknesses are compared and evaluated [6, 10, 11, 12]. The focus of these texts vary. Some comparisons target all site-remedy-techniques; others have a focus on assessing completed ISTT-projects with emphasis on ”lessons learned” [9, 13, 14, 15]. Other publications assesses environmental and economic performance of ISTT-technologies and solutions [16, 17, 18].

Despite the body of literature already existing on ISTT-technologies, some knowledge gaps remain, not least for the Swedish context. There has been an expressed interest for investigations with a more significant focus on the Swedish narrative of the technology and in-depth assessments of the more recent Swedish projects by actors working in the field. This project targets to filling this gap.

## 1.1 Aim and objectives

The aim of the study is to analyse ISTT-projects conducted in Sweden and provide relevant experience feedback. To concretize the task, five research questions were constructed:

1. To what degree is the contamination reduced in Swedish ISTT-projects?
2. Under which conditions has the technology been proved to work well and less well?
3. What are the perceived strengths and challenges experienced in Swedish ISTT-projects?
4. Can any time- or cost drivers be identified?
5. How are the post-remediation follow-up programs designed?

[1] The presence of more than one soil types with different attributes in terms of for instance permeability and heat capacity. Examples: Clay, Moraine, Crystalline bedrock.

The study's primary focus is not to compare the applied technical solutions but rather to present and discuss the application of ISTT nationally, considering various data and perspectives.

## 1.2 Limitations

The study only considers thermal conduction heating (TCH)- and electrical resistance heating (ERH) projects. Conducted remediation's with steam enhanced extraction (SEE) are not included. Due to current scarce experiences, the feedback limited to the remediation of sites contaminated with chlorinated solvents.

# 2

# Theory

While the research field of contaminated sites is an interdisciplinary topic covering areas beyond soil remediation and technical solutions, this chapter aims to describe the concepts and physical mechanisms that together create the foundation on which the ISTT-technologies are based. Additionally, the necessary background and technical description of ISTT-technologies are provided, followed by the chemical properties of chlorinated solvents in the context of contaminated sites.

## 2.1 Soil resistivity

Soil resistivity is a term used to describe how slow or difficult it is to pass an electrical current through the media, the reverse concept of electrical conductivity. The resistance transforms the electrical current into heat losses to the surroundings. Table 2.1 presents soil resistivity values for a selection of soil types.

**Table 2.1:** Typical values of resistivity for a selection soil types [19].

| Soil type | Typical values of soil resistivity $(\Omega - m)$ |
|---|---|
| Clay | 40 |
| Shale, slates, sandstone etc. | 120 |
| Peat, loam and mud | 150 |
| Sand and clay mixtures | 200 |
| Moraine gravel | 1000 |
| Sand | 2000 |
| Solid granite | 25 000 |

Soil resistivity is sensitive to moisture, chemical content and temperature, and may vary greatly. As the table 2.1 shows, soil types with presumably higher water content have a resistivity one to two orders of magnitude lower.

## 2.2 Thermal conduction

In-Situ Thermal Treatment, as its name suggests, utilizes heat to remove contaminants in a controlled manner. The heat that is applied travels through the soil via *thermal conduction*. Thermal conduction is the movement of electrons and microscopic collisions between particles leading to the transfer of kinetic and potential energy from one body to another. It takes place in all phases: solid, liquid and gas. The rate depends on the temperature gradient between the bodies and the conductive properties of the interface in which the heat transfer [20].

The spontaneous direction of the heat flows towards thermal equilibrium (from hot to cold). The rate in which heat moves within a body is, in engineering science, commonly denoted as thermal conductivity: $\kappa$ ($\mathrm{Wm^{-1}K^{-1}}$). Values for the thermal conductivity in a variety of soil- and rock types are given in table 2.2 together with the values for water and air [20].

**Table 2.2:** Thermal conductivity for a selection of soils, sedimentary- and magmatic bedrocks together with values for water and air at room-temperature [21].

| Soil type | $\kappa(Wm^{-1}K^{-1})$ Frozen | $\kappa(Wm^{-1}K^{-1})$ Non-frozen |
|---|---|---|
| | Soils | |
| Clay | 2.0-2.3 | 0.8-1.1 |
| Silt | 2.3-3.2 | 1,2-2,4 |
| Sand | 0.4-2.5 | 0.4-3.3 |
| Moraine | 0.5-2.7 | 0.6-2.5 |
| Peat | 0.3-0.6 | 0.4-1.7 |
| | Sedimentary bedrocks | |
| Limestone | N/A | 1.5-3.5 |
| Shale | N/A | 1.5-3.8 |
| Sandstone | N/A | 2.5-6.5 |
| | Magmatic bedrocks | |
| Granite Granodiorite | N/A | 3.8-4.3 |
| Quartz syneit Tonalite | N/A | 2.5-4.0 |
| Syneit | N/A | 2.0-3.0 |
| Monzonite | N/A | 1.6-3.9 |
| Diorite | N/A | 1.6-3.0 |
| Gabbro | N/A | 2.2-3.4 |
| Peridotote | N/A | 3.5-4.5 |
| Air at 25°C | | 0.026 |
| Water at 25°C | | 0.61 |

## 2.3 Hydraulic conductivity

Hydraulic conductivity, sometimes referred as permeability, in the context of ISTT and contaminated sites, is a value indicating the soil´s property to transmit liquids and gases through its matrix. The property is often denoted as a coefficient $K$ and is an essential consideration in order to predict, and evaluate the movement of substances in contaminated sites. It is also commonly used in the feasibility-assessment of different remediation alternatives. Table 2.3 presents a list of coefficients for various sediments ranging from rapid to impermeable [20, 22].

**Table 2.3:** Hydraulic conductivity for a variety of soil materials [22].

<table>
<tr><th>K (m/s)</th><th>Soil type</th><th>Classification</th></tr>
<tr><td>10</td><td rowspan="3">Clean gravel</td><td rowspan="6">Rapid</td></tr>
<tr><td>$10^{-1}$</td></tr>
<tr><td>$10^{-2}$</td></tr>
<tr><td>$10^{-3}$</td><td rowspan="2">Clean sands,<br>Sand/gravel mixtures</td></tr>
<tr><td>$10^{-4}$</td></tr>
<tr><td>$10^{-5}$</td><td rowspan="5">Fine sands,<br>Organic and inorganic slits,<br>Sand, slits and clay mixtures,<br>Stratified clay deposits, etc.</td></tr>
<tr><td>$10^{-6}$</td><td rowspan="2">Moderate</td></tr>
<tr><td>$10^{-7}$</td></tr>
<tr><td>$10^{-8}$</td><td rowspan="4">Slow</td></tr>
<tr><td>$10^{-9}$</td></tr>
<tr><td>$10^{-10}$</td><td rowspan="2">Impermeable soils<br>e.g. homogeneous clay</td></tr>
<tr><td>$10^{-11}$</td></tr>
</table>

## 2.4 Chlorinated aliphatic hydrocarbons in soil

Common characteristic for chlorinated aliphatic hydrocarbons (CAH) is their mobility in soil and groundwaters. With a density greater than water, CAH:s are categorized as DNAPL and which penetrate the groundwater surface and enter the saturated zone and aquitard[1]. Contrary to petroleum products, which are lighter than water and denoted as Light Non-Aqueous Phase Liquids (LNAPL), and which stays on top on the ground water surface. The low relative viscosity of CAH:s leads to high diffusion rates and although the water solubility is low, the generally high toxicity is enough to enable hazardous groundwater concentrations. Additional features enhancing the mobility, is the low surface tension between the chlorinated solvents and water, together with weak chemical interaction between the contaminant and various sediments. The surface tension enables the compounds to enter small fractions and pores and the poor sorption to soil- and rock materials reduces the movement retardation of the solvent [2, 4, 24, 23, 25]. Skeletal structures of the substances primarily found in chlorinated solvents are provided in figure 2.1.

[1]Note: DNAPL´s ability to penetrate into an aquitard is dependent on the properties of the soil matrix. If the soil in the aquitard is too compact, it will act more like an turnstile, causing the DNAPL to flow horizontally along side the layer instead.

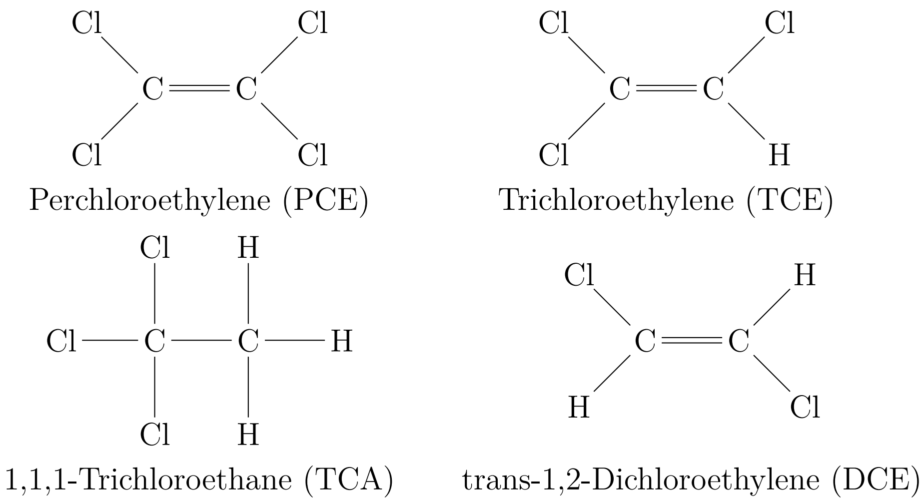


**Figure 2.1:** Skeletal structures of the four most common CAH-contaminates, only one isomer is included.

Chlorinated aliphatic hydrocarbons are persistent compounds in nature. Released into the environment, little to no natural degradation can be expected although, under ideal conditions, natural bio-degradation takes place. Additional natural mitigating effects mainly constitutes of vaporization which is dictated by the boiling temperatures that ranges between 32-121°C for the given CAH:s [2, 23, 24, 25].

Further, all compounds presented in Fig 2.1 forms an heterogeneous azeotropes with water. This means that for a specific mixture-ratio, the compound and water forms a liquid phase that has a lower boiling point than the constituents in pure form, deviating positively from Raoult's law (showing greater vapour pressure compared to an ideal gas). The proportions that yields the lowest boiling point is commonly referred to as the *eutectic point* or *eutectic mixture* for which the vaporized gas has the same content proportions as the liquid mixture. The eutectic boiling point for TCE and PCE, as example, is 73 and 88°C [26] compared to their corresponding boiling points in pure form being 87.2 and 121°C respectively.

## 2.5 ISTT-technologies

In-situ thermal treatment are site remediation technologies that utilizes heat to mobilize and extract contaminants. The term in-situ refers to the feature that the treatment is applied directly in the soil, contrary to ex-situ in which the contaminated soil is removed and transported to treatment plants for processing [27]. The heat can cause different effects depending on the generated temperature and type of contaminates. Summarized, the means of remediation falls in to two categories; remediation through evaporation or destruction of contaminants. Evaporation can be attained by heating the soil to temperatures that exceeds the boiling point of contaminant, or by steam stripping[2]. Destruction of contaminants mainly takes place via oxidation[3], pyrolysis[4] and hydrolysis[5][11, 28].

The main benefit of utilizing heat, compared to injection based treatments, is the relatively low dependency on soil heterogeneity. Ranging from sand to clay, the thermal conductivity varies with a factor of ±3 compared to the hydraulic conductivity that has a corresponding factor of $\geq 10^6$ (table 2.2 & 2.3). This excludes the case of bed-rock which is virtually impermeable but in all know cases show sufficient heat transfer abilities [14].

The main difference between ISTT-technologies is the way that the heat is generated. Two of the most common methods are electrical resistant heating (ERH) which utilizes an electrical current to warm up the soil, and thermal conduction heating (TCH) which operates by means of conductive heat transfer. Technical description for the two approaches are provided in the following subsections.

### 2.5.1 TCH

In Situ Thermal Desorption (ISTD) in the context of site-remediation technologies, is the combined use of TCH and vacuum-systems to extract contaminants from the soil. The heating is conducted by drilling and installing resistive electrical heating elements in wells. The steel casing is electrically isolated from the elements using ceramic material. As the element is connected to a power source and put under electric current, resistance occurs that generates heat with high efficiency. Temperature range for the wells is typically between 750-800°C with an upper limit of approximately 900°C [5, 15]. The heat transfers from the element to the casing via radiant heating, and from the casing to and through the surrounding materials via thermal conduction and fluid convection[6] [5].

Initially this type of thermal treatment was developed and used for enhanced oil recovery applications. As the knowledge on in situ heating and fluid recovery increased, the technology's application expanded to include various hazardous waste site cleanups [29]. To this date, the technology has been used to treat sites contaminated with substances ranging from low boiling volatile organic compounds (VOC) and chlorinated volatile organic compounds (CVOC) to high boiling polyaromatic hydrocarbons (PAH), polychlorinated biphenyl (PCB) and dioxins. It have also been applied in both saturated and unsaturated soil settings [5].

[2] Or just "stripping" refers to the physical process in which one or more components are separated from a liquid by a crossing steam flow.

[3] The chemical reaction in which a reagent gives away one or more electrons in the process. Oxidation may be expressed in terms of oxygen transfer. Substances gaining oxygen or loses hydrogen and/or electrons in a reaction are subject to oxidation

[4] The process of heating a substance to the point in which it decomposes. Substances change chemical composition but no combustion takes place.

[5] The chemical reaction in which a substance decompose in reaction with water.

[6] Heat transfer due to bulk movements in liquids

There are multiple design solutions when applying the technology. Each situation requires a thorough analysis of site-specific conditions to determine the most appropriate design. Figure 2.2 presents the conceptual model of a system where vertical extraction wells are installed near each heater supplemented with horizontal extraction screens in the vadose zone. This particular design is for a site with high Non-Aqueous Phase Liquids (NAPL) saturation where the target was to minimize condensation during heating [5]. As the heat transfers horizontally from each well, groundwater and present NAPL vaporizes. The contaminated steam moves towards the wells due to increased permeability generated by the temperature and phase transition in the vicinity of the heaters. The contaminants are captured by both the vertical vacuum installations and the shallow screens in the vadose zone as it moves up along the heater boring´s (note that actual site-designs are equipped with additional instruments for sampling, monitoring and controlling progress) [5].

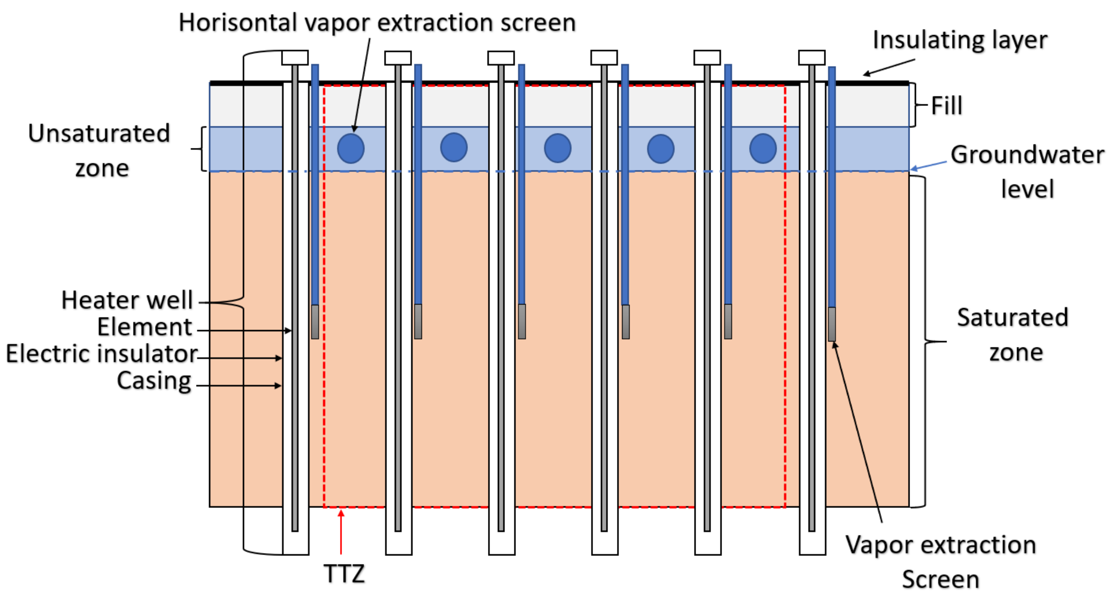


**Figure 2.2:** Conceptual cross section model of a site with TCH-system and vacuum extraction. The thermal treatment zone (TTZ) is marked with red dotted line. Image recreated from Kingston et. al. (2010) [5].

The above-surface equipment varies from site to site. The main considerations are the type of contaminants, size, depth, and extent of the contamination of the treatment area, together with local prerequisites and requirements. One example of an above-ground system is illustrated in Fig 2.3.

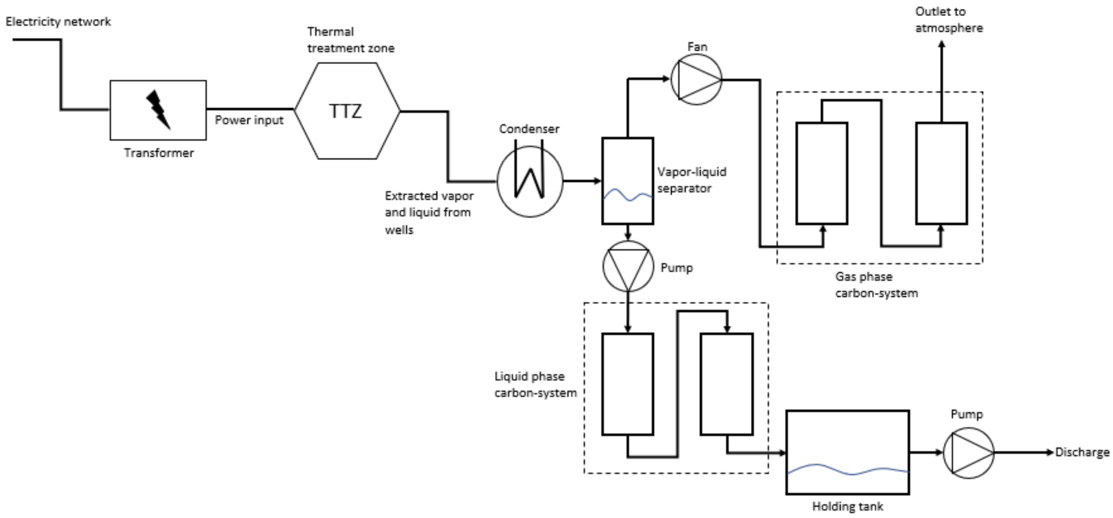


**Figure 2.3:** Example of components in an above-ground TCH- and vacuum system. Image recreated from Kingston et. al. (2010) [5].

A common addition to the system in figure 2.3 is a supplementary water treatment system in case of high ground water levels that requires dewatering. In such system, the groundwater is extracted, monitored and treated via pumps to maintain and control a uniform water table.

**Advantages**

The main technical advantages and contamination characteristics (e.g. contaminant(s), depth, soil matrix, extent of contamination) of the treatment area favoring the application of TCH found in literature can be summarized as follows:

- Relies fully on thermal conductivity which is relatively unaffected by subsurface heterogeneity.
- Has highly predictable heating pattern and treatment duration.
- Enables treatment of various contaminants simultaneously.
- Requires relatively short treatment periods. Time frame spanning from months to year (See figure A.1 in appendix for approximate treatment periods in relation to well spacing).
- Generates low final concentrations with reduction up to $\geq 99\%$.
- Is a very aggressive treatment. Suitable for recalcitrant contaminants such as most CVOCs, DNAPL, creosote, coal tar and PCBs.
- Wells can readily be adjusted in depth, practical for sites with deep contamination.
- Effectively treats source zones with high mass concentrations and significant NAPL presence.

[5, 6, 30]

**Disadvantages**
On the contrary, the following conditions and features found in literature challenge the technology:

- Significant heat losses in the case of large surface areas.
- Buildings and other structures hindering or complicating installation of wells.
- Wide-spread and shallow contamination lowers the effectiveness of the performance (heat losses, costs ineffective).
- Contaminants with a high boiling point below the groundwater table, where dewatering is difficult, is challenging to treat.
- A high groundwater flow (which is difficult to handle) will lead to significant heat losses (heuristic rule for suitable groundwater flow is $\leq$ 30 cm/day).
- Higher unit costs for small sites (heuristic for minimum treatment volume is $\leq 2300\text{m}^3$).

[5, 6, 30]

### 2.5.2 ERH

Electrical resistant heating (ERH) is an ISTT-method based on passing an electrical current between electrodes. Unlike TCH where conductive heating is generated from the electrodes themselves, ERH utilizes properties in the soil. Most ground materials are good insulators, limiting the passage of electrical currents. It is this resistance that in turn generate the elevated temperatures. ERH is attained by installing a system of electrodes in wells. Opposite to ISTD, the well-annulus can be filled with electrically conductive materials to increase the effective diameter of the electrode. The system is then connected to a power source where electricity is delivered to the electrodes via a power control unit (PCU). During operation, the electrical current naturally seeks the easiest pathway to conduct through the subsurface. Hence, the more electrically conductive zones gets heated first. Over time, as the more conductive zones are heated and local water volumes gets boiled away, the temperature in the less conductive material becomes gradually elevated. To prevent electrical current from flowing to a distant sink, the PCU is equipped with isolation transformers. These devices transfer electrical power to the electrodes while isolating them from the power-source, forcing the current to flow only between the electrodes. Thermal conduction also plays a role in ERH, mainly in the vicinity of the heater wells due to the temperature of the electrodes. ERH have an in-situ temperature range up to the boiling point of water at local pressure conditions (typically 100-120°$C$). Vaporized contaminants are extracted via vapour recovery wells (vacuum pumps), commonly co-located with the electrodes in so called "combination wells" or via other conventional vacuum systems [5].

ERH-based remediation technologies was developed by the U.S. Department of Energy inspired by oil production technology to improve remediation methods based on vapor extraction in low permeability soils. ERH have been applied to treat a large variety of contaminants such as VOCs, CVOCs (especially of LNAPLs and DNAPLs), pesticides, PAH compounds and creosote.

The well design for ERH projects varies significantly depending on the local settings and requirements (e.g. contaminant(s), soil matrix, physical obstacles and remediation targets). Figure 2.4 presents a schematic figure of an ERH combination-well equipped with two electrodes at different depth intervals, a water injection system with four injection slots to enhance the electrical conductivity, one return slot for the water, and one internal vent for vapour recovery.

The distribution of the ERH-wells is dependent on site-specific conditions but two configurations are dominating: triangular and hexagonal (see figure 2.5). Both configurations are based on generating uniform heating with as few installations as possible. A triangular configuration is perceived as the simpler way to attain uniform voltage between electrodes. The system runs on three-phase alternating current and can, with relative ease, be mapped over irregularly shaped areas. Hexagonal configuration has mainly been deployed in pilot testing, although vendors for full scale application is available today. The main difference in operating the two configuration is the need for more advanced system control for the hexagonal mapping to prevent local hot- and cool-spots from emerging.

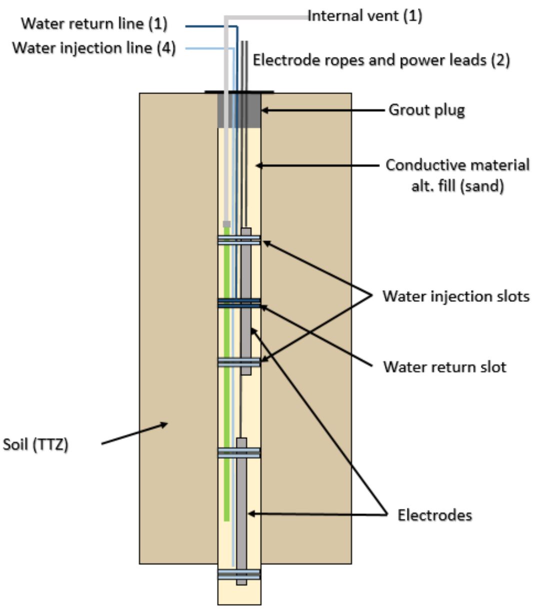


**Figure 2.4:** Schematic figure of an ERH combination well. Image recreated from N. Rahm (2017) [52].

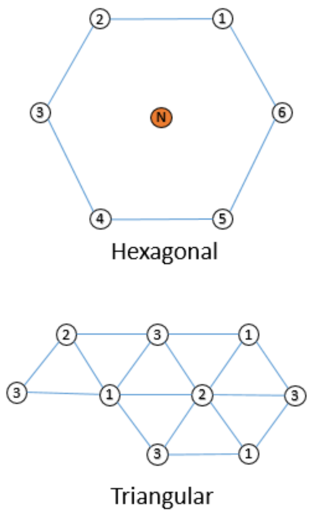


**Figure 2.5:** Illustration of hexagonal and triangular well configurations. Image recreated from U.S. Army Corps of Engineers (2014) [6].

The above ground equipment required to operate an ERH-system typically includes: power-transformer, power control unit, injection water with holding tank, pressure and vacuum pumps, condenser, water storage tank, flow meters, activated carbon treatment systems together with cables and equipment to support operation and maintenance. Figure 2.6 presents the system chart for a typical ERH-site design.

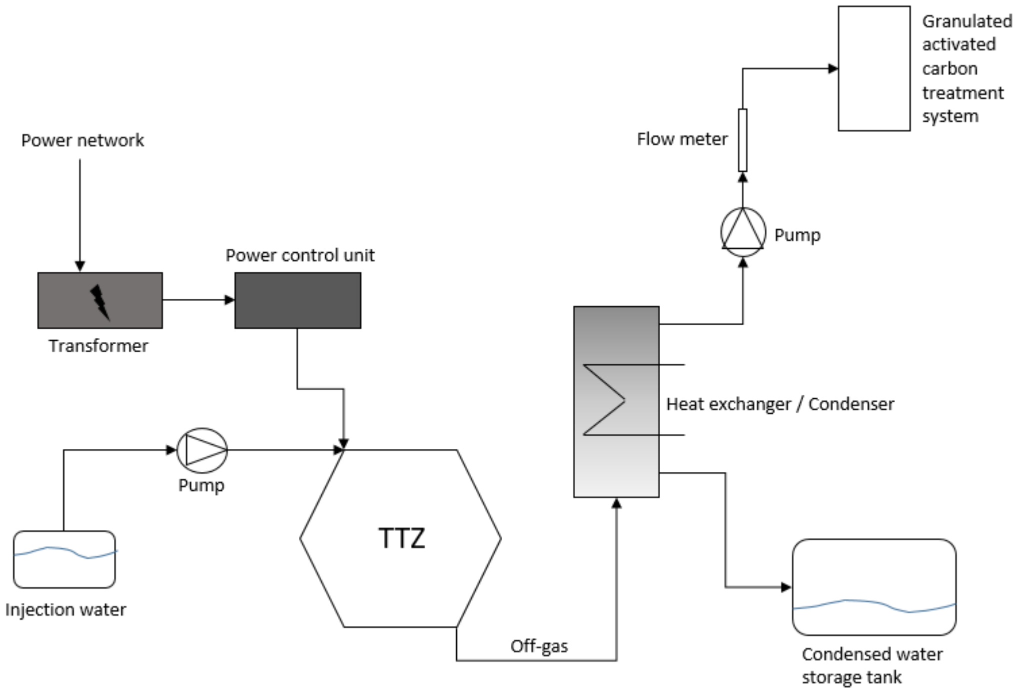


**Figure 2.6:** Illustration of a schematic ERH system.

**Advantages**
The settings and conditions found in literature that favours the application of ERH are listed below.

- The treatment is self-correcting in that the most electrically conductive zones will dry out first. Dry soil is less conductive causing the electrical current to find another path whilst the local soil moisture resets.
- Enables distinct heating zones as the electrodes can be installed at specific depth intervals, and be independently operated with power input.
- ERH is applicable in all soil types, including sedimentary bedrock, and is relatively unaffected by subsurface heterogeneity.
- Commonly applied to treat chlorinated ethenes (or ethylenes) and ethanes where other DNAPL is present as well.
- Commonly applied to treat below existing buildings. The format of the electrodes entails less strict requirements on overhead clearance. Electrodes have been successfully installed with an angle to treat areas otherwise difficult to reach.

- ERH can achieve very low final concentrations.
- The post-treatment soil temperature cools down on the time-scale of months to a year. During this period, bio-remediation and hydrolysis effects are enhanced, driving the remediation further.

[5, 6, 31]

**Disadvantages**
The settings and conditions found in literature that challenges the application of ERH are listed below.

- May suffer from great heat losses in the case of high groundwater flows. Engineered measures to slow down groundwater flows can mitigate this effect.
- May suffer from great heat losses in the case of small sites, or sites with large surface-to-volume ratio.
- Some PAH compounds can be difficult to remediate. Concentration reduction for compounds with a boiling point of $\leq 300°C$ is typically $\geq 85\%$. Compounds with higher boiling point tend to not be significantly reduced.
- Sites with landfills or other sources of metal debris may affect the path of the electrical current and consequently the heating pattern.

[5, 6, 31]

# 3 Methods

The approach to answer the research questions consisted of three main tasks — the identification and selection of Swedish ISTT projects to include, a document study on publications covering the projects and a conducting set of interviews with representatives from the actors involved. The purpose of the document study was to compile data and information to get a quantitative picture of the application in Sweden. The scope of the interviews was to gather perspectives and experiences not included or hard to distinguish in the documents and to nuance the findings of the document study. This chapter aims to describe the methodologies used in order to conduct the three tasks.

## 3.1 Objectives

As a part of conducting the quantitative and qualitative studies, a set of objectives was constructed to concretize requirements, success criteria, the expected outcome and which research question[1] the objective aim to answer, see table 3.1.

**Table 3.1:** Project objectives and how they answers the research questions, inspired by Kingston et. al.(2010) [5].

| Objective | Data requirements | Success Criteria | Results | Research question |
|---|---|---|---|---|
| Quantitative | | | | |
| Mine and compile data on Swedish ISTT-projects | Data on site settings, technology approach/design, monitoring data and measurements, results and control programs | Data exists in documentation, ability to obtain documentation | Tables of compiled relevant findings | 1, 2, 4 |
| Qualitative | | | | |
| Compile perspectives and experiences via interviews | Perspectives and experiences from all major parties involved in ISTT-projects | Interviewees available, remembers experiences, relevant interview questions | Summarized statements of main take-aways | 2, 3, 4, 5 |

[1]Refers to the 5 research questions listed in section 1.1, Aim and objectives.

## 3.2 Identification and selection if Swedish ISTT projects

In order to identify relevant projects, a screening was performed by reaching out to individuals that have been involved in the Swedish application of ISTT of contaminated sites. In the screening process five projects was identified that had been completed or close enough that relevant documents, data and involved actors were available or could be identified. With the provided time frame and in order to get the most extensive picture of the Swedish application, all five projects where included in the study. The names of the five projects selected is as follows:

- Kvarnholmen
- Färgaren
- Järnsågen
- Reno
- Nymans

## 3.3 Document study and methods for compilation of data

The objectives of the document study was to review and compile publications on conducted ISTT-projects in Sweden by mining data and information from each site. Requirements on obtained data focused on comparability across project and aiding the review on the ISTT-application. The gathered information cover the following:

- Soil settings: Geologic description, Groundwater level, flow and direction.
- Contamination: Contaminants, pre-treatment concentrations.
- Remediation approach: Objectives, technology, site-design, measurement methods.
- Level of remediation: Extracted mass, mass- and content reductions, remaining contamination level.
- Verification of results
- Energy
- Costs

The documents were subject to evaluation regarding reliability and accuracy. The following documents and information sources was included in the study:

- Final Report (regional or municipal).
- Final project report and evaluation (procured or hired actor).
- Unpublished measurements, data bases and results on energy consumption, costs and remediation.

### 3.3.1 Indicators and key figures

Information and data obtained in documents were compiled by utilizing indicators and key figures from R. Anderson's literature review on *Efficient remediation of contaminated sites* (2017) [32] and inspired by the critical review of thermal treatment technologies conducted by Kingston et. al (2010) [5]. Further selection was based on what was deemed relevant and possible with given information and time frame.

According to Anderson (2018) [33], existing indicators used for assessing site remediation approaches can operate in one out of three levels: technical, project or national. Indicators that operate at a technical level targets the efficiency and effectiveness of a specific treatment for a particular contaminant(s). Project-level indicators have the same focus but in relation to time, costs, amounts, risk reduction and fulfillment of project goals, etc. The broadest, national level, indicates efficiency and effectiveness in relation to national remediation programs [33]. Due to the scope of this thesis, only indicators operating on a technical- or project level were considered. A summary of R. Anderson's (2017) [32] identified indicators is provided in Table 3.2

**Table 3.2:** Summary of efficiency/effectiveness indicators on each level, recreated from R. Anderson (2017) [32].

| Level | Efficiency | Effectiveness |
|---|---|---|
| National | | No. sites assessed<br>No. sites started<br>No. construction completed<br>Liability reduction<br>No. sites completed<br>Sites per year<br>Environmental indicators<br>No. sites identified<br>No. sites ongoing<br>No. sites ongoing/completed for res. construction |
| Project | Time per amount excavated<br>Cost per amount excavated<br>Cost per remediation area<br>Cost per amount contaminant removed<br>Cost per risk-ratio<br>Cost per person in area<br>Total project time<br>Total project cost | Total project time<br>Total project cost<br>Cancer risk reduction<br>Total amount of contaminants removed<br>No lives saved<br>Accident risks from RA<br>Area remediated<br>Amount soil remediated<br>No. soil species affected<br>Surface water protection<br>Groundwater protection<br>Emissions<br>Consumption of clean soil for refilling |
| Technical | Degradation<br>Removal<br>Immobilization<br>Remediation time<br>Cost per volume<br>Cost per weight<br>Translocation factor | |

Two commonly used terms in the context of assessing performance are efficiency and effectiveness [32]. In Swedish, these two terms are fused in the word "effektivitet". To clarify the difference between the English terms, their respective definition according to Oxford Dictionary of English [34] are provided below:

- Effective: Successful in producing a desired or intended result [34].
- Effectiveness: The degree to which something is successful in producing a desired result [34].
- Efficient: Achieving maximum productivity with minimum wasted effort or expense. Preventing the wasteful use of a particular resource. Working in a well-organized and competent way [34].
- Efficiency: The state or quality of being efficient [34].

### 3.3.2 Generalized geologic type-setting

A set of site descriptors was recreated from Kingston et al. [5] with the purpose to enable generalization of geological conditions to facilitate the comparison. Each descriptor represents an idealized geological scenario to which each project was categorized in to, based on "most fitting". The idealized scenarios adopted were as follows:

- **Setting A:** High- to moderate permability sediments. Relatively homogeneous.
- **Setting B:** Moderate- to low permability sediments inter-bedded with more permeable layers and lenses.
- **Setting C:** High- to moderate permability sediments inter-bedded with low- to impermeable layers, lenses and boulders.
- **Setting D:** Fractured bedrock (crystalline rock)
- **Setting E:** Weathered bedrock (sandstone, limestone, etc.)

A scenario of impermeable sediments and homogeneous settings was not created. Typically, impermeable sediments are found in layers with increasingly permeable materials (creating scenario B), although the size of the layers is subject to large variations [5]. However, massive layers of clay can be found in the Swedish geology that would fit the scenario but these sites would not be suitable to remediate with ISTT.

## 3.4 Interviews

With the aim of nuancing the findings from the document study and gather experiences on the Swedish projects, a set of interviews was carried out. Individuals were selected with the goal to include representatives from all the major parties involved in the project organizations to cover as many perspectives as possible. This in turn to enhance the quality of the experience feedback. Figure 3.1 illustrates the main actors and the hierarchy in Swedish ISTT project organisations.

Further considerations in the selection of participants was to retrieve corresponding perspectives and experiences across projects. In order to fulfill this requirement, the chosen approach was to aim to interview representatives from every major party in the project organization for at least two projects. Figure 3.1 illustrates the selection.

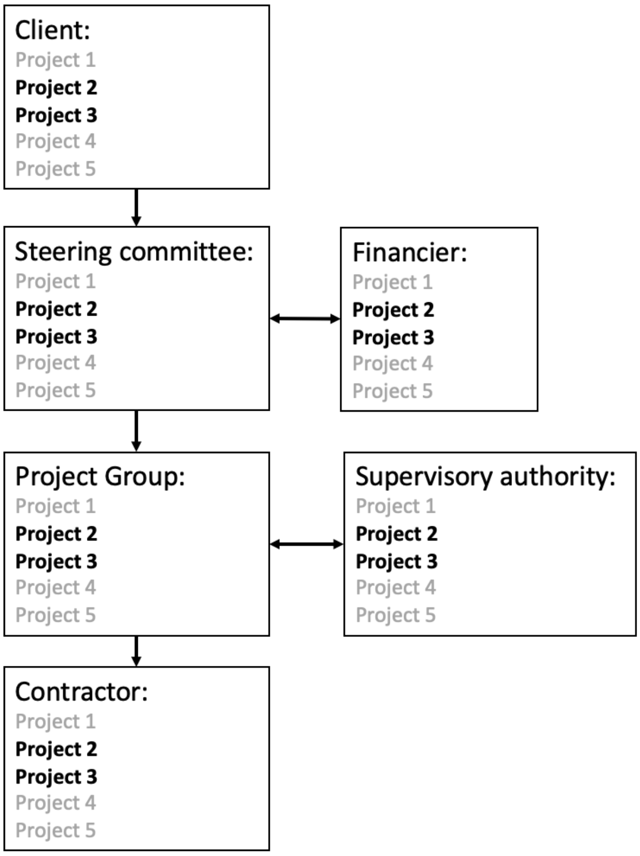


**Figure 3.1:** The project organization in Swedish ISTT-projects. An example of the intended minimum interview selection is illustrated in bold font. Arrows indicate the hierarchy within the project organisation.

The client is typically the municipality or private actor that put forth the request and initiates the project. It is the client that appoints relevant personnel to the steering committee such as the project manager. Additional examples of individuals that can be part of in this group is the client CFO and head of strategy and development. If the project is publicly funded, the steering committee is the body in the organization that handles the communication with the financier, which usually consists of the Swedish EPA or the county administrative board. The project manager appointed by the client is also often part of the project group. This group manage the on-site activity of the project. In addition the the project manager, a technical project manager or support and representatives from the county and supervisory authority can be part of the project group. The contractor is the procured firms that provides the ISTT-related services.

### 3.4.1 Semi-structured interview

The sought information in the interviews regards experiences from projects, the technology, and its application. It includes personal perceptions, and the emphasis on what is important may differ between respondents. In terms of interview format and finding balance between flexibility, reliability and comparability, semi-structured interviews was deemed most fitting. Semi-structured interviews are characterized by a prepared interview guide consisting of a set of questions in a particular order. The guide's purpose is to secure that vital information is gathered and enhance reliability and facilitate comparisons. Further, the interview methodology allows the interviewer and respondent to follow up on thoughts and ideas that comes forward during the interview and to temporarily deviate from the guide. The interview format is considered the most suitable approach when there is only one interview occasion, time is limited, and comparability is important [35].

### 3.4.2 Interview format

The interview design was set to one occasion per individual and the interview guide contained 12 questions. Due to COVID-19 and the geographic distribution of respondents, interviews were primarily conducted by video conference or phone call. Interviewees were contacted via e-mail or phone with an introduction to the project. If desired, the interview template was provided beforehand. All dialogues from the interviews were recorded with permission from the respondent. Recordings were used to process content from the interviews to summarized answers to the questions in the template. All answers were sent to the respective respondent for adjustments and confirmation of statements before use. The interview template can be found in appendix A.1.

### 3.4.3 Qualitative data analysis

The processing of interview results was conducted following a step-by-step method by K. Löfgren [36]. The initial step was to get familiar with the results, browsing through the content, and taking notes of first impressions. The second step consisted of reviewing the results again, carefully, and coding relevant pieces by labeling words, opinions, actions, and more. Decisions about relevance were based on whether the topics were: recurrently mentioned by respondents, highlighted as important by respondents, or related to concepts and findings in literature. Step three included a review by making changes, filtering, and categorizing the content. The last two steps focused on labeling the categories and assessing hierarchies among the them. Finally, the results were compiled in tables.

# 4
# Description of case studies

## 4.1 Reno, Visby

**History:** Reno is the name of a now closed dry cleaning business on the address Senapen 25 in Visby on Gotland. The 770 $m^2$ facility is located in a small neighborhood approximately 500m east from the medieval city wall in Visby. Reno operated between the years 1964 and 1980 with an estimated annual consumption of 2 tonnes of PCE. After confirming high concentrations of PCE in the surrounding soil, a site remediation project got initiated in 2014, founded by the Swedish EPA.

**In situ treatment record:** Prevailing soil conditions was described as a combination of clay and moraine with thin lenses of sand. Selected treatment technology for the site was electrical resistive heating (ERH). The installed subsurface system design consisted of 48 wells with combined heating and vacuum extraction function. Each well was equipped with two electrodes installed at separate depths together with upper and lower vacuum pipes. Additionally installed well instruments were grounding electrode and water pipe to sustain moisture for enhanced convective heat transfer. Soil temperature was monitored in six wells, measured at six depths. The treatment zone was covered by an isolating and waterproof sheet and three control measuring points were installed along the edge of the area.

**On-site equipment:** The above ground system included vacuum pumps and fans, containers with operation and control systems, a water separator, carbon filters, and general equipment to support operation and maintenance.

**Monitoring:** Both the contractor and external organization conducted process monitoring. Contractors supervised 17 site and process points with a resolution in time spanning from minutes to months. The control subjects included pore gas, groundwater, vacuum, soil temperature, safety, energy consumption, air flow and contaminant concentrations. The organisation procured to perform additional environmental control sampled seven items with a sampling frequency varying from monthly to single measure over five years depending on location and attribute. These items included pore gas, groundwater, soil, indoor air quality and soil settlement. See appendix A.2 for detailed example.

**Remediation results:** The first verification in soil post treatment indicated that measurable remediation targets had been attained in terms of average values, but not for maximum concentration in single samples. Inability to prolong the treatment due to worn out equipment led to a revision of the measurable remediation targets to indoor air quality for which the remediation showed sufficient reduction. The final remedial system performance is estimated to a 98-99,9% soil concentration reduction in the source zone. Total contaminant mass is estimated to an approximately 90% reduction, and the reduced groundwater content is considered likely to be more than 90%.

## 4.2 Nymans, Uppsala

**History:** Nymans workshops are located in central Uppsala. The area is populated by offices and residence buildings with an industrial record going back to the late 1800s. The previous activity at Nymans constitutes of different metal industries, mainly bicycle manufacturing, where TCE was used in the degreasing process of metal surfaces. During the assessment for further exploitation of the area, a variety of contaminants was identified on the surrounding soil. Amounts of metals, oil products, and PAH were identified in addition to significant levels of TCE.

**In situ treatment record:** The geological conditions at the site were described as a shallow layer of filling material, including sand, gravel, stone, and construction materials. Sediments underneath the filling included layers of clay and moraine with occasional sand lenses. The technology implemented to remediate the site was ERH. The layout consisted of 55 heater wells deployed over three separate areas with a total size of 505 $m^2$. Each well was equipped with two electrodes installed at 3-5 and 7-9 meters depth, respectively. Each heater was further equipped with water injection slots to enhance heat transfer and to provide a steady circulation of water between the heaters and the 27 extraction wells distributed in the three areas. Additional installments included 14 temperature monitoring wells measuring at every meter from the surface to 9 meters depth. Out of the total installations, eight heating wells, four vacuum pumps, and one temperature monitoring well were installed indoors. Final measures included asphalting of the ground surface outdoors.

**On-site equipment:** Above ground equipment consisted of a fan system providing vacuum, a water injection system, stationary gas chromatography set-up, two containers for energy transmission, knock-out tank, carbon filters, potassium permanganate filters, bag filters, air cooler, storage tanks, vacuum pipes, hoses, connections and some additional materials necessary for the operation.

**Monitoring:** During operation, both contractor and external organization conducted process monitoring. Contractors monitored 13 site and process points including pore gas, groundwater, vacuum, soil temperature, energy consumption, air flow, safety, local environment and contaminant concentrations with a resolution spanning from minutes to months. The external control organization monitored four site and process points with resolution varying between monthly basis to single measures over five years. Included in the control program was soil, groundwater, pore gas and soil settlement.

**Remediation results:** After 165 days of operation, the system was closed down. Verification-samples indicated concentration reduction of ≥99 % based on both soil- and groundwater measurements.

## 4.3 Färgaren, Kristianstad

**History:** The plot Färgaren 3 is located in the district of Långebro, west of Kristianstad. Between approximately 1930 and 1980, a local dry-cleaning business that used PCE as detergent operated the now demolished facility. Due to the lack of municipal water and sewage systems at the time, sewage water and possibly chlorinated solvent waste was released out in the soil or wells located in the vicinity of the facility. Two assessments of the contamination was performed, one pre-study in 2004 and a full assessment in 2012 resulting in a full scale remediation.

**In-situ treatment record:** Soil settings in Färgaren were described as layers of clay, mud, and peat of varying thickness on top of a layer of permeable sand with occasional sand/limestone boulders. The treatment selected for the remediation was combined excavation and ISTT with a TCH- and vacuum system. The layout consisted of 92 heaters reaching 22 meters down in the ground and 13 shallow vacuum wells deployed in a constructed extraction layer (0.5 m of gravel covered with 2 m of fine sand) applied over the treatment area. Additional subsurface installments included four groundwater pumps to maintain the water level and 11 wells for monitoring the temperature profile of the treatment volume.

**On site equipment:** Other on site equipment included transformers, a power unit, storage containers, radiator/condenser, carbon filters, control systems, and additional equipment to support the operation.

**Monitoring:** Safety and control measures were undertaken by both contractor and environmental controller hired by the client. The control program consisted of 16 items covering soil temperature, contamination, groundwater (pressure, level and contamination), air and water outlets, noise, extracted flows and surrounding subsurface infrastructure. The test frequency of the items vary from continuous measurements (e.g. contaminant concentration in extracted vapours) to quarterly measurements (e.g. sampling of the groundwater in the surrounding area).

**Remediation results:** As the mass of the daily cumulative extracted contaminants asymptotically reached insignificant rates, treatment seized. The first verification round of soil samples indicated that remediation targets were achieved in all but one sample location. Supplementary treatment was conducted at and in the vicinity of the identified location for 3 weeks. The final verification indicated a concentration reduction of $\geq$99.9 %.

## 4.4 Järnsågen, Trollhättan

**History:** The facility at Järnsågen 3, located in Halvorstorp, part of eastern Trollhättan, operated as a residence from 1974 to 2013. The building was demolished in 2013 to facilitate remediation due to the building's history as a dry-cleaning business between 1950 and 1974. Similar to Färgaren 3, the lack of water and sewage systems and unknown waste management at the time initiated an investigation of contamination. The investigation determined that the site was indeed contaminated with chlorinated solvents resulting in the remediation of the site.

**In situ treatment record:** Geological settings at Järnsågen from surface and down consisted of a surface layer of asphalt, bearing layer of soil, 3 to 8 meters of clay and crystalline bedrock with spots of moraine in the boundary layer. The treatment selected for the site was to excavate the sediment and thermally treat the bedrock with TCH. Heat was delivered via 60 heater wells reaching 21.5 meters down in the bedrock. Extraction was conducted via 14 shallow vacuum wells installed in an artificial extraction layer applied on the bedrock surface post excavation. Further installations included nine temperature monitoring wells measuring at every meter, 15 groundwater sampling wells with slots at three different depths (6, 11 and 20 m), and a roughly 8 meter deep well equipped with a pump to provide a draw down of the water table.

**On site equipment:** The above ground system included liquid- and gas treatment plants with active carbon filters and occasional hydrazine filters preceded by knock-out tank, pumps, buffer tanks, condensers, and heat exchangers. A power unit and transformers to provide sufficient energy input were present as well.

**Monitoring:** Controllers hired by the client monitored the impact on the immediate surroundings. Controls were conducted following two programs, one targeting impacts on air and water/groundwater and one focusing on soil subsidence. In summary, the two control programs the covered groundwater levels and contamination, indoor air quality, water outlet of the water treatment plant, pore gas pressure and movement, air outlet of the thermal treatment and the general effects on the immediate surrounding. Frequency of the measurements varied from twice a week for the analysis of the air outlet from the treatment plant to single measurements on, for instance, inspection of the adjacent road.

**Decontamination results:** As the daily cumulative mass extraction decreased to the magnitude of a hundred grams, power input seized. Verification samples were difficult to take due to dried up wells, but the number of samples gathered all indicated very low levels of contamination. Additional verification was conducted months after treatment, strengthening the initial sampling results, and resulting in a final estimated mass reduction of $\geq$99 %.

## 4.5 Kvarnholmen, Nacka

**History:** The municipality of Nacka adopted a new vision for the Kvarnholmen area at the beginning of the millennium. Parts of the new idea included removing old industry facilities located on the southern part of the peninsula-like area to enable new construction projects. At the eastern end of the industrial area there were three cisterns, previously used for storing various chemicals and residues. The cisterns were demolished in 2012, and in connection with the new construction projects, contamination in the form of chlorinated aliphatics was identified in the ground.

**In situ treatment record:** Geological soil settings of the treated volume consisted of fractured bedrock. The remediation targeted the 15 meters deep unsaturated zone to secure non-hazardous contamination under future constructions in the source and edge zones of the contamination. Treatment was conducted using 113 TCH combination wells deployed over the 1238 $m^2$ large area, reaching down to a depth of around 30 meters (extraction filters installed in the vadose zone only, minimum 5 m above groundwater table). Additional extraction was conducted via 30 shallow horizontal installments. Groundwater inside demarcation was monitored through 8 wells, sampling at three different depths in the saturated part of the treatment zone. Lastly, temperature monitoring and pore gas measurements were gathered at 12 locations.

**Decontamination results:** After 23 weeks of operation treatment was seized. Verification of sufficient remediation was conducted in pore gas sampling points and in the groundwater sampling points located closest to the surface (remediation only targeted the vadose zone and groundwater in direct contact with the above-lying pore gas). The remaining contamination in the unsaturated volume was estimated few grams compared to the pre remediation estimation of contaminants of approximately 300 kg.

# 5
# Results

This chapter presents the findings of the conducted document study and interviews. First are the projects expressed numbers containing compiled data and indicators for a selection of project- attributes and performances to provide a picture of the Swedish application. Following to the data mined in the document study is the interview results. Replies to a selection of questions are compiled in figures and tables together with summarized answers from the interviewees. Two projects was prioritized. Interviewees in prioritized projects are treated in individual text-summaries. The remaining projects are covered together.

Table 5.1 presents the sources included in the study for each project. All projects contain some figures that are entirely- or partly based on unpublished documents and estimations. These figures mainly occur in the economic performance assessment due to differences and uncertainties in the aggregated numbers provided in their official reporting.

**Table 5.1:** Documents and sources from which information has be gathered. 1: Final reports (regional or municipal), 2: Final project reports and evaluation (procured or hired actor), 3: Unpublished measurements, data bases and results on energy consumption, costs and remediation.

| Source type | Kvarnholmen | Färgaren | Järnsågen | Reno | Nymans |
|---|---|---|---|---|---|
| 1 | | x | x | | |
| 2 | x | | | x | x |
| 3 | x | x | x | x | x |

## 5.1 Case-studies: The projects in numbers

This section presents the compiled results from the document study for the five projects. Data is categorized in five subsections: Site description, Design parameters, Operational results, Remediation results and Energy & Economic performance. All data is summarised in tables and a brief presentation of how the data was obtained.

### 5.1.1 Site description

Table 5.2 presents the assigned conceptual soil conditions for each project. Project Kvarnholmen and Järnsågen are assigned soil setting D: Fractured bedrock. Färgaren are assigned soil setting A: High- to moderate permability soils and relatively homogeneous. Reno and Nymans are assigned soil setting B: Moderate- to low permability sediments inter-bedded with increasingly permeable layers and lenses. All assigned settings have been verified by involved actors from each project.

**Table 5.2:** Assigned generalized geological type-settings according to the description in section 3.3.2

| | Kvarnholmen | Färgaren | Järnsågen | Reno | Nymans |
|---|---|---|---|---|---|
| Soil setting | D | A | D | B | B |

A selection of site attributes are presented in Table 5.3 for each project. No particular CAH was reported as a primary contaminant in project Kvarnholmen. The most shallow contamination treated with ISTT is 9 meters. ERH has been applied on smaller volumes and shallow sites compared to TCH. The distance to the groundwater table is large in Kvarnholmen.

**Table 5.3:** Selection of data on thermal treatment zone. Tech refers to the technology used, Cont is the primary contaminant, Area is the treatment area in $m^2$, Depth is the maximum treatment depth in meters, GW is the ground water level in meters below ground and TV is the Treatment zone volume in $m^3$

| Site ID | Tech | Cont | Area ($m^2$) | Depth ($m$) | GW ($m_{bg}$) | TV ($m^3$) |
|---|---|---|---|---|---|---|
| Kvarnholmen | TCH | CAH | 1238 | 30 | 14-15 | 29 607 |
| Färgaren 3 | TCH | PCE | 914 | 20 | 3-4 | 16 000 |
| Järnsågen 3 | TCH | PCE | 500 | 20 | 1-2 | 7 500 |
| Reno | ERH | PCE | 650 | 9 | 2-3 | 5 805 |
| Nymans | ERH | TCE | 506 | 9 | 5.7-6.1 | 3036 |

### 5.1.2 Design parameter

Table 5.4 includes data on well installations. Sites with combination wells show the lowest density both in ERH- and TCH projects. The layout is dominated by heaterwells. Project Nymans shows a noteworthy high value on the density of monitoring wells.

**Table 5.4:** Well-settings for each project. *Heater* refers to heater wells and *Extract* refers to extraction wells. *Monitor* includes wells measuring temperature, pressure and pore gases. *GW-monitor* refers to groundwater monitoring wells. [a] *Combination wells* [b] *Shallow horizontal wells.*

| Site ID | Technology | Well density (borings/$m^2$) | | | |
|---|---|---|---|---|---|
| | | Heater | Extract | Monitor | GW-monitor |
| Kvarnholmen | TCH | 0.0913[1] | 0.0913[a] (+0.024)[b] | 0.011 | 0.006 |
| Färgaren 3 | TCH | 0.100 | 0.014 | 0.012 | N/A |
| Järnsågen 3 | TCH | 0.120 | 0.028 | 0.018 | 0.01 |
| Reno | ERH | 0.074[a] | 0.074[a] | 0.01 | N/A |
| Nymans | ERH | 0.095 | 0.053 | 0.027 | N/A |

### 5.1.3 Operational results

Table 5.5 contains temperature data on the thermal treatment. The TCH projects operate at higher temperatures but over a shorter duration. The ERH-treatments operates under more moderate temperatures, occasionally exceeding the boiling point of water in specific regions. With the available data it can be observed that $T_b$ was not attained throughout the entire treatment zone in project Kvarnholmen and Reno. The coldest region was found at the top surface area in both cases. The long duration in project Reno is partly due to subsurface malfunctions involving clogged extraction wells.

**Table 5.5:** Selection of temperature results from operation. $T_{max}$ refers to to the maximum temperature through out the thermal treatment zone (TTZ) with values for both the warmest and the coldest sections. Average duration above $T_b$ and 100°C, targets the treatment period for which the average temperature in the TTZ exceeded the boiling point of the primary contaminant and water (at surface conditions). The eutectic boiling point for PCE and TCE is 88 and 73°C, respectively [26].

| Site ID | Primary contaminant | Technology | $T_{max}$ TTZ (C) | | Average duration above: (d) | | Treatment Duration (d) |
|---|---|---|---|---|---|---|---|
| | | | Low | High | $T_b$ | 100°C | |
| Kvarnholmen | CAH | TCH | 70 | 180 | 92 | 80 | 162 |
| Färgaren 3 | PCE | TCH | 85 | 121 | 77 | 67 | 134 |
| Järnsågen 3 | PCE | TCH | 80 | 138 | 78 | 68 | 117 |
| Reno | PCE | ERH | 70 | 102 | 123 | 0 | 306 |
| Nymans | TCE | ERH | 85 | 99 | 130 | 0 | 165 |

### 5.1.4 Performance results

Table 5.6 presents data on changes in measured concentration before and after ISTT. Values are given in the media targeted by the project's measurable remediation targets. No official data on average concentrations were provided in the project Kvarnholmen. Concentrations are calculated based on samples taken pre-treatment, and the most recent measurements provided in the Kvarnholmen reporting. Further clarification for Kvarnholmen is that the groundwater remediation values target the top region of the water table as only this part of the groundwater was subject to remediation goals. A summary of measurable remediation targets for all prijects is presented in appendix A.2

**Table 5.6:** Change in average and max concentration pre- and post treatment. Values are given for the media targeted by the project's measurable remediation targets. Groundwater and pore gas is denoted in the table as GW and PG respectively.

| Site ID | Average contamination | | | | | |
|---|---|---|---|---|---|---|
| | Soil (mg/kg) | | GW ($\mu$g/l) | | PG (mg/m$^3$) | |
| | Pre | Post | Pre | Post | Pre | Post |
| Kvarnholmen | | | 32 100 | 104 | 143 | 18.1 |
| Färgaren 3 | 81 | 0.06 | | | | |
| Järnsågen 3 | | | 52 000 | 409 | | |
| Reno | ≥69 | 1.3 | | | | |
| Nymans | 24.2 | 0.2 | 1956 | 2.9 | | |
| | Max contamination levels | | | | | |
| Kvarnholmen | | | 42 000 | 192 | 1 300 | 200 |
| Färgaren 3 | 1000 | 1.3 | | | | |
| Järnsågen 3 | | | 160 000 | 2600 | | |
| Reno | 2300 | 44 | | | | |
| Nymans | 292 | 2.9 | 8910 | 4 | | |

Regarding the project Reno, 2 300 mg/kg was the highest test result obtained by soil samples. However, during operation, free phase DNAPL occurred in the extraction systems indicating the presence of concentrations ≥10 000 mg/kg. Additionally, average pre-treatment concentration was back calculated from average end concentrations and used for reporting estimations on content reduction (see Table 5.7). Values for max concentrations in Färgaren and Järnsågen was obtained from graphs.

Table 5.7 presents the estimated mass removal and content reduction. No official estimation on content reduction was reported in the project Kvarnholmen. To obtain an estimation, the presented value in the table was calculated under the assumption that all extracted contamination originated from the TTZ, together with official estimations on remaining contamination in both the saturated and unsaturated zone.

**Table 5.7:** Estimated mass removal and content reduction of primary contaminant in TTZ. Values are provided for media corresponding to the project's measurable remediation targets.

| Site ID | Est. mass removal | Est. content reduction (%) | | |
|---|---|---|---|---|
| | (kg) | Soil | GW | PG |
| Kvarnholmen | 300 | | | ≥99 |
| Färgaren | 1450 | ≥99.9 | | |
| Järnsågen | 250 | | ≥99 | |
| Reno | 119 | ≥98 | 90 | |
| Nymans | 44 | 99 | ≥99.9 | |

An observation from Table 5.7 is that reductions are typically equal or larger than two orders of magnitude. The only exemption in this pattern is the groundwater reduction in project Reno.

### 5.1.5 Energy- and economic performance

The obtained values on energy performance presented in Table 5.8 refer to the total consumption, including the operation of vacuum pumps and other equipment. The data indicates a considerable variation in ERH-performance. TCH-remediation's in fractured bedrock is more energy-intensive compared to project Färgaren. The variation in MWh/kg is far greater than kWh/$m^3$ and the noteworthy low MWh/kg in Table 5.8 is due to the relatively high estimated mass removal presented in in table 5.7 indicating that performance is favored by high contaminant mass. Project Nymans has remarkably high energy consumption in relation ti both the treatment volume and kilograms extracted.

**Table 5.8:** Energy performance of the projects.

| Site ID | Energy consumption | | |
|---|---|---|---|
| | MWh | kWh/$m^3$ | MWh/kg |
| Kvarnholmen | 7761 | 262 | 25.9 |
| Färgaren 3 | 3800 | 240 | 2.62 |
| Järnsågen 3 | 2260 | 300 | 9.04 |
| Reno | 1032 | 178 | 8.67 |
| Nymans | 2064 | 645 | 51.6 |

Table 5.9 presents the project- and ISTT costs. The ISTT cost is defined as the contractor's expense in isolation, i.e. preparatory work, projections, site-restoration, control programs, etc. are excluded from Table 5.9. Trends in the results are weak. A trivial observation is that projects constituting of combined excavation and ISTT-treatment has a lower ISTT cost share.

**Table 5.9:** Cost for project in total and ISTT in isolation together with the the share of the total cost. [a] *Projects with combined excavation and ISTT treatment.*

| Site ID | Project and ISTT-cost (Mkr) | | |
|---|---|---|---|
| | Project cost | ISTT cost | Share (%) |
| Kvarnholmen | 93.0 | 48.0 | 51.6 |
| Färgaren 3 | 52.3 | 25.1 | 48.0[a] |
| Järnsågen 3 | 49.3 | 19.2 | 38.9[a] |
| Reno | 23.1 | 14 | 60.6 |
| Nymans | 18.0 | 15.3 | 85.0 |

Table 5.10 presents the economic performance of the ISTT treatment for each project in terms of cost per unit of volume and contaminant mass extracted. The values were calculated based on the data presented in Tables 5.3 and 5.8 and follows the same trends. The TCH-remediation's performed in fractured bedrock at Järnsågen and Kvarnholmen show both great variation between themselves and inferior economic performance compared to in the soil setting at Färgaren 3. Further. The ERH-project at Nymans show very high costs both compared to the ERH-project at Reno and the TCH-projects.

**Table 5.10:** ISTT economic performance of the projects.

| Site ID | Project economic key-figures | |
|---|---|---|
| | kr/$m^3$ | tkr/kg |
| Kvarnholmen | 1621 | 160 |
| Färgaren 3 | 1569 | 17.3 |
| Järnsågen 3 | 2560 | 76.8 |
| Reno | 2412 | 117.6 |
| Nymans | 5039 | 357.7 |

The cost distribution between different project phases are provided in Table 5.11. Preparatory work refers to tasks leading up to the remediation including site investigations (För- & Huvudstudie) and preparatory investigations (åtgärdsförberedande arbete). Site preparation relates to measures in order to gain sufficient access to the treatment site e.g., manage constructions and subsurface piping on site.

**Table 5.11:** Cost distributions in the five projects expressed in % of total project cost. Unidentified figures are given as "-".

| | Project | | | | |
|---|---|---|---|---|---|
| Phase cost (%) | K | F | J | R | N |
| Preparatory work | 12 | 13 | - | 6 | 4 |
| Projection & management | 27 | 4 | 4 | 7 | 10 |
| Site preparations | - | 12 | 7 | 25 | - |
| Excavation & mass treat. | N/A | 16 | 23 | N/A | N/A |
| ISTT | 52 | 48 | 53 | 60 | 84 |
| Site-reset & Unprovisioning | 8 | - | 9 | >1 | 1 |
| Control programs, Lab-analysis, Follow-up work | 2 | 7 | 5 | 1 | 1 |

## 5.2 Interview results

Figure 5.1 presents the interviews carried out in this study. Conducted interviews include at least one representative from each project. The 15 representations in Figure 5.1 corresponds to 10 individuals due to some actors being involved in more than one project or represents more than one actor. The selected projects were Nymans and Färgaren. The targeted selection of interviewees illustrated in Figure 3.1 have not been fulfilled. Representatives missing is a client- and steering committee representative for project Färgaren and a representative for the supervisory authority in project Nymans. Since project Nymans was privately funded the financier representative was considered to be the same as the client.

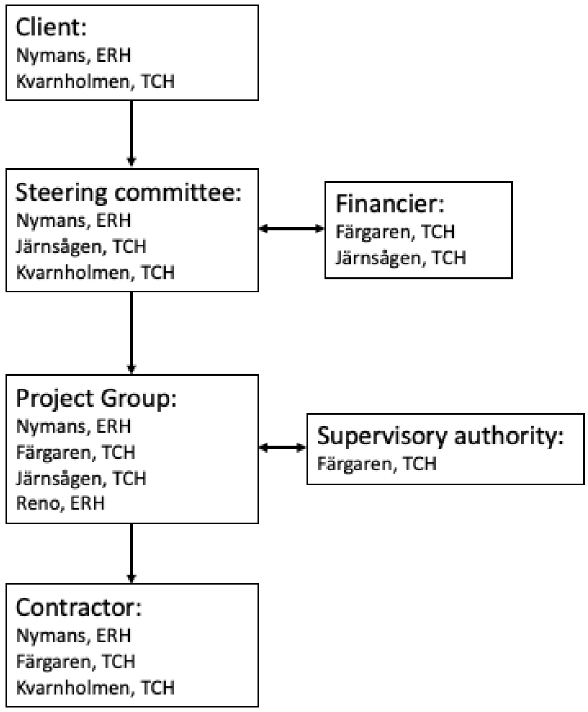


**Figure 5.1:** Illustration of conducted interviews.

### 5.2.1 Project strengths

Tables 5.12 and 5.13 present compiled results on project strengths from all conducted interviews separated by technology. Codes are aggregated in themes and categories based on which aspects they target and whether they relate to the ISTT-technology or the project performance ”in general”. There is no client abbreviation because for all cases the client representative was the same as the steering committee representative. Each table is followed by descriptions of the results in Färgaren and Nymans separately and combined for the remaining projects.

**Table 5.12:** Analysis of perceived strengths in TCH-projects. The interviewees are denoted with abbreviations in the tables where SC is the steering committee, PG is the project group, F is the financier, SA is the supervisory authority and CTR is the contractor.

| | Theme | Codes | Interviewees |
|---|---|---|---|
| Application of ISTT | Characteristics of the technology | Limited impact on local surrounding (noise, pollution, etc) | SC |
| | | Robust and stable method and design | CTR, PG |
| | | Site design possible to adjust during installation phase | PG |
| | | Extensive data collection enabling transparency and well-informed decision making | SC, PG |
| | Installation of equipment | Few obstacles during procedure | CTR, SC, SC, PG |
| | | Managed the large depths in the installation phase | CTR |
| | Results | Completed the remediation on time | SC, SC, F, F |
| | | Achieved the remediation targets | SC, SC, F, F, PG |
| | | Costs withing estimated intervals | SC, SC, F, F, PG |
| Project in general | Performance of specific party or individual | Competent individuals enhanced the project performance | F |
| | | Client commitment facilitated the work. | F |
| | | Effective decision making | SC |
| | | Contractors ability to fulfill client requests and requirements | SC |
| | | Project management and contractors performance | SC |
| | | County administrative board´s commitment | SC |
| | Communication and information | Transparency in ISTT progress and reporting | SC |
| | | Transparent and accommodating culture in organization | F |
| | | Good dialogue with the Swedish EPA | F |
| | Misc. | Project organizations continuity and stability facilitating the work | SA, F |
| | | Project organizations continuity and stability facilitating the work | SC |
| | | Extensive site knowledge enabled well-informed decisions | SA |

## Färgaren

The **Project group representative** started the interview with expressing that the expectations were high. International experience had showed that far-reaching remediation is possible with TCH in conditions similar to Färgaren. Despite this, the final concentration still exceeded the expectations of the respondent. Additional strengths mentioned were the small number of changes and additional work necessary during execution, and thus the estimations of both costs and performance were as realised. The project representative further highlighted the contractor's ability to measure extracted contaminants and that these measurements enable relatively accurate estimations on how much contamination was present in the area pre-treatment.

The **Contractor representative** in project Färgaren recognized the site design and smooth execution as strengths in the project. Customizing and carefully designing installations and layout based on site-specific conditions is believed to pay off during execution (e.g. by preventing- and improving the possibility to manage problems).

The **Financier representative** highlighted the final concentration as a project strength and that the treatment progressed in a manner that met their expectations. Apart from the ISTT-execution, the representative considered the project organization in its entirety as another strength. Actors with the superior experience won the procurement, there was a continuity in the project personnel, and the commitment of the client (the municipality in this case) was pointed out as an essential factor for the project success. As a final remark, the facility's location was lifted as an enabling factor with emphasis on the lack of existing constructions and residents on site and in the near surrounding.

The **Regulatory authority representative** raised the preparatory work as a critical prerequisite for project success. Project Färgaren was preceded by ten years of investigations that created a basis for decision-making. Like the financier representative, the project organization was mentioned as an important factor with emphasis on continuity. Having the same group of individuals is considered to have enhanced the ability to build up both competence and trust.

## Järnsågen & Kvarnholmen

The project Järnsågen is considered a highly successful remediation in terms of execution and results. Like Färgaren, the limited number of changes, additional work, and extensive data collection were lifted as a strength. Further similarities between the projects up-sides were the view on the client commitment as key. The county involvement and competence provided by the consultant hired as support was mentioned as notable actor performances in Järnsågen. Other general aspects specifically mentioned regarding Järnsågen was the transparent and accommodating culture in the organization. The project was granted funding at an early stage, facilitating the communication with the public. Questions and information were managed admirably, both internally and towards local residents. On the technical side, the flexibility in localisation of the wells during the installation phase was lifted as a positive aspect. The locations of the wells could be adjusted after sampling the borings and improve the demarcation of the treatment zone. The remediation process entailed limited impacts on the local surrounding, which was also perceived as a positive feature of the technology and the project.

Project Kvarnholmen was the deepest remediation at the time but despite the technical challenges, the installation-phase and treatment was conducted according to plan with small friction. Underlying factors mentioned were similar to Färgaren as the site-design and planning were lifted as a project strength. The representative from the client highlighted transparent communication and reporting of measurements by the contractor, and that the procured contractor managed to stick to the estimated timeline and budget. Effective procurement and decision-making were lifted as general strengths to.

**Table 5.13:** Answers regarding strengths in the ERH-projects. The interviewees are denoted with abbreviations in the tables where SC is the steering committee, PG is the project group, F is the financier, SA is the supervisory authority and CTR is the contractor.

| | Theme | Codes | Interviewees |
|---|---|---|---|
| Application of ISTT | Characteristics of the technology | Possible to perform in dense/urban areas | CTR, PG |
| | | Good possibilities for adjustment and steering | CTR |
| | | Simulations and modelling enabling accurate estimations | CTR, PG |
| | | Extensive data collection enabling transparency and well-informed decision making | CTR, SC |
| | Results | Completed the remediation on time | SC |
| | | Achieved the remediation goals | PG |
| | | Costs withing estimated intervals | PG |
| Project in general | Performance of specific party or individual | Contractors ability to fulfill client requests and requirements | SC |
| | | Project management and contractor performance | SC |
| | Communication and information | Transparency in ISTT progress and reporting | SC |

### Nymans

The **Project group representative** for Nymans raised the numerical simulation utilized by the ERH-contractor as a strength in the project. The simulation generated accurate estimations on a variety of parameters such as treatment duration and energy consumption. Another strength of the project was the generated results and the successful implementation of the technology in an urban area without moving subsurface cables and piping.

The **Client representative** highlighted the competence and support provided by the external management consultant and the procured contractor throughout the project. The procured contractor satisfactorily responded to client demands, updated, and communicated the remediation progress in a transparent manner. An additional positive part from the representatives perspective was that the remediation process kept to the set time frame.

The **Contractor representative** voiced the numerical simulation as one of the project strengths, like the project representative. Additional features provided by the simulation apart from parameter estimations are that the simulation could be used as a reference to the actual progress. For instance, a deviation in the heating pattern in a specific volume may be compensated directly by adjusting the power input in that region, increasing the control of the treatment. Like the project representative, the successful implementation of the technology in an urban area was lifted as an achievement as well.

### Reno

The **Project group representative** raised the fact that Reno was one of the first remediation's using ERH nationally. Attaining the measurable remediation targets on a facility with a building is perceived as the main strengths of the project.

## 5.2.2 Project challenges and weaknesses

Figures 5.14 and 5.15 present compiled results on project challenges and weaknesses from all conducted interviews separated by technology. Codes are aggregated in themes and categories based on which aspects they target and whether they relate to the ISTT-technology or the project performance "in general". There is no client abbreviation because for all cases the client representative was the same as the steering committee representative. Each figure is followed by descriptions of the results in Färgaren and Nymans separately and combined for the remaining projects.

**Table 5.14:** Analysis of challenges and weaknesses in the TCH-projects . The interviewees are denoted with abbreviations in the tables where SC is the steering committee, PG is the project group, F is the financier, SA is the supervisory authority and CTR is the contractor.

| | Theme | Codes | Interviewees |
|---|---|---|---|
| Application of ISTT | Characteristics of the technology | Treatment caused rising of the groundwater table and flooding of the water treatment plant | CTR, PG |
| | | Entrainment of particles in the extraction vapours caused problems in the treatment plant | PG, CTR |
| | | Time gap between sampling and lab-analysis delayed the detection of malfunctioning filters | SA |
| | Installation of equipment | Misplaced wells | SC |
| | | Scarce number of control sampling wells in the plume area - limited monitoring | SC |
| | | Delays due to other ongoing activity on site | SC |
| | | Some abnormalities could have been avoided if contractor had higher presence on site | SA |
| Project in general | Preparatory work | Inability to quantify DNAPL in rock | PG |
| | Project time-line | Delays in procurement due to appeals | F |
| | | Long project duration | F |
| | | Delays due to conflicts | F SC |
| | Communication and information | The inherent risks of using new/advanced and expensive technology - ability to defend costs | SC |
| | | Building the project organization | SC |
| | | Information asymmetry - project relied on a few key individuals | SA |
| | | Communicating information outwards to the public | SC |
| | Misc | Supervision protocol - level of involvement by the regulatory authority | SA |

## Färgaren

The **Project group representative** raised groundwater management as a project challenge. In the early stages of the project, a draw down of the groundwater table was believed to occur due to the vaporization and extraction, forming a groundwater gradient towards the treatment zone. During operation, the contrary happened as the expanding forces due to the heating process and the locally reduced pressure created by the extraction system caused a rise of the groundwater table. Combined with the already shallow levels, the elevated groundwater generated a risk of flooding the water treatment plant, enforcing additional measures to be implemented. Another technical challenge that emerged during the operation was a high level of particles in the extraction system, negatively affecting the treatment plant. The cause of the issue was a shallow layer of clay resulting in particle entrainment.

The **Contractor representative** voiced the same challenges as the project representative and that the prevailing circumstances forced the system to be operated at a lower power input than designed for, to sustain a stable extraction.

The **Financier representative** raised the aspect that although the ISTT-treatment is relatively quick, this category of remediation still takes a considerable amount of time considering the preparatory work, procurement, and accountability questions.

The **Regulatory authority representative** found it sometimes challenging to respond to or challenge the competence and flow of information within the project. The level of involvement in order to conduct appropriate supervision was heavily discussed, and the authorities relied on the project management and their control. An issue identified during operation was the time gap between the control sampling of the treatment plant and the laboratory response which delayed the detection of malfunctions.

## Järnsågen & Kvarnholmen

The project Järnsågen faced technical challenges in assessing the level of contamination. Current methods feature the possibility to determine whether free phase TCE/PCE is present in fractured bedrock. However, it is not possible to quantify the mass very exact, leading to uncertainties about the risks. The contamination in Järnsågen had also formed a plume of contaminants in the groundwater but the limited number of wells available in this area restricted the monitoring. General challenges in the project consisted of conflicts, lack of competition, and the limited experience. The main conflict revolved around a disagreement about groundwater management delaying the project by 1.5 years. The fact that only one contractor delivered the desired ISTT-services at the time required a different procurement process. The limited experience (regarding ISTT-remediation project) posed challenges in structuring the project organization. The project management further highlighted the importance of monitoring and managing expenses and to be aware of the risks of involving new, advanced, and expensive technologies. In public projects such as Järnsågen, the project management must be able to defend costs on one side but can not challenge each bill on the other.

Project Kvarnholmen faced challenges during installation and implementation. Some wells were misplaced and other on-going activity at the site caused both delays and damaged equipment.

**Table 5.15:** Answers about challenges and weaknesses in the ERH-projects. The interviewees are denoted with abbreviations in the tables where SC is the steering committee, PG is the project group, F is the financier, SA is the supervisory authority and CTR is the contractor.

| | Theme | Codes | Interviewees |
|---|---|---|---|
| Application of ISTT | Installation of equipment | Subsurface equipment failure and clogged extraction wells | PG |
| | | Drilling issues | PG |
| | | Other on-going activity hampering the installation | SC |
| | Results | Incomplete remediation and malfunctions forced change of remediation targets | PG |
| | | Poor initial energy estimations | SC |
| | | High kWh/kg contaminant-ratio | SC |
| Project in general | Preparatory work | Inaccurate subsurface pipe blueprints hampering installation | CTR |
| | | Few sampling points leading to uncertainties in contaminant situation | CTR, PG |
| | Project time-line | Delays in procurement | SC |
| | Communication and information | Information asymmetry, project relied on a few key individuals | SC |

## Nymans

The **Client representative** voiced the final extracted mass as an anticlimax for the project as very expensive measures resulted in limited improvement. The respondent further voiced concerns regarding the initial estimations (before the numerical simulation) on energy consumption as it deviated heavily from the actual case. Further challenges in the perspective of the respondent consisted of an appeal in the procurement procedure causing delays. Since there was another ongoing activity on the site to consider, the time delay caused issues in the project plan.

The **Contractor representative** raised the uncertain site settings and prerequisites as the main challenge in the project. Inaccurate blueprints on subsurface cables and piping posed problems in well-deployment, hence delaying the project. Uncertain oil presence caused difficulties in parameter estimation, dimension the treatment plant, and required additional measures during operation.

## Reno

The Reno project faced challenges in attaining the measurable remediation targets. The subsurface equipment suffered from malfunctioning as the slots in the extraction system clogged. The operational issues resulted in unachieved remediation targets, and the inability to prolong treatment further forced a change of remediation targets. The purpose of the remediation was to secure non-hazardous concentration in the building on the facility. Changing the measurable targets from soil to air quality in all parts of the building verified that the remediation was sufficient.

### 5.2.3 Perceptions and lessons learned

The observable trend in project strengths presented in Table 5.12 and 5.13 is the actor distribution of between general- and ISTT-themes. Actors involved in the application and execution of the technology identifies ISTT-aspects as project strengths to a greater extent than actors not working directly with the technology. There is, however, one major and two minor deviations from this pattern. The major deviation is related to the theme results where both the recurrent mentioning and variation of representatives stand out. The only main actor group not mentioning results explicitly as a project strength is the contractor and the regulatory authority. The two, less significant, deviations regards ISTT features and implementation, as the management in the projects, i.e. the project group and steering committee representatives highlights the data collection and smooth operation recurrently.

Trends in the answer distribution for the project challenges (in 5.14 and 5.15) is similar as for the project strengths but weaker. There remains a pattern in which actors involved in the on site activity identifies ISTT-themes as challenges of the project. Financier-representatives continue to highlight general project aspects, but client/steering committee, project group, and regulatory authority show a relatively even distribution between the two. Further observations is that both the number of themes and codes identified are similar for project strengths and challenges. The absolute number of identified challenges is, however, less than for project strengths i.e., actors mentioned more strengths than challenges on average. A set of positive and negative perceptions were decoded from the interviews results. These were identified based on the number of actors that expressed opinions or reasoning in line with the given statement, where the positive and negative perceptions with the most widespread support are listed below.

**Positive perceptions**

- Can reach low final concentrations.
- Applicable in all soil- and rock materials.
- Can treat a wide range of contaminants, simultaneously.
- Robust technology.
- Feasibility is relatively unaffected by contamination depth.
- Flexible installation-phase / adjustable site design.
- No need for off site treatment or land filling.
- Sustainability potential: solutions involving the use of ISTT have scored high in multi-criteria assessments.
- The treatment process can be measured and observed and hence provide good control.

**Negative perceptions**

- Costly.
- Energy intensive.
- Requires high power delivery on site.
- Only decontaminates within the treatment zone.

The Swedish perceptions of the technology identified in this study correspond well with the advantages and disadvantages found i literature (section 2.5.1 and 2.5.2). Only single statements with new perceptions was obtained, targeting positive aspects of the technology in terms of: flexibility during installation phase in that the well positioning could be adjusted to new findings far in to the installation process and high scores in multi-criteria calculations suggesting that ISTT may play a role in achieving sustainable remediation solutions.

When asked about key experiences and lessons learned, 5 out of 10 representatives where able to respond with specific events. Remaining interviewees referred back to project strengths and weaknesses and is excluded from this section to avoid repetition.

One noteworthy lesson learned revolved around the effect of groundwater flow. Although the groundwater flow underneath the thermal treatment zone caused considerable heat loss and prevented targeted treatment temperature, a significant remediation was still achieved in sections where the target temperature had not been attained. This suggests that flushing with heated water have contributing effects to the remediation. Another project representative stated the importance of keeping in mind that chlorinated solvents are rarely found alone. Historically, chlorinated solvents has been used for various degreasing processes and that oils, fats and other substances are most likely to be present as well and should thus be considered when designing the treatment plants. The same observation was made by an additional respondent but from a different perspective. Management of variations in the extracted gas (presence of oil and other compounds) could be better accounted for if there was a way to continuously analyse the extracted gas with sufficient accuracy, for instance gas chromatography (GC). Gains from such system would consist of reduced wear and damage on equipment and better purification of the gas stream before going to the exhaust. However, the technical challenges are many. Taking GC as an example, the presence of contaminants, oils, air, moisture and other compounds constantly changes in the extracted gas, and must be adjusted for accordingly in order to maintain the baseline and accurate results.

Lessons learned also included experiences revolving around communication. Two respondents in managing roles voiced the importance of approaching the local residents at an early stage, i.e. to treat concerns and unease of the project and technology before any resistance emerges. It was further stated that having the funding granted for the entire project at an early stage facilitated this communication in contrast to the case when the funding is provided in bits. This reasoning was further motivated by ISTT being a relatively new technologies that required economic muscles which may affect the way that the remediation decision is received among residents.

### 5.2.4 Cost drivers and desired development

In an attempt to shed light on the most time and cost volatile parts in Swedish ISTT-projects, respondents were asked what they considered to be the main drivers. Answers are summarized in Table 5.16. Four out of ten respondents where able to identify a particular phase or activity as cost driver in their respective project.

**Table 5.16:** Challenges in time and cost estimates

| |
|---|
| Conflicts |
| Prices from tenderer |
| Procurement appeals |
| Preparatory work, how much investigation is needed |
| Electricity prices |
| Drilling |
| New obstacles / First times |

# 6 Discussion

This chapter aims to discuss the findings of the document study and conducted interviews. First, results from each study are treated with a focus on trends and patterns. After the results have been covered, the discussion moves on to some suggestions of considerations for further studies. The chapter ends with some final remarks regarding ISTT, and it's role in Swedish soil remediation projects.

## 6.1 Document study and interview results

The operational results can be presented in various ways due to the amount of data in these projects. The selection of operational results focuses on providing a sufficient picture of the temporal- and temperature differences among the projects as these patterns were highlighted as important by actors involved with the technologies. How data was presented deviated between the projects and temperatures and duration could not be uniformly compiled. Some projects presented data in terms of average values for zones, while others reported the progress of the thermal treatment by depth. In terms of providing an accurate representation of heating patterns, raw data sheets for all projects would have been the preferred basis. Unfortunately, the untreated data was not attainable for all projects and thus some treated or aggregated figures were used instead. The comparison of raw data and aggregated values affects the accuracy of the results presented in Table 5.5. Particularly the values for maximum temperature in the thermal treatment zone which had the largest difference in the resolution of raw data between the projects. Nevertheless, the results gives an idea of the temperatures possible to obtain and the variations that can be expected. A final remark is that along with that the technology gets more established, the reporting of results will probably, or at least should, be more unified.

In terms of attained remediation, the values in Table 5.7 indicates that the Swedish projects are well in phase with the claimed performance in literature and international experience. The treatment duration's (Table 5.5) and corresponding well spacing (Table 5.4) for the TCH projects show slightly slower treatment than heuristic models (see appendix A.1). However, these values are dependent on site specific conditions and Table A.1 adapted from Kingston et. al. [5] includes no disclosure for under which conditions the estimations are accurate.

There is a trend between economic performance in Table 5.10, efforts put in to preparatory work in Table 5.11 and answers in the interview. In the project with the best economic and energy performance, Färgaren, the preparatory work had the highest share of the total project cost and the preparatory work was voiced as a prerequisite for the success in the interviews. For example, one statement that is arguably interlinked with the perceived strength in project Färgaren was: customizing and carefully designing the technology based on site-specific conditions. Looking at the other end of the scale, a anticlimax regarding the extracted contaminant mass, and uncertainties in the soil- and contaminant situation when starting the treatment was perceived. This reasoning is supported in literature where refinement efforts to increase understanding of geology and accuracy in treatment volume is lifted as a good investments [15]. However, this is not the only correlation between these numbers, and to adequately justify the trend, further investigation is required. For instance, a correlation also exists in terms of treatment volume, where the projects with larger treatment volumes perform better, indicating some economy-of-scale effect. There is also a set of site specific attributes and prerequisites that are important to keep in mind in this assessment. For instance, project Nymans which showed poor economic performance was also the only site for which the delimitation of the treatment zone led to more than one area. Separated treatment regions result in larger surface areas in relation to treatment volume, which in turn leads to higher energy losses. In literature, the boundary and the minimizing of the treatment area are lifted as a critical considerations for reducing remediation costs [15]. In terms of efficiency, such as $kWh/m^3$, the performance is undoubtedly negatively affected. Finally it is important to consider technology. Although two projects deploy the same type of technology the equipment and systems may be of varying quality. Taking the ERH-projects as an example, the technology used in Nymans was significantly different compared to Reno, although both are based on ERH. One example is the choice of materials where, for instance, the extraction wells in Nymans where made in stainless steel with superior durability compared to the epoxy wells installed at Reno. Nymans also artificially created a water flow between the heater and extraction wells which significantly reduced the issue of clogged slots (a problem faced at Reno) together with enhanced electrical conductivity. Combined, this resulted in Nymans treatment duration being close to half of the one in Reno and with superior final concentrations.

Based on results in Table 5.6 together with discussions in the interviews, there is some inherent differences in results depending on for which media (soil, groundwater or pore gas) the measurable remediation targets are expressed. For soil concentration, contaminants adsorbed to soil particles, dissolved in groundwater, and as vapours in pores are all accounted for, eliminating risks for re-contamination and providing superior accuracy in estimation of contaminant mass. The main downside with this type of sampling is that it is not integrative, which means that the soil samples only tell the situation in that particular volume. The effect of this is that a large amount of samples is required to create a statistical foundation for the treatment volume (Note: this is a simplification of reality where more that one ”type” of samples is commonly used for assessments, including screening methods). Groundwater and pore gas samples, on the other hand, are to some degree integrative. Extracting one cubic meter of groundwater from a sample point is representative of a larger volume. However, contaminants adsorbed to soil particle surfaces and trapped in awkward spaces are left unaccounted for and may diffuse back into the gas/liquid-phase after the completion of the remediation treatment.

Commenting on delays and the difficulties in procurement, appeals where expressed as common. Based on discussion from the interviews it appears that underlying reasons include that the decision making in the procurement process is subjective combined with the uniqueness and the economic scale of the projects. In the selection process the tenderer´s offers are subject to a review by the client and any consultants hired as support. And as the decision is made, it was voiced that there is no real down side for the losing party to appeal the decision. But this issue transcends ISTT-projects and the scope of this thesis and is a case for further research on the challenges of public procurement [37, 38].

The interview results shows a pattern in answer distribution where the contractor and other actors that worked close to the ISTT recurrently mentioned properties of the technology, whilst representatives that operated more distant from the on-site activity voiced more general project aspects. It is not surprising that the contractor avoids commenting the results as it is their expertise, and that the steering committee, who is responsible for a lot more than the technology itself, voices more general items such as results. The interview template contained questions that targeted strengths and challenges both on a project- and technology level but this was evidently not enough to attain answers distributed accordingly. If this pattern was anticipated, the interviewee could have been better guided through the different interview questions.

## 6.2 Considerations for future ISTT-projects

One of the research questions in the scope targeted the monitoring programs implemented in Swedish ISTT-projects. The question was investigated in both the document study and through four questions in the interview template. However, no comprehensive comparison was deemed feasible as the programs are tailored for each site and was primarily based on the experience of the consultant. The time span of the ISTT projects varies between 3 to 10 years with a sampling frequency ranging from single measures to a few occasions annually. The program is typically suggested by consultants hired as client support, technical project leader, or similar, and are reviewed among actors within the project organization before being implemented. The underlying philosophy of the programs was expressed by one project representative to be a monitoring program over a long duration with relatively low test frequency to ensure that the end result is kept at an economically feasible cost. The somewhat arbitrary nature of the monitoring programs is probably a result of many different factors. The limited available expertise and concentrated knowledge base can be seen as a factor and that standardized procedures are yet to be developed. Following the same reasoning regarding the information asymmetry expressed by actors operating more distant from the on-site activity: the concentrated experience may pose challenges for the remaining management to adequately review site monitoring propositions post remediation and yield higher risk of errors performed by the monitoring program developer to pass unnoticed. With that said, the situation of assessing monitoring programs will most likely be subject to improvement in future projects. As more ISTT-projects are completed, more experiences become available that can facilitate the critical review of propositions on monitoring programs.

Signs of development can already be observed, as there seems to have emerged some disagreement regarding what to include in the monitoring programs. Some actors argues that the monitoring should stick to the targeted contaminants and monitor the changes over a time period sufficient to determine the result and completion of the project. Others find that monitoring should include additional attributes of the treatment zone as well. These attributes include, for instance, the effects on biological life and geology of the temporary, but very elevated, temperature. The advocates motivates the inclusion could increased the understanding of the effects related to thermal treatment and provide additional setting in which ISTT-solutions is preferred and not. To this date, none of the conducted projects with completed or still active monitoring programs have included these attributes so far.

## 6.3 The role of ISTT in Sweden

The experience on ISTT-projects is still arguably limited, posing challenges in providing a complete picture of the state of the art application. Despite the limited number of implementations, the projects conducted nationally contain globally unique achievements such as the crystalline bedrock setting in Järnsågen and unique depth of the TTZ in Kvarnholmen (soon to be beaten by the ongoing activity in Varberg [39]). However, the geological settings and contamination for which the technology has been deployed are rather specific. All the Swedish projects targets the remediation of chlorinated solvents on sites characterised as more or less impermeable sediments, and great depths. Explanation for this fact, both supported in literature and further confirmed by the interview results, might be the costs. Required monetary investment is considered one of the most common draw backs [5, 6]. The average cost of publicly funded excavation remediation projects revolves around 1100-1400 kr/m$^3$ which is significantly lower than most numbers presented in Table 5.10 [9].

The question is if this is an appropriate comparison. Results obtained in question 5a of the interview template: *"what is the most important factors in order to select ISTT as remediation approach"* which rather ended up in discussions about *"why was ISTT selected for this particular project"*, the answers commonly landed in the conclusion that no other alternatives where deemed feasible. For instance, project

Nymans was occupied by buildings with cultural heritage status hampering the possibility of excavation. Färgaren faced geological settings complicating excavation and was interested in a time-frame ruling out alternative in-situ measures. ISTT was thus considered, the only and most cost-effective treatment. As a final remark on this topic, one contractor representative lifted this reasoning and further clarified that the statement on ISTT being the most cost efficient solution, has no intention to draw focus from the fact that the technology is expensive. But that it is arguably relevant to include other economic references than remediation approaches deemed as inadequate when assessing the costs.

# 7

# Conclusion

To conclude the findings of the thesis, some brief answers are provided to each of the research questions provided in section 1.1.

1. To what degree is the contamination reduced in Swedish SITT-projects?
   - Decontamination attained in Swedish ISTT-projects are in line with results found literature and international experience. Reductions for all remediation targets is in the range of 98-99.9% except one. Both ERH and TCH were able to attain far reaching results.
2. Under what conditions have the technology been proved to work well and less well?
   - Geological conditions of Swedish ISTT-projects can be described in generalized type-settings as 1. *High- to moderate permability sediments. Relatively homogeneous*, 2. *Moderate- to low permability sediments interbedded with increasingly permeable layers and lenses*, and 3. *Fractured bedrock*. Contaminants treated are limited to chlorinated solvents, mainly TCE and PCE. In the final remediation results, all projects have been successful but the efficiency in attaining that, is subject to great variation. Biggest negative impact on efficiency indicators such as $MWh/kg$ of removed contaminants is deemed to be large surface area of the thermal treatment zone in relation to the volume. It was further observed that treating sites with high groundwater table and sediments with high water-content pose technical issues due to particle entrainment.
3. What are the perceived strengths and challenges experience in Swedish ISTT-projects?
   - Data collection and the good results are the most recurrent mentions. On average, actors identified more positive than negative aspects although the number of codes identified is similar. Benefits of data collection targets most of the main actors since it provides a sense of control over the progress, facilitates communication and enables well informed decisions. The results are highlighted both in terms of execution (according to plans and estimations) and final concentration.

4. Can any time- or cost drivers be identified?
    - The majority of the time- and cost drivers identified are deemed to take place in the preparatory phase of the projects including: appeals during procurement caused significant delays for some projects, prices from tenderer was subject to significant fluctuations and unease and criticisms from local residents which required additional efforts.
5. How are the post-remediation monitoring programs designed?
    - Follow-up programs implemented on completed ISTT-projects are subject to great variation. The follow-up period found in current experience range from 3 to 10 years. The sampling frequency varies from single occasions to quarterly and monthly measurements. Any form of standardised method or approach is yet to be developed. There are different philosophies regarding the focus of the monitoring programs with some actors argues for the inclusion of other aspects than only the control of the remediation targets. These other aspects are for example the effect on geology and biological life in treatment zones.

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# A

# Appendix

## A.1 Interview template

Syftet med detta examensarbete är att sammanställa svenska termiska in-situ-saneringsprojekt(ISTT) med mål att ge erfarenhetsåterföring. Arbetet består av två delar; en kvantitativ dokumentanalys av offentliga publikationer rörande projekten och en kvalitativ analys i form av intervjuer. Målet med intervjuerna är att samla in olika perspektiv på teknikens användning i Sverige samt att komplettera/nyansera innehållet i dokumentanalysen.

Intervjuerna kommer hållas under semi-strukturerade former d.v.s att samtalen ej strikt kommer begränsas till intervjumallen. Jag vill därför uppmuntra till att ta upp erfarenheter, reflektioner eller åsikter under intervjun som ej behandlas i intervjumallen som ni anser vara relevant för projektets mål. Längden på mötet beräknas vara mellan 30-60min och genomförs via prioriteringsordningen: 1. Video-samtal, 2. Telefon-intervju, 3. Mail. Frågorna i intervjumallen presenteras på kommande två sidor.
Om du godkänner kommer samtalet att spelas in med mikrofon för att underlätta

bearbetning av materialet. Efter intervjun kommer sammanfattande anteckningar skickas ut för godkännande. Samtliga deltagare kommer att anonymiseras i rapporten och innehållet från mötena kommer presenteras främst i form av parafrasering, citering och i tabeller.

### A.1.1 Frågor

1. Vänligen presentera dig själv! (Ex: Namn, Utbildning, Sysselsättning)
2. Redogör för vilket/vilka projekt ni varit involverade i samt vilken position.
3. Vad anser ni var projektets styrkor, vad gick bra?
4. Vad gick mindre bra, vilka utmaningar stötte ni på?
5. Vad är din syn på ISTT som saneringsmetod? (Ex Styrkor, Svagheter)
    (a) (Angående valet av teknik) Vad anser ni vara de viktigaste faktorerna för att välja ISTT som saneringsmetod?
6. Någon särskilld erfarenhet eller läxa du tagit med dig efter att ha deltagit i projektet(en)
    (a) (Angående teknikens prestation och utveckling) ISTT saknar reella konkurenter under vissa förhållanden, t.ex sanering av berg. Anser ni att detta är något som påverkar tekniken? (Ex. Utveckling, Prestation)
7. Vilka delar av projektet anser ni är svårast att uppskatta när det kommer till tid och kostnad?
8. I vilka delar, av de projekt ni deltog i(eller generellt), anser ni att det finns störst utvecklings-/förbättringspotetial?

**Frågor gällande kontrollprogram**

1. Beskriv processen för framtagandet av kontrollprogram.
2. Beskriv beslutsprocessen för avgörandet om en site är klar eller behöver fortsatta åtgärder.
3. Anser ni att kontrollprogrammet(en) är på en bra nivå gällande t.ex tidsram och testfrekvens?
4. Gällande uppskattningen av kvarvarande föroreningsmassor och spridning, hur säkra skulle ni säga att dessa uppskattningar är?

Tack!

## A.2 Data and measurements

| Contractor monitoring program | | |
|---|---|---|
| Control Subject | Frequency | Measurement technology |
| Pore gas VE | 3rd min | GC-online |
| Pore gas VE | 14:e day | Carbon filter, LAB |
| Pore gas VB | 14:e day | PID |
| Porgas Carbon-1 | 3rd min | GC-online |
| Porgas Carbon-1 | 14:e day | Carbon filter, LAB |
| Pore gas UT | 3rd min | GC-online |
| Pore gas UT | 14:e day | Carbon filter, LAB |
| Groundwater VE | 14:e day | LAB |
| Groundwater Carbon-1 | 14:e day | LAB |
| Groundwater UT | 14:e day | LAB |
| Vacuum | 14:e day | Vakuum gauge |
| Soil temperature | hour | Temperature gauge |
| Saftey inspection | 14:e day | Ocular |
| Power / Energy | hour | kW/kWh gauges |
| Air flow | hour | m3/h |
| PCE in extracted air | monthly | Pore gas VE Volume |
| PCE in groundwater | monthly | Groundwater VE Volume |

**Figure A.1:** Example of contractor monitoring recreated from the remediation report in project Reno [52]. Abbreviations: VE refers to vacuum extraction, VB to vacuum boring/well, LAB stands for Laboratory analysis and GC is short for gas chromatography.

| External inscpection | | |
|---|---|---|
| Control Subject | Frequency | Measure tech |
| Porgas PIPE | 6 times | LAB |
| Grundwater PIPE | 6 times | LAB |
| Indoor Air | Pre,During,Post | LAB |
| Soil | Post | LAB |
| Indoor Air-Long time | 3month-1yr | LAB |
| Groundwater-Long time | 3month-1yr | LAB |
| Ground Settlement | 3rd month | Balance |

**Figure A.2:** Example of external supervisory monitoring recreated from the remediation report in project Reno [52].

## A.3 ISTD well spacing

**Table A.1:** Relation between well spacing and typical treatment duration for ISTD of CVOC source zones, adapted from Kingston et. al. (2010).

| Heater well density (well/$m^2$) | Treatment duration for CVOC source zone (days) |
|---|---|
| 0.108 | 60-80 |
| 0.075 | 90-120 |
| 0.048 | 120-180 |
| 0.027 | 300-400 |

**Table A.2:** Summary of measurable remediation targets. [a] *Project Kvarnholmen had different remediation targets depending on depth and distance from source zone.* [b] *Remediation target for the groundwater was set to 90% of the initial concentration.*

| | Remediation targets | | |
|---|---|---|---|
| Site ID | Soil (mg/kg) | GW ($\mu$g/l) | PG (mg/$m^3$) |
| Kvarnholmen | | 14000-61000[a] | 134-290[a] |
| Färgaren | 1 | | |
| Järnsågen | | 5200-12000[b] | |
| Reno | 2.1 | | |
| Nymans | 4.3 | | |